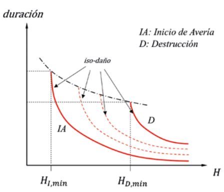
SERIES 1 Works for shielding against the oscillations of the sea

TRANSLATED VERSION OF THE ORIGINAL SPANISH TEXT

RECOMMENDATIONS FOR MARITIME WORKS



ROM 1.1-18

(Articles)

Recommendations for Breakwater Construction Projects

Puertos del Estado

GOBIERNO DE ESPAÑA
MINISTERIO DE FOMENTO

ROM 1.1-18

[Articles]

Recommendations for Breakwater Construction Projects

Print Version 1.5
30 October, 2018

EDITION:
Puertos del Estado

DRAFTING COMPOSITION:
Miguel Á. Losada
With the collaboration of the Environmental Fluid Dynamics Research Group (GDFA), Andalusian Institute for Earth System Research (IISTA), University of Granada.

ENGLISH TRANSLATION:
Pamela Faber
University of Granada

PRE-PRESS:
Cillero & de Motta

PRINTER:
Calidad Gráfica Araconsa for Cillero & de Motta

I.S.B.N.:
978-84-88740-12-0

www.puertos.es/es-es/ROM

Index

SECTION III: PROCEDURE FOR BREAKWATER PROJECTS

SECTION IV: VERIFICATION OF THE BREAKWATER IN A PROJECT PHASE

SECTION V: EVALUATION OF COSTS, OPTIMIZATION AND RISK LEVEL

APPENDICES

Figures

SECTION I: INTRODUCTION, GENERAL FRAMEWORK AND ORGANIZATION OF THE ROM 1.1-18

SECTION II: SPECIFIC PROJECT BASES

SECTION III: PROCEDURE FOR BREAKWATER PROJECTS

SECTION IV: VERIFICATION OF THE BREAKWATER IN A PROJECT PHASE

SECTION V: EVALUATION OF COSTS, OPTIMIZATION AND RISK LEVEL

Tables

SECTION I: INTRODUCTION, GENERAL FRAMEWORK AND ORGANIZATION OF THE ROM 1.1-18

SECTION IV: VERIFICATION OF THE BREAKWATER IN A PROJECT PHASE

Preamble

Recommendations for Breakwater Construction Projects (ROM 1.1-18) completes the regulatory framework of Puertos del Estado for maritime infrastructures that protect land areas against marine dynamics (i.e. wave oscillations). It is a revision and expansion of the ROM 0.0-01 and ROM 1.0-09, which incorporates the following main innovations:

1. Integration of technical tools (in Spain, the ROM Program) and financial and economic tools (in Spain, MEIPOR-16) to coordinate breakwater construction projects (or any other maritime infrastructure) with the investment project of the harbor area and planning objectives (see Sections 1 and 5).
2. Linking of technical recommendations (ROM) to economic recommendations (MEIPOR) in a dual technical-economic optimization system, subject to safety and operationality requirements as well as financial-economic investment requirements, contingent on an acceptable risk and sensitivity analysis (see Sections 1 and 5).
3. Organization of the social and environmental, and technical-economic design process in stages of increasing complexity and decreasing uncertainty, beginning with exploratory studies and ending with the construction and investment projects of the breakwater. This also depends on the level of expertise of the participants as well as the minimum project execution times (see Sections 1 and 2).
4. Hierarchization of the breakwater in spatial area, subsets (or systems), subsystems, as well as operational stoppage and failure modes, and their integration with a temporal description in terms of states, loading cycles, years of useful service and the financial-economic life of the structure (see Sections 2 and 3).
5. Unification of the ultimate and serviceability limit states to verify failure modes and adjust the criteria for the distribution of the joint failure probability (see Sections 3 and 4).
6. The general incorporation of the evolution of damage and repair strategies with cost analysis in the technical-economic design model of breakwaters, such as the three elements that are necessary to formulate and resolve the dual system of technical-economic optimization (ROM) and of economic-financial optimization (MEIPOR) (see Section 4 and 5).

The methodology applied in the ROM 1.1-18 is described in the ROM 0.0-01. With all of its specificities, it reinforces and is the driving force behind the conservation, repair, readaptation and dismantling of port and maritime works. It also points to the need for experimental studies to verify Construction and Investment Projects (of whatever type) and to map out new basic research lines that will help to revise current recommendations and create new ones. The international prestige of the ROM program is an additional motivation to attain these objectives. The basic premises of this methodology can be found in a wide range of books on reliability and risk theory as well as in numerous technical articles. The most relevant of these references are cited throughout this ROM and listed in one of the annexes.

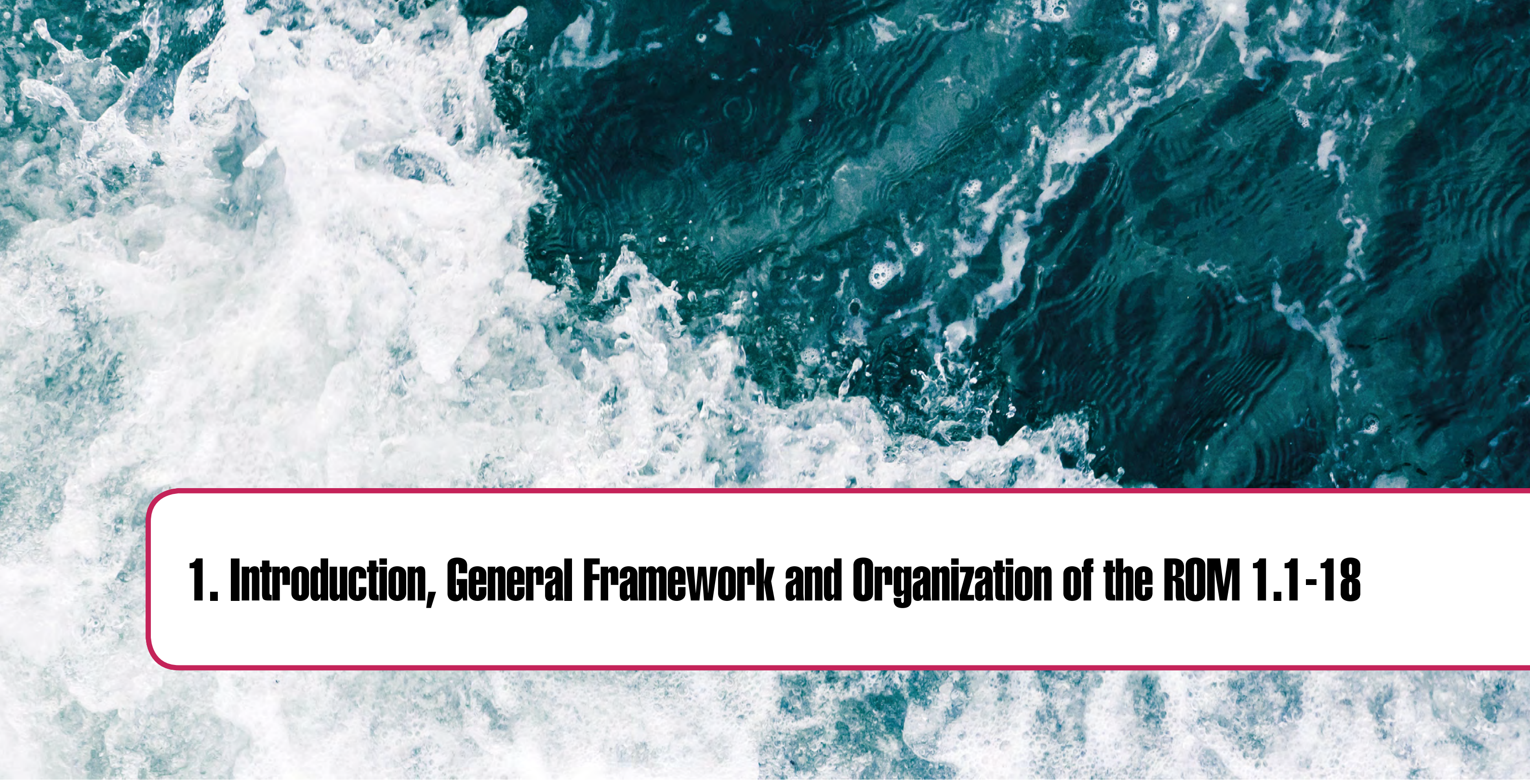
When applying the ROM 1.1-18, it is advisable for engineers to be familiar with the recommendations of the ROM Program that are most closely related, particularly the ROM 1.0-09, ROM 2.0-11, ROM 3.1-99 and ROM 0.5-05. Furthermore, when applying the ROM 1.1-18 in Spain, engineers should also have an in-depth knowledge of the *Método para la Evaluación de Inversiones Portuarias* [Method for the Evaluation of Port Investments] or MEIPOR-16, published by Puertos del Estado and used to analyze the financial and economic profitability of port investments. Generally speaking, when the ROM 1.1-18 is applied outside of Spain, the investment evaluation method currently in force in that country should always be used. In all likelihood, it will not differ significantly from the MEIPOR-16 or the *Guide to Cost-Benefit Analysis of Investment Projects of the European Union* (CE, 2002) on which the MEIPOR-16 is based.

The ROM 1.1-18. should only be applied by expert engineers or under the supervision of senior engineers with many years of experience in the field of harbor and maritime works, coastal engineering, and offshore structures. Precisely for this reason, it is not a textbook to help users learn how to carry out a construction project. Instead, it is a text that guides and helps engineers to apply a methodology that they must first be familiar with. Accordingly, users of the ROM 1.1-18 and MEIPOR-16 should possess a solid background on numerical and statistical methods, risk and reliability, macroeconomy and coastal ecology as well as specific notions of coastal, port and maritime engineering, construction, and geotechnical engineering, as well as materials and atmospheric engineering.

The ROM 1.1-18 takes into account other recommendations of the ROM Program, but always avoiding any repetition or duplication. It is composed of the following documents: *Articles* and *Manual for Breakwater Design and Guide for the Application of the ROM Articles* and three annexes titled *Technical Project Specifications*, *Characterization of Sea Oscillations*, and *Examples*. The manual and the three annexes can be downloaded from the Puertos de Estado website and are 'living documents', subject to constant revision and updates through a regulated procedure that gives them technical validity and timeliness.

Section I. Table of contents

SECTION 1: INTRODUCTION, GENERAL FRAMEWORK AND ORGANIZATION OF THE ROM 1.1-18



1. Introduction, General Framework and Organization of the ROM 1.1-18

Each breakwater as a whole as well as each of its subsets, subsystems, and components should fulfill project objectives, as defined by the developer and by the regulations currently in force. In the ROM 0.0-01, these objectives are reflected in the project requirements regarding the structural safety and operationality of the infrastructure that should be satisfied during the different stages of the project. The ROM 1.1-18 incorporates the approach described in the ROM 0.0-01 regarding the spatial and temporal variability of the project into the conception, design, verification, and optimization of the breakwater. Also applied in this process is the Method for the Evaluation of Port Investments (MEIPOR), whose general objective is to financially and economically evaluate the value generation of an investment project with a specific focus on its risk-return trade-off.

This section presents the general framework of the ROM 1.1-18 in connection with MEIPOR. The objective is to establish the guidelines for the elaboration of preliminary studies and the corresponding breakwater project, This also involves a decision-making process that integrates the investment project and the construction project of a breakwater or any other harbor infrastructure. This introduction begins with the current legal framework and then goes on to provide the recommendations and conclusions for port planning. It finalizes with the organization of the construction project in terms of its stages of completion or development, as reflected in the specific activities (tasks or milestones to be performed in each one.

1.1 GENERAL FRAMEWORK

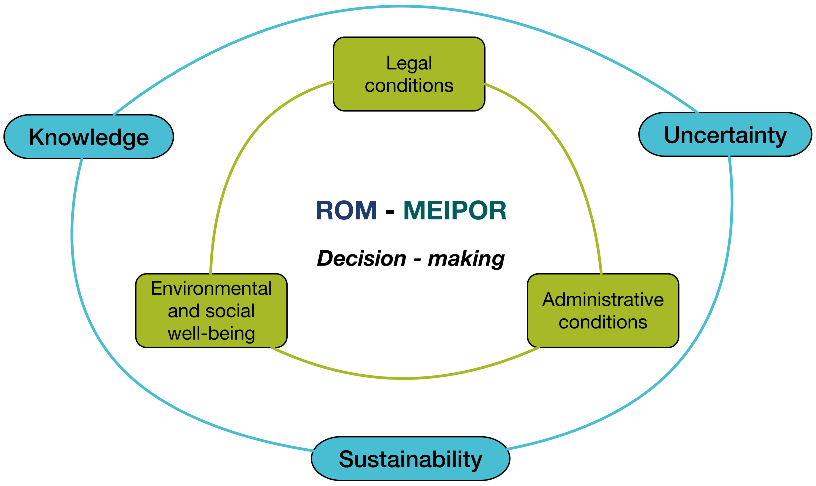
Maritime ports are nodes that are integrated in commercial, logistic, and transportation networks. Their main function is the safe and efficient transfer of goods and passengers between maritime and land transportation nodes, such as highways, railways, and shipping lanes.

Although harbors were originally a refuge and safe haven for vessels, they have evolved and have acquired a commercial, industrial, logistic, leisure or even military function. The service area of ports now has infrastructures related to the following: (a) control of sea oscillations (breakwaters and maritime structures; (b) maritime safety and operationality of the area (berthing and mooring areas); (c) land use and exploitation of the area; and (d) modes of land transportation access.

Regardless of the type of harbor infrastructure, economic decision-making should be based on value generation and be subject to appraisal by management and monitoring mechanisms that guarantee the achievement of general interest goals.

For this reason, the corresponding financial-economic and technical-economic recommenda-tions should also envisage environmental and social welfare needs in the decision-making process as well as the legal and administrative conditioning factors in the service zone.Aspects to be considered include the current state of knowledge, sustainability requirements, adaptation to global warming, and the random nature of project factors and processes.

Figure 1.1: ***Conditioning factors for harbor infrastructure decision-making***



1.1.1 Ports of general interest, current legislation

In Spain, the general framework that regulates the design construction, maintenance, repair, and dismantling of port and maritime structures is the Merged Text of the Law of State Ports and of the Merchant Fleet (*Texto refundido de la Ley de Puertos del Estado y de la Marina Mercante'*), enacted by Royal Decree 2/2011 of 5 September 2011.

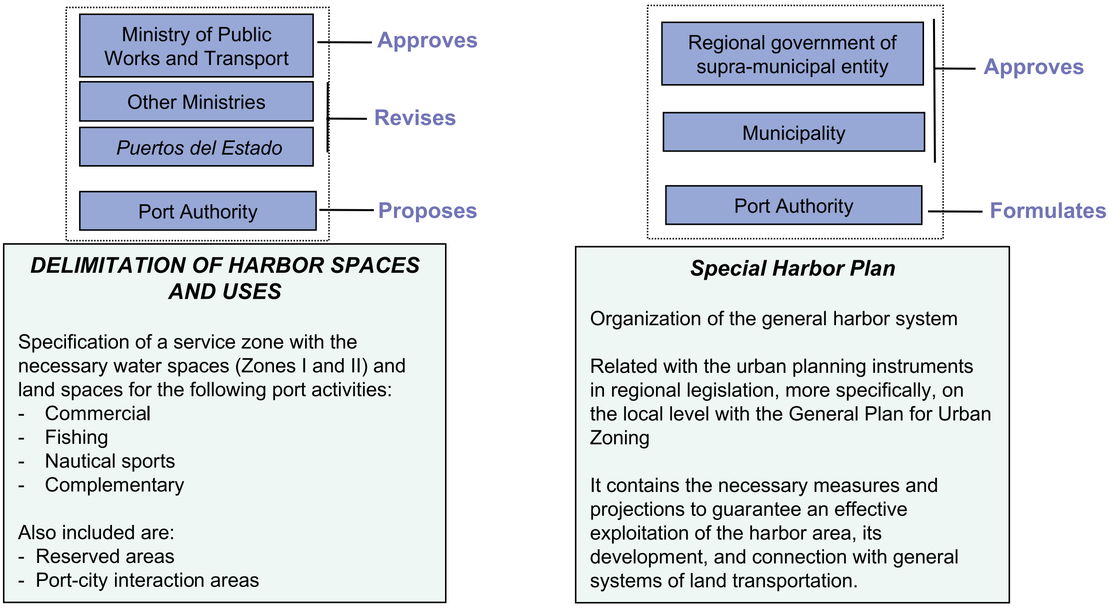
Within this framework, a maritime port is defined as a set of land areas, maritime waters and installations located on sea or estuary shores,with the artificial, natural or physical conditions and the organization permitting port traffic, and which are authorized for these activities by the competent administration.

Of the regimes within this framework, this ROM particularly focuses on those that are directly related to the design and construction of ports of general interest, economic and budget regulations, and all aspects related to the public domain.

1.1.2 Public domain, service zone, urban structure of the port

In Spain, ports of general interest are owned by the government. They are part of the maritime-terrestrial public domain (MTPD) and integrate the state port public domain (SPPD).They possess a service zone that includes the land and water areas necessary for all commercial, fishing, sporting and sailing activities as well as any other complementary or auxiliary activities.They also have reserved spaces as well as spaces for port-city interaction.This service zone is determined and regulated by the Ministerial Order regarding the Delimitation of Port Areas and Uses]. Moreover, the service zone along with the port public domain, subject to the maritime signalling service, should appear as the general port system in urban planning projects approved by government authorities.The general port system is developed in a specific plan or similar instrument, which establishes the necessary measures and provisions that will guarantee the efficient exploitation of the port space, its development, and connection with the general land transportation systems.This plan for harbor development is an integral part of the general municipal development plan, and is considered a future area planning project.

Figure 1.2: ***Legal entities for the administration of port land area***



1.1.3 Port Planning: Analysis and Documents

According to Spanish law, Puertos del Estado in collaboration with port authorities is responsible for designing the Strategic Framework of the General Interest Port System, which can be further developed in strategic plans and master infrastructure plans, and which will subsequently be implemented in business plans.

The actual strategic plan is the responsibility of the port authorities and should include the following: (i) definition of the strategic actions and objectives; (ii) action guidelines; and (iii) action plan. This type of strategic plan does not require environmental impact evaluation.

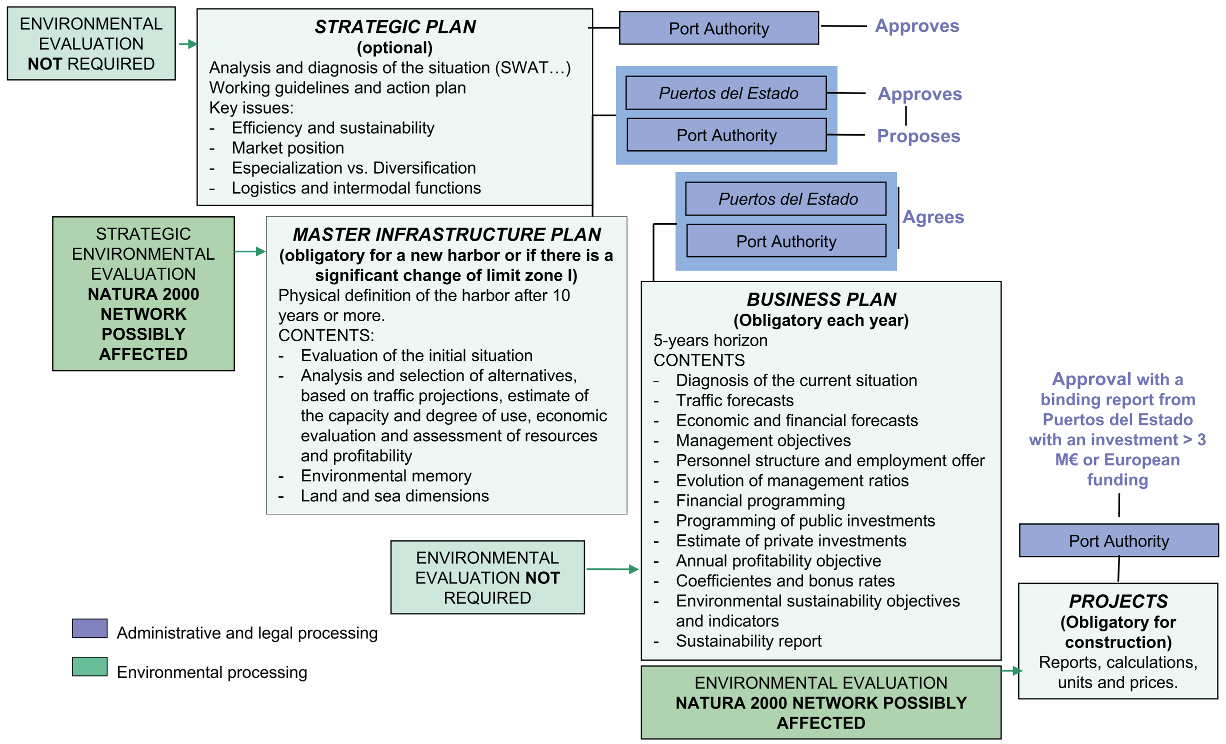
The master infrastructure plan is obligatory in the construction of a new state-owned port. It is also required in the case of the expansion of an existing port or the construction of new infrastructures that significantly modify the seaside boundaries of the port. This plan includes the evaluation of the initial location of the port in the moment when the plan is being drawn up as well as a definition of the development needs of the port with a minimum temporal horizon of 10 years. For this purpose, different options are analyzed, and the best alternative is selected. This decision is based on the following criteria: (i) traffic predictions: (ii) estimate of infrastructure and installation capacity as well as their use in each development phase; (iii) the economic valuation of investments and resources; (iv) potential economic and financial profitability. This includes not only seaside activities, but also landward actions, particularly the road and railway networks of the service zone, which should be in line with the current and predicted land accesses.

The master plan requires a strategic environmental evaluation as well as the evaluation of possible impacts on the Natura Network, when applicable. The plan is finally approved or ratified when an agreement is reached by Puertos del Estado and the port authorities. When the port is new, its construction must also be approved by the Ministry of Public Works and Transport.

The business plan for the port is elaborated annually and includes a situation diagnosis, port traffic forecasts, economic and financial predictions, management objectives, environmental sustainability objectives and indicators, personnel organization and employment offers, evolution of management ratios, financial and public investment programming, estimated private investments, annual profitability target, and correction coefficients as well as the corresponding rebates from harbor dues.

The business plan does not require an environmental impact evaluation and is approved and mutually agreed upon by Puertos de Estado and port authorities.

Figure 1.3: ***Port planning instruments and requirements for environmental impact evaluation***



1.1.4 Investment projects and port construction

The public investment program integrated in the business plan reflects the development of a set of investment projects in port infrastructures from which their construction projects are derived.

In the state port system, a construction project with its complementary studies is required for a new port as well as for new infrastructures or the expansion of an already existing port. In this case, it is then approved by port authorities with a binding report from Puertos de Estado, when necessary. The approval of a construction project entails a declaration of public utility and the need to occupy public property for forced expropriation and temporary occupation.

A construction project should always be in harmony with its investment project. It should also be in consonance with the master infrastructure plan that proposes and approves it. Furthermore, construction projects are subject to the environmental impact evaluation procedure in accordance with applicable legislation.

Figure 1.4: ***Flowchart for the design of basic infrastructure projects***

Project → **Port Authority** elaborates it and approves it; **Puertos del Estado** issues binding report

Construction → **The Port Authority** directs the construction work, tenders it, awards the contract, and settles it; **Puertos del Estado** participates in the technical committee that evaluates the offers; **Inspections are performed by the Ministry of Public Works and Transports:** Modifications, public works reception…

1.1.5 Objectives of the ROM Program and MEIPOR

Since its creation in 1987, the main objective of the ROM (Recommendations for Harbor and Maritime Works) Program has been to provide a set of technical norms and criteria that can be applied to the design, construction, exploitation, maintenance, repair, and dismantling of all harbor and maritime works, of whatever type, regardless of the materials, tools, and elements used in their construction.

In Spain, MEIPOR (Method for the Evaluation of Port Investments) is a method used to facilitate decision-making in the design of investment projects for general interest ports. The general objective of MEIPOR is to measure the value generation of a project as well as its financial-economic viability, based on its risk-return trade-off.

ROM and MEIPOR are thus two complementary tools that support the technical-economic and financial-economic decision-making process in the development of harbor areas and their infrastructures. The general objectives of the joint application of the dual ROM-MEIPOR system to ports are the following:

(a) To establish the indispensable economic, financial, environmental, social, and technical connection between plans, projects, and instruments used in the organization, management, and exploitation of harbor infrastructures.
(b) To optimize the entire cycle associated with harbor works so as to facilitate the coordination of investment projects and construction projects.
(c) To provide the environmental, financial, and economic documentation and technical support necessary for decision-making during the implementation, development, and management of investment projects in the port service zone.

Specific objectives and the ROM 1.1-18 method

In this context, the ROM 1.1-18 is the technical-economic instrument that facilitates and supports decision-making for breakwater investment projects. It has the advantage of incorporating un-certainty in the project design process as well as the verification of project requirements. It also includes the cost analysis that is a necessary part of any assessment of financial-economic prof-itability. The results obtained are thus more accurate and their interpretation is also more objective, thanks to this heuristic, empirical approximation.

One of the specific objectives is to provide maritime engineering with an efficient method that can be used to design, construct, maintain, repair, and dismantle a breakwater, whose purpose is to protect a harbor area from climate agents. For this reason, it should comply with a previously specified set of environmental, social, economic, and technical requirements.

As explained in the ROM 0.0-01 and ROM 1.0-09, this method is based on a process that optimizes breakwater design and management, based on a set of project requirements, quantified in terms of acceptable levels of risk regarding the structure and form of the breakwater. Strictly speaking, the inclusion of uncertainty means that risk calculation is based on the product of the probability of non-compliance with requirements and the resulting consequences of this non-compliance. Nevertheless, the ROM method does not involve the direct calculation of this type of risk. Instead, it specifies a limit or threshold for the joint failure or operational stoppage probability of the breakwater during its useful life.

The operationality and safety thresholds established in this ROM depend on the nature or importance of the breakwater within a certain harbor area, from an economic as well as a socioenvironmental perspective. Its nature or importance is estimated, depending on the foreseeable consequences stemming from the non-attainment of breakwater objectives. The ROM classifies the nature of a breakwater based on a set of intervals of socioenvironmental and economic indicators known as the ERI (Environmental Repercussion Index) and SERI (Social and Environmental Repercussion Index). Despite the fact that they are related to the consequences of a worst-case failure mode, they are simple to calculate.

In sum, with these premises, the assumption is that the dimensions and properties of a breakwater in a project design should be the result of a technical-economic optimization process, subject to a series of previously specified constraints or boundary conditions.

The construction project

When this method is applied, the final result is a construction project (in line with the master infrastructure plan in Spain). The project, accompanied by other documents, defines and determines the dimensions of the subsets, subsystems and components of the breakwater. It also determines the characteristics of the construction materials so that they will maintain their geometry and strength. It also specifies the procedures and instruments necessary for breakwater construction, maintenance, and repair.

One of the project annexes should provide the supporting calculations that the probability of damage, which would jeopardize the use of the structure, is clearly delimited within its useful life as well as other project phases.

The construction project should include a quantitative estimate of the operationality of the harbor area, directly conditioned by the presence of the breakwater. It should also contain a quantitative evaluation of the consequences of any possible non-compliance with admissible operationality limits because of the temporary or definitive loss of the structural attributes of the breakwater as well as the repair costs.

Furthermore, depending on the location and administrative environment of the harbor area, the construction project should take into account the legal dimensions of environmental protection and land-use planning. This includes all aspects related to water quality and coastal ecosystems as well as the morphodynamic processes and evolution of the coastal physiographic unit.

The Annexes of the General Technical Specifications for the Project (see Article 1.5 of this section) includes a general index of the contents of a construction project. This is a living document, which is regularly revised and updated through a strictly regulated procedure that gives it technical validity and timeliness.

Implications of the application of the dual ROM 1.1-18-MEIPOR system

The coordination of objectives and methods in the dual ROM 1.1-18-MEIPOR system involves different, though not incompatible, types of risk evaluation as well as the use of new methods and tools.

Risk evaluation

The ROM 1.1-18.-MEIPOR system envisages two clearly defined types of risk:

(a) Risk stemming from the construction project, associated with the safety and operationality of the infrastructure, as described in the ROM Program.
(b) Risk stemming from the investment project, associated with factors, such as demand fluctuations and investment costs as well as the financial-economic profitability, reflected in MEIPOR.

The risks related to the evaluation of investment costs and financial-economic profitability are linked to those related to the infrastructure (i.e. structural safety and operationality) by means of a dual system of technical-economic optimization (ROM Program) and financial-economic optimization (MEIPOR). Both types of optimization are subject to a set of simultaneous compatibility restrictions.

New methods and instruments

To achieve concurrent risk objectives, it was necessary to expand the work method proposed in the ROM 0.0-01. This signified incorporating the analysis of the spatial and temporal evolution of the failure modes and overall verification, spatially hierarchized in subsets, subsystems, and components. To facilitate the decision-making process, it was necessary to add diagrams of components, triggering and propagation trees, as well as decision-trees.

Generally speaking, both the technical-economic and financial-economic systems are based on the characterization of the non-fulfilment of project objectives. The first system reflects this in failure and operational stoppage modes. The second describes the non-fulfilment of objectives in terms of the lack of financial-economic profitability and the financial sustainability of the harbor area.

These new instruments help to calculate the necessary information for the technical-economic optimization of the breakwater and to evaluate the financial-economic profitability of the investment project. Essentially, these are the probability functions of the infrastructure in relation to the safety and operationality as well as to the total costs of the construction project and their distribution during the different project phases.

This technical and economic duality in the conception and formulation of the breakwater design and its subsets (applicable to any other port infrastructure) is part of the specific objectives of the ROM 1.1-18, which gradually materialize as the project develops.

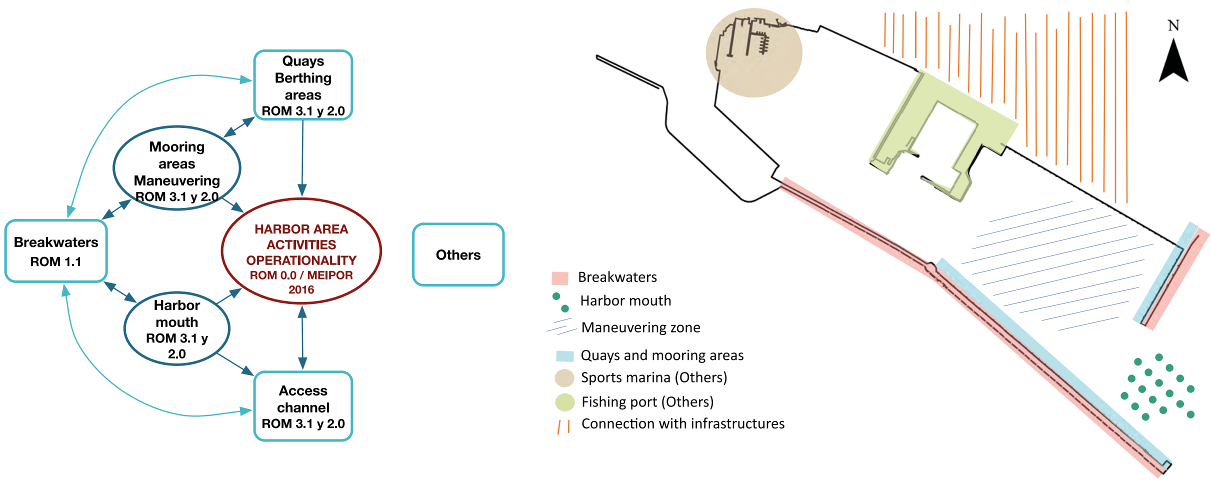
1.2 LAYOUT OF THE HARBOR AREA AND BREAKWATERS

The master infrastructure plan is the port planning document that generally has the necessary scope, for example, to determine the need to construct a breakwater or substantially extend the life of an already existing one. This analysis includes the coupling of both solutions in the rest of the harbor area with a temporal horizon of at least ten years. If the final decision is to construct a breakwater, the master plan should specify the possible configurations of the structure, and select and recommend the most suitable design options. The conclusions and recommendations in the master plan are the starting point of a breakwater project.

The layout of a harbor area, constructed in open waters, or in an unprotected location, mainly depends on the area to be protected, marine dynamics, bathymetry of the sea bottom, and land accesses. Furthermore, other conditioning factors can play an important role, such as the topography as well as the economic resources and construction materials.

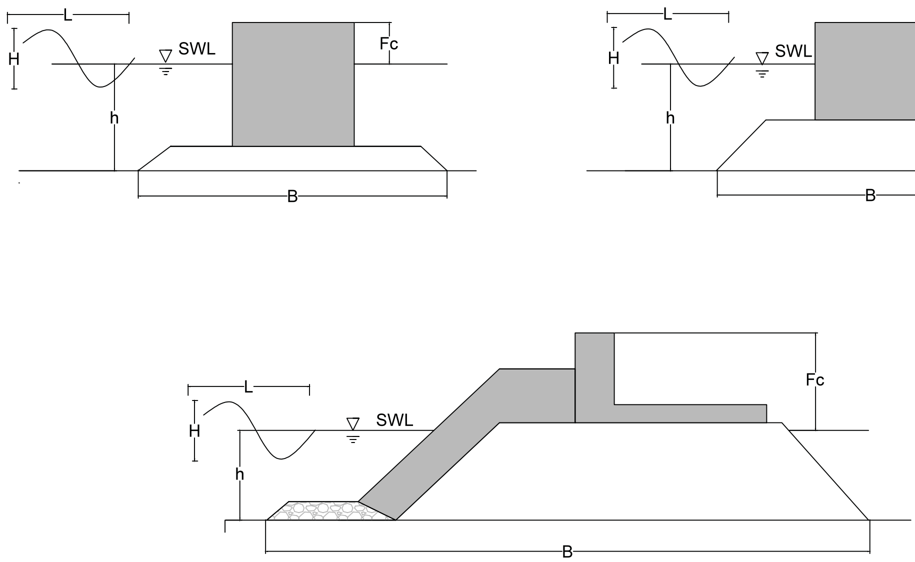
The design of the structure depend on a variety of factors, such as the general and operational nature of the area, traffic intensity and vessel types expected, required service quality levels, local marine, atmospheric, and climate agents, as well as the soil and topography.

Figure 1.5: ***Integration of the breakwater in the harbor area, Port of Motril***



This ROM focuses on the design of breakwaters for the protection of a harbor area (maritime port) or a shoreline against the prevailing wave action. A standard breakwater section is usually composed of a core of granular material, protected with armor layers of riprap or rockfill and covered with a superstructure of mass or reinforced concrete. The most conventional types are vertical, composite, and sloping (or rubble-mound) breakwaters, (see Figure 1.6). Their resistance to wave action mainly comes from the weight of their components along with the weight of adjoining units through mechanisms of unit friction and interlocking. Certain texts refer to such structures as "gravity breakwaters".

Figure 1.6: ***Breakwater sections and parameters representing vertical, composite, and sloping breakwaters***



When a breakwater is constructed to protect a harbor area, it should satisfy a set of very strict conditions in regard to wave energy transmission either from the overtopping of the crown or propagation through the breakwater section. In such cases, the relative height, $(h + Fc)/H$, of the breakwater generally has dimensions on the order of $1, O(1)$, and a relative width, B/L, on the order of $1/10, O(1/10)$, where h is the depth at the site; and H,L,Fc,B are, respectively, the characteristic wave height, characteristic wavelength, freeboard, and the representative magnitude of the breakwater width.

COMMENT

This ROM does not specifically address the design of fixed or floating maritime structures, offshore structures, and coastal groins. Without exception, the methodology described in the ROM 1.1-18 can be applied to the design of all of these breakwater types. Coastal groins, whether transversal, oblique, or parallel to the coast, are usually constructed with the same materials. Their types are geometrically similar to breakwater types. However their dimensions and structural shape are different since they are generally not subject to such restrictive conditions in regard to energy transmission, and are usually located in zones where the design wave is limited by wave breaking as well as other factors.

They are generally designed with the assumption that overtopping will occur at the crown and that the core will filter the sediments (beach sand) to favor their retention. In such cases, their relative height (Fc/H) is low (i.e. at or below sea level) and the relative width, B/L, is the minimum value necessary for construction with terrestrial means. However, there are a wide range of coastal groin types and contexts. At certain locations, such as Zurriola beach in San Sebastián (Spain), the project design of a coastal groin to protect the coastline was designed similarly to that of a breakwater. From a technical perspective, it would be suitable to apply the methods and tools in this ROM (even MEIPOR) to its project design, construction, and management.

The site and layout of a breakwater, its distribution, and typology determine the access channel, mouth, docking and maneuvering zones, and when applicable, location of the berthing and mooring areas. Moreover, the breakwater interferes with marine dynamics, especially the wave action, which conditions the levels of use and exploitation of the breakwater as well as its safety, and suitability for harbor area service.

The actions of the agents at the location often alter the geometry of the breakwater as well as the shape and resistance of its materials. Furthermore, during its construction as well as during its useful life, the breakwater can suffer damage that evolves over time. This damage may affect harbor activities and/or the safety of the structure. This evidently has an impact on its performance and suitability for service, which obviously constrains its operationality.

The beginning of the deterioration and failure of the breakwater as well as its spatial and temporal evolution is random and mainly depends on the following:

(a) Type,subsets, and units of the breakwater such as the level of damage experienced and the separation between this damage and destruction (resilience);
(b) Simultaneity and compatibility of the predominant agent values as well as their temporal evolution and duration;
(c) Variability of the formal and structural response of the breakwater;
(d) Maintenance and repair strategies adopted.

1.3 TASKS AND MILESTONES IN A BREAKWATER PROJECT DESIGN

The application of the dual ROM 1.1-18-MEIPOR system requires a sequence of tasks and milestones that must be closely interrelated so that the planning, project design, and management phases will be coherent. These tasks include the following:

(a) Conception and definition of the structure: purpose and nature of the infrastructure, including the selection of breakwater response and its failure assessment lines as well as how they are triggered and propagated.
(b) Definition of the means and mechanisms as well as the adoption of the necessary construction, maintenance, and repair strategies so that breakwater performance will be in consonance with its conception and purpose during its useful life and in all other project phases.
(c) Evaluation of the breakwater design by verifying its compliance with project requirements and other indicators, including, when applicable, its adaptation to the consequences of global warming.

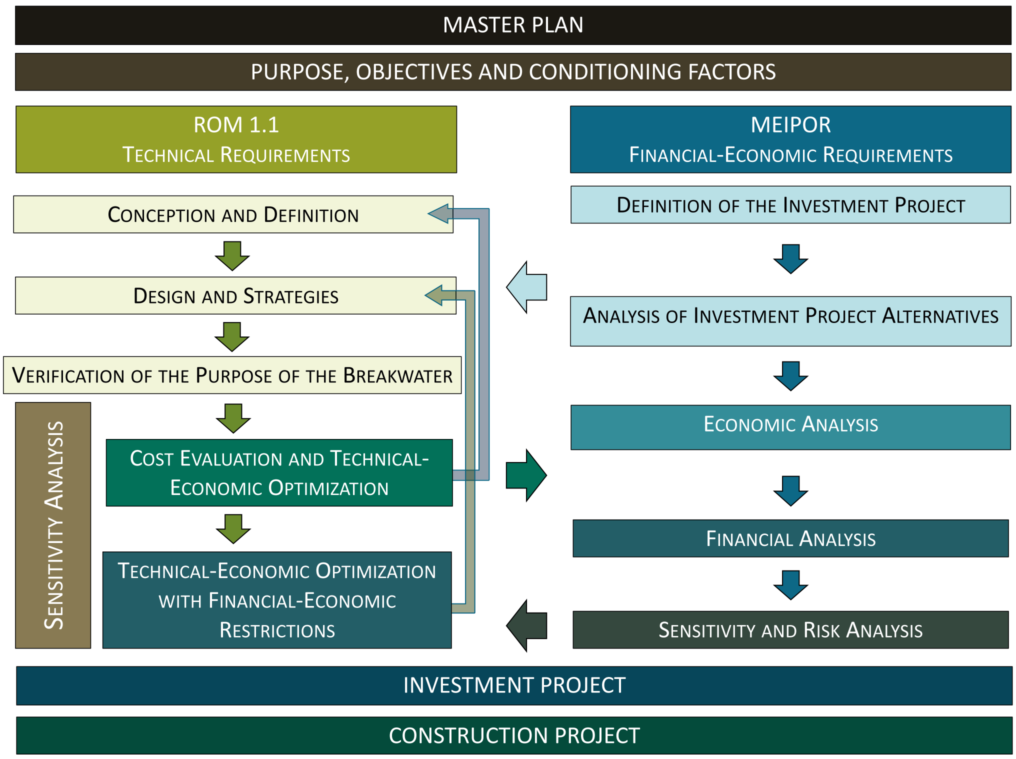
(d) Evaluation and technical-economic optimization of decisions related to cost allocation, namely, the costs derived from the construction, maintenance, repair, and dismantling of the structure as well as the costs generated by the potential impact of operational stoppages and structural failures on port activities.
(e) Evaluation and financial-economic optimization of decisions associated with value generation, particularly in relation to the allocation or distribution of revenues, margins, profits or surpluses among all associated agents, including society in general. For this purpose, resource needs should be taken into account as well as the previously adopted decision and implementation strategies.

Depending on the decisions adopted in the master infrastructure plan, the formal and structural conception and performance of the breakwater, its suitability for service, and its operationality are mainly conditioned by the following:

(a) Purpose, spatial location (site) and distribution of the harbor area;
(b) Agents and actions at the site;
(c) Profile, bathymetry, and characteristics of the terrain
(d) Environmental and legal conditioning factors

Once the purpose of the breakwater is specified in consonance with its nature and purpose, the project designer should draw up the blueprint of the breakwater, delimit each of its subsets and select the principal failure modes that will determine its reliability and operationality. The design of each subset is based on these failure modes and the indicators of the joint probability of failure and operational stoppage during the useful life of the structure.

Figure 1.7: ***Organization of a breakwater project***



1.4 CLASSIFICATION OF CONSTRUCTION PROJECTS AND DEVELOPMENT LEVELS

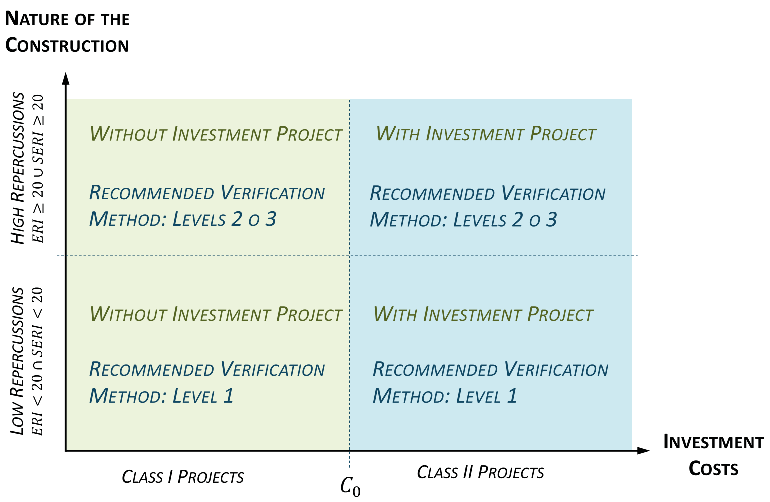
This ROM identifies four types of project, depending on the nature and importance of the structure (as specified by the ERI, SERI, OIER, and OISER in the ROM 0.0-01), and the total investment cost (see Figure 1.8).

Based on the nature of the structure, projects are classified as those with hypothetical reper-cussions derived from failures, which are valued as low or high. The first category corresponds to projects with a SERI and ERI lower than 20, whereas the second corresponds to any other situation.

Depending on the investment, the dual ROM-MEIPOR system also classifies projects in two categories: I and II. Category I construction projects are linked to an investment project ($C_I > C_0$), whose profitability should be evaluated. Category II projects are not linked to an investment project ($C_I \leq C_0$). C_0 is the dimensionless economic parameter, whose value depends on the economic structure and on the level of economic development in the country where the structure will be built. Consequently, it will vary over time (see section 2.11 of the ROM 0.0-01).

In Spain, $C_0 = 3$ M€ is the threshold of the total investment cost. When this threshold is exceeded, it is necessary to implement ROM-MEIPOR. Therefore, each construction project contains a sequence of duly justified development levels and criteria to facilitate decision-making. MEIPOR specifies the conditions required for its application.

Figure 1.8: *Classification of projects, depending on the nature of the construction work and the size of the investment*



1.4.1 Development levels of the breakwater project

The breakwater project has two clearly differentiated phases. The first phase focuses primarily on the performance of the breakwater as a structure that protects a coastal area and verifies any non-compliance with project objectives by means of failure and stoppage modes focused on the safety and operationality of the structure. This is a basically technical approximation and includes the cost analysis described in the ROM 1.0-09.

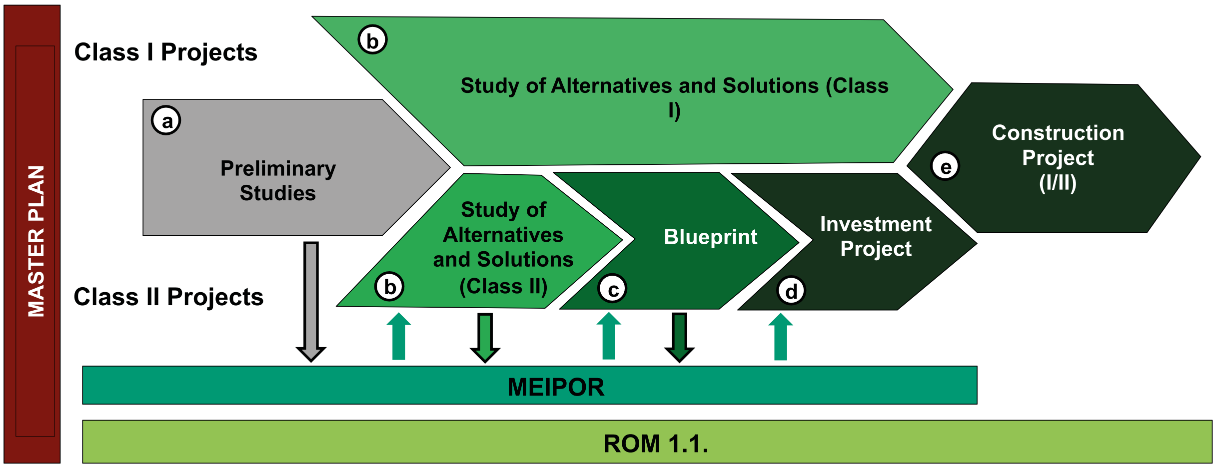
In the second phase, the breakwater is analyzed as a protective structure within the harbor area. The frequency of breakage and repairs are quantified in the objectives and purposes of the port area, such as those related to its economic and financial profitability. Accordingly, this leads to the elaboration of decision trees as well as to strategies for the construction, exploitation, repair, and dismantling of the breakwater. In the optimization of the structure, this analysis interweaves technical and financial-economic aspects, and links the reliability and operationality of the breakwater in each project phase to its social and environmental implications and the investment risk level.

The sequence of activities leading to the construction project (e.g.. the conception, verification, and optimization of the structure) are specified in the implementation of preliminary studies and projects, whose development level progressively increases in complexity and accuracy at the same time as it delimits its uncertainty. This ROM proposes the following development levels:

(a) Preliminary Studies
(b) Study of Alternatives and Solutions
(c) Project Draft
(d) (Investment Project
(e) Construction Project

At each level, it is necessary to make decisions regarding the plan view of the breakwater, its typology, construction process, and the total financial and economic costs. Only Category II projects involve the implementation of levels (c) and (d).

Figure 1.9: ***ROM 1.1-18 levels of project development***



1.4.2 Objects and activities, depending on the development level of the project

This article indicates the specific objectives and most relevant activities (tasks and milestones), depending on development level of the project. At the end of each article, there is a summary table of the main activities to be carried out in each of the development levels. For the sake of clarity, they are organized in conceptual blocks of work packages and decision-making:

(a) Design of the structure;
(b) Project and construction strategies and decision-making;
(c) Verification of the technical requirements of the project and failure probability;
(d) Calculation of total costs;
(e) Sensitivity analysis and technical-economic optimization;
(f) Financial-economic optimization and risk analysis.

Also included is information regarding the selection criteria of the results at each development level of the project so that they can be transferred to the next development level.

Preliminary studies

For the elaboration of the preliminary studies, the following information is required:

(a) Master infrastructure plan;
(b) Function of the projected structure, nature, and exploitation, social, and environmental requirements;
(c) Conditioning factors of the site: morphology, materials, and construction processes;

(d) Characterization of the climate agents and of the land and soil at the site;
(e) Forms to consider in the plan view and available studies.

Specific objectives at this development level are the following:

(a) To perform a preliminary analysis of the technical-economic viability of different plan-view forms and typologies;
(b) To use simple criteria to determine the environmental, social, and economic repercussions of the construction (ERI, ISERI, OISER, and OISER) and specify the project requirements for each one;
(c) To perform a preliminary analysis of the construction processes and their conditioning factors;
(d) To make a preliminary appraisal of the investment risks;
(e) To use SWOT analyses or similar techniques to select and propose the most suitable options for the study of alternatives and solutions.

The most relevant activities (tasks and milestones) are the following:

(a) To analyze and characterize the different plan-view forms and analyze the function of the breakwater as a protective structure in the harbor area;
(b) To select the optimal breakwater typology, determine the dimensions of its main alignment, and delimit the other subsets and special sections by means of relations, standards, and engineering criteria;
(c) To consider the construction processes and means, estimate the implementation time, and use unitary costs to evaluate the costs of the construction and its dismantling.
(d) To verify the adaptation of the structure to the possible consequences of global warming by means of deterministic criteria.
(e) To calculate the financial-economic profitability of the investment by means of homogeneous, deterministic criteria.
(f) To write a preliminary environmental report and, when necessary, a preliminary social report with the most critical aspects of each one of the options analyzed.
(g) To specify the field campaigns, studies, and data processing necessary for the following development levels of the project.

Contents of the preliminary studies

The preliminary studies will be defined in a document containing a justified and hierarchical catalogue of the most suitable options in order to begin the study of alternatives and solutions.

Summary Table

Table 1.1: Summary table of preliminary studies

		Development	Tools
Conception of the structure	Hierarchy of the structure	Preliminary	Diagrams of components
	Characterization of modes and relations	Preliminary	-
	Temporal evolution of the breakage	NO	-
	Spatial evolution of the breakage	NO	-
	Probability distribution	Preliminary	Distribution techniques
Decision-making	Timing strategies	Preliminary	Descriptive Tools
	Repair strategies	NO	-
Verification of requirements	Reliability evaluation	Preliminary	Standard statistics, Diagrams of components, Level I
	Operationality evaluation	Preliminary	Standard statistics, Level I
Calculation of costs	Construction costs	Preliminary	General tables
	Repair costs	Preliminary	Coefficients
	Loss of operationality and externalities	Preliminary	Coefficients
	Dismantling costs	Preliminary	Coefficients
Selection criteria		YES	SWOT or similar
Sensitivity and optimization		Preliminary	Critical variables, Discrete analyses

Study of alternatives and solutions

To elaborate the study of alternatives and solutions, it is first necessary to have the following information:

(a) Results from the preliminary studies;
(b) Data from field campaigns as well as complementary studies;
(c) Estimates of the financial-economic margins of the project.

Specific objectives of this development level are the following:

(a) To identify and design the various alternatives and solutions, depending on the plan-view and selected subsection forms as well as on their nature and purpose;
(b) To compare the technical-economic viability of each alternative, including their potential adaptation to the consequences of global warming;
(c) To reevaluate the environmental, social, and economic repercussions as well as to specify the project requirements for each alternative and the corresponding risk indicators;
(d) To compare construction processes and means, their conditioning factors, and the total costs of the project; Category II projects would also require an initial estimate of the financial-economic costs;
(e) To compare the interaction of the maritime infrastructure with the shoreline as well as other environmental studies;
(f) To technically and economically optimize the main characteristics and dimensions of the structure. For Category II projects, this includes an initial estimate of financial-economic requirements;
(g) To calculate and compare investment risks;

(h) To use multi-criteria analysis or similar, to select the alternative that is the most favorable solution to begin the construction project in the case of Category I projects or to begin the blueprint in the case of Category II projects.

The most relevant activities (tasks and milestones) are the following:

(a) To study, in simplified form, the structural, geotechnical, and hydrodynamic performance of each plan-view configuration as well as subsets of the breakwater and to analyze its function as a protective structure of the harbor area.
(b) To dimension the sections of the breakwater subsets for different configurations of stoppage and failure modes and the subsystem hierarchy, taking into account the evolution of damage during the useful life of the structure.
(c) To analyze and compare the designs resulting from activity (b) with those obtained by the Level I Method, when applicable.
(d) To evaluate the impact of the design on the useful life of the infrastructure in the context of different repair strategies and on the safety and operationality of the harbor area.
(e) To study the construction processes and means, estimate the implementation time, and evaluate the most probable costs, including those for the repair, maintenance and dismantling of the structure with a preliminary consideration of construction strategies.
(f) To quantify the interaction of the structure with shoreline morphodynamics as well as its influence on water quality and address the administrative and legal conditioning factors for each one.
(g) To verify the adaptation of the structure to the possible consequences of global warming.
(h) To analyze the sensitivity of project requirements to the main characteristics and dimensions of the structure and to perform a simplified technical-economic optimization of these characteristics and dimensions. Category II project also require an estimate of financial-economic requirements.
(i) To calculate the financial-economic profitability of the investment for each alternative, based on homogeneous, semi-probabilistic criteria, and estimate the level of risk of each one.
(j) To specify the bases for the environmental report and, when applicable, the sociological report, highlighting the most critical aspects of each alternative.
(k) To collect and incorporate the weighted opinions of users, managers and administrators of the harbor area in relation to the different alternatives.
(l) To propose and specify, when applicable, the field campaigns, studies, and data compilation and processing required for the work in subsequent project development levels.
(m) To transfer to MEIPOR, when applicable, the damage costs as well as the total costs of each alternative and its temporal evolution.

Contents of the study of alternatives and solutions

Alternatives and solutions will be analyzed in a report that contains a hierarchical and justified catalogue of the alternatives and solutions selected to begin the construction project (in the case of a Category I project) or to begin the project draft (in the case of a Category II project). An environmental report and sociological report should be included.

Summary table

Table 1.2: ***Summary of the study of alternatives and solutions***

		Development	Tools
Conception of the structure	Hierarchy of the structure	Simplified	Diagrams of components
	Characterization of modes and relations	Simplified	Upper and lower bounds
	Temporal evolution of the breakage	Simplified	Standard models
	Spatial evolution of the breakage	NO	-
	Probability distribution	YES	Distribution techniques
Decision-making	Timing strategies	Simplified	Chronogram
	Repair strategies	Simplified	Upper and lower bounds
Verification of project requirements	Evaluation of reliability	Simplified	Standard statistics, Diagrams of components Synthetic cycles
	Evaluation of operationality	Simplified	Standard statistics Numerical modelling studies Field campaign data
Calculation of costs	Construction costs	Simplified	Chronogram Tables of costs
	Repair costs	Simplified	Standard statistics
	Loss of operationality and externalities	Simplified	Scenarios
	Dismantling costs	Simplified	Chronogram Tables of costs
Selection criteria		YES	Multi-criteria or similar Decision theory
Sensitivity and optimization		Simplified	'Critical' variables Continuous analyses Scenarios Classification algorithms

Project draft

For the elaboration of the blueprint, the following information is required:

(a) Study of alternatives and solutions;
(b) Field campaign data and complementary studies;
(c) Basic data, conclusions or recommendations of the environmental impact study or, where applicable, the social impact study;
(d) Preliminary results of the MEIPOR financial-economic analysis.

This development level has the following specific objectives:

(a) To design the infrastructure and verify the project requirements in all project phases.
(b) To determine the economic and technical viability of the alternative selected as a solution, depending on the configuration of the modes, infrastructure management strategies, and their impact on the harbor area.
(c) To analyze and, when applicable, adapt the design of the selected alternative to the possible consequences of global warming.
(d) To analyze construction processes and means, as well as their conditioning factors and costs.
(e) To determine the interaction of the maritime infrastructure with the shoreline and incorporate, where applicable, the conclusions and recommendations of the environmental impact study.

(f) To technically and economically optimize the characteristics and dimensions of the structure, considering the financial-economic requirements defined by MEIPOR.
(g) To estimate the risk level of the investment in the infrastructure and its impact on the harbor area.

The most relevant activities (tasks and milestones) are the following:

(a) To determine the constructive, structural, geotechnical, and hydrodynamic performance of the breakwater subsets, considering the spatial and temporal variability of the agents at the site.
(b) To incorporate the indications and constraints derived from the environmental study and from the legal requirements.
(c) To design and verify the safety and operationality of the breakwater in each of its sections, sets, and elements, based on the its possible failure modes and their potential impact on the harbor area.
(d) To calculate the costs of the construction, maintenance, repairs and dismantling of the breakwater, based on design criteria, construction strategies, and decision-making.
(e) To technically and economically optimize the dimensions and properties of the structure.
(f) To transfer the necessary information to MEIPOR in order to perform the financial and economic analysis and to estimate the risk level of the alternative selected as a solution, always considering the consequences of breakwater damage on the operationality of the harbor area in different economic scenarios.

Contents of the project draft

The project draft consists of a report that explains the purpose and nature of the infrastructure and its formal and structural conceptualization. It also specifies the results of the financial-economic profitability study as well as the investment risk level. Furthermore, it contains annexes with the information, basic premises, conditioning factors, requirements, and crucial indicators for the elaboration of the investment project and construction project.

Summary table

Table 1.3: Summary table of the blueprint

		Development	Tools
Conception of the structure	Hierarchy of the structure	Complete with details	Diagram of components
	Characterization of modes and relations	Complete with details	Dependency models
	Temporal evolution of the breakage	Complete with details	Specific models
	Spatial evolution of the breakage	Complete with details	Spreading activation networks
	Probability distribution	NO	-
Decision-making	Timing strategies	Complete with details	-
	Repair strategies	Complete with details	Bounds, Decision trees
Verification of requirements	Reliability evaluation	Complete with details	Diagrams of components Spreading activation networks, Decision trees, Physical model tests
	Operationality evaluation	Complete with details	Physical model tests
Calculation of costs	Construction costs	Complete with details	Timing strategy
	Repair costs	Complete with details	Repair strategy
	Loss of operationality and externalities	Complete with details	-
	Dismantling costs	Complete	Dismantling strategies
Selection criteria		NO	-
Sensitivity and optimization		YES	Specific techniques

Investment project

For the elaboration of the infrastructure investment project, apart from the indications in MEIPOR-16 the following information is also required:

(a) Blueprint;
(b) Conclusions and recommendations of the environmental impact study and, when applicable, the social impact study;
(c) Other studies and complementary financial-economic reports.

Specific objectives of the (MEIPOR-16, 2016) investment project are the following:

(a) To manage the investment with criteria based on value generation;
(b) To enrich the construction project with an analysis of the productive economic investment and of the achievement of general interest goals, including safety and environmental aspects;
(c) To apply the effects of the investment project to the agents involved in its development;
(d) To evaluate the risk of the investment project, incorporating the life cycle of the breakwater in different project implementation scenarios;
(e) To specify the financial-economic requirements applicable to the breakwater construction project.

The most relevant activities (tasks and milestones) of the investment project are the following:

(a) To specify the context and define the objectives of the investment project;
(b) To identify, characterize, prioritize, and select the solutions;

(c) To determine the financial-economic effects of the project on the agents involved in its development;
(d) To determine the breakdown of investment costs;
(e) To determine the statistical distribution of the financial-economic profitability indicators of the project, including the construction and repair processes and strategies for the breakwater as well as decision-making;
(f) To optimize and analyze the sensitivity of the project to various risk categories and estimate the statistical distribution of the risk level of the investment project.

Contents of the investment project

The investment project should include a report stating the expected financial-economic profitability of the project as well as the results of the sensitivity analysis and the analysis of scenarios and risks. It should also include an evaluation of the risk level of the project, and, when applicable, the information required for the construction project as well as the financial-economic monitoring of the construction, management, and exploitation of the breakwater within the context of the harbor area and the annexes necessary to understand and verify it.

Construction project

For the construction project, the following information is necessary:

(a) Study of alternatives and solutions for Category I projects, and the blueprint and an investment project of the harbor area and the infrastructure for Category II projects;
(b) Conclusions and recommendations of the environmental impact study and, where applicable, those of the social impact study.

The specific objective of the construction project is to provide the alternative selected as a solution (in Category I projects) or the blueprint and the investment project (in Category II projects), with a contractual, administrative, and technical form. The goal is to construct the breakwater, fully implementing its operation, management, exploitation, maintenance, repair, and dismantling, all based on processes of technical-economic optimization and, where applicable, of financial-economic optimization.

The most relevant activities (tasks and milestones of the construction project are the following:

(a) To technically and economically develop and compete the project;
(b) To perform a technical-economic optimization of the dimensions and properties of the construction by incorporating in the case of Category II projects the MEIPOR financial restrictions included in the investment project;
(c) To implement and verify the timing strategies of the construction;
(d) To implement and verify the repair strategies and the available means;
(e) To develop an observation plan for the construction work and for monitoring damage;
(f) To obtain probability functions of the total costs of the project, depending on the construction, exploitation, maintenance, repairs and dismantling.
(g) To perform the complete technical-economic optimization of the structure, applying, when necessary, the MEIPOR financial-economic requirements.
(h) To verify the project requirements, the adaptation to the possible consequences of global warming, and where applicable, an acceptable risk level of the investment project.
(i) To elaborate documents, blueprints, technical specifications, etc., necessary for the effective implementation and monitoring of the construction work.

Contents of the construction project

The construction project should at least comprise the documents necessary for the contractual development and the implementation and monitoring of the construction work. These include the report, general plan, detailed plan, technical specifications, measurements, budget, construction plan, safety and health study, and a study of the construction and demolition waste management. Furthermore, the annexes of the report should include the starting data and bases, technical justification of the solution adopted, plan for the management, exploitation, maintenance and dismantling of the structure, and the price justification.

The "Annexes of the general technical specifications for the project" (see Article 1.5.1) provide a general index of the contents of a breakwater construction project.

Tasks and milestones of the development levels in this ROM

Sections 4 and 5 specify the most relevant tasks and milestones described in Article 1.4, and show them in the summary tables for the project development levels (Table 1.1 and Table 1.3), related to the following:

- Verification methods (Article 4.4);
- Calculation of total costs and technical-economic optimization (Article 5.4).

Along with the conception and design variants (Article 2.8), these tasks constitute a wide and flexible methodological space to optimize the objectives of the construction project.

1.5 CONTENTS AND ORGANIZATION OF THE ROM 1.1-18 IN SECTIONS

The ROM Program establishes the foundations for the construction project of the most common types of breakwater: vertical breakwaters, composite or berm breakwaters, and sloping breakwaters, with or without a crown wall. However, the approach proposed is no longer limited to conventional breakwater types. Based on the analysis of the performance of each subset of a typical breakwater section, it is now possible to design breakwater types with subsets and units, adapted to the individual needs of each investment project.

More specifically, this ROM 1.1-18 provides the following:

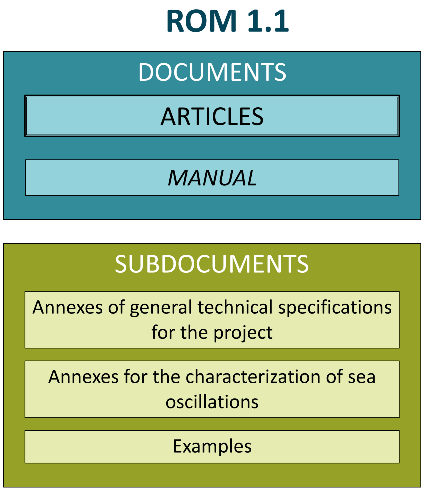
(a) Methods for specifying project requirements and for verifying that the project as a whole and each of its subsets comply with these requirements in all of the project phases.
(b) Technical tools to design and plan the means and processes of the construction, maintenance, repair, and dismantling of any type of breakwater.
(c) Criteria and methods to evaluate the total costs of the infrastructure, including those of its construction, maintenance, repair, and, when applicable, dismantling.
(d) Criteria and methods for the technical-economic optimization of the construction work in compliance with the financial-economic requirements in the investment project.
(e) Development levels for the implementation of the breakwater construction project, when applicable, within the framework of the investment project.

These procedures, criteria and methods depend, among other things, on the project development level, maintenance and repair strategies, and the evaluation of the consequences of breakwater damage for the management and exploitation of the harbor area, as set out in the following sections.

1.5.1 Organization of the ROM 1.1-18

The ROM 1.1-18 is structured in two documents and three subdocuments (see Figure 1.10). Although originally conceived to be applied to any breakwater construction project, most of the methods and tools developed for this ROM can also be used in the investment projects of other maritime infrastructures in the harbor area, such as berthing and mooring areas, navigation channels, etc.

Figure 1.10: ***Table of contents of the ROM 1.1-18***



Articles

The *Articulado* specifies the procedures and methods that can be used to attain and verify the objectives of a breakwater project according to the ROM 0.0-01, ROM 1.0-09 and other recommendations. It is structured in five sections, as described in what follows.

- **S1. Introduction, general framework and organization of the ROM 1.1-18.** This section explains the general context of the ROM 1.1-18 and its connection to the financial-economic analysis tools for harbor infrastructures. It also describes the applicable legal framework, the objectives and their scope, organized in consonance with the development levels of the construction project. It concludes with a description of the organization, structure, and contents of the set of documents in the ROM 1.1-18 along with a catalogue of the recommendations and standards on which it is based.
- **S2. Basic premises of the project.** This section describes the foundations and general criteria for the conception of a breakwater and elaborates on those presented in other documents of the ROM program, particularly the ROM 0.0-01. It establishes the methodologies, procedures, and tools used to gauge the spatial and temporal variability of the agents and response of the breakwater, the characterization and description of its state and the spatial and temporal evolution of the damage, with special attention to possible maintenance and repair strategies.
- **S3. Design procedure.** This section addresses the application of the criteria in Section 2 to breakwater design. It presents the main breakwater typologies and their characteristic elements as well as the criteria and strategies for their structure and design. It also describes the most relevant failure and stoppage modes in the different subsets of the breakwater.
- **S4. Verification of the breakwater in a project phase.** This section explains the technical requirements of the construction work, its implementation framework as well as the methods, tools and indicators used to verify compliance, considering the spatial and temporal evolution of the damage as well as maintenance and repair strategies. It also includes a description of the recommended verification procedures, depending on the nature of the construction work and the development of the project.
- **S5. Cost evaluation, optimization and risk level.** This section establishes the requirements of the construction work in relation to the financial-economic needs of the harbor area. It provides the methods, tools, and indicators that can be used to calculate the costs associated with the different phases of the life cycle of the construction, to perform the technical-economic optimization with and without restrictions, and to evaluate the risk level of the investment.

The ROM 1.1-18 ends with the following annexes:

- **A-I. Symbols and definition**
- **A-II. Comments and examples**
- **A-III. MEIPOR financial-economic indicators I**
- **A-IV. References**
- **A-V. Drafting of the ROM 1.1-18**

COMMENT

The bibliography consulted for the ROM 1.1-18 is copious and wide-ranging. The references cited are only a small sample and not necessarily representative of the huge number of publications that reflect the many years of research and professional experience in this field.

Manual for breakwater design and for the application of the articles in the ROM 1.1-18

The purpose of the *Manual* is to facilitate the implementation of the recommendations in the ROM 1.1-18 Articles. This document presents approaches, methods and tools compatible with the indications of the ROM 1.1-18 Articles, and should be periodically updated so that it is in consonance with the current level of knowledge and its limitations. This manual is composed of the following three chapters:

- **C1. Description of the construction site.** This chapter explains the purpose of the harbor area and the breakwater. In addition, it establishes the geometric foundations for the description of the site and of the construction as a whole. It also provides information regarding the elements that must be considered in the design of a maritime structure i.e. (topography and bathymetry; seabed and seismic activity; maritime and atmospheric climate agents; shoreline morphodynamics and water quality; quarries and riprap).
- **C2. Breakwater types and failure and stoppage modes.** This chapter provides the infor-mation needed to design a certain breakwater type, based on the dominant agents in the subset. It describes the regimes and domains of the hydrodynamic performance of the breakwater and its subsets. A set of recommendations is also provided for the design and pre-design of the layout, subsets and sections. Moreover, a set of formulas is also given for the design and pre-design of the layout, subsets, and sections. Also specified are the formulas that can be used to calculate the geometry of a breakwater section and its hydrodynamic performance in response to climate agents. Finally work methodologies are proposed for the verification of the technical requirements of a breakwater and its subsets in relation to failure and stoppage modes.
- **C3. Evaluation of breakwater construction and repair costs.** This chapter presents a set of methods and tools that can be used for the organization of the construction process, definition of construction and repair strategies, and statistical characterization of the costs of the different project phases and their temporal distribution.

Annexes of the general technical specifications for the project

The ROM 1.1-18 is progressively enriched by annexes with information regarding important aspects relevant to the design, construction, and exploitation of a breakwater, such as the following:

- *General index of the contents of a breakwater construction project;*
- *Specifications regarding quarry material for breakwaters;*
- *Technical specifications for the dredging of the seabed;*
- *Solutions for specific aspects of breakwater construction;*
- *Catalogue construction units and cost;*
- *Characterization of exceptional earthquake and tsunami conditions;*
- *Specifications for experimental verification in a wave flume and wave basin;*
- *Specifications for the numerical verification and applications of numerical codes;*
- *Specifications for field campaigns.*

Annexes for the characterization of sea oscillations

These annexes are composed of crucial information that can be used to characterize the agents at the construction site. This is a necessary first step in the design, verification, and optimization of the breakwater. The following should be considered:

- **Sources of climate data.** The information from climate databases supports and further enriches the other data used for the application of the Recommendations for Maritime Works. These recommendations should be periodically updated with data from new sources or revised data from existing sources. This annex initially includes a description of the different data sources for atmospheric and maritime climate agents provided by Puertos del Estado.
- **Characterization of the agents at the location site.** This annex describes numerical and analytical methods and tools used to characterize maritime, atmospheric and climate agents at the site, based on probability models. In addition, it provides techniques for data pre-processing, the transformation of agents, joint analysis for the study of operationality and reliability, as well as numerical simulation methods for the state descriptors of the main variables. This annex also includes a set of subroutines, functions, and procedures that can be used for the practical implementation of the methodologies and approaches described.

Examples

This document is composed of a set of partial examples of the characterization of agents and also of breakwater design and verification, structured in terms of the project development level.

1.6 RELATION WITH OTHER ROM RECOMMENDATIONS, INSTRUCTIONS, AND STANDARDS

The ROM 1.1-18 is part of the Series 1 of the ROM Program, focused on breakwater design and construction. It takes into account other ROM recommendations, which use probabilistic techniques (and methods based on the overall performance of the system), especially those that target the design of the configuration of harbor areas, access channels, maneuvering zones, mooring and berthing areas, and shoreline water quality.

Furthermore, the following documents and software have been taken into account:

(a) Eurocodes and official instructions for related technical fields;
(b) ISO 2394: General principles on reliability for structures;
(c) ISO 23469: Bases for design of structures-seismic actions for designing geotechnical works;
(d) ISO 21650: Actions from waves and currents on coastal structures;
(e) Criteria for the selection of breakwater types and their related optimum safety levels, PIANC report 196-2016;
(f) Recommendations for the increased durability and service life of new marine concrete infrastructure, PIANC report 162-2016;
(g) Seismic guidelines for ports. ASCE technical Council on lifetime Earthquake Engineering, Monograph 12, 1998;
(h) Technical standards and commentaries for port and harbour facilities in Japan, 2009;
(i) The Rock Manual. CIRIA C683, 2007;
(j) Coastal Modeling System (SMC), "IHCantabria'", Directorate-General of Coastal Sustain-ability and the Sea, Ministry of Agriculture, Food, and the Environment, http://smc.ihcantabria.es/.

To correctly apply this ROM, it is also necessary to consider other official codes and instructions in the field of civil engineering in Spain as well as in the European Union. This is the context of breakwater construction as specified in certain ROM recommendations.

- **ROM 0.0-01**. *General Procedure & Requirements for the Design of Maritime & Harbour Structures*
- **ROM 0.5-05**. *Geotechnical Recommendations for the Design of Maritime & Harbour Works*
- **ROM 1.0-09**. *Breakwater Recommendations (Calculation and Project Factors, Climate Agents*

- **ROM 2.0-11**. *Design and Construction of Berthing and Mooring Areas*
- **ROM 3.1-99**. *Maritime Configuration of HARBORS: Access Channels and Floatation Areas*
- **ROM 5.1-13**. *Quality of Coastal Water in Sea Port Areas*

Water quality in Spain is regulated in legal texts such as the Water Framework Directive and in the revised text of the Water Act. All aspects related to shoreline morphodynamics should be adapted to the provisions in the Spanish Coastal Law as well as to those in documents referring to Integrated Coastal Zone Management of the European Union. For this purpose, it is advisable to apply the methods and tools developed in the ROM 5.1-13 and in the *Manual de Costas*, particularly Volume IV on shoreline environment.

COMMENT

The tasks and milestones associated with each of project development levels should be performed by qualified technical personnel. Table 1.4 gives an estimate of the number of people as well as the work hours necessary to carry out the activities for each of the project development levels in Spain. Because of the wide range of cases possible, field campaigns, laboratory experiments, and project management work are not included. Evidently, in other countries, the values in the table could substantially differ. For this reason, it is necessary to revise and adapt them to each situation.

TABLE OF INDICATIVE VALUES FOR WORK HOURS (SPAIN)

***Table 1.4:* Indicative values for technical personnel, qualifications, and estimated number of work hours in the construction project (Spain)**

		Percentage	Work hours
Preliminary Studies	Senior Engineer (1)	40	200
	Qualified Engineer (1)	40	200
	Others (1)	20	100
	Total (3)		500
Study of Alternatives and Solutions	Senior Engineer (1)	30	450
	Qualified Engineer (2)	40	600
	Others (2)	30	450
	Total (5)		1500
Blueprint	Senior Engineer (1)	20	600
	Qualified Engineer (3)	60	1800
	Others (4)	20	600
	Total (8)		3000
Investment Project	Total (4)		3000
Construction Project	Senior Engineer (1)	20	1000
	Qualified Engineer (3)	60	3000
	Others (4)	20	1000
	Total (8)		5000

Section II. Table of contents

SECTION II: SPECIFIC PROJECT BASES

2. Specific Project Bases

In the ROM 0.0-01, the objectives of a maritime project are formulated in a set of project requirements for each project phase from the time of its construction until its eventual dismantling. These requirements are verified, considering the following types of variability: (1) spatial variability of the design; (2) temporal variability of the conditions of the structure; (3) spatial and temporal variability of the actions of natural agents and the response of the system to these agents as well as to the function of the infrastructure as part of the harbor area.

This ROM 1.1-18 provides an in-depth explanation of these concepts, methods, and tools, and adapts them to the needs of a breakwater and to MEIPOR. Specific project bases are formulated and developed for the design, verification, and optimization of the breakwater, in the light of different damage levels and repair strategies.

2.1 GENERAL APPROACH TO BREAKWATER PLANNING AND DESIGN

The structural and formal planning of a maritime infrastructure can be organized in four main thematic blocks with the following specific objectives:

1. spatial and temporal organization of the project;
2. characterization of the state of the construction work and its components;
3. spatial and temporal evolution of the failure modes;
4. evaluation of total costs and optimization.

The spatial and temporal organization of the project is the organic work framework for the project design, verification of project requirements, and specification of the time phases of the project as well as the breakwater subsets, subsystems, and units pieces.

The state of the structure and its components define the temporal unity of the project. Its characterization identifies the elements that are vulnerable to failure or stoppage, along with the mechanisms conducive to such problems. It also establishes the hierarchical relations between the different spatial and temporal organizations of the project.

This characterization is based on the following:

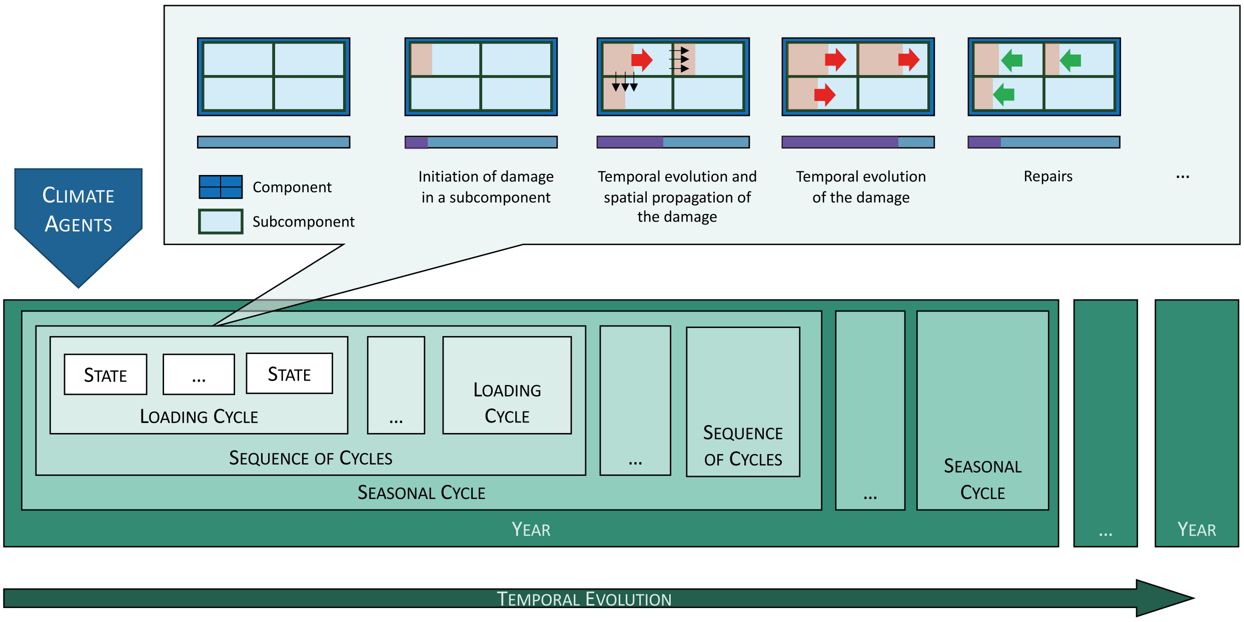
(a) Sample space and space of events describing the failure or stoppage of the different system components.
(b) Modes as well as the set of modes that can affect the performance of the breakwater and its design.
(c) Relations between the state of the components at different hierarchical levels as depicted in diagrams of breakwater components.

The spatial and temporal evolution of the failure and stoppage mode, its manifestation, persistence, and propagation makes it possible to define and delimit the monitoring mechanisms conducive to the fulfillment of project requirements. This evolution can be quantified by means of the following:

(a) triggering and propagation trees;
(b) models of the evolution of the damage or stoppage;
(c) strategies that monitor the propagation of the damage.

The evaluation of the total costs and of the technical-economic optimization of the infrastructure permits the prediction of the annual costs of its performance in regard to safety and operationality in each of the project phases. These results can thus be connected with the financial-economic optimization of the investment project. In other words, this is the information required for decision-making, based on risk level and sensitivity analysis (MEIPOR).

Figure 2.1: ***Workflow for breakwater design, verification, and optimization, considering the spatial and temporal evolution of the failure and stoppage modes***



2.2 SPATIAL AND TEMPORAL ORGANIZATION OF THE PROJECT

2.2.1 Temporal organization: project phases

The life cycle of a breakwater is the time period from the beginning of its construction until its transformation, change of use, or dismantling. This time interval is organized in phases, according to the main or primary function of the structure though it may also have other secondary functions. In each phase, climate agents (as well as other agents) interact with the breakwater and its subsets. This interaction may or may not affect the fulfillment of project objectives.

Breakwater project phases

Considering the objectives, function, and main activity in the time period, the following project phases can be identified (for more details, see Section 2.4.2 of the ROM 1.0-09),

Construction

The construction phase lasts from the beginning of construction until the structure goes into operation, in other words, when it is able to perform the function that it was conceived for.

Service phase

The service phase begins the moment that the subset of the structure can fulfill its primary function and ends with its remodelling, transformation or dismantling. This project phase may be partially or totally interrupted during the maintenance and repair phase.

Maintenance and repair

The maintenance and repair phase includes the time periods during which maintenance and repairs are periodically or occasionally performed, and which may involve a temporary reduction of the safety, service, and/or use and exploitation of the structure in one or more of its subsets or of the harbor area.

Remodelling, transformation, and dismantling

This project phase includes the time periods in which the remodelling/reconstruction, transformation or dismantling of the structure is continuously or intermittently performed. These actions may involve a temporary reduction of the safety, serviceability, and/or use and exploitation of the structure in one or more of its subsets or of the harbor area.

Other phases and subphases

Other phases or subphases can be defined when the entry into service of the structure is partial or when in one of the phases, situations are expected to occur, which are of particular relevance to the safety, serviceability or operationality of the breakwater or one of its subsets.

Duration of a project phase

The duration of each project phase should be determined by the project developer, on the basis of a wide range of factors, such as those related to the construction process, behavior of the materials or soil, maintenance, functionality, and serviceability of the structure, as well as economic considerations, and relevant legislation.

The service phase is finished when the structure begins to be dismantled. It thus is the end of the structure's useful life (see PIANC, 2016). Section 2.4.2.2 of the ROM 1.0-09 establishes the minimum duration (V) of a breakwater in:

(a) $V \leq 5$ years for breakwaters and their provisional subsets.
(b) $V > 5$ years for breakwaters and their definitive subsets.

The possible extension of the useful life of a structure beyond the initially projected time period requires, at the very least, a verification of the project requirements in the new service phase. Among other things, this verification should envisage a revision of the ERI, SERI, OIER, and OISER indexes, recent maritime climate data, and its interaction with the structure, history of cumulative damage by different modes, repairs, and the state of the structure at the end of its previous service phase.

Subphase duration

The duration of a project subphase is determined in the same way as the duration of a project phase. If the subphase is due to a partial entry into service, its duration should not exceed 5 % of the duration of the service phase with a maximum of 5 years. However, if the subphase is due to situations of special relevance for the safety, serviceability or operationality of the breakwaters, its duration will be the same as that of these situations.

Hierarchy of time scales in a project phase

Throughout each phase, the project factors, particularly, the climate agents, show variability cycles on different scales, which include the following (ROM 0.0-01, Section 2.4.2 and ROM 1.0-09, Section 2.4.2),

(a) Pluriannual cycle
(b) Meteorological year
(c) Seasonal cycle
(d) Calm cycles and loading cycles
(e) Meteorological state
(f) Basic manifestation of a climate agent (e.g. individual wave in a meteorological state).

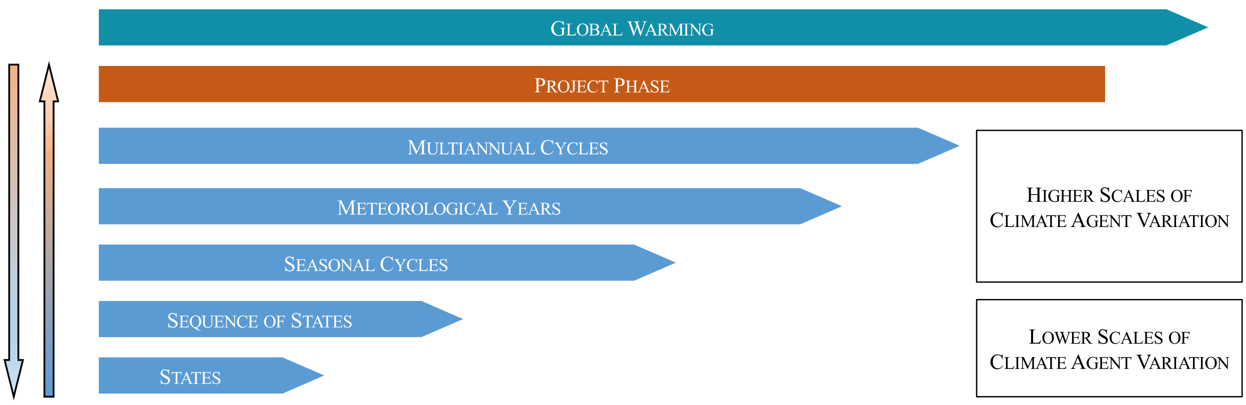
Life cycle and adaptation to the consequences of global warming

The life cycle of a breakwater begins the moment when its construction project is approved. If the projected life cycle is equal to or longer than 50 years, the project should integrate and verify the consequences of global warming in the objectives, safety, and operationality of the breakwater by quantifying the spatial and temporal evolution of the models of the joint, conditional, and marginal probability of the climate agents and their actions.

COMMENT

By definition, the meteorological state is the time period in which the manifestation of climate agents, their actions, and the functional or structural response of the breakwater is assumed to be stationary in a statistical sense. For this reason, the state is generally considered to be the basic time interval in which project requirements and the intended function of the breakwater are verified. The occurrence and evolution of damage, repairs, operationality levels, and financial-economic balance of the harbor activity is conditioned by the sequences of states and their variation scales in cycles, years, etc. (See ROM 1.0-09, Section 3.1.3).

Figure 2.2: ***Hierarchy of the time scales of the project***



2.2.2 Spatial organization: subsets

A breakwater is defined and spatially characterized in subsets. A subset is a continuous section of a breakwater in which the characteristic values of soil and climate agents are regarded as uniform and its temporal evolution is simultaneous and compatible. A subset has a certain structural and formal typology although its geometric dimensions may gradually vary to adapt to subtle changes in the bathymetry and properties of the seabed.

Breakwater subsets

A breakwater can have the following subsets:

- Land connection subset either with dry land, with a maritime work, or with the water in the case of a detached breakwater. (The connection with another breakwater can also be regarded as a transition.)
- Main alignment that controls and protects the structure against the prevailing wave action.
- Secondary alignments and changes in alignment that link the different subsets of the breakwater from the land connection subset to the head or upper part of the breakwater.
- Head or upper part that is the final subset of the breakwater.
- Transitions where changes occur in the geometry of the breakwater and which are generally associated with significant longitudinal variations in some of the project requirements or in project agents and actions.

Transitions and part of a subset

A transition subset (part of a breakwater subset) should be adapted when abrupt changes are expected to occur in any of the following: (1) climate or soil agents; (2) bathymetry and nature of the seabed; (3) alignment and typology of one of the breakwater's parts and unit pieces; (4) its purpose.

More specifically, a transition subset should be adapted when either of the following events occurs:

(a) The socioenvironmental or economic repercussions of two consecutive subsets are significantly different, either from a general or operational perspective.
(b) The longitudinal variability (throughout the breakwater) of the state descriptors of one of the predominant agents exceeds the average value of the subset by 10-20% (e.g. significant wave height or predominant wave direction, presence of currents, etc.).

Precise delimitation of a subset

The delimitation of a subset is based on the spatial variability of the climate agents (sea oscillations) and on the properties of the topography. Also important are the layout of the breakwater and the isolines of the threshold values, which define the operationality and loading cycles of the breakwater in the surroundings of the harbor area. Moreover, it is necessary to take into account the spatial variability of the soil (bearing capacity and deformability) and the spatial variability of the breakwater foundations in relation to the action of incoming wages and other project agents.

These calculations should be based on statistical downscaling methods, applied to the agents and using information stored in climate databases.

Influence of wave train dynamics on the delimitation of subsets

Wave train dynamics at the location site and the interaction between wave action and the breakwater plan and section can be determining factors in the delimitation of breakwater subsets. It is particularly important to consider that the interaction between the breakwater and incident wave does the following:

(a) It changes the dimensions of the breaker zone and the way that the waves break on the breakwater front and at the toe (see Section 3.4.6 of the ROM 1.0-09).
(b) It generates spatial and temporal variations (amplitude and phase) of waves propagating on the front and toe, and waves overtopping the breakwater when (a) they encounter obliquity; (b) there are abrupt changes in the typology of the section or boundary conditions, as occurs in the land connection, head and alignment changes of the breakwater.

COMMENT

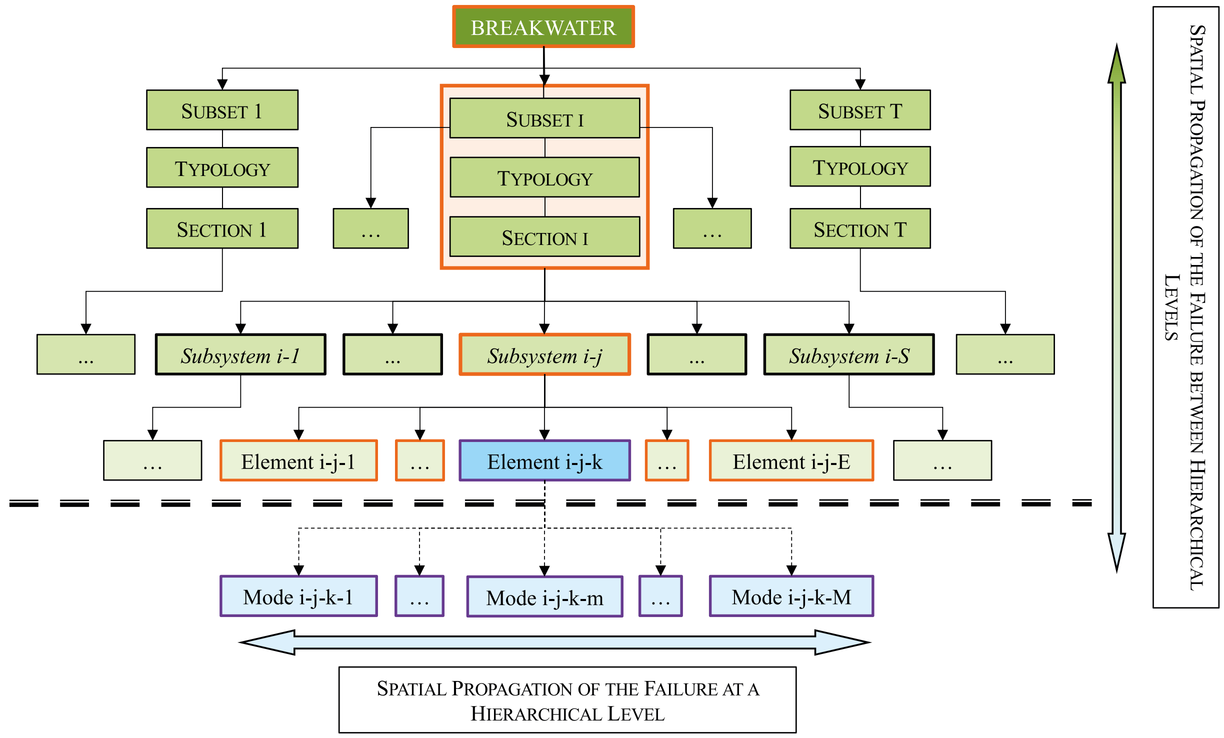
The relevance of those spatial and temporal variations depends, among other things, on the angle of wave incidence, the relative depth, h/L_i, and the typology, where L_i is a characteristic wavelength of the wave action, and h is a representative depth of the subset.

In these circumstances, the length of the subset should depend on the dimensionless monomial, l/L_i, either by resolving the elliptic wave propagation equations with numerical models (e.g. MSPE, see ROM 1.0-09 See 3.4.3.1), or experimentally with a wave flume, capable of generating a directional wave train. Initially, it is advisable to precisely delimit a minimum subset length of $l > 2L_i$ on one side and the other of the section that is the source of the longitudinal variability. This should be verified in the draft project.

Hierarchy of spatial scales in a subset

A breakwater subset is defined by its layout dimensions and typology characterized by a certain geometry as well as a structural and formal configuration. When regarded as a system, this configuration can be decomposed into smaller units, known as subsystems, and these in turn can be decomposed into structural units, and so on. Its performance against the action of agents can be analyzed according to the hierarchy of spatial scales, in other words, in subsystems, elements, etc. Typically, the performance of each is described and quantified (on that scale) by one or various forms or mechanisms that can affect (on that scale) the safety, use and exploitation of the subset. Figure 2.3 shows this spatial hierarchy (or cascade distribution) for the analysis and evaluation of the performance of a subset.

Figure 2.3: ***Subset performance according to construction states***



2.3 SUBSET PERFORMANCE ACCORDING TO CONSTRUCTION STATES

The time scale of the forms and mechanisms that can affect the safety, use, and exploitation of a subset can be described by states of the construction (or its subsets). Its characterization includes the following:

(a) Sample and event space
(b) Failure and stoppage modes
(c) Complete set of modes
(d) Event space and component diagrams

2.3.1 Sample and event space

The sample space explicitly characterizes the breakwater state. It can be used to identify a set of positions that delimit each possible events (e.g. generally failure and stoppage modes) whose joint or individual occurrence leads to the non-compliance with the project objectives of a breakwater subset.

When suitably justified, non-compliances with project objectives can be analyzed by means of other sample spaces that do not use failure and operational stoppage modes.

2.3.2 Failure and stoppage modes

A mode is defined as the manner, form, or mechanism in which the failure or operational stoppage can occur.

Characterization of failure or stoppage modes

Section 2.3.2 of the ROM 1.0-09 characterizes a mode in terms of the following elements:

(a) temporal and spatial domains, and parts and units of the section affected;
(b) predominant agents and other agents as well as simultaneity diagrams;
(c) mechanism or way in which modes occur and the actions that trigger them, observation, and metrics;
(d) verification forms, and when applicable, verification equation, format, and resolution;
(e) status as principal mode and statistical dependence on other modes;
(f) spatial and temporal evolution of the mode, state-by-state accumulative process, damage levels, from the beginning until the subsequent destruction or repair of the structure (see Article 2.4), and, when applicable, the potential triggering of other modes.

The description of a stoppage mode includes, apart from previously mentioned elements, the possible actions to reduce the recurrence, duration, and consequences of the operational stoppage mode.

COMMENT

The characterization of a mode is based on the statistical uniformity hypothesis of the agents, actions, and response in the subset and its stationarity in the time interval (state). The climate agents of the overtopping or erosion of the toe-berm are wave train dynamics, sea level (astronomical and meteorological tide), wind, and current.

Spatial and temporal modes caused by climate or soil agents

The spatial characterization of the failure and stoppage modes of a subset caused by climate or soil agents involves the part of the section (foundation, central body, superstructure, etc.) where the stoppage can occur, and the elements potentially affected.

When the climate agents are predominant or significantly participate in causing the mode, the temporal domain used to characterize it is the meteorological state. Nevertheless, it is possible to adopt other temporal modes that are higher in the hierarchy (e.g. loading cycle) or lower (e.g. individual wave).

Diagram of predominant agents

If there is more than one predominant agent, it is advisable to create a sequential diagram of the different combinations of agents that can simultaneously and significantly participate in the triggering and spatial and temporal evolution of the failure or stoppage mode. Generally, the concomitance of agents and their threshold values at the beginning and propagation of the mode are determined, depending on their joint probability.

Mechanism, observation and metrics

The description of a mode should include the following: (1) form or way that it is triggered and the processes that participate in its spatial and temporal evolution; (2) observation technique and magnitudes (geometric dimensions, construction material, number of displaced units, etc.) applied to characterize the damage level of the mode. In such cases, it is advisable to previously establish the biunivocal correspondence between the damage (or stoppage) level and the observed magnitudes and measurements. This correspondence depends on the mode and the damage (or stoppage level).

Verification methods

Depending on whether it is a principal or non-principal mode as well as on the project development stage, the occurrence of the mode can be verified by one of the following methods:

(a) resolution of a verification equation formulated according to:
  1. threshold values of the predominant agents that trigger the failure or stoppage mode;
  2. combinations of agents and actions that participate in the mechanism or failure or stoppage mode.
(b) experimentation in the laboratory or at the building site for a set of specific work and operating conditions;
(c) application of standards of good practice or other sets of regulations and guidelines.

2.3.3 Complete set of modes

The complete set of modes consists of a collection of mechanisms whose isolated or joint occurrence leads to non-compliance with project requirements or the non-fulfillment of project objectives. This complete set unambiguously describes all of the failure and operational stoppage modes, indistinctly related to the formal and structural safety as well as to the operationality of the harbor area, and which are mainly caused by interaction with climate, hydraulic, soil, and use-and-exploitation agents.

Mutually exclusive modes and dependent modes

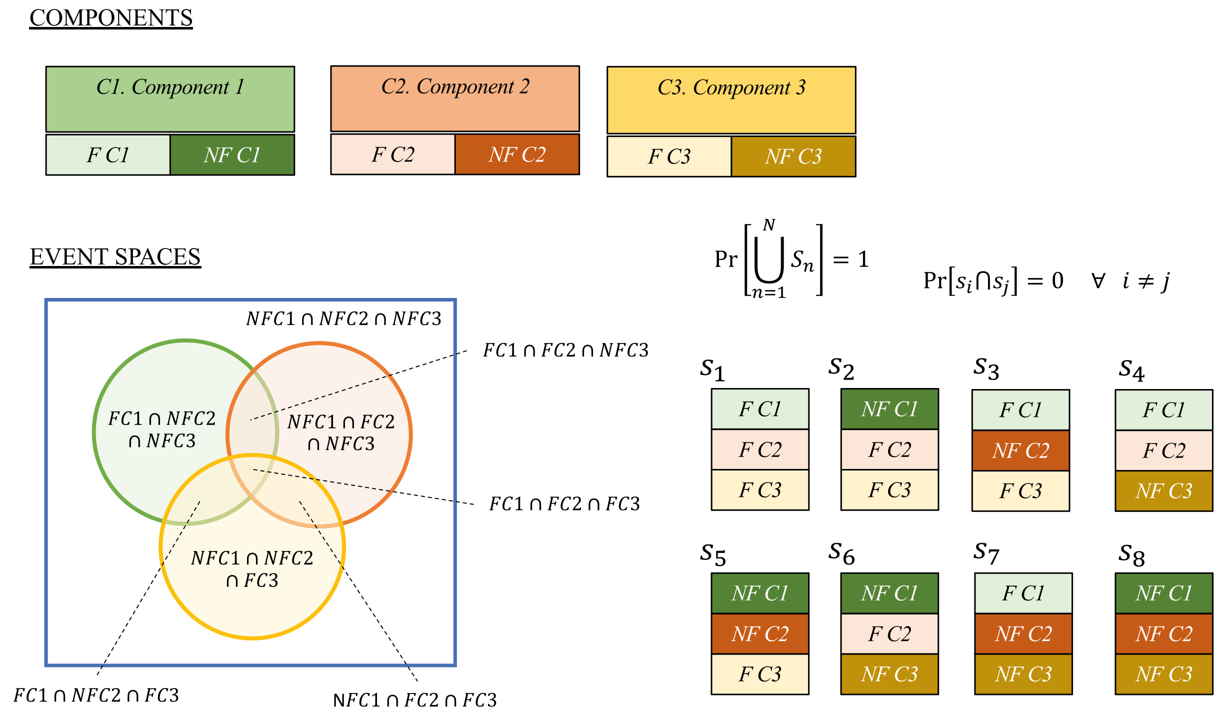
A set of modes are mutually exclusive if the occurrence of one mode excludes the occurrence of the others (i.e. their intersection is an empty set). When this is not the case, the modes are regarded as non-exclusive and may be statistically dependent.

Two modes that are not mutually exclusive are statistically independent if their joint probability is equal to the product of their marginal probabilities. When this is not the case, they are considered to be dependent and may be positively or negatively correlated. If the correlation is positive, the failure or stoppage of one mode is related to the failure or stoppage of the other. If the correlation is negative, the failure or stoppage of a mode is not related to the non-failure or non-stoppage of the other.

2.3.4 Event spaces and component diagrams

After defining the set of failure or stoppage modes, the event space describes the set of all combinations of modes that can simultaneously occur in a state as the result of the verification of the state of the structure (see Section 2.7.1 of the ROM 1.0-09). The combinations of modes that comprise the event space should be represented by Venn diagrams (Figure 2.4).

Figure 2.4: ***Event space for a set of three components***



COMMENT

Figure 2.4 shows a set of three components and a Venn diagram, which represents the space of possible events, depending on whether these components are in a situation of failure (stoppage) or non-failure (operational). The probability of the event space is the unit, where each event has a null intersection. The lower right-hand area shows the combinations with the possible situations of the different components, which correspond with each of the Venn diagram areas, and which are graphical representations of the relations between the units or parts as a whole.

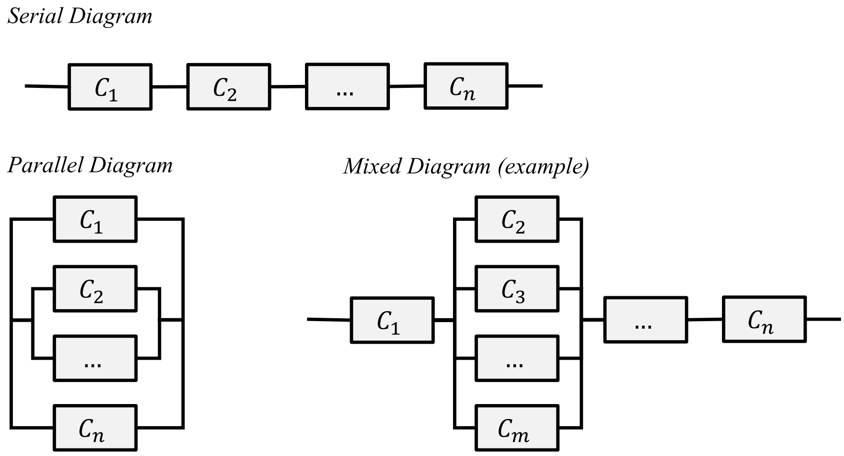
Component diagrams and the structural and formal design of the subset

Component diagrams help to verify the state of the structure (subset) in a specific temporal domain. They define the possible combinations of failure or operational stoppage modes that can cause non-compliance or non-fulfillment of project requirements or objectives.

The configuration of a component diagram reveals the purpose and nature of the infrastructure and its subsets as well as its event space. When it is used to calculate the failure or stoppage probability, it is also necessary to consider the relations of exclusion or dependency between components. The following three types of diagram (see Figure 2.5) are generally sufficient for this purpose:

(a) serial;
(b) parallel;
(c) mixed, with serial or parallel components.

Figure 2.5: ***Typology of component diagrams***



In the case of a serial diagram, the system fails (or project objectives are not fulfilled) if at least one of its components fails. In a parallel diagram, the system fails or project objectives are not attained when there is the simultaneous occurrence of the situations that describe components of the diagram. A component diagram with serial and parallel components allows users to consider situations in which the non-fulfillment of project objectives can be associated with at least one component or with the concurrent non-fulfillment of a group of them.

These diagrams are useful in the design of the breakwater and the failure probability distribution. They can also be applied to calculation, subset reliability, definition of repair strategies, and configuration of decision trees.

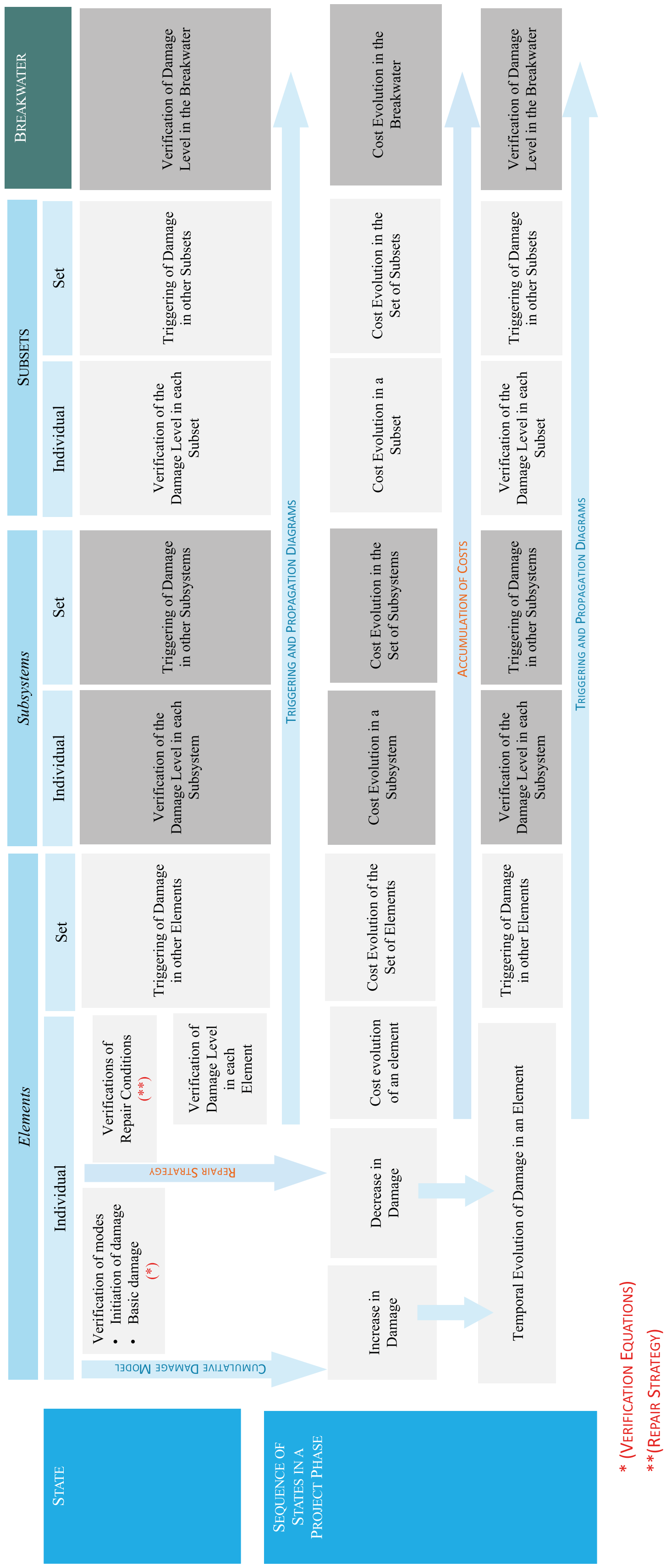
2.4 CHARACTERIZATION OF THE TEMPORAL EVOLUTION OF DAMAGE

This ROM considers the design of a breakwater at advanced damage levels. For this purpose, cumulative damage models are proposed from the initiation of damage until the destruction of the breakwater. These models are generally applied at the state level (temporal domain). The verification of the construction in a project phase includes the integration, state by state, of its response to the agents and cumulative damage.

One of the results of this work method is the spatial and temporal evolution of the different failure modes in each subset, its consequences, and costs. The unification of the modes assigned to the ultimate and serviceability limit states also homogenizes the decision-making process and the calculation of the risk level of the investment.

Figure 2.6 presents a summary of this work method and the main tools used to implement it.

Figure 2.6: ***Diagram that evaluates the cumulative damage and its consequences***



2.4.1 Conceptual model of the temporal progress of the level of cumulative damage

This article presents some simple models that can be used to analyze the temporal evolution of the damage level and corresponding operational stoppage time, depending on the temporal evolution of the predominant agent. The result is the state curve of cumulative damage. Its mathematical description should satisfy certain conditions of temporal compatibility as will be described further on.

A conceptual model of cumulative damage should contain at least the following components:

(a) description of the damage and the way that it accumulates;
(b) probability model of damage levels;
(c) parametric levels between agents and actions, and verification equation, depending on the damage level;
(d) when applicable, a model of the magnitude of the initial damage, conditioned to the magnitude of the agents and action;
(e) the integral form of cumulative damage for the application of a Gaussian distribution model.

Damage described using state curves

Damage to a breakwater component should be described by using one or more observable and measurable magnitudes that permit the quantification of its importance and level of progress. Once reached the threshold values of the predominant agents that trigger and activate the mode, the progress of the damage depends on the temporal evolution of those agents as well as on the structural and formal response of the section. Depending on this process and the observed magnitudes, the temporal evolution of the cumulative damage can be schematically described in terms of the following:

(a) sequence of (dynamic) equilibrium states;
(b) increasing and unlimited continuous curve;
(c) mixed behavior.

In the first case, each damage level is a formal and structural "equilibrium" state and remains in that state as long as there is no significant increase in the values of the agents and actions that caused the damage.

In the second case, the damage progresses indefinitely without increasing the threshold value of each of the predominant agents and mainly depends on its persistence. In certain cases, the damage can progress even when the values of the predominant agents are lower than the threshold values that triggered it.

The mixed behavior model describes the progress of the cumulative damage by means of a sequence of equilibrium states followed by unlimited progress or vice versa, without a a non-stop process.

In all cases, the boundary conditions of the affected units limit the evolution of damage. Consequently, they influence the way that the damage progresses and also the possibility of reaching equilibrium states in the evolution of the damage.

COMMENT

The spatial evolution of the loss of units pieces from the main armor layer ends is generally said to end when the secondary layer becomes visible. The structure is then declared to have reached the destruction level. Depending on the morphology of the section, destruction can occur without the geometry of the armor layer reaching intermediate equilibrium states (step model).

When the breakwater section is composed of only one type of unit (natural rockfill or over quarry run without intermediate layers), the displacement of the stones and their relocation in the structure usually forms equilibrium geometries that remain stable as long as the wave train dynamics that created them does not become stronger. In these cases, if the project objectives and conditioning factors are complied with, destruction occurs when the breakwater shows a landward to seaward breach that allows the waves to propagate inside the harbor area, and which breaks the continuity of the linear profile of the structure. Breakwater damage and its evolution is the focus of much research that analyzed the results of numerical and experimental studies, such as Benedicto (2004), Maciñeira (2005), Clavero (2007), Guanche (2007), Gómez-Martín (2015) and Campos (2016).

Equilibrium states and damage levels

Damage can be classified in the following level:

(a) non-failure;
(b) beginning of failure;
(c) evolution levels of failure;
(d) destruction state.

The initiation of the failure should unambiguously identify and quantify a damage state in terms of one or more observable and measurable magnitudes such as the following: (i) minimum value of displaced units in a breakwater section; (ii) variation in the geometry (distance, depth, area, etc.) of a granular system; (iii) movements (displacements and overturning) of the rigid solid section. In the preliminary studies, the beginning of the failure should be specified beforehand. For this purpose, it should be accurately determined and established during optimization and sensitivity studies of the infrastructure. The selection of the initiation of damage is linked to the maintenance and repair strategy (decision trees) and should appear in the total costs of the project that condition the construction project objectives and the financial-economic risk of the investment project.

The destruction state is associated with the resistance threshold of the unit, subsystem, and parts of the section, and eventually of the subset and other subsets of the breakwater. The declaration of a destruction state signifies that the structure no longer fulfills the project objects and is thus an alert to the need for an immediate intervention so that complete destruction can be avoided. In the laboratory, destruction is assumed to occur when the progression of damage only depends on the number of waves impinging on the section.

When damage progresses indefinitely without arriving at the total fatigue, malfunction, or rupture of the component, it is advisable to select/delimit a maximally admissible level of damage, equivalent to the destruction state, and specify the circumstances that would trigger an immediate intervention to prevent the destruction of the breakwater.

When the behavior of the damage is mixed, it is necessary determine the damage levels that will presumably lead to a change in performance and, in this case, select/delimit a maximally admissible level of damage.

Randomness of the structural response and the probability model

Each level of damage should be associated with the combinations of the values of predominant agents causing the damage. It is also important to keep in mind that for each combination, the response of the structure is a random process described by a probability function.

The probability model of the (physical magnitude) that describes the level of damage or stoppage is estimated by the statistical data fitting. These data can be obtained by conducting experimental studies in the laboratory or at the project site or by means of analytical or numerical models. In all of these cases, the experiment and its time scale should be adapted to the needs of the project.

If there are no data available, in a first approach, the cumulative geometric deformations, displacements, and movements of the breakwater structure as a rigid solid composed of parts and units can be assumed to follow a Gaussian probability model. In this case, the mean value of the damage increases when the values of the predominant agents also increase. Although its variance grows higher for the lower damage levels, it usually stabilizes at more advanced damage levels.

Randomness of the initial damage

Usually, the values of agents and actions causing the initiation of damage are random variables with a probability model. Its parameters (mean values and variance) depend on the agents (magnitude and duration) and their variability as well as on the mode and typology. These values are the starting point of cumulative damage curves, and may not be controlled a priori by the same mechanisms that govern the accumulation. Because of their importance in the cumulative damage model, these mechanisms should be specifically and independently characterized.

2.4.2 Curves of the mean cumulative damage

The description of damage evolution is specified by means of one or various of the following curves:

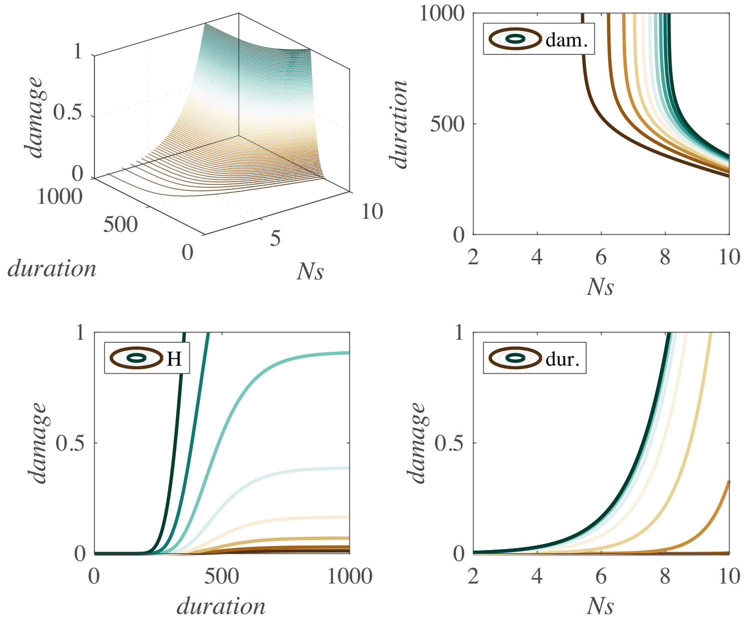
(a) iso-duration curves, based on the characteristic magnitude of the predominant agent and of the mean cumulative damage;
(b) iso-mean-cumulative-damage curves, based on the characteristic value of the predominant agent and its duration;
(c) iso-characteristic-value curves, based on the duration and mean cumulative damage.

When the predominant agent is wave train dynamics, the behavior of the damage should be described according to the meteorological state. This description should at least include its duration, stability number (dimensionless variable) associated with the characteristic wave height and period, and the accompanying sea levels.

COMMENT

Figure 2.7 displays examples of mean damage curves. The upper left panel shows the surface defined by the variables of damage, duration, and the characteristic value of the agent. The upper right panel depicts the iso-mean-cumulative-damage curves, based on the characteristic value of the predominant agent and its duration. The lower left panel shows the iso-characteristic-value curves, based on the duration and cumulative damage. Finally, the lower right panel depicts the iso-duration curves, based on the characteristic magnitude of the predominant agent and the mean cumulative damage.

Figure 2.7: ***State curves of the mean cumulative damage. Ns = stability number associated with the characteristic wave height of the sea state; d = mean cumulative damage; dur = characteristic duration of the sea state***



The selection of mean cumulative damage curves should be based on an accurate theoretical conceptualization of the processes and, when applicable, on experimental studies in the laboratory or at the location site. In this case, it will be based on dimensional analysis and conditions of temporal compatibility (as will be explained further on). Moreover, it is usually the case that the temporal evolution of the probability function of the cumulative damage satisfies the central limit theorem (see Section 2.4.3 for an example).

Iso-duration curves based on the predominant agent and the mean cumulative damage

Generally speaking, the cumulative damage function (and its uncertainty) tend to grow when there is a corresponding increase in the action of the predominant agents that triggered the failure. The mean cumulative damage level can be described with continuous mathematical functions or in steps of the predominant agents or actions (or terms). If the predominant agent is wave train dynamics, the wave height should be the main variable, whereas the wave period and sea level should be the characteristic parameters of the function or evolution curve.

This curve helps to define following: (a) start-destruction interval for a damage level; or (b) total operationality stoppage interval for an operationality level. The values of the principal agents that delimit the interval between damage initiation and destruction should be well defined in order to decide and enable intervention before the total destruction of the breakwater. It is important to analyze whether the evolution of the mode is tridimensional and includes sufficient information for its quantification, for example, the longitudinal dimension of the mode, maximum number of units in the volume, etc.

The function types (see Figure 2.8) that can be used to characterize these curves are the following:

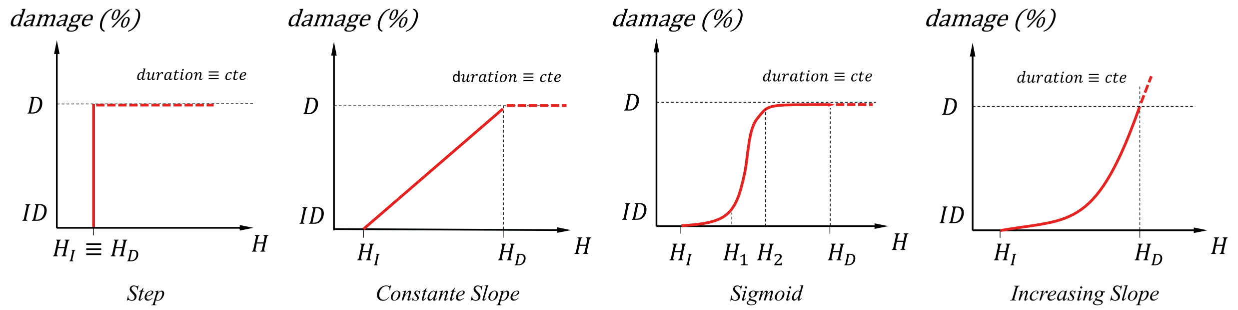
(a) **Step function.** The step function associates the initiation of damage and destruction for the same predominant agent value. It is a binary model of failure-non-failure and operational stoppage-non-operational stoppage for a mode assigned, respectively, to an ultimate limit state or an operationality state. It can be applied to construction projects with a low ERI and SERI, as verified by Level I Methods and whose investment cost is less than C_0 (dimensionless magnitude of the cost in Spain).

(b) **Constant slope curve.** The constant slope curve establishes a linear relation between the predominant agent value and the damage level. It is determined by two value pairs, (H_I, ID) and (H_D,D), where ID designates the initiation of damage, and D represents destruction; H_I and H_D represent the agent values at which the damage level is reached. The slope of the line measures the residual resistance capacity of the section (resilience) against destruction. This model represents a breakwater with a constant residual resistance capacity. In contrast, the step model represents a breakwater without a residual resistance capacity or one that is non-resilient.

(c) **Sigmoid-type function (e.g. hyperbolic tangent).** The sigmoid-type function identifies three regions of damage or gradual loss of operationality, depending on their residual resistance capacity: (1) region with a high resistance capacity not very sensitive to variations of the agent's value; (2) region with a low resistance capacity, very sensitive to slight variations of the agent's value; (3) region that recovers a high resistance capacity until reaching the destruction state. The residual resistance capacity of a breakwater generally depends on its deformation capacity and on the modifications caused by the agent.

(d) **Increasing slope function (e.g. potential or exponential).** The increasing slope function defines an increasing and unlimited data magnitude with the value of the agent. The predominant agent value corresponding to a sufficiently high slope makes it easier to select the values associated with the levels of destructive damage.

Figure 2.8: ***Iso-duration curves, based on the predominant agent and the mean cumulative damage. ID = initiation of damage; D = destruction; H = characteristic wave height of the sea state; H_I = characteristic wave height of ID; H_D = characteristic wave height of D; H_1, H_2, characteristic wave heights of the successive damage states in the time interval (ID - D)***



Indefinite progress of the damage

During the design process of the structure, it is necessary to identify the conditions of the principal agent and the subsets in which the damage, once initiated, can increase indefinitely until the destruction of the structure. This often occurs when the deformation of the section does not moderate the action of the agents since the breakwater units are displaced from the structure.

This situation occurs when the damage affects the following: (1) a straight subset because of the oblique impingement of a wave train; (2) breakwater head, change of alignment, or the base. In such cases, it is advisable to model the evolution of the damage with sharply-sloping straight lines or as a step.

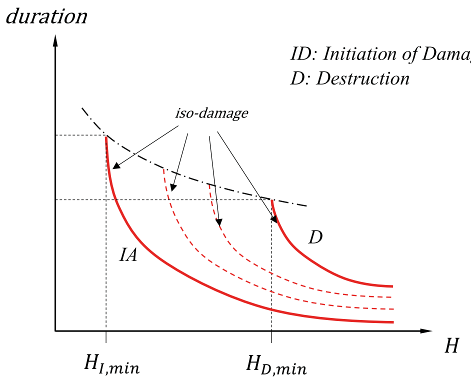
Mixed behavior of certain failure modes

In certain typologies, sections or units, the evolution of the damage can be described with a mixed pattern. It would first manifest itself in one or various equilibrium states, suddenly followed by the destruction of the breakwater. This behavior is quite frequent in a single-layer armor, slender unit pieces in the main layer, protection berms, etc. In such cases, the model of damage evolution should include the following threshold values: (i) start; (ii) impaired performance; (iii) destruction by predominant agents. For example, this could be represented by a sigmoid function with three well-defined domains. These thresholds should be verified with laboratory experiments. In any event, such studies are necessary when the ERI and SERI of the structure exceed the values in Article 1.4, or in the case of a Class II investment project.

Iso-mean-damage-value curves, based on the predominant agent and the duration

Iso-mean-damage-value curves describe the characteristic value of the predominant agent and the duration (persistence) required for a given iso-value of the damage. This is accomplished by providing the threshold values necessary for the agent to cause a given damage level.

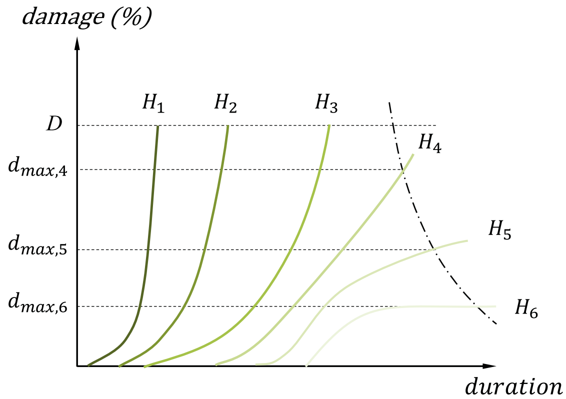
Figure 2.9: *Iso-mean-cumulative-damage-value curves, based on the predominant agent and the duration. $H_{i,min}$ = characteristic wave height (with a minimum duration $t_{I,min}$), necessary to reach state ID. $H_{D,min}$ = characteristic wave height (with a minimum duration $t_{D,min}$), necessary to reach state D*



Iso-characteristic-value curves of the agent, based on the duration and cumulative damage

For each characteristic value of the predominant agent, these curves describe the cumulative damage, based on the duration of the loading. They can be used to characterize the minimum duration of one of the magnitudes of an agent, which is required to attain a given damage level.

Figure 2.10: *Iso-characteristic-value curves of the characteristic agent (wave height H_1, H_2, ...), based on the duration and mean cumulative damage o D. Where -.-.- is the line that separates the regions in which characteristic sea states, H_1, H_2, H_3 with a well-defined duration can cause the destruction level*



Temporal compatibility of the cumulative damage curve

The ROM 1.1-18. generally determines the damage level, based on the cumulative damage in the breakwater section quantified from the beginning of a certain stage (e.g. entry in service, after repair, etc.). The mathematical function that models cumulative damage is specified in dimensionless terms (dependent variables) and should satisfy the compatibility condition. Accordingly, if D is the damage produced by a loading cycle of duration $t = t_1+t_2$, d_1 is the damage produced in time interval t_1, and d_2 the damage produced in time interval t_2, then $D = d_1+d_2$. Mathematically, the cumulative damage can be expressed as follows:

$$d(d_0, N_s, t) = q\left[q^{-1}(d_0, N_s) + t, N_s\right] \tag{2.1}$$

where N_s is the stability number of the dimensionless agent; d_0 is the initial damage (Castillo et al., 2012); and t is the time elapsed from the initial moment.

When the meteorological states do not have the same duration, the duration of each state can be transformed into other equivalent durations (with the same damage evolution), and taking into account the magnitude of the agents and the accumulation model q(t;H).

COMMENT

A specific case of damage evolution in systems that do not reach equilibrium steps, is the cumulative damage model of the potential type of form:

$$d(d_0, N_s, t) = \left[d_0^{1/b} + (a\, N_s^c)^{1/b}\, t\right]^b \tag{2.2}$$

This model is composed of three parameters: a and c quantify the increase in associated damage associated with a magnitude of agent H; b expresses the power showing how the damage accumulates. This function is part of the family of more general scale models, given by the expression:

$$d(d_0, N_s, t) = q\left[q^{-1}(d_0) + \alpha(N_s)\, t\right] \tag{2.3}$$

where α is a function of the dimensionless agent N_s.

2.4.3 Trajectory of cumulative damage in a loading cycle

A loading cycle defines the temporal evolution of the state descriptors of climate agents that continuously exceed a pre-established threshold value. It is represented as a *time–agent* histogram, in which the width of each bar is the state duration. Once the duration and the average state period are known (usually the zero up-crossing period, or $m_{0,1}$, the mean number of waves in the state is calculated. It is assumed that the types of damage are geometrically similar, in other words, that the dimensionless geometry of the damage is independent of the state in which the damage occurred. With this assumption, the iso-characteristic-value curves for *duration-damage* with an agent-value parameter, is used to determine the trajectory of cumulative damage, based on the histograms of the cycle.

In the calculation of the temporal trajectory of damage, the wave action also depends on the characteristic wave period, angle of wave incidence, and sea level in the meteorological state. When sea level variations are significant in comparison to the characteristic dimensions of the section, it is advisable to work with sea-level steps, considering the geometric conditioning factor derived from the other steps.

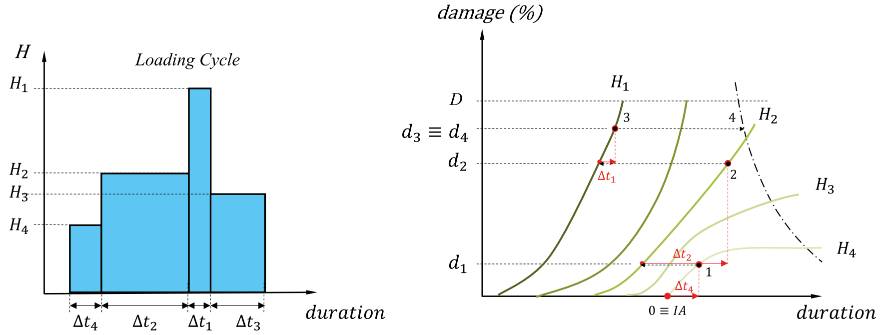
The evolution of the damage in a breakwater is a multivariate process, which should be taken into account in its theoretical and experimental determination. Depending on the importance of the breakwater, this calculation can be simplified in various ways.

COMMENT

Damage accumulation process in the loading cycle

Figure 2.11 shows the cumulative damage during a loading cycle, subdivided in four meteorological states of different durations. The first state corresponds to a characteristic value of the predominant agent H_4, associated with a stability number t $N_{s,4}$ and a duration Δt_4. The cumulative damage is obtained by using this duration, and the initiation the damage at 0 in the curve $H_4 \rightarrow N_{s,4}$. The level of damage reached (point 1) is the initial damage for the following state ($H_2 \rightarrow N_{s,2}$ and duration Δt_2). The procedure is repeated in this state and in the following one. Finally, the last state with value $H_3 \rightarrow N_{s,3}$ is unable to increase the cumulative damage, regardless of the duration of the state.

Figure 2.11: ***Example of cumulative damage in a loading cycle. Trajectory of the damage (red vectors), depending on the characteristic wave height of the state and its duration, both of which correspond to the loading cycle represented by the histogram. It does not include the dependence of the characteristic wave period***



The previously mentioned curves can be fitted, based on experimental laboratory data as shown in what follows. The experiment consisted of eight steps of increasing wave height and a constant wave period, where each step had a duration of 1000 waves. The cumulative damage because of the displacement of unit pieces from the main armor layer of a sloping breakwater was quantified by the eroded area in each experimental step. Figure 2.12 shows the fitting of the power-type function, (see equation 2.2) to data obtained from this experiment, which was conducted in a wave-current flume by the Environmental Fluid Dynamics Research Group (GDFA-UGR).

Figure 2.12: ***Iso-value curves of the fitted model for different values of H y $d_0 = 0$***

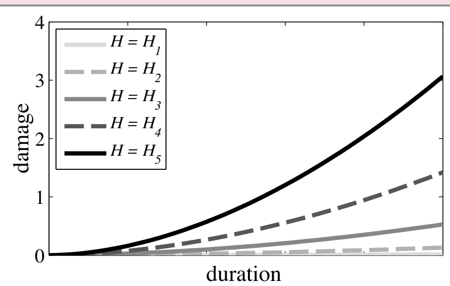
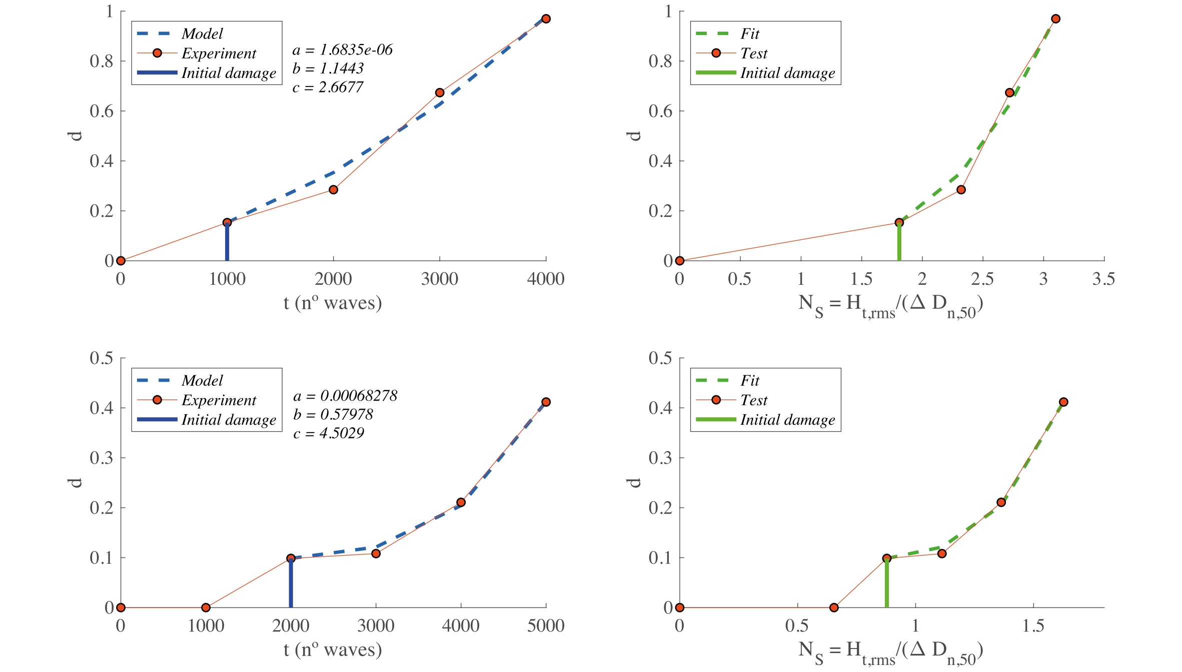


Figure 2.13 shows the fitting of a power function (equation 2.2) to experimental cumulative damage values, depending on the number of waves in the state (figure on the left) and on the stability number (figure on the right). The coefficient values of the data fitting are shown on the left side. The upper panel (a) shows the results of data (period T = 2:5 s) of Van der Meer, 1988, for a homogeneous rubble-mound breakwater (D = 36 mm). The lower panel (b) shows the results of experimental data (period T = 2 s) for a sloping breakwater (D = 26 mm) with a crown wall, which were obtained and analyzed by the Environmental Fluid Dynamics Research Group (GDFA-UGR).

Figure 2.13: **Experiments on measured cumulative damage and data fitting**



2.4.4 Time dependency of the probability model of cumulative damage

The probability density function (PDF) of the random variable, cumulative damage, depends on the PDF of the initial damage and on the sequence of states. When both are known, it is possible to calculate the density functions and the damage distribution based on the following.

Randomness of the initial damage

If the initial damage distribution is defined by f_{d0}, and the parametric expression that describes cumulative damage d is expressed by $q(t,N_s)$ for a temporal sequence of states defined by $H_s(t)$ or $N_s(t)$, the PDF of cumulative damage at the end of time t, (see equation 2.4), is expressed as follows:

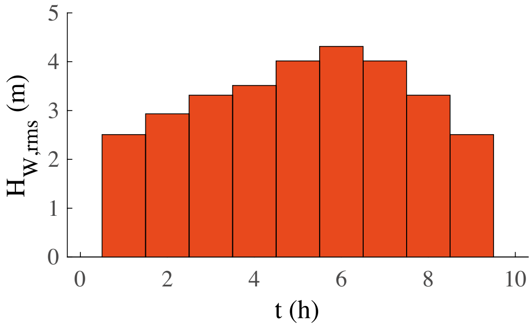
$$f_d(d,t,N_s) = \frac{q'\left[q^{-1}(d,N_s) - t,\, N_s\right]}{q'\left[g^{-1}(d,N_s)\right]}\, f_{d_0}\left\{q\left[q^{-1}(d,N_s) - t,\, N_s\right]\right\} \tag{2.4}$$

COMMENT

TEMPORAL EVOLUTION OF THE CUMULATIVE FAILURE PROBABILITY

The following example analyzes the evolution of the damage throughout the loading cycle of Figure 2.14, based on the root mean squared wave height $H_{W,rms}$. The assumption is that the breakwater must be repaired when the damage (with value d_0) starts, but the repair work has still not begun. More specifically, it analyzes the temporal evolution of the PDF of the cumulative damage, using two strategies: (a) repair work is required at low damage values, but the damage is not exhaustively monitored; (b) repair work is required at higher damage values, but the damage is monitored more closely.

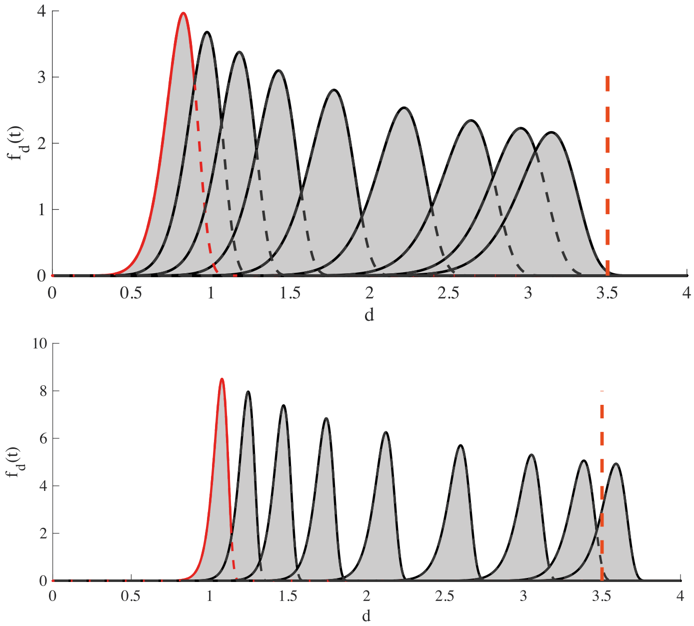
Figure 2.14: ***Sequence of states of the characteristic cycle analyzed***



At the beginning of the cycle, the first step is to define the initial damage that needs to be repaired. This is specified by two Weibull probability functions. In case (a), the PDF has a mean value of μ_a and a standard deviation σ_a, whereas in case (b), the mean value $\mu_b = 4/3\mu_a$ and the standard deviation $\sigma_b = \sigma_a/2$. Furthermore, the value of damage d_c is defined. This value is critical since it requires the total restoration of the breakwater section. What is being defined here are two strategies in relation to damage repair. In both cases, the critical damage is the same, but the damage levels selected to begin repair work are different: (a) a conservative strategy entailing repair work at initial levels of damage; (b) a riskier strategy for a more advanced level of damage.

The results of both strategies are depicted in Figure 2.15, cumulative damage model for the previous example (see Figure 2.13). This figure shows the density function of initial damage (red line) and cumulative damage in each of the states in the loading cycle. Moreover, the dashed line indicates the critical level of damage, d_c = 3:5. The area below the PDF in interval d_c, *destruction* provides the failure probability, p_{f,d_c} of the breakwater section at the end of the loading cycle if it is not repaired. For strategy (a), the area below the curve is very small (negligible), whereas for strategy (b), the area below the curve is large and includes the modal damage value. The reliability of the structure if the structure is not repaired when the loading cycle appears is s $r = 1 - p$.

Figure 2.15: ***Temporal evolution of cumulative damage probability for the two PDFs of initial damage: the first PDF represents a conservative repair strategy, whereas the second PDF represents a riskier repair strategy***



Random nature of the sequence of states in a loading cycle

The estimation of cumulative damage probability functions can be generally based on the central limit theorem. According to this theorem, the sum of the damage in a sufficiently high number of states tends to have a distribution in the form of a Gaussian bell curve, regardless of the damage probability function in an individual state.

For a power-type cumulative damage model,

$$d(d_0, N_s, t) = \left\{ (d_0 - \gamma)^{1/b} + \int_0^t \alpha\,[N_s(t)]\,dt \right\}^b,$$

where γ and b are constants and $N_s\,(t)$ is the sequence of states that originate the damage. With these assumptions, the temporal evolution of the distribution function $F_d\,(d,t)$ of cumulative damage in loading cycle is,

$$F_d(d,t) = \Phi\left[\frac{(d-\gamma)^{1/b} - \mu_0 - k\,t}{\sqrt{\sigma_0^2 + r\,t}} \right], \qquad (2.5)$$

where $\Phi(d)$ is the standard normal distribution function; μ_0 and σ_0^2 are the mean value and variance of $((d_0-\gamma)^{1/b}$, and kt and rt are the mean value and variance of $\int_0^t \alpha\,[N_s\,(t)]\,dt$.

COMMENT

SEQUENCE TO ESTIMATE THE PARAMETERS OF THE DAMAGE EVOLUTION MODEL

Castillo et al. (2012) proposes the following work sequence to estimate the parameters of the previous model: μ_0 y σ_0^2 (initial damage); γ and b (breakwater characteristics); and k and r (response characteristics of the agents),

1. Estimation of the mean value and the standard deviation of the initial damage (e.g. by means of experimental studies or previous experience).
2. Estimation of parameters γ and b of the cumulative damage model by means of laboratory experimentation.
3. Definition of cumulative damage aN_s^c by means of laboratory experiments to fit parameters by adopting, when necessary, conservative criteria (confidence level) so that the result always falls in the safe zone.
4. Application of parameters k and r, based on available historical data and the fitted models resulting from the previous steps:

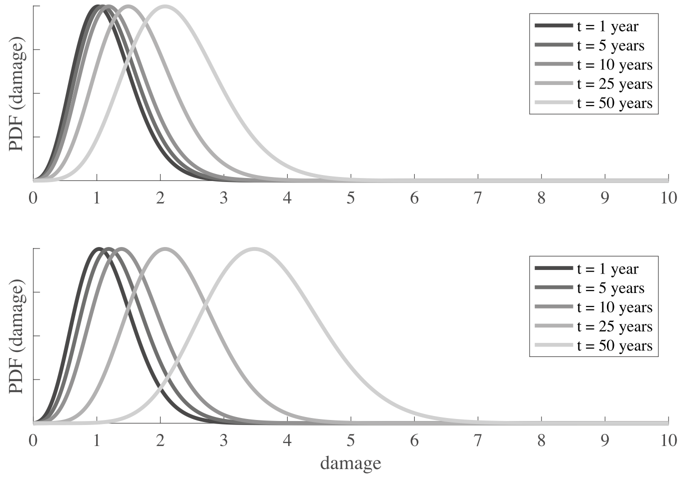
$$k \approx \frac{\int_0^t \alpha\,[N_s\,(t)]\,dt}{t}$$

$$r \approx \frac{\sum_{i=0}^{t} \left\{ \int_i^{i+1} \alpha\,[N_s\,(t)]\,dt - k \right\}^2}{t}$$

5. Application of the equation 2.5 in order to estimate the temporal variation of reliability and failure probability.

Figure 2.16 shows the time-dependent cumulative density functions, corresponding to the equation model, 2.5 for parameters b = 1.8, γ = 0, μ_0 = 1 and σ_0 = 0.25, for the same cumulative damage function but with different maritime climate characteristics. The upper panel corresponds to $k = 0.01$ years^{-1} and $r = 5 \cdot 10^{-4}$ years^{-2} and the lower panel to $k = 0.02$ years^{-1} and $r = 10^{-3}$ years^{-2}.

Figure 2.16: **Temporal evolution of the probability of cumulative damage, considering agent variability**



2.4.5 Temporal progress of other cumulative variables

If the predominant agent is wave train dynamics, the principal failure modes of a breakwater usually belong to the outer perimeter subsystem (as described in Section 3). Their occurrence is reflected in geometrical changes in the section, number of unit pieces displaced, movements as a rigid solid, etc. Their importance is described in terms of progressive levels of cumulative damage, beginning at the initiation of damage and continuing to the final level of destruction. This discrete sequence specifies the temporal progress of each of the failure modes of the landward and seaward outer perimeter, which surround the central body (main layer and berms), and the crown wall or superstructure of the section. The temporal evolution of the cumulative damage is usually described by means of the following variables (damage metrics).

(a) main layer and berms: geometric form and/or cumulative number of displaced unit pieces;
(b) crown wall and superstructure: displacements and/or overturning as a rigid solid section in regard to its initial position;
(c) overtopping: number of episodes and cumulative value of wave-by-wave overtopping.

COMMENT

The conceptualization of overall breakwater performance in the design of its outer perimeter subsystem is explained in Vílchez et al., 2017 and Molines et al., 2018.

In such conditions, the function describing the temporal evolution of the damage, $A(A_0, Q, t)$, should satisfy the compatibility condition. From a very general perspective, it can be expressed as reflected in equation:

$$A(A_0, Q, t) = q\left[q^{-1}(A_0, Q) + t, Q\right] \qquad (2.6)$$

where Q is the dimensionless value of the agent and A_0 is the value of the initial damage (Castillo et al., 2012).

This cumulative model can be applied on different scales, such as the following:

(a) State scale: random sequence of waves with a given height, period, and duration.
(b) Loading cycle scale: random sequence of wave height, period, direction, and duration states.
(c) Year (or seasonal) scale: random sequence of loading cycles with a random form and duration.

Temporal evolution of the damage with alternating process directions

Some of the processes that affect the stability of a sloping breakwater have cumulative cycles in which the original geometry of the project design is recovered. These cycles alternate with erosion cycles, as well as with the displacement of unit pieces and geometrical changes in the section. The mathematical-statistical model of damage evolution is applicable, for example, to erosion as well as to sediment accumulation, such as scour and bar formation at the breakwater toe and face, or sediment propagation and accumulation at its core. Equation (2.6) can be applied to erosion as well as to accumulation as long as the process continues in the same direction.

To apply the model to an alternating cumulative-erosive process, the functions that evaluate the cumulative process should be made compatible with those of the erosion process, always bearing in mind the morphological state or geometry of the structure. Since there is little information available regarding how to make functions compatible, it is necessary to perform studies at the appropriate scale to develop a mathematical expression in consonance with the process analyzed. The selection of the scale is crucial for experimental results to be representative and applicable to the scale of the prototype.

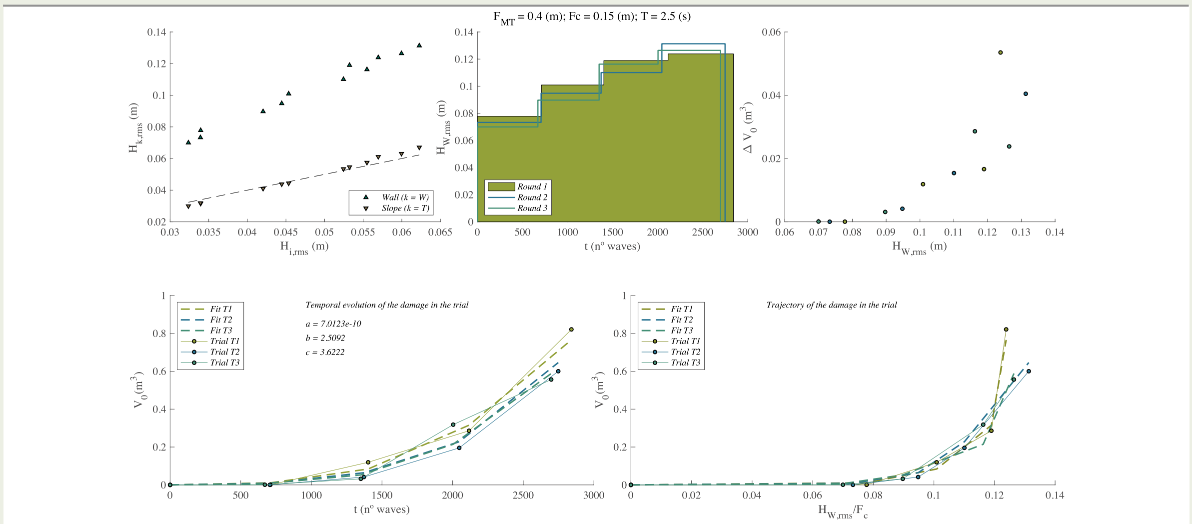
EXAMPLE

Cumulative model of the overtopping volume in a loading cycle

The cumulative overtopping volume in a state (Figure 2.17), the total number of waves that overtop the breakwater during a loading cycle, or the number of overtopping episodes during the useful life of the infrastructure are variables that can be modeled with the cumulative function as long as the necessary compatibility conditions are fulfilled. Figure 2.17 shows the experimental results of the cumulative overtopping volume of a mixed breakwater for four sequences of sea states (800 waves per state) with a constant wave period and an increasing significant wave height. The experiment was repeated in three rounds (1, 2 and 3), and the experiment was conducted in the wave-current flume of the Environmental Fluid Dynamics Research Group (GDFA-UGR).

Based on these results, the following overtopping magnitudes can be defined: (a) variation rate of the overtopping volume compared to the relative freeboard; (b) mean overtopping volume per state: (c) mean overtopping volume of the waves flowing over the breakwater, etc. All of these magnitudes must be taken into account when designing a breakwater and delimiting the consequences of overtopping in relation to its safety and operationality.

Figure 2.17: ***Experimental results for the cumulative overtopping volume. Cumulative water volume in three rounds of four wave cycles of equal wave period and duration and an increasing significant incident wave height ($H_{i,rms}$). The results of the cumulative model are displayed in relation to the root mean square wave height at the crown wall ($H_{W,rms}$)***



Temporal progress of project costs

Section 5 of these Articles, (see Articles 5.3.1 and 5.3.2) structures the investment and operational costs of the investment project, which are attributable to the breakwater in the form of: (a) construction costs; (b) repair costs; (c) dismantling costs; (d) maintenance costs; and (e) costs derived from the loss of operationality during the exploitation phase of the breakwater. The total cost throughout the life cycle (temporal progress) of the breakwater is a cumulative random variable, in the same way as each of the costs that comprises the total.

Article 5.3.3, (see Article 5.3.1 recommends the application of this model to estimate the probability models of the total cost of the life cycle of the breakwater. Similarly to cumulative damage, other statistical descriptors can be defined for the cost. These descriptors describe cost performance on other time scales, such as annual average cost or other magnitudes related to the financial-economic analysis of the breakwater.

2.4.6 Operational stoppage levels and temporal evolution of the operational stoppage

The operationality of the harbor area is one of the objectives of the financial-economic analysis of the infrastructure. The design of the area, its layout,, and the reliability and the operationality depend on this analysis.

According to the ROM 0.0-01 each breakwater subset should satisfy project requirements in regard to operationality. Accordingly, there are two ways of analyzing operational stoppage in relation to breakwater performance:

(a) When the value of the agent (wave height, wind speed, etc.) exceeds a threshold value in the subset or in another infrastructure of the harbor area, and the subset is no longer operational, though without any formal or structural failures. The level of full operationality is recovered when the value of the agent no long exceeds the threshold value.
(b) When there are structural failures in the subset or breakwater. Full operational conditions are not recovered until the damage is repaired or the subset is reconstructed.

In both cases, the level of non-fulfillment of requirements can be specified by three levels or thresholds of operationality.

(a) full operationality;
(b) partial or restricted operationality;
(c) complete operational stoppage, with or without closing access to the port.

Duration of an operational stoppage

The loss of operationality without any structural failure in the breakwater or one of its subsets can be represented by a step function, a sharply sloping straight line, hyperbolic tangent, and power function, based on the threshold value of the agent. The duration of the loss of operationality is usually related to the length of threshold value exceedance of the agent.

The duration of the loss of operationality caused by structural failures in the breakwater or one of its subsets depends, among other things, on the time and means available to remedy the failure. It also depends on the length of time needed for repairs. To determine this loss operationality, it is first necessary to define a specific threshold value for this scenario, in relation to the values of the different agents that condition the operationality of the structure.

In the time interval that elapses from structural failure to the recovery of full operationality, duration is a cumulative variable. The temporal progress and PDFs of the cumulative duration are modeled similarly to the cumulative damage variable. They can be used to define other state (statistical) variables, related to the loss of operationality. They are useful for the sensitivity analysis (see Article 5.4.3) in order to reduce the recurrence and duration of the stoppage mode and also minimize economic repercussions.

Operationality in exceptional work and operating conditions

The ROM 0.0-01 (see Sections 4.5 and 4.6) analyzes operationality during and after exceptional work and operating conditions WOC_3, such as the following:

- $WOC_{3,1}$, unforeseen exceptional work and operating conditions
- $WOC_{3,1,1}$, unforeseen exceptional work and operating conditions of the physical environment
- $WOC_{3,1,2}$, unforeseen exceptional work and operating conditions caused by accidental circumstances
- $WOC_{3,2}$, foreseen exceptional work and operating conditions

In all these cases, the project should analyze and, where appropriate, specify the operationality required during post-exceptional work and operating conditions $WOC_{1,3}$. Similarly, when exceptional work and operating conditions are foreseen, the operationality levels should be specified in the construction and investment projects and be totally consistent with the master infrastructure plan.

2.5 FAILURE PROBABILITY AT AN ADVANCED DAMAGE LEVEL

The ROM 1.1-18 links the destruction level to the failure probability assigned in the joint probability distribution among the principal modes of the subset. The calculation of joint probability and its distribution among the main failure modes are described in Section 7.5 of the ROM 0.0-01 and in Sections 2.5.3 and 2.5.4 of the ROM 1.0-09.

If a generic failure mode is designated by:

- D_0, initial level of damage;
- D_f, damage level at which destruction is declared;
- $Pr\ [D_0, V]$, probability that a certain damage level will be reached in a time interval V (e.g. useful life);
- $Pr\ [D_f\,|D_0, V]$, probability that in a time interval V a certain damage level will be reached D_f, if the damage has reached level D_0,

The probability of the failure mode in time V, Pf ;V, is the following:

$$P_{f,V} = Pr\,[D_0, V] \cdot Pr\,[D_f|D_0, V] \tag{2.7}$$

where the second factor is a conditioned probability and its value depends on the following: (1) the conception of the structure (expressed by triggering and propagation trees); (2) repair strategy that determines the construction and repair costs, among other things. Equation 2.7 helps to quantify the distribution of the joint probability of failure (project requirement dependent on the ERI) for different breakwater designs.

2.5.1 Conceptions for breakwater design

The design of a breakwater is harnessed by two conceptions that are extreme points on a continuum:

- Ultimate limit state (ULS) design at the initial damage level
- Critical design for continuous repairs.

Between these two extremes, there are a wide range of options, which the ROM 11 categorizes as "ULS design at an advanced damage level". These options combine breakwater dimensions, repair strategies with the construction materials and tools, and the total cost of the breakwater. All options must not exceed the joint failure probability of the principal modes with regard to safety during the useful life of the subset.

ULS design at the initial damage level

If it is assumed that

$$Pr\,[D_f|D_0,V] = 1$$

the initiation of damage is equivalent to destruction, then the failure mode is assigned to an ultimate limit state (ULS). This signifies that to recover operationality. The subset must be reconstructed. When applied to the principal failure modes of the subsets, this determines the breakwater's construction cost, probable reconstruction costs, and the financial-economic profitability of the assets. The scope of the technical-economic decision is defined by specifying when the failure begins and how to reconstruct the section.

In the case of the displacement of unit pieces from the main armor layer, which can also occur during laboratory experimentation, it is customary to consider a minimum number (or percentage) of unit pieces displaced from their original position to determine the initial damage level, and consequently, the destruction level and the need, in theory, to repair or reconstruct the subset.

Critical design for continuous repairs

If it is assumed that,

$$Pr\,[D_0,V] = 1$$

$$P_{f,V} = Pr\,[D_f,V] < 1$$

the breakwater is sized with the presupposition that it will require continuous repairs during its useful life to avoid its destruction and to fulfill its construction objectives.

In the case of a rubble mound breakwater designed with a much lower weight than the weight at the initiation of damage, the main layer of the breakwater would slowly acquire an S-shape as it gradually lost material over time. To prevent a breach in the structure, which would allow waves to enter the harbor area and eventually lead to the destruction of the breakwater, the breakwater must be continuously repaired with additional rockfill. The scope of the technical-economic decision-making is defined by specifying how to provide the different subsets of the breakwater with a constant supply of this material.

SLS Design, at an advanced level of damage

If it is assumed that

$$Pr\,[D_0,V] < 1; Pr\,[D_f|D_0,V] < 1;$$

with the condition,

$$P_{f,V} < Pr\,[D_0,V]\cdot Pr\,[D_f|D_0,V] \tag{2.8}$$

the scope of breakwater design decisions broadens considerably. To size the subset, it is necessary to do the following: (1) specify when the failure begins and select its probability, $Pr\,[D_0,V]$; (2) define the most suitable repair strategy to avoid destruction and select its probability $Pr\,[D_f\,|D_0,V]$.

As the probability of damage decreases, the conditioned probability of reaching the destruction level increases. The decision in favor of a design mode and the probability distribution between the two factors of equation 2.8 should be based (scope of decision) on environmental, legal, financial-economic and technical criteria. Furthermore, these criteria should be based on the technical-economic optimization (ROM) of the construction project and on the financial-economic optimization of the investment project, according to Section 5 (MEIPOR).

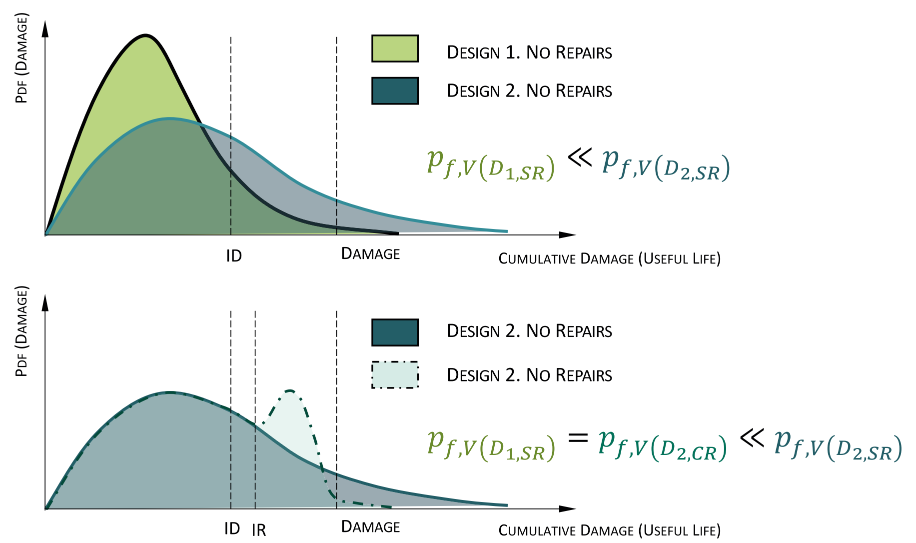
COMMENT

Figure 2.18 shows the probability density functions (PDF) of cumulative damage during the useful life of the breakwater. These functions correspond to a given failure mode whose maximum admissible failure probability should not exceed 0.05.

The upper image corresponds to the design of a breakwater section with two reliability values without considering the repairs in the event of a failure. In the first design option ($D_{1,SR}$), the probability of the initiation of damage (ID) is 0.25 and the probability that this damage will progress and lead to a failure ($F_{failure}$) is 0.2. In the second design option ($D_{2,SR}$), the probability of initial damage is 0.4 and the probability that this damage will develop and lead to a failure is 0.5. Both of these probabilities are significantly greater than those of the first option. Consequently, (1) the costs of the first construction of a breakwater with the second design option are lower than those of the first option: (2) the resilience of this breakwater is also significantly lower; (3) the probability of failure during its useful life (area below the corresponding PDF curve in the interval *cumulative damage* $> F_{failure}$, is also much greater.

The bottom image represents the density functions of the cumulative damage, corresponding to the second option, $p(ID)$ = 0.4 and $p(F_{failure})$ = 0.5, with and without a repair strategy. The repair strategy involves an intervention after the SR damage level has been reached. Consequently, (1) the total cost of the structure increases because it includes the repair costs for each repair strategy; (2) in this case, the probability that the damage during the structure's useful life will develop and lead to failure decreases to 0.125. Accordingly, this satisfies the starting requirement of a maximum admissible failure probability of 0.05 during the useful life of the breakwater.

Figure 2.18: ***Probability density functions (PDFs) of the cumulative damage during the structure's useful life for design options 1 and 2 with and without repairs. In this case, the repair strategy is implemented when the damage level is SR. ID and IR indicate the initiation of damage and of the repairs, respectively. $F_{failure}$ indicates the maximum admissible failure. The probability of failure during the structure's useful life is the area below the corresponding PDF in the domain Damage > $F_{failure}$. When repairs are included, the shape of the PDF of the cumulative damage during the structure's useful life is different in the interval Damage > (SR)***



This example reflects the relevance of the study of alternatives and solutions with a view to selecting the ones that best comply with project requirements in relation to project safety according to the ROM 0.0-01. On the other hand, these alternatives and solutions should be selected based on operationality requirements, total costs, temporal distribution of costs throughout the useful life of the structure, as well as other social, environmental, and technical project conditioning factors.

2.5.2 Indicators of the temporal evolution of reliability

To correlate the repair strategy with the model of the temporal accumulation of failure, it is advisable to quantify the temporal evolution of the project requirements in relation to the safety and operationality of the structure during its useful life (or during another project phase). For this purpose, the following concepts can be used: reliability function, reliable life, hazard function, and availability rate.

Variation of the failure probability over time

The reliability function $R(t)$ describes the probability that a component operates suitably (without malfunctioning) during a given time period t_V (measured from a starting time, which can be the beginning of operation, the beginning of damage D_0, or others). This function can be expressed by means of equation 2.9

$$R(t) = \int_t^{\infty} f_W(t)\,dt = 1 - F_W(t) \tag{2.9}$$

where W is the random variable of survival time; $f_W(t)$ is its density function: $F_W(t)$ is its distribution function; and t is the time interval considered. This variable, W, describes the interval elapsed from a reference time t_0 (for example, when the structure or its components begin to operate, when it begins to malfunction, etc.) until it reaches a certain damage level (for example, the time at which failure or destruction occurs).

For stationary processes, the function $R(t)$ of a mode can be expressed in terms of a random variable that describes the time interval between failures, U, by means of expression 2.10, and the risk of failure or the probability that there will be at least one failure in the time interval $t < t_V$, by its complementary value $P_f(t)$,

$$R(t) = 1 - \lambda_U \cdot t + \lambda_U \int_0^t F_U(w)dw \tag{2.10}$$

where F_U is the distribution function between failures; $\lambda_U = 1/\mu_U$ is the mean failure rate per time unit; and μ_U characterizes the mean value of U. The upper and lower values that delimit the range of application of this model are $R(t) \geq 1 - \lambda_U \cdot t$ and $P_f(t) \leq \lambda_U \cdot t$, for $t \leq 1/\lambda_U$.

Reliable life, t_r

Reliable life is the time that elapses so that reliability at start-up, destruction or another cumulative damage level can decrease to a given level, r.

Hazard function, $h(t)$

The hazard function describes the failure rate of the system such that lower values are related to longer times until failure and vice versa. This function can be expressed in terms of $R(t)$ by means of equation 2.11.

$$h(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t+\Delta t)}{R(t)\Delta t} = \frac{f_W(t)}{R(t)} \tag{2.11}$$

Availability rate of a component, T_D

The availability rate quantifies the time during which a component is in good condition in a given time period (e.g. useful life). In the simplest case, when the performance of the component is assumed to be stationary, the availability rate, T_D, can be obtained with expression 2.12

$$T_D = \frac{\tau_F}{\tau_F + \tau_R} \quad (2.12)$$

where τ_F is the mean time between failures; and τ_R is the mean time needed to repair the component.

Estimate of functions and indicators

The indicators and functions λ_U, μ_U, $f_U(W)$, $f_w(t)$, $P_f(t)$ and $R(t)$ can be obtained by means of the Monte Carlo simulation of the behavior of the failure modes during the structure's useful life. The results of the simulation depend on the design and repair strategy. In the current state of knowledge, it is advisable to use physical model tests to verify the accumulation models (see Article 2.4.4).

COMMENT

As part of the study of alternatives and solutions, the project design should envisage concepts such as (a) initiation of damage, ID, D_0; and (b) destruction, D, D_f. This means considering one of the following two working hypotheses:

(a) The initiation of damage signifies a reversible failure. When the damage is repaired, the purposes and objectives of the structure are fully recovered.
(b) Destruction signifies an irreversible failure. Compliance with project requirements can only ensured with if the subset is reconstructed.

If the project design envisages other damage levels, it should also specify the repairs or reconstruction to be performed and its implications for the recovery of project requirements.

When it is a question of working with the initiation of damage and destruction, it is possible to obtain approximate analytical expressions of the functions and indicators of the temporal failure evolution based on the following hypotheses:

- The process is stationary.
- Damage occurs in the same way as Poisson processes with a mean failure rate (usually in years) of $\lambda_\alpha = 1/\mu_\alpha$, where a designates D_0 as the initiation of damage and D_f as the destruction.
- The survival time and temporal reliability for each failure mode can be approximated based on the frequency with which the predominant agents (usually the dynamics of the wave train) exceed certain threshold values.

The mean damage rates, λ_{D_0} and λ_{D_f} can be obtained from the return periods of the extreme distribution of the predominant agent that causes these events. The failure probability and temporal reliability for damage D_0 and D_f take values $P_{f,\alpha}(t) = 1 - \exp(-\lambda_\alpha \cdot t)$ y $R_\alpha(t) = \exp(-\lambda_\alpha \cdot t)$, whose bounds are the following:

(a) if $t \leq 1/\lambda_\alpha$ $\quad P_{f,\alpha}(t) \leq \lambda_\alpha \cdot t$
$R_\alpha(t) \geq 1 - \lambda_\alpha \cdot t$

(b) if $t > 1/\lambda_\alpha$ $\quad P_{f,\alpha}(t) \leq 1$
$R_\alpha(t) \geq 0$

Moreover,

(a) mean survival time with no damage event from the structure's entry into service or from the last repair event is $\mu_{W,D_0} = 1/\lambda_{D_0}$;
(b) mean survival time with no destruction event from the structure's entry into service or from the last reconstruction event is $\mu_{W,D_f} = 1/\lambda_{D_f}$;
(c) danger function is constant and equal to $h(t) = \lambda_{D0}$ for the design option at the initial damage level and $h(t) = \lambda_{D_f}$ for the design option at the destruction level;
(d) reliable life for a minimum reliability, r, is $t_r = -(1/\lambda_{D0}) \cdot ln(r)$ for the design option at the initial damage level and $t_r = -(1/\lambda_{D_f}) \cdot ln(r)$ for the design option at the destruction level.

Potential resilience index of the project design, PRI

The PRI quantifies the possibility that the damage of a principal mode will progress and end in destruction, supposing that its failure probability is $P_{f,V}$, (as assigned in the joint probability distribution). Its value can be estimated with the following equation 2.13,

$$PRI = 1 - \frac{P_{f,V}}{Pr\,[D_0, V]} = 1 - Pr\,[D_f | D_0, V] \tag{2.13}$$

This index is defined in the interval $[0,1]$, where the values, $PRI = 0$ and $PRI = 1$, correspond, respectively, to the following situations: (a) $P_r\,[D_f\,|D_0, V] = 1$ (ULS Design) (the failure signifies immediate reconstruction), and (b) $P_r\,[D_f\,|D_0, V] = 0$, hypothetical situation in which the level of destruction during the structure's useful life is highly improbable (probability of occurrence equal to or less than 10^{-4}).

In intermediate situations, $[0 < PRI < 1]$, (Design SLS), the structure can be repaired before destruction occurs, but the probability that this will occur is not null (in all cases, greater than 10^{-4}).

COMMENT

Based on the premises explained in the previous Comment, if the structure is always repaired at the initiation of damage, D_0, destruction only occurs with the frequency that the dominant agent (wave train dynamics) produces damage, D_f, in other words,

$$P_r\,[D_f\,|D_0, V] = P_r\,[D_f\,, V],$$

and the potential resilience index (PRI), (equation 2.13), can be expressed in terms of the reliability function ($R(t)$) corresponding to a project design at the initial damage level and a function corresponding to a project design at the destruction level,

$$IRP = 1 - \frac{Pr\,[D_f, V]}{Pr\,[D_0, V]} = 1 - \frac{1 - \exp\left(-\lambda_f \cdot V\right)}{1 - \exp\left(-\lambda_0 \cdot V\right)} \approx 1 - \frac{\lambda_f}{\lambda_0} = 1 - \frac{\mu_0}{\mu_f} \tag{2.14}$$

When $\mu_0 = \mu_f$, then $PRI = 0$, which corresponds to a ULS-type model (reconstruction), whereas if $\mu_0 << \mu_f$, then $PRI \rightarrow 1$, which corresponds to an SLS-type model, based on frequent repairs.

2.6 ANALYSIS OF THE SPATIAL EVOLUTION OF THE DAMAGE

If the damage of a principal failure mode in a subsystem is not immediately repaired, the progress of the damage could trigger other failure modes of the subsystem, of other subsystems and of other subsets. This process can be expressed by specifying connections between components (elements of a subsystem, subsystems of a subset, or subsets of the breakwater), which map the progression of the loss of structural reliability and operationality if the damage is not repaired. The implementation of repair strategies controls the progress of damage as well as the spreading of the damage to new modes, which restricts the failure probability of the structure.

2.6.1 Triggering and propagation trees

One way to describe the spatial evolution of the damage is by means of triggering and propagation trees of the failure. If one or more breakwater components start to malfunction because of a failure or operational stoppage mode, and no repair strategy is envisaged, the triggering and propagation tree provides a graphical description of the evolution of the modes causing the damage as well as of the modes subsequently triggered by these and which eventually lead to the destruction of the breakwater. The definition of the failure of each component should be fitted to the definition in the component diagrams, in accordance with the purpose and nature of the structure and its parts.

To elaborate triggering and propagation trees, the following should be considered: (1) components that can become damaged as a consequence of the evolution of the damage/destruction of another or other components; (2) combinations of components and their respective damage levels that trigger damage in those components. Furthermore, it is advisable to consider the following: (a) different mechanisms can converge in the same failure; (b) the damage to the same component can diverge in the propagation of different failure mechanisms in other components.

COMMENT

Figure 2.19 shows the section of a sloping breakwater whose principal failure modes are the following:

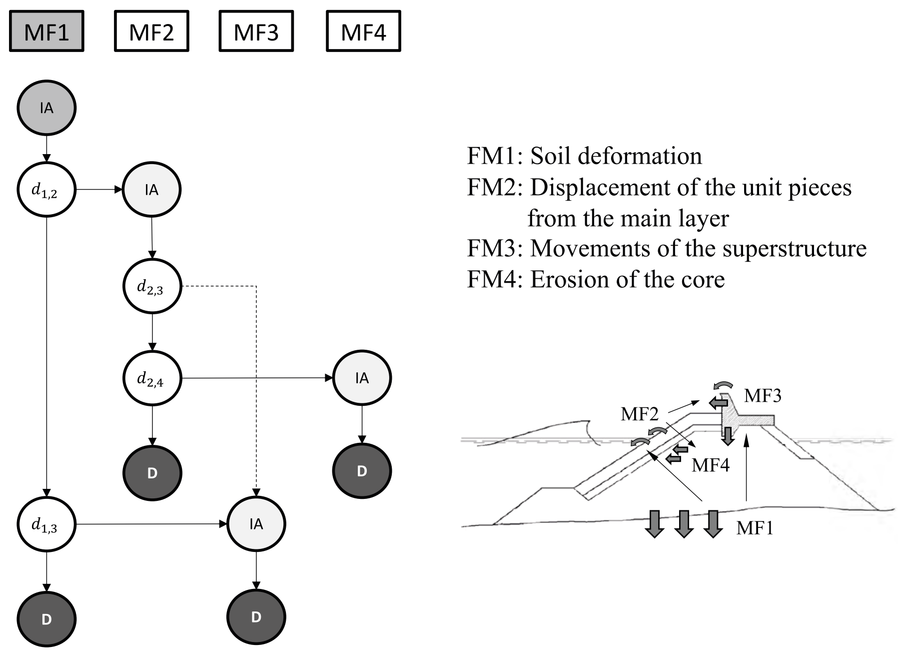
(a) soil deformation, ($FM1$),
(b) displacement of units from the main armor layer, ($FM2$)
(c) displacement of the superstructure, ($FM3$)
(d) core erosion, ($FM4$).

Damage does not evolve dependently. Instead, the progression of certain types of damage lead to the beginning of others. This generates relations that can be expressed by means of triggering and propagation trees.

Figure 2.19 shows a triggering and propagation tree, based on the following assumptions:

(a) The initiation of damage (ID) of the mode, ($FM1$) begins;
(b) When the soil deformation ($FM1$, foundation subsystem) reaches damage level $d_{1,2}$, this triggers the displacement of unit pieces from the main armor layer, ($FM2$);
(c) When the soil deformation ($FM1$) reaches damage level $d_{1,3}$, and/or when the displacement of unit pieces from main armor layers ($FM2$) reaches damage level $d_{2,3}$ this causes the displacement of the superstructure ($FM3$);
(d) If the displacement of unit pieces ($FM2$) reaches damage level $d_{2,4}$, the core (internal subsystem) becomes exposed and vulnerable, and the failure ($FM4$) begins.
(e) If the structure is not repaired, the progression of any of these types of damage is conducive to the destruction level (D).

***Figure 2.19:* Example of a triggering and propagation tree**



2.6.2 Decision tree

The breakwater project depends on the design option selected. Based on the initiation and progress of the main failure modes, the project also depends on the repair strategies adopted. The results obtained with these strategies (including the decision not to repair the structure) can be graphically compared by means of a decision tree. The first node of this tree represents the moment that one of the breakwater components begins to fail at an initial time t_0; it displays the paths and possible outcomes of this event. The structure of the tree and its outcomes depend on the repair strategy adopted and how the failure is triggered and spreads to other components as a result of the initial damage.

The decision tree should be based on the following information: (1) repair options, conditioning factors, and the ensuing consequences if the structure is not repaired; (2) probability of destruction before the end of the useful life of the structure; (3) repair and reconstruction costs. Furthermore, it is necessary to characterize the average survival time (or another statistic), calculated from the initiation of damage from any intermediate node of the decision tree until, for example, destruction (usually stemming from the non-repair condition).

It is also a good idea to calculate the average survival time for conflicting repair strategies. In all likelihood, the lowest value will be associated with the non-repair strategy of some or all of the breakwater components. In contrast, the highest value will be associated with immediate- repair strategy (when the damage begins) with a total availability of all materials, means and tools. The average survival time associated with the optimal strategy to be selected, considering the costs of each option, will be in the interval between those two values, (see Article 5.3.1).

Depending on whether the temporal scale of analysis or the damage level is set, the decision tree can adopt, respectively, the form of a probability tree or of a survival tree. These two repair strategy characterizations are connected to each other by means of the reliability function $R(t)$.

Probability tree

For each component included in it, this decision tree represents the probability of reaching a certain damage level during a given time interval (e.g. season, year, or useful life). This probability is conditioned by the probability of success of each repair decision, which, in turn, depends on the procedures and means assigned to it.

Survival tree

For a given damage level of each component (usually the one that causes the failure), this decision tree represents the average survival time (or other statistic) from time t_0 until failure is reached. This time is conditioned by the 'probability of success' of each repair decision, which, in turn, depends on the procedures and resources assigned to it.

2.7 IDENTIFICATION OF PROJECT FACTORS AND CRITICAL COMPONENTS

According to the ROM 0.0-01, Section 3.4, the set of project factors are the parameters, agents and actions used to define, design, verify, and optimize the construction project. Its organization in classes facilitates sensitivity analyses as well as the formulation and resolution of the dual optimization system. To formulate the objective function and corresponding constraints of each of the financial-economic and technical-economic optimization problems, it is necessary to systematically manage and classify the data stemming from the design and verification of the breakwater, subset, section, and elements (see Section 5 of the ROM 1.1-18).

The identification and classification techniques (classification trees, random forests, etc.) fed with information from Monte Carlo simulations (Solari and Van Gelder, 2011), for example, are valuable support tools. They can be used to identify and classify the project factors and components of the structure (subsets, subsystems, modes, etc.)

whose damage/failure contributes significantly to the risk of the structure (either individually or because it triggers other types of damage) and to its dependence on repair strategies that control this risk.

Such techniques are supported by learning algorithms that have the double function of (1) identifying predictors for the modeling, among other things, the range of values of a relevant response variable (useful life, repair costs, etc.); (2) construction models of the most probable outcomes of a given strategy based on the predictors specified.

COMMENT

The following model analyzes the evolution of three failure modes, A, B and C, corresponding to modes ($FM1$), ($FM2$) and ($FM3$) of the triggering and propagation tree in Figure 2.19 with different repair strategies in order to determine the strategy with the lowest cost. Each strategy is characterized by the following:

(a) value of the damage that triggers the repairs of each mode (predictors R_A, R_B and R_C);
(b) time required for the repair of each mode (predictor t_A, t_B and t_C);
(c) costs of the repair machinery, which are inversely proportional to its performance;
(d) costs of reconstruction if one or more modes reach the destruction level.

Figure 2.20 shows the classification tree of the project factor, total cost of repairs, depending on when the repairs start and their duration.

Figure 2.21 shows the relative importance of some of the predictors that define the repair strategies. This is one of the results obtained with the algorithm, and is delimited by the range of values used in the simulation.

The classification algorithm (in this case, a tree-like algorithm), fed with the results of the costs of each strategy, obtained from simulations, explains the total cost during the repair phase.

In Figure 2.20, each rhombus indicates the reference value of a predictor (see the caption on the left), which the algorithm identifies as being relevant to the cost. For predictor values lower than the reference value, the branches on the left (with a minus sign) are those considered. For predictor values higher than the reference value, the branches on the right (with a plus sign) are taken into account. The results in the rectangles represent the expected cost according to the branches followed, expressed according to the reference cost, C_0, (see ROM 0.0-01 and ROM 1.0-09).

***Figure 2.20:* Classification algorithm of the total cost of repairs, depending on the initial repair strategies and their duration**

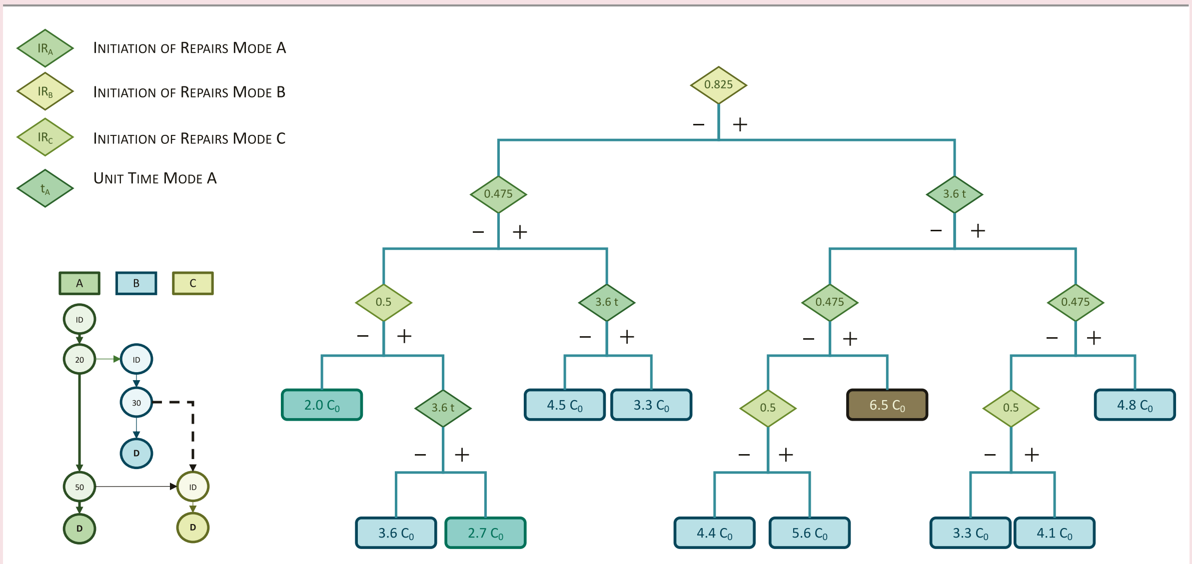
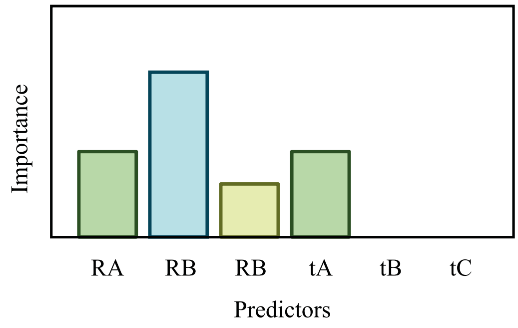


Figure 2.21: ***Relative importance of the predictors that define the different repair strategies***



2.8 VARIANT IN THE CONCEPTION AND DESIGN OF A BREAKWATER

Section 2 presents the specific bases for the construction project of a breakwater (or another maritime structure). The organizational structure and the spatial and temporal hierarchy of the construction project opens a wide range of variants for the conception and design of a breakwater, its layout, selection of the typology in each subset, design of the elements according to project requirements, distribution of the joint probability in accordance with safety and operationality, total costs, as well as legal, environmental, and social conditioning factors.

Of all the possible variants, the three analyzed in what follows are representative of the following: (1) the classical variant, whose most representative texts are the ROM 0.0-01 and PIANC (2016); (2) variant that considers the damage evolution; (3) variant integrated in the dual ROM-MEIPOR system, conducive to the financial-economic and technical-economic optimization of the investment with the constraints associated with project requirements (ROM 0.0-01) and its financial sustainability with acceptable risk a (MEIPOR-16).

2.8.1 Variant 1: Subsets with independent failure and stoppage modes and a maximum level of damage

This variant is developed in the ROM (ROM 0.2-90 (1990), ROM 0.0-01 (2001) and ROM 1.0-09 (2009)), as well as in the PIANC (2016). Among others, its underlying hypothesis is the spatial and temporal independence of the performance of each subset and its failure and stoppage modes in the face of climate and soil agents.

The application of this variant involves the following:

- The principal failure modes of a subset are represented by a flowchart or a tree-type diagram showing that maximum damage levels are conducive to the destruction of the breakwater.
- The principal failure modes are assigned to the ULS (even though their performance agrees with the SLS).
- The joint probability distribution is applied to the principal modes and the other (non-principal) modes are designed according to good-practice guidelines.
- The technical-economic optimization of the total costs of the subset.

Optimization usually applies to the worst-case failure mode (even though there is no technical reason not to apply it to each of the principal modes) supposing that:

- Subsets do not affect each other.
- Damage is immediately repaired.
- There are no budget limitations.
- There is no impact on the operationality of the area.

2.8.2 Variant 2: Subsets with independent stoppage and failure modes and the temporal evolution of the damage

This variant is developed in the texts of the ROM 0.0-01 and ROM 1.1-18-MEIPOR (2006). Its underlying hypothesis is the spatial independence of the temporal evolution of the performance of its failure and stoppage modes in the face of climate and soil agents.

The application of this variant includes the following:

- The principal failure modes of a subsets are represented by a serial/parallel/mixed diagram or by a tree-type diagram that ends in maximum damage levels or the destruction of the structure.
- The joint failure probability (ULS) is assigned to the destruction level of damage.
- The joint probability distribution is applied to the principal modes and the other (non-principal) modes are designed according to good-practice guidelines.
- The cumulative evolution of the damage is analyzed and specific repair strategies are developed.
- The technical-economic optimization of the total costs of the subset envisages the independent evolution of each principal failure mode as well as previously defined repair strategies and decision-making.
- This process is combined with the financial-economic optimization as well as with a sensitivity analysis and evaluation of investment risk.

It is advisable to apply the optimization to those modes whose occurrence most contributes to the total costs of the infrastructure (principal modes), supposing that:

- Subsets do not affect each other.
- Damage is not always immediately repaired.
- There are budget limits.
- There is mostly no impact on the operationality of the area.

2.8.3 Variant 3: Subsets with concomitant/dependent failure and stoppage modes interlinked with other failure modes

This variant is applied in the dual ROM 1.1-18-MEIPOR (2016) optimization. The subsets as well as the failure and stoppage modes can spatially and temporally evolve in a simultaneous way, thus triggering other modes related to climate and soil agents.

The application of this variant includes the following:

- The principal failure modes of a subsets are represented by a serial/parallel/mixed diagram.
- The joint failure probability (ULS) is assigned to the destruction level of damage.
- The joint probability distribution is applied to the principal modes, considering the simultaneous and compatible values of agents and actions; the other (non-principal) modes are designed according to good-practice guidelines.
- The cumulative evolution of the damage is analyzed and triggering and propagation trees of the damage between modes are formulated.
- Criteria for decision making are specified. Also devised are repair strategies answering the questions of when, how, and how much.
- A dual (technical-economic and financial-economic) optimization is performed that focuses on the total costs and financial sustainability of the construction and investment projects.
- A sensitivity analysis is performed and the investment risk is assessed.

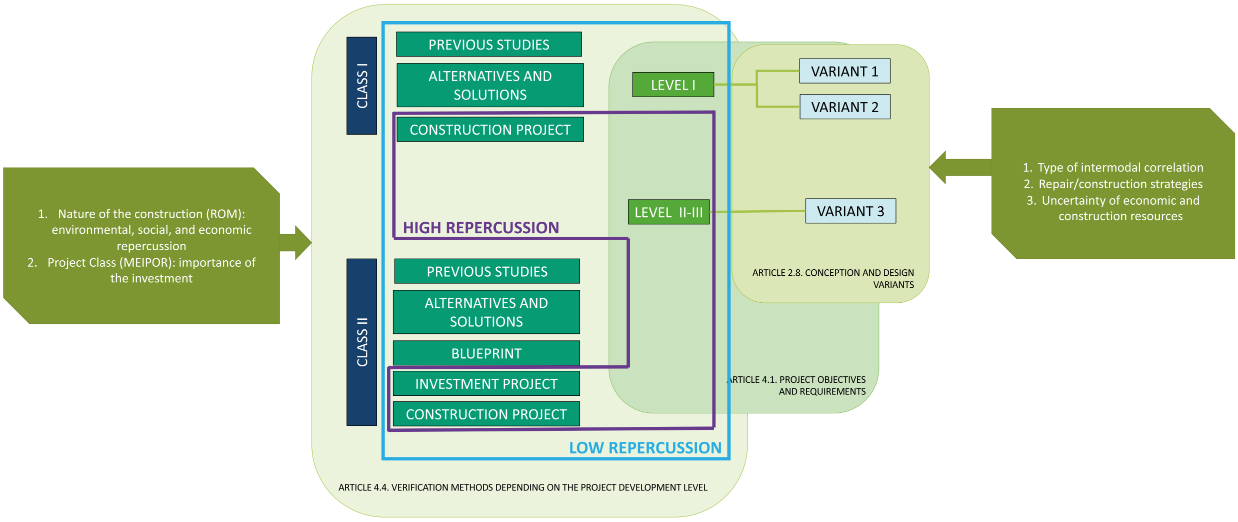
The dual optimization process involves considering and quantifying the following:

- The degree to which subsets affect each other and the impact of this on repair strategies.
- Delayed repairs and the consequences of this decision.

- Limitations on the budget and on the temporal distribution of resources;
- Impact on the operationality of the damaged area and its repair strategies.

Figure 2.22 shows the interconnection between these variants and their conception, verification methods (according to the ROM methodology) and project classes (MEIPOR).

Figure 2.22: Interconnection between variants, verification methods, and project classes



Section III. Table of contents

SECTION III: PROCEDURE FOR BREAKWATER PROJECTS

3. Procedure for breakwater projects

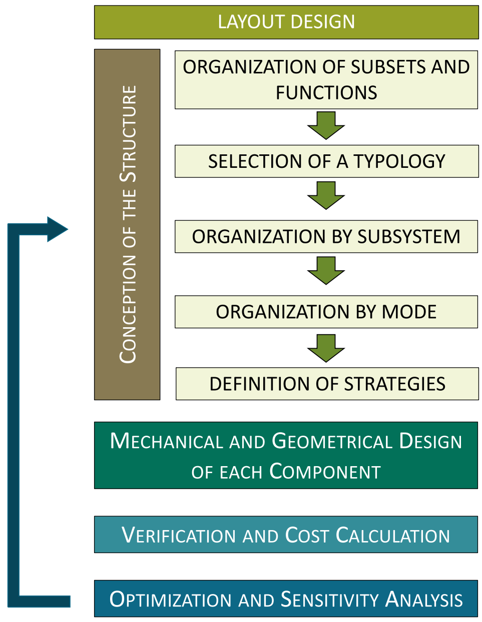
As stated in the specific project bases in Section 2 of the ROM 1.1-18, the elabo-ration of the construction project of a breakwater should follow this sequence:(a) layout; (b) conception of the structure and specification of subsets; (c) selection of subset types; (d) design; (e) verification of the environmental, legal, and technical requirements; (f) calculation of the total costs; (g) technical-economic optimization and sensitivity analysis.

Section 3 focuses on the following: (1) description of a connected set of possible breakwater typologies; (2) organization of subsets and their parts in subsystems and identification of principal failure modes in each one; (3) characterization of each mode and their spatial and temporal evolution. These are some of the activities that must be performed previous to verifying compliance with project requirements,performing the technical-economic optimization of the breakwater and its subsets, and the verifying compliance with the financial-economic restrictions specified in the investment project (see Sections 4 and 5).

3.1 CONCEPTION OF THE STRUCTURE AND DESIGN SEQUENCE

This section proposes a general sequence and describes the instruments that can be used to design, size, verify, and optimize a breakwater and its subsets. Figure 3.1 shows a diagram of the elements in this sequence and the information flow.

Figure 3.1: ***General sequence for the conception and design of a breakwater***



3.1.1 Tools for the conception of the breakwater

The conception of the breakwater is the responsibility of the project designer, who should use the instruments described in Section 2 (e.g. diagrams, triggering and propagation trees, and decision trees). These tools help to design the structure, define its nature and purpose, and delineate its dimensions. Figure 3.2 shows the tools and their interrelations according to the spatial work scale, component diagrams, and the propagation of failure modes.

First, the project designer should specify the necessary and sufficient conditions that define when and in what way the breakwater (its subsets, parts, and elements) would not fulfill the following types of project objective:

(a) Construction project objectives, in relation to all of its subsets, parts, and subsystems in relation to the safety and operationality of the subset;
(b) Investment project objectives of the harbor area, in relation to financial-economic profitability and the investment risk of the infrastructure and the harbor area.

Any non-compliance with project objectives (i.e. a failure that affects safety and a stoppage that affects operationality) is characterized in terms of the event space and set of modes that can occur in the structure. This information is used to construct diagrams of hierarchically organized components (see Article 3.3). These diagrams are the graphical representation of the conception of the structure, and their level of detail will vary depending on the nature and development stage of the project.

Selection and configuration of hierarchical levels

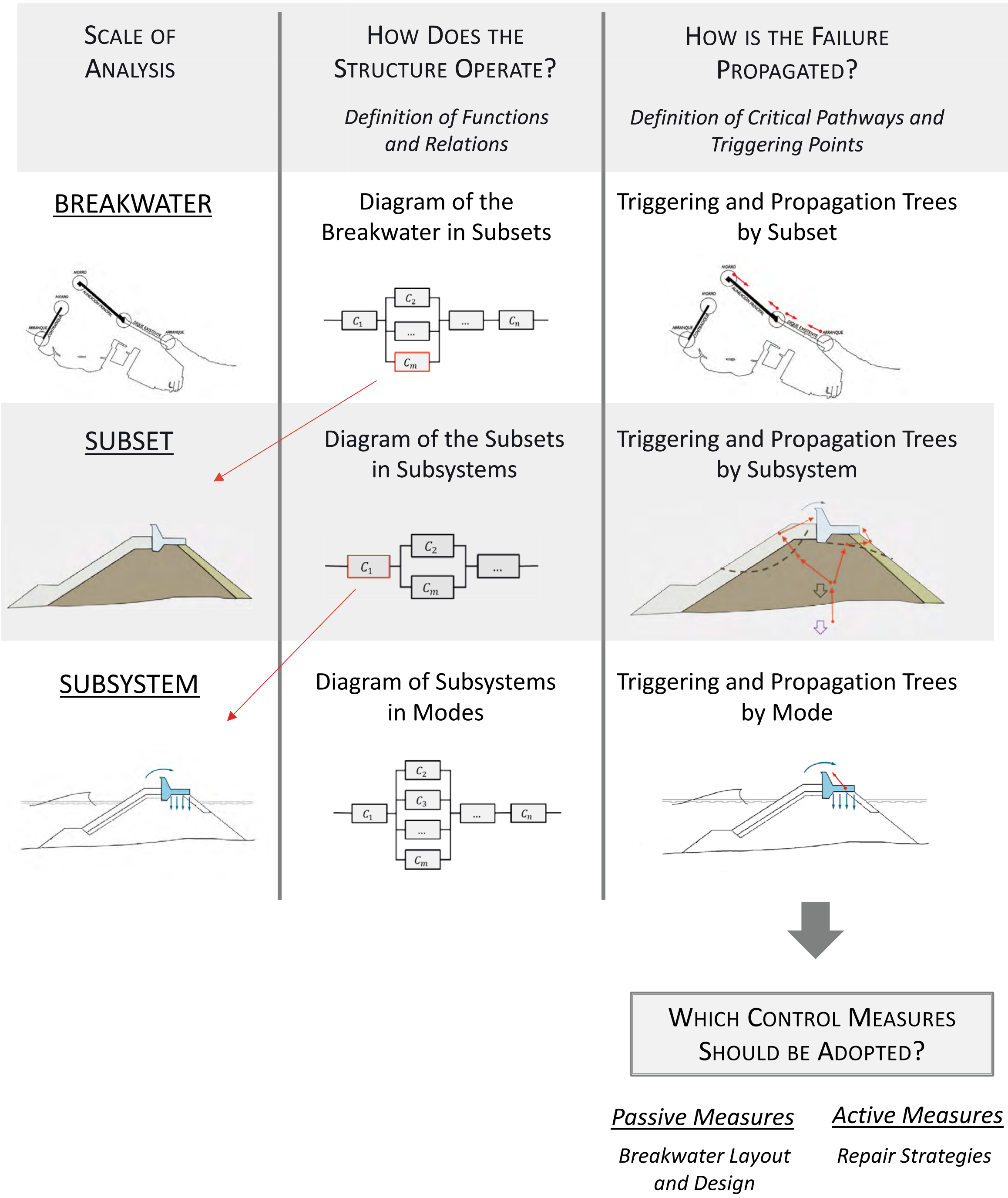
Accordingly, the breakwater is defined as a sequence of hierarchical levels with the following configuration

(a) breakwater composed of a set of subsets, its event space, and the corresponding diagram of its subsets;
(b) each subset composed of subsystems, their event spaces, and the corresponding diagrams of the subsystems in the subset;
(c) each subsystem composed of a set of elements, their event spaces, and the corresponding diagrams of the failure and stoppage modes of the subsystem.

Inclusion of the spatial and temporal evolution

When planning the breakwater and considering the spatial and temporal evolution of each failure mode, the project designer should map out the critical progression of inter-component damage. by elaborating one or more triggering and propagation trees (see Article 3.6). Similarly, it is also necessary to specify possible repair strategies (by means of one or more decision trees (see Article 3.7), calculate the total costs of the construction, and verify that the construction is in consonance with its initial conception and purpose.

Figure 3.2: ***Tools and logical sequence for the planning and design of the breakwater, according to the scale of analysis, working methodology, and failure propagation***

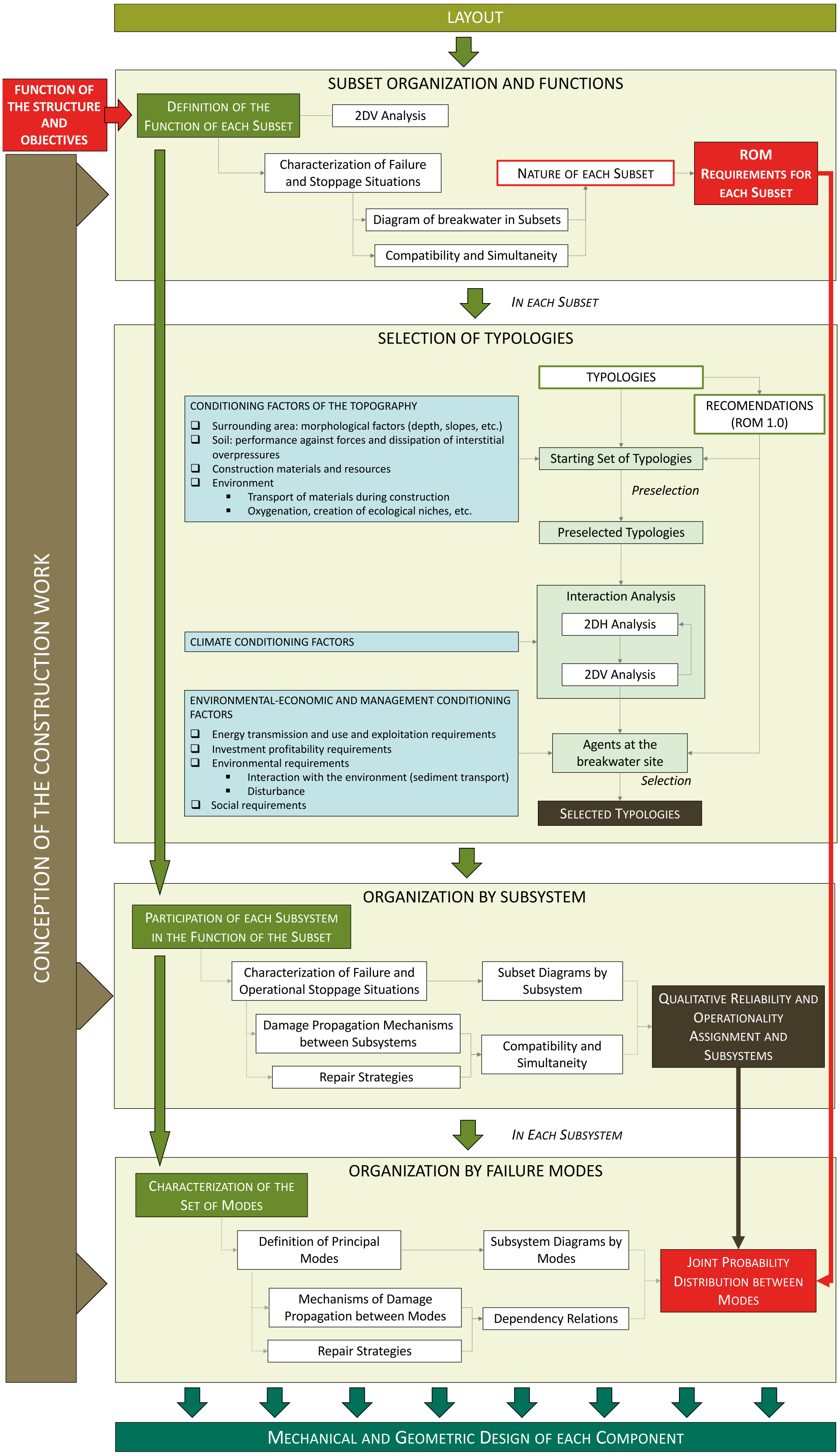


3.1.2 Logical sequence of activities

Figure 3.3 represents a sequence of activities for the planning and design of the breakwater. The first step consists of selecting the layout and the last step is the specification of the mechanical and geometric design and configuration of each component (element, part, subsystem, and subset). A possible sequence of activities is the following:

- Configuration of the structure in hierarchical levels and assignment of a function and objectives to each one.
- Selection of the most suitable typologies that will ensure fulfillment of project objectives in line with the set of requirements and conditioning factors of the construction project.
- Characterization of the situations conducive to the failure or stoppage of each component (subsets, subsystems, element, etc.) in accordance with the general design of the structure and the hierarchical levels adopted.
- Creation of component diagrams that describe the optimal performance of the structure at each hierarchical level.
- Selection of the principal modes affecting the safety and operationality of the structure, description of their processes, and the specification of the failure and stoppage criteria as well as their connection with the functions and objectives of each breakwater component.
- Definition of the threshold that characterizes each of the damage levels, and analysis of the possible dependency relations between the different failure modes in each subsystem, subset, and the entire breakwater.
- Specification of the probability distribution of failure and stoppage in each subset, and its distribution at each hierarchical level, while taking into account the dependency relations between modes and the repair strategies that affect their joint probability of occurrence.
- Integration of the previously mentioned results in the project of the breakwater and its components with verification that:
  - (a) probability of the occurrence of non-principal modes is negligible;
  - (b) dependency relations are in consonance with the conditions of simultaneity and com-patibility of modes.

Figure 3.3: ***Logical sequence for the planning and design of the breakwater***

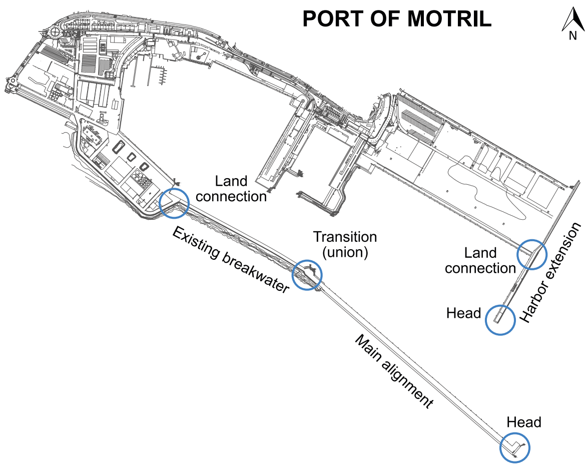


3.2 TYPOLOGY AND SELECTION CRITERIA

When selecting a breakwater typology that fulfills project requirements, it advisable to apply the logical sequence described in the previous section, and represented in Figures 3.2 and 3.3. More specifically, it is a question of the following:

(a) Division of the breakwater design in subsets (see Article 2.2.2), bearing in mind that an alignment can be composed of more than one subset (see Figure 3.4);
(b) For each subset, specification of the project requirements, depending on its participation in the fulfillment of the project objective (see Article 4.1.1);
(c) Assignment of one or more (formal and structural) typologies to each subset, taking into account that their geometric dimensions can gradually vary in order to adapt to slight changes, mainly in the bathymetry, nature of the seabed, and characteristics of the wave action.
(d) Hierarchical organization of each typology in subsystems and of each subsystem in units with the functions of each in the performance of the subset.

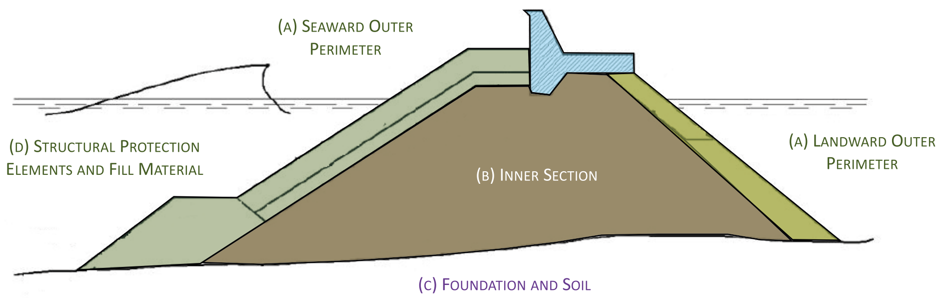
***Figure 3.4:* Subsets in the breakwater and harbor extension of the Motril port**



Then, for each typology, the following systems should be identified (see Figure 3.5),

(a) outer perimeter, landward and seaward of the section;
(b) core of the section;
(c) foundation and soil;
(d) armor units, structural elements, and fill material.

***Figure 3.5:* Subsystems of a sloping breakwater subset: (a) outer perimeter; (b) core of a section;(c) foundation and soil; (d) armor units, structural elements, and fill material**



3.2.1 Description of a typology

The section of a breakwater typology is composed of at least three parts with various subsystems:

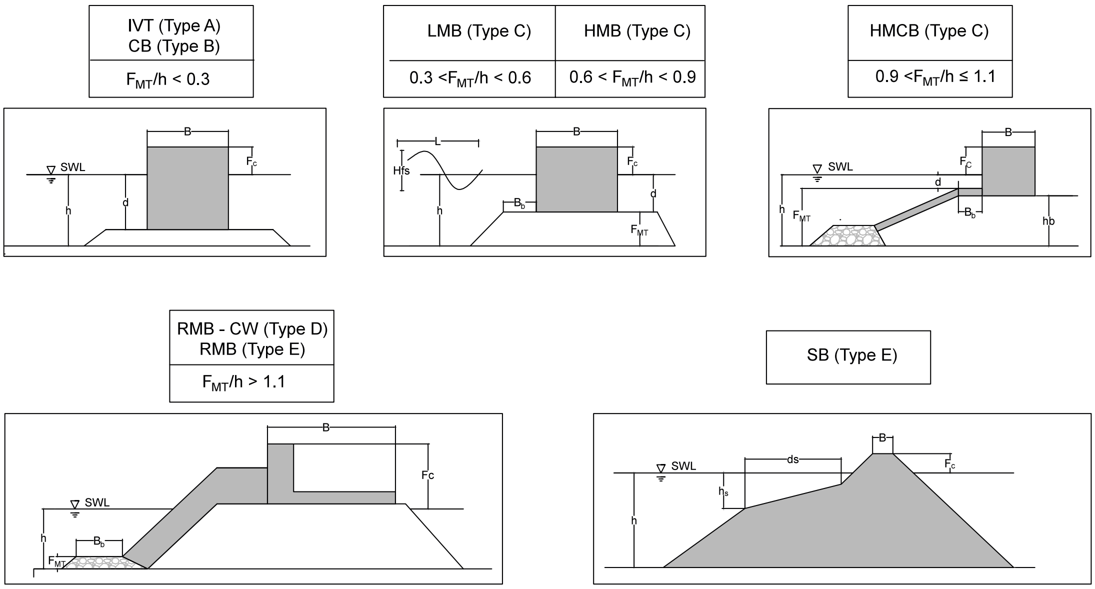
(a) Foundation that determines the way that the structure transmits forces to the ground, and which comprises: (a) a leveled bed; (b) the foundation layer.
(b) Central body that determines the hydrodynamic performance of the breakwater against wave action, and which is composed of the following: (a) landward and seaward outer perimeters that control wave transformation; (b) core that controls the landward propagation of wave and transmits the result of the wave action to the foundation.
(c) Superstructure that controls overtopping at the crown wall and the junction between subsets, and when applicable, provides an access landward.

To improve and expand the description and design of the structure, the breakwater designer may envisage the possibility of defining other parts of the breakwater.

Figure 3.6 represents some of the most usual breakwater sections. They are only some of the closely related sets of possible typologies. The layout and dimensions of each part of a breakwater can vary slightly, depending on the breakwater type. These parts are formed by granular systems, natural and artificial protection elements, rigid solids, and other structural elements.

The two most common typologies are a vertical or reflecting breakwater and an S-shaped or dissipative breakwater (also known as a berm breakwater). They delimit the hydrodynamic performance of different breakwater typologies against incident wave energy partition. These breakwater types include mixed or composite breakwaters, the traditional or Iribarren breakwater, and all variants.

Figure 3.6: ***Conventional breakwater typologies (graphics and nomenclature taken from Kortenhaus and Oumeraci, 1998)***



3.2.2 Environmental and technical factors affecting the selection of breakwater typologies

When selecting a breakwater type, the following technical factors should be considered (see Section 2.2.4 of the ROM 1.0-09):

(a) performance against maritime and climate agents, particularly wave action;
(b) ground soil, interaction with climate agents, and breakwater response;
(c) morphological conditioning factors, such as topography, bathymetry, and ground surface;
(d) availability of construction resources and materials;
(e) requirements for breakwater use and exploitation as well as for its partial entry into service;
(f) legal and environmental requirements.

Interaction of the breakwater and its subsets with wave action and other sea oscillations

The design and selection of a breakwater type should be based on the analysis of the interaction in the horizontal plan (2DH analysis) and cross-section (2DV analysis) of the construction as a whole and its contours with sea oscillations, mainly, wave action (see Figure 3.3). This analysis should provide the following results: (a) incident energy partition in each breakwater subset, depending on the characteristics of the incident wave train for the different sectors of wave incidence; (b) variation along the breakwater section of the incident wave train caused by energy radiation/reflection/transmission from the following:

(a) specific subsets, mainly the breakwater land connection and alignment changes;
(b) the crown and throughout the section;
(c) typology changes in the subset and between subsets;
(d) sudden changes in the depth and characteristics of the seabed and, when applicable, the ground surface and soil.

Wave-breakwater interaction

It is advisable to begin the 2DH analysis by initially distributing the wave energy in each subset, depending on the type and characteristics of the incident wave train, mainly, the incident wave angle relative to the subset, θ, relative depth, h/L, and wave period, T_z. This first approximation should help to determine the following:

- hydrodynamic performance of the breakwater as a whole;
- whether certain breakwater subsets are located in the breaker zone; on the front and toe of certain subsets even though they would not break in the absence of the breakwater.

Water circulation and quality, and its interaction with shoreline morphology

When applying the methods and instruments in the ROM 5.1-13, it is best to perform a 2DH analysis of water circulation and quality as well as of sediment transport in the harbor area and its surroundings. Also to be included is the spatial and temporal evolution of water quality and the spatial and temporal transformation of the shoreline morphology in the set of operational stoppage and failure modes of the harbor area. The result of the verification depends on the layout of the infrastructures in the harbor area, and particularly on the typology of the breakwater.

Review of the incident energy distribution

The 2DV analysis quantifies energy partition by calculating the reflection, transmission, and dissipation coefficients (see Section 2.2.2 of the ROM 1.0-09). This result should be contrasted with the initial distribution adopted in the 2DH analysis. When there is a significant discrepancy, the analysis should be repeated until the results of both studies coincide. The 2DV analysis can be based on data from experimental or numerical studies (Lara et al., 2011).

Comparative analysis of the performance of breakwater typologies against wave action

The comparison of the performance of different breakwater typologies should be based on the following:

(a) Performance against maritime climate agents

- wavebreaking on the breakwater front or over the crown, and the type of wave breaking that occurs;
- incident energy partition on the breakwater: dissipative/reflecting;
- spatial variation of the wave height on the breakwater section;

(b) Interaction with the structure and response of the ground and soil
- pressures on the superstructures: impulsive/reflecting;
- movement of the seabed; potential formation of bars and troughs;
- bearing capacity of the soil: soft or easily deformed;
- dissipation capacity of interstitial overpressures and the momentary liquefaction poten-tial.

(c) Requirements for breakwater use and exploitation and for its partial entry into service
- wave transformation in the sheltered area, reflections, and the affected surface;
- overtopping of the breakwater crown, and whether it is occasional, frequent, or non-submerged overtoppable.

(d) Environmental requirements
- sea oscillations in the harbor area and the surroundings of the breakwater and the affected surface;
- water quality in the harbor area and its surroundings;
- sediment transport processes in the harbor area and its surroundings;
- spatial and temporal evolution of the littoral environment and coastline.

These results help to characterize the failure and stoppage modes of the subset and their mutual interactions as well as the possible processes of spatial and temporal triggering and propagation of damage.

3.2.3 Economic factors for the selection of breakwater typologies

Because of the severe conditions at breakwater sites and their impact on the construction, maintenance, repair, and dismantling costs in the investment project, the selection of breakwater type should satisfy the investment requirements insofar as the funds allocated as well as their distribution over time. For this reason, possible breakwater typologies should be classified on the basis of these economic indicators, which can be calculated as explained in Section 5:

- initial investment costs, depending on typology (construction and dismantling);
- average annual costs, depending on typology (maintenance and repair).

It is useful and beneficial to categorize the technical-economic selection of a typology as follows:

(a) Typologies that are robust, simple, and longlasting from a structural perspective. Although their initial investment costs are high, their average annual maintenance costs are relatively low along with the probability of damage during their useful life.

(b) Typologies that are structurally conceived with the capacity to accumulate damage while still being operational. Despite the fact that the initial investment costs are relatively low, the average annual maintenance and repair costs can be significant in order to comply with the investment project requirements of financial sustainability and acceptable risk.

3.3 BREAKWATER PERFORMANCE AND THE CONFIGURATION OF DIAGRAMS

According to Article 2.3.4 of Section 2, the response of the breakwater to climate and soil agents and also to use and exploitation agents can be represented by means of component diagrams(structural reliability) and operational stoppage (operationality). This article explains how to create such diagrams and outlines their application.

3.3.1 Component diagrams for safety purposes

Diagrams of breakwater components should be hierarchical with the following levels: (a) subset as a component of the breakwater: (b) subsystem or subsystems as components of the subset; (c) failure mode as a component of the subsystem. When necessary, the component diagram should include the spatial and temporal evolution of the damage and its effect on the safety of the structure.

Configuration with and without the evolution of the damage

If the breakwater is designed on the assumption that the initiation of damage in one of its components (subset, subsystem or mode) signifies its destruction, then the diagrams should envisage the following:

(a) The number of mutually exclusive (not simultaneously occurring) components should be selected a priori;
(b) The interdependence of the failure among components is low or very limited;
(c) The failure of the component is irreversible, and the costs (and time required) are associated with the complete reconstruction of the component to restore the operationality of the breakwater.

If the breakwater design includes the spatial and temporal evolution of the damage of its components, the component diagram should take the following into account:

(a) Temporal evolution of: (a) joint probability of the failure modes of the subsystems in a subset (reliability of the subset); (b) operationality of the breakwater and harbor area.
(b) Repair strategies adopted, such as: (a) intervention before the breakwater reaches destruction level; (b) degree of dependency and simultaneity of damage in breakwater components; (c) operationality of the breakwater and harbor area; (d) repair costs and times (previous to the destruction) of the subsystem, subset, or breakwater.
(c) Non-repair of breakwater (for whatever cause) and its subsequent destruction: (a) costs (and time required) are associated with the complete reconstruction of the component; (b) probability of occurrence should be included in the verification of the joint failure probability.

Diagrams of the breakwater subsets

The configuration of the diagram of the breakwater subsets reveals the nature and purpose of the breakwater. It also helps to define the repair strategies and configure the decision trees. When applicable, it should help to identify the critical subsets and reevaluate the social, environmental and economic repercussion indexes. Based on them, project requirements should be recalculated in relation to: (1) useful life; (2) joint probability of failure; (3) operational indicators.

As indicated in Section 2 (Specific bases for the project, Article 2.2.2, Figure 2.3), the procedure is the following:

- precise delimitation of the breakwater subsets, such as its land connection, secondary alignment, change in alignment, main alignment, and head;
- specification of how the breakwater functions and how and when each of its subsets experiences a failure;
- establishment of the dependency relations between them;
- identification of the most reliable subsets for different reasons (e.g. construction, repair, maintenance, operation, etc.).

Then, the following is described:

- event space of all the possible combinations of failed subsets in the breakwater that can simultaneously occur, and then subsequently occur;
- time when one breakwater subset or two or more of its subsets fail. In the first case, the breakwater diagram is serial; in the other cases, the diagram of the breakwater is usually mixed.
- calculation of the joint failure probability of the breakwater.

The calculation of the joint failure probability of the breakwater is based on the failure probability of the breakwater subsets. It is necessary to consider the number of subsets that could fail, as well as whether the failures of the subsets are mutually exclusive or whether they are interdependent. This information is used to verify whether the breakwater as a whole (i.e. its layout) and each of its subsets comply with the project requirements and objectives.

Diagrams of the subset and its subsystems

The configuration of the diagram of the breakwater subset and its subsystems reveals how the section functions against sea oscillations, and how it transmits wave action to the foundation and soil of the breakwater. It helps to define repair strategies and configure decision trees, Furthermore, it identifies critical subsystems, and when necessary, it helps to reevaluate the social, environmental, and economic repercussion indexes of the subset. These indexes can be used to determine its useful life, joint failure probability, and operationality indicators.

To create this diagram, in accordance with Section 2 (Specific project bases. Article 2.2.2, Figure 2.3), the following actions are advisable:

- organization of the subset in subsystems, such as the outer perimeter, core of the section, foundation and soil, armor units, structural elements, and fill material;
- specification of how each subsystem functions as well as how and when it fails;
- establishment of dependency relations between subsystems;
- identification of the most reliable subsystems in the subset.

This conception of the subset should be reflected in the distribution of the joint failure probability among subsystems in relation to safety (project requirements). It is then necessary to describe the following:

- event space of all the possible combinations of failed subsystems in the breakwater, which can simultaneously or subsequently occur;
- time when one breakwater subset or two or more of its subsets fail. In the first case, the breakwater diagram is serial; in the other cases, the diagram of the breakwater will possibly be mixed.
- calculation of the failure probability of each subsystem.

The calculation of the joint failure probability of the breakwater is based on the failure probability of the breakwater subsets. This means considering the number of subsets that should fail, and whether the failures of the subsets are mutually exclusive or whether they are interdependent. This information is relevant in order to verify whether the subset complies with the project requirements and objectives. It should be reflected in the distribution of the joint failure probability among its subsystems.

COMMENT

The organization of subsystems is based on the role that each plays in the incident energy partition (Clavero et al., 2012; Vílchez et al., 2016b) and the ensuing consequences for the flow of water over and through the section as well as for the pressures and subpressures on breakwater elements and the superstructure (Vílchez et al., 2011).

Diagrams of the subsystem and its failure modes

The configuration of the diagram of the subsystem and its failure modes reveals how the subsystem resists wave action. Likewise, it helps to define repair strategies, and configure decision trees. It also identifies critical subsystems, and contributes to the reevaluation of the social, environmental and economic repercussion indexes of the subset. These indexes can be used to determine the subsystem's useful life, joint failure probability, and operationality indicators. According to Section 2 (Specific project bases. Article 2.2.2, Figure 2.3), the following procedure should be followed:

- organization of the subsystem in terms of the set of failure modes in relation to safety;
- specification of how each mode functions and when each mode fails, generally by means of a verification equation;
- establishment of dependency relations between failure modes;
- identification of the most critical modes for the reliability of the subsystem and those modes that are principal, non-principal or susceptible to becoming so.

It is then a question of describing the following:

- event space with all the combinations of failure modes of the subsystem, which can occur simultaneously and subsequently;
- time when the subsystem fails, either due to the occurrence of one of its failure modes or to the occurrence of two or more modes; in the first case, the subsystem has a serial diagram, and in the other cases, it is possibly mixed.
- calculation of the failure probability of each failure mode.

This information is used to verify whether the subsystem complies with project objectives and purposes, and it should reflect the distribution of the joint failure probability of its failure modes.

Event space of failure modes: initiation of damage / destruction

When representing the initiation of damage/destruction, it is customary to state that the subsystem fails when one or more principal failure modes occur, and that these modes are mutually exclusive. In this case, the configuration of the subsystem is a serial diagram of the principal failure modes. This type of configuration signifies that the occurrence of a failure mode is synonymous with the destruction of the subset. It is irreversible since without reconstruction, the subsystem can no longer function as part of the subset and breakwater.

Event space of the failure modes: evolution of the damage

When the design considers the evolution of damage to the modes of the subsystem and their possible interactions, it is usually said that the subsystem fails when at least one these modes reaches the destruction level and thus is incapable of performing the function of the subset and breakwater unless it is reconstructed. The diagram of principal modes generally has a mixed configuration.

Nevertheless, a breakwater project that envisages the evolution of damage directly depends on the repair strategies adopted as well as on the decisions of when and how much to repair with a view to minimizing the probability of destruction of the subset during the residual life of the breakwater. This approach is expressed by means of a combination of the following: (1) diagram of failure modes; (2) triggering and propagation trees; (3) possible repair strategies and decision-making.

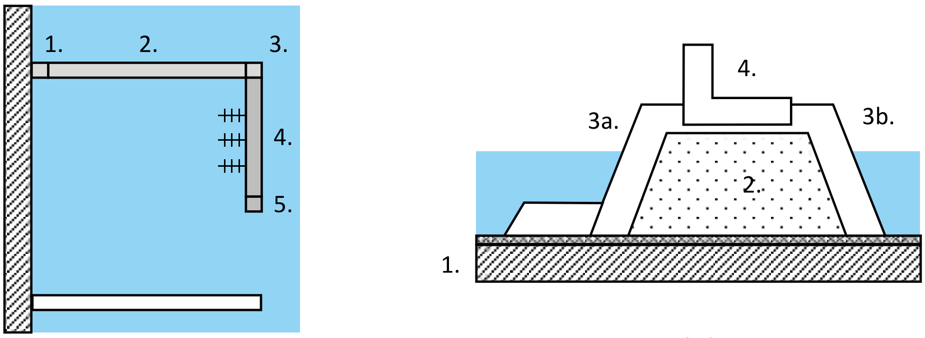
The joint probability distribution in relation to safety and the transformation of principal modes into non-principal modes are two elements that the project designer can use to design the response of each subsystem. The technical-economic optimization and sensitivity analysis are techniques that quantify the effectiveness of the initial design and of the repair strategies. The financial-economic profitability analysis, financial-economic optimization, and the calculation of investment risk levels are effective instruments to decide the total investment costs.

EXAMPLE

Spatial hierarchy of the breakwater: subsets, subsystems, and the diagram of failure modes

Figure 3.7 outlines the layout of a breakwater, its subsets, and the section of the typology by identifying its subsystems. The breakwater is assumed to no longer function properly if a failure occurs in its main alignment or head. Both types of damage evidently affect the operationality of the harbor area and its access. In addition, the diagram envisages the availability of construction resources and materials so that once the subset begins to fail, it can be repaired before it reaches the destruction level. For this reason, construction is not contemplated for either of the subsets.

Figure 3.7: ***Left panel: diagram of the breakwater subsets. Right panel: diagram of the subsystems in a subset***

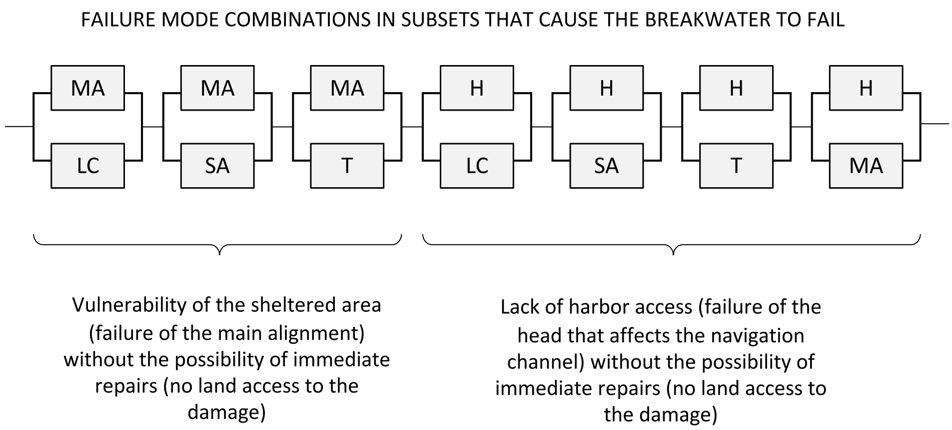


1. Land connection (LC)
2. Secondary alignment (SA)
3. Transition (T)
4. Main alignment (MA)
5. Head (H)

1. Inner section (IS)
2. Foundation and Soil (FS)
3. Outer Perimeter (OP)
    a. Seaward outer perimeter (SOP)
    b. Landward outer perimeter (LOP)
4. Superestructure (SS)

Figure 3.8 shows a component diagram in which the main alignment and head shelter the harbor area and delimit the navigation channel and its navigability. The main function of the other subsets (land connection, secondary alignment, and transition) is to provide land access to the two subsets that shelter the area. In the case of damage, they thus permit immediate intervention. The component diagram describes this conception of the structure, namely, that the breakwater is said to fail when its main alignment or head fails, and when it is no longer possible to access the breakwater by land in order to repair it.

Figure 3.8: ***Diagram of breakwater components***

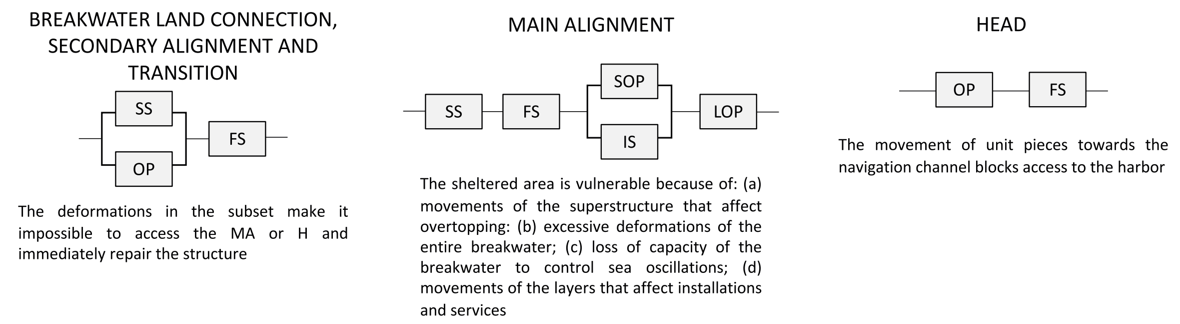


According to the event space of the failure modes of the subsets and the configuration of the diagram, the notation of each failure mode of each subset indicates the following:

(a) **Failure in LC/SA/T:** Failure in the land connection (LC); secondary alignment(SA); or transition (T), which blocks land access to the main alignment (MA) or head (H), and there is insufficient time to repair the breakwater before its destruction.
(b) **Failure in the MA:** Failure in the main alignment (MA), which leaves the sheltered area unprotected but still maintains land access so that the structure can be repaired before its destruction.
(c) **Failure in the H:** Failure in the breakwater head (H), which blocks maritime access to the port, but still maintains land access so that the structure can be repaired before its destruction.

Figure 3.9 represents the possible diagrams of the components of the breakwater subsets. Each diagram corresponds to the definition of the failure described by the components of the various breakwater subsets (see Figure 3.8).

Figure 3.9: ***Component diagram of each subset***



The breakwater land connection, secondary alignment, and transition are said to fail when there is no longer land access to the main alignment (MA) or the head (H), and there is insufficient time to repair the breakwater before its destruction. The breakwater reaches this state when its superstructure and armor layers are no longer accessible, or when its foundations and/or ground soil have suffered excessive deformation. Accordingly, the failures of each subsystem can be defined as follows:

(a) **Failure in the SS:** Movements in the superstructure (SS), which do not permit transit along the main alignment (MA) or the head (H), and there is insufficient time to repair the breakwater before its destruction.
(b) **Failure in the OP:** Deformations of the outer perimeter (OP), which do not permit transit along the main alignment (MA) or the head (H), and there is insufficient time to repair the breakwater before its destruction, even in the absence of the superstructure.
(c) **Failure in the FS:** Deformations, severe sinking, or breakage in the foundations and soil (FS), which block the land access of vehicle traffic to the main alignment or head, and there is insufficient time to repair the breakwater before its destruction.

The main alignment is said to fail when the sheltered area is no longer protected, even though an immediate intervention is possible that will prevent the destruction of the subset. This situation can happen when damage to the superstructure leads to excessive overtopping, and there is also damage to the armor layers and core, which increase wave transmission. It can also occur because of the excessive deformation of the foundations or soil that affects the entire subset. Accordingly, the failures of each subsystem are defined as follows:

(a) **Failure in the SS:** Damage in the superstructure (SS), which increases overtopping.
(b) **Failure in the FS:** Deformations, severe sinking or breakage of the foundation and soil (FS), which increase the transmission of wave energy to the sheltered area.
(c) **Failure in the LOP-SOP/SC:** Damage to the landward outer perimeter (LOP) and the seaward outer perimeter (SOP) as well as to the section core (SC), which increases wave transmission into the sheltered area.
(d) Failure in the LOP: Displacement of the armor layer units on the landward outer perimeter, which leave the installations and service zones of the sheltered area unprotected.

The failure of the head makes it impossible to access the port since it significantly affects navigation safety. However, an immediate intervention can prevent the destruction of the breakwater. This state begins when there is a displacement of armor layer units from the head, when there is a change of morphology, or when deformations in the foundations and soil affect the entire subset. Accordingly, the failures of each subsystem are defined as follows:

(a) **Failure in the OP:** Displacement of armor layer units or a change in the morphology of the outer perimeter (OP) toward the navigation channel, which can be immediately repaired so as to prevent the destruction of the subset.
(b) **Failure in the FS:** Deformations and severe sinking of the foundation and soil (FS).

3.3.2 Component diagrams for operationality purposes

Diagrams for operationality purposes have two hierarchical levels:

(a) breakwater and subsets: operational stoppage modes in one or more breakwater subsets, directly related to the design or typology of the subset and its function.
(b) harbor area and breakwater: modes of operational stoppage related to (1) the layout and design of the breakwater; or (2) the formal and structural failures in the breakwater and its subsets.

Diagrams of the operational stoppage modes of the breakwater

The configuration of this diagram is similar to the configuration of component diagrams for safety purposes. Accordingly, it is necessary to consider the following.

Depending on the location of the docks, the design of the harbor mouth and access channel and the operational, formal, and structural dependence of the subsets, the diagram of the subsets can be serial or mixed. In both cases, the diagram should show when the breakwater is no longer operational.

The configuration of the operationality diagram only includes the subsystems and stoppage modes related to the activities performed in each subset. The reason for this is that they are not accompanied by a structural failure of the system, and that full operationality is recovered once the causes of the stoppage are eliminated. Each operational stoppage mode should describe: (i) how the stoppage is produced; (ii)predominant agent or agents causing the stoppage; (iii) actions and threshold values either of the agents or their actions; (iv) responses that determine whether operationality is limited or definitively lost.

The relations between the different stoppage modes can be established, depending on whether they are mutually exclusive, and if they are not, whether they are statistically independent. The operationality of a subset (or subsystem) is usually said to be limited or lost when at least one of its stoppage modes occurs. When operationality is totally lost, the diagram has a serial configuration. When operationality is only partially lost, the configuration of the diagrams is possibly mixed, with serial and parallel combinations. This indicates that loss of operationality can occur because of the simultaneity and convergence of various modes in one or various subsystems. It is thus advisable to elaborate the diagram of concomitant agents and their values that contribute to the attainment of operational stoppage thresholds. The operationality of the subset is calculated, based on the stoppage probability of the modes (organized by subsystem). The number of modes and subsystems should thus be taken into account, and whether the modes and subsystems are mutually exclusive or whether they are interdependent.

Diagram of operational stoppage modes in the harbor area

The breakwater shelters the harbor area and its infrastructure and installations in different ways. The layout and typology of the breakwater depend on the operationality objectives in the harbor area. For this reason, the harbor area should be organized into subareas (navigation channel, maneuvering and mooring area, berthing area, etc.). For each subarea, it is necessary to specify the project requirements in regard to operationality.

Non-compliance with these requirements in each of the harbor subareas is reflected in the operational stoppage modes. The operationality of a subarea is said to be limited or lost when at least one of its stoppage modes occurs. When operationality is totally lost, the diagram has a serial configuration. When operationality is only partially lost, the configuration of the diagrams is possibly mixed, with serial and parallel combinations. This indicates that loss of operationality can occur because of the simultaneity and convergence of various modes in the subarea. It is thus advisable to elaborate the diagram of concurrent agents and their values that contribute to the attainment of operational stoppage thresholds.

This procedure facilitates the elaboration of diagrams of the overall loss of operationality of the harbor area, depending on each subarea and considering the diagrams of potential non-compliance with operationality requirements.

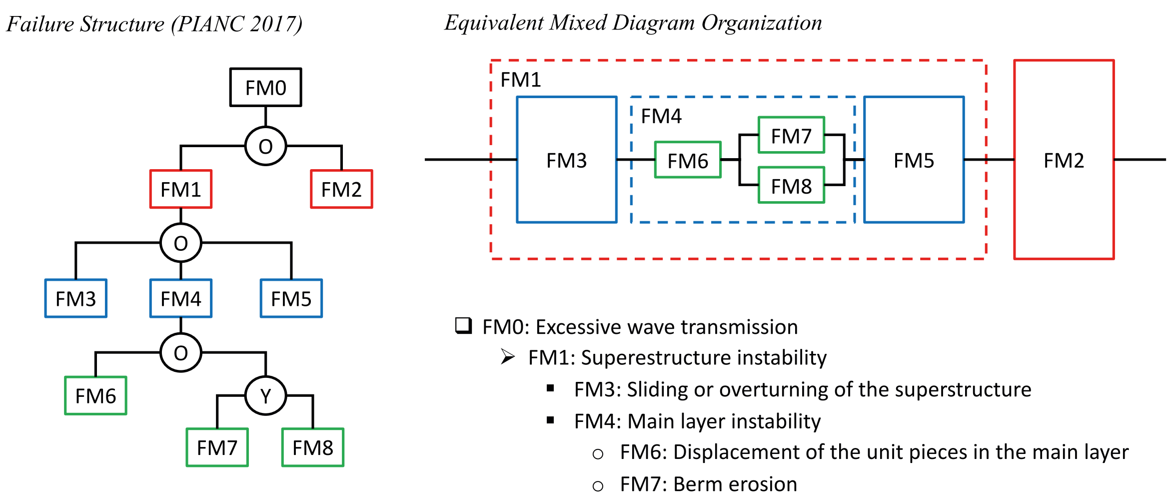
COMMENT

Component diagrams in other technical texts

Other technical texts, e.g. PIANC (2016), use the concept of failure tree. However, this "tree" only represents one possible configuration of a breakwater failure. It specifies whether each failure mode is sufficient in itself to produce the failure (OR), or if the failure occurs simultaneously with one or more failure modes (AND). It should be highlighted that even though such failure trees generally characterize situations in which there is a loss of safety, they are also applicable to situations involving a loss of operationality. Despite the similar nomenclature, failure trees are not related to the trees described in Articles 2.6 and 3.7, but rather to component diagrams.

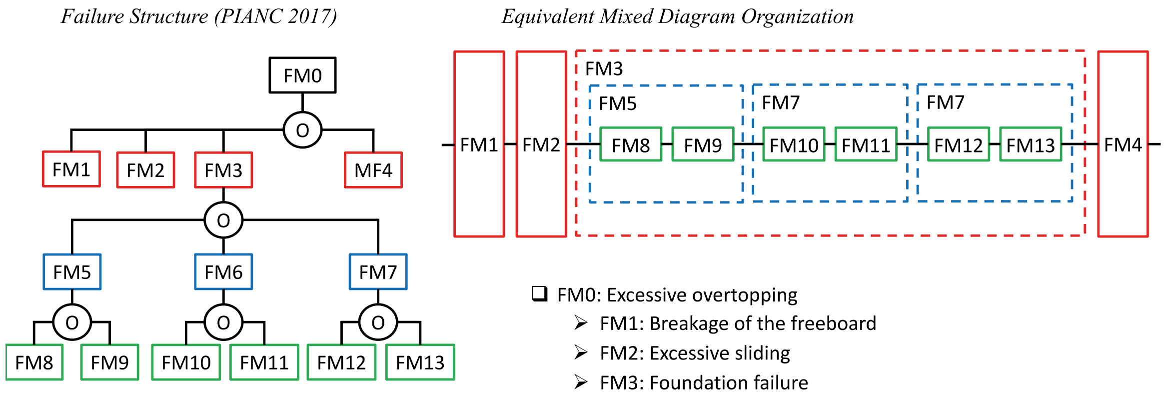
The following figures show examples of two failure trees in PIANC (2016) and the corresponding component diagrams in this ROM. The first tree (Figure 3.10) shows a possible configuration of failure conditions that can cause excessive wave transmission in a breakwater with a crown wall. Figure 3.11 shows a possible configuration of failure conditions that can lead to the excessive overtopping of a vertical breakwater.

***Figure 3.10:* Failure tree (PIANC, 2016) and component diagram corresponding to excessive wave transmission through a sloping breakwater with a crown wall (ROM 1.1-18)**



- FM0: Excessive wave transmission
  - FM1: Superestructure instability
    - FM3: Sliding or overturning of the superstructure
    - FM4: Main layer instability
      - FM6: Displacement of the unit pieces in the main layer
      - FM7: Berm erosion
      - FM8: Displacement of the sea bed
    - FM5: Erosion of the back slope
  - FM2: Breaching of the parapet wall

***Figure 3.11:* Failure tree (PIANC, 2016) and component diagram corresponding to excessive wave transmission onto a sloping breakwater with a crown wall (ROM 1.1-18)**



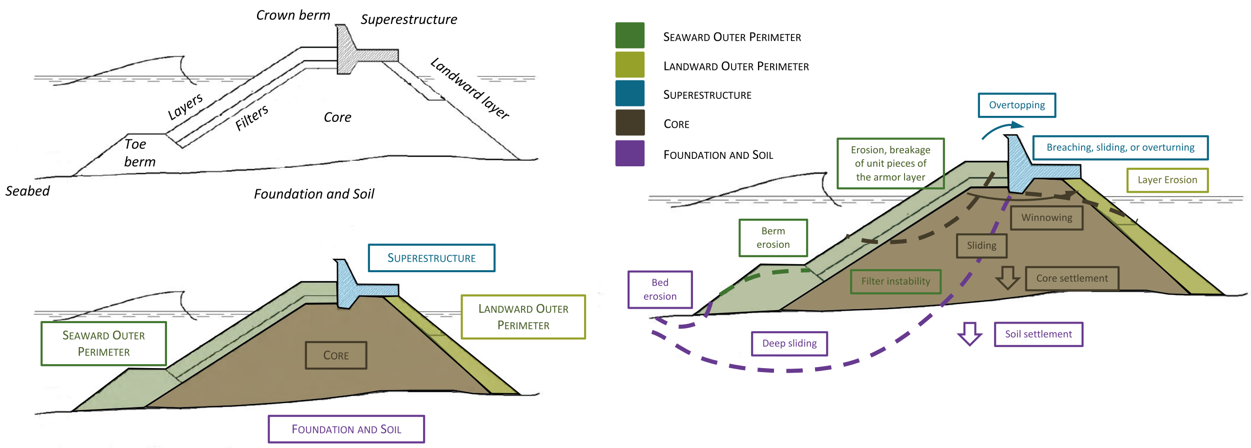
- FM0: Excessive overtopping
  - FM1: Breakage of the freeboard
  - FM2: Excessive sliding
  - FM3: Foundation failure
    - FM5: Failure due to settling
      - FM8: Soil failure
      - FM9: Foundation failure
    - FM6: Failure due to sliding
      - FM10: Soil failure
      - FM11: Foundation failure
    - FM7: Erosion failure
      - FM12: Soil failure
      - FM13: Foundation failure
  - FM4: Overturning

3.4 PRINCIPAL FAILURE AND STOPPAGE MODES IN A BREAKWATER

Failure and stoppage modes describe the mechanisms that reduce the reliability (loss of safety) and the operationality of the breakwater and its components, respectively. The beginning and evolution of the failure can be observed in changes in shape or in the strength of the structure. These changes affect the performance of the breakwater against incident waves and in relation to other maritime, atmospheric and climate agents, use and exploitation agents, and the foundation. Furthermore, these alterations can affect the capacity of the breakwater to shelter and protect the harbor area, which restricts or impedes the activities carried out there. The calculation of the joint failure probability, operationality, and its consequences are used to estimate the total investment costs and the level of risk.

The following articles concisely describe the principal failure modes that should be considered in each of the breakwater's sets and subsystems (in its useful life as well as in other project phases). Notwithstanding, some of these may become non-principal modes when standards of good practice and other recommendations are followed (see Figure 3.12).

Figure 3.12: ***Principal elements and modes, organized by subsystems in a sloping breakwater (diagram adapted from Burcharth, 1992)***



3.4.1 Subset with a straight alignment

The bathymetry along with the width and orientation of the harbor mouth, wave characteristics inside the harbor area and the fleet determine breakwater design, the mooring and maneuvering area, and the layout of the docks and berthing areas.

Generally, the main alignment of the breakwater is perpendicularly oriented in the direction of the dominant wave propagation (highest energy content) and/or the direction of the predominant (most frequent) wave propagation. The 2DH analysis is used to calculate the longitudinal variability of the agents as well as of their landward and seaward actions, due to the interaction of energy radiated from the edges of the main alignment, generally, the head and change of alignment, and the energy reflected by the section.

The sheltered zone of the harbor area is usually located at a minimum distance from the harbor mouth, about three to five wavelengths corresponding to the predominant wave period. If the length of the main alignment or its orientation is unsuitable, this restricts the operationality requirements of the harbor area. In such cases, it is necessary to envision the temporary closure of the port and determine the threshold values and their probability of exceedance.

If dredging of the harbor area is envisaged, it should be remembered that the wavelength is in correlation with water depth, and that abrupt changes in bathymetry affect the direction of wave propagation (refraction) They also reflect incident waves, significantly altering the design oscillatory patterns of the harbor area.

Principal failure modes in each subsystem. 2DV analysis

The results of previous studies are the starting point for determining the critical section or sections of the main alignment and the complete set of its principal failure modes with the 2DV analysis. The project designer can complete this list of principal failure modes with others, depending on the characteristics of the local wave action, breakwater typology, available construction material and processes, soil, and bathymetry. In this case, the additional failure modes should be located in one of the subsystems or a specific subsystem should be identified for them. It is necessary to consider the following principal failure modes, organized according to subsystems:

Outer perimeter of the section

These modes should be ordered, depending on the side of the section where they are located: on the side that is oriented toward the sea and crown (seaward side) and on the side oriented towards land (landward side).

On the seaward side, the modes should describe the response of the seabed at the face of the breakwater and of the central body and superstructure to climate agents. A priori, the following are generally considered to be principal modes:

(a) changes in sea bottom depth at the face of the breakwater, erosion/accumulation, and bar formation;
(b) change in the geometry of the toe berms and crown because of the loss of unit pieces or because of sea bottom or soil deformation;
(c) when relevant, change in geometry because of the erosion of the main armor layer (e.g. due to loss of unit pieces, sliding, face-to-face fitting, heterogeneous packing, etc.) or deformations in the breakwater core and soil foundation;
(d) loss of static equilibrium of the structure or superstructure;
(e) local loss of stability, plastic overturning of the structure or superstructure;
(f) transmission of sea oscillations by overtopping the crown, when this involves a failure in one of the main installations.

On the landward side, the principal failure modes should describe the following:

(a) changes in the sea bottom: erosion/accumulation, bar formation, and liquefaction;
(b) changes in the geometry of the main armor layer because of the loss of unit pieces or other causes;
(c) sliding layer caused by climate agents and use and exploitation agents (vessel maneuvering), and loss of unit pieces because of overtopping or wave transmission;
(d) loss of stability of the berm, main armor layer, and crown wall.

Section core

This set of failure modes are all related to changes in breakwater geometry (accumulative changes) and deformations (excessive changes), more specifically of the granular fill material, because of the action of climate agents as well as other agents. These modes include:

(a) deformation and sliding of secondary armor layers;
(b) loss of bearing capacity, deformation and loss of stability of the breakwater core;
(c) loss of function in the filter layers;
(d) transmission of the sea oscillations through the breakwater;
(e) liquefaction and scouring caused by wave propagation from the face and/or the effect of other agents such as vessels or their propellers as they are navigating or docking.

These modes can be verified as non-principal when standards of good practice are applied to breakwater design and construction, and the recommendations in the ROM 0.5-05, and the Annexes of the ROM 1.1-18 are strictly followed.

However, modes that can trigger other failure modes, (e.g. sinking of the superstructure and alterations in the geometry of the subset), which affect the hydrodynamic performance of the breakwater are initially regarded as principal modes.

Foundation and soil

This set of failure modes are all associated with the joint behavior of the foundation, bedding layer, granular fill material, and soil. Principal failure modes include the following:

(a) liquefaction;
(b) loss of bearing capacity and soil deformability;
(c) overall loss of stability of the ground-structure system.

Some of these modes can be verified as non-principal when standards of good practice are applied to breakwater design and construction, and the recommendations in the ROM 0.5-05 are strictly followed.

PROTECTION ELEMENTS, STRUCTURAL ELEMENTS, AND FILL MATERIALS

In regard to protection elements, whether natural (e.g. natural rock revetment) or artificial (mass concrete blocks), principal failure modes include the following:

(a) breakage of unit into pieces;
(b) loss of fatigue resistance in the section;
(c) loss of durability (progressive structural, formal, and aesthetic deterioration).

Besides the previously mentioned modes, breakwater elements made of mass and reinforced concrete require verification of the failure modes as specified in the regulations of each country (in Spain, the Spanish Structural Concrete Code (EHE-08). In this case, it is assumed that they are non-principal modes.

For the fill material as well as other materials, the principal failure modes are their deterioration and loss of durability during the useful life of the breakwater. However, these modes can become non-principal modes when they satisfy the technical specifications related to the admissible behavior in the marine environment in reference to structural deterioration and durability. In this case, it is advisable to specify auscultation and inspection methods as well as the threshold value of the failure progression indicators to delimit when and how one can act to minimize the consequences.

Straight subsets with oblique wave incidence: 3D analysis

In each of the subsystems described in the 2DV analysis, it is necessary to consider the behavior of the subset with oblique incidence in five sectors (see previous comment): (a) normal; (b) oblique;(c) very oblique; (d) Wrebster sector; (e) quasi parallel to the orientation of the breakwater. Each should be analyzed in terms of their failure modes as well as their behavior due to the obliqueness of the corresponding sector.

When the incidence angle is located in:

- **Sector (a):** the behavior of the sections is generally known to be similar to their behavior when the incidence angle is normal. However, the wavebreaking conditions and evolution of pressures (impulsive and reflecting phases) against the vertical wall or superstructure should be analyzed. When necessary, the sector angle can be reduced, for example, from −10° to 1° so that it is better adapted to the working hypothesis for the normal sector. The remaining sectors should be adjusted accordingly.
- **Sectors (b) and (c):** the rise and return of the water can occur in zones separated by a distance proportional to the wavelength at the breakwater toe, depending on the typology and slope of the structure as well as the wave period and incidence angle. These zones are characterized by a significant increase in (1) water velocity and spatial and temporal gradients; (2) drag and inertial forces on the granular elements and crown wall or superstructure; (3) overtopping. In obliqueness conditions, it is best not to allow for an abrupt change in the breakwater section or typology since in its proximity, there might be an increase in wave height and/or a channel for the return flow. In all cases, the change should not coincide with a water return zone associated with oblique incidence,
- **Sector (e):** breakwater performance should be assessed when the incidence angle exceeds approximately 65°. In this case, (1) the breakwater acts as though it were a channel wall; (2) the wave train propagates through the subset alignment; (3) the drag and inertial forces and the horizontal forces on the walls are at maximum height around sea level and decrease with depth,. The granular protection layer of the outer and inner perimeter of the breakwater is not designed to respond to the actions of a wave train propagating along the subset. Once the failure has begun, certain elements partially or totally lose the support of the neighboring units. Their extraction then only depends on the persistence of climate agents without the need to significantly increase the wave height. The temporal evolution of this type of damage can be represented with a step-type iso-duration curve or by a sigmoide curve, whose central area is approximately vertical (see Figure 2.8).

In the case of breakwaters in which wave reflection is dominant (i.e. vertical or composite breakwaters with a crown wall below sea level), it is also necessary to consider the following:

- the greatest horizontal forces on the walls are produced for incidence angles in the sector (−15° to 15°), instead of for normal incidence;
- when the incidence angle is greater than approximately 65°, the pressure regime on the crown wall and the superstructure is approximately hydrostatic;
- if the breakwater has a berm or slope protecting its central body or superstructure, it is necessary to verify whether the wave incidence angle on the wall is the same as the angle at the toe since refraction on the face of the breakwater can be significant.

COMMENT

Generally speaking, there are five wave incidence sectors:

(a) normal, (−15°- 15°)
(b) oblique, (15°- 35°)
(c) very oblique, (35° - 55°)
(d) Wrebster sector (55° - 65°)
(e) quasi-parallel to the layout of the breakwater (> 65°)

The minimum reflection coefficient modulus with a null phase at the breakwater toe occurs in the Wrebster sector (55° - 65°), depending on the non-linear characteristics of the incident wave train and the breakwater typology. This sector approximately separates wave incidence angles with and without a 'Mach stem wave'. The spatial extension, perpendicular to the breakwater, of the running wave increases with the incidence angle (> 65°), which is theoretically infinite for a parallel incidence, (90°), to a breakwater (assuming the subset is of infinite length).

3.4.2 Subsets with non-straight alignments and transitions

These subsets include the head, alignment changes, transitions, and the land connection of the breakwater. To begin the selection, it is necessary to consider the same principal failure modes corresponding to the subset with a straight alignment. These modes are organized, according to the same subsystems.

Nevertheless and independently of wave incidence, certain failure modes have a spatial and temporal evolution in these subsets, which is different from that in a straight alignment. Generally, this occurs for one of the following reasons: (a) the interaction of the waves with the subset causes the convergence-divergence of the energy flux; (b) the response of the section depends on the lateral support received.

In regard to the first reason, it is necessary to verify that wave transformation in the subset is abrupt, namely, that the length l $(l > 1.5L)$ is not sufficient to produce non-linear effects, where L is the wavelength at the breakwater toe. In these conditions, the wave height can be quantified by applying linear wave theory and the energy flux conservation hypothesis between two orthogonals. As for the second reason, non-linear models of wave transformation should be applied to calculate the variation in wave height (and all the processes that depend on it, such as waves rising and falling, overtopping, pressure on the crown wall, etc.), which produce the convergence-divergence of the energy flux.

A simple way to identify the relevance of the lateral support in the triggering of the mode is to compare the geometry and layout of the elements in the straight alignment with those of the non-straight alignment or transition. In that alignment, the hydrodynamic behavior of the waves, their action, and the response of the breakwater is assumed to be "two-dimensional". This signifies that any part or element in the subset has the necessary and sufficient support so that the failure will occur 'mainly' on the 2DV plane. In this case, the transversal variation of the failure is due more to the 'geometrical conditions of the damage' than to a change in the hydrodynamic behavior of the waves and of the breakwater response.

If there is no lateral support or if it is conditioned, the element can fail. Once the damage has begun, it evolves without any solution of continuity until the destruction of the breakwater. There is thus no need to increase the wave height (step or sigmoide function between the wave height and the damage level (see Figure 2.8).

In such cases, it is best to size the element based on the following: (a) initiation of damage; (b) evolution of the damage while ensuring the capacity for immediate intervention, depending on the nature of the subset; or (c) its classification as a non-principal mode.

Head

The response of the head to the actions of soil and climate agents mainly depends on its connection to the rest of the breakwater, its typology and geometry (slope and relative radius), and the incident wave characteristics. Depending on the wave transformation stemming from its interaction with the head and breakwater, the following failure and stoppage modes should be considered:

Radial perimeter of the head

Failure modes can occur at any location of the subset, whether seaward or landward, depending on the incidence angle of the waves. This subsystem includes the modes that describe the response of the sea bottom, central body, and superstructure to the climate agents at the radial perimeter of the head. It is necessary to analyze the spatial and temporal evolution of the failure, particularly the zone of origin and the direction of its progress, taking into account the three-dimensional behavior of the wave action (convergence-divergence) and the structural system. For this reason, the head should be geometrically described in sections that are spatially homogeneous in regard to wave action and structural response. In certain cases, it is advisable to provide a spatial and temporal description of each sector where oblique wave incidence occurs.

A priori, the principal failure modes include the following:

(a) erosion of the armor layer and changes in the shape of the head in the various circular sectors of its geometry;
(b) erosion of the toe berm, foundation, and seabed in the inner and outer perimeter of the head:
(c) loss of overall stability of the crown wall or of the superstructure;
(d) erosion and deformation of the inner slopes because of the propagation of wave energy through the harbor mouth.

Interior of the head

This set of failure modes are all related to changes in breakwater geometry (accumulative changes) and deformations (excessive changes), more specifically of the granular fill material, because of the action of climate agents, in accordance with the diagram for subsets with a straight alignment.

Foundation and soil of the breakwater head

This set of failure modes are all associated with the joint behavior of the foundation, bedding layer, granular fill material, and soil, in accordance with the diagram for subsets with a straight alignment. In the case of the heads of vertical or composite breakwaters, or sloping breakwaters with a superstructure, it is important to consider that on the channel-side, this type of head does not have the lateral contribution of the other sections of the subset. Furthermore, it directly supports the oscillatory action associated with the spatial and temporal changes of the accelerations and pressures caused by each incoming wave. Generally speaking, for breakwaters with a high ERI and SERI, the stability of the head should be tested at a suitable scale (1 : 40 or less). The model should include the main alignment or at least a significant length that represents the radiation processes from the head and their interaction with it.

Protection elements, structural elements, and fill material

In regard to protection elements, whether natural (e.g.) natural rock revetment) or artificial (mass concrete blocks), principal failure modes are the following:

(a) breakage of unit into pieces;
(b) loss of fatigue resistance in the section;
(c) loss of durability (progressive structural, formal, and aesthetic deterioration);
(d) displacement of structural elements or pieces of these elements and fill material to the navigation channel and harbor area.

Besides the previous failure modes, in the breakwater head, it is necessary to consider a new failure mode, namely, the displacement of certain elements of the head with consequences for navigation safety.

Changes in breakwater alignment and transitions

The interaction of the incident waves with changes in the breakwater alignment and with subset transitions is reflected in refraction (convergence) and wave shoaling, and possibly the radiation of the incident wave energy. It is thus necessary to analyze the variation in wave height and the incidence angle in the outer perimeter of the subset and along the subset. The kinematics and dynamics of the sheet of water should also be quantified. The following failure modes should be considered:

(a) erosion of the armor layers, toe berm, crown berm, and crown wall;
(b) transmission of the wave energy through and over the section because of overtopping, affecting the stability of the inner structure.

Land connection and secondary alignment

The land connection is the union of the breakwater with land or another existing breakwater. It is the boundary with the secondary alignment. It is usually located in shallow areas where waves break. The following processes are thus relevant:

- variation in mean sea level;
- generation of longitudinal currents and return currents in the breaker zone;
- sediment transport processes.

The incidence angle and wave height depend on the configuration of the sea bottom and its nature. They also depend on the secondary alignment that determines the junction area and the location of the breakwater land connection. Wave dynamics in these two subsets is generally very oblique or quasi-parallel to their orientation. For other incidence sectors, it is necessary to analyze the reflection of the wave trains on the breakwater, and particularly landward wave propagation, refraction-shoaling, interaction with the incident wave train and wave breaking, as well as the landward or seaward circulation with inverse refraction. (One of the mechanisms of return current generation is the stationary interaction of wave trains with oblique incidence.)

The selection of the principal failure modes of these subsets is performed in accordance with the diagram for subsets with a straight alignment. Moreover, it is necessary to quantify wave interaction (taking into account the different sectors of wave incidence) with the secondary alignment, namely, the breakwater land connection and adjacent coastline. The following should also be verified:

(a) erosion (scouring) and sediment accumulation in both subsets;
(b) spatial and temporal variation of the bathymetry and coastline on the adjacent shore.

3.4.3 Principal failure modes caused by other agents at the breakwater site

This article considers principal failure modes in relation to safety, triggered by other climate and seismic agents, which in certain locations can be predominant and condition the investment project.

Seismic movements

Failure modes should be determined by an analysis of the behavior of the structure-water-soil system in the face of a seismic agent. The magnitude of the earthquake can be determined by applying the probabilistic methods used to determine climate agents. With a few exceptions, on the coastline of Spain and nearby islands, seismic activity is regarded as an exceptional work condition.

In the case of an earthquake, principal failure modes include soil liquefaction and the sliding of subset elements.

Tsunamis and meteotsunamis

Tsunamis caused by sliding tectonic plates or of seismic origin as well as meteotsunamis of meteorological origin are included in the statistical analysis of climate agents, particularly in the determination of the variations in mean sea level with periods longer than five minutes. They are differentiated by wave groups. When relevant, all of the failure modes in Article 3.4.1 should be considered for the straight subsets and for non-straight alignments and transitions (see Article 3.4.2).

3.4.4 Failure modes in the construction, maintenance and repair phases

In these project phases, the failure modes depend on the construction process and method as well as their sequence. In each case the failure modes should be determined by the analysis of the interaction between the different construction states and climate agents. The results are used to define the breakwater subsets, and for each subset, the possible subsystems in which the failure and stoppage modes are grouped.

If the construction is to be interrupted during winter or for any other reason, the following are necessary:

(a) project design of the protection structure of the subsets that have not been completed (containment wall or winter head);
(b) description of the failure modes of the structure and their spatial and temporal evolution;
(c) verification of compliance with the project requirements for construction stoppage.

The occurrence of these modes should be included in the technical and economic offer of the construction. In addition, their probability should be delimited and their consequences in all scenarios should be quantified.

3.4.5 Stoppage modes related to the activities of the harbor area

Principal operational stoppage modes are those related to the transformation of sea oscillations (mainly in the form of waves), the modification of the general circulation of air and water, variation in bathymetry and the coastline because of the breakwater, and in each of its subsets. These modes include:

(a) sea oscillations, excessive currents and wind velocity in the access channel, harbor mouth, maneuvering zone, and mooring areas;
(b) excessive sea oscillations because of the transmission and landward overtopping of the subset (dock, crane, access path) or the land zone (land accesses, warehouses), and the area surrounding the land connection of the breakwater.

In erosionable moving sea bottoms (mud, sand, and gravel), the seaward depth of the breakwater is governed by processes of wave energy transformation on the breakwater, particularly bar formation due to sediment accumulation and scour troughs from erosion. These processes take place in different subsets of the breakwater and certain zones of the harbor area, and they can abruptly alter the slope and depth of the sea bottom. Such modes include the following:

(a) abrupt variations of the sea bottom in the landward and seaward profile of the breakwater;
(b) progressive sediment accumulations in the access channel, harbor mouth, maneuvering zone, and mooring areas.

3.5 JOINT PROBABILITY DISTRIBUTION OF FAILURE AND STOPPAGE IN THE SUBSET

The joint probability distribution of failure (or stoppage) involves assigning values to the reliability (or operationality) of the principal failure (or stoppage) modes in a breakwater subset. This distribution should based on the nature and function of the subset, as well as its performance in relation to different agents, and project factors. It is part of the conception and design of the breakwater and its subsets and of the selection of principal modes, non-principal modes, and modes subject to obligatory verification by codes, instructions, and other regulations.

The possible assignment of one part of the joint failure probability to a mode (considered as a principal mode) is based on the following criteria:

(a) Its spatial and temporal domain is structured within the context of the subset and project phase.
(b) Whether the project design is ULS or SLS (see Article 2.5).
(c) It is based on the relations in component diagrams and triggering and propagation trees between modes and repair strategies.
(d) The failure probability assigned to each of the principal failure modes that share the same predominant agent and which is sized at the initiation of damage with the same agent value is only calculated once. However, the same is not applicable to its consequences, which should be calculated for each mode, taking into account the simultaneity of their occurrence.
(e) The procedure followed is described in Section 2.5.3, equations 2.45 and 2.46, of the ROM 1.0-09, which are used to establish the upper and lower bounds of the joint probability.

Since probability distribution is an iterative process, it should be repeated throughout the successive project development stages.

1. This process begins with the distribution of the joint probability of failure (or stoppage) among the principal modes, as described in Section 2.5.4.3 of the ROM 1.0-09,
2. Probability distribution is verified in the study of alternatives and solutions.
3. Probability distribution is delimited by the financial-economic optimization of the investment project.
4. Probability distribution is decided by the technical-economic optimization of the total cost of the breakwater in its useful life when elaborating the blueprint of the construction project.

Section 5 of this ROM 1.1-18 discusses the coordination between the financial-economic and technical-economic optimizations and their respective sensitivity analyses.

3.5.1 Selection of principal and non-principal modes

Apart from what was mentioned in the previous article, the selection of principal modes that contributes to the joint failure probability is based on: (1) the evaluation of the consequences of the occurrence of the mode en general; (2) the construction, maintenance, and repair costs derived from the mode; (3) the analysis of the environmental, social, and economic consequences produced by the failure or stoppage. The specification of the set of principal modes should take into account the technical-economic optimization of the total cost of the breakwater and its subsets during their useful life.

A principal mode can become a non-principal mode when it is possible to reduce the probability of its occurrence (or risk level) to negligible values with slight increases in the geometry or mechanical properties of the element or part of the subset without any significant changes in cost.

For breakwaters, the threshold of the significant contribution to the failure or stoppage prob-ability is set at 10^{-4}. Any mode whose probability of occurrence is below that threshold can be regarded as non-principal.

Modes verified by other codes, regulations, and guidelines

When compliance with a certain code or set of regulations is obligatory, the verification of the mode will be performed as stipulated in those instructions.

If the regulations are deterministic, then the mode does not contribute to the joint probability of failure or operational stoppage. Nor does it contribute to the risk level of the subset in the useful life of the infrastructure. However, if the predominant agent is random (e.g. wave action), the probability of exceedance of the design value should be equal to or less than 10^{-4}. This probability is assumed to be representative of the probability of occurrence of the mode. In other cases, it should be regarded as a principal mode or susceptible to be transformed into a non-principal mode.

3.6 TRIGGERING AND PROPAGATION TREES AND THE PROPAGATION OF FAILURE OR STOPPAGE

If the breakwater design takes into account the spatial and temporal evolution of the failure and stoppage modes as well as their interactions, it is necessary to analyze and define when and how the failure (or stoppage) is triggered, and how it affects the spatial and temporal evolution of the damage in the subsets, subsystems or modes.

Each tree represents a connected sequence of non-compliance with project objectives. The branches connect failure (or stoppage) modes. The node is a convergence point for other branches whose origin and destination is in other modes. Each node specifies the level of damage required to trigger it as reflected in the threshold values of agents, actions or responses, as well as the possible design options that indicate whether the damage can be repaired, and if so, the magnitude of the repair work. This is the information required to analyze repair strategies and make decisions.

It is advisable to create triggering and propagation trees for each of the three work and operating conditions of the breakwater and its subsets: (i) normal operational conditions; (ii) extreme work and operating conditions; (iii) exceptional work and operating conditions. In the first case, the tree depicts the operational stoppage modes and levels of operationality (full, restricted, or canceled). For extreme work and operating conditions, the configuration of the tree is based on the principal failure modes and a possible spatial and temporal evolution of the damage, according to the mode diagram.

Finally, certain cases require the elaboration of the triggering and propagation tree of modes in exceptional work and operating conditions. The purpose is to analyze the possible and progressive collapse of the breakwater in one or various subsets or subsystems, as well as simultaneously, and in the post-exceptional operational and extreme conditions described in Chapter 4 of the ROM 0.0-01. In Spain, failure modes caused by seismic agents and tsunamis (maritime climate agent) are included in these conditions.

The ROM 1.1-18 analyzes the unforeseen exceptional conditions in Section 5, Article 5.6, stemming from Nature, human error, system failure, etc., whose formulation is based on the impossibility of guaranteeing zero risk. This is done by quantifying the accident rate and the difference between the social acceptance of an assumable event as opposed to that of an event to be avoided at all costs.

3.6.1 Design for safety purposes (extreme work and operating conditions)

Triggering and propagation trees can be created for the whole breakwater, subset, subsystem, or part, or for a set of elements. In all cases, the tree should reflect the way that the failure (of the breakwater, subset, subsystem, a part, or a set of elements) is declared in the component diagram, and particularly, the failure modes that should occur (whether simultaneous or not).

Between breakwater subsets

The tree should reflect the failure propagation between subsets, and should specify the failure modes, subsystems and subsets that trigger them. Furthermore, the tree should state the options and conditioning factors for the repair work. It should also include the ensuing consequences if the damage is not repaired, the survival time of the subset and breakwater, and the risk of the breakwater losing its land connection subset. In this case, it is necessary to analyze whether a breach at the breakwater land connection (or in another subset) would block access by land to the damaged zone, and how this would affect construction processes and resources, implementation time, and the corresponding cost.

Between subsystems of a subset

The tree should reflect the failure propagation between subsystems and specify the failure modes that trigger them. Furthermore, the tree should state the options and conditioning factors for the repair work. It should also include the ensuing consequences if the damage is not repaired, the survival time of the subset and breakwater, and whether the failure of one of the subsystems would lead to the destruction or collapse of the subset. It may also be necessary to analyze whether the deep sliding of the foundation and soil could lead to the destruction of the subset and the need for its total reconstruction with materials and processes similar to those used in its initial construction.

Between failure modes of a subsystem

The tree should reflect the propagation of one or various failure modes in the subsystem to which it belongs and specify the failure modes that trigger them. Moreover, the tree should state the options and conditioning factors for the repair work and the ensuing consequences if the damage is not repaired. It should also specify the survival time of the subsystem and its impact on the survival of the subset and breakwater, when this survival time determines the destruction or collapse of the subset. Accordingly, a partial or total sequence of some or all of the failure modes of the subsystem should be created.

In the case of the outer subsystem of any breakwater subset, the work sequence can be the following:

- toe erosion →
- sinking, scouring, loss of toe berm elements →
- sliding of main armor layer, loss of unit pieces, and variation in the geometry of the main armor layer →
- loss of unit pieces of the crown →
- sinking, shifting, and displacement of the superstructure.

This sequence can continue in the inner subsystem

- failures in the access path →
- erosion of the inner armor layer (mooring area and service infrastructure).

The end result is the destruction or collapse of the subset and, if it is necessary to restore the functionality of the breakwater, then its reconstruction would be carried out with the same type of tools and materials as were used in its initial construction.

The triggering and propagation tree graphically expresses this process and permits the design of repair strategies, resources, time, and costs. This makes it possible to monitor the spatial and temporal evolution of breakwater safety and its possible destruction or progressive collapse at different intervention and cost levels.

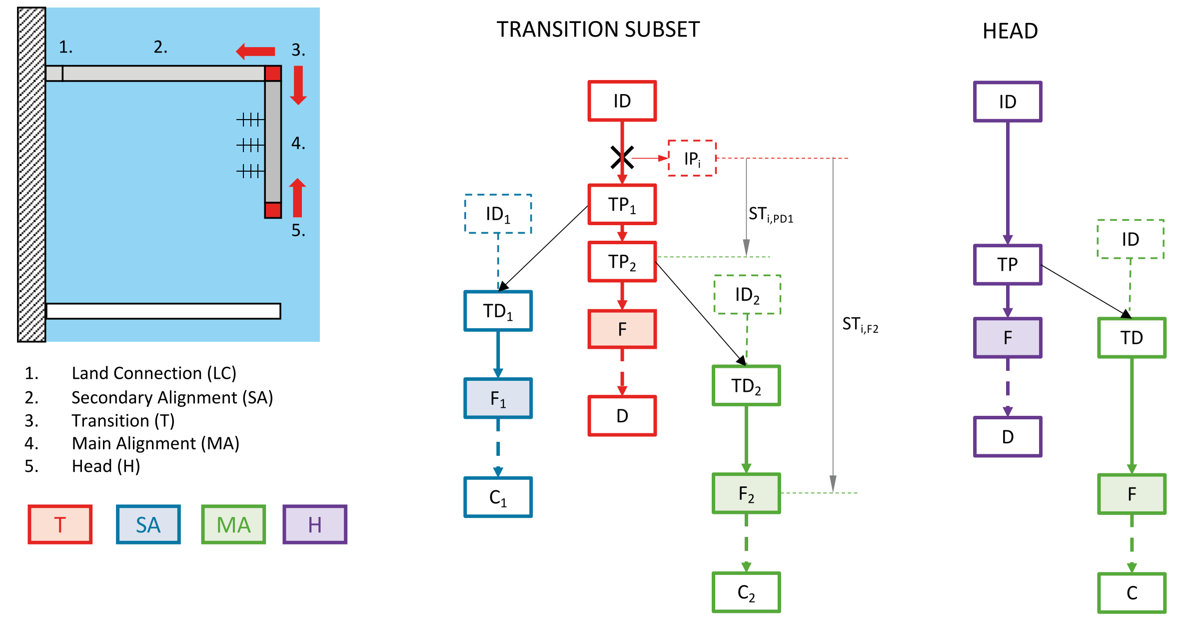
EXAMPLE

Triggering and propagation trees of the failure propagation in different subsets, subsystems, and modes

The examples given are possible diagrams of failure triggering and propagation in breakwater subsets and subsystems as described in Figure 3.7. Each diagram specifies the initiation of damage (ID) of each component, the triggering points that signal the magnitude of the damage that subsequently triggers damage in other components (either before or after the failure), triggering points (TP) that signal the magnitude that triggers damage in components (ID or others), the points of failure (F) that describe the damage causing the failure as represented in the component diagrams, and the destruction points that signify the collapse (C) of the subset associated with damage values that require the total reconstruction of breakwater components.

Figure 3.13 represents the trees corresponding to the transition and head of the breakwater. In the first case, the damage leaves the secondary alignment (SA) and main alignment (MA) laterally unprotected, which triggers their subsequent failure. In the second diagram, the effect is the same, though only the main alignment (MA) is affected. One can also define intermediate points (IP) from which the survival time (ST) of each component can be evaluated, usually in non-repair conditions. If the damage in each subset continues to progress, the structure then reaches the failures in the component diagram of Figure 3.8.

Figure 3.13: ***Triggering and propagation trees in the transition and head subsets***



Figures 3.14 y 3.15 represent the triggering and propagation trees of the failure propagation corresponding to the breakwater land connection, secondary alignment, and transition subsets. The sequence that describes the land connection of the breakwater begins with deformations in the foundation and ground soil, which in turn cause deformations in the core of the sections. Once there is a certain level of deformation in the core, the geometry of the layers begins to be affected. This finally leads to significant movements in the superstructure.

The sequence describes the second part of the erosion and displacement of the unit pieces in the seaward zone of the outer perimeter. When this damage progresses towards the crown, it can induce movements and settlements that connect with the mechanism in the first tree.

If the damage in each subsystem progresses, the breakwater will then experience the failures in the component diagram component in Figure 3.9.

Figure 3.14: ***Triggering and propagation tree of the failure affecting the subsystems in the following subsets: breakwater land connection, secondary alignment, and transition. This is a consequence of the deformations and movements of the foundations and soil***

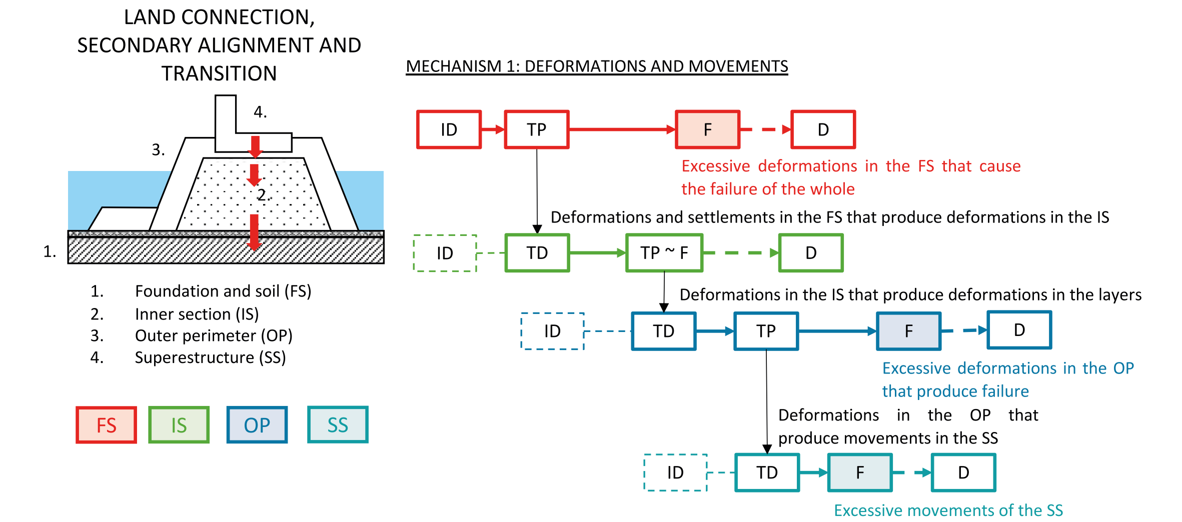
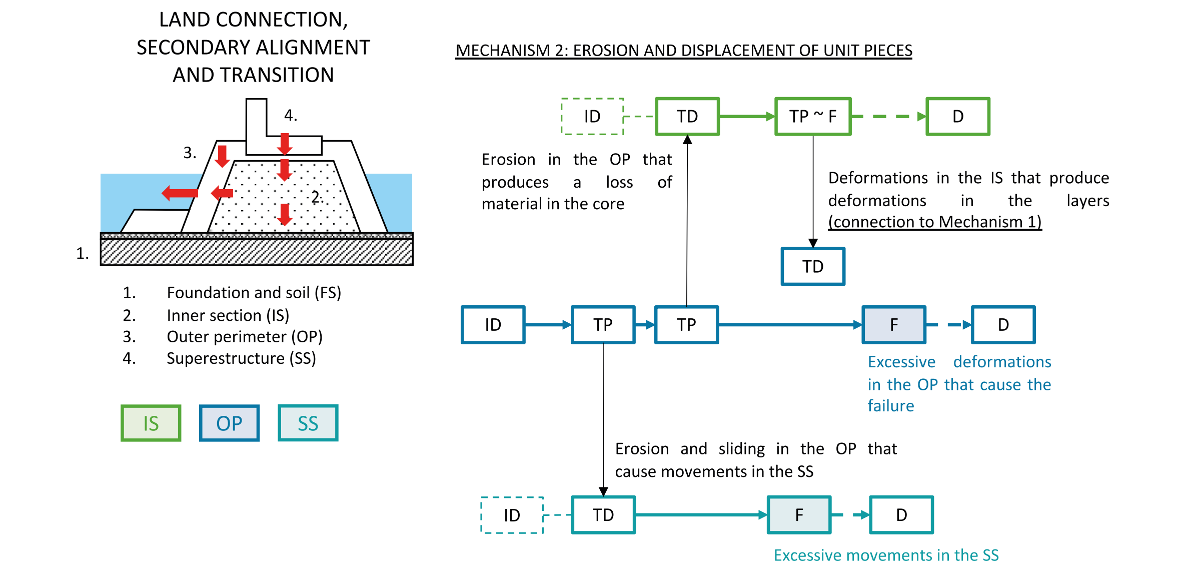


Figure 3.15: ***Triggering and propagation tree of the failure affecting the subsystems of the following subsets: breakwater land connection, secondary alignment, and transition. This is a consequence of the erosion and displacement of the unit pieces of the outer perimeter***



Figures 3.16 y 3.17 represent the triggering and propagation tree of the failure corresponding to the subsystems of the main alignment. The sequence that describes the triggering of the failure stems from deformations in the foundation or soil that in turn cause deformations in the section core. Once a certain level of deformation is reached in the core, the geometry of the armor layers then begin to be affected. This finally causes significant movements in the superstructure. When these movements are excessive, they affect overtopping, which can then cause movement in the unit pieces in the landward zone of the outer perimeter.

The sequence describes the second part of the erosion and displacement of unit pieces in the seaward zone of the outer perimeter. When it progresses towards the crown, it can trigger movements in the superstructure that affect overtopping, and this can cause movements in the unit pieces of the outer perimeter of the landward zone. Likewise, if the damage in the outer perimeter advances sufficiently, areas of the core are left exposed. This causes the core to lose material, which then leads to movements and settlements that are linked to the mechanism of the first tree. If the damage in each subsystem progresses, then the failures in the component diagram in Figure 3.9 occur.

Figure 3.16: ***Triggering and propagation tree of the failure in subsystems of the principal alignment as a consequence of the deformations and movements in the foundation and soil***

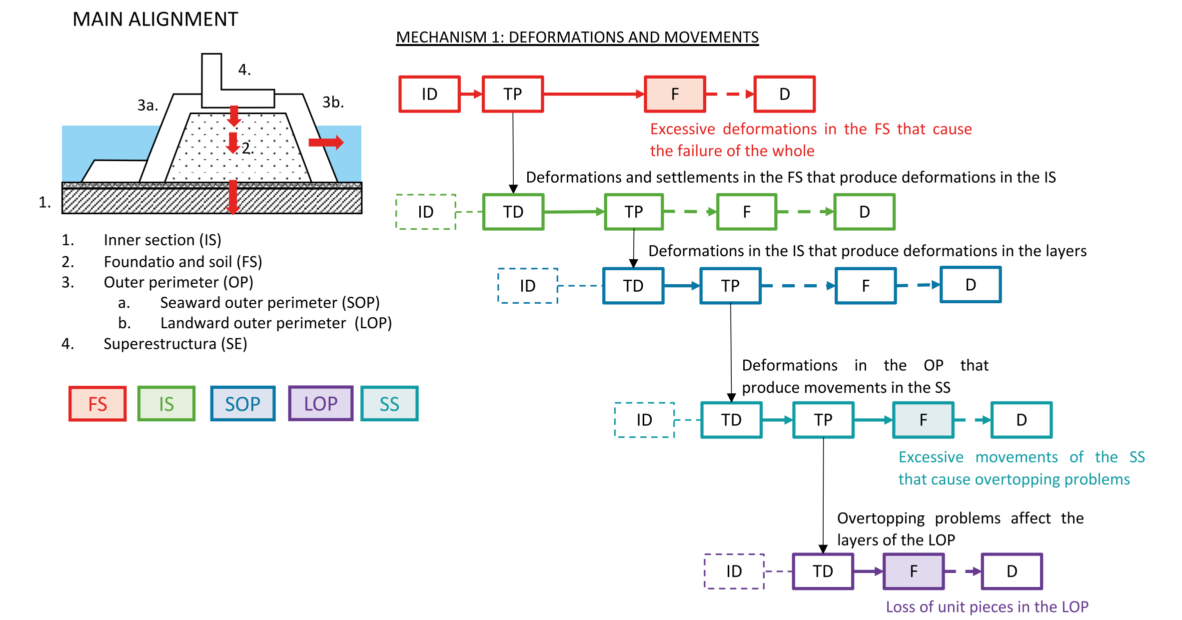
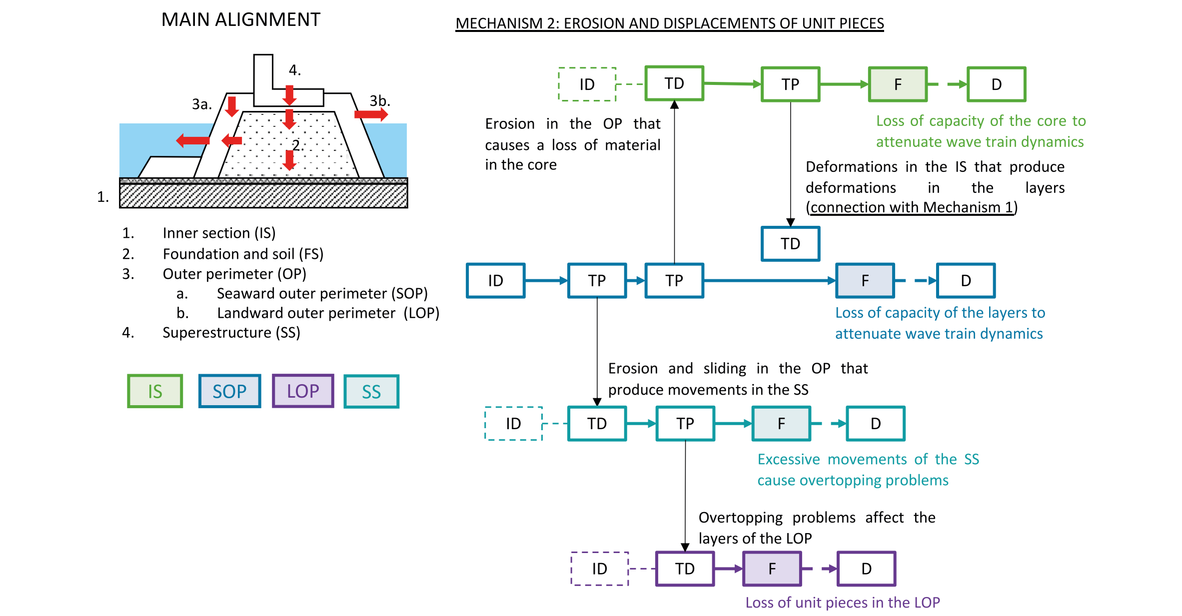


Figure 3.17: ***Triggering and propagation trees of the failure between subsystems of the main alignment as a consequence of the erosion and displacement of the unit pieces of the outer perimeter***



3.6.2 Design for operational purposes (normal work and operating conditions)

It is a good idea to create triggering and propagation trees for all of the breakwater or for specific subsets. In all cases, the tree should reflect the way in which the operational stoppage is declared (either for the harbor area, a specific subarea, or a subset) in the component diagram. It should also highlight the participating agents and whether their occurrence is simultaneous.

To analyze the spatial and temporal evolution of operationality in the harbor area or one of its subarea, a tree should be created for the whole breakwater. The tree should specify the value of the operationality indicators of the ROM 0.0-01, stoppage duration and maximum number of stoppages as well as what is recommended in this Section 3, Article 3.3.2. To analyze the spatial and temporal evolution of the operationality in a breakwater subset, it is advisable to elaborate the tree for the subset and specify the values of the operationality indicators of the ROM 0.0-01, stoppage duration, and maximum number of stoppages.

3.6.3 Design for post-exceptional work and operating conditions

In accordance with Section 5, Article 5.6 of this ROM 1.1-18 for certain breakwaters with specific purposes at certain locations, it is necessary to create the triggering and propagation trees of failure modes in the whole breakwater or a subset, linked to post-exceptional work and operating conditions. In Spain, these work and operating conditions arise when there is an exceptional event such as an earthquake or tsunami or after an extremely violent storm, among other causes. The procedure followed is similar to the one for extreme work and operating conditions. In all cases, the tree should reflect how the failure (of the breakwater or subset) is declared in the component diagram, and in particular, the failure modes that should occur (whether they are simultaneous or not).

3.7 DESIGN OF THE EVOLUTION OF DAMAGE AND REPAIR STRATEGIES

The design at the advanced level of damage extends the capacity of the project designer and planner to configure the structure so that it best suits the conditioning factors and requirements of the construction project and the financial sustainability of the investment project.

To design and size a breakwater that considers the spatial and temporal evolution of the breakwater, it is necessary to specify the following requirements:

- **reliability of the structure during its useful life:** damage level associated with failure probability in the mode during the structure's useful life (reliability requirement).
- **operationality:** the damage threshold that conditions how, and to what degree the breakwater and harbor area is operational (operationality requirement).
- **repair strategy:** (a) when, how, how much, and in what time period should the structure be repaired (technical requirement); (b) resources available to carry out the repair work (financial-economic requirement).

The decision to design a project that envisages the evolution of damage and repair strategies (instead of opting for a ULS design) is motivated by the following technical-economic, financial-economic, and environmental factors:

(a) harbor area management model and use and exploitation requirements;
(b) availability of construction materials and resources;
(c) characteristics of the maritime climate agents;
(d) financial-economic requirements of the investment project throughout the useful life of the structure
(e) environmental requirements.

3.7.1 Elaboration of repair strategies

Repair strategies should specify when, how, and to what degree it is necessary to intervene to assure that the performance of the structure is adapted to the initial conception of the project designer and that it fulfills project requirements.

The elaboration of a repair strategy and the specification of criteria that define it is based on the following factors:

(a) relative importance of the failure of the components in higher-order hierarchical elements;
(b) model of damage evolution that includes the damage initiation rate in each component and the speed at which it progresses;
(c) triggering of the failure in other components, its importance, and model of evolution;
(d) application criteria;
(e) implementation procedures.

The application criteria should include: (a) a clear indication of when (or in which circumstances) repairs should begin; (b) the state of the structure when it can no longer function (damage level at which repairs should begin); (c) priority of each repair job, when there is a lack of resources, in contrast to other repair jobs that can be carried out simultaneously.

The procedures for carrying out repairs are generally described in Article 3.8. In addition, it is important to underline that repairs do not lead to an immediate result. Instead, once the criteria for starting repair work are all present, the damage can continue during a certain time interval. Among other things, this depends on the following:

(a) capacity to detect damage;
(b) availability of resources;
(c) mobilization times;
(d) operationality levels of the machinery along with the climate agents;
(e) performance of the repair work, etc.

Repair strategies when the structure's useful life is about to end

Damage can occur that signifies the failure of the breakwater or one of its parts, particularly during the final stages of the service phase. Apart from the total restoration of the structure, it is necessary to envisage other alternatives (e.g. partial restoration, complemented by intensive damage monitoring and maintenance). However, it is also necessary to address cost as well as the risk and consequences of the progression of the damage during the rest of the structure's life.

COMMENT

DESIGN WITH AND WITHOUT REPAIR STRATEGY

Design with repair strategy

If the breakwater design follows a ULS model, once the initial damage level of a principal mode occurs, the subset must be reconstructed to restore the functionality of the breakwater project. In this eventuality, it is rare to specify repair strategies or allocate funds in the budget. This breakwater design option prioritizes the conception of a robust design that generally has a high initial cost.

Damage management involves the analysis of when damage first begins until the 'real' destruction of the breakwater. It also involves estimating the survival time of the subset. The decision to reconstruct the breakwater depends on the following:

- evolution of the damage;

- consequences for the operationality of the harbor area;
- availability of economic resources

Section 5 describes the method of calculating the costs of a construction project. These costs include the initial construction of the breakwater and the probable costs of its reconstruction.

Design with repair strategy

A repair strategy permits a less robust design. In this design, there is a greater probability that damage will begin, but there is a lesser probability that damage will lead to failure as long as the programmed maintenance work is performed and, when necessary, repair work. This breakwater design option prioritizes the conception of a design with an initial construction cost and a repair cost that are suitable for the protection needs of the harbor area as well as the financial-economic resources of the project developer.

In such cases, for each probability $Pr\,[D_0, V\,]$ selected, the probability that the damage will progress from D_o until the failure of the breakwater depends on the existence of a repair strategy. This probability is delimited by the maximum failure probability assigned to the failure mode in the probability distribution. Accordingly, the investment is distributed between the construction phase and the structure's useful life. Section 5 describes the method used to calculate the costs of the construction project, which include those of the initial construction and probable cost of repair work and, when applicable, of reconstruction.

3.7.2 Decision tree for selecting repair strategies

The result of each repair strategy can be transformed into an estimate of associated costs that facilitate decision-making (see Article 5.3.1). The comparison of repair strategies is facilitated by decision trees, in the version of survival trees and probability trees.

Not surprisingly, the smallest mean survival time is associated with the non-repair strategy of some or all the breakwater components, whereas the largest is associated with the immediate repair strategy (at the initiation of damage) with a total availability of resources.

The mean survival time associated with the optimal strategy, considering the costs of each option, is in the interval between those two values.

COMMENT

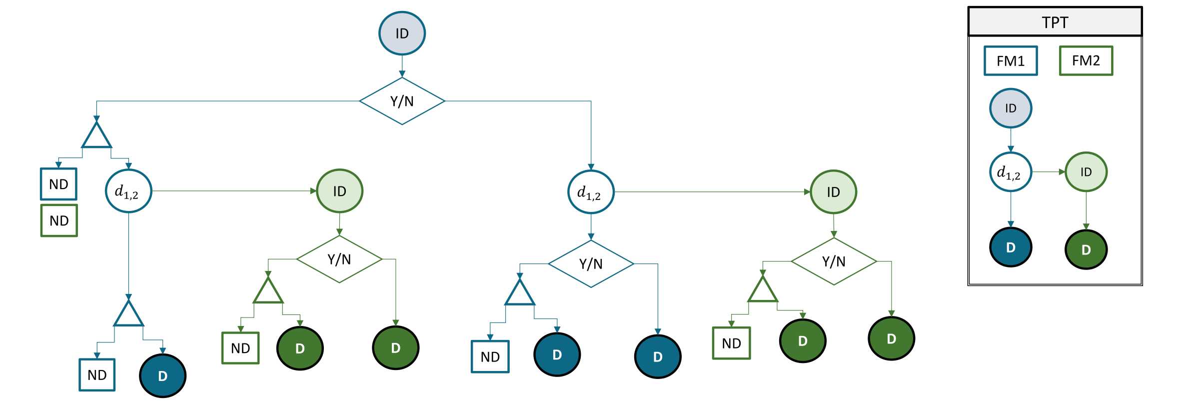
Decision tree for triggering and propagation tree and possible repair strategies

Figure 3.18 shows the decision tree for the triggering and propagation tree on the top right, where ND, IntD, and D correspond, respective to the states of 'no damage', 'initiation of damage', and 'destruction'. Mode 2 is triggered when mode 1 reaches damage $d_{1,2}$. In this case, possible strategies are the following:

(a) to repair both modes when damage begins;
(b) to repair mode 1 when the damage begins and to not repair mode 2;
(c) to repair mode 1 after reaching $d_{1,2}$ and to repair mode 2;
(d) to repair mode 1 after reaching $d_{1,2}$ and to not repair 2:
(e) to not repair mode 1 and to repair mode 1;
(f) to not repair either mode.

Decisions to repair or not to repair damage are designated by triangular boxes, where the left path represents successful repairs and the right path signifies the opposite.

Figure 3.18: ***Example of a decision tree***

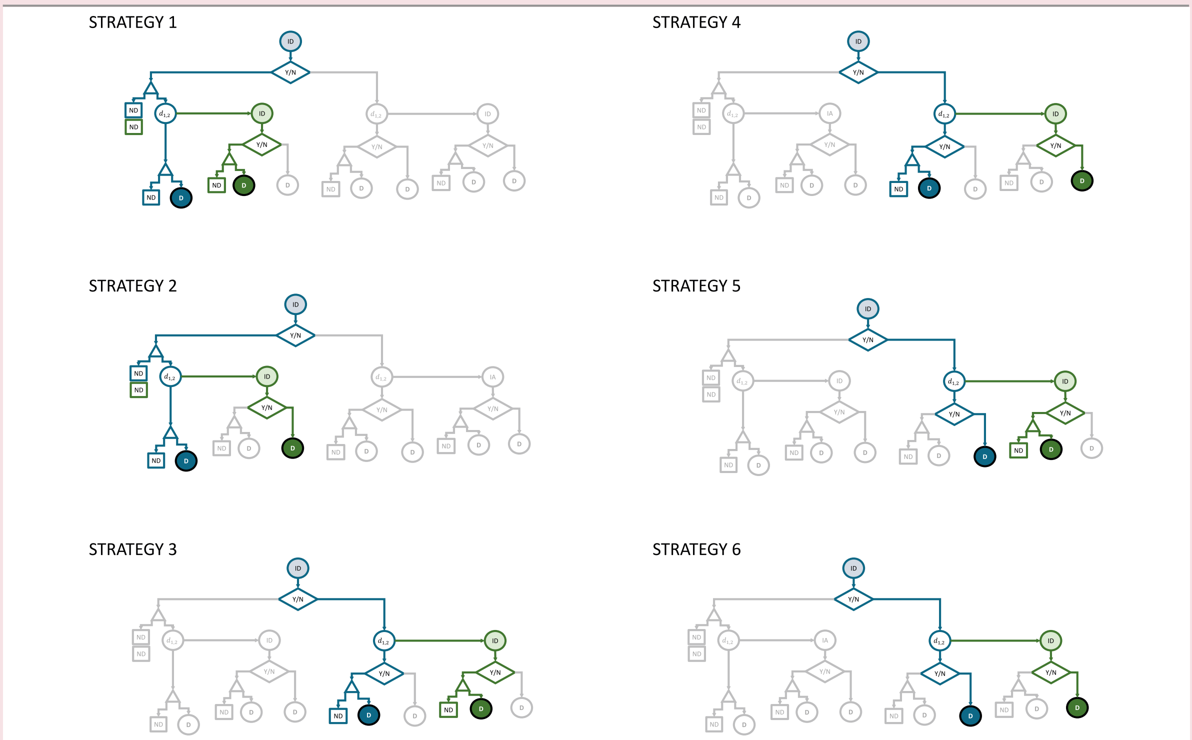


Based on the options defined in the previous tree, six strategies can be defined (Figure 3.19). Strategies range from starting repairs when the damage begins in any mode (strategy 1) to not repairing (strategy 6). The results of each strategy after a certain time interval and the probability that they are reached jointly depends on the following:

- strategy;
- agents;
- probabilities that the repairs will be successful;
- models of damage evolution;
- triggering and propagation trees elaborated.

Once a certain time interval and repair strategy have been selected, the probability of a certain damage level in each mode can be obtained, depending on the probability of success of the repair work that will prevent the damage from progressing to the next level.

Figure 3.19: ***Possible strategies defined with the decision tree in Figure 3.18***



3.8 ORGANIZATION OF THE CONSTRUCTION, PROCESSES, AND RESOURCES

Construction costs and expected repair costs, and the cost of their financial-economic repercussions because of non-compliance with the purposes of the breakwater depend on the credibility of the construction project, particularly the construction cost and the expected repair costs during the useful life of the structure. These costs are linked to the organization as well as to the construction resources and processes available. Their study and related decisions should be included in the different project development stages from preliminary studies to the construction project.

In particular, the decision regarding alternatives and solutions should analyze the economic and technical connectivity between initial construction processes and repair processes as described in what follows. This list of tasks and milestones complements and expands the list in Section 1 of this ROM 1.1-18. It is a good idea to consult both at the same time.

3.8.1 Preliminary studies

The organization and planning of all the construction, repair, and dismantling work is based on preliminary studies that analyze all aspects of the context that can affect the construction work, such as the following:

(a) characteristics of the road network and the connection to other transport infrastructures;
(b) level of access to services such as energy, water, communications;
(c) existing installations;
(d) maritime and terrestrial climate characteristics;
(e) soil and orography characteristics;
(f) availability and cost of resources and materials;
(g) characteristics of the work market and supply chains.

3.8.2 Description of construction subphases and procedures

The work to be done is organized in subphases that cover all processes of supply, prefabrication, transport, and implementation. Different procedures are evaluated for each one, and are characterized according to the following:

(a) measurement of the work to be done as well as the tasks and construction units involved;
(b) materials and resources required to carry out the work, including production and supply estimates, mobilization times, supplies, stockpiles, and costs;
(c) installations (energy supply, storage areas, workshops, offices, and other services);
(d) other requirements for the implementation of each subphase, including its restrictions and dependence on other subphases;
(e) failure and stoppage modes for each of the tasks in the subphase, interdependence relations and consequences;
(f) estimates of operationality, performance, and cost of the work.

3.8.3 Planning of the construction strategy

Work sequence and chronogram

It is necessary to define the work sequence and progress of the different subphases of each subset (e.g. by means of minimum distances between different fronts). This is a question of precisely delimiting the following: (i) operating windows of each subphase of the work; (ii) analysis of the possibility and duration of seasonal stoppages; (iii) different protection strategies.

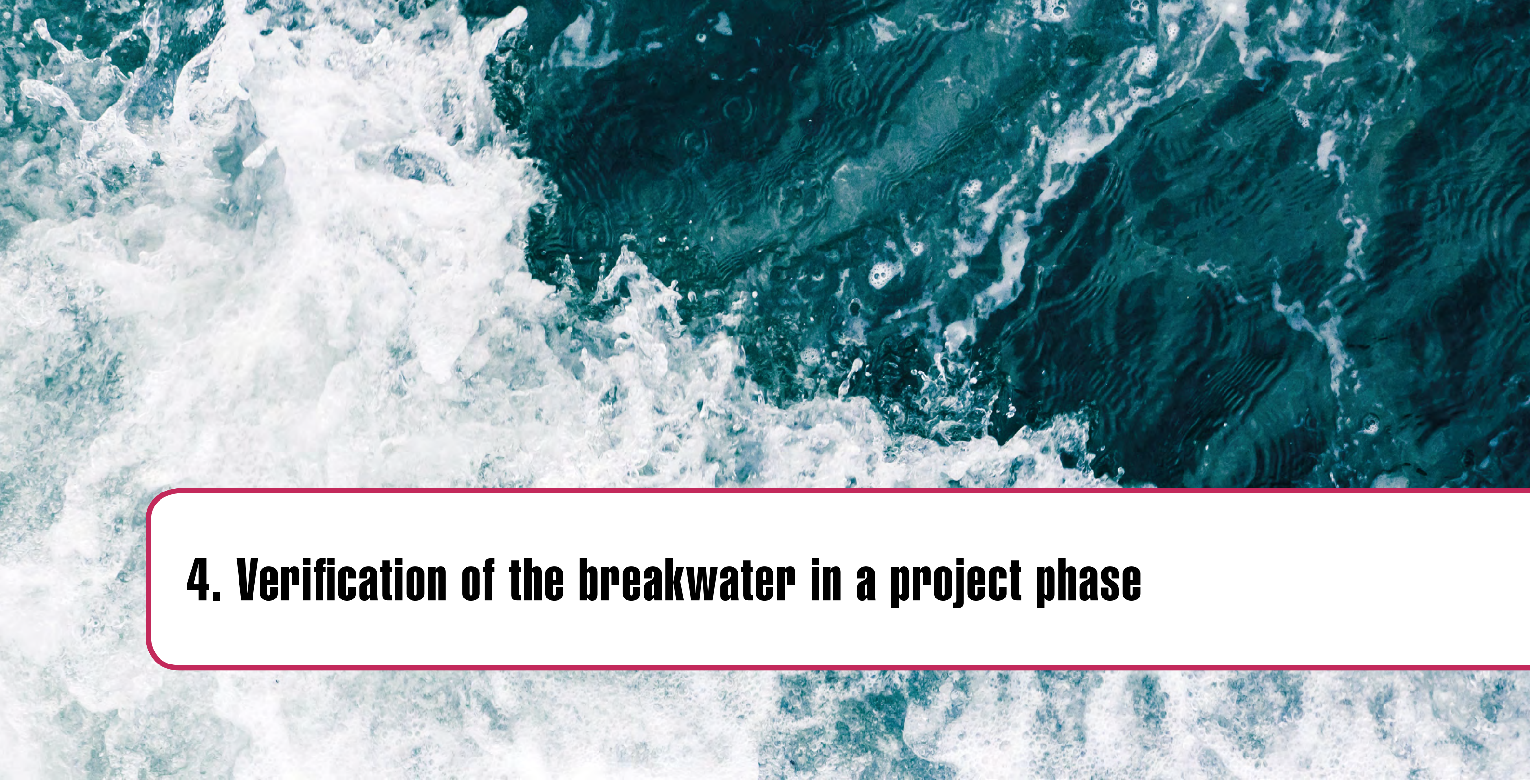
The timing strategy is shown in a chronogram that includes the beginning and ending dates of the construction phase as well as the beginning and ending dates of each of the construction subphases that comprise the implementation of the project work.

Resources and availability

The construction strategy is reflected in the definition of the resources assigned to each subphase and their characteristics. It includes the resources, performance, climate conditions, and the production and supply speeds to make the progress of the work better fit the chronogram as well as the need for extra resources, stockpiles, and supplies.

The availability of materials should be studied in the construction work zones. It is necessary to verify that the quarries and/or deposits are able to provide materials that comply with the project requirements. They should also have the capacity to supply the quantities of material necessary, and possess the corresponding permissions. Also to be considered is the creation of special installations, such as concrete or aggregate-crushing plants. An evaluation should be made of the possible impacts of the construction resources and timing strategy on the road network capacity. This should be accompanied by an assessment of the design of accesses, signaling, access paths, etc.

Section IV. Table of contents



4. Verification of the breakwater in a project phase

To be able to properly function, the breakwater should preserve its structural and formal characteristics over a given period of time and provide the nec-essary operationality conditions for harbor area activities during its useful life (and other project phases). This general objective is achieved when the break-water and its components (subsets, parts, subsystems, and elements) maintain their geometry and resistance properties with a joint failure probability, ROM 0.0-01.

This section explains the procedure that can be used to verify whether the breakwater project satisfies the project objectives, based on the spatial hierarchy of the components and the different time scales recommended in Section 2. According to the ROM 0.0-01, the specification of this proce-dure depends on the nature of the subset as well as the project class and development stage.

4.1 OBJECTIVES AND REQUIREMENTS OF A BREAKWATER PROJECT IN THE ROM PROGRAM

In this context, verification should determine whether the project objectives (especially, the technical requirements of the "*Programa de Recomendaciones para Obras Marítimas (ROM)*" are satisfied). It is also a question of verifying whether the performance of the structure and its components are in consonance with the initial conception of the project designer.

Regarding the fulfillment of project objectives, the ROM 0.0-01 requires the verification of a set of requirements related to the reliability and operationality of the construction work in a certain spatial and temporal frame (i.e. breakwater subset and project phase). The determination of these requirements depends on the consequences of the failure and operational stoppage, approximately evaluated with indicators of the subset nature in a project phase. In fact, this procedure accurately delimits a lower threshold of the acceptable risk level of the project.

Generalization of the requirements at other spatial and temporal scales

The hierarchization of the breakwater in subsets, parts, subsystems, and elements as well as the division of a project phase in subphases of lesser duration makes it easier to generalize those requirements to other components and to other spatial and temporal scales. The procedure used to verify project requirements is similar to that described in the ROM 0.0-01. In other words, it is independent of the subphase and hierarchical level analyzed.

4.1.1 Nature of the subset in a project phase

According to Section 1.7.1 of the ROM 0.0-01, the project developer, whether public or private, should specify the general nature of the construction work and its subsets. When this information is not available, the definition of the structure should be based on the economic repercussion index (ERI) and the social and environmental repercussion index (SERI).

Similarly, the project developer, whether public or private, should specify the operational nature of the construction work and its subsets. When this information is not available, the definition of the structure should be based on the operational economic repercussion index (OERI) and the operational social and environmental index (OSERI), as defined in the ROM 0.0-01, Section 2.7.

Economic repercussion indexes: ERI and OERI

The ERI assesses the economic repercussions of the reconstruction of the subset and of the cessation or its foreseeable impact on the economic activities directly related with it in the event of the destruction of the breakwater. This indicator accurately delimits the minimum useful life of the subset, according to the indications in the ROM 1.0-09, Section 2.4.2.2.

The OERI assesses the cost of the total loss of operationality of the subset. It delimits the minimum operationality of the subset in the time interval considered (usually one year) as specified in the ROM 1.0-09, Section 2.5.1.

Social and environmental repercussion indexes: SERI and OSERI

The SERI qualitatively assesses the expected social and environmental impact in the case of the total destruction of the subset. It evaluates the possibility and repercussion of the following: (a) loss of human lives; (b) damage to the environment as well as to the historical and artistic heritage; (c) social alarm generated, considering that the failure occurs, once the economic activities directly related to the construction work have been consolidated.

This index delimits the maximum probability of exceedance in relation to the safety and serviceability in a project phase (generally, its useful life) or in the time interval of exploitation considered. The maximum values of the joint failure probabilities are specified in the ROM 1.0-09, Section 2.5.1.

The OSERI evaluates the expected social and environmental repercussion in the case of the total loss of operationality of the subset within the time interval considered. Its value determines the average number of annual operational stoppages that are admissible for the sheltered area, as specified in the ROM 1.0-09, Section 2.5.1.

Project requirements for the subset

In each project phase, all breakwater subsets should comply with the following requirements:

- minimum useful life;
- maximum joint probability of the principal failure modes, specified for the structure's useful life;
- minimum operationality delimited by the occurrence of a maximum number of annual stoppage modes and certain maximum duration.

Minimum useful life

The useful life of the structure is the duration of the in-service phase. It generally corresponds to the time period during which the structure performs the main function for which it was designed. In the "*Programa de Recomendaciones para Obras Marítimas (ROM)*", the minimum duration of the useful life of the subset depends on the ERI of the subset.

The useful life of the other project phases is determined by the project phase objectives and their environmental, social, and economic correspondence with the objectives during the useful life of the structure.

The minimum duration of the in-service phase is shown in Table 4.1,

Table 4.1: ***Minimum useful life based on the ERI***

ERI	Useful life (years)
≤ 5	15
6 - 20	25
> 20	50

COMMENT

In Spain, from 2013, the time period for concessions in the maritime-terrestrial public domain (MTPD) and state-port public domain (SPPD) has been lengthened. For this reason, it is advisable to re-analyze the joint failure probability of the structure, including the prolongation of the concession. It is thus necessary to consider the following: (a) duration of the new concession; (b) damage level of the breakwater and its components at the end of their initially projected useful life; and when applicable (c) models of damage evolution of the different modes and repair strategies.

MAXIMUM JOINT PROBABILITY OF THE PRINCIPAL FAILURE MODES OF A SUBSET

This probability is delimited in the useful life of the subset (Section 2.2, ROM 0.0-01). The calculation of this value is based on the SERI of the subset (ULS design) (see Table 4.2):

Table 4.2: ***Maximum joint probability in the in-service phase***

SERI	P_f	β
< 5	0.20	0.84
5 - 19	0.10	1.28
20 - 29	0.01	2.32
≥ 30	0.0001	3.71

COMMENT

CORRESPONDENCE BETWEEN THE JOINT FAILURE PROBABILITY (TABLE 4.2) AND CALCULATION VARIANTS AND LEVEL I, II, AND III METHODS

These recommendations adopt a single table with the maximum joint probability values of the principal failure modes in a subset. These values are applied to breakwaters with a ULS design (initiation of damage) as well as to breakwaters with an SLS design (spatial and temporal evolution of the damage).

When the ERI and SERI of the breakwater are low (Level I) and the breakwater construction project is not associated with an investment project (Figure 1.8, Section 1), (ULS design), the project designer selects the levels of initiation of damage (SD) and destruction (D) a priori. The initial hypothesis is that initiation of damage and destruction occur almost simultaneously (step model). Consequently, the failure probability is the same for the two levels. This means that the only way to recover the initial project objectives is to reconstruct the subset.

If the project designer decides to work with two clearly differentiated levels of damage, then there is a certain margin to incorporate the evolution of the damage between the points selected. The evolution of damage can thus be included in the design, and the resilience of the structure until its destruction can be calculated once the damage begins.

In Spain, for a sloping breakwater, it is customary to consider a third state or intermediate level (ID, Iribarren damage). In such cases, the project designer can link the maximum joint probability of failure to a given damage level.

Depending on the subset, typology, subsystem, and failure mode considered, the evolution of the damage from one level to another can be described by (Figure 2.8 of Section 2, Article 2.4):

(a) **Step model:** this model considers that the initiation of damage and destruction occur almost simultaneously (step model). Therefore, the failure probability is the same for both levels, and the only way to recover initial project objectives is to reconstruct the subset.
(b) **Constant slope model:** once the damage has begun, the destruction level is reached if the meteorological state continues over a sufficiently long time period (without variation in sea level). If the failure probability is linked to destruction, a certain amount of time is available for repairs before destruction eventually occurs. This margin depends, among other things, on the breakwater type, subset and wave incidence angle. This includes: (a) the main alignment of a sloping breakwater constructed with slender unit pieces (e.g. tetrapods, dolos) or with a single layer with special pieces (e.g. acropods); (b) vertical-wall breakwater head; (c) subset with a wave incidence that is very oblique or parallel to the breakwater, etc. The failure probability can be assigned to the destruction level, but once the damage has begun, if there is no realistic and effective intervention strategy, the only way to recover project objectives is to reconstruct the subset.
(c) **Sigmoide-type model:** once begun, the damage stabilizes as long as the action does not increase in magnitude. This is the usual behavior in sloping breakwaters protected by a main armor layer of compact unit pieces, configured in two layers. Once extracted, the majority of the unit pieces remain in the section, forming an equilibrium slope. In this type of situation, the breakwater design is such that it is repaired when the Iribarren damage (ID) level is reached, and it is reconstructed at the damage (D) level. By linking failure probability to destruction, there is ample margin for intervention (repairs/reconstruction) once damage has initiated or once the Iribarren damage (ID) level has been reached.

Breakwater calculated by a Level I method

As described in Article 2.8, "Variants in the conception and design of a breakwater", the calculation of the total costs of a Level I breakwater (Variant 1) signifies the following: (1) it can be immediately repaired or reconstructed; (2) there are sufficient economic resources for this purpose. Consequently, the certainty that a Level I breakwater will fulfill project objectives depends on the following:

- accurate representation of breakwater performance;
- suitable selection of damage level linked a failure probability;
- degree of fulfilment of the hypotheses of immediate intervention and the availability of sufficient economic resources.

Depending on the breakwater type, subset, location and conception of the breakwater, this design option can lead to oversized breakwaters. In other cases, it can produce undersized breakwaters (possibly abandoned to their fate). In those cases in which there are no economic provisions for intervention, it may be necessary to seek other financial options such as extraordinary budgets, declaration of emergency construction work, etc. when repair/reconstructions are indispensable for the operationality of the harbor area. If there are serious doubts about compliance with repair/reconstruction assumptions, one way to reduce project uncertainty is to apply Variant 2 (described in Article 2.8) to calculate the total costs of the breakwater that include, in certain contexts, the analysis of the temporal evolution of the damage.

Method to calculate a Level II or III breakwater

When the ERI or SERI of the breakwater is high (Level II or III), and it is associated with an investment project, (Figure 1.8 of Section 1) (SLS), damage levels evolve in time and space. It is necessary to specify the relation between the point when the damage initiates and the following levels of damage leading to destruction with the triggering and progression of other failure modes (see Article 2.8, Variant 3).

> The decision regarding the damage thresholds are associated with the progress, propagation, and interaction with other failure modes, repair strategies, and total costs. They are the result of a dual optimization system and directly affect the financial sustainability of the investment project.
>
> This ROM 1.1-18 proposes approaches, methods, and tools that can be used to model the spatial and temporal evolution of the damage, and to define repair strategies as an integral part of the breakwater design so that it is better suited to project objectives. In such cases, the joint probability of failure among the principal modes is distributed at the destruction level. Its transposition to other damage levels is specified in Section 2, Article 2.5.

Minimum operationality, average number of stoppages, and their probable maximum duration

The operationality of a subset is the complementary value of the probability of stoppage as opposed to all the principal stoppage modes in a given time interval, usually one year (Section 2.2, ROM 0.0-01). Its minimum value is based on the OERI. The average number of operational stoppages in a time interval (one year) is based on the OSERI, and the probable maximum duration of an operational stoppage is based on the OERI and the OSERI.

The operationality in the time interval (one year) is greater than or equal to the value shown in the Table 4.3:

Table 4.3: Minimum operationality in the in-service phase

OERI	$r_{f,ELO}$	β_{ELO}
≤ 5	0.85	1.04
6 - 20	0.95	1.65
> 20	0.99	2.32

The average number of stoppages in the time interval (one year) is less than or equal to the value shown in Table 4.4:

Table 4.4: Average number of annual stoppages, based on the OSERI

OSERI	Average number of stoppages
< 5	10
5 - 19	5
20 - 29	2
≥ 30	0

The probable maximum duration of an operational stoppage in a given time interval (one year) is less than or equal to the value shown in Table 4.5:

Table 4.5: Maximum probable duration of a stoppage based on the OERI and OSERI

	OSERI			
OERI	< 5	5 - 19	20 - 29	≥ 30
≤ 5	24 h	12 h	6 h	0
6 - 20	12 h	6 h	3 h	0
> 20	6 h	3 h	1 h	0

COMMENT

To harmonize the design with damage evolution and the use and exploitation of the subset, this ROM expands admissible levels of operationality. The values given in Tables 4.3, 4.4 and 4.5 are indicative, and are generally associated with the complete cessation of activity in the subset. The specification of operationality levels and the thresholds adopted should be based on the analysis of financial-economic profitability and of the financial sustainability of the investment project (MEIPOR-16).

Indicators of harbor operationality

Indicators of harbor operationality can be formally applied to the set of infrastructures and elements that configure the harbor area and its services. The process followed is similar to that recommended for the breakwater and its subsets (Section 3): (i) hierarchization of the components of the harbor area in systems, subareas, and infrastructures; (ii) establishment of their relations; (iii) quantification of the consequences of the operational stoppage of the services in the harbor area.

Based on this information and by simulating the state of the area, including vessel traffic and the transport of goods, it is possible to estimate the global operationality and risk level of the harbor area during its useful life or in any other time period. According to the MEIPOR, operationality indicators of the area and its subareas are based on the analysis of financial-economic profitability as well as the financial sustainability of the investment project.

However, in the preliminary studies and study of alternatives and solutions, it is possible to define and determine (as with the ROM method) the ERI, OERI, SERI, and OSERI indexes of each harbor subarea. In this case, the values in the previous tables could possibly be used.

4.2 GENERAL VERIFICATION PROCEDURE

Generally speaking, in the ROM Program (Chapters 4-6 of the ROM 0.0-01 and Section 2.6 of the ROM 1.0-09), the verification of the project objectives of the breakwater subset related to safety is performed in terms of failure modes that characterize the way in which one or various subset components can lose their formal and structural capacity. This verification makes sure that the probability of occurrence of the failure modes does not exceed the values in Table 4.2. The ROM 1.0-09 provides criteria that can be used to specify the values of the project requirements in other project phases.

Similarly, the verification of project objectives of the subset related to operationality is per-formed in terms of operational stoppage modes that characterize the way in which one or various components cause a loss of operationality in the subset. This verification checks whether the time period considered (any year of the structure's useful life) complies with the values in Tables 4.3, 4.4 and 4.5.

4.2.1 Evaluation of the behavior of a mode

The triggering of a mode and the ensuing levels of failure (and operational stoppage) can be specified by means of the following:

- resolution of a (verification) equation
- physical experimentation in the laboratory or on site
- numerical experimentation
- standards of good practice

Resolution of a verification equation

Usually, the verification equation of a failure (or stoppage) mode is the same one that characterizes the structural (or operational) and formal behavior of the breakwater, and it is formulated at the state scale. When the predominant agents are climate or soil agents, the equation terms are based on dimensionless monomials related to site characteristics, wave train dynamics, soil, breakwater performance, and materials.

Laboratory or on-site experimentation

The verification of the failure and stoppage modes of a subset can be carried out by means of duly accredited physical experimentation in the laboratory or on site (Pérez-Romero et al., 2009). In all cases, it is necessary to specify the components thus verified, time scale of verification, and dimensionless monomials of the agents, actions, and processes that characterize the performance of the structure and its formulation.

The scope, number of experiments and repetitions, work and operating conditions, calm and loading cycles, and the states and their duration depend on the following:

(a) nature of the construction work and the cost of the investment project
(b) project development stage
(c) design modality and whether it envisages damage evolution

In general, laboratory verification is not necessary for projects with a low ERI and SERI (Level I) and without an investment project (Class I). This type of verification would only be performed if there were a specific local feature in a subset that had to be checked and if the project designer or the government developer of the construction decided that it was advisable to do so.

It is necessary to experimentally verify breakwaters and subsets with a high ERI and SERI (Level II or III). This is particularly the case for subsets (i.e. head, alignment changes, and transitions) and the outer perimeter subsystem of other alignments that most affect the sensitivity of the design results. This type of design takes damage evolution into account, and includes the elaboration of triggering and propagation trees as well as repair strategies.

COMMENT

It is advisable to consider the following:

- The scope of experiments should be the focus of a project with objectives, implementation, and analysis of the results.
- The results obtained should provide the necessary information for the construction work and the subsequent application of MEIPOR.
- The confidence level of the experimental result should be obtained by repeating the same experiment a minimum number of times.
- The laboratory should not be used to create a project design, but rather to verify it.

The objectives and technical specification of experimental trials can be found in the "Annexes of general technical specifications for the project" in this ROM.

Numerical experimentation

The failure and stoppage modes of a subset can be verified by numerical experimentation with codes that have been duly calibrated and validated (Vílchez et al., 2016a). In addition, it is also necessary to specify the following:

(a) components that have been verified;
(b) time scale of the verification process;

(c) dimensionless monomials of the agents, actions, and processes that characterize the performance of the breakwater;
(d) formulation, as itemized in the previous article.

COMMENT

The objectives and technical specification of a numerical experiment can be found in the "Annexes of general technical specifications for the project" in this ROM.

Verification by means of standards of good practice

A failure or stoppage mode can be verified by applying standards of good practice only when it is regarded as non-principal or the necessary measures have been taken to consider it as such. In all cases, however, it is necessary to meet the same technical requirements as for other types of verification.

Other verification procedures of a mode

When project requirements or modes and their corresponding verification equation do not adequately describe non-compliance with project objectives, other duly justified verification procedures should be implemented with the reasons for their suitability or unsuitability. When necessary, a procedure should be specified to determine project requirements as well as the method, spatial and temporal scales, or criteria to verify the mode or set of modes. When applicable, a method will be devised to quantify the consequences of the occurrence of the set of modes, and it will be included in the costs of the investment project.

In all cases, these verification procedures should have the same technical requirements as the other types of verification.

4.2.2 Verification equation: concept and formulation

In general, the (meteorological) state is the time scale for the verification equation of failure modes caused by soil or climate agents. The elaboration and development of a verification equation should include at least the following (Chapters 4 and 5 ROM 0.0-01):

- formulation and format of the equation;
- criteria to assign and combine values with project factors and terms;
- method of equation resolution.

The formulation of the equation conditions the application of its results to the useful life of the structure or to another project phase. It also depends on the nature of the subset and stage of project development.

Formulation and format of the state equation

The formulation of the equation should permit the quantification of the manner in which the damage is produced and how it progresses. Generally, it is a balance between terms that are favorable and unfavorable to the triggering and progress of the damage, and depends on the damage level considered. The formulation of the state equation should be fitted to the verification level corresponding to the variant selected.

According to Section 4.4 of the ROM 0.0-01, the format of the verification equation could be "Global Safety Coefficient", Z, or "Safety Margin", S. Generally, the failure modes whose predominant agent is wave train dynamics (e.g. outer perimeter subsystem) has a verification equation in the safety margin format. For failure modes whose predominant agent is the ground soil (e.g. foundation and soil subsystem), the usual equation format is that of the safety coefficient.

The safety coefficient is the quotient of favorable terms, $X_1(x,t)$, and unfavorable terms, $X_2(x,t)$. Positive verification occurs when the safety coefficient exceeds a certain minimum value, $Z(x,t) > Z_c$,

$$Z(x,t) = \frac{X_1(x,t)}{X_2(x,t)} > Z_c \tag{4.1}$$

where t denotes time; and x designates the spatial location and geometry of the component and of the subset in the damage level considered. The values of Z_c depend, among other things, on the nature of the construction, work and operating conditions, and reliability of the equation. Z_c and $Z(x,t)$ are dimensionless values. The safety margin is the difference between the favorable terms, $X_1(x,t)$, and unfavorable terms, $X_2(x,t)$. Positive verification is granted when $S(x,t) > S_0$,

$$S(x,t) = X_1(x,t) - X_2(x,t) > S_0 \tag{4.2}$$

where S_0 is a value greater than or equal to zero. Among other things, it depends on the nature of the construction, work and operating conditions, and the reliability of the equation. If the equation term are dimensional, the S_0 and $S(x,t)$ are dimensional as well.

Time dependence of S and Z and state descriptors

When the predominant agent or agents in the failure mode are climate, soil or seismic agents, among others, the value of the safety coefficient and safety margin varies with the temporal variability of the agents. Strictly speaking, they are thus random variables with a probability model and state descriptors.

Depending on the failure mechanism and formulation of the equation, critical values of $S(t)$ or $Z(t)$ can be out-of-phase with the dominant agent. In addition, the frequency band of its spectral density function can differ from that of the predominant agent.

When the failure modes of the breakwaters are due to wave action, the instantaneous response of the structure as a rigid solid is acceptable. On that assumption, the time series corresponding to the vertical displacement of the free surface as well as to those of the actions and equation terms can be subdivided into a sequence of time intervals, for example, between up-crossing steps (or another equivalent level). For each interval, it is necessary to define random variables, positive and negative peaks, maximum peak value or amplitude, and maximum vertical distance between positive and negative maximums.

The value pairs, time interval-random variable, can be used to form sample sets and infer the probability model and its state descriptors. In addition, for each of them, it is possible to estimate the probability model and the descriptors of the maximum value in the state, depending on the number of value pairs in the sample, which is equivalent to the duration of the state.

If the verification is performed at the beginning of the damage, (except in the durability analysis that focuses on the temporal deterioration of the structural and formal capacity of the component), X_2 is an independent time value even though its value has the same probability of exceedance in all states of the useful life of the construction as long as it does not malfunction, and the damage is not repaired.

Damage level and spatial and temporal evolution of the equation terms

When the project design envisages the evolution of the damage, the verification equation should quantify the balance of the equation terms at the damage level considered. $X_1(x,t)$ and $X_2(x,t)$ should value the action of the predominant agents at the damage level of the component and its response, respectively, where x denotes the spatial location of the component and its geometry with the damage level considered, and t is the time (or state) in which it is verified. For the failure modes of the outer perimeter of the subset, it is customary to use the same verification equation for the different damage levels, including the destruction level. These are considered in the value of the dimensionless monomial that quantifies, for example, the function or stability number of the unit pieces of the main armor level of a sloping breakwater.

4.2.3 Integrated verification of the principal modes of a subsystem

The verification of the behavior and interaction of two or more failure modes of the components of the same subsystem (e.g. toe berm, main armor layer, and superstructure) can be performed, as previously mentioned, either individually or simultaneously. In this case, each verification equation should be integrated in a system that should be simultaneously resolved. When necessary, different restrictions or geometric conditioning factors can be added to the system.

The verification equations should be formulated in the same time domain with the same or different project factors. Accordingly, if the failure modes caused by the same predominant agent occur in different places (e.g. berm subsystem, main armor layer, superstructure), the local values of the state descriptor are then related, depending on the spatial evolution of the predominant agent.

COMMENT

In the current state of the art, there is no technical limitation to the simultaneous formulation and verification (for the same state) of the failure modes of the outer perimeter subsystem, at least until the geometric changes in the section affect the behavior of the agent and the failure modes begin to interact.

During the experiment (composed of various wave train runs), it is customary to take the breakwater section to the destruction level without repairing it and without observing or measuring other failure modes. Generally, the experimental results of the principal failure modes of the outer perimeter of the breakwater independently include the damage evolution curves without accounting for the behavior of the other modes.

However, laboratories are able to conduct experiments to analyze the simultaneous performance of various modes and their simultaneous evolution. To strengthen this type of experimental practice, it is first necessary to minimize scale effects, and secondly, to expand the means and techniques used to observe the temporal evolution of the performance of the components of the breakwater, subset, or subsystem, the measurement of the damage level, and its triggering and progress in the other components.

The simultaneous evolution of the project factors on the outer perimeter of the breakwater and the progressive measurement of damage is necessary to formulate the integral system of verification equations of the principal failure modes of the outer perimeter subsystem.

This knowledge should favor the design of infrastructures with a more reduced first-construction cost, more efficient maintenance and repair strategies, and investments more in accordance with the financial sustainability of the harbor area.

4.2.4 Verification methods

In the context of these recommendations, the assignment of term values and the resolution of the verification equation is performed by using one of the following methods: Level I, Level II, and Level III (see Section 4.10 of the ROM 0.0-01). These methods differ in the way that values are assigned to the equation terms (see Section 2.6.1 of the ROM 1.0-09), the resolution of the equation, and its result.

The choice of method depends on the level of detail and accuracy of the expected results, which depends in turn on the nature of the breakwater and the stage of project development (see Table 4.4 of this section).

A Level I method generally requires less information to assign values. However, its uncertainty is greater, its scope more limited, and the reliability of the project is not well defined. This type of method is advisable at initial stages of project development, and the result can be used as a reference during the rest of the process. Level II and III methods are most suitable when project objectives entail the following:

- adaptation of total costs to budgetary resources and the financial sustainability of the investment project;
- minimization of uncertainty and maximization the reliability of the construction project;
- decision-making, based on the acceptable risk level of the investment project.

In all cases, it is necessary to specify the conditions to be satisfied in order to declare or not declare the damage level analyzed. When the equation result does not exceed a minimum value of the safety margin or safety coefficient, operational failure or stoppage is said to occur. The minimum values are specific to each way of formulating and resolving the equation despite shared compatibility relations.

COMMENT

In certain technical texts (e.g. Eurocodes), the global safety coefficient methods are classified as Level 0, and partial coefficient methods are classified as Level I.

Assignment of values in a verification equation

Depending on the criterion used to assign values to agents and actions, the terms of the verification equation, $X_1(x,t)$ and $X_2(x,t)$, can take the following types of value: (a) values that continuously vary over time (time series); (b) discrete values at finite time intervals; (c) a single value in the state. For (b) and (c), values could be state descriptors or characteristic values, multiplied or not multiplied by weighting coefficients. This determines the quantity, quality, and type of initial information, and conditions of the verification method to be applied. Generally, the application of Level I methods are based on deterministic and semi-probabilistic criteria. In contrast, Level II and III methods are linked to semi-probabilistic and strictly probabilistic criteria.

Deterministic criteria

The values are nominal and chosen for technical reasons, based on experience or on other considerations. Neither the variability nor the random nature of the agents and parameters of the physical environment is quantified. The safety margin and safety coefficient take higher values as the uncertainty of the equation and the data increase, and whether the terms were affected by weighting coefficients (Chapter 5 of the ROM 0.0-01).

Semi-probabilistic criteria

The magnitudes of the agents and equation terms (particularly, those of the seismic and climate physical environment, use and exploitation, and soil) are characteristic values, based on their respective marginal, conditional, or joint probability models. If the value of the predominant agent is assigned, based on its probability of exceedance in the project phase, the safety margin should be positive and the safety coefficient should be greater than or equal to the unit.

Probabilistic criteria

The term values of the equation are a result of its own resolution process, taking into account the marginal, conditional, or joint probability models of the participating agents and parameters. The safety margin is positive or equal to zero, and the safety coefficient is equal to the unit.

Result of the state

The result, $S(t)$ or $Z(t)$, of the resolution of the verification equation depends on the time scale of the variables that intervene in the terms $X_1(t)$, $X_2(t)$. The criterion used to declare or not declare the verification of the failure mode is whether these values, one of the statistics, or a deterministic value is greater than or equal to a critical value, $S_{min} > S_0$, $Z_{min} > Z_c$. Generally, critical values are specific to each verification method.

Deterministic values and the Level I method

If deterministic values are assigned and the equation is resolved by a Level I method, the result of the equation is a value of the safety margin or safety coefficient. The mode is verified if the values are greater than or equal to the critical values specified for that failure mode or limit state with the criteria and combination of factors and terms adopted for a work condition in the project phase.

State descriptors and Level I, II, or III methods

If it is a question of the state descriptors of the predominant agents (e.g. maximum wave height in the state or of the terms), the result of the equation is a safety margin or safety coefficient value associated with that descriptor. This value is compared with the specified critical value. In this case, the probability that the failure mode will occur at least once in a given time interval (e.g. project phase) can be approximated by means of the product of the probability that in that time interval, the values of the predominant agents will be exceeded by the probability that once the state occurs, the failure will occur.

If the probability model of the state descriptors of the predominant agents is known, it is then possible to analytically or numerically calculate the distribution function (derived function) of the safety margin or safety coefficient, and use this information to obtain the probability of exceedance of the critical value.

If there is no duly calibrated verification equation, formulated with the state descriptors of the predominant agents, but there is an equation obtained with regular wave trains, the distribution function of the equation terms (and of the result, safety margin, or safety coefficient) can be resolved by applying the hypothesis of equivalence between actions due to regular and irregular wave trains.

Time series and Level II or III methods

If it is a question of the time series of equation terms, and the equation is resolved a significant number of times with the different time sequences of the agents, it is possible to infer the probability models of high-peak random variables and their maximum and minimum value in the state, and the distribution function of the minimum values of the safety margin or safety coefficient. This information can be used to estimate the probability that the critical value, S_0 or Z_c will be exceeded.

COMMENT

The description of the waves in a state in the time and frequency domains is described in Chapters 3 and 4 of the ROM 1.0-09. This description is based on the formulation of the waves at one location as a stationary random process. The vertical displacement of the free surface is a Gaussian variable. The crests (positive peaks) and troughs (negative peaks) between two upcrossings through the mean level follow a Rayleigh distribution. Very generally, the probability model of the wave height is the Rayleigh distribution of the root mean square wave height or other statistics (e.g. significant wave height or its correspondence in the frequency domain proportional to the square root of the zero-order moment of the energy spectrum). Assuming the statistical independence of successive waves, the maximum wave height in a state with N waves follows a Rayleigh distribution to power N.

With these assumptions, the wave action, terms of the verification equation, and when applicable, of the safety margin and safety coefficient can be described similarly to the wave train dynamics. In certain cases, particularly with non-linear verification equations, the time series can have other temporal, harmonic, and subharmonic scales of wave frequencies.

To facilitate verification, it is best to reduce the number of project factors in the terms of the verification equation. In the case of probabilistic methods, the ordering of the factors helps to simplify the verification methods, whereas in the case of deterministic verification methods, this organization is strictly necessary. It is advisable to apply the procedure explained in Sections 4.7 and 4.8 of the ROM 0.0-01.

Assignment of values and results in an integrated verification (equation system)

To simultaneously verify the principal modes, for example, of a subsystem, all of its equations should be formulated in the same temporal domain (meteorological state) and with the same method (Level I, II or III). The assignment of values in each verification equation should follow the previously mentioned guidelines. The resolution of the equation system indicates whether all of the failure modes of the system are safe in that state.

COMMENT

Formally, the actual verification procedure assumes the following: (1) independence of the behavior of each principal mode; (2) absence of interaction between these modes, even when one or various of them have been triggered and/or the damage has evolved; (3) representativity of a verification equation even though it has been obtained in different conditions from those of the project. The confidence in the result is based on the assumption that if the elements in each mode are given values worse than those of the predominant agents, the structure thus calculated is reliable. In other words, it is assumed that the set formed by the "supposedly worst" results for each mode is a satisfactory point for the project design.

In the current state of the art, it is possible to apply an integrated verification even with different damage levels for each principal mode of a subsystem. The main difficulty does not reside in the procedure, but rather in the coherent selection between the wide range of equations with which it is possible verify each failure mode, These equations are mostly obtained in experiments performed with specific (and differentiated) criteria of each laboratory.

An integral verification by states, even based on the previous assumptions, with concurrent values of shared agents and simultaneous values for non-shared agents (assigned by a method of partial coefficients or coefficients based on the joint probability function) offers a design with the greatest potential for the technical-economic optimization of the subset and the associated joint failure probability.

Furthermore, if this verification is based on integrated experimentation with compatible equations and the assignment of concomitant (compatible and simultaneous) values of the agents, actions, and terms, the reliability of the design and the total costs should be greater.

4.3 VERIFICATION OF THE MODES FOR THE SUBSET AND PROJECT PHASE

To verify compliance with the project phase objectives of the breakwater, it is necessary to extend the verification and, when necessary, the failure or stoppage probability from the spatial scale of element and temporal scale of state to the spatial scale of subset and the temporal scale of project phase (see Article 4.1.1).

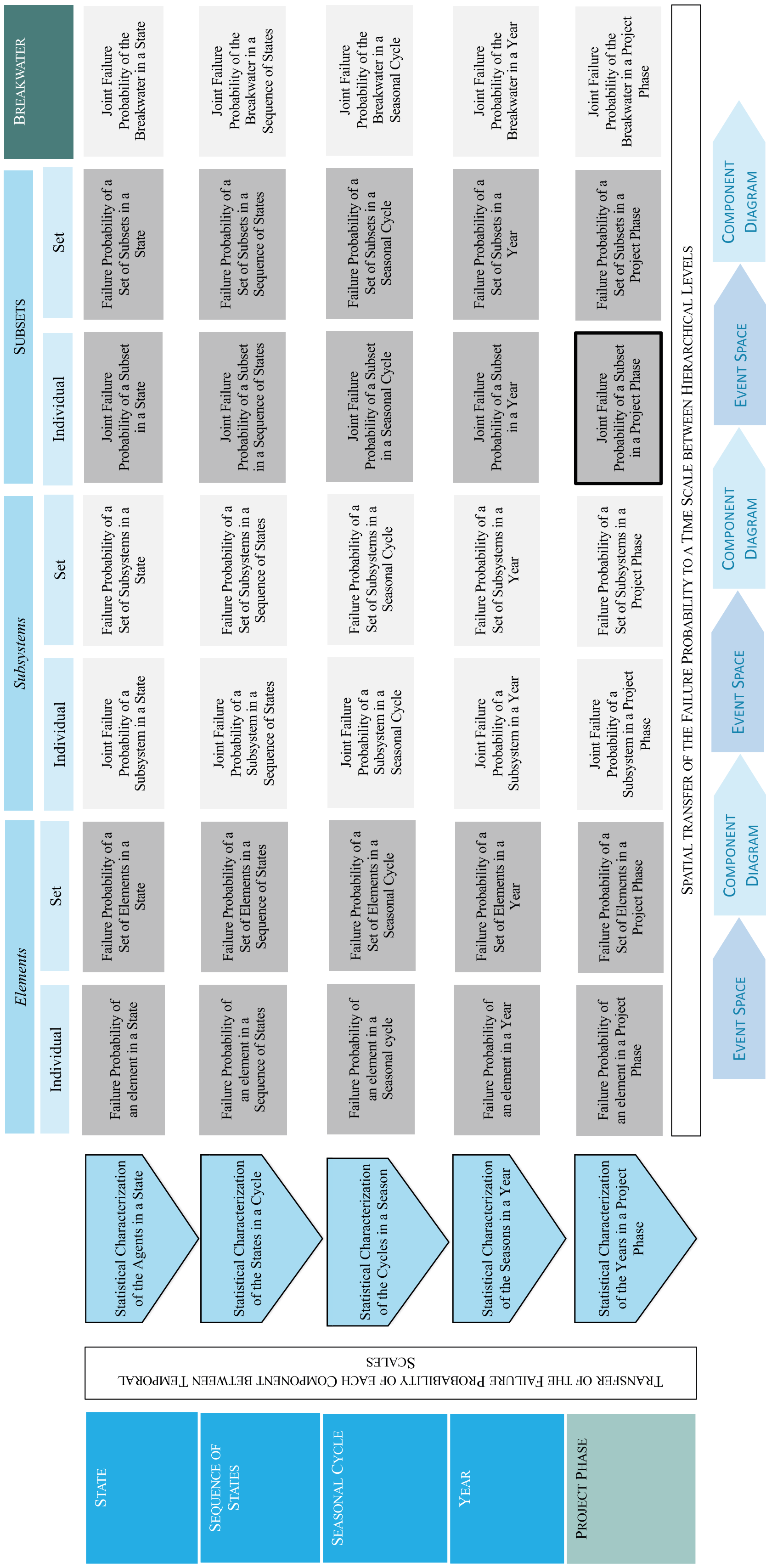
4.3.1 Spatial and temporal scales for the verification of project requirements

Based on its definition and formulation in the state, this ROM 1.1-18 proposes the following sequence of time scales:

(a) Format of the state equation and state variables
(b) Random loading cycle
(c) Random sequence of loading cycles
(d) Groups of years
(e) Useful life and other project phases

This movement from one scale to another depends, among other things, on the equation format and the participating state variables. It also depends on the method and project development stage. In particular, the evaluation of the probability at different spatial scales in a given time period should be based on the following: (a) joint probability models of the different failure or stoppage modes in the time interval considered; (b) criteria describing the failure lines, their progression, and triggering; and (c) component diagrams that express the combination of elements in the event space that assumes the non-compliance of higher-order components with the project requirements.

Figure 4.1: ***Relations between spatial and temporal scales for the verification of a breakwater***



4.3.2 Recommendations for verification with Level I methods

Level I methods include methods of the global safety and partial safety coefficients, as described in Chapter 5 of the ROM 0.0-01. In both cases, the project factors and term values are established with deterministic or semi-probabilistic criteria.

Level I methods are based on important simplifications of the reality. This reality is taken into account by means of coefficients that affect project factors in the calculation states. Generally, they do not consider the damage level and define repair strategies in very basic terms (immediate repairs or non-repair).

Selection of the calculation states and work and operating conditions

The verification equation should be formulated for certain combinations of agents and actions that can intervene in the occurrence of the mode and which depend on the following work and operating conditions (WOCs) (ROM 0.0-01, Section 4.5):

(a) WOC_1, normal work and operating conditions that include the possible states in which the probability of operational stoppage is very small or where the actions of concomitant agents have a joint failure probability in relation to safety that is small though not negligible.
(b) WOC_2, extreme work and operating conditions that integrate all possible states in which the failure probability in relation to safety and serviceability is not negligible.
(c) WOC_3, exceptional work and operating conditions that include related possible project states whose probability of occurrence is small and significantly less than that corresponding to extreme work and operating conditions, due to exceptional use and exploitation reasons or because of unforeseen or accidental environmental causes. These causes should be the focus of the corresponding accident rate analysis as commented in Section 5, Article 5.6.

The selection of the project values of the predominant agents in semi-probabilistic formulations should take the following into account.

Characteristic states of extreme or exceptional work and operating conditions

The selection of states is based on joint extreme regimes of the principal agents of each mode. When there are no joint regimes, then it is necessary to use marginal extreme regimes of the leading agent and conditional regimes of the agents that depend on it.

The selection depends on the probability of exceedance in the project phase. This probability should be less than or equal to the probability value that corresponds to the project requirement for the mode, based on the distribution of the joint probability considered.

The definition of the probability of exceedance is based on the exceedance of some or all of the variables considered, depending on their participation in the mode.

Characteristic states of normal operational conditions

The selection of states is based on the joint mean regimes of the principal agents of each operational stoppage mode. When there are no joint regimes, then it is necessary to use the marginal mean regimes of the leading agent and the conditional regimes of the agents that depend on it.

The selection is based on the following:

(a) probability of exceedance in the project phase, which should be less than or equal to the probability value corresponding to the project requirement for the stoppage mode based on the joint probability distribution considered.
(b) frequency and duration of the stoppages that should be less than or equal to the values in the project requirements.

The definition of the probability of exceedance is based on the exceedance of some or all of the variables considered, based on their participation in the mode. If work and operating conditions are defined by combinations of concomitant agents, the selection of states depends on the compatibility of the limits and of the operational thresholds that occur simultaneously.

Conditions of the compatibility and simultaneity of the actions

The conditions of the compatibility and simultaneity of the actions in the verification can be specified by means of weighting coefficients that generally depend on the work and operating conditions in which the verification state is framed. These factors should follow the recommendations in the ROM 0.0-01, Chapters 4 and 5, and alternatively in the ROM 0.5-05 for ground soil failure modes. If these factors are not available, they should be previously calibrated so that they comply with the requirements in this ROM. In the case of project factors regulated by other regulations and instructions, the factors should be determined according to the provisions in them.

Joint probability in relation to the principal modes

The resolution of the verification equation only informs whether the failure or stoppage occurs in the state considered, according to its failure or stoppage criteria, application hypothesis, and uncertainty.

If the verification equations are formulated with deterministic criteria, the method does not provide information regarding the probability of non-compliance with project requirements.

If the verification equations are formulated with semi-probabilistic criteria, the probability of occurrence of the mode in the time interval is linked to the criteria adopted to define the representative values of the project factors, partial coefficients, and safety coefficients considered. More specifically, as an approximation at this project development stage, the probability of exceedance of the predominant agent or agents in the occurrence of the mode can be taken as its probability of occurrence. The joint probability in relation to the principal modes is calculated in consonance with component diagrams, based on the following:

(a) Hierarchical structure of the breakwater.
(b) Logical relations that relate the occurrence of modes with the stoppage or failure of the subset: serial (probability of intersection), parallel (probability of union), or mixed.
(c) Probabilities of each mode in the project phase and their dependency relations.
(d) Repair strategies of the damage.

4.3.3 Recommendations for verification with Level II and III methods

Level II and III methods can be used to evaluate the probability of occurrence of a mode in a time interval, based on the statistical models of the project factors of the verification equation. Level II methods use a simplified procedure based on the functional transformations of these factors expressed as independent and reduced Gaussian variables. Level III methods evaluate that probability by numerically or analytically integrating a multidimensional function in the domain of occurrence of the modes.

For the verification of the project requirements by means of probabilistic methods, the following options should be considered:

(a) event sequences (Level II or III methods)
(b) non-stationary simulation (Level III method)

Event sequences

This procedure is based on the division of the project phase in independent event sequences (time intervals), characteristic of extreme conditions (verification of reliability) or normal operational conditions (verification of operationality) that load to the mode. The number of events of this type in the project phase could be a deterministic variable (e.g. if the block maxima method is applied) or a random variable (e.g. if the block maxima method is applied by calm or loading cycles), see Chapter 7 of the ROM 0.0-01. This procedure can have the following sequence:

1. Characterization of the joint distribution of project factors in the worst conditions (usually peaks) for the non-occurrence of the mode considered.
2. In the case that the number of events in the project phase is a random variable, characterization of its probability function.
3. Resolution of the probability of occurrence of the mode in one of these events with Level II or III methods.
4. Calculation of the probability of occurrence of the failure mode in a project phase, considering its probability of occurrence in an event and probability model of the number of events in the phase.
5. Calculation of the probability of occurrence of the stoppage mode throughout a project phase, considering, in addition to the previous information, the duration of the time interval in which stoppage conditions are maintained.

Verification during the structure's useful life

The joint probability in relation to the principal modes is calculated in consonance with the component diagrams, based on the following:

(a) Hierarchical structure of the breakwater.
(b) Logical relations that relate the occurrence of failure and stoppage modes of the subset: serial (probability of intersection), parallel (probability of union), or mixed.
(c) Probabilities of each mode in the project phase and their dependency relations.
(d) Repair strategies of the damage.

COMMENT

This approximation does not include the sequence of occurrence and propagation of the modes or the time dependencies of possible events (e.g. triggering, waiting periods, etc.). Maintenance and repair strategies are simply specified (e.g. binary, non-repair/immediate repair).

Non-stationary simulation of the project phase

With this procedure, it is possible to incorporate the result of the damage evolution and its spatial propagation as well as the result of maintenance and repair strategies. It is based on the following: (a) generation of sequences of states that encompass the entire project phase; (b) the resolution of the verification equation of each model in all of them. The verification of compliance with project requirements is outlined as follows:

1. Generation of time series of the dynamic and kinematic variables of water, wave dynamics, velocity, accelerations, and pressures.

2. Generation of wave sequences and their phase-integrated actions (period).
3. Generation of sequences of state variables, agents, and actions.
4. Verification in each state of the following: (a) failure and stoppage modes; (b) propagation of damage and triggering of new modes; (c) repair process.
5. Verification of project requirements during the structure's useful life.

Based on the probability models of the agents, sequences of states are numerically generated. In these sequences, the descriptors of the variables should be adapted to the following: (a) their joint probability distributions; (b) temporal variability scales, including foreseeable global warming tendencies; (c) temporal dependency of the values in each state on those of the preceding ones.

The time domain of the simulations is generally the project phase to be verified. Nevertheless, to avoid an excessive number of operationality and reliability verifications, it only necessary to simulate the calm and loading cycles, respectively. In these cases, it is best to characterize the frequency of the cycles and the time interval between them with their corresponding temporal variation scales.

Verification of the subset and breakwater by means of a sequence of states

The state-by-state verification of the construction should be performed as follows:

(a) Transformation of the agents in the presence of the structure.
(b) Verification of the operationality conditions of the subset (see Article 2.3.2).
(c) Verification of the initiation of damage in the different modes and the progression of the damage (see Articles 2.3.2 and 2.4.1).
(d) Spatial progression of the damage and the triggering of other modes (see Article 2.6).
(e) Evaluation of the consequences of the failure of each higher-order component (see Article 2.3.4).

In addition, once the repair strategy has been defined, it is necessary to evaluate whether the conditions are appropriate to begin the work, and if the repairs can be performed with the available resources, tools, machinery, etc. (see Article 3.7).

COMMENT

The values assigned to the project factors of the verification equations and the damage evolution in the different modes should be consistent with each other. As previously mentioned, the set of principal modes of the subsystem should be simultaneously verified in each state. This course of action signifies that the climate and soil agents that interact with the breakwater are the same, and that the values in their respective verification equations are locally determined, according to their position and subset type.

Verification in the structure's useful life

Each simulation obtains the result of the verification of the different project requirements, more specifically, a Bernouilli event indicating whether there has been a failure in the subset, the percentage of time that the subset has been exploited, and the average number of stoppages in a reference time interval (usually, one year). A sufficient number of repetitions of the project phase should be simulated to ensure the required level of statistical significance. The set of results obtained then constitutes a sample of independent values.

An estimate of the joint probability of failure (or stoppage) in the structure's useful life is the relative frequency of failures (or stoppages) in the simulations.

4.3.4 Verification of exceptional work and operating conditions, WOC_3

The verification of a breakwater design in exceptional work and operating conditions has specific and differentiated treatments, depending on their cause. If the causes are foreseeable, $WOC_{3,2}$, for reasons of use and exploitation, the structure should be verified by temporarily reinforcing the structure. The simultaneous and compatible values of the agents and actions in the verification equation are adopted, depending on the nature of the structure and its control mechanisms.

On the Spanish coastline, there is generally no need to verify the design of the breakwater against seismic and tsunami agents (see ROM 1.0-09). Nevertheless, depending on the nature of the structure and the investment project, it may be necessary to verify the breakwater and its subsets against an earthquake or tsunami. Both agents are usually assigned to exceptional accidental work and operating conditions of the physical environment $WOC_{3,1,1}$. In these conditions, the following failure modes should be verified in the three sections of the breakwater:

(a) Foundation and ground soil and central body: superficial and deep sliding.
(b) Central body and superstructure: overtopping without failure of the superstructure and its consequences (on the inner slope, mooring area, etc.).
(c) Superstructure: sliding and overturning of the superstructure.

In these cases, it is necessary to consider the actions caused by the dynamic pressures during an earthquake or tsunami. Its establishment and formulation should follow the recommendations in the ROM 0.5-05.

The project values of the seismic agent should be in consonance with regulations currently in force in Spain. The hydrodynamic characteristics of the earthquake are selected based on the requirements of the exceptional work and operating conditions.

When the probability of exceedance of the value of each agent (earthquake and tsunami) is lower than 10^{-4}, it is then regarded as a non-principal mode. When this is not the case, the design conditions should be specified a priori, and the following should be considered: (a) characteristics of the structure; (b) probability of occurrence of the earthquake and tsunami; (c) minimum reliability and operationality to be guaranteed once the event has occurred.

Depending on the nature of the structure and the investment project, it may be necessary to verify the accidental, unforeseen, exceptional work and operating conditions, $WOC_{3,1,2}$. According to Section 5, Article 5.6, this verification should be performed as part of an analysis of the accident rate.

EXAMPLE

DISTRIBUTION FUNCTION OF THE SAFETY MARGIN IN A BREAKWATER WITH A FRONTAL OSCILLATING CAMERA

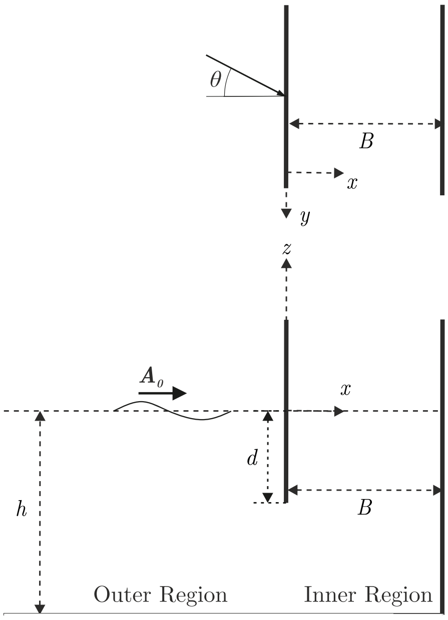
In a meteorological state, the wave train dynamics at the breakwater site varies over time. The water flow and forces on the breakwater subsets, parts, and elements also vary. The formulas to determine their value, the verification equations of the corresponding failure and stoppage modes, and their resolutions can be presented at different temporal variability scales of the agents and actions.

For example, let us consider an infinitely long breakwater (y axis), composed of an impermeable, slender, vertical slab, at a distance B from an impermeable vertical wall. This is at a relative submergence ($d/h = 0.64$), separating the outer region (region 1) from the inner region (region 2), as can be observed in Figure 4.2. The freeboard of the slab and wall is sufficient so that the vertical movement of the water column is not limited. The water depth is constant in the entire work domain (Figure 4.2).

Hydrodynamic performance and calculation model

The waves that obliquely impinge on the slab are reflected on it and are transmitted to the inner region through the opening underneath the slender slab. There the waves are reflected on the vertical wall. One part of the reflected energy escapes (irradiates) towards the outer region and the other is re-reflected towards the wall, and thus, successively. The oscillatory flow to pass from one side of the slab to the other alternatively converges and diverges, forming vortexes and dissipating energy in the process.

Figure 4.2: ***Diagram of the structure***



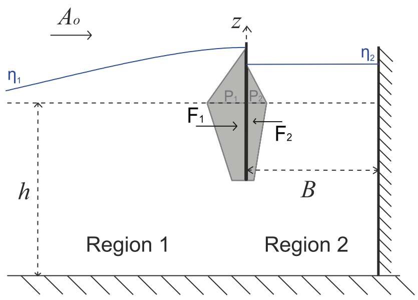
The hydrodynamic performance of the system is obtained by resolving the problem of the boundary of the mass conservation equations in both regions, boundary conditions at the free surface boundary and the bottom, and the flow compatibility conditions in the opening, considering energy dissipation. The problem is resolved for each of the sinusoidal components of the random phase. Each component is characterized by a certain frequency and amplitude from a JONSWAP energy spectrum.

The result of the model is the temporal variation of the free surface of the sea in the outer regions, $\eta_1(t)$, and inner region, $\eta_2(t)$. Applying linear wave theory, the temporal evolution of the pressure field, $p_k(z,t)$, on one side and the other of the slab, depending on the free surface η_k,

$$P_k(z,t) = \begin{cases} \rho_\omega g \left(\frac{coshk(h+z)}{coshkh} \eta_k - z \right) & z < 0 \\ \rho_\omega g \left(\eta_k - z \right) & z > 0 \end{cases} \quad k = 1,2 \tag{4.3}$$

where $k = 1,2$ identifies the inner and outer regions, respectively.

Figure 4.3: ***Diagram of the hydrodynamic variables of the study***



Integrating the respective pressure laws of each region in $x = 0$ (equation 4.3), from the foot of the slab, at depth d, to the free surface ηk, the result is the temporal evolution of force per unit of width in each of them (Figure 4.3). The temporal evolution of the resulting force or total force on the slab is obtained as the difference between both forces,

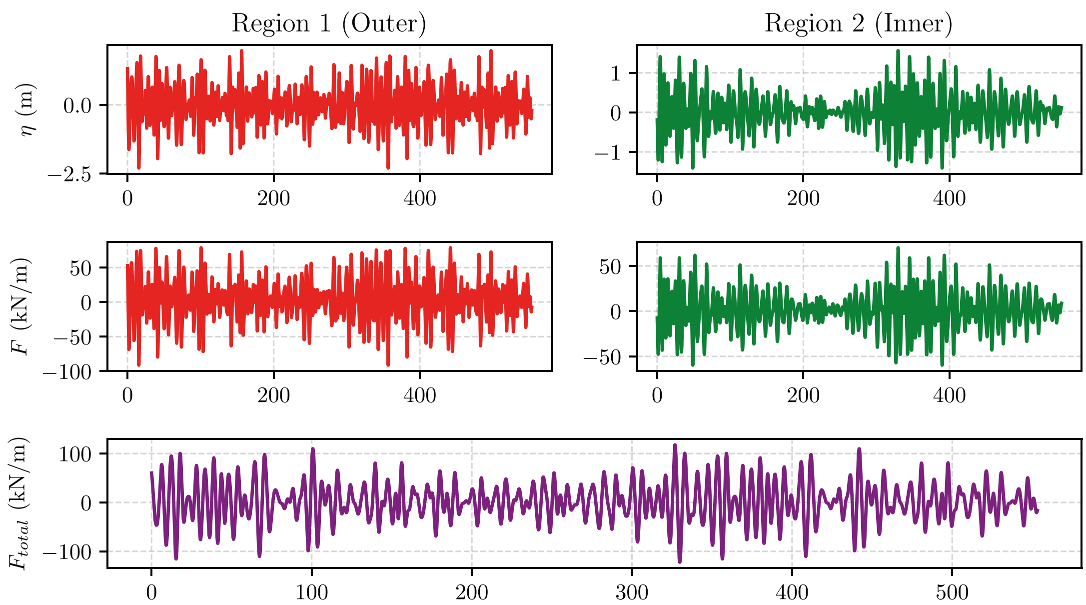
$$F_t(t) = F_1(t) - F_2(t) = \int_{-d}^{\eta_1} P_1(z,t)dz - \int_{-d}^{\eta_2} P_2(z,t)dz \tag{4.4}$$

The total direction of the force, $F_t\ (t)$, oscillates landward-seaward, based on the lag (difference) between the vertical displacements of the free surface from one side to the other of the slab. In the time series of the force, it is possible to identify the up-crossings, and in the time interval elapsed between two consecutive zeroes, to take the highest positive peak (landward F_{land}), and the greatest negative peak (seaward, F_{sea}).

Probability models and state descriptors

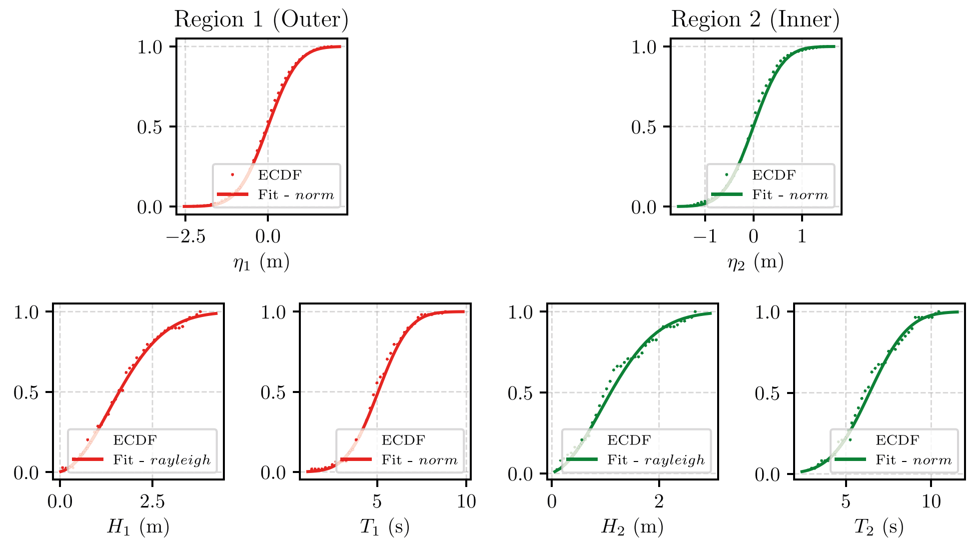
For example, a time record of irregular wave action is generated, according to a JONSWAP-type spectrum. It has γ = 1 at a depth of 10 m; mean wave period of T_z = 11 s; significant wave height H_{m0} = 7 m; and duration ≈ 3000 s (350 waves). Figure 4.4 shows the time record of the free-surface elevation and force in the two regions as well as the total force during the first 700 s.

Figure 4.4: Time series of the free surface and force in the regions defined and the total force on the structure



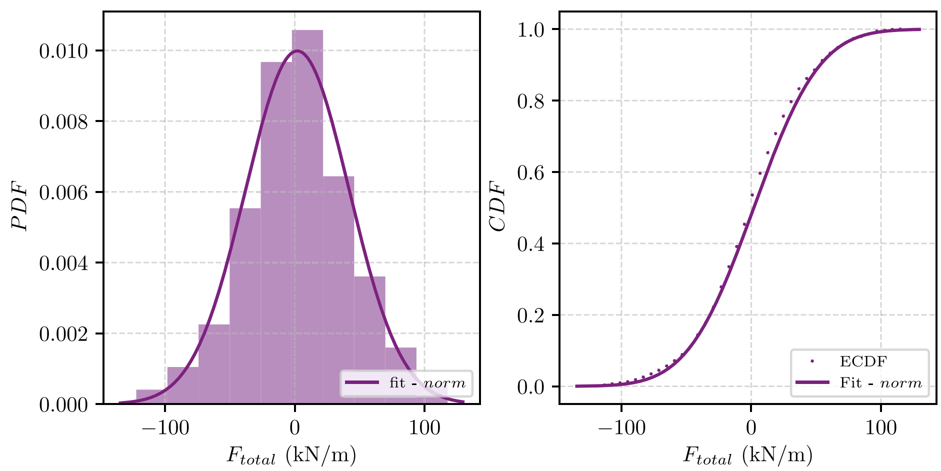
As can be observed in Figure 4.5, the vertical displacement of the free surface in both regions shows a Gaussian behavior (σ_{η_1} = 1.49 and σ_{η_2} = 1.2). The distribution function of the wave height in each region is fitted to a Rayleigh distribution function (σ_{H_1} = 2.91 and σ_{H_2} = 2.13). The individual number of waves in the outer and inner regions is respectively 358 and 342, (slightly higher and lower than the number of waves in the incident wave train).

***Figure 4.5:* Cumulative distribution functions of the free surface, wave heights, and wave periods in defined regions**



The resulting force is the difference between the two Gaussian random variables. For this reason, it is also a Gaussian variable (μ_{F_t} = 5.83 and μ_{F_t} = 112.93), as shown in Figure 4.6.

***Figure 4.6:* Probability density and cumulative distribution functions of the total force on the structure**



The positive and negative peaks of the resulting force, obtained by identifying the up-crossings (Figure 4.7) are fit to a bi-parametric Weibull function of shape and scale ($k_{F_{land}}$ = 1.47, $\lambda_{F_{land}}$ = 157.64) and ($k_{F_{sea}}$ = 1.52, $\lambda_{F_{sea}}$ = 145.78), respectively (Figure 4.8). The value of the shape parameter is lower than the corresponding value of the Rayleigh function, k = 2. The number of up-crossings in the time force series is approximately equal to that of the waves (350).

***Figure 4.7:* Zero up-crossings in the time series of the total force and (landward) positive peaks and (seaward) negative peaks in each of them**

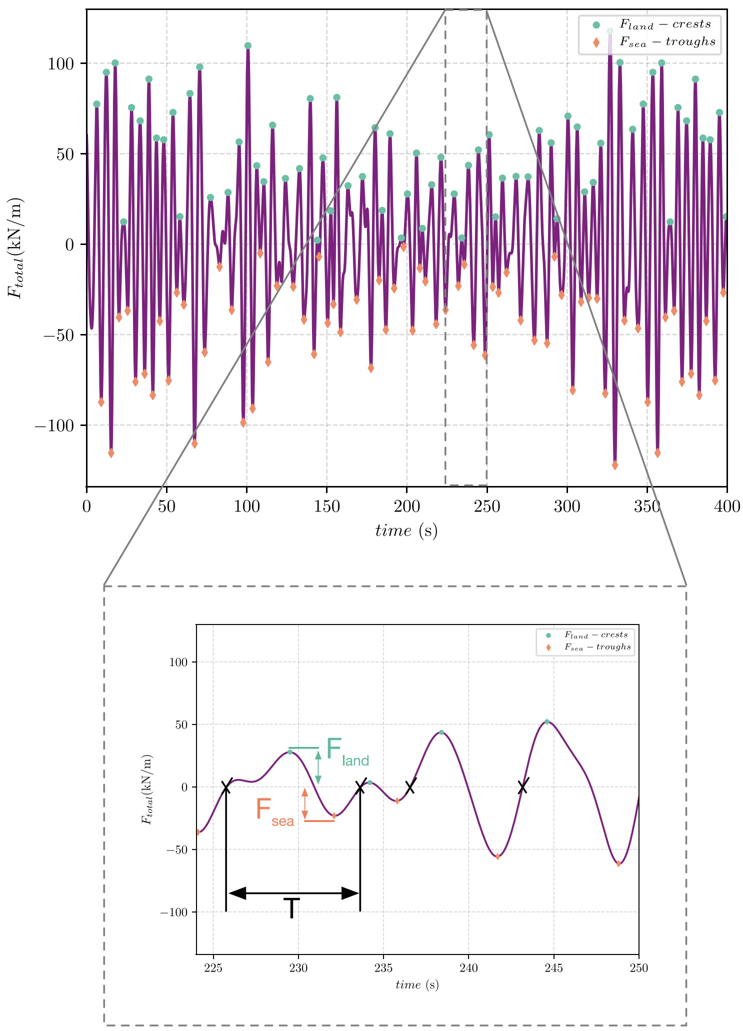
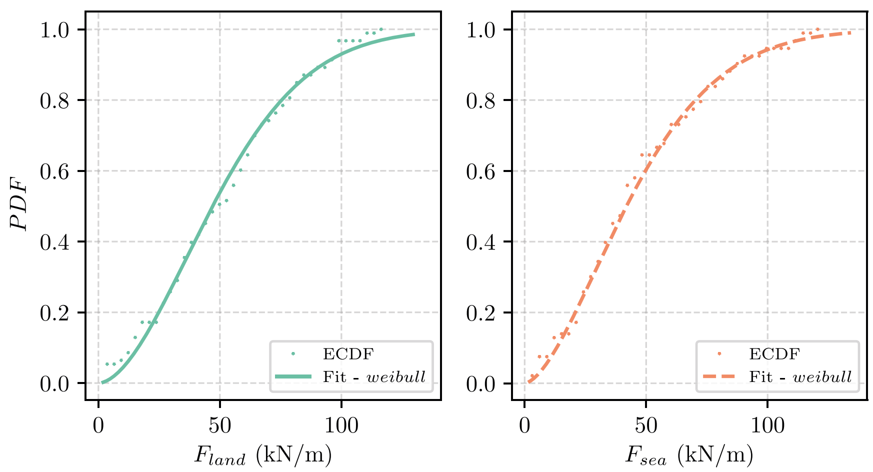


***Figure 4.8:* Cumulative distribution function of the landward force peaks and seaward force peaks**

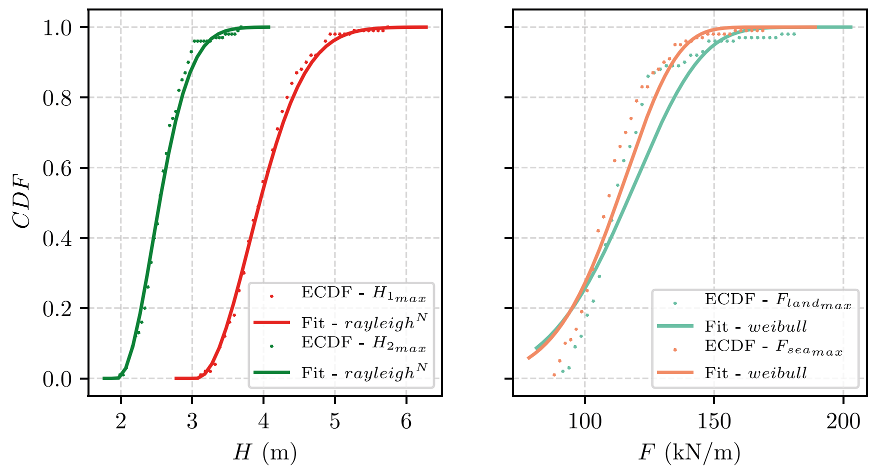


The comparison of the time series of the vertical displacements in each region with the time series of the resulting force shows that the peaks over the structure (F_{land} and F_{sea}) are not concurrent with the free surface peaks on both sides of the slab. The force on both sides of the slab is fitted to a Weibull distribution function with shape parameter $k \approx 1.5$.

Maximum landward and seaward force

The simulation of M time records of waves provides a sample of the values of the random variables $F_{land_{max}}$ (maximum landward force in each simulation) and $F_{sea_{max}}$ (maximum sea-ward force in each simulation).The values of both samples have a Weibull distribution (Figure 4.9) of parameters of ($k_{F_{land_{max}}} = 7.07, \lambda_{F_{land_{max}}} = 357.12.09$) and ($k_{F_{sea_{max}}} = 7.12, \lambda_{F_{sea_{max}}} = 335.99$).

***Figure 4.9:* Cumulative distribution functions of the maximum wave height values and the values of the maximum landward and seaward forces in each simulation**



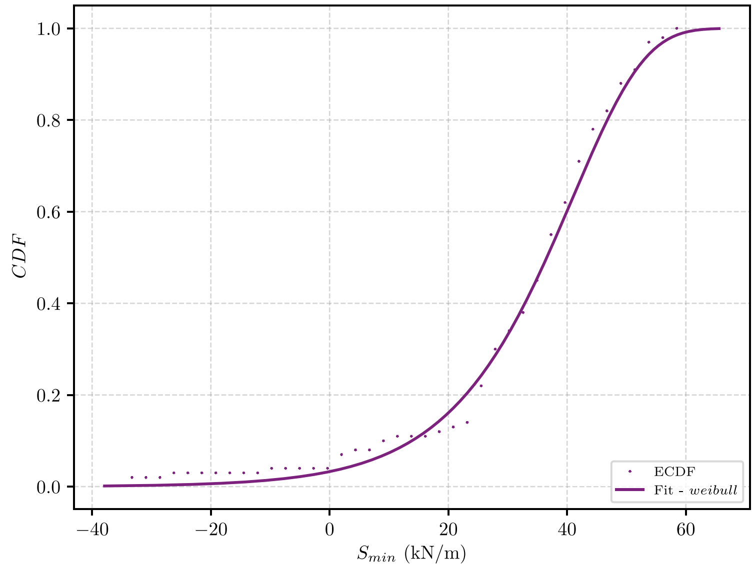
Verification equation

If the total force peaks had been a Rayleigh distribution, the distribution of the maximum landward peak and seaward peak in M peaks would have been $F(Rayleigh)^M$.A verification equation of the shear failure mode of the front slab, formulated as a safety margin (difference between favorable and unfavorable terms) is the following:

$$S = r - F_c \tag{4.5}$$

where S is the safety margin, which should be positive and defines the failure; r is the shear resistance of the slab; and F_c is the calculation value of the maximum landward or seaward force. Assuming that r is constant and equal to 150 kN/m, the minimum safety margin value is calculated in each simulation. Figure 4.10 shows the minimum safety margin values in each simulation, along with the distribution function of the best Weibull fit, $k_{S_{min}} = 2.89$, $\lambda_{S_{min}} = 128.8$. The probability that $S \leq 0$ during the meteorological state is 0.06. The probability of shear failure in the slab is $S \leq 0$ on the condition that in a certain time interval (useful life), the design meteorological state will be exceeded at least one time.

Figure 4.10: ***Cumulative distribution function of the minimum value of the safety margin in each simulation***



The formulation of the problem and its resolution are given in Jalón et al., 2018.

4.4 VERIFICATION METHODS AND PROJECT DEVELOPMENT STAGE

The verification method depends on the nature of the subset and project development stage. According to Section 4.10.4 of the ROM 0.0-01, the verification method of the construction project depends on the ERI and SERI of the subsets of the breakwater. If there are different methods, depending on the subset, the verification method of the breakwater construction project should be the method for the subset with the highest ERI and SERI values. Table 4.6 specifies the recommended resolution method, depending on the ERI and SERI indexes.

Table 4.6: ***Recommended resolution based on the general nature of the subset***

	ERI			
ERI	Non-significant	Low	High	Very High
Low	[1a]	[1b]	[1b] y [2] o [3]	[1b] y [2] o [3]
Medium	[1b]	[1b]	[1b] y [2] o [3]	[1b] y [2] o [3]
High	[1b] y [2] o [3]	[1b] y [2] o [3]	[1b] y [2] o [3]	[1b] y [2] o [3]

where

- Level I: [1a] Global safety coefficient or safety margin, [1b] Partial coefficients;
- Level II: [2] Statistical moments and optimization techniques;
- Level III: [3] Integration and numerical simulation.

COMMENT

Level I, II and III methods are of increasing complexity, but of decreasing uncertainty. The methods indicated should be understood as the minimum recommended, but if more information and practical experience are available, then the structure could be verified at a higher level. Nonetheless, the use of a Level I method is recommended in all cases, at least during the initial stages of project development as a starting point for the design and sensitivity analyses, and as a reference that can be used to evaluate the results.

4.4.1 Verification methods, depending on the project development stage

The verification method in each project development stage depends in turn on the nature of the structure and the project class (Figure 1.8, Section 1, Article 1.4.1).

In the case of projects with a medium or low ERI and SERI, and for Class I projects that do not require an investment project, the preliminary studies and the study of alternatives and solutions can be verified with Level I methods. The study of alternatives and solutions leads directly to the elaboration of a construction project and its implementation with these same methods.

For projects with a high ERI and SERI, and for Class II projects that require an investment project, the preliminary studies and the study of alternatives and solutions can be verified by Level I methods. However, the draft project and the construction project of the adopted solution should also be implemented with Level II or III methods. In these cases, it is advisable to analyze and compare the Level I designs with the Level II or III probabilistic methods.

Formulation in Level I methods

If the predominant agents are climate and seismic agents, a deterministic formulation should only be applied in the preliminary studies. The agents should have nominal values selected from their probability model, either by delimiting their probability of exceedance or by using another equivalent criterion. For other stages of project development, the formulation of the predominant climate and seismic agents and their actions should be semi-probabilistic.

4.4.2 Working hypotheses and simplifications, depending on the stage of project development

For breakwaters whose construction project also requires verification with Level II or III probabilistic methods (apart from Level I methods), the following working hypotheses and simplifications can be adopted. For Level I methods, additional simplifications should be adopted in consonance with the stage of project development.

Preliminary studies

WORKING HYPOTHESES

Preliminary studies should consider the following work hypotheses:

(a) The relations between the failure of the different hierarchical levels of the construction should be defined in component diagrams as well as the hypotheses of mutual exclusion and dependence.
(b) Verification should be simultaneously performed in the entire set of principal modes, organized according to their spatial distribution and location in consonance with the hierarchy of subsets and subsystems.
(c) The values of the agents in the verification equations should be the result of the interaction of the events with the different subsets and subsystems of the structure.

To compare Level I designs with Level II or III designs, it is necessary to additional simplify the Level I method in consonance with the project development stage

Simplification hypotheses

The following simplification hypotheses can be applied to the preliminary studies:

(a) The verification of the elements in the main alignment can be performed with a reduced number of (dominant) modes and good practice standards can be applied in the others.
(b) For all practical effects, the failure of one component should lead to its destruction and the need to reconstruct the subset to satisfactorily recover project objectives.
(c) The probability of occurrence of a dominant mode can be regarded as equal to the probability of presentation of the predominant agents that produce the mode.
(d) Repair strategies can be defined in simple terms of immediate repair or non-repair.
(e) In regard to subsets not in the main alignment, it is sufficient to verify compliance with standards of good practice in their geometric relations with the main alignment and the physical characteristics of the subset.
(f) Potential global warming effects should also be considered by simply adopting reasonable sea level values during the breakwater's useful life and the estimates of competent organisms.
(g) The advancement of construction work and its cost should only depend on the typology of the subset and its dimensions.

For each layout and typology considered, the principal failure modes should be defined, and their relations with the failure of the entire subset depicted in a component diagram (see Article 2.3.4). The dominant modes should be identified from the set of principal modes. The failure probability distribution in the structure's useful life can be performed for the dominant modes, based on the component diagram and hypothesis of mutual exclusivity and interdependence of modes, and in any case, making use of duly justified reference values (see Article 3.5).

Verification of reliability

Verification of reliability can be performed with Level I methods in a reduced number of charac-teristic states in extreme work and operating conditions, which the structure is subject to. These should be selected so that the probability of failure in the structure's useful life is lower than the probability obtained from the probability distribution. In any case, the values of the predominant agents are representative of their interaction with the breakwater. The values of the other agents should be simultaneous and compatible with the statistics of the predominant agent.

In each characteristic state, all of the principal failure modes are simultaneously verified. When the values in the verification equation are given, the resolution provides the value of the safety margin. If this value is negative (failure of the mode), it is assumed that the probability of exceedance of the predominant agent value is a measurement of the probability of occurrence of the mode. When this same method is applied to the other dominant modes, it is possible to verify whether the subset design complies with the probability distribution and the hypotheses of mutual exclusivity and dependence used to define it.

Verification of operationality

The verification equation is a state equation that specifies the relation between the threshold values of the agents. When these values are either exceeded or not attained, there is a cessation of activities related to the stoppage mode under consideration. The analysis of the average regime of the agents provides an estimate of the average number of annual operational stoppages and their duration.

Verification of the construction process

The costs and average construction periods depend on the typology and dimensions of the breakwater, and can be calculated by standard procedures. The values obtained can be weighted, according to the severity of the maritime climate in the area and the uncertainty of the soil.

Study of alternatives and solutions

At this project development stage, certain working hypotheses and simplifications are specific of one project class or another.

Working hypotheses

The following working hypotheses should be considered:

(a) The relations between the failure of the different hierarchical levels of the construction should be defined in component diagrams as well as the hypotheses of mutual exclusivity and dependence.
(b) Verification is simultaneously performed in the entire set of principal modes, organized according to their spatial distribution and location in consonance with the hierarchy of subsets and subsystems.
(c) The values of the agents in the verification equations are the result of their interaction with the different subsets and subsystems of the structure.

Additionally, in Class I projects and for each solution selected, the following should be considered:

(a) Generally, the damage of the different modes can progress over time from an initial dam-age value to another one indicative of failure or destruction. This evolution should be characterized by the corresponding cumulative damage model.
(b) The spatial evolution of the damage is represented in triggering and propagation trees:

Simplification hypotheses

The following simplification hypotheses can be applied:

(a) The verification of the elements in the main alignment can be performed with a reduced number of (dominant) modes and by applying good practice standards in the others.
(b) The performance of the subset can be quantified for different levels of damage and damage evolution throughout the loading cycle by adjusting standard models.
(c) Damage does not propagate between modes or components.
(d) If a loading cycle causes the initiation of damage but not total failure, the subset can be repaired before the next loading cycle. In this case, the operationality, performance, and cost of equipment should be adapted to this hypothesis.
(e) The probability of occurrence of a dominant mode could be regarded as equal to the prob-ability of the presentation of a loading cycle of the predominant agents that cause this mode.
(f) The repair costs could be estimated, based on the damage level reached in the modes in which the failure occurs.
(g) Potential global warming effects should also be taken into account by simply adopting reasonable sea level values in accordance with the breakwater's useful life and the estimates of responsible agencies.
(h) The frequency of exceedance of the operationality thresholds of construction materials and tools can be used to estimate the effective performance of the construction work.

For each alternative considered, the principal failure modes should be defined, and different failure relations between the hierarchical levels of the breakwater, as depicted in a component diagram (see Article 2.3.4). The dominant modes should be identified from the set of principal modes. The distribution of failure probability in the structure's useful life can be performed for the dominant modes, based on the component diagram and hypothesis of mutual exclusion and dependence between modes, and in any case, making use of duly justified reference values (see Article 3.5. When necessary, it is possible to use duly justified levels of joint probability.

Furthermore, in Class II projects and for each solution selected, the following should be considered:

(a) The evolution and propagation of damage occurs during loading cycles.
(b) The temporal evolution of damage of the principal modes can be fit to standard analytical models.
(c) The evaluation of repair strategies can be performed by modeling the periods of calm between loading cycles by means of simple hypotheses.
(d) The potential effects of global warming should be considered based on future scenarios proposed by competent organisms and taking into account the life cycle of the breakwater.
(e) The frequency of exceedance of the operationality thresholds of construction materials and tools can be used to estimate the effective performance of the construction work.

For each solution considered, the principal failure modes should be defined, as well as the failure relations between the hierarchical levels of the breakwater, as depicted in a component diagram (see Article 2.3.4). In addition, the results of the different repair strategies and consequences of global warming should also be considered.

Verification of reliability

The behavior of the breakwater and its components should be verified in the sequence of states of a reduced number of loading cycles characteristic of the extreme conditions that the structure will be subject to. The cycles should be selected in such a way that the failure probability in the useful life of the mode considered should be lower than that of the probability distributions. The cycles should be described in terms of the duration of the growth branch, duration of the decline branch, and the simultaneous and compatible values of the non-predominant agents in each of the branches. In all cases, the agent values for verification are those that are transformed by their interaction with the breakwater.

The verification should be performed in each of the states of the characteristic loading cycles. The substitution of the descriptors in the verification equation of the modes with the damage evolution model provides the value of the safety margin. In the case of modes verified at advanced damage levels, once initiated, the average cumulative value will progress according to a cumulative damage model, based on the state descriptors of the cycle (see Article 2.4.1).

If the failure of the mode occurs, it is assumed that the probability of a loading cycle of greater or equal intensity is a measurement of the probability of occurrence of the mode. Applying the same method to the other dominant modes can verify whether the subset design complies with the established probability distribution and the hypotheses of mutual exclusion and dependence used for its definition.

The repair costs can be estimated by analyzing the evolution of the damage of the different modes in other more frequent cycles but whose intensity is not sufficient to trigger the failure.

Furthermore, for Class II projects and the selected solution, reliability is verified with Level III methods by means of simulation techniques (see Article 4.3.3), which evaluate the spatial and temporal evolution of the damage and the effects of the repair strategy. Simulations can be performed by loading cycles in the project phase and should comply with the following requirements:

- The behavior of each principal descriptor in a cycle should fit the characteristics imposed on its non-stationary marginal probability function in the range of its upper tail.
- The series thus generated should reflect the time dependency of each descriptor with itself as well as with the other descriptors.
- The series thus generated should reproduce the statistics of the duration of the cycles, the intervals between them, and their non-stationary nature.

- The series thus generated should envisage the effects of global warming by means of tendencies or scenarios.

This verification is performed in each of the loading cycles in the useful life of each of the simulations with the agent values transformed by their interaction with the breakwater. It is divided into two parts that may or may not be subsumed within the same model: (1) ascertainment of the initiation of damage and its value: (2) accumulation of damage.

The ascertainment of the damage level is performed at the state level, based on two criteria: (a) resolution of a state equation (verification equation), which depends on the meteorological state descriptors or other random state variables; (b) application of the triggering and propagation trees of the failure, according to the damage level reached in another or other modes.

The damage accumulation is carried out, according to Article 2.4.1. Whether the damage reaches its critical value or whether there is a failure in a mode without a damage evolution model, the destruction of the component is assumed to occur, and the consequences of this failure should be evaluated for other higher-order components (component diagram).

The effect of repair strategies should be delimited in the performance of the structure and its associated costs. For this purpose, decision trees should be constructed and the effect of at least three strategies analyzed:

(a) No repairs;
(b) Repairs when damage initiates;
(c) Intermediate.

The viability of these strategies is verified by modeling the periods between loading cycles defined by agent values lower than the threshold values that limit the construction processes. Another way to verify viability is by comparing statistics that are representative of the average time of the construction work and of the time between loading cycles that might cause the damage to progress

The reliability of the construction or subset can be evaluated based on the frequency of failures in a sufficient number of simulations.

Verification of operationality

The verification of operationality can be performed similarly to the procedure described in the preliminary studies. The only difference is in the level of detail as well as the quality and accuracy of the data, which are the basis for verification.

Moreover, for Class II projects and the selected solution, the verification of operationality can be carried out by analyzing the region of operational stoppage in the joint distribution functions of the state descriptors, analyzed by means of Level II or Level III methods. When necessary, they can be based on simulations. The average number of operational stoppages can be obtained by fitting a model for the number of up-crossings over an operational threshold.

Verification of the construction process

It is necessary to estimate construction costs and average construction times, based on breakwater typology and dimensions. Also necessary to consider are the effectiveness of operations and timing strategies. For this purpose, one should bear in mind how often the climate agents exceed the operationality thresholds of the work as well as the uncertainty of the ground soil response.

Furthermore for Class II projects and the selected solution, it is possible to estimate the statistical distributions of the construction costs and time periods, based on the breakwater type and dimensions, as well as the effectiveness of the operations and timing strategies. For this purpose, it is possible to use simulations that take into account the frequency and duration of the operationality intervals of the construction materials and tools along with the timing strategies and their associated costs.

Blueprint and construction project

Working hypotheses

The blue and construction project include a complete analysis of the spatial and temporal behavior of the structure. The following working hypotheses should be considered:

(a) The relations between the failure of the different hierarchical levels of the structure are defined by means of component diagrams as well by hypotheses of mutual exclusion and dependence.
(b) All principal modes of each subset are verified by means of probabilistic techniques. The non-principal modes are verified by means of deterministic techniques, good practice standards, or other similar codes.
(c) The verification is performed simultaneously in the entire set of principal modes, organized according to their spatial distribution and location in consonance with the hierarchy of sets and subsets.
(d) The values of the agents in the verification equations are the result of their interaction with the subsets and subsystems of the structure.
(e) Generally speaking, the damage of the different modes can progress in time from an initial value to another value indicative of failure or destruction, and this evolution would be characterized by means of the corresponding cumulative damage model.
(f) The spatial evolution of the damage should be represented in triggering and propagation trees.
(g) The repair strategies are based on the creation of decision trees that provide an accurate characterization of the beginning and end of the construction work as well as the requirements for its implementation.
(h) The effects of global warming should be specifically considered by means of covariables that affect the parameters of the probability models of project factors.
(i) The description of the construction process should accurately characterize the criteria and requirements for the progress of the different aspects of the construction.

The classification of the failure modes and relations between the hierarchical levels of the breakwater should be those of the solution selected.

Verification of reliability

The performance of the structure should be verified by means of a complete simulation of the state sequences throughout the useful life of the structure. This information makes it possible to study the behavior of the infrastructure as well as the maintenance and repair work during the loading cycles as well as during the calm and operationality periods. These simulations should meet the following requirements:

- The behavior of each descriptor should fit characteristics imposed by its function of non-stationary marginal probability (considering the effect of global warming) in the range of its central body and its upper and lower tails.
- The series thus generated should reflect the time dependency of each descriptor with itself as well as with the other descriptors.
- The series thus generated should reproduce the statistics of the duration of cycles, the time intervals between them, their non-stationary nature, and periods of calm and operationality.

The simultaneous verification of all of the modes in each state of each simulation is performed similarly to the process described in the study of alternatives and solutions. For this purpose, it is necessary to consider the component diagrams, triggering and propagation trees, and decision trees.

The repair strategy for breakwater damage should contain all the information required in each simulation state to evaluate the following:

(a) resources and time necessary to begin the repairs of the mode;
(b) planning and chronogram of the repair work;
(c) thresholds of the agents and operationality requirements to delimit the delays and stoppages programmed in the repair work;
(d) strategies and decisions if the damage is not repaired in the stipulated time.

This information authorizes the evaluation of the state of the construction (damage levels/failure of components) over time and its impact on the operationality of the harbor area. The reliability of the structure or subset and its temporal evolution can be calculated from the frequency of failures in a sufficient number of simulations and the monitoring of the state of the breakwater throughout its useful life.

Verification of operationality

The verification of operationality is performed simultaneously with the verification of reliability. If the stoppage is not due to the occurrence of a single event but rather to the combination of various simultaneously occurring events, the verification is performed on the basis of operationality diagrams.

Verification of the construction process

The statistical distributions of construction costs and time periods are obtained from the simulation of climate agents during the project phase and from the verification of the timing strategies and their costs, considering the failures, delays, and possible setbacks that can occur.

4.5 SENSITIVITY ANALYSIS ACCORDING TO THE PROJECT FACTORS

A sensitivity analysis should be performed that evaluates the effect of the different factors in the verification on its result in order to determine the following: (1) availability of sufficient information to verify the reliability and operationality of the structure; (2) marginal cost to increase reliability. This analysis should provide those 'critical' factors, whose impact on the variables of interest is expected to be greater.

Depending on the stage of project development, it is possible to apply methods with different levels of complexity, such as discrete methods, elasticity analysis in the context of the reference value, classification algorithms (see Article 2.7) , and Level II methods (see Section 4.13.1.5 of the ROM 1.0-09).

Among others, it is necessary to consider the influence of these factors on the following sets of technical variables:

- Reliability and operationality of the construction and its components
    - probability of failure in the subsets, subsystems, and elements;
    - probability of stoppage in the subsets, subsystems, and elements.

- Failure of the construction by modes
    - number of damage initiations induced by natural agents;
    - number of damage initiations induced by other modes;
    - progression rate of the damage once initiated;
    - number of failures (failure progresses until destruction);
    - minimum safety margin.

- Spatial vulnerability and failure lines
  - number of failures of each element;
  - number of failures of each subsystem;
  - number of failures of each subset.

- Repair strategies
  - number of damage events that progress to an undesirable level;
  - number of times that it is not possible to begin repair work because of lack of resources;
  - number of time that it is not possible to begin repair work because of operationality issues;
  - average time from when the need for repairs is declared until when repair work is begun.

Section V. Table of contents

SECTION V: EVALUATION OF COSTS, OPTIMIZATION AND RISK LEVEL

5. Evaluation of costs, optimization and risk level

The main objective of a breakwater is to ensure that harbor operations and logistics related to maritime transport, their interconnection with other transport modes, and the integral management of vessels proceed smoothly and safely. In order to be competitive, these activities must be performed with the highest level of efficiency. This is accomplished by optimizing the total costs, limiting the investment risk, and complying with current legislation, particularly environmental regulations.

This section presents the methods and instruments that can be used to optimize the breakwater project from the technical-economic perspective of the ROM program and contingent on the results obtained from the financial-economic optimization in accordance with MEIPOR. This double condition is framed in a dual optimization system with simultaneous and compatible restrictions. Finally, this system is related to the analysis of the accident rate of the harbor are within the context of the set of exceptional work conditions, WOC_3.

5.1 CONTEXT OF COST EVALUATION IN SPAIN

In Spain, cost evaluation activities are performed with a technical instrument as well as a financialeconomic instrument. The technical instrument is known as the ROM Program (*Recommendations for Maritime Works*), in this case the ROM 1.1-18., and the financial-economic instrument is MEIPOR-16. Given that both share objectives, approaches and procedures, they should be used in coordination.

MEIPOR-16 ensures the coherence of the investment project with the most recent version of the Guide to Cost-Benefit Analysis of Investment Projects of the European Union (CE, 2002), published in 2015. Accordingly, it incorporates and reinforces an analysis of alternatives. The purpose is to verify the suitability of the solution, based on an analysis of the financial profitability of the capital and financial sustainability of the project. Also included are an economic analysis and a sensitivity and risk analysis of the investment project. Furthermore, in consonance with the (*Recommendations for Maritime Works*), particularly the ROM 0.0-01, MEIPOR-16 incorporates recommendations, calculation methods, and statistical evaluation criteria during the useful life of the breakwater.

Among the objectives of the ROM Program is the technical-economic optimization of the infrastructures in the harbor area with a view to satisfying project requirements related to safety and operationality. For this purpose, Section 7.8 of the ROM 0.0-01 recommends defining and designing of the breakwater from two complementary and mutually-enriching perspectives:

(a) project requirements related to safety and operationality in each project phase;
(b) economic optimization (minimum total cost) of the project in the life cycle of the structure, subject to certain restrictions.

As previously mentioned, these approaches to designing the breakwater are not mutually exclusive and thus are concurrent in the technical-economic optimization of the breakwater since they delimit the problem. In all cases, the results obtained should agree with those of the analysis of the financial-economic profitability of the investment project (Section 7.8.3.1 of the ROM 0.0-01).

This section of the ROM 1.1-18 presents the conceptual framework for the evaluation of the total costs of the breakwater (or maritime structure) in each project development stage, including the construction project and its technical-economic optimization. This evaluation is based on the breakwater design (in the harbor area and its surroundings) with a focus on safety and operationality. It is also in consonance with the conclusions and recommendations for harbor planning in the current legal/environmental framework. The final step is the calculation of the socio-economic indicators of the infrastructure, which are passed on to MEIPOR with a view to elaborating an investment project with an acceptable risk level.

The following articles present different options for integrating both strategies in the conception and design of the breakwater and its subsets. This is achieved through the problem statement and resolution of the technical-economic optimization of the construction project integrated in a dual optimization system.

5.2 COST-EVALUATION OBJECTIVES AND THE DUAL OPTIMIZATION SYSTEM

The construction project of the breakwater should incorporate the optimization of its construction and maintenance costs. It should also envisage the eventual costs of its repair and dismantling during the useful life of the structure. Furthermore, in Class II projects, the construction project should be in consonance with the estimates resulting from the analysis of the financial-economic profitability of the investment project.

As stated in the ROM 0.0-01, cost optimization is not restricted to new construction projects, but is also applicable to other maritime and harbor projects, such as those for the maintenance, repair, reconstruction, or dismantling of the breakwater.

To coordinate decision-making in the technical-economic sphere of the ROM and the financial economic sphere of the MEIPOR, it is advisable to jointly set out and optimize construction and investment project objectives. These dual optimization activities could possibly be performed in the following sequence:

1. technical-economic optimization of the infrastructure (breakwater) with the incorporation of the requirements and conditioning factors defined in the design planning studies;
2. financial-economic analysis and risk analysis, including the results of the previous technical-economic optimization (which is part of the financial-economic studies and cost-benefit analysis of the investment project or one of its development stages);
3. initiation of another optimization cycle with the new project requirements and conditioning factors adjusted to the MEIPOR results;
4. iteration of this sequence until a design is obtained that satisfies the objectives of both the investment and construction project, and which also complies with all environmental, social, and legal requirements and constraints.

This ROM addresses the technical-economic optimization of a breakwater and its corresponding sensitivity analyses. The financial-economic optimization of the harbor area and its dependence on the breakwater should be performed in MEIPOR, 2016. Thanks to their generality, these methods and techniques can also be applied with little or no variation to other maritime and harbor structures.

5.2.1 Capitalization costs of a breakwater

The capitalization cost of a breakwater throughout its life cycle consists of the costs of (a) the initial investment; (b) maintenance work; (c) repair and construction work; and (d) loss of operationality in the harbor area because of failures in the infrastructure. These four costs are random variables with a joint distribution function that should be determined within the context of the investment project. In MEIPOR-16, these costs directly affect the following cash flows:

(a) Investment costs that include the initial costs, fixed investment costs, and variations in working capital. They are regarded as separate items in the economic analysis, and include the fixed costs of the following:
- elaboration and entry-into-service of the project;
- reconstruction, adaptation, and expansion during the useful life of the structure;
- environmental replacements and adjustments.

(b) Operational costs that include regular payments made by each agent and planned for the proper functioning or operation of the infrastructure of the investment project. From an accounting perspective, these costs or expenditures are required so that they breakwater subset can provide suitable use and exploitation conditions of the harbor area and, when applicable, of its installations.

(c) Operating revenues that include the cash inflows from the exploitation of the investment project for each agent, and which compensate the disbursements related to operation and investment costs. Among other things, they depend on the reduction and cessation of the activities and services in the harbor area.

Furthermore, it is necessary to consider external aspects attributable to the project, which include social and environmental aspects that affect the community. It is rather unusual for a method of financial-economic analysis to evaluate the benefits of environmental aspects. This is generally included in the investment costs and the maintenance and exploitation costs required to guarantee compliance with environmental requirements.

COMMENT

In the near future, legislation will possibly be expanded and new laws will be enacted that will serve as a guide for the incorporation of environmental aspects and considerations. Meanwhile, since the nature of the subset is based on a qualitative calculation of the ERI for the occurrence of the worst mode (related to safety and operationality), the aspects considered (and expanded to other principal modes) can be used to estimate this cost.

5.3 CONSTRUCTION PROJECT COSTS OF A BREAKWATER

The construction project should be based on an analysis of the public service, production, and economic investment. This analysis should include safety and environmental aspects that permit the following: (1) evaluation of the viability of the project for its promoters; (2) a technical-optimization of the structure as a whole and each of its parts.

For this purpose, this ROM 1.1-18 organizes the costs of the breakwater as follows:

- construction costs;
- repair costs;
- dismantling costs;
- maintenance costs;
- costs due to the loss of operationality of the activities and services associated with the breakwater.

The evaluation of these costs for the different typologies, designs, and construction and repair strategies are the basis for the technical-economic optimization of the structure and its subsets.

5.3.1 Organization of the calculation of the total costs

The unification of the technical-economic analysis for the optimization of the breakwater requires the separation of costs, based on time scales and the spatial hierarchy described in Article 2.2. It is also advisable to establish links and parallels with the instruments used to configure the technical aspects of the structure.

Time scales and spatial hierarchy

According to the temporal organization (Section 2, Article 2.2.1), the investment costs are calculated for each project phase. In this way, the construction, repairs, and dismantling costs are assigned to their respective project phases, whereas the maintenance costs and those for loss of operationality are assigned to the exploitation phase. If necessary, costs can be assigned by defining the specific subphases. Costs can be accumulated in different time intervals, either by accounting for their variability or the financial-economic analysis of the project. It is customary for the technicaleconomic optimization to be based on the total as well as the yearly calculation during the useful life (or complete life cycle) of the construction.

According to the spatial organization (Section 2, Article 2.2.2), the total costs of the breakwater are evaluated for each subset, considering the contribution of each of the breakwater parts, subsystems, elements, and subelements.

Cost diagrams

This procedure (Section 2, Article 2.3.4) is used to structure cost diagrams in component diagrams. They support the probability distribution since they organize the costs of the failure as well as the costs to avoid failure in terms of different designs and strategies. Along with each component diagram, there should be an evaluation of the total cost of the failure and its consequences in the set of elements analyzed. Likewise, each component in the diagram is assigned the following: (1) reconstruction costs; (2) costs of the loss of operationality regarding the activities and services affected during this work.

In a parallel way, it is advisable to estimate the costs attributable to each component to avoid the failure of the whole structure. For serial elements, costs are linked to the construction and accumulation, when applicable, of the average repair costs throughout the phase (including those related to the loss of operationality). For parallel elements, a cost estimate for each component is linked to the construction, either the accumulated costs, depending on the repair strategy, or to the reconstruction costs (including in both cases, those generated by the loss of operationality).

Cost propagation trees

Based on the same procedure (Section 2, Article 2.6.1), cost propagation trees complement the decision trees since they include an economic evaluation of the repair costs, based on the strategies defined. Consideration is given to the mode in which the damage began as well as those in which it is triggered. Each strategy incorporates an estimate of the number of repairs in the time interval considered. This is accompanied by an evaluation of the following: (1) evaluation costs; (2) costs corresponding to the loss of operationality of activities and services affected during this work; (3) costs corresponding to the consequences of the failure of the strategy weighted by its probability.

Probability model of the variable of (cumulative) cost

The total cost throughout the vital cycle of the breakwater can be treated in the same way as the damage level of an element (Section 2, Article 2.4.4), namely, as a cumulative random variable. The evolution of the costs accumulated in a given time interval can be modeled, depending on a few predominant agents, according to Equation 2.6. Moreover, the analysis and characterization of the temporal evolution of its probability function or one of its statistical descriptors can be performed following the indications in Article 2.4 for these types of model (see Article 5.3.3).

5.3.2 Cost calculation in the construction project

The following describes the procedures recommended for the evaluation of costs in the construction, dismantling, exploitation, and repair phases.

The total costs are best calculated by classifying them as; (1) direct costs; (2) indirect costs; and (3) damage and material losses. They are subsumed in the direct costs of the structure, implementation costs, material costs, and fixed costs. The indirect costs include all expenses not directly attributable to specific units of the structure, but rather to the entire structure or part of it. The total costs are the sum of the previous costs and those associated with the damage, losses and delays experienced in the different project subphases.

Construction and dismantling phases

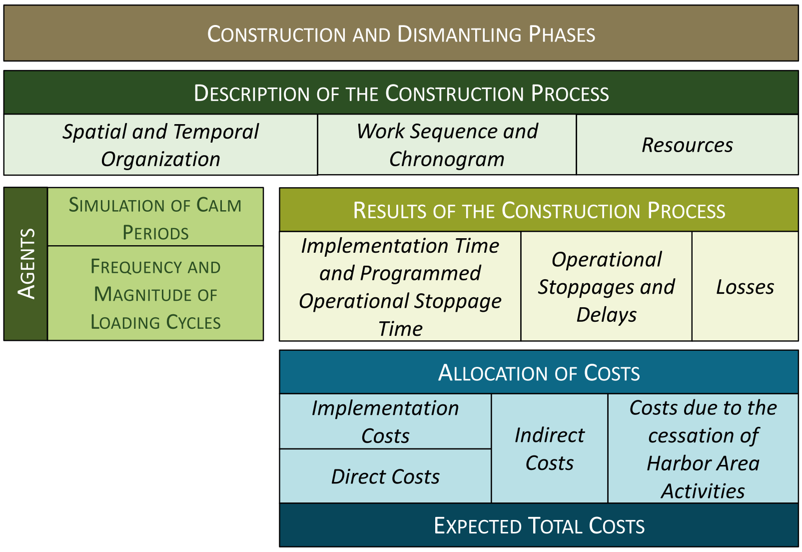
The costs in the construction and dismantling phases depend on the work strategy and the characteristics of the maritime climate at the site. The calculation of these costs should include the following: (a) implementation costs of the work; (b) costs of damage and losses; (c) additional costs because of delays; (d) costs derived from the impact on other infrastructure or services.

Generally speaking, the cost evaluation of the construction process of a breakwater is performed for each construction subphase in all of the breakwater subsets and transitions in consonance with the strategy defined and considering the characteristics of the maritime climate at the location.

The planning should envisage the implementation requirements of each subphase. These include the restrictions on the progress and the dependence of the subphase on the progress of other subphases as well as the periods of seasonal stoppage. The construction and dismantling work should take into account the performance and operational levels of the resources available.

The sequence of the work and its degree of interdependence can best be characterized by means of a Monte Carlo simulation. The initial development stages of the construction project can be modeled with simpler techniques, such as a Monte Carlo simulation based on a hypothesis that simplifies the necessary information and reduces the required implementation time.

Figure 5.1: ***Calculation sequence of the descriptor of the total construction and dismantling cost***



Repair phase

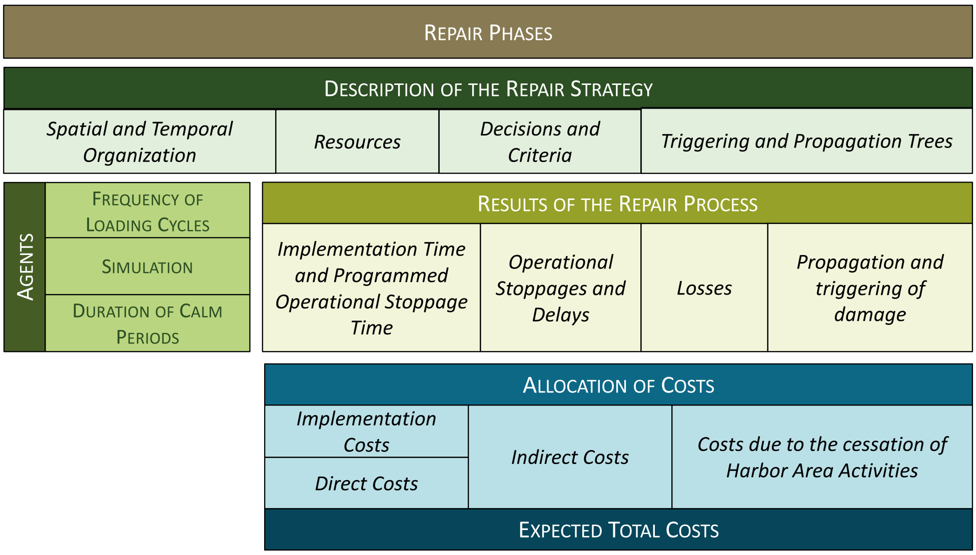
The calculation of the repair costs involves the quantification of the following:

(a) Frequency of repairs at the time scale;
(b) Descriptor of the specific costs of each repair action.

The first item depends on the criteria used to begin repairs, on models of the spatial and temporal evolution of the damage, and on the statistical description of the magnitude and frequency of the maritime climate at the location, especially of the storm events associated with the upper tails of the agents. It is evaluated by integrating the cumulative damage in a synthetic loading cycle and by calculating its frequency of presentation. This dependence should be expressed with a variable characteristic of the magnitude of the cycle.

The second item depends on the work strategy, which is based on the same elements used to calculate costs in the construction and dismantling phases. Additionally, it is necessary to consider the propagation of damage and its effects during the time intervals of the repair phase when repairs cannot be performed for logistic reasons, work organization, or operational stoppage.

***Figure 5.2:* Calculation sequence of the descriptor of the total repair cost**



Exploitation phase

The exploitation costs attributed to the breakwater basically stem from the following:

(a) Monitoring the state of the structure and its maintenance;
(b) Reduction or cessation of the activities in the area surrounding the breakwater and in the harbor.

Although the costs related to the first item can be calculated as a fixed allocation with the required frequency in the project and a value in accordance with the tasks envisaged, the costs related to the second should be evaluated considering their random nature.

For the losses due to the reduction or cessation of harbor services and activities caused by the breakwater, it is necessary to include those derived from operational stoppage modes, failures, or damage in one of the breakwater components before the repair phase begins. In both cases, the costs are evaluated on the one hand, by calculating the frequency and duration of operational stoppage events, and on the other, the estimated losses from these events.

The frequency and duration of the operational stoppage modes can be evaluated based on its verification equation and the statistical description of the magnitude of the climate agents and their frequency of presentation. In any case, the characteristics of these agents should be specified in the location and their interaction with the structure should also be taken into account.

The frequency of the reduction or cessation of activities due to failures or damage is evaluated, based on the following:

- verification of each failure mode;
- climate agents and soil performance agents;
- response of the structure and each of its elements, based on the interaction of the agents and typology of the structure.

The duration of these periods depends on the cumulative damage model and on the repair strategies.

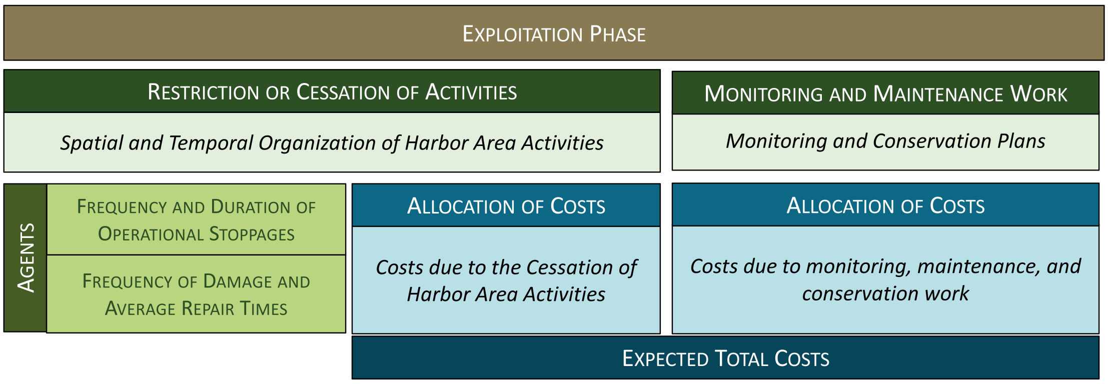
The calculation of the costs associated with the reduction or cessation of the activities can be characterized by an expected value per time unit with an uncertainty due to: (1) the management and exploitation of the infrastructure; (2)

the behavior and evolution of transportation (particularly maritime traffic) and also the financial-economic systems. These factors, which directly affect the investment project and decision-making, are the focus of MEIPOR-16.

COMMENT

The technical statistics and simulation data in this ROM can be applied to the analysis of the uncertainty of the macroeconomic evolution of the economy and other magnitudes that intervene in the financial-economic analysis required in MEIPOR-16, as reflected in the Calculation of the PDF of the profitability of the investment project, depending on the damage level of the breakwater.

Figure 5.3: ***Calculation of the descriptor of the total cost of exploitation***



5.3.3 Calculation of the descriptor of the total costs

The descriptor of the accumulated total costs, C_T, of the breakwater, usually the expected value, can be expressed by the terms in the equation 5.1

$$C_T(t) = \sum_{\tau=1}^{T} \left\{ C_{\underset{\tau}{CON}}(\bar{x}, c_{CON}, \psi_{CON}; t) + \sum_{s=1}^{S} \left[C_{\underset{\tau,s}{MAN}}(c_{MAN}; t) + \sum_{m=1}^{M} C_{\underset{\tau,s,m}{REP}}(\bar{x}, c_{REP}, \psi_{REP}; t) \right] + C_{\underset{\tau}{DES}}(\bar{x}, c_{DES}, \psi_{DES}; t) \right\} + C_{CA}(\bar{x}, c_{CA}, \psi_{GES}; t) + C_{EXT} \qquad (5.1)$$

where C represents a cost descriptor; x is a vector with the project factors; c designates the unit costs; and ψ represents the strategies. The indexes τ, s and m correspond to the hierarchical levels of *subset*, *subsystem*, and *mode*. The subindexes, CON, MAN, REP, DES, CA, GES, and EXT correspond respectively to the construction, maintenance, repairs, dismantling, cessation of activities, management, and external features and aspects. Finally t represents the time elapsed from a reference instant.

Temporal compatibility of the accumulation of the total costs

The total costs during time t from an initial reference point (beginning of construction, entry in service, etc.) are obtained from the sum of the partial costs that depend on the time elapsed, on the random presentation of climate and soil agents that can cause damage, and when applicable, possible repair/reconstruction interventions. Each equation term of the total costs complies with the necessary condition for the application of the time compatibility model (Castillo et al., 2012).

Similarly to other cumulative variables, the costs that accumulate over time are calculated as follows: if C_{T_i} is the cost produced during $t = t_1 + t_2$, c_1 is the cost produced in time t_1; and c_2 is the cost produced in time t_2; then $C_{T_i} = c_1 + c_2$. Mathematically, this can be expressed as:

$$C_{T_i}(c_0, C_H, t) = q\left[q^{-1}(c_0, C_H) + t, C_H\right] \tag{5.2}$$

where C_H is the repair cost due to the occurrence of the failure (or stoppage mode); c_0 is the initial cost; and $q\,(t, C_H)$ is the way that the cost accumulates, depending on the failure mode and its predominant agents, H.

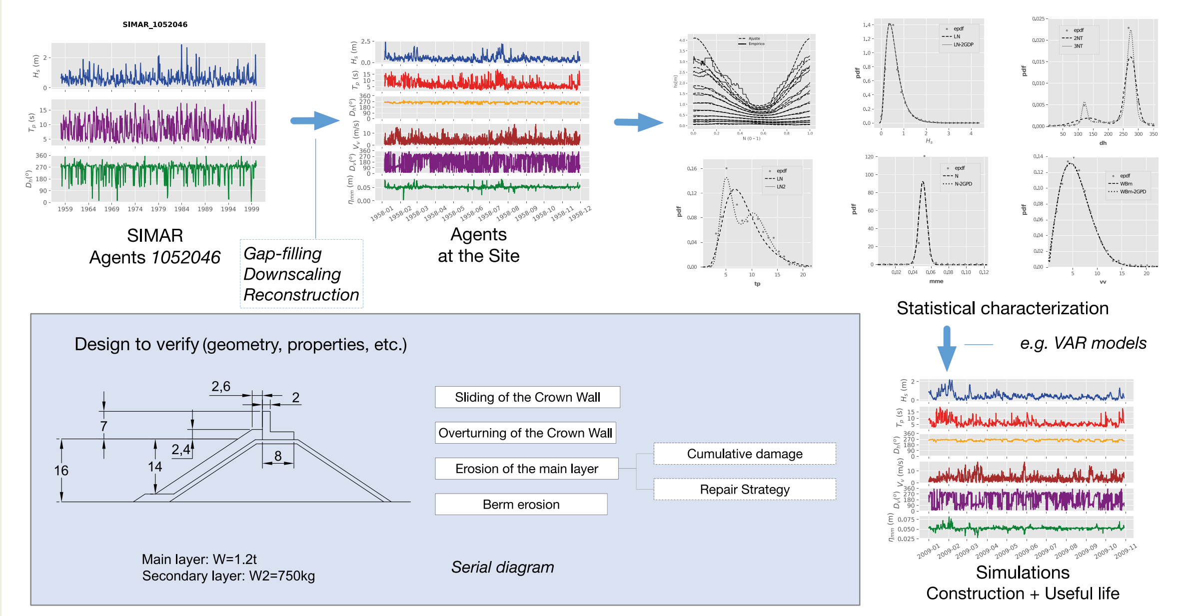
EXAMPLE

Calculation of the total costs of a breakwater

The following figures present results related to the calculation diagram of the total costs of a breakwater. Its longitude is 500 m in a single subset. The outer subsystem has three principal modes. Only the repair costs of the toe berm are shown. The complete example can be found in the *Manual para el diseño de diques de abrigo y de ayuda a la aplicación del Articulado de la ROM 1.1-18*.

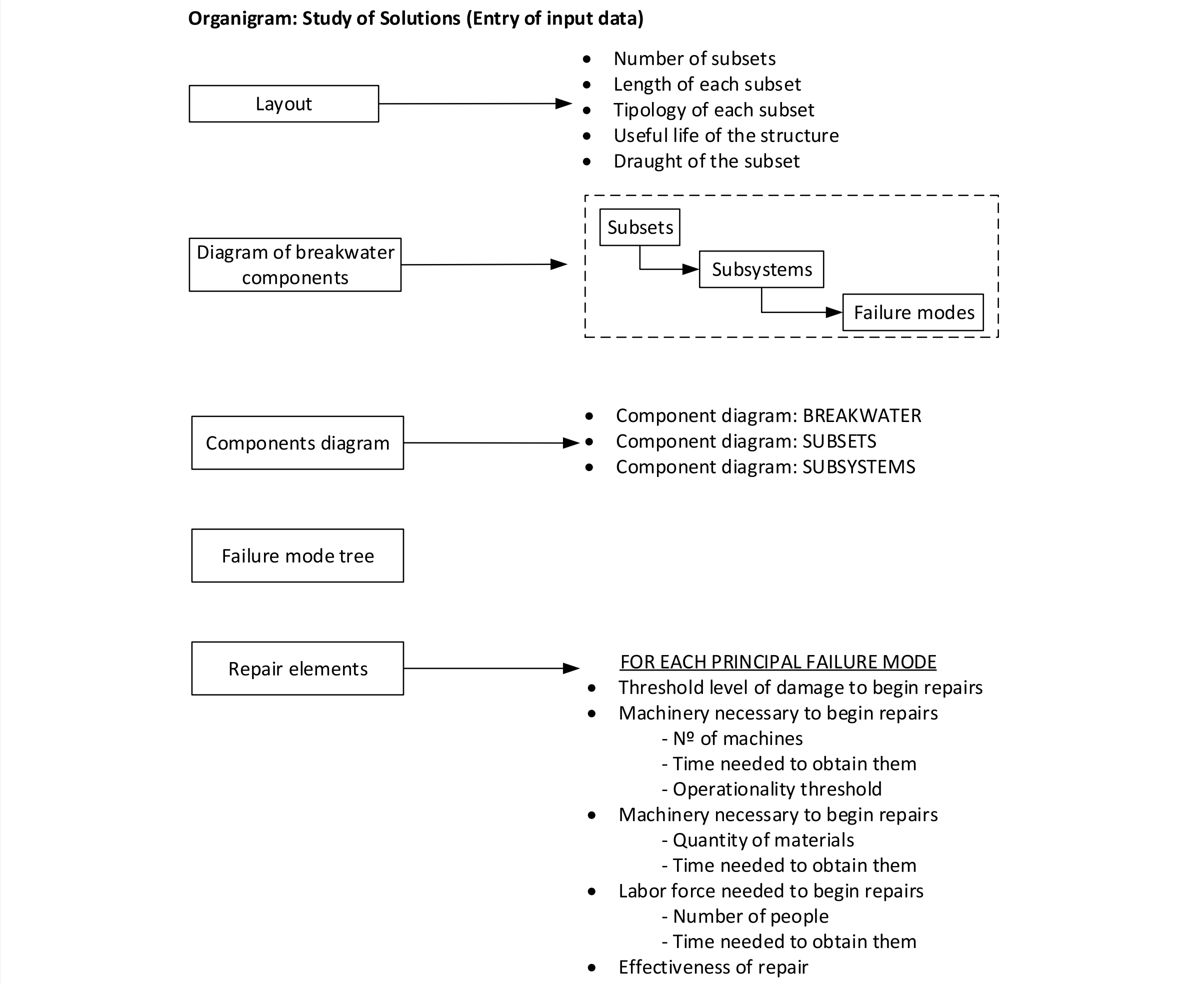
Figure 5.4 shows a diagram of the necessary input data for the calculation procedure: (1) characterization of the climate agents at the breakwater site; (2) typology and preliminary design of the section; (3) Monte Carlo simulation of the time series of the interaction by years. The results are presented for the last five years.

Figure 5.4: Characterization of climate agents at the site and typology of the sloping breakwater



The organizational chart in Figure 5.5 represents the information used to calculate the repair costs.

Figure 5.5: ***Diagram of the input data necessary to calculate the repair costs with a Monte Carlo numerical simulation***



An analysis of two repair strategies is performed. The first strategy is conservative and the second is more risky, as reflected in the following construction resources:

- Five trucks with a cost of 25 €/h each.
- Two hopper barges with a cost of 80 €/h each and a threshold wave height lower than 1.5 m and 3 m of draught.
- 300 m^3 of quarry run with a total cost of associated materials of 3000 €.
- 15 machinists with a cost of 10 €/h each.

In this example, the time elapsed from the repair order to when the work actually begins is at least 24 h since the port in this example does not have the resources and all of the work must be outsourced.

This conservative strategy considers a damage level threshold of 20% for the repairs, whereas the riskier strategy has a threshold value of 50%.

The figure 5.6 shows the triggering and propagation trees of the three failure modes, *FM_1*, *FM_2*, and *FM_4*. The terms *S*, *SbS* and *FM* correspond to Subset, SubSystem, and Failure Mode, respectively. According to the diagram, if the damage level of the Failure Mode 1 reaches 20%, this activates the initiation of damage in Failure Mode 2. And if the damage level reaches 50%, this activates the initiation of damage in Failure Mode 4. Likewise, the initiation of damage in Failure Mode 2 can trigger damage in Failure Mode 4 if the damage level reaches 30%.

***Figure 5.6:* Example of a triggering and propagation tree of failure propagation**

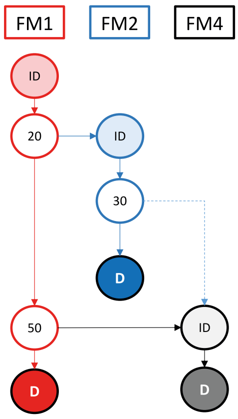
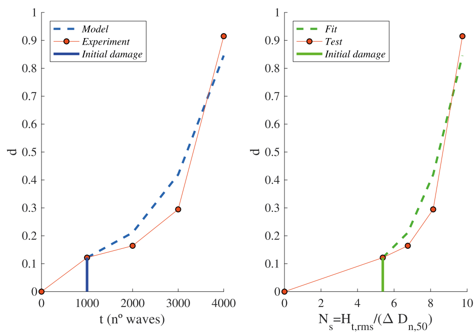


***Figure 5.7:* Fit parameters of the power curve of cumulative damage for the failure mode, erosion of the toe berm**

Cumulative damage curve for the failure mode: Berm erosion



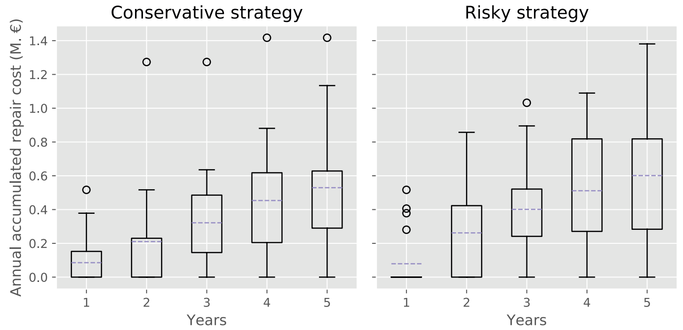
$$d(d_0, N_s, t) = \left[d_0^{1/b} + (aN_s^c)^{1/b}\, t\right]^b$$

Failure mode: Berm Erosion
Verification type: SLS
Parameter a=2e-8
Parameter b=0.729
Parameter c=5.295

The damage accumulation in the mode is calculated by means of a power curve of parameters ($a = 2e-8$, $b = 0.7129$ y $c = 5.5295$) shown in Figure 5.7. The curve is obtained from the toe berm data with rockfill material for a sloping breakwater of Van Gent and Van der Werf, 2014 and analyzed by Vílchez et al., 2015. More specifically, the data of Figure 5.7 correspond to the configuration of a wider and thicker toe berm in high water conditions and low wave steepness.

The boxplots of Figure 5.8 show the distribution of accumulated repair costs over a five-year period for the two repair strategies. The bars in the boxplots indicate the values of the average costs of all the simulations performed. The cost sample was obtained by means of n repetitions of the cost assignment process, based on the Monte Carlo simulation of new climate series.

Figure 5.8: ***Boxplots with the accumulated repair costs in euros over a five-year period for the failure mode, erosion of the toe berm***

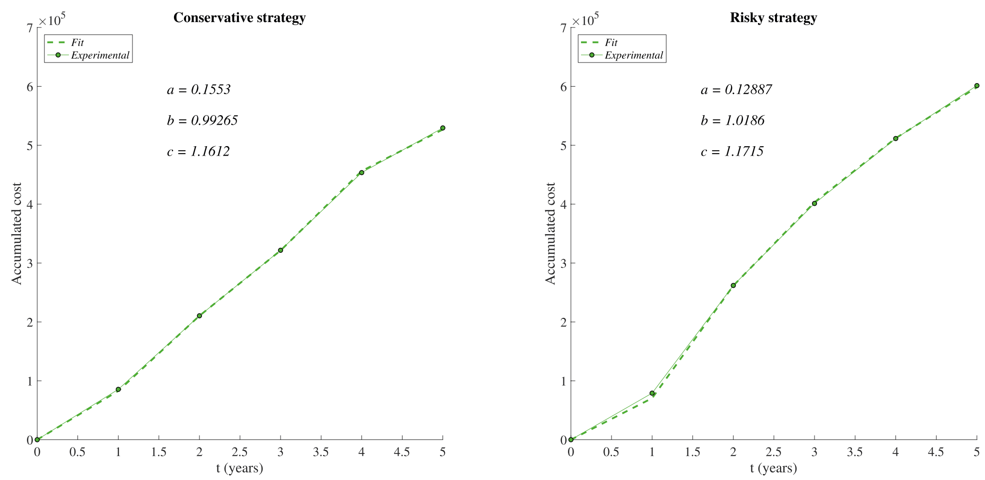


The average repair costs are fit by means of a power of cost accumulation model (Equation 5.3). The fit parameters are shown in Figure 5.9.

$$C(c_0, H, t) = \left[c_0^{1/b} + (a\, C_H{}^c)^{1/b}\, t\right]^b \tag{5.3}$$

This model is composed of three parameters. More specifically, parameters a and c control the mode in which the repair costs are generated, C_H, and which are caused by the predominant agents (wave train dynamics), whereas parameter b designates the power in which the cost is accumulated.

Figure 5.9: ***Fit parameters of the power curve of the repairs for the failure mode, toe berm erosion***



Given that b is close to one, the accumulated cost of repairs in the toe berm experiences a linear growth over time.

5.4 TECHNICAL-ECONOMIC OPTIMIZATION AND SENSITIVITY ANALYSIS OF THE CONSTRUCTION PROJECT

According to Equation 5.1, the breakwater design with its dimensions and properties as well as its construction strategies of repair, management, and exploitation can be conceived as a technical-economic optimization problem, which minimizes the objective function of the total costs, subject to financial, economic, and technical constraints.

The general approach proposed in this ROM is described in Mínguez et al. (2006), which includes the evolution of the damage. This methodology allows for different levels of complexity, depending on the project development stage. Moreover, the organization of the breakwater in hierarchical levels, project phases, and time scales facilitates the partial optimization of the project within a global procedure of increasing complexity.

5.4.1 Elements that define a technical-economic optimization method

An optimization method should include the following elements:

(a) spatial and temporal domains in which the problem is defined;
(b) project factors;
(c) univariate or multivariate functions;
(d) restrictions;
(e) hypotheses of the model and their resolution.

Spatial and temporal domains

Spatial and temporal domains should be in consonance with those proposed in Section 2 of this ROM:

(a) spatial domain: breakwater, subset, subsystem, set of elements, etc.;
(b) temporal domain: life cycle, useful life, project phases, year, seasonal cycle, loading or operational cycle, meteorological state, wave sequence, etc.

In general, the technical-economic optimization of the breakwater is performed during its life cycle. It includes all project phases and is applied to each of the subsets of the breakwater.

Identification of the project factors

One way of identifying and organizing the project factors (parameters, agents, and actions) that intervene in the formulation and resolution of the technical-economic optimization problem is the following:

(a) Factors to be optimized. Their mean value (or other statistical descriptor is determined in the optimization of the objective function. They are usually dimensions of the elements, subsystems or parts of the construction.
(b) Factors that are previously specified or imposed by regulations, and thus are not optimized (e.g. unit costs, properties of materials; etc.).
(c) Parameters of the project probability factors, which are regarded as random.
(d) Dependent or non-basic factors, whose expression is based on the previously mentioned project factors.

Initially, all project factors can be regarded as random variables. In this case, deterministic project factors are a special case of these.

Objective function

In general, the objective function for a breakwater is a statistical descriptor of the total (accumulated) cost of the subset or breakwater in its life cycle. This total cost is determined by adding up the costs in all of the project phases: initial construction phase, construction and exploitation phase, dismantling and repair phase, as well as for the cessation and influence of the economic activities directly related to the structure, even those providing new services after the entry into service of the harbor area.

Because of the random nature of the climate agents and the breakwater response, the total accumulated cost is a random variable with a probability model that evolves over time, and which can be determined according to Article 5.3.1 of this section.

One way of relating the technical-economic optimization to the analysis of financial sustainability proposed in MEIPOR-16 is to define the annual expected cost of the breakwater subset as an objective function. This cost is obtained from the sum of the expected cost of the annual damage and the equivalent annual cost of the investment. This calculation usually adopts the hypothesis of statistical independence of the years in the structure's life cycle, as explained in Section 2.5.4.3 of the ROM 1.0-09.

The objective function in any of the spatial and temporal domains identified in the breakwater project is defined, depending on the purposes of the optimization.

Restrictions on the optimization of the objective function

The technical-economic optimization of the breakwater (e.g. minimization of the total cost of the project) is subject to technical-economic restrictions as well as legal, social, and environmental constraints. Generally, technical restrictions are imposed to delimit the performance of the breakwater in relation to its safety, operationality, and cost. The following types of restrictions are proposed:

(a) Restrictions on the verification equation coefficients of each principal failure and stoppage mode:
- global safety coefficients;
- partial coefficients.

(b) Restrictions on the probability of occurrence of a mode and of the set of principal modes specified in the ROM 0.0-01 and ROM 1.1-18:
- joint probability distribution by independent modes;
- joint probability of failure or delimited stoppage (Section 7.5 of the ROM 0.0-01), or the equivalent annual occurrence rate of the mode during the useful life of the structure (under certain conditions).

(c) Multiple restrictions, combining coefficients and probability of occurrence:
- global or partial safety coefficients and the reliability index of the mode;
- global or partial safety coefficients and the annual rate of occurrence of the mode.

(d) Restrictions on the variability domain of the statistical descriptor of the total costs and its spatial and temporal domain.
- total cost (mean value and standard deviation) of the delimited construction project in its life cycle or the delimited average annual cost (Mínguez et al., 2006);
- delimited total cost in a phase (e.g. construction or repairs) (Mínguez et al., 2006).

Hypothesis of the optimization model

The optimization problem of a breakwater design can be resolved by adopting certain hypotheses and simplifications that can either reduce its complexity or its implementation times. These include the following:

(a) statistical independence of the loading and operational cycles and the thresholds, the variables that describe them, and the probability models considered;

(b) evaluation of non-compliance with project requirements by means of failure and stoppage modes and their state equations;

(c) spatial and temporal evolution of the modes as well as their triggering and progress;

(d) construction strategies, processes, and repairs.

Resolution method and technique of the optimization problem

The resolution method depends on the complexity of the problem to be resolved and the project development stage. When the total cost of the breakwater is optimized with a single principal failure mode, it is then possible to apply Level II analytical methods or Monte Carlo simulations of the loading and operational cycles in the life cycle of the infrastructure (Level III).

If the optimization problem includes a multivariate objective function, conditioned and independent restrictions, and various failure or stoppage modes, it may be necessary to apply techniques and numerical models such as GAMS or AIDS. In this case, a sensitivity analysis (see Article 5.4.3) should be included in the formulation and resolution of the optimization problem so as to reduce the complexity as well as the number of variables.

5.4.2 Simplified optimization method

The project bases of a breakwater as stated in the ROM 0.0-01 and expanded in ROM 1.1-18 provide a unified way of applying a technical-economic optimization method that also facilitates an objective and homogeneous comparison of the data and designs of alternatives and the selection of solutions. This method is suitable for the optimization of Class I projects with an ERI < 20 and SERI < 20 (Article 5.4.5).

The most relevant premises and hypotheses of this analytical method are the following:

1. A non-overtoppable breakwater belongs to an interrelated set of typologies that are described by the dimensions of their main parts, elements, and subelements as well as the construction materials used.
2. The interaction of the breakwater with the incident wave train is described by the partition of incident energy by means of simple functions.
3. The probability functions of the statistical descriptors of the wave action on the face and over the breakwater can be defined in terms of the models corresponding to the breakwater toe, and these in terms of their corresponding deep-water models.
4. The failure modes of the outer subsystem are the principal modes of the breakwater, and one of the main sources of uncertainty in the project.
5. Each mode is described by a verification equation that depends on local point descriptors of the design of the meteorological state.
6. The beginning and spatial and temporal evolution of the damage of each mode can be described by a cumulative function dependent on the exceedance and the duration of the local descriptors of the meteorological state of the design and the possible repair strategies.
7. The repair cost of each failure mode of the outer subsystem can be described by a cumulative function that depends on the exceedance and duration of the local descriptors of the design meteorological state and the possible repair strategies
8. The total cost of the breakwater during its useful life is calculated as the sum of the construction cost of the outer and inner subsystems as well as the foundation and soil. It depends on the initial design and probable repair costs of damage to the outer system and its possible repair strategies.
9. The repair strategies (when and how to perform them and how much they cost) are decision-making elements in the optimization problem.

This is the way to obtain an analytical expression of the total accumulated cost of a typology in a breakwater subset and the geometric dimensions of the outer subsystem expressed in terms of the descriptors of the meteorological state (mainly the root mean squared wave height) at the breakwater toe or in deep waters.

This function can be minimized in regards to the waves at the breakwater toe or in deep waters with certain constraints related to the project requirements, activation and propagation of the failure modes, repair strategies of the subset, and the total investment cost. If the optimization is of a design that envisages the evolution of damage, it can also be conceived in terms of survival time.

This analytical method becomes increasingly complex as the construction project develops and converges with the general method as new modes, subsystems, and their relations are incorporated into the analysis.

5.4.3 Sensitivity analysis of the breakwater design

The sensitivity analysis reveals how the design of the breakwater and subset vary with the fluctuation of the values of certain project factors. More specifically, this analysis, which is performed simultaneously with the optimization as well as after it, does the following:

(a) It provides information relative to the participation of different project factors in the activation and propagation of a failure mode in a subset, part of a subset or in one of the subsystems.
(b) It focuses on the transformation of principal modes into non-principal modes in a subsystem or in a subset.
(c) It quantifies the importance of the principal modes of a subsystem in the total cost, life cycle, and annual equivalent cost of the subset.
(d) It quantifies the importance of the organization of the breakwater in subsets and types in the total cost during the life cycle and in the equivalent annual cost of the breakwater.

Technique and resolution

Generally, the resolution of the sensitivity analysis of the total cost or annual equivalent is based on the Monte Carlo simulation technique or on advanced optimization methods, which simultaneously resolve both problems.

When the behavior of a single mode is analyzed (e.g. in preliminary studies, and in certain cases, in the studies of alternatives and solutions) or its spatial and temporal evolution, the sensitivity study can be resolved with a Level II method (see Section 6.3 of the ROM 0.0-01).The result of the application of the method can be either the critical failure point and the failure or stoppage probability, or the sensitivity indexes of the factors in Section 6.6 of the ROM 0.0-01.

5.4.4 Sequence for the optimization and technical-economic sensitivity analysis of the breakwater cost in is life cycle

The following section explains the sequence of tasks in the optimization process of the design of a breakwater and its subsets. The objective function is defined by the total cost of the construction project, as restricted by the joint probability of failure of the principal modes (Figure 5.10). The importance and scope of this sequence depends on the project development stage. This sequence is an expanded version of the sequence in the "Design of breakwaters based on life-cycle analysis" (Chapter 9 of PIANC, 2016).

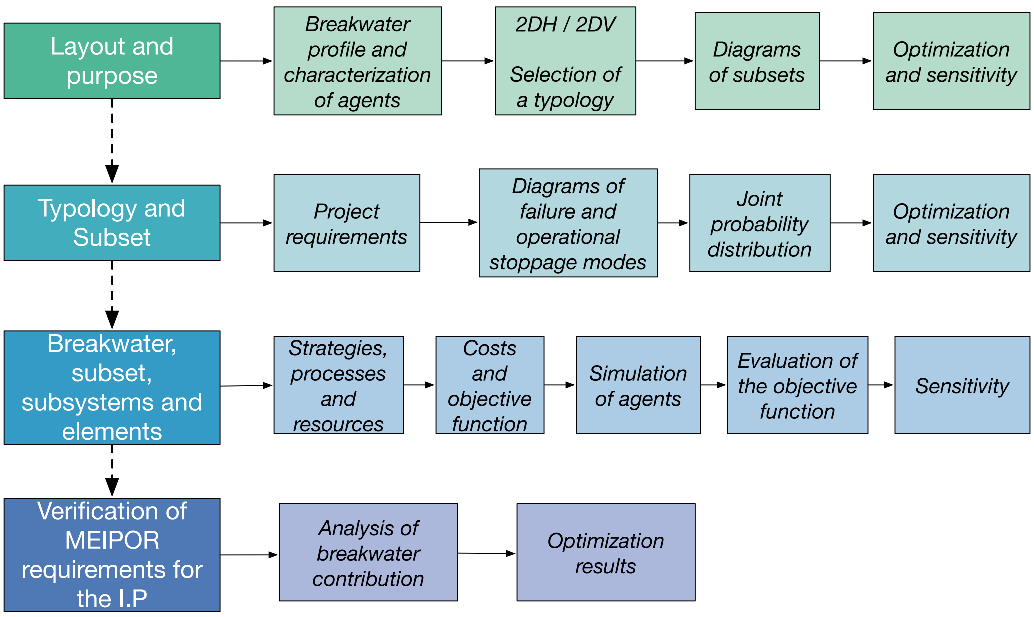
(a) For each planform and intended purpose of the breakwater regarding the harbor area:
  1. Categorization of breakwater in subsets and characterization of climate and soil agents, use and exploitation agents, and materials;
  2. 2DH and 2DV analyses and selection of possible typologies;
  3. Configuration of subsets, depending on the purpose of the breakwater;
  4. Optimization and sensitivity analyses of the layout of the breakwater and its subsets.
(b) For each typology and subset
  5. Calculation of the project requirements;
  6. Hydrodynamic behavior of the section, conceptualization of the design, and configuration of the diagrams of the failure and stoppage modes;
  7. A priori distribution of the joint probability of failure and pre-design of the section;
  8. Optimization and sensitivity analyses of each typology in each subset.
(c) For the breakwater, its subsets, subsystems, and elements
  9. Specification of the strategies, processes and construction resources, conservation and repairs;
  10. Specification of costs and selection of the objective function and its restrictions;
  11. 'Simulation' of climate agents in the presence of the breakwater and its subsets;

12. Evaluation of the objective function and its optimization;
13. Sensitivity analysis by subsets, parts, subsystems, and elements.

(d) Verification of the MEIPOR requirements of the breakwater investment project

14. Analysis of the breakwater's contribution to the financial profitability objectives of the investment and capital, to the economic profitability analysis, and to the financial sustainability of the investment project.
15. Incorporation of the results of the financial-economic optimization obtained in the application of MEIPOR and, when necessary, the reformulation of the project requirements and restrictions of the optimization problem.

Figure 5.10: ***Sequence of tasks of the optimization process of the design of a breakwater***



5.4.5 Recommended optimization model of the accumulated cost

The complexity and time necessary for the optimization and sensitivity and risk analysis increase with the following:

(a) economic cost and environmental and social relevance of the investment project;
(b) nature of the breakwater and its relevance for the objectives of the investment project.

According to MEIPOR-16, the economic cost and the social and environmental relevance of the investment project determines whether the studies and analyses in the document should be incorporated. Moreover, the nature of the subset, quantified by the environmental, social, and economic indexes, determines the verification method and development stage of the breakwater construction project, as indicated in Article 1.4 and specified in Article 4.4.

Then, a specification is given of the evaluation of the project costs, the technical-economic optimization, and the sensitivity analysis, depending on the ERI and SERI indicators and the relation between the investment cost CI and the dimensionless economic parameter C_0 (Figure 1.8).

Class I project: $C_I \leq C_0$. No MEIPOR required.

(a) $ERI < 20 \cap SERI < 20$. Simplified economic optimization.
- principal failure mode (which defines the ERI and SERI).
- ULS optimization, based on the predominant agent (Suárez Bores, 1976 and PIANC, 2016).
- comparison with the breakwater that satisfies project requirements.

(b) $ERI \geq 20 \cup SERI \geq 20$. Technical-economic optimization.
- project requirements focused on safety and operationality and expressed by multiple restrictions (safety coefficients, partial coefficients and failure probability or annual rate of failure/storms).
- sensitivity analysis.

Class II project: $C_I > C_0$. MEIPOR required.

(a) $ERI < 20 \cap SERI < 20$. Simplified economic optimization.
- principal failure mode (which defines the ERI and SERI).
- ULS optimization based on the predominant agent (Suárez Bores, 1976 and PIANC, 2016), but delimiting the total cost and the annual average cost of the construction project to that imposed by MEIPOR.
- comparison with the breakwater that satisfies the project requirements.

(b) $ERI \geq 20 \cup SERI \geq 20$
1. Technical-economic optimization and sensitivity analysis with the following:
   - multiple restrictions related to safety and operationality (safety coefficients, partial coefficients and failure probability or annual rate of failure/storms) and model of spatial and temporal evolution of the failure and stoppage modes.
   - restrictions derived from the analysis of financial-economic profitability and of financial sustainability imposed by MEIPOR.
2. Optimization of the dual system of construction projects and of investment and risk assessment.

5.5 ANALYSIS OF THE PROFITABILITY AND RISK LEVEL OF THE INVESTMENT PROJECT

According to MEIPOR-16, the investment in harbor infrastructures should be based on the generation of value and should possess mechanisms that envisage public service as well as general interest goals. In this type of context, the objective of the dual ROM-MEIPOR system is to establish the necessary and indispensable financial-economic, environmental, social, and technical connection in harbor planning design, construction projects, and the organization, management, and exploitation of their infrastructures.

This connection is established in all stages of the construction project (Figures 1.8 and 1.9). It is quantitatively specified by resolving the dual system of technical-economic optimization of the breakwater and the financial-economic optimization of the investment project. Finally, it is delimited by assessing the risk.

A detailed explanation of the financial-economic optimization can be found in MEIPOR-16. This article only contains the elements of connectivity and compatibility in the resolution of the dual optimization system of the construction and investment projects.

5.5.1 ROM 1.1-18-MEIPOR connectivity

The drafting of the construction project of the breakwater depends on the economic, productive, and public service analysis that includes environmental and safety aspects. It permits the following:

1. to evaluate the viability of the project for its promoters;
2. to optimize the construction as a whole as well as each of its parts.

Function of the breakwater in the financial-economic viability of the investment project

The analysis of the investment should be based on an evaluation of the project objectives and their context, as characterized by the following:

(a) promotion of the new and improved port facility;

(b) embedding of that facility in the different transportation sectors;
(c) logistics and maritime-terrestrial commerce;
(d) institutional-social-economic framework where it is situated.

The purpose of the breakwater construction is contribute to the fulfilment of the investment project objectives, and particularly the activities in the harbor area with predetermined levels of reliability and operationality.

As part of the financial-economic assessment, it is important to quantify the capacity of the breakwater to facilitate activities in the harbor area with acceptable levels of reliability and operationality, and compare this with an exploitation scenario without the presence of the breakwater.

Indicators that can help make decisions regarding the advisability of its construction are the following:

(a) total project investment;
(b) variation of the annual net income;
(c) sensitivity of the financial-economic profitability.

These indicators are evaluated for two project scenarios, one with a breakwater and the other without. If the more favorable scenario is to construct the breakwater, then its total cost should be delimited and its risk margin in the investment project should be assigned.

For this purpose, in the various construction development stages, the total breakwater costs are evaluated, including the estimated costs of its repair as well as those derived from its lack of operationality.

5.5.2 Suitability and optimization of the investment project

The objectives of the investment project are specified in the following:

- evaluation of the financial profitability of the project as well as of the capital available for its promotion;
- economic analysis of the effects that the project has on the agents, traffic, and related operations;
- probability that the project will continue to have a high performance level even though future conditions and calculation hypotheses may be different from those initially considered.

The harbor investment project is regarded as viable (i.e. it is a possible solution) when it complies with the minimum requirements MEIPOR-16, or their equivalent in the financial-economic instrument considered:

(a) Net Present Financial Value of the Capital, Capital-NPFV (C) of the investor/operator, positive participant;
(b) financial sustainability of the project for the port authority and investor/operator, correct participant;
(c) Net Present Economic Value of the project NPEV (I), positive.

To deem an investment project viable, MEIPOR-16 also includes previously established thresholds of the risk level. These requirements can generally be complied with by means of diverse project alternatives, but some of them optimize an objective function by satisfying certain restrictions, which makes them more attractive for their development and implementation.

Elements for a financial-economic optimization

The same as with the technical-economic optimization, the financial-economic optimization of the investment project should include the following elements:

(a) spatial and temporal domains in which the problem is defined;
(b) project factors;
(c) univariate or multivariate objective function;

(d) restrictions;
(e) model hypotheses and their resolution.

The work sequence of the MEIPOR contains the information required to define and delimit the elements of the financial-economic optimization problem.

5.5.3 Dual optimization system and acceptable risk level

Although MEIPOR and the ROM program share methodologies and project development stages, they differ in certain aspects of the spatial and temporal organization of the project and its description by probability models. In no case, however, do these differences preclude the concurrent formulation of the objective functions and shared restrictions, and their resolution by means of an iterative process.

The objective function and the restrictions of the financial-economic optimization can be formulated, based on the financial-economic profitability indicators of the project, capital and its costs.

MEIPOR-16 evaluates the investment risk derived from the probability that the indicators of financial-economic profitability of the project have a lower value (or higher, depending on the indicator) than a critical reference value. The risk is considered acceptable when this probability is lower than the reference value (level of acceptable risk). The use of probability models to calculate the risk level is explained in Section 3.6 of MEIPOR.

5.5.4 ROM 1.1-18-MEIPOR connectivity indicators

The final result of the dual optimization system should be the estimate of the acceptable risk level of the investment project, and the contribution of the breakwater to this risk level, as proposed in the draft project and more specifically defined in the construction project. This includes the construction and repair strategies (scenarios) as well as the analysis of risk due to the non-fulfilment of project objectives and the purpose of the breakwater.

EXAMPLE

CALCULATION OF THE PDF OF THE PROFITABILITY OF THE INVESTMENT PROJECT, DEPENDING ON THE DAMAGE LEVEL OF THE BREAKWATER

In the case of a Class II investment project, the breakwater project should be in harmony with the conclusions and recommendations in MEIPOR. In these conditions, the dual optimization system is a valuable instrument that can be used to design a breakwater that best corresponds to the needs of the harbor area during its useful life or in other temporal domains (e.g. concession time, loan repayment period, etc.). MEIPOR applies a set of functional equations of the project factors (agents, actions, and function terms) that may or may not evolve over time to obtain different indicators of the financial-economic behavior of the investment project.

The values of the factors correspond to those described in Chapter 3, Section 3.8.1 of the ROM 0.0-01, without a probability model, representative or characteristic nominal value, and with or without values higher or lower than the confidence interval. Only in certain cases is the selection of the project factor value based on its probability function.

If the joint probability models of the project factors are known, then the analysis of the investment project objectives (through the values of its indicators) can be generally formulated and resolved in a given time interval. The result is the joint probability (reliability) of the fulfillment of project objectives in that time interval, as indicated in Section 6.2 of the ROM 0.0-01.

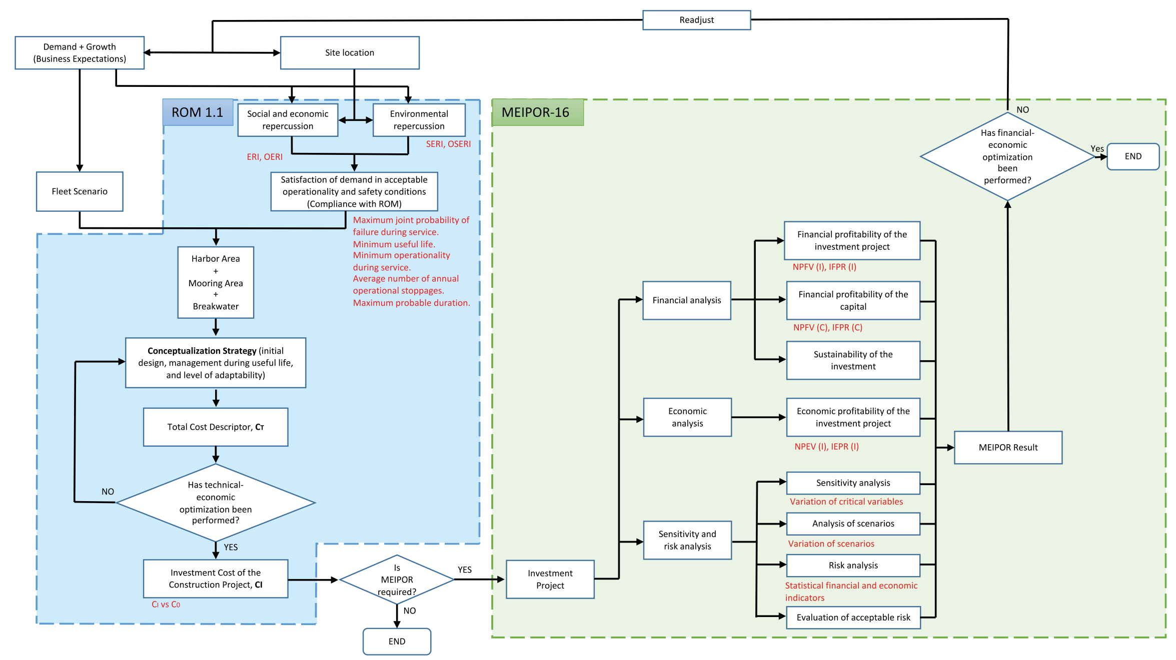
Similarly to the verification of the project requirements of a construction project, the overall approach may initially seem complex and in certain cases, not viable. One way to resolve and eliminate these difficulties is to segregate the problem in subproblems, depending on the project objectives and factors, and then resolve each one with additional hypotheses.

The construction projects associated with a Class II investment project and addressed with Level II and III verification methods are a good example of how requirements of reliability and operationality in the useful life of a breakwater are transferred to the investment project and decision-making through the analysis of the total costs of the infrastructure.

This example calculates the probability models of the financial-economic indicators that depend on the performance of the breakwater in relation to the safety and operationality of a small container terminal of a port, based on its capacity to meet three types of demand, qualitatively identified as *decreasing, moderately increasing* and *heavily increasing*. The approach, justification, and detailed explanation of the calculation processes and results for other terminal sizes can be found in (IH Cantabria and McValnera, 2018).

Figure 5.11 summarizes the workflow in this example of the application of the dual ROM 1.1-18-MEIPOR 2016 system.

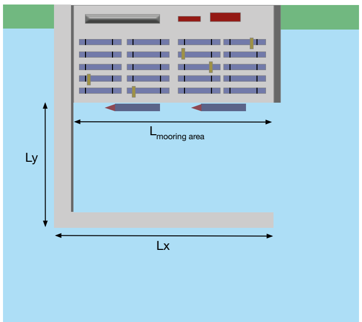
Figure 5.11: Workflow of the example



Design criteria of a small terminal

When the concession was initially granted, the terminal was designed to meet a demand of 160,000 TEUs carried by Panamax vessels in two mooring areas constructed for efficient operation (Figure 5.12). Moreover, the loading scale is constant during the life of the concession. A constant annual growth or declining growth rate of the number of scales is specified. The length of the berthing line is 480 m.

***Figure 5.12:* Sketch of berths and dimensions**



The following demand scenarios are defined:

- demand decreasing to 80,000 TEUs at the end of the concession (case 1);
- moderately increasing demand that reaches 220,000 TEUs at the end of the concession (case 2);
- heavily increasing demand that reaches 360.000 TEUs at the end of the concession (case 3).

Figure 5.13 (adapted from the *Manual de Capacidad Portuaria* of the Fundación ValenciaPort) shows the service levels of the terminal.

***Figure 5.13:* Service levels compared to average annual productivity**

Service level	Relative waiting period	SERVICE LEVELS			
D	> 0.20	red	red	red	red
C	0.10 - 0.20	red	green	green	green
B	0.05 - 0.10	red	green	green	green
A	until 0.05	red	green	green	green
		< 35	35 - 50	50 - 65	> 65
		Average annual productivity of a moored vessel (P) (cont/h)			
		D	C	B	A
		Service level			

Design criteria of an outer breakwater

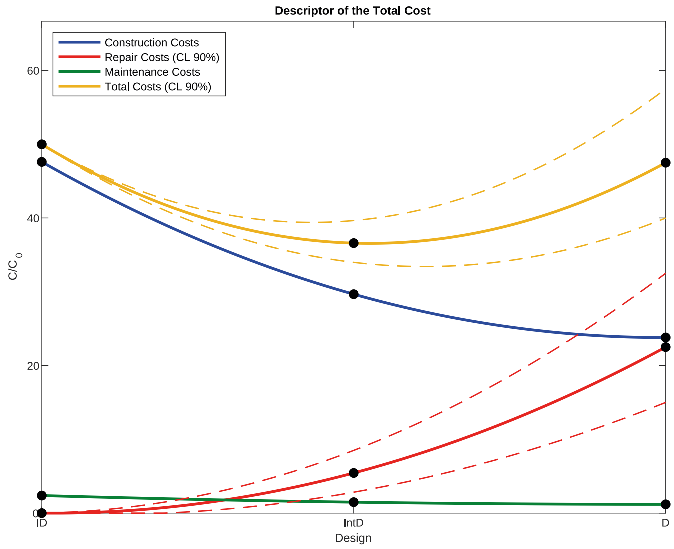
Figure 5.12 shows the planform of the outer breakwater, and the design of its geometry and subsets. The following project requirements are based on the ERI, SERI, OERI, and OSERI:,

(a) Useful life: > 50 years
(b) Joint probability of the principal failure modes: $p_f < 0.10$
(c) (Annual) operationality: $p_0 > 0.95$

The length of the primary and secondary alignments are based on the following operationality requirements: L_x = 2100 (m) and L_y = 370 (m), respectively. The minimum depth in the harbor area is 15 m.

The typology of all the breakwater subsets and the design of the section is formulated according to an *ad hoc*, variant, which is an intermediate design between variants 1 and 2. For this purpose, three types of damage are defined, namely, initiation of damage (ID), intermediate damage (IntD), and destruction (D) of the principal failure mode (extraction of unit pieces from the main armor layer). The assumption is that damage will be repaired when it reaches (ID) with no economic or technical limitations and that the operationality of the construction will not be affected. Figure 5.14 shows the curves reflecting the variation of the total costs (sum of the construction, maintenance, and repairs). These costs, which are dimensionless, are represented by the unit cost C_0 (reference value), based on the damage level, identified as (ID), (IntD) and (D). CL indicates the confidence level.

Figure 5.14: Variation in total costs in relation to the design damage level



The results are obtained with a Monte Carlo simulation of the operationality of the terminal (mean regimes of meteorological states) and of the hydrodynamic performance of the breakwater (extreme regimes of meteorological states).

Results

Figure 5.15 represents the temporal evolution of the probabilities of achieving the estimated increase in demand (case 2) and the need for expansion in order to offer the appropriate level of service. The crossover of the curves occurs after approximately eight years.

Figure 5.15: Temporal evolution of fulfillment probabilities, based on decision-making

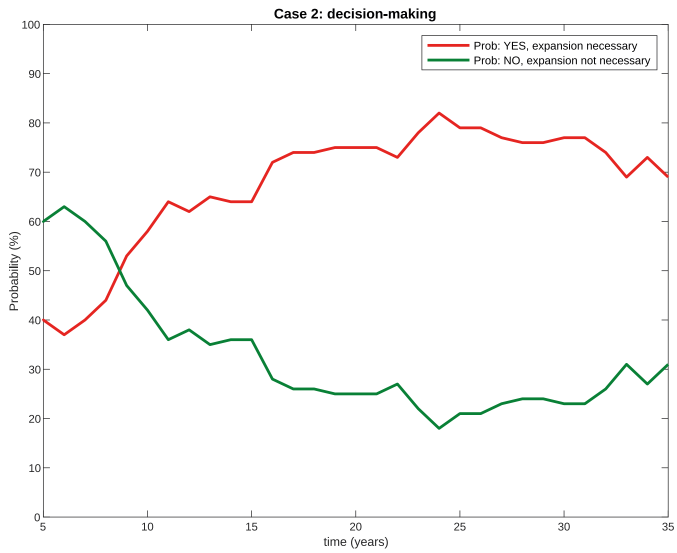
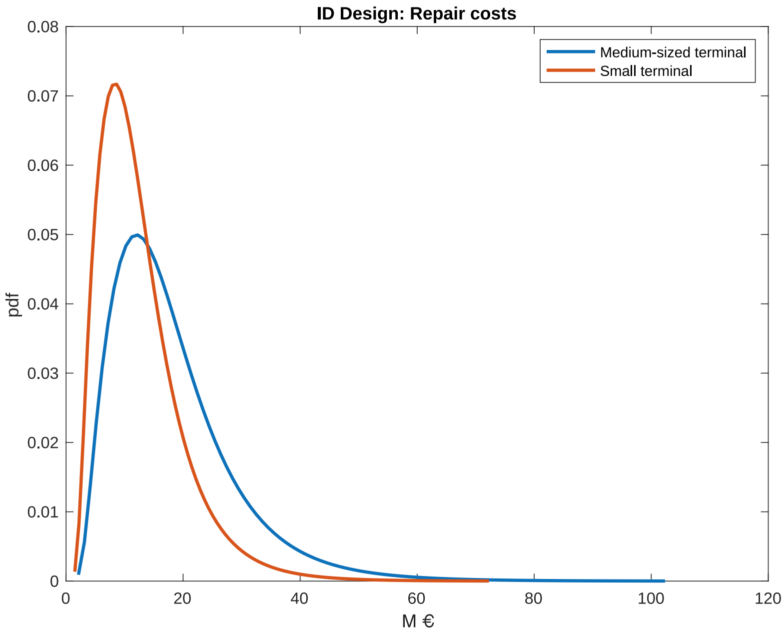


Figure 5.16 represents the PDF of the repair costs of the breakwater (small and medium-sized terminals). The difference between the planform configuration and dimensions of the section is reflected in the form of the function.

Figure 5.16: *Probability density function of the repair costs for a design that envisages Iribarren-level damage*



Figures 5.17, 5.18 and 5.19 represent the PDF of the Internal Financial Profitability Rate (IFPR) of the Port Authority and of the Operator and the Internal Economic Profitability Rate (IEPR), respectively, for the three temporal evolution hypotheses of the demand. The three figures include the discount rate.

Figure 5.17: *Probability density function of the IFPR for the three cases considered*

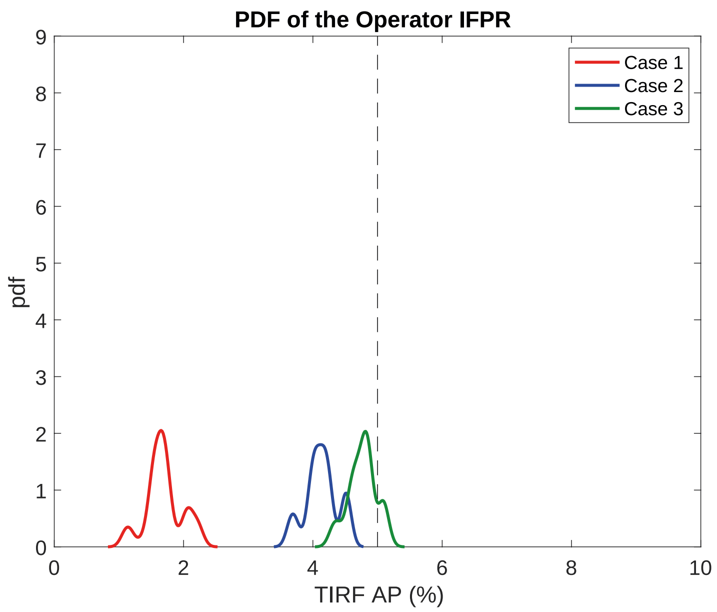


Figure 5.18: ***Density function of the IFPR of the Operator for the three cases considered***

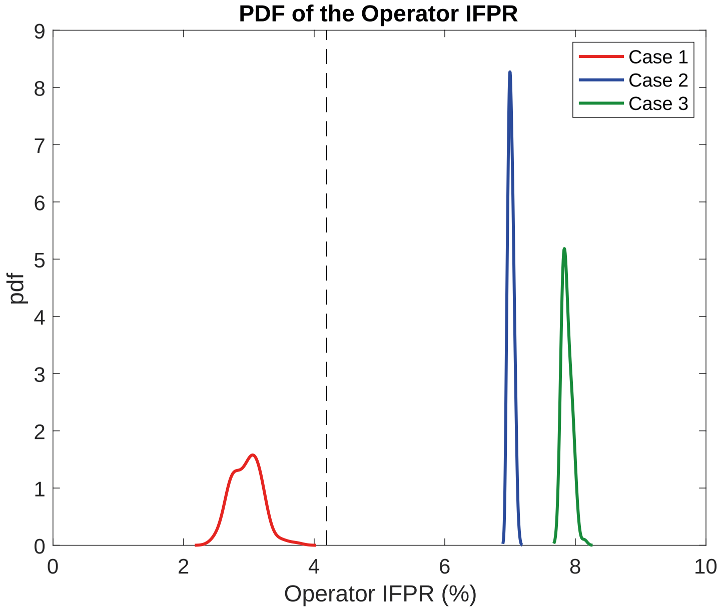


Figure 5.19: ***Probability density function of the IEPR for the three cases considered***

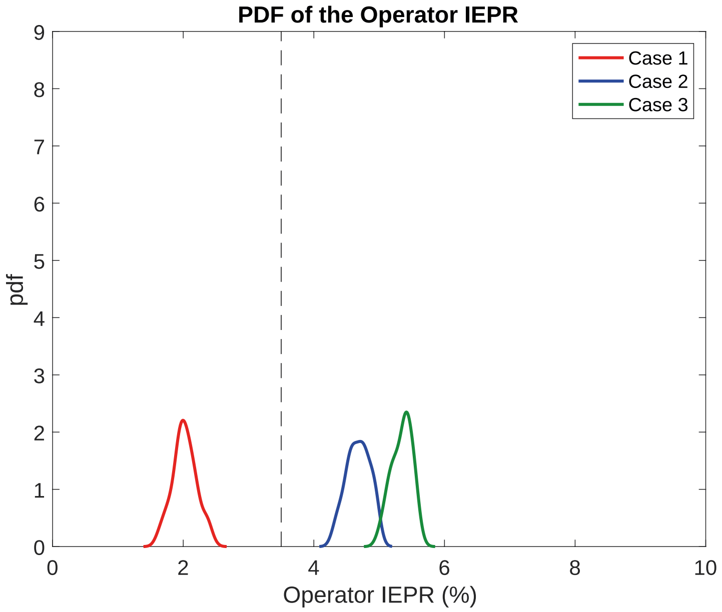


Figure 5.20 presents the results of the sensitivity analysis of certain investment project indicators, due to optimistic and pessimistic deviations, modeled as a 20-percent increase or decrease in the construction cost and compared with the neutral hypothesis (without deviations). The table shows the elasticity values of the financial-economic indicators for moderate increase in the demand (case 2). The results greater than 1 are highlighted in red.

Figure 5.20: ***Results of the sensitivity analysis for optimistic and pessimistic scenarios***

CASE 1	PESSIMIST	OPTIMIST
Elasticity of the NPFV MA	2.91	2.91
Elasticity of the IFPR MA	3.59	4.87
Elasticity of the Oper NPFV	0.00	0.00
Elasticity of the Oper IFPR	0.00	0.00
Elasticity of the NPEV	3.93	3.93
Elasticity of the IEPR	2.24	2.78

CASE 2	PESSIMIST	OPTIMIST
Elasticity of the NPFV MA	8.82	8.82
Elasticity of the IFPR MA	1.48	2.01
Elasticity of the Oper NPFV	0.00	0.00
Elasticity of the Oper IFPR	0.00	0.00
Elasticity of the NPEV	3.81	3.81
Elasticity of the IEPR	0.99	1.22

CASE 3	PESSIMIST	OPTIMIST
Elasticity of the NPFV MA	30.23	30.23
Elasticity of the IFPR MA	1.29	1.75
Elasticity of the Oper NPFV	0.00	0.00
Elasticity of the Oper IFPR	0.00	0.00
Elasticity of the NPEV	2.26	2.26
Elasticity of the IEPR	0.86	1.07

In this example, the uncertainty associated with safety-related breakwater performance is transferred to the financial-economic results and is reflected in the design premises. This type of segregated diagram for the fulfillment of investment project objectives is simple and can be usefully applied to breakwaters whose construction project is implemented with Level II or III methods.

However, in Spain, the integral application of the dual system (without segregations) depends on the work load. Consequently, it depends on the implementation time, knowledge, method, model, and available information.

5.6 EXCEPTIONAL WORK AND OPERATING CONDITIONS AND ANALYSIS OF THE ACCIDENT RATE

The dual ROM-MEIPOR system evaluates investments in maritime transport infrastructures, while complying with the conditioning factors and project requirements in the ROM 0.0 as well as other ROM documents in normal work and operating conditions WOC_1 and extreme work and operating conditions WOC_2 (Chapter 4, ROM 0.0-01).

Because of their rarity, neither of the two documents specifically addresses investment and construction projects in exceptional work and operating conditions $WOC_{3,1}$, or in post-exceptional conditions (operational $WOC_{1,3}$ and extreme $WOC_{2,3}$) derived from their occurrence. However, their rarity does not exclude the need to consider them, particularly, when their occurrence can involve loss of human life or irreversible damage to the environment and ecosystems.

5.6.1 Analysis of the accident rate

The objective of this type of analysis is to analyze and quantify the accident risks (natural origin, human error, system failure, etc.) of transportation infrastructures in all project phases and their consequences. More specifically, the objectives are the following:

- identification and classification of potential accidents in terms of their severity and consequences;
- prediction of their frequency of occurrence;
- analysis of the way to prevent potential accidents and transfer their results to the construction project in order to consider them;
- development of safety protocols in relation to fortuitous work and operating conditions of the physical environment and accidental work and operating conditions.

In shoreline areas where the probability of presentation of seismic movements or tsunamis, though small, is not negligible (based on danger maps elaborated in the EU), it is recommendable to undertake an accident rate analysis of the harbor area and its impact on the infrastructure designed. For this reason, planning studies as well the Master Infrastructure Plan should specifically envisage the need for accident rate studies.

The results of the analysis should specify two indexes:

- accident rate and its consequences;
- social perceptions of the accident as assumable or non-assumable.

This analysis is based on the premise that there is no zero risk, and that in most cases, a reduction in the accident rate or in its consequences can be quantified in financial terms. It requires a study of opportunity costs that considers the evolution of public opinion in this regard.

Methods to evaluate the accident rate

To analyze the temporal evolution of the breakwater in relation to safety and operationality, Section 2 of this ROM 1.1-18 proposes the use of decision trees and triggering and propagation trees of damage. These diagrams help to specify the interdependency of the different project factors. Because of its open structure for the reproduction of failure and stoppages, it is necessary to simulate the set of intervening variables.

The analysis of the accident rate is conditioned by the rarity of such events, which is evident in the scarce amount (or total absence) of available information. For this reasons, one of the most suitable methods is the Bayesian network that uses directed graphs, which, unlike tree diagrams, can be closed. Furthermore, the joint probability of all variables can be defined by means of the conditional probabilities of each node, given its predecessors.

COMMENT

During the application of the ROM 3.1-99, Design of the *Maritime Configuration of Ports, Access Channels, and Harbor Basins*, it was observed that the methods for designing these structures did not contemplate an analysis of the accident rate. The proposal is to transfer this analysis to further studies with a view to implanting operational procedures (Sanchidrián, 2001). This article highlights a series of options that can be helpful to formulate an analysis of the accident rate of other maritime structures, particularly, of a breakwater.

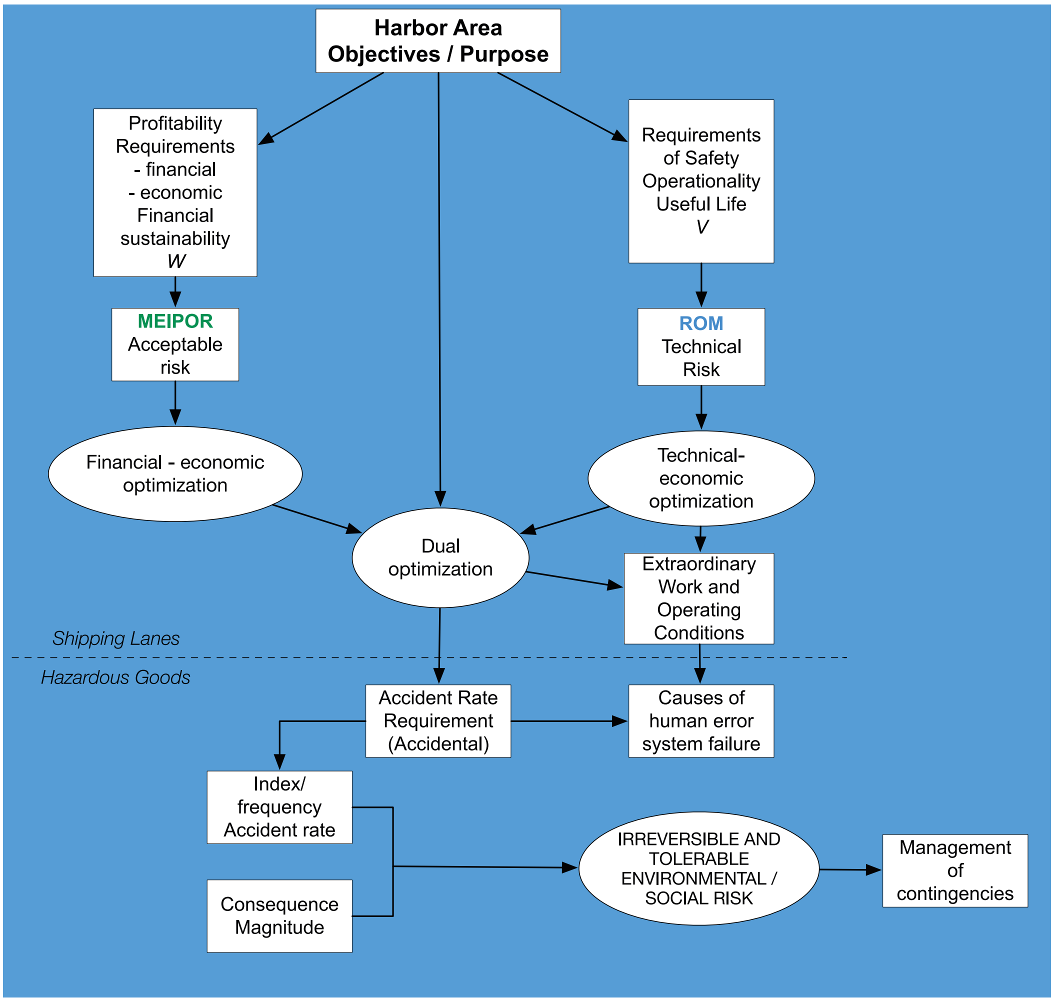
The methodological triad

When it is necessary to analyze the accident rate of the infrastructure in the harbor area, the work method includes the three instruments described in this document

- MEIPOR (2016): *Method for the Evaluation of Port Investments* that analyzes the financial-economic profitability and financial sustainability of the investment risk.
- ROM 1.1-18: *Recommendations for the Construction Project of Breakwaters* that explains how to draft and implement construction projects of infrastructures have been technically and economically optimized by delimiting any risk to their safety and operationality.
- Exceptional work and operating conditions: Analysis of the accident rate of the infrastructures with a view to quantifying and preventing the loss of human life, protected species, and irreversible damage to the environment.

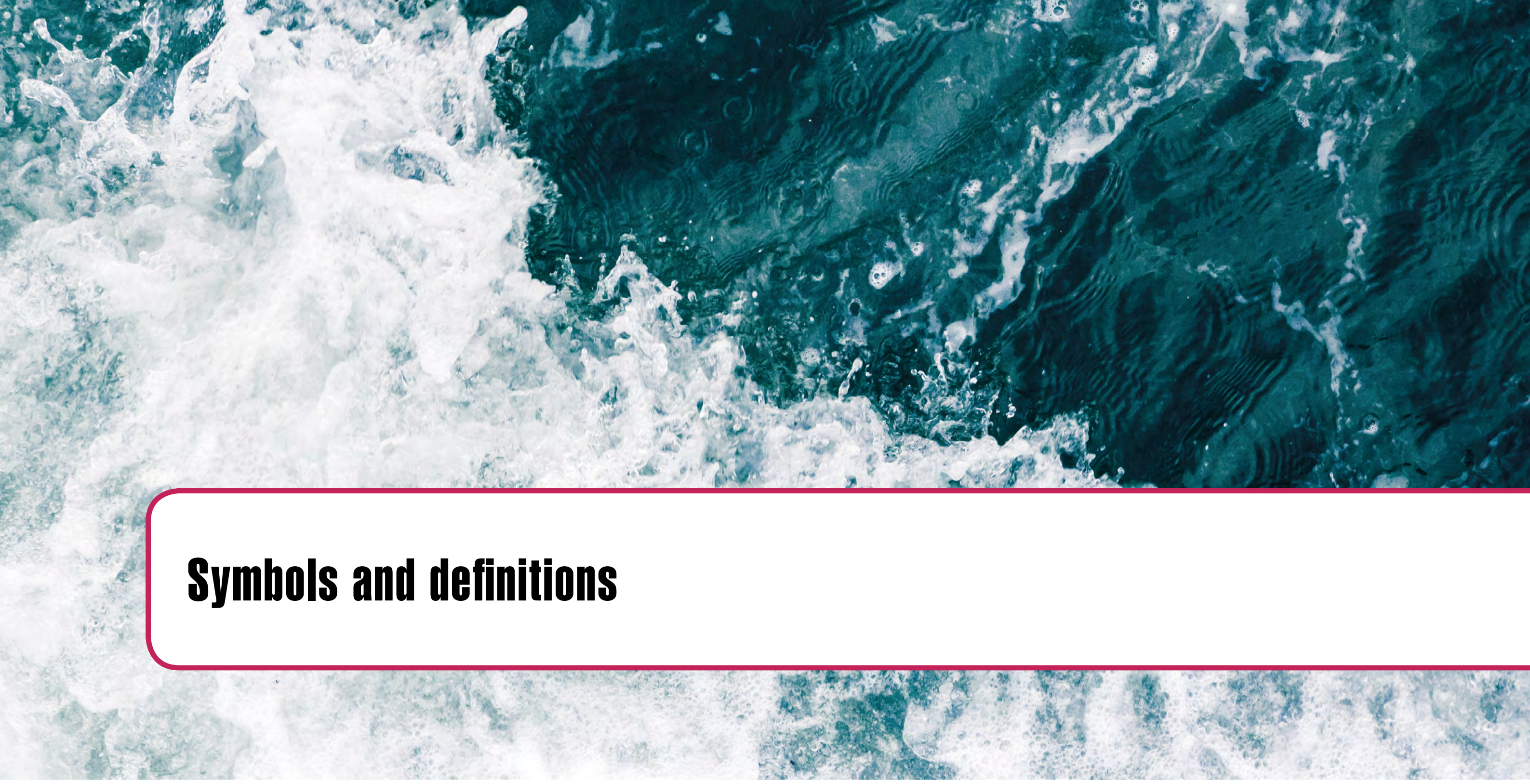
The joint and integrated use of these three instruments (see Figure 5.21) facilitates the application of multi-criteria techniques for analysis and decision-making, and consequently, the assignment and distribution of the responsibilities related with each of these acts.

Figure 5.21: Flow chart of the interconnection of the three instruments



Appendices. Table of contents

APPENDICES



Symbols and definitions

SYMBOLS

This section defines the symbols used in *Articulado de la ROM 1.1-18* and lists them by section.

◆ **Section 1**

- h: representative depth of the breakwater subset
- Fc: freeboard
- H: characteristic wave height
- B: representative magnitude of the breakwater width
- L: characteristic wave height
- C_I: investment costs
- C_0: dimensionless economic parameter, whose value depends on the economic structure and level of economic development in the country where the structure will be built
- B/L: relative breakwater width
- Fc/H: relative breakwater height
- SWL: local mean sea level

◆ **Section 2**

- C_0: dimensionless economic parameter
- V: useful life of the breakwater
- h/L: relative depth
- L_i: characteristic wavelength
- h: representative depth of the breakwater subset
- l/L: relative length of a breakwater subset
- C_i: breakwater component (subset, subsystem and/or failure mode)
- N_S: stability number associated with the characteristic wave height of the sea state
- d: average cumulative damage
- dur: characteristic duration of the sea state
- C_0: dimensionless economic parameter, whose value depends on the economic structure and level of economic development in the country where the structure will be built
- H_I: value of the agent at which damage initiates

- H_D: value of the agent at which destruction is reached
- d_0: initial damage
- D: damage produced by a loading cycle of duration $t = t_1 + t_2$
- d_1: damage in time interval t_1
- d_2: damage in time interval t_2
- q: cumulative damage model
- t: time elapsed from the initial moment
- a: parameter of the power-type cumulative damage model
- b: parameter of the power-type cumulative damage model
- c: parameter of the power-type cumulative damage model
- α: function of the dimensionless agent N_s
- T: characteristic wave period
- $D_{n,50}$: equivalent diameter* *of the porous material
- $H_{W,rms}$: root mean square wave height at the breakwater wall
- $H_{T,rms}$: root mean square wave height on the breakwater slope
- $H_{i,rms}$: incident root mean square wave height
- f_{d0}: density function of initial damage
- μ: mean value of the density function of initial damage
- σ: standard deviation of the density function of initial damage
- d_c: critical damage value
- $p_{f,dc}$: failure probability
- $p_{f,V}$: failure probability of the mode in time V
- r: reliability of the structure
- γ: constant of power-type cumulative damage model
- F_d: distribution function of the cumulative damage in a loading cycle
- Φ: normal distribution function
- μ_0: mean value of $(d_0 - \gamma)^{1/b}$
- σ_0^2: variance of $(d_0 - \gamma)^{1/b}$
- kt: mean value of $\int_0^t \alpha\,[N_s\,(t)]\,dt$
- rt: variance of $\int_0^t \alpha\,[N_s\,(t)]\,dt$
- D: damage produced
- D_0: value of initial damage
- Q: dimensionless value of the agent
- $R(t)$: reliability function
- t_V: mean time period from an initial moment
- $WOC_{3,1}$: unforeseen exceptional work conditions
- $WOC_{3,1,1}$: unforeseen exceptional work and operating conditions of the physical environment
- $WOC_{3,1,2}$: unforeseen exceptional work and operating conditions caused by accidents
- $WOC_{3,2}$: foreseen exceptional work and operating conditions
- $WOC_{1,3}$: post-exceptional work and operational conditions
- D_0: initial damage level
- D_f : damage level at which total destruction is declared
- $P_{f,V}$: probabilidad de fallo del modo en el tiempo V
- $D_{1,SR}$: design 1 without repairs
- $D_{2,SR}$: design 2 without repairs
- $D_{1,CR}$: design 1 with repairs
- $D_{2,CR}$: design 2 with repairs
- W: random variable of survival time
- f_W: density function of survival time
- F_W: distribution function of survival time
- t_0: reference time
- U: random variable that describes the interval between failures
- f_U: density function of the time between failures
- F_U: distribution function of the time between failures
- λ_U: mean failure rate per time unit

- μ_U: mean value of U
- t_r: reliable life, time that elapses so that reliability at entry into service, destruction or another cumulative damage level can decrease to a given level
- $h(t)$: danger function
- T_D: availability rate of a component
- τ_F: mean time between failures
- τ_R: mean time needed for repairs
- λ_{D_0}: mean Poisson rate for the initiation of damage
- λ_{D_f}: mean Poisson rate for the destruction of the breakwater
- μ_{W,D_0}: mean survival time with no destruction event from the entry into service of the structure or from the last repairs event
- μ_{W,D_f}: mean survival time with no destruction event from the entry into service of the structure or from the last reconstruction event
- IRP: potential resilience index of the design
- $d_{i,j}$: damage level in failure mode i that triggers the initiation of damage in mode j
- R_i: damage level at which repairs are started in mode i
- t_i: unit time for the repairs of mode i
- F: failure
- NF: non-failure
- S_n: event n
- H: characteristic wave height
- V_0: accumulated overtopping volume
- F_{MT}: toe berm height
- Fc: freeboard

Section 3

- ϑ: incidence angle relative to the breakwater subset
- h/L: relative depth
- h: depth at breakwater toe
- T_z: mean wave period
- L: wavelength at the breakwater toe
- D_0: initial damage level
- V: useful life of the breakwater
- C_i: breakwater component (subset, subsystem and/or failure mode)
- F_{MT}/h: relative berm height
- F_{MT}: toe berm height
- SWL: mean water level
- B_b: toe berm width
- Fc: freeboard
- B: breakwater width
- d: height of water column over the toe berm
- H_I: incident wave height
- h_b: height of breakwater foundation
- d_s: slope width of an S-shaped breakwater
- h_s: slope height of an S-shaped breakwater

Section 4

- Z: safety coefficient
- Zc: minimum safety coefficient value (depending on the failure mode)
- S: safety margin
- S_0: critical safety margin (depending on failure mode)
- X_1: favorable terms, depending on the damage considered
- X_2: unfavorable terms, depending on the damage considered

- x: spatial location of the damage
- t: time of the damage
- d/h: relative submergence
- d: depth of a semi-submerged slab
- η: free surface
- p: pressures on the breakwater
- F: forces on the breakwater
- γ: peak-shaped parameter of the JONSWAP spectrum
- H_{m0}: zero-order moment wave height
- ρ_ω: water density
- g: gravity acceleration
- r: shear resistance of the slab (favorable term)
- Fc: maximum landward or seaward force (unfavorable term)
- B: width of the structure (distance between the submerged slab and vertical wall)
- ϑ: incidence angle relative to the breakwater subset
- A_0: incident wave amplitude
- h: depth at breakwater toe
- η_1: free surface in the outer region
- η_2: free surface in the inner region
- F_1: force exerted on the semi-submerged slab by the outer region
- F_2: force exerted on the semi-submerged slab by the inner region
- F_{total}: total force on the semi-submerged slab
- H_1: wave height in the outer region
- H_2: wave height in the inner region
- T_1: wave period in the outer region
- T_2: wave period in the inner region
- F_{land}: total landward force on the semi-submerged slab
- F_{sea}: total seaward force on the semi-submerged slab
- H: wave height
- F: force on the semi-submerged slab
- S_{min}: minimum value of the safety margin

Section 5

- C_T: total accumulated costs of the breakwater
- τ: hierarchical level of the breakwater subset
- s: hierarchical level corresponding to the subsystems of the breakwater
- m: hierarchical level corresponding to the failure modes of the breakwater
- $\overline{x}$: vector that includes the project factors of the breakwater
- C_{CON}: descriptor of the total costs of breakwater construction
- C_{MAN}: descriptor of the total costs breakwater maintenance
- C_{REP}: descriptor of the total costs of breakwater repair
- C_{DES}: descriptor of the total costs of breakwater dismantling
- C_{CA}: descriptor of the total costs of the cessation of breakwater activity
- C_{EXT}: descriptor of the total costs related to the externalities of the breakwater
- c_{CON}: unit costs of breakwater construction
- c_{MAN}: unit costs of breakwater maintenance
- c_{REP}: unit costs of breakwater repairs
- c_{DES}: unit costs of breakwater dismantling
- c_{CA}: unit costs of the cessation of breakwater activity
- Ψ_{CON}: breakwater construction strategy
- Ψ_{REP}: breakwater repair strategy
- Ψ_{DES}: breakwater dismantling strategy
- Ψ_{GES}: breakwater management strategy
- t: time elapsed from a reference moment

- C_{Ti}: total cost of the breakwater from t_1 to t_2
- c_0: initial cost (related to the construction of the breakwater)
- C_H: repair cost due to the failure or stoppage mode
- q: form of cost accumulation based on the failure mode and its predominant agents
- a: parameter of the power-type cost accumulation model
- b: parameter of the power-type cost accumulation model
- c: parameter of the power-type cost accumulation model
- C_I: investment costs
- C_0: dimensionless economic parameter, whose value depends on the economic structure and level of economic development in the country where the structure will be built
- WOC_1: normal operational work and operating conditions
- WOC_2: extreme operational work and operating conditions
- $WOC_{3,1}$: unforeseen exceptional work and operating conditions
- $WOC_{1,3}$: post-exceptional operational work and operating conditions
- $WOC_{2,3}$: post-exceptional extreme work and operating conditions
- N_S: stability number of the characteristic wave height in the sea state
- d_0: initial damage

◆ **Annex MEIPOR Financial-Economic Indicators**

- $NPFV(I)$: net present financial value of the project
- $(\Delta CF_{proj})_t$: differential free cash flows of the project for the agent considered in year t in a non-project scenario and a project scenario
- $i_{financ.proj}$: Financial Discount Rate of the project
- t: corresponding year in the horizontal time horizon of the project (beginning in year 0)
- T: number of years in the horizontal time horizon of the project
- $IFPR(I)$: Internal Financial Profitability Rate of the project
- $Payback$: period of investment payback
- $(FC_{net})_t$: net cash flows for an agent in year t in a non-project and project scenario
- t': calculation year within the horizon of the investment project
- $(Coverage_{debt.service})_t$: coverage ratio of the debt service for the agent in year t
- $(\Delta I_{op})_t$: operating revenues in year t in a non-project and project scenario
- $(\Delta C_{tax})_t$: tax payments in year t in a non-project and project scenario
- $(\Delta C_{op})_t$: operational costs in year t in a non-project and project scenario
- $(\Delta C_{financ})_t$: funding costs (repayment of capital and interests) in year t in a non-project and project scenario
- $NAEC(I)$: net annual economic value of the project
- $(\Delta E_{total})_t$: variation in the total surplus of year t
- i_{social}: 'social' discount rate of the project
- $IEPR(I)$: Internal Economic Profitability Rate of the project

ACRONYMS

This section lists the acronyms used in the *Articulado de la ROM 1.1-18.*

- LC: breakwater land connection
- IntD: Intermediate (Iribarren) damage
- MA: main alignment
- SA: secondary alignment
- FS: foundation and soil
- WOC_i, with i = 1,2 ó 3: work conditions
- d: damage
- D: destruction
- ID: initiation of damage
- MTPD: maritime-terrestrial public domain

- SPPD: state-port public domain
- SLS: serviceability limit state.
- ULS: ultimate limit state
- F: failure
- RI: resilience index
- ERI: economic repercussion index
- OERI: operational economic repercussion index
- SERI: social and environmental repercussion index
- OSERI: operational social and environmental repercussion index
- IS: inner section
- H: head
- MEIPOR: Method for the Evaluation of Port Investments
- FM: failure mode
- AP: activation point
- OP: outer perimeter
- LOP: landward outer perimeter
- SOP: seaward outer perimeter
- IP: intermediate points
- TD: total destruction of the subset
- ROM: Recommendations for Maritime Works
- ND: no damage
- SS: superstructure
- SbS: subsystem
- T: transition
- ST: survival time
- NPEV: net present economic value
- NPFV: net present financial value

DEFINITIONS

This section defines the most frequent concepts and terms in the *ROM 1.1-18*.

- **Alternatives:** project options.

- **Amplitude:** for oscillatory or wave movements and electromagnetic signals, maximum variation or displacement from a zero value or rest position. It also refers to any physical magnitude that varies periodically or quasi-periodically in respect to a given reference level.

- **Aptitude for service/functionality:** complementary value of the joint failure probability in the project phase or subphase in regard to the failure modes assigned to the serviceability limit states.

- **Armor layers:** layers of unit pieces in a sloping breakwater.

- **Basic variable:** variable that characterizes the agent or the action in a cycle, more specifically, the period (and length) and the amplitude.

- **Bathymetry:** spatial variability of the sea bottom (depths).

- **Bearing capacity:** capacity of soil to support the loads applied to the ground (in reference to foundations). Technically, bearing capacity is the maximum average contact pressure between the foundation and earth, which should not produce shear failure or an excessive differential settlement.

- **Bedding layer:** permeable coarse-grained fill material that facilitates load sharing and the release of interstitial pressure, thus providing a high resistance to shear strength and low deformability.

- **Berm breakwater or S-shaped breakwater:** breakwater made of loose materials, which has a main layer with a berm. This berm is located slightly above mean sea level, and is made of light-weight materials to ensure its static stability. When a berm breakwater is subjected to design loading, the profile of its outer layer is modified until it attains a state of equilibrium.

- **Breaking zone:** area offshore in which waves approaching the coastline start to break, usually in water depths of 5 to 10 meters. Its width can range from tens to hundreds of meters.

- **Breakwater land connection:** subset or section of a breakwater that connects it to the land or to another breakwater.

- **Breakwater:** protective structure built to reduce wave train dynamics through a combination of reflection and dissipation of the incident wave energy.

- **Calm cycle:** period of time during which the values of variables that define the sea state continuously remain below the calm threshold.

- **Central body of the breakwater:** main load-bearing section of a breakwater against wave train dynamics, which can lead to its transformation by processes, such as wave breaking or reflection.

- **Characteristic wave:** oscillation that propagates from the open sea to the coast and whose statistical variables are characteristic of a sea state.

- **Coastal zone:** area that facilitates the sustainable use and exploitation of the littoral environment, such as the correction, protection or defense of the coastline, the generation, conservation and nourishment of beaches and swimming areas, as well as the exchange of land-sea transversal flows of a wide variety of substances.

- **Coastline:** line on the Earth's surface that separates a dry land surface from an ocean or sea.

- **Conditioned density function:** density function of a random variable X conditioned by the occurrence of a value of the random variable Y that measures the probability of X in the subpopulation fulfilling the condition of the given value of Y.

- **Conditioned function:** function in which the density and distribution function of one of the variables is conditioned to the occurrence of a value or range of values of another variable.

- **Construction phase:** project phase lasting from the beginning of construction until the entry in service of the breakwater, namely, the moment when the structure is able to fully perform the main function for which it was initially conceived.

- **Core:** Innermost section of a coastal defense structure, which underlies the outer layers. It is not subject to the direction action of the waves, and should prevent turbulence from affecting the inside of a port or harbor area.

- **Covariance:** statistical measure showing the degree to which two random variables U and V, $Cov[U,V]$, vary or move together. It is the expected value of the product of their variations with respect to their mean values.

- **Crown berm:** horizontal area constructed on both faces of a sloping breakwater to reduce wave run-up and overtopping and to allow access to the breakwater for maintenance purposes.

- **Crown:** highest point on a maritime structure. The crown or crest wall is a concrete structure located on the crown to allow access to the breakwater as well as to partially reduce overtopping and breakwater volume.

- **Current:** stream of water which moves with a velocity much greater than the average or in which the progress of the water is concentrated, and which can be the result of factors, such as tides, waves, river discharge, etc.

- **Damage:** breakage or failure that prevents the breakwater from functioning properly.
- **Danger function:** function that describes the probability of a system failure in a time interval, $t + \Delta t$, on the condition that it has not occurred previously.
- **Decision tree:** decision support tool that uses a tree-like diagram of decisions and their possible consequences to determine event outcomes and possible results.
- **Deformation:** change of size or shape of a body due to internal stresses caused by one or more applied forces.
- **Density function:** function that determines the probability of a random variable X, which is continuous, $f(x)$, and measures the intensity or probability rate of the value x.
- **Deterministic formulation:** mathematical expression in which the predominant and non-predominant agents and actions and of parameters take nominal or determined values, independently of their probability of exceedance.
- **Directional wave tank:** tank used in laboratories to obtain time series of instantaneous and basic variables of the wave dynamics in port and shoreline areas. The results depend on the time series with which the paddles are activated as well as their response.
- **Dismantling, transformation, and remodeling phase:** project phase that begins the moment when the breakwater subset is able to perform the main function for which it was initially conceived, and which ends with its remodeling, transformation or dismantling. This phase can be partially or totally interrupted during the maintenance and repair phase.
- **Dismantling:** process of tearing down and removing a structure and, when necessary, restoring the location to its original conditions before the structure was there.
- **Distribution function:** function that describes the probability that X or an accumulated distribution function is a function, $F(x)$, which assigns each event its probability of non-exceedance.
- **Distribution of extremes:** distribution that determines the probability that any extreme value X is less than another value x.
- **Dock:** structure built on the coastline or the shore of a navigable river where ships are loaded, unloaded or repaired, and where other operations are also performed.
- **Docking area:** area where a vessel's movement is restricted, for example, by means of one or various anchors.
- **Draught:** water depth required for a ship to float. As a safety measure, there should always be sufficient room under the keel to allow for a full cargo. Also draft.
- **Economic repercussion index (ERI):** index that quantitatively evaluates economic repercussions because of the reconstruction of the structure or because of the foreseeable cessation or modification of its activities in the event of its destruction or loss of total operationality.
- **Erosion:** modification of the geometry of the main armor layer or foundation bed because of the loss of the materials that compose it.
- **Estimation:** value provided by the estimator when it is applied to a specific case.
- **Event:** outcome formed by a sample element or a combination of sample elements, which represents a manifestation or project state. The sample elements are the simplest events that permit the description of the set of possible events.

- **Exceedance duration:** time interval (e.g. meteorological year or useful life) during which the state descriptor remains higher than the selected value.

- **Exceptional work conditions:** set of project states associated with certain project factor values that have a very low probability of exceedance, and which have a probability of occurrence much smaller than the predominant project factors that define extreme work conditions. Their occurrence can be unexpected and accidental or they can occur for foreseeable use and exploitation reasons. These conditions can be either predictable or unexpected. When they are unforeseen, they can be caused by environmental agents or by unexpected events.

- **Extreme regime:** distribution function of the highest value of the peaks of the loading cycles in each meteorological year.

- **Extreme value:** largest value that a random variable can take in a given number of observations.

- **Extreme work conditions:** conditions defined by foreseeable maximum values of the variable in a given period of time.

- **Failure mode:** geometric, physical, mechanical, chemical or biological form or mechanism that causes the structure or one of its components to go out of service because of structural reasons. A failure mode is assigned to an ultimate or serviceability limit state for its verification.

- **Filler:** artificial deposit of natural materials from the Earth's crust (e. g. soil, rocks) or special artificial elements (e.g. tetrapods, dolos) or industrial or urban waste material (rubble, slag).

- **Foundation:** section of a breakwater in contact with the land surface, and thus, the point where stress is transferred to the ground and soil.

- **Frequency:** number of times that a certain event occurs. Inverse of the period, $f = \frac{1}{T}$.

- **Global circulation:** world-wide system of winds by which the necessary transport of heat from tropical to polar latitudes is accomplished, thus compensating the action of solar radiation.

- **Granular filler:** filler composed of gravel and/or sand extracted from the ground, and which has very little fine-grained material.

- **Head:** end of a breakwater, which is generally the part most exposed to the action of sea or ocean waves.

- **Histogram:** multiple-bar graphical representation, used in statistics to represent the frequency distribution of a group as a function of some variable. The frequency of each class is proportional to the length of its associated bar. The vertical axis represents the frequencies, and the horizontal axis represents the values of the variables, generally signaling the class midpoints in other words, half of the interval in which the data is clustered.

- **Incident energy or energy flux:** rate of energy flow through a reference or control volume surface in the time unit.

- **Initiation of damage:** state of the construction in which there is incipient damage in some part because of one of the principal failure modes.

- **Instantaneous variable:** variable that describes the instantaneous movements of the fluid, vessel, particles, etc. It can be kinematic (velocity and acceleration of the fluid particle) or dynamic (pressures and shear stresses on the particle surface per unit of volume).

- **Joint density function:** density function of the joint probability of two random variables, X and Y, which are continuous, $f(x,y)$, and which measure the probability rate of the intersection of events, X and Y, in other words, of the simultaneous occurrence of X and Y.

- **Joint distribution:** distribution of the probability that two events X and Y will occur simultaneously. In the case of two random variables, this is called a bivariate distribution,but the concept generalizes to any number of events and random variables.

- **Landward side:** side of the structure that is sheltered from the waves.

- **Level I methods:** verification methods of failure modes in which project design factors and term values are calculated generally with deterministic criteria. Examples of this type of method include global and partial safety coefficient methods.

- **Level II methods:** verification methods in which the verification equation is defined according to first-order statistical moments, and in which, thanks to functional transformations, it is expressed in terms of reduced and independent Gaussian variables. This method relates the failure probability to the minimum distance from the origin of the coordinates to the surface of the failure (G=0), which is a verification equation in safety margin format. In the time interval, the distribution functions and covariance of the project factors should be known.

- **Level III methods:** verification method used to obtain the solution of the verification equation by integrating a multidimensional function in the failure domain. This integration is complex, and generally the failure domain and project factor values can be obtained by numerical simulation techniques (e.g. Monte Carlo simulation). In the time interval, the joint distribution of the project factors intervening in the verification equation should be known.

- **Limit state methods:** calculations to verify that for each failure or stoppage mode, the project requirements are met in regards to reliability, functionality, and operationality in all project phases and states, assigned to limit states of safety, serviceability, and use and exploitation.

- **Liquefaction:** process that eliminates the capacity of a low-density, saturated granular soil to resist shear stress because of an increase in interstitial pressure caused by vibrations or rapid loading.

- **Loading cycle:** sequence of meteorological states that begins when certain statistical descriptors that define the state exceed a given threshold, and which ends when they fall below it again. Sea loading cycles are also known as storms.

- **Longshore current:** littoral current that moves parallel to the shore, usually generated by waves breaking at an oblique angle to the shoreline.

- **Main alignment:** breakwater subset that provides shelter for the harbor and controls sea oscillations.

- **Main layer:** outermost layer and most resistant element of a sloping breakwater against which wave energy is dissipated.

- **Main propagation direction:** direction with the maximum energy flux.

- **Maintenance and repair phase:** project phase that includes the time intervals in which maintenance and repair work is circumstantially carried out, and which may involve a reduction in safety and in the aptitude for service or the use and exploitation of the work in one of its subsets or in the harbor area.

- **Maneuvering area:** area in or bordering the harbor where vessels may stop or start to navigate as well as change direction.

- **Marginal density function:** probability density function that measures the probability rate of variable X in the total population, apart from another variable.

- **Marginal functions:** density and distribution functions of one of the variables, independently of the values of the other.

- **Maritime climate:** characterization of marine dynamics over long periods of time or the statistical description of temporal variation in terms of sea states at a given location. It can be defined according to one-dimensional and bidimensional statistics of geometric-statistical and spectral parameters, representative of the meteorological state in the area under study.

- **Mass concrete:** concrete with no structural reinforcement.

- **Maximum stoppage duration:** maximum expected time of an operational stoppage.

- **Maximum wave height:** estimate of the largest single wave that will occur in a particular sea state.

- **Mean period:** average period of the waves observed, weighted by wave energy.

- **Mean time between cycles:** time period between two loading cycles.

- **Mechanism:** way in which a failure or stoppage occurs.

- **Meteorological state:** state that describes and characterizes the simultaneous manifestation of atmospheric agents (wind speed and direction, precipitation, fog, etc.) and marine agents (sea waves,meteorological and astronomical tide, other long-period oscillations and currents).

- **Meteorological year:** time period from 1 October until 30 September of the following year, which is regarded as the meteorological pulse of the planet.

- **Mixed breakwater:** breakwater consisting of a granular base which is the foundation for the reflecting structure. The performance of the breakwater as a wave-reflecting or wave-breaking structure depends on the foundation depth and characteristics of the incident waves.

- **Monte Carlo simulation:** analytical technique for modeling a process or system subjected to random forcings, and calculating the probability distribution of possible outcomes. It involves performing a large number of trial runs called simulations, and inferring a solution from the collective results of the trial runs. The objective is to understand the behavior of the system or to evaluate various strategies that can be used to operate the system, using the Monte Carlo algorithm.

- **Mooring and berthing area:** area where vessels to carry out passenger and cargo handling operations. This includes all activities related to the loading, unloading, embarking, and disembarking of passengers, vehicles, and cargo.

- **Mouth:** opening that functions as the entrance or exit of a port or dock.

- **Mutually exclusive modes:** modes in which the occurrence of one mode excludes the occurrence of the others as well as those that are not mutually exclusive.

- **Nature of the subset:** indicator of the importance of each subset, as measured by the environmental, social, and economic repercussions generated in the event of its destruction or irreversible loss of its functionality. It is thus indicative of the magnitude of the consequences derived from the eventual failure of the breakwater after its entry into service.

- **Non-principal modes:** failure or stoppage mode for which small increases in the total costs of the structure significantly improve the reliability, functionality or operationality of the structure when affected by the mode.

- **Normal incidence:** angle at which wave trains perpendicularly impinge on a pre-established alignment, generally a breakwater or coastline.

- **Normal work conditions:** conditions in which an installation can operate without any constraints or limitations, and in which its exploitation or operationality is not affected by environmental elements.

- **Oblique incidence:** angle at which wave trains impinge on a pre-established alignment, generally a breakwater or coastline.

- **Operational cycle:** sequence of meteorological states in which the value of certain descriptors that define the state continuously remains below a threshold value of operationality.

- **Operational economic repercussion index (OERI):** index that quantitatively evaluates the costs of the operational stoppage of a subset of the structure.

- **Operational limit state:** state in which the exploitation of the port area is temporarily reduced or suspended because of causes external to the structure without any structural damage.

- **Operational nature:** indicator of the environmental, social, and economic repercussions generated because of an absence or reduction in operationality conditions in the area protected by the breakwater or its accesses. It is thus indicative of the magnitude of the consequences derived from the operational stoppages in the serviceability phase of the breakwater.

- **Operational social and environmental repercussion index (OSERI):** index that qualitatively estimates the social and environmental impact of an operational stoppage mode of the maritime structure. For this purpose, it values the possibility and consequences of the loss of human life, damage to the environment, loss of historical and cultural heritage, and social disruption.

- **Operationality:** complementary value of the stoppage probability in a project phase or subphase, as considered in relation to the stoppage modes assigned to the operational stoppage limit states.

- **Outer seawall:** non-principal breakwater whose function is to protect the harbor area from less severe sea states and to delimit the harbor mouth and the port area.

- **Overtopping:** part of the water that is carried over the top or crest of a coastal defense structure as a consequence of wave train dynamics, and which does not return directly to the sea.

- **Partial entry in service:** situation when breakwater or one of of its subsets temporarily be-gins to function during the construction phase. In this case, the admissible failure probability during this transition stage should be specified in the project design, based on the environmental and social consequences of the failure in this situation and including conditions related to construction.

- **Peak period:** period of maximum wave energy, as reflected in the wave spectrum.

- **Port area:** area where port and logistic operations are performed, pertaining to the integral management of vessels, and all aspects of maritime transportation as well as its connections with land and air traffic. Sport, nautical, industrial and military operations are also carried out in this area.

- **Principal modes:** failure or stoppage mode for which the improvement of the reliability, functionality or operationality of a subset of a structure is difficult, or can only be achieved with significant increases in the costs of the structure.

- **Probabilistic formulation:** formulation in which the values of the equation terms are determined, based on their respective probability models in the phase analyzed. They are calculated from probability models of parameters and agents.

- **Probability of occurrence of the failure/stoppage mode in the time interval:** product of dangerousness and vulnerability.

- **Project phase:** temporal sequence of project states during which the subset of a structure maintains the same main activity although it can have other secondary activities. Project phases include the following: preliminary studies and project design, construction, service, maintenance, repairs, and dismantling. The duration of the serviceability phase is the useful life of the subset.

- **Project:** in the context of the ROM program and documents, set of activities that includes the preliminary study and drafting of the project, construction, exploitation, maintenance, repairs (if necessary) and the dismantling of a maritime structure.

- **Propagation direction:** direction in which a wave travels.

- **Radiation:** propagation energy in the form of electromagnetic waves or subatomic particles through a vacuum or material medium.

- **Random variable:** Measurable function that assigns real values to the elements of the sample space.

- **Refraction:** process by which the direction and height of a wave changes when it moves from one water depth to another or when it obliquely impinges on a current.

- **Regime:** in statistics, distribution function of one or various state variables in a given time interval. In hydrodynamics, this refers to specific flow conditions (laminar, turbulent, or oscillation, and Stokes or Boussinesq).

- **Reinforced concrete:** concrete in which metal bars or wire are embedded to increase its tensile strength.

- **Reliability:** complementary value of the joint failure probability in the project phase or subphase against the failure modes assigned to the ultimate limit states.

- **Repair time:** time period during which breakwater is repaired because of damage caused by storms.

- **Resilience:** capacity of a system to withstand damage without being completely destroyed.

- **Risk:** product of the probability that an event will occur with negative consequences.

- **Safety coefficient:** relation between the maximum capacity of a system and the value of the actual demand that it is subject to.

- **Safety margin:** $S = x1 - x2$, where $x1$ and $x2$ designate actions that oppose or favor the occurrence of the failure mode.

- **Safety threshold state:** state that describes and characterizes the beginning and end of a storm or loading cycle. It is usually related to extreme work conditions, in other words, the occurrence of the most severe meteorological states.

- **Sample space:** set of all possible values of the sample population.

- **Sample:** in statistics, part of a population.

- **Sea state curves:** curves that define the sequence of sea states that continuously occur over time. They represent the evolution of a given statistical parameter in the sea state, such as the significant wave height.

- **Sea state:** time interval in which any sea wave manifestation can be considered to be statistically stationary. It can be characterized by a representative wave height and period (e.g. significant wave height,mean period or peak period).

- **Seaward side:** breakwater face that receives waves from the sea.

- **Secondary alignments:** alignments that connect the various breakwater subsets.

- **Secondary layers:** inner layers of a sloping breakwater, which support the main layer and are the transition to the core.

- **Seism:** tremor of the earth's surface, usually triggered by the release of underground stress along fault lines within the Earth. The released energy passes through the Earth as seismic waves (low-frequency sound waves) that propagate in all directions and which cause the shaking. The point at which the earthquake originates is called its hypocenter. When earthquakes occur under sea water, they can produce a tsunami.

- **Serviceability limit state:** project state in which the structure as a whole or one of its subsets or elements becomes unusable or out of service because the service requirements specified in the project are not met. In this state, there is a reversible or irreversible loss of functionality in the structure or one of its parts, due to environmental, aesthetic or structural failure or because of a legal determinant. This state considers all those failure modes that reduce or condition the use and exploitation of the structure, and which can signify a reduction in the useful life or the probability of its survival because of the deterioration of the properties of construction materials or soil, of strains or excessive vibrations in the structure for the use and exploitation of the structure or cumulative geometric alterations.

- **Serviceability phase or useful life:** project phase that includes the time intervals in which remodeling/ reconstruction, transformation, or dismantling and restoration activities are continuously or discontinuously carried out at the site.

- **Sheltered area:** water and land surface sheltered from the action of atmospheric and marine dynamics.

- **Shoaling:** propagation of a wave train from deep to shallow waters, which causes the wave height to increase. Both wave celerity and length decrease, whereas the wave amplitude varies as a consequence of the reduction in the energy propagation velocity. These two modifications result in a change of the wave steepness value H/L.

- **Shore:** fringe of land composed of two zones, the inner continental platform and the breaker or surf zone. As the location of harbor areas, it is where maritime constructions and ports are built.

- **Significant wave height:** mean wave height of the highest third of the waves in a sea state.

- **Sloping breakwater with or without a crown wall:** breakwater with a sloping frontal or seaward wall composed of granular material. It dissipates wave energy by wave-breaking, friction with the granular material and wave transmission towards the harbor area. Also *rubble mound breakwater.*

- **Social and environmental repercussion index (SERI):** index that qualitatively evaluates the expected social and environmental impact in the event of the destruction or total loss of operationality of the maritime structure. It values the possibility and consequences of the loss of human life, damage to the environment, loss of historical and cultural heritage, and social disruption. The failure in the structure is always considered to have occurred when the economic activities directly related to the structure have been consolidated.

- **Solutions:** alternatives that fulfill the formulation of the problem (project requirements).

- **Spatial domain:** surface on which an activity takes place, whether physical or mathematical. In the case of oscillatory motion, this domain is defined according to the wavelength L and relative depth, $\frac{h}{L}$ where h is the water depth.

- **State curves:** curves that represent the temporal evolution of a state descriptor at a given point in the sea.

- **State descriptors:** descriptors that represent the statistical or frequency variability in a given state.

- **State duration:** time period that elapses before a significant change in a process occurs, and thus, the time during which the hypotheses that it is based on are fulfilled.
- **Statistic:** any function of the observed or sample values that is quantifiable and that does not have any unknown parameters.
- **Stoppage time:** time period during the construction of the breakwater in which it is impossible to work because of damage, storms, or other circumstances.
- **Submerged breakwater:** breakwater similar to a submerged breakwater without a crown wall, but whose crest is below low tide.
- **Subset of structure:** continuous set of sections (or breakwater alignments) that fulfills a specific function in line with the objectives and exploitation requirements of the structure. This set is subject to the same action levels of all agents, particularly the predominant agents, and are part of the same formal and structural typology.
- **Superstructure or crown wall:** structure that protects the breakwater from overtopping and provides an access path to the land and even a mooring area landward from the breakwater.
- **Survival functions:** function that describes the exceedance probability of an event.
- **Survival time:** random variable that designates the time elapsed from a reference point (usually the breakwater's entry into service) until a failure occurs in one of its systems or components.
- **Threshold value:** value below which no effect is expected to appear.
- **Tidal currents:** periodic movements of water driven principally by the astronomical tide, and which can be flood tides or ebb tides, depending on whether they are incoming or outgoing.
- **Time distribution:** series or continuous data record of a variable during a given time interval.
- **Time domain:** time interval in which an activity takes place, whether physical or mathematical. In the case of oscillatory motion, this domain is defined according to the wave period T and number of waves.
- **Time series:** sequence of observations or simulations of a variable, listed in time order.
- **Toe berm:** protective element, composed of granular material that is located at the breakwater toe, and which is the foundation of the protective layers.
- **Total annual construction cost:** sum of the estimated cost of the damage annually produced by each of the principal modes and the equivalent annual cost of the investment.
- **Total exploitation and maintenance cost:** all costs (with their corresponding schedule) necessary so that the subset can provide suitable use and exploitation conditions for the harbor area and its installations, while complying with operationality, functionality, and reliability requirements.
- **Total investment cost:** sum of the estimated cost of the accumulated annual damage produced by each of the principal failure and stoppage modes and the cost of the investment.
- **Transition of a breakwater:** subset of the breakwater between two alignments or typologies. This section can be a structurally weak part of the breakwater.
- **Transmission (of wave energy):** process by which part of the incident energy produced when a wave train interacts with the breakwater is transmitted landward through or over the breakwater section.

- **Tsunami:** long wave with a period between fifteen minutes and an hour and a height of over 15 meters when it reaches land. It can be generated by the sudden displacement of water by submarine earthquakes, landslides, volcanic eruptions, submarine slumps or other causes.

- **Ultimate limit state:** project state in which the structure as a whole or one of its subsets or elements becomes unusable or goes out of service because the safety requirements specified in the project are not fulfilled. This state produces the deterioration, breaking, or collapse of all or part of the structure. It considers all those failure modes due to the loss of equilibrium of all or part of the structure as a rigid solid or due to the excessive plastic strains, breakage, loss of stability, accumulation of strains, progressive cracking, or fatigue under repeated loads.

- **Unit piece of the main layer:** large quarry rock or prefabricated concrete block of a certain shape that is used as the main protection against wave train dynamics on the main armor layer of a sloping breakwater.

- **Use and exploitation cycle:** sequence of meteorological states in which the probability of a stoppage mode assigned to the operational limit states is not significant either in the calculation of the joint probability of operational stoppage in the useful life of the structure or in the number of operational stoppages or in the duration of the operational stoppage.

- **Use and exploitation threshold state:** state that describes and characterizes the beginning and end of an interval of calms and of the operational cycle during which the structure and its installations are operational, and use and exploitation are thus possible; it is usually associated with normal operational work conditions.

- **Useful life:** time interval during the serviceability phase of a structure or one of its subsets. Generally speaking, this corresponds to the time during which the structure or one of its subsets fulfills the main function for which it was conceived.

- **Variance:** measure of the dispersion of a random variable in respect to its mathematical expectation.

- **Verification equation:** functional relation between project factors that describe the occurrence of each failure mode. This equation can have different formats: global safety coefficient, safety margin, etc.

- **Vertical breakwater:** breakwater with a vertical face, in which the central body and super-structure are composed of a single structural element, which reflects the incident energy flux. It can also be composed of a permeable vertical structure.

- **Vessel:** watercraft with a deck, which, because of its size and strength, is suitable for navigation and the water transportation of goods and passengers.

- **Wave breaking:** energy dissipation process that occurs when waves reach shallow water areas or excessively steep areas with an uneven profile.

- **Wave group:** series of two or more waves propagating together in which the wave direction, wave length, and wave height vary only slightly.

- **Wave height:** vertical distance between the trough of a wave and the following crest.

- **Wave period:** time interval between two successive crests or between two successive zero crossings.

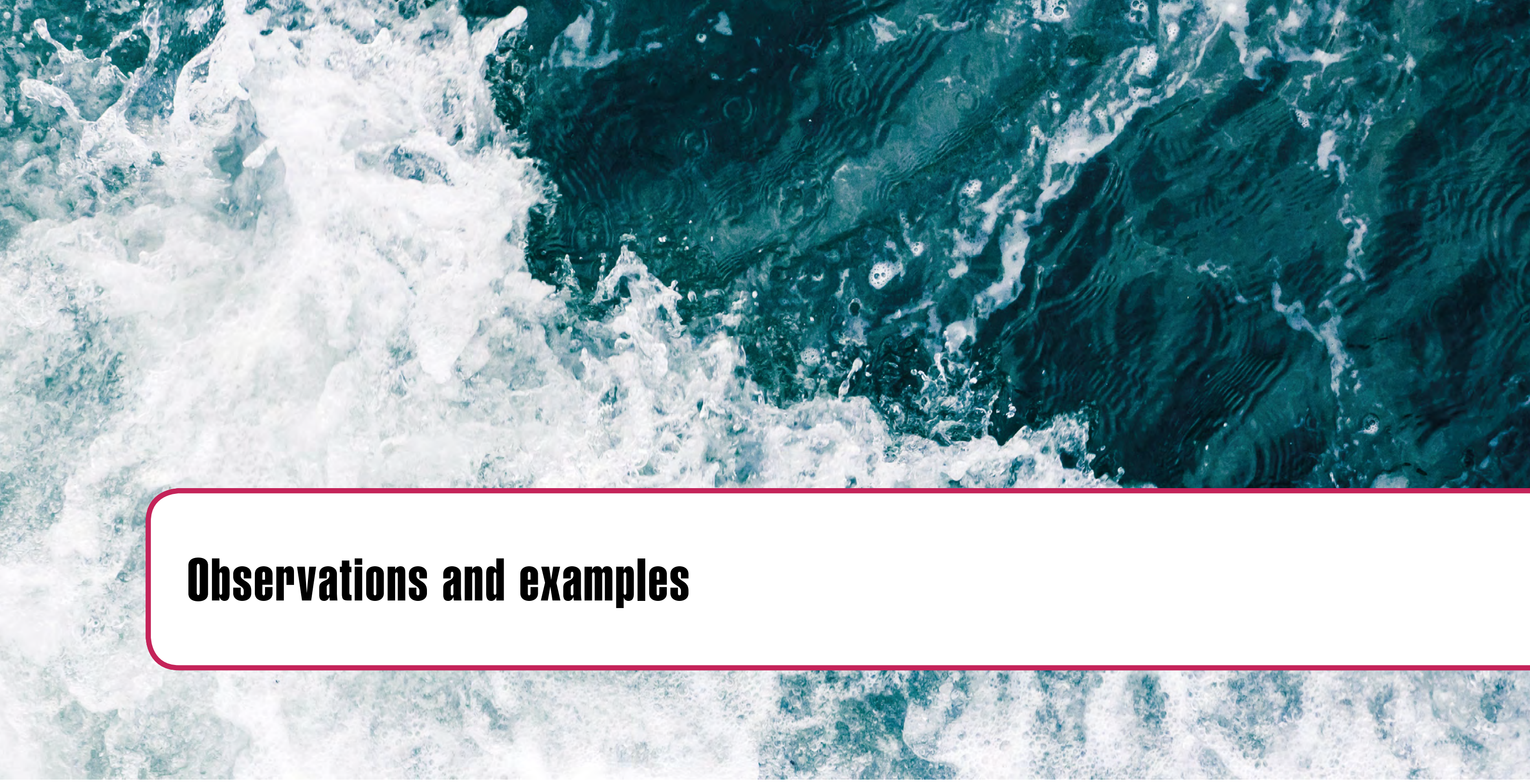
- **Wave propagation:** transmission of waves through a medium. During this process, the waves undergo a series of transformation processes that affect their height, period, direction, and spectrum. The propagation processes most frequently used in the evaluation of this transformation are shoaling, refraction, diffraction, and the transmission and breaking of waves.

- **Wave train:** indefinite repetition of the wave cycle.

- **Wavelength:** horizontal distance between the crest (or trough) of one wave and the next in the same wave train.

- **Waves:** oscillatory movements in a body of water produced by the continuous action of the wind on the water surface (fetch) during a certain time period and manifested by an alternate rise and fall of the water surface. This phenomenon produces a set of random oscillations that are more or less irregular with different propagation directions and with wave periods from 1 to 30 seconds.

- **Wind:** natural movement of the air in the atmosphere, especially in the troposphere because of air pressure differences due to temperature variations (cold air moves downward and warm air moves upward).



Observations and examples

OBSERVATIONS

- Diagram of the cumulative damage process in the loading cycle, Article 2.4.3
- Temporal evolution of the cumulative failure probability, Article 2.4.4
- Sequence used to estimate the parameters of the damage evolution model, Article 2.4.4
- Component diagrams in other technical texts 3.3.2
- Design with and without a repair strategy, Article 3.7.1
- Diagram of the decision tree for a spreading and activation network and possible repair strategies, Article 3.7.2
- Correspondence between the joint failure probability (Table 4.2) and the Variants and Level I, II, and III Methods, Article 4.1.1

EXAMPLES

- Cumulative model of the overtopping volume in a loading cycle, Article 2.4.5
- Spatial hierarchy of a breakwater: subsets, subsystems, and failure mode diagram, Article 3.3.1
- Spreading and activation networks for different subsets, subsystems, and modes, Article 3.6.1
- Distribution function of the safety margin in a breakwater with a frontal oscillating camera, Article 4.3.4
- Calculation of the total costs of a sloping breakwater 5.3.3
- Calculation of the PDF of the investment project profitability, based on the damage level of the breakwater, Article 5.5.4

Bibliography

THEORETICAL BACKGROUND

Castillo, E. (2012). *Extreme value theory in engineering.* Elsevier.

Kottegoda, N.T. and Rosso, R. (2008). *Applied statistics for civil and environmental engineers.* Blackwell Chichester, UK.

Losada, M. A. (1989). "Recent developments in the design of mound breakwaters". In: *Handbook of Coastal and Ocean Engineering. University of Cantabria*. Chapter 21.

REFERENCED ARTICLES

Burcharth, H. F. (1992). "Reliability evaluation of a structure at sea". In: *Design and Reliability of Coastal Structures, short course during the 23rd ICCE in Venice* (cited on page 10, 102).

Castillo, M., Castillo, E., Fernández-Castelli, A., Molina, R. and Gómez, R. (2012). "Stochastic Model for Damage Accumulation in Rubble-Mound Breakwaters Based on Compatibility Conditions and the Central Limit Theorem". In: *Journal of Waterway, Port, Coastal, and Ocean Engineering* 138.451-463 (cited on pages 63, 67, 68, 166).

Clavero, M., Vílchez, M., Pérez, D., Benedicto, M. I. and Losada, M. A. (2012). "An unified design method of maritime works against waves". In: *Coastal Engineering Proceedings* 1.33, page 76 (cited on page 95).

Jalón, M. L., Lira-Loarca, A., Baquerizo, A., and Losada, M. Á. (2018). "An analytical model for oblique wave interaction with a partially reflective harbor structure". In: *Coastal Engineering*. ISSN: 0378-3839. DOI: https://doi.org/10.1016/j.coastaleng.2018.10.015. URL: http://www.sciencedirect.com/science/article/pii/S0378383918302679 (cited on page 148).

Kortenhaus, A. y Oumeraci, H. (1998). "Classification of wave loading on monolithic coastal structures". In: *Proc. of the 26st International Coastal Engineering Conferece, ASCE*, pages 867-880 (cited on page 10, 91).

Mínguez, R., Castillo, E., Castillo, C. and Losada, M. A. (2006). "Optimal cost design with sensitivity analysis using decomposition techniques. Application to composite breakwaters". In: *Structural Safety* 28.4, pages 321-340 (cited on pages 171, 172).

Molines, J., Herrera, M. P. and Medina, J. R. (2018). "Estimations of wave forces on crown walls based on wave overtopping rates". En: *Coastal Engineering* 132, páginas 50-62 (véase página 68).

Pérez-Romero, D. M., Ortega-Sánchez, M., Moñino, A. and Losada, M. A. (2009). "Characteristic friction coefficient and scale effects in oscillatory porous flow". In: *Coastal Engineering* 56.9, pages 931-939 (cited on page 129).

PIANC (2016). Recommendations for the increased durability and service life of new marine concrete infrastructure. Report 162. PIANC (cited on page 41).

Sanchidrián, I. (2001). "Consideración de los riesgos accidentales en los métodos de dimensionamiento de las áreas de navegación y flotación". In Spanish. In: *Información mensual de Puertos del Estado* 86, pages 65–80 (cited on page 185).

Solari, S. and Van Gelder, P. (2011). "On the use of Vector Autoregressive (VAR) and Regime Switching VAR models for the simulation of sea and wind state parameters". In: *Marine Technology and Engineering* (cited on page 78).

Van Gent, M. and Van der Werf, I. (2014). "Toe Stability of Rubble Mound Breakwaters". In: *Coastal Engineering Proceedings* 1.34, page 22 (cited on page 169).

Van der Meer, J. W. (1988). "Stability of Cubes, Tetrapodes and Accropode". In: *Proceedings of the Breakwaters '88 Conference; Design of Breakwaters*. Edited by L. Institution of Civil Engineers Thomas Telford, pages 71–80 (cited on page 64).

Vílchez, M., Moyano, J., Clavero, M., Miguel, M., and Losada, M. (2011). "Forces and subpressures on nonovertoppable vertical breakwaters". In: *Proceedings of the 6th International Conference of Coastal Structures* (cited on page 95).

Vílchez, M., Clavero, M., and Losada, M. A. (2015). "Verification of Rock Toe Stability Applying the Hydraulic Performance Curves". In: *Proceedings of the Coastal Structures and Solutions to Coastal Disasters 2015* (cited on page 169).

Vílchez, M., Clavero, M., Lara, J. L., and Losada, M. A. (2016a). "A characteristic friction diagram for the numerical quantification of the hydraulic performance of different breakwater types". In: *Coastal Engineering* 114, pages 86–98 (cited on page 129).

Vílchez, M., Clavero, M., and Losada, M. A. (2016b). "Hydraulic performance of different nonovertopped breakwater types under 2D wave attack". In: *Coastal Engineering* 107, pages 34–52 (cited on page 95).

Vílchez, M., Clavero, M., Baquerizo, A., and Losada, M. A. (2017). "An Approximation to the Statistical Characteristics of Wind Waves in Front and from the Toe of the Structure to the Toe of the Crown of Nonovertopped Breakwaters". In: *Coastal Engineering Journal* 59.03, page 1750012 (cited on page 68).

REFERENCED BOOKS

CE (2002). *Guía del análisis costes-beneficios de los proyectos de inversión.* In Spanish. DG Política Regional de la Comisión Europea (cited on pages 16, 159).

MEIPOR-16 (2016). *Revisión y Actualización del Método de Evaluación de Inversiones Portuarias (MEIPOR).* In Spanish. Puertos del Estado (cited on pages 15, 16, 36, 80, 128, 159, 160, 161, 166, 172, 175, 176, 177, 178, 216, 217).

PIANC (2016). *Criteria for the selection of breakwater types and their related optimum safety levels. Report 196.* PIANC (cited on pages 10, 41, 47, 80, 100, 101, 174, 175, 176).

ROM 0.0-01 (2001). *ROM 0.0. Procedimiento General y las Bases de Cálculo en el Proyecto.* In Spanish. Puertos del Estado, page 218. ISBN: 84-88975-30-9 (cited on pages 15, 19, 24, 25, 28, 29, 39, 41, 45, 48, 70, 71, 73, 78, 79, 80, 81, 110, 115, 123, 124, 125, 127, 128, 130, 132, 133, 135, 138, 139, 140, 148, 159, 160, 172, 173, 174, 178, 184).

ROM 0.5-05 (2005). *ROM 0.5.-05. Geotecnia para las Obras Marítimas y Portuarias.* In Spanish. Puertos del Estado. ISBN: 84-88975-52-x (cited on pages 16, 41, 103, 104, 139, 142).

ROM 1.0-09 (2009). *ROM 1.0-09. Recomendaciones del diseño y ejecución de las Obras de Abrigo.* In Spanish. Puertos del Estado. ISBN: 978-84-88975-73-7 (cited on pages 15, 16, 24, 29, 39, 41, 47, 48, 50, 52, 53, 71, 79, 80, 91, 92, 109, 124, 128, 132, 134, 142, 155, 172).

ROM 2.0-11 (2011). *ROM 2.0-11. Obras de atraque y amarre: Criterios generales y Factores de Proyecto.* In Spanish. Puertos del Estado. ISBN: 978-84-88975-78-2 (cited on page 16, 42).

ROM 5.1-13 (2013). *ROM 5.1-14. Calidad del Agua Litoral en las Áreas Portuarias.* In Spanish. Puertos del Estado. ISBN: 978-84-88975-81-2 (cited on pages 42, 92).

ROM 0.2-90 (1990). *ROM 0.2-90: acciones en el proyecto de obras marítimas y portuarias.* In Spanish. Puertos del Estado. ISBN: 9788474337013 (cited on page 80).

ROM 3.1-99 (1999). *ROM 3.1-99. Configuración Marítima de los Puertos: Canales de Acceso y Áreas de Flotación.* In Spanish. Puertos del Estado. ISBN: 978-84-49805-13-4 (cited on pages 16, 42, 185).

Suárez Bores, P. (1976). *Optimización de obras marítimas.* In Spanish. Universidad Politécnica de Madrid (cited on pages 175, 176).

OTHER DOCUMENTS REFERENCED IN THE TEXT

Benedicto, I. (2004). "Comportamiento y evolución de la avería de los diques de abrigo frente a la acción del oleaje". In Spanish. PhD thesis. Universidad de Granada (cited on page 58).

Campos, A. (2016). "A methodology for the analysis of damage progression in rubble mound breakwaters." PhD thesis. Universidad de Castilla-La Mancha (cited on page 58).

Clavero, M. (2007). "Comportamiento de los diques en talud frente a la acción del oleaje y criterios para el reparto de la probabilidad conjunta de fallo en la vida útil". In Spanish. PhD thesis. Granada (cited on page 58).

Gómez-Martín, E. (2015). "Análisis de la evolución de averías en el manto principal de diques en talud formado por escolleras, cubos y cubípodos". In Spanish. PhD thesis. Universidad Politécnica de Valencia (cited on page 58).

Guanche, R. (2007). "Análisis de la funcionalidad y estabilidad de obras marítimas mediante un modelo numérico basado en las ecuaciones de Reynolds." PhD thesis. Universidad de Cantabria (cited on page 58).

IH Cantabria and McValnera (2018). *Aplicación metodológica del análisis de rentabilidad económico-financiera del proyecto de construcción e inversión de una obra marítima mediante el uso dual ROM-MEIPOR*. In Spanish. Technical report (cited on page 179).

Lara, J. L., Ruju, A., and Losada, I. J. (2011). "RANS modelling of long waves induced by a transient wave group on a beach". In: *Proceedings of the Royal Society A*. Volume 467, pages 1215–1242 (cited on page 92).

Maciñeira, E. (2005). "Determinación de una fórmula para el cálculo de la estabilidad del morro de los diques en talud. Análisis de los distintos factores que intervienen." In Spanish. PhD thesis. Universidad de A Coruña (cited on page 58).

MEIPOR Financial-Economic Indicators

This Annex includes the definitions of some of the indicators used in MEIPOR 2016 for the financial-economic profitability, financial sustainability, and risk assessment of the investment project, and when relevant, the equations used for its evaluation. The only indicators included are those that participate in the dual optimization and which favor the economic, financial, and technical dialogue between the ROM 1.1-18. and the investment manual. Since this Annex is merely informative, it is advisable to consult MEIPOR 2016, which is the original source.

FINANCIAL-ECONOMIC INDICATORS

MEIPOR defines two profitability indicators: (a) financial indicators; (b) economic indicators.

Financial profitability indicators (FPI)

This Annex defines the FPI of the project (FPIP) and those of the capital (FPIC).

Financial profitability indicators of the project (FPIP)

FPIPs include the following:

- **Net Present Financial Value of the project, (NPFV) (I)**
  The NPFV is the sum of the value of the differential cash flows of the project discounted at the first year of the contract through the definition of a financial discount rate of the project for each agent (equation 5.4).

$$NPFV(I) = \sum_{t=0}^{T} \frac{(\Delta CF_{proj})_t}{(1 + i_{financ.proj})^t} \tag{5.4}$$

Where

- $NPFV\,(I)$: Net Present Financial Value of the project.
- $(\Delta CF_{proj})_t$: Differential free cash flows of the project for the agent considered in year t in a non-project scenario and a project scenario.
- $i_{financ.proj}$: Financial Discount Rate of the project.
- t: Corresponding year in the horizontal time horizon of the project (beginning in year 0).
- T: Number of years in the horizontal time horizon of the project.

◆ **Internal Financial Profitability Rate of the project (IFPR) (I)**
The IFPR is the financial discount rate that leads to the NPFV (I) equal to 0. It is calculated from the following equation 5.5:

$$0 = \sum_{t=0}^{T} \frac{(\Delta CF_{proj})_t}{[1 + IFPR(I)]^t} \tag{5.5}$$

Where

- $IFPR(I)$: Internal Financial Profitability Rate of the project.
- $(\Delta CF_{proj})_t$: Differential free cash flows of the project for the agent considered in year t in a non-project scenario and a project scenario.
- t: Corresponding year in the horizontal time horizon of the project (beginning in year 0).
- T: Number of years in the horizontal time horizon of the project.

Financial profitability indicators of the capital (FPIC)

FPICs include the following:

◆ **Net Present Financial Value of the capital (NPFV(C))**
The NPFV (C) is the sum of the value of differential cash flows of the project discounted at the first year of the contract through the definition of a financial discount rate of the capital for each agent. It is calculated similarly to the NPFV (I) (Equation 5.4), but using the financial discount rate of the capital and the differential cash flows of the capital.

◆ **Internal Financial Profitability Rate of the capital (IFPR (C))**
The IFPR (C) is the financial discount rate that leads to an NPFV (C) equal to 0. It is calculated similarly to the IFPR (I) (Equation 5.5), but using the differential cash flows of the capital.

Economic profitability indicators

These indicators include the net present economic value of the project (NPEV (I)) and the internal economic profitability rate (IEPR (I)).

◆ **Net Present Economic Value of the project (NPEV (I))**
This indicator is the sum of the differential flows of the project, discounted at the first year of the contract through the definition of a financial discount rate of the project for each agent (Equation 5.6).

$$NPEV(I) = \sum_{t=0}^{T} \frac{(\Delta E_{total})_t}{(1 + i_{social})^t} \tag{5.6}$$

Where

- $NPEV\ (I)$: Net Present Economic Value of the project.
- $(\Delta E_{total})_t$: Variation in the total surplus of year t.
- i_{social}: 'social' discount rate of the project.
- t: year corresponding in the time horizon of the project (beginning at year 0).
- T: number of years of the horizontal time horizon of the project.

- **Internal Economic Profitability Rate (IEPR (I))**
  This indicator is the financial discount rate that leads to an NPFV (I) equal to 0. Its calculation is based on Equation 5.7:

$$0 = \sum_{t=0}^{T} \frac{(\Delta E_{total})_t}{[1 + IEPR(I)]^t} \tag{5.7}$$

Where

- $IEPR(I)$: Internal Economic Profitability Rate of the project.
- $(\Delta E_{total})_t$: Variation in the total surplus of year t.
- t: Corresponding year in the horizontal time horizon of the project (beginning in year 0).
- T: Number of years in the time horizon of the project.

OTHER ELEMENTS AND INDICATORS

This category includes cash flows, debt service coverage ratio, payback period, and the variation of the total surplus.

Cash flows

These are the net and free cash flows of the project and the capital.

- **Free cash flows of the project**
  For each year and agent, the following cash inflows and outflows are considered, taking into account the differences between a non-project scenario and project scenario:
  - Inflows: operating revenues and residual value of the investment.
  - Outflows: investment costs, operational costs, and taxes.

- **Net cash flows of the project**
  For each year and agent, the following cash inflows and outflows are considered, taking into account the differences between a non-project scenario and a project scenario:
  - Inflows: operating revenues and total funding received (own financial resources and/or outside contributions).
  - Outflows: investment costs, operational costs, taxes, and funding costs (repayment of the capital and interests).

- **Free cash flows of the capital**
  For each year and agent, the cash flows corresponding to resources external to the investment costs are added to the free cash flows of the project. This generates the following inflows and outflows, taking into account the differences between a non-project scenario and a project scenario:
  - Inflows: operating revenues, residual value of the investment and external funding received (loans and subsidies) by the agent considered.
  - Outflows: investment costs, operational costs, taxes, and funding costs (repayment of the capital and interests).

Coverage ratio of the debt service

Coverage ratio of the debt service measures the possibility of repaying the debt (repayment of capital and interests) with the cash flows generated by the project, as calculated by Equation 5.8:

$$(Coverage_{debt.service})_t = \frac{(\Delta I_{op})_t - [(\Delta C_{op})_t + (\Delta C_{imp})_t]}{(\Delta C_{financ})_t} \quad (5.8)$$

Where,

- $(Coverage_{debt.service})_t$: coverage ratio of the debt service for the agent in year t.
- $(\Delta I_{op})_t$: operating revenues in year t in a non-project scenario and project scenario.
- $(\Delta C_{tax})_t$: tax payments in year t in a non-project scenario and project scenario.
- $(\Delta C_{op})_t$: operating revenues in year t in a non-project scenario and project scenario.
- $(\Delta C_{financ})_t$: funding costs (repayment of capital and interests in year t in a non-project scenario and project scenario.
- t:Year of calculation within the horizon of the investment project.

Payback period

This includes the payback periods of the investment (I) and the capital (C).

- **Period of investment payback (I)**
  This period is the time necessary to recover the initial investment with the exploitation flows of the project. This is calculated with the Equation 5.9:

  $$0 = \sum_{t=0}^{Payback(I)} (\Delta FC_{proj})_t \quad (5.9)$$

  where

  - $Payback(I)$: Payback period of the investment (I).
  - $(\Delta FC_{proy})_t$: Differential free cash flows of the project for the agent considered in year t in a non-project scenario and project scenario.
  - t: Corresponding year in the time horizon of the project (beginning in year 0).

- **Payback period of the capital (C)**
  This period is the time necessary to recover the amount of own resources. It is calculated similarly to the Payback (I) (Equation 5.9), but using the differential cash flows of the capital.

Variation of the total surplus

The variation of the total surplus is evaluated in each year of the time horizon. It corresponds to the sum of the variations of the surplus of the producer and consumer as well as externalities, including the surplus variations of the (i) Port Authority; (ii) participating Investor/Operator; (iii) other Port Authorities; (iv) other operators of the transport chain; (v) the society/community. The calculation of these surpluses is described in detail in MEIPOR-16.

FINANCIAL SUSTAINABILITY

A project is considered to be financially sustainable for an agent when in each year of the time horizon considered, the cumulative net cash flows are positive:

$$\exists \text{ Financial Sustainability} \quad \text{if} \quad \sum_{t=0}^{t'} (CF_{net})_t > 0 \quad \forall\, 0 < t' < T \qquad (5.10)$$

Where

- $(CF_{net})_t$: Net cash flows for an agent in year t in a non-project and project scenario.
- t': Calculation year within the horizon of the investment project.
- T: Number of years considered for the project.

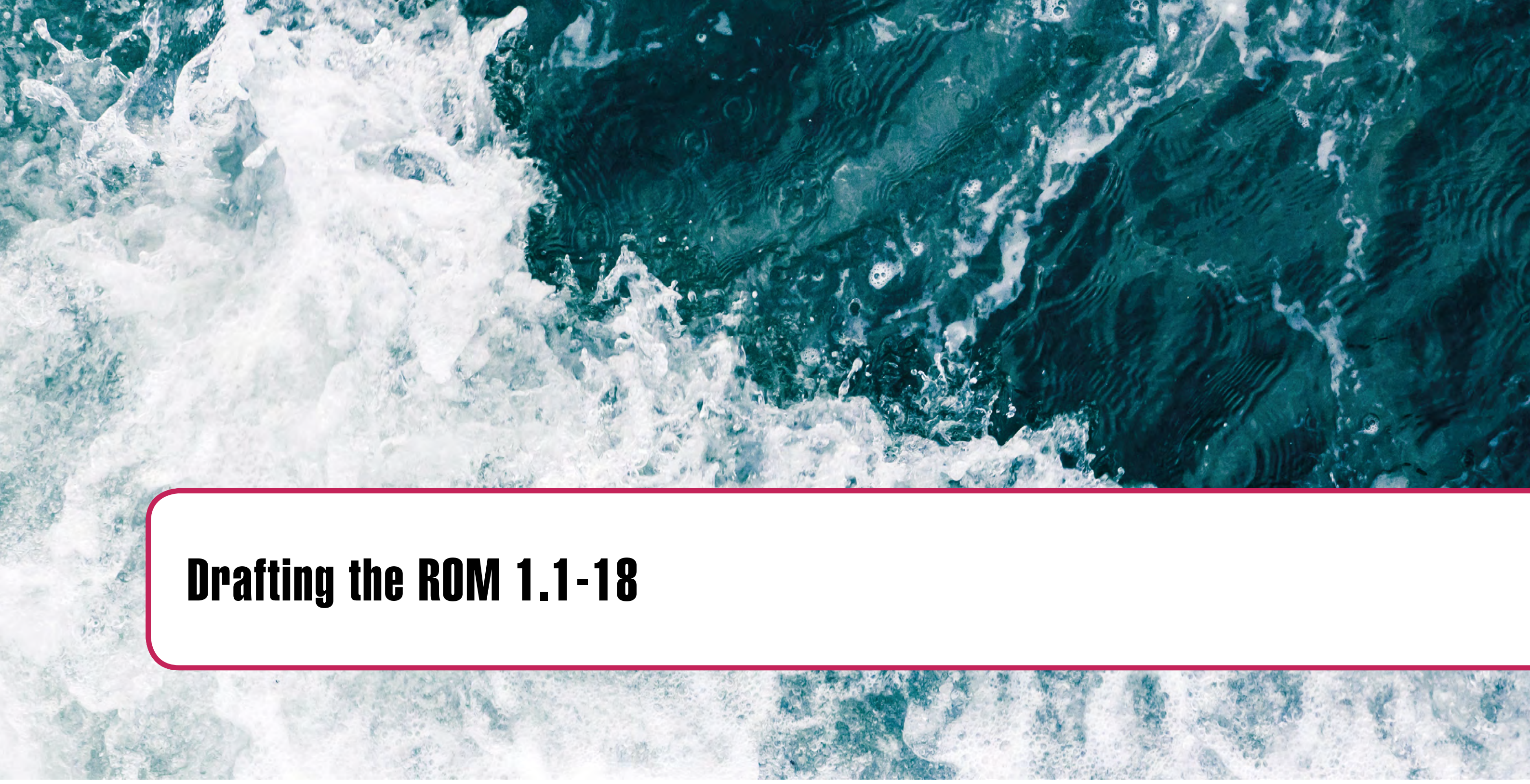
Because of its importance for the calculation of sustainability, the calendar of cash inflows and outflows should be accurately specified.

ACCEPTABLE RISK LEVEL

In MEIPOR-16, the risk level is characterized in the two ways, each with its own level of detail:

(a) through the distribution function of the financial and economic profitability indicators;
(b) through the expected value of these indicators.

The first case (a) assesses the probability that the indicators are below a critical value regarded as acceptable and verifies whether this probability exceeds the reference value. The second case (b) assesses whether the expected value exceeds an acceptable limit value.



Drafting the ROM 1.1-18

This ROM 1.1-18 "*Recomendaciones para el Proyecto de Construcción de Diques de Abrigo*" was drafted by Miguel Ángel Losada Rodríguez (University Granada) under the mandate of Puertos del Estado, government agency of the Spanish Ministry of Public Works and Transport with the collaboration of a standing working group of experts. All proposals were adopted by consensus after discussions of the Technical Committee composed of the following members:

Arana Burgos, Manuel (Puertos del Estado, Spain)
Besio, Giovanni (USG, Italy)
Esteban Lefer, Francisco (FCC, Spain)
Folgueras Rodríguez, Pedro (IISTA, Spain)
González Herrero, José Manuel (Acciona Ingeniería, Spain)
da Graça Neves, Maria (LNEC, Portugal)
López Lara, Javier (IH Cantabria, Spain)
Martín Soldevilla, Ma Jesús (CEPYC-CEDEX, Spain)
Medina Folgado, Josep Ramon (UPV, Spain)
Moyano Retamero, José (Port Authority of Málaga, Spain)
Sanchidrián Fernández, Carlos (PROES Consultores, Spain)
de los Santos Ramos, Francisco (Port Authority of the Bahía de Algeciras, Spain)
Silva Casarín, Rodolfo (UNAM, Mexico)
Solari, Sebastián (IMFIA, Uruguay)

The following experts provided observations and feedback regarding the content of the articles:

Benedicto Iruiñ, Izaskun (PROES Consultores, Spain)
Peña González, Enrique (UDC, Spain)

The following members of the Environmental Fluid Dynamics Research Group of the University of Granada contributed to the ROM 1.1-18 "*Recomendaciones para el Proyecto de Construcción de Diques de Abrigo*":

Baquerizo Azofra, Asunción
Bello Millán, Francisco J.
Bergillos Meca, Rafael J.
Clavero Gilabert, María
Cobos Budia, Manuel

Díaz Carrasco, Pilar
Folgueras Rodríguez, Pedro
Jiménez Portaz, María
Lira Loarca, Andrea M.
Magaña Redondo, Pedro J.
Ortega Sánchez, Miguel
del Rosal Salido, Juan
Vílchez Solís, Montserrat

The following participants were invited to revise and discuss the first draft of the text in a meeting celebrated on 30 May 2018:

Ametller Malfaz, Sergi (SENER)
Antunes, António (Etermar)
Arana Burgos, Manuel (Puertos del Estado)
Barceló Vogt, Mateo (CA Baleares)
Bayarri Cebrián, Francisco José (Generalitat Valenciana)
Bayo Martínez, Antonio (Port Authority of Almeria)
Benedicto Iruiñ, Izaskun (PROES)
Besio, Giovanni (Universitá Degli Estudi di Genova)
Brògueira Dias, Emílio (Portos do Douro, Leixões e Viana do Castelo)
Burgos Teruel, Marcelo (Port Authority of Valencia)
Cánovas Losada, Íñigo (PROINTEC)
Castellote Armero, Marta (ICC Eduardo Torroja)
Castillo Cano-Cortés, Luis Castillo (AYESA)
Clavero Gilabert, María (University of Granada)
Corral López, Jesús (OPTIMASIPU)
Corredor Molguero, Antonio (OHL)
de los Santos Ramos, Francisco Javier (Port Authority of the Bahía de Algeciras)
Díez Rilova, Margarita (Generalitat de Catalunya)
Díez Rubio, Galo (DG Costas)
Enamorado Martínez, César Andrés (Ferrovial)
Escartín García, F. Javier (MARCIGLOB)
Esteban Lefler, Francisco (FCC)
Fernández-Alonso Trueba, Macario (MCVALNERA)
Ferrante, Andrea (Ministro delle Infrastrutture, Italia)
Folgueras Rodríguez, Pedro (University of Granada)
García Hernández, Sara (Port Authority of Alicante)
García Pérez, Francisco (Port Authority of Motril)
García-Valdecasas Bernal, José María (Puertos del Estado)
Gómez-Martín, M. Esther (Polytechnical University of València)
González Herrero, Jose Manuel (ACCIONA Ingeniería)
González Patiño, Noelia (DRAGADOS)
Iglesias Rodríguez, Gregorio (University of Plymouth)
Lope Carvajal, Ana (Puertos del Estado)
López Lara, Javier (University of Cantabria)
Maciñeira Alonso, Enrique (AP Coruña)
Martín Soldevilla, María Jesús (CEDEX-CEPYC)
Medina Villaverde, José María (BTP Infraestructuras)
Molina Sánchez, Rafael (Polytechnical University of Madrid)
Mora Quintero, Javier I. (Port Authority of Tenerife)
Moyano Retamero, José (Port Authority of Málaga)
Muñoz-Calero, Ramón (Port Authority of Gijón)
Nasarre López, Jorge (Port Authority of Baleares)
Negro Valdecantos, Vicente (Polytechnical University of Madrid)

Neves, Maria Graça (Laboratório Nacional de Engenharia Civil)
Ollero Marín, Manuel (CA Andalucía)
Paramio Cabrera, Juan Manuel (Port Authority of Melilla)
Peña González, Enrique (Universidade da Coruña)
Peña López-Pazo, Alfonso (Port Authority of Huelva)
Pérez Rubio, Susana (Puertos del Estado)
Pindado Rodríguez, Miguel Ángel (Port Authority of Barcelona)
Pita Olalla, Eloy (INCREA)
Quevedo Baquerizo, Elena (SENER)
Rezabal Arocena, Saioa (CA País Vasco)
Robert Lopes, Miguel (CONSULMAR)
Rodríguez Dapena, Álvaro (Puertos del Estado)
Rodríguez Arevalo, Ignacio
Rodríguez-Rubio Mediavilla, Pablo (Port Authority of the Bahía de Algeciras)
Sánchez Luzón, Olga Ma (Port Authority of Avilés)
Sanchidrián Fernández, Carlos (PROES)
Segura Ballesté, Carles (Port Authority of Tarragona)
Suñé Recio, Juan Carlos (Port Authority of the Bahía de Algeciras)
Tomasicchio, Giuseppe (Universitá del Salento)
Valdés Fernández de Alarcón, José María (CEDEX-CEPYC)
Vara Plazas, José (Berenguer Ingenieros)
Varela de Andres, Jose Antonio (SACYR)
Vázquez Romero, Miguel (DRAGADOS)
Vidal Pascual, César (University of Cantabria)

Finally, the ROM 1.1-18 "*Recomendaciones para el Proyecto de Construcción de Diques de Abrigo*" benefited from the collaboration of the following institute:

Instituto de Mecánica de los Fluidos e Ingeniería Ambiental (University of the Republic, Uruguay)