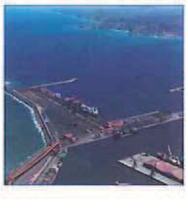
SERIES 0 Description and characterization of project factors of maritime structures

TRANSLATED VERSION OF THE ORIGINAL SPANISH TEXT

RECOMMENDATIONS FOR MARITIME STRUCTURES



ROM 0.0

General procedure and requirements in the design of harbor and maritime structures. PART I

MINISTERIO DE FOMENTO

Puertos del Estado

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General procedure and requirements in the design of harbor and maritime structures. PART I

1st Edition
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FOREWORD

In April 1990,the Spanish Ministry of Public Works and Urban Development,and more specifically, the *Dirección General de Puertos y Costas*, published the first set of Recommendations for Maritime Structures, entitled *Acciones en el proyecto de obras marítimas y portuarias* [Actions for the design of maritime and harbor structures].This was the beginning of an extremely useful program of technological development that has led to the elaboration of a series of technical guides for maritime and harbor structures.Despite the fact that these recommendations do not as yet have the status of official regulations, they have provided essential guidelines for the designers of maritime structures, who are striving to attain objectives of reliability, functionality, and quality.

In the years following the publication of this first volume, and with the subsequent application of the various Recommendations, the ROM documents have gained both national and international prestige, and are now regarded as an extremely useful technical and scientific tool.Apart from their application by the Port Authorities at both a national and state level,and their use by private construction companies, the ROM documents are also studied in Spanish Universities, and are frequently adopted in Europe and South America as a basis for defining technical criteria for maritime structures and infrastructures.

The experience acquired over the last decade in the application of these recommendations and the resulting advancement of knowledge has underlined the necessity of making a revision of the ROM Program. Logically, this revision has begun with the first document published, the ROM 0.2-90, which is the basis for current calculation procedures.The present volume, the ROM 0.0, is a revision of the chapters regarding general criteria and design requirements included in that first document.As such, it develops and specifies various concepts mentioned in the ROM 0.2-90, and extends the frame of verification of the failure modes by the incorporation of probabilistic Level II and III Verification Methods. This publication will soon be followed by the other sets of Recommendations listed in Chapter 1.

It is now up to engineers to wisely apply these Recommendations with a view to their subsequent modification and improvement. In this sense, we hope that readers of this volume will not hesitate to send us any suggestions, questions,and criticisms that they might have regarding their content. Only after a period of reflective application combined with user consultation can the ROM documents acquire a sufficiently solid foundation, conducive to their future acceptance as technical standards.

I wish to express my gratitude to all of those who have contributed in any way to the publication of the ROM 0.0 since I am well aware how difficult it is to create a publication of this nature. In the decade following the publication of the ROM 0.2-90, I was responsible for the ROM documents, first as the technical editor and secretary of the Committee, and later on, as its President and person responsible for the Department of Technology and Technological Standards. Each of these Recommendations is an integral part of my life, and all of them together constitute a source of pride that one feels for a job well done.

It gives me great satisfaction to be able to write the foreword for this first volume of the revised ROM program.This revision is another step towards increasing its prestige and influence in the world of national and international engineering.If in my former position,I was one of the initiators of the ROM Program, now as President of the Puertos del Estado, I am even more committed to its consolidation and future advancement as an instrument for the technological development of maritime engineering and Spanish harbor installations.

Madrid, December 2001

José Llorca Ortega
President of *Puertos del Estado*

1.The titles, order, and sequence of certain Recommendations and Series may be modified during their elaboration and development.

CHAPTER 1
Introduction

1 Introduction

1.1 The ROM Program

The elaboration of the "Recommendations for Maritime Structures" **(ROM Program)** began in 1987 with the creation of the Technical Committee whose task was to draw up Recommendations that would guide both national agencies and private companies in the design, construction, maintenance, and exploitation of Marine Constructions, particularly Maritime Structures. This program was structured as shown below:

Series 0: General recommendations
Series 1: Outer structures: breakwaters
Series 2: Inner structures: docks and mooring and anchoring structures
Series 3: Maritime and ground configuration of harbors
Series 4: Harbor superstructures

The Recommendations in the list below are the result of a detailed study carried out by the Technical Committee with the help of experts, as well as public and private agencies and organisms:

- **Series 0.**

ROM 0.2: *Actions in the design of maritime and harbor structures*
This Recommendation is now replaced by the recommendations in the present volume.
ROM 0.3: *Climatic actions I: Waves*
ROM 0.4: *Climactic actions II:Wind*
ROM 0.5: *Geotechnical recommendations for maritime structures*

- **Series 3.**

ROM 3.1: *Design of the maritime configuration of harbors, navigation channels, and flotation areas*

- **Series 4.**

ROM. 4.1: *Recommendations for the design and construction of harbor pavements.*

The impact and acceptance that the ROM Program is presently receiving in technical circles, its vast scope, and the publication of this ROM 0.0 are all factors that have led to the revision of the Program.

1.1.1 Organization of the ROM Program series[1]

- **Series 0. Description and characterization of project factors of harbor and maritime structures**

ROM 0.0: General procedure and project design
ROM 0.1: Description of construction materials

1. The titles, order, and sequence of these Recommendations and Series may be modified in the course of their development.

ROM 0.2: Project factors of use and exploitation
ROM 0.3: Description of the physical environment I: Sea oscillations
ROM 0.4: Description of the physical environment II:Atmospheric processes
ROM 0.5: Description of the physical environment III: Soil
ROM 0.6: Description of the physical environment IV: Seismic agents
ROM 0.7: Methods and techniques of visual inspection,sounding, and monitoring

- **Series 1: Maritime structures against sea oscillations**

ROM 1.0: General criteria for maritime structures
ROM 1.1: Dikes and breakwaters
ROM 1.2: Fixed and floating maritime structures

- **Series 2: Inner harbor structures**

ROM 2.0: General criteria for inner harbor structures
ROM 2.1: Docks
ROM 2.2: Berthing, mooring, and anchoring structures
ROM 2.3: Special structures:sluices, slips, launching, waterways, and dry docks

- **Series 3: Planning, management, and exploitation of harbor areas**

ROM 3.0: Studies of planning,management, and exploitation
ROM 3.1: Design of harbor and flotation areas
ROM 3.2: Design of harbor areas on land
ROM 3.3: Beaconage and control systems in harbor areas
ROM 3.4: Management and exploitation of harbors

- **Series 4: Superstructure and ground installations of harbor areas**

ROM 4.0: General criteria
ROM 4.1: Pavement in harbor areas
ROM 4.2: Vehicle access and transit
ROM 4.3: Harbor urban development
ROM 4.4: Harbor ground installations

- **Series 5: Maritime and harbor structures in the physical environment**

ROM 5.0: General criteria and environmental impact study
ROM 5.1:The quality of water in harbor areas
ROM 5.2: Maritime and harbor structures on the coastline

- **Series 6: Technical, administrative, and legal specifications**

ROM 6.0:Administrative and legal aspects of the design structure
ROM 6.1: Technical specifications for construction, maintenance, and repair
ROM 6.2: Technical specifications for management and exploitation

- **The EROM Program**

This program includes the comments of users as well as the people who apply the different Recommendations. In this sense, the program is similar to technical journals in that it can be regarded as an open forum of discussion for the publications of the ROM program.

1.1.2 Elaboration of the ROM 0.0

This ROM 0.0 is a revision of some of the chapters on general criteria and project design presented in the ROM 0.2: *Actions in the design of maritime and harbor structures*. It is, therefore, a revision and expansion of concepts originally presented in the first ROM, which had to be updated because of the acquisition of greater knowledge and practical experience in the application of concepts. The framework for the verification of failure modes has also widened its scope to include probabilistic Level II and III verification methods.

The ROM 0.0 has been elaborated by *Puertos del Estado* under the supervision of the Technical Division of Harbor Infrastructure and Services. The following people have participated in the project:

- Chairman: Antonio Martin Oliver, Puertos del Estado
- Coordination of the Committee: José Llorca, Mª Dolores Cancela and Juan Ignacio Grau, Puertos del Estado
- Project Development: Miguel A. Losada, Universidad de Granada

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- Antonio Vacas Jaramillo, Sato
- Jesús Villanueva Fraile, Autoridad Portuaria de Bilbao

English translation
- Pamela Faber Benitez, University of Granada

1.2 Aim and scope of application

The main objective of the ROM 0.0 is to provide a set of standards and technical criteria for the design, construction, exploitation, maintenance, repair, and dismantling of maritime and harbor structures of all types and designs, no matter what materials, techniques, and elements are used for these purposes.

The scope of application encompasses all aspects related to harbor activity, management and maintenance of the coastline, the exploitation of marine resources, navigation, as well as the interaction of the harbor activity with the physical environment.

The ROM 0.0 consists of two parts, published in separate volumes. Part I is made up of seven chapters and focuses on the general process and design requirements for maritime and harbor structures. Part II is made up of two chapters, the first of which is an explanation of the help program for the application of the general procedure. The second chapter in this section presents a series of basic concepts upon which this ROM 0.0 is based. Figure 1 is a schematic outline of the organization of the contents of Part I of this ROM.

1.3 Justification and contents

A procedure is understood as a sequence of activities that must be carried out in order to attain a specific objective. In this case, the objective is to guarantee the safety, serviceability, and exploitation of the maritime structure. Within the context of this ROM 0.0, calculation should be understood in its widest sense, and signifies the verification of the structure against failure and operational stoppage modes, as well as the estimation of the joint probability of failure of the subset of the structure during each of the project phases. The general procedure described in this recommendation includes different methods to be applied in sequence, but non-stop, which help to determine if a project design alternative satisfies the safety, serviceability, and exploitation requirements in consonance with the recommended levels of reliability, functionality, and operationality during all of the project phases.

This sequence of activities is organized in the following manner:
General Project Criteria
Project requirements
Verification procedure
Level I, II, and III Verification Methods
Probability of failure and operationality

The description of the objectives of these activities,which is offered in the following sections,also summarizes the contents of the different chapters in these Recommendations.

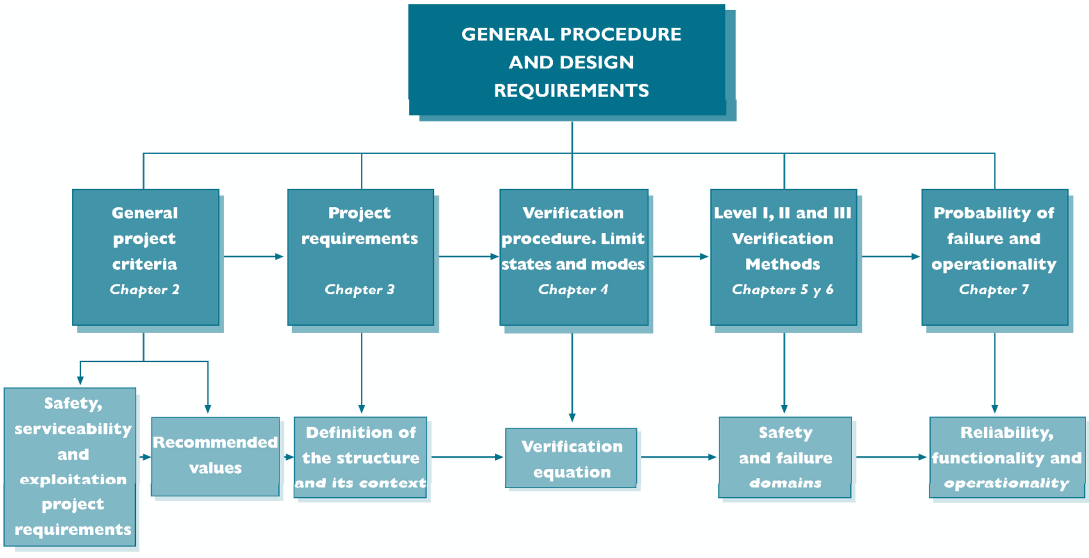


Figure 1.1: ROM 00: Organization and Contents

Chapter 2: General Project Criteria

Every maritime structure should comply with certain requirements of reliability, functionality, and operationality during a specific time interval.One of its purposes is to permit or facilitate a series of economic activities which will have social repercussions as well as impacts on the physical environment.The main objective of the project design of the structure or subset is the verification of these objectives, and requirements, repercussions, and impacts.

The general calculation procedure should begin by defining and situating the structure in time and space in terms of safety, serviceability, and use and exploitation.To this end, Chapter 2 defines the following concepts:intrinsic nature, permanence, project phases and duration,verification method of the maritime structure and its elements, and finally, the probabilities against one mode as well as against the whole set of failure and stoppage modes. On the basis of these concepts, it is possible to estimate the useful life of the structure, the joint probability of failure against the principal failure modes assigned to ultimate and serviceability limit states, minimum operationality, and the average number of admissible technical breakdowns.

Chapter 3: Project requirements

This chapter defines the subset of the structure and its immediate environment in terms of the following project factors: parameters, agents, and actions. Parameters identify and quantify properties of the physical environment, soil, and the structure, particularly its geometry. Agents define what can interact with the structure and its environment, as well as when and how this interaction can take place. Actions refer to when, how, and to what degree such agents interact with the structure and its environment. Finally, criteria are provided to specify the values of these factors, and whether they are random or deterministic. They are then organized statistically according to class membership, which helps define their compatibility and the combination types of the terms in the verification equation

Chapter 4: Verification procedure

The procedure is a guide for the verification of the whole maritime structure, each subset, and each of its elements in all project phases and work and operating conditions. Given the complexity of the verification, it is necessary to establish a method for this purpose, as well as for the organization of the verification process. This chapter presents and describes this process.

First, the objectives of this type of calculation are defined, followed by the development of the limit state method and the corresponding failure and stoppage modes, which describe the causes, mechanism, way, etc. in which the failure or stoppage of the subset occurs. The section also describes the states related to reliability and functionality through ultimate and serviceability limit states, as well those related to operationality, through operational stoppage limit states. This is followed by the analysis of the verification equation format of each of the modes and also of the equation terms involved. Criteria are then described for the organization of the project factors and terms of the equation. On the basis of this organization, the simultaneity of action and the compatibility of term values are specified, in consonance with the work and operating conditions.

Finally, after analyzing the different time intervals in the calculation of the probability of occurrence of one or all of the modes, verification and calculation methods are proposed in the ROM Program.

Chapter 5: Level I Verification Methods

This chapter provides a detailed description of the application of Level I Verification Methods. These methods are recommended to verify and evaluate the reliability, functionality, and operationality of the maritime structure against the failure and operational stoppage modes, when their general intrinsic nature is low or medium (see table 4.5).Methods considered are the global safety coefficient method and the partial coefficients method. These methods are developed according to the procedure described in Chapter 4, particularly, the organization of factors and terms, their simultaneity, and compatibility. Furthermore, a logical sequence is established to determine weighting and compatibility coefficients, affecting the terms of the verification equation expressed in the safety margin format. However, these methods do not provide the probability of failure of the maritime structure against the mode. For this reason, an approximate way of arriving at this estimate is proposed.

Chapter 6: Chapter 6: Level II and III Verification Methods

This Chapter focuses on the development of Level II and III Methods for the verification of failure and operational stoppage modes, assigned to limit states and subject to work and operating conditions that can occur in a time interval.When one of these methods is used to solve the verification equation, the result is a number and a probability associated with this number, which indicates the level of safety, serviceability or exploitation that the subset of the structure has against the failure or stoppage mode in the time interval.

The first part of the chapter describes Level II Verification Methods, which can be applied by using various types of approximation.The most popular of these is that derived by linearizing the verification equation around the failure point.This method is thus known as a first-order or linear approximation method (FORM).This is followed by a description of Level III Verification Methods, which include simulation methods.Regarding the latter, this ROM proposes a method based on the Monte Carlo algorithm.

Given that the majority of the verification equations of the failure and operational stoppage modes are obtained to be applied with Level I Methods,and more particularly, with the global safety coefficient, criteria are proposed to facilitate the conversion from one format to the other with no reduction of existing safety standards.

The theoretical concepts underlying Level II and III methods, and which justify the explanations given in this chapter, are developed in Part II, published in a separate volume, which includes various examples of how to apply the two methods used to verify the same failure mode.

Chapter 7: Probability of failure and operationality

The reliability, functionality and operationality of the subset of the structure change over time. Chapter 2 recommends maximum values for the overall probability of failure of the subset against the modes assigned to the ultimate and serviceability limit states and the minimum operationality in the useful life project phase. This chapter offers an analysis of the temporal evolution of the safety, serviceability, and operationality of the subset, and proposes different techniques to determine the probability of failure occurrence in the project phase, based on its probability of occurrence in a time unit interval.Thereafter, diagrams of modes are used to apply the calculation to principal failure and stoppage modes that can occur in the project phase. Criteria are also provided to study the overall probability of failure in structures of a low or medium intrinsic nature in relation to the principal failure modes.

Recommendations are given concerning the advisability of carrying out economic optimization and cost-benefit studies of the subset of the structure. Such studies help to give probabilities of failure different from those recommended in tables 2.3, 2.4, and 2.5. Moreover, the elaboration and application of a plan of visual inspection, sounding, and monitoring is advised. All collected data should be used to analyze the residual reliability, functionality, and operationality of the subset until the end of the structure's useful life. Criteria are also specified for the development of maintenance and repair strategies.

CHAPTER 2
General Project Criteria

2 GENERAL PROJECT CRITERIA

2.1 Introduction

A maritime structure is built for specific functions,either creating the possibilities for or facilitating economic activities within its immediate context, all of which generate social repercussions as well as an impact on the environment.A maritime structure must be safe and reliable for the time that it remains in operation.Throughout its life, it goes through different phases.These pertain to its structure, shape, and use and exploitation, depending on the spatio-temporal variation of the project factors.

For a variety of reasons or causes, the structure may lose its resistance (loss of safety),structural capacity (loss of serviceability),and/or operational capacity (loss of exploitation) due to factors described in failure modes and operating stoppage.This may occur suddenly or gradually, temporarily or permanently, as well as partially or totally.

(1) The most relevant concepts in these Recommendations are defined in the following section.

The main objective of this ROM 0.0 is to establish a general procedure and design considerations, which will make it possible to ascertain if a project design alternative is reliable in regards to safety, functional in regards to its serviceability, and operational in regards to its use and exploitation.The resulting procedure depends on the general project criteria described in this Chapter.

2.1.1 Contents and organization of the chapter

Figure 2.1 is a schematic outline of the contents, scope, and organization of this chapter. First, basic concepts are defined, and then the aim and project criteria of a maritime and harbor structure. Space and time are specified in terms of a subset of the structure and time intervals, respectively.The provisionality of the structure is also defined as well as the duration of the project phases, such as its useful life.

The following section is an introduction to the determining factors and the calculation processes, which are explored in greater depth in Chapter 3. Afterwards, the general and operational intrinsic natures of the subset of the structure are defined, and a method is proposed for their specification in the event that the developer of the structure has not previously done so. An in-depth description of this method can be found in the annex to this chapter.The general calculation process is the subject of the section that follows.It contains a short introduction to the procedure for defining the limit states, working and operating conditions (WOCs),and types of combination, all of which are discussed in greater detail in Chapter 4.This section concludes with an outline of the verification methods applied in these Recommendations, which are further explained in Chapters 5 and 6.

The next chapter specifies all of the elements related to the binomials of safety-reliability, serviceability-functionality, and use and exploitation-operationality; and proposes methods to calculate the following: (1) probability of occurrence of a mode in a specified time interval; (2) probability of occurrence of a mode in a project phase; (3) overall probability of a subset of the structure in regards to its safety, serviceability, as well as its use and exploitation during a project to stage. The chapter concludes with the recommended values for its useful life, the overall probability of failure, and the operationality according to the general and operational intrinsic nature of the subset of the structure.

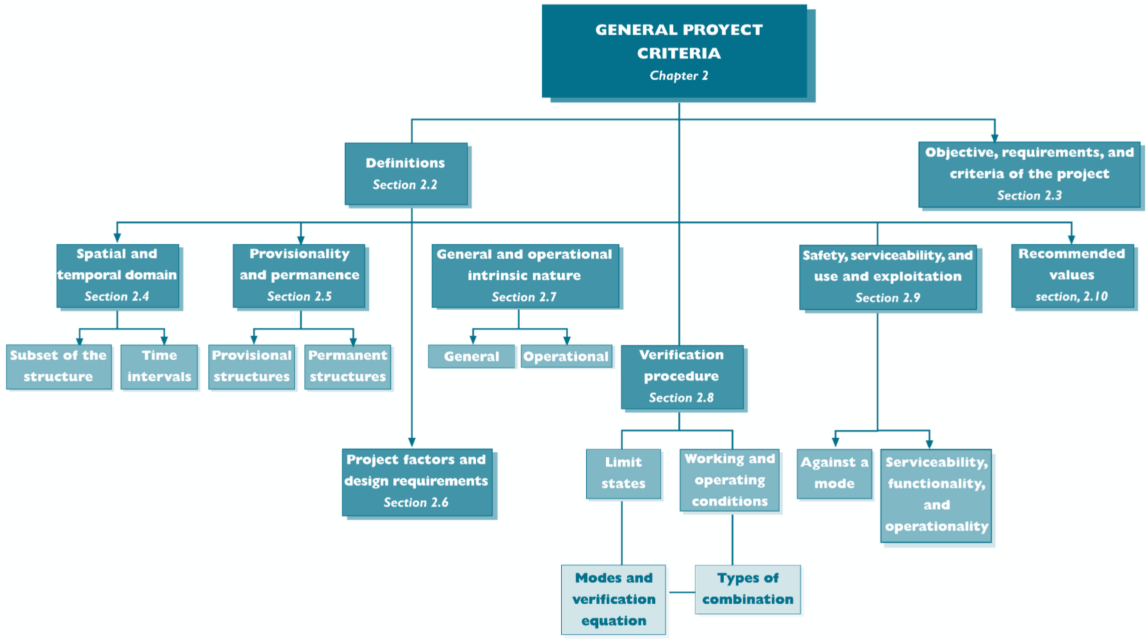


Figure 2.1: Chapter 2. Organization and contents.

2.2 Definitions

To determine the general criteria for the project the following concepts must first be defined:

2.2.1 Project

In the context of ROM documents, project refers to the set of activities that encompass the design, construction, exploitation, maintenance, repair, and dismantling of a maritime structure.

2.2.2 Parameters[2]

(2) In these Recommendations, they are sometimes called project parameters.

Way of characterizing the geometry of the construction and the terrain,as well as the properties of the physical environment, soil, and building materials.

2.2.3 Agent

(3) In contrast to patient,an agent carries out the action rather than suffering its effects. Agents cause activity in the maritime structure, its individual components, and its immediate environment.

Any entity that can significantly affect the safety, serviceability and use and exploitation[3] of a structure and its immediate environment. Agents whose effect is predominant in the occurrence of the failure or stoppage mode are called predominant agents.

2.2.4 Action

Any manifestation which an agent may produce in the structure and its immediate environment as a result of their mutual interaction. Action thus encompasses such notions as the force and loads applied to the structure, stress-induced movements, stress-related deformations, etc. The relation between agents and actions is established by a function in which project parameters also can intervene.

2.2.5 Project factors

Set of parameters, agents and actions. The magnitude (and direction) of the project factors, and thus, the operational characteristics and the structural responses of the maritime structure as a whole vary or may vary during its project phases.

2.2.5.1 Predominant factor

Factor that triggers a failure or stoppage mode[4].

(4) Failure and stoppage modes are defined in sections 2.2.1.3 and 2.2.1.4.

Note *In general, the project parameters are those factors that are predetermined in the verification process. They may be treated as statistical variables, but their distribution function and representative values, once specified, are taken to be known and determined. Conversely, agents and actions are those that directly participate in the specification of the structure insofar as its typology and dimensions are concerned. For example, in the case of a breakwater, the characteristics of the soil's mechanical strength can be regarded as parameters and be defined a priori. Wave height and period define and characterize the agent waves, and their values depend on the criteria related to possible malfunction and the probability of failure of the structure.*

The action, in this case, the horizontal force on the overtopped vertical seawall, is produced by the interaction of the waves and the structure. The height and frequency of the wave and the water depth define and characterize the agents of the physical environment. The density of the water, concrete, and filling material, as well as the acceleration of gravity can be regarded as parameters.

In the study of the diffusion of the ejection plume ejected from a submarine outfall under the agents, waves, currents, and gravity, the project factor water density, defines and characterizes the agent in the same way as the height of the wave and the velocity of the current.

2.2.6 Subset of the structure

Components of the maritime structure which together fulfill a specific function, relevant to the objectives and requirements for the use and exploitation of the structure. They are subject to the same levels of action (initiated by the agents), and are a part of the same formal and structural typology.

2.2.7 Project requirements

The project of a subset should be in consonance with project determinants, such as the following:

- Location in space (site) and time (project phases)
- Requirements for exploitation
- Geometry of the subset and the soil
- Properties (parameters) of the physical environment and materials

• Agents and the actions they perform,which can have an impact upon the maritime structure and the environment, as well as the specific activities carried out there

2.2.8 Project design alternative

As soon as the determinants of the project have been identified, design alternatives of the specified subset are elaborated, which define the following:
• The geometry of the subset and the soil
• The project factors (parameters, agents and the actions) which can have an impact upon the maritime structure and the environment,as well as the specific activities carried out there.

2.2.9 Time interval

Time frame in which the project factors of a specific subset of the structure are described, classified, selected, and evaluated. Similarly, the safety, serviceability, and exploitation are also verified.

2.2.9.1 Time interval unit

Time frame in which statistical information is available to describe project factors by means of probability models.

2.2.10 State

Time interval in which any manifestation of the structure and environment as described, characterized, and evaluated by project factors, regarded as stationary from a statistical perspective.

Note *The discretization of the continuous manifestation in states is a simplification of the actual stochastic process. In order to facilitate its identification, a state is said to refer to a project factor or group of factors. For example, the sea state normally refers to the wind waves; the tidal state to the tide;the weather state to the climate, etc. In the same way, the structural response, shape, and exploitation of the work can be described by states. The temporal sequences of the operational and structural outcomes are ordered in curves of project states. During the occurrence of each of these states, the manifestations are considered to be stationary from a statistical point of view.*

The duration of any state depends on the temporal variability of the project factors, as well as the reaction time of the maritime structure. One of the project objectives is that the structure be reliable, functional, and operational within the framework of the project requirements for all of the project states. If the actual sequence of project states is not known beforehand, the verification must be made for the worst possible states, or limit states.

2.2.10.1 Project state

Set of manifestations of the project factors and of the structural response and the operational characteristics of both the maritime structure as a whole and any of its individual components,in which each manifestation is regarded as stationary from a statistical point of view.

2.2.11 Project phase

Temporal sequence of project states during which the subset of the structure maintains the same primary activity though it can have other secondary ones. Types of project phases are preliminary surveys and construction design, useful life, maintenance, repair, and dismantling. Each phase lasts for a certain period of time. The duration of the useful life phase is the useful life of the subset.

2.2.12 Limit state

Project state in which the maritime structure as a whole or any of its individual components is considered to be unusable or out of service because it fails to meet the structural or operational safety requirements laid down in the project. Limit states are classified in ultimate limit states (ULS), serviceability limit states (SLS), and operational limit states (OLS) (section 4.3.).

Note *Generally speaking, maritime structures are built to protect goods and services from the actions of the sea and atmosphere. It is not usually possible, mainly for economic reasons, to build maritime structures capable of operating under all prevailing meteorological and marine conditions. Despite the fact that a structure must remain safe throughout its useful life, it is to be expected that at times it will not be operational because the dynamic actions of the sea and atmosphere exceed certain threshold values. For this reason, it is advisable to define operational limit states, which unlike the ultimate and serviceability limit states, make it possible to assess the temporal loss of the operational capacity of the installation, caused by the actions of different physical agents prevailing upon the maritime structure, but without the structural failure of any of its parts.*

2.2.13 Failure mode

Entity or mechanism, whether it be geometrical, physical, mechanical, chemical biological, etc., for which the structure or any of its elements has to be taken out of service for structural reasons. Failure modes are either ascribed to ultimate or serviceability limit states for their verification. Once a failure mode occurs, it is necessary to carry out repairs or reconstruction to recover the appropriate safety and operational level of the structure.

2.2.14 Operational stoppage mode

Cause, reason or motive, whether it be geometrical, physical, mechanical,chemical, biological,etc., for which the structure, or any of its components has to be taken out of service or its operational level reduced. Once the cause of the stoppage disappears, the structure and its installations become operational again at the level specified in the project.

Note *When the a maritime structure is designed, one should bear in mind that it is not possible to guarantee "total operationality". In other words, there is no assurance that the structure will last forever. Generally speaking,in the same way as other public works constructed in the physical environment,such as airports, highways, etc., maritime structures can suffer operational stoppages without there necessarily being any type of structural failure.*

2.2.15 Principal mode

Generally speaking, maritime structures are built to operate in the presence of agents[5] of the physical environment, soil, and of use and exploitation. They should be reliable, functional and operational against the failure modes or stoppage caused by them. Their economic, social and environmental repercussions can be classified according to the indices of economic, social, and environmental repercussions. The geometric dimensions of the structure can be determined in

(5) A set of mutually exclusive and collectively exhaustive agents is given in Chapter 3,section 3.6.

terms of these modes. To evaluate the overall probability of failure[6] in the subset of the structure during its useful life, only the principal modes of failure and stoppage are taken into account.

(6) The overall probability of failure is an approximation to the joint probability of failure of the structure against all the plausible failure modes.

Note *The dock of Levante, which is part of the Port of Almería, is built of concrete blocks and is used as a dock for passenger vessels. One of the objectives of the project is to make sure that for the structure as a whole, none of the possible failure or stoppage modes occurs in any of its components. Principal modes of these ultimate limit states are: sliding between the rows of concrete blocks and berm, overturning, total loss of static equilibrium, loss of soil-bearing capacity, and liquefaction under seismic action. The occurrence of any of these modes has economic, social, and environmental repercussions, which, as explained in subsequent sections, give the dock a general intrinsic nature between the following values: 6 < ERI = 20; 5 = SERI < 20.*

However, one of the dock parts can break down, such as the failure of a fender or a bollard, though this occurrence has no significant consequences for the reliability, functionality, and operational capacity of the subset of the structure. These are not principal modes and though their probability of occurrence in the useful life of the structure should be stipulated, it should not be considered in the calculation of the overall probability of the subset (see Chapter 7).

2.2.16 Work and operating conditions (WOC)

Set of project states characterized by the simultaneous occurrence of specific project factors. Types of WOCs are the following: normal work and operating conditions (WOC_1); extreme work and operating conditions (WOC_2,); and exceptional work and operating conditions (WOC_3).

2.2.17 Types of combination

Simultaneous presentation of project factors. They help to determine the compatible values of project factors and terms that can simultaneously occur in a specific time interval unit, and thus, enter into the verification equation. Such project factors are said to be concurrent.

2.2.18 Safety

A subset of a structure is considered to be safe when it meets the safety requirements specified in the project and required by current regulations throughout all the states that arise in all of the project phases.

2.2.19 Serviceability

A subset of a structure is in service when it meets the shape and structural requirements, specified in the project and required by current regulations throughout all the states that arise in all of the project phases.

2.2.20 Use and Exploitation

A structure or a subset and its installations are in exploitation when they meet the use requirements specified in the project and required by current regulations.

2.2.21 Probability of failure

Probability that a subset of the structure fail to meet safety or serviceability requirements in a specific time interval because of the occurrence of a failure mode. This is generically known as probability of failure.

2.2.22 Overall probability of failure

Probability of a failure during the useful life of the subset against the principal failure modes ascribed to all of the ultimate limit states or serviceability limit states. It should be regarded as an approximation to the joint probability of failure against all the failure modes.

Note *In section 2.10, recommendations are given for the maximum values of the overall probability of failure in the useful life of the subset of the structure for all the ultimate and serviceability limit states.*

2.2.23 Reliability

(7) The complementary value of the probability p is 1-p.

Reliability is the complementary value[7] of the overall probability of failure against the principal modes ascribed to all the ultimate limit states.

2.2.24 Functionality

Functionality is the complementary value of the overall probability of failure against the principal modes ascribed to all the serviceability limit states.

2.2.25 Probability of stoppage

Probability that a subset fail to meet the exploitation requirements in a specific time interval because of the occurrence of a stoppage mode. This is generically known as probability of operating stoppage.

2.2.26 Overall probability of stoppage

Probability of breakdown during the useful life of the subset, against all the principal stoppage modes ascribed to all of the operational stoppage limit states.

2.2.27 Operationality

(8) The terms, reliability, functionality, operationality applied to safety, serviceability, and use, and exploitation usually are accompanied by the word level,as in reliability and safety level.

Complementary value of the overall probability of stoppage in the project phase against the principal stoppage modes, ascribed to all of the stoppage limit states[8].

2.3 Objective, requirements, and criteria of the project

The objective of any project is to create a maritime structure, which,as a whole and in each of its parts and elements, satisfies all safety, serviceability, and use and exploitation requirements in each of the phases of the project by doing the following:

- studying design alternatives and determining the project factors that: (1) define the geometry of the various structural elements of the construction and soil; (2) characterize the physical environment and the building materials; (3) evaluate the agents and their actions

- verifying if the levels of reliability, functionality, and operationality, recommended in section 2.10 are met.

2.3.1 Project criteria

Project criteria are used to define and verify a project and its design alternatives.At the very least, the following criteria should be considered:

- Spatial and temporal domain
- Provisionality and permanence
- Project factors
- General and operational intrinsic nature
- Calculation process
- Reliability, functionality, and operationality levels
- Recommended values

The following sections describe the project criteria in greater detail.

2.4 Spatial and temporal domain

Generally speaking,the maritime structure is located at a certain site and is built to carry out certain functions over a specific period of time. It is advisable to define spatial units and part of the structure in terms of their typology and environment.

Furthermore, from the time of its construction until it is dismantled or used for other purposes, the maritime structure as a whole and each of its parts goes through successive states, which are called project states.These states characterize both its operational capacity and properties referring to structure and shape, i.e. its activity.The project states can be grouped in time intervals of greater duration, the sequence of which constitutes the project phases.

2.4.1 Subset of a structure

The structure is divided into subsets in order to better describe, classify, select, and evaluate the project factors, as well as to establish the spatial domain for the verification of the safety, serviceability, and exploitation levels.

2.4.2 Time intervals

Temporal framework within which the project factors are classified,selected,and evaluated for the verification of safety, serviceability, and use and exploitation levels. The following time periods should be taken into consideration (see figure 2.2):

- Short-term
- Long-term
- Project phase

The first two time intervals can be defined in terms of the temporal variability of the project factors and their duration. Project phases are defined in terms of the principal activity of the structure. Time intervals of longer duration can be described as sequences of shorter time intervals. In this case, the shorter interval is referred to as the time interval unit.

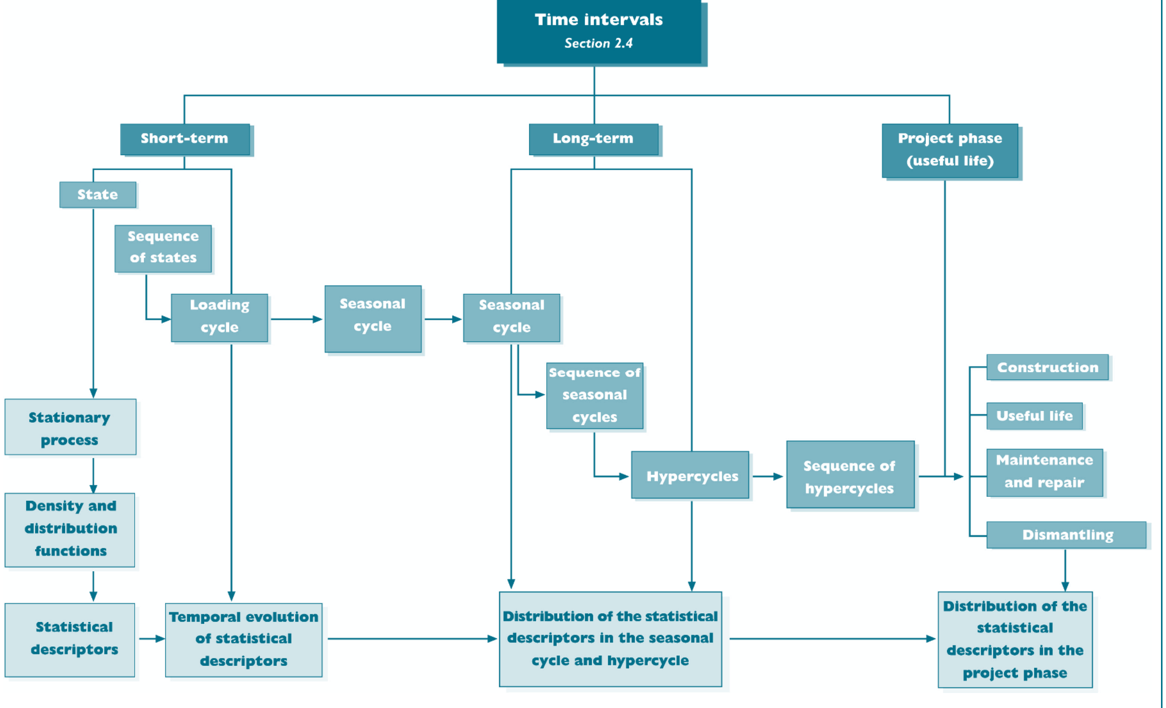


Figure 2.2: Time interval organization.

2.4.2.1 Short-term

State and loading cycle belong to this subset of time intervals.

Note *In general terms, the value of the project factors and the behavior of the maritime structure or its environment varies over time in a way that is very difficult to predict. Time variability can be broken down into time intervals during which the processes that cause this variability can be regarded as stationary in a statistical sense. This makes it possible to describe the behavior of the project factor value by using probability models in which the statistical descriptors or parameters of the model are constant. For each time interval, the basic outcome of the project factor is defined, normally as a random variable.*

2.4.2.1.1 State

Time interval in which the manifestation of project factors and of the structural or operational response in a subset of the structure or site is considered to be stationary in a statistical sense. The duration of a state depends on the temporal variability of the project factors, as well as the structural response. When the state refers to an overall structural response, it is called a project state.

The outcomes are described by variables whose value changes over time. This variability can be statistically described by probability functions and their corresponding statistical descriptors.

Note *During the state, a sequence of basic outcomes of the project factor or factors occurs. For example, a "sea state" contains a number of wave heights, which are defined by the maximum vertical distance between two consecutive upcrossings through the mean water level. In this case, the basic outcome of the sea state is the height of the wave. Given the variability of the wave sequence, the sea state outcomes, under certain conditions, can be described in terms of a random variable, for example, the mean of the highest one third of the waves denoted by the significant wave height. This is known as the state variable or statistical descriptor.*

2.4.2.1.2 Loading cycle

Sequence of states that begin at the moment that the statistical descriptor which is representing the state, upcrosses a certain threshold value and ends when, after a period of time, it downcrosses it again.

Note *An example of a loading cycle is a sequence of sea states that have a significant wave height which is superior to a certain threshold value (e.g. $H_s \geq 3m$). This cycle is known as a storm cycle. If the sea state descriptor values are lower than a certain threshold value, the cycle is denoted calm.*

2.4.2.2 Long term

Time intervals of long duration which include among others, seasonal cycles and hypercycles.

2.4.2.2.1 Seasonal cycle

Sequence of loading cycles, whose duration is normally a meteorological year.

Note *In the southern Mediterranean regions, a meteorological year begins on October 1 and lasts until September 30 of the following year, and can be regarded as the "planet's pulse". Moreover, a meteorological year is the economic pulse of Western civilization. The useful life of a structure is generally defined in years. From an environmental, social and economic perspective, loading cycles can be grouped in seasonal cycles, which last a year. However, this generalization does not always apply since at sites where climatic manifestations are linked to the monsoon period, or when the economic cycle is strictly seasonal, seasonal cycles are not a year long, but can last four months, two months, etc.*

2.4.2.2.2 Variability hypercycle

Sequence of seasonal cycles, whose duration depends on the site.

Note *It is well-known that in the temperate zones of the planet, there are sequences of humid years followed by sequences of more or less dry years. This phenomenon has not as yet been satisfactorily explained. There is presently not enough statistical information available to determine these hypercycles. However, in the future, after measurements have been consistently recorded over an extended time period, it will be possible to analyze the hypercycles of marine and atmospheric dynamics. On the basis of data available from the Iberian Peninsula, the length of hypercycles usually ranges from seven to eleven years.*

2.4.2.3 Other time intervals

Short and long time intervals are defined in terms of the temporal variability of agents of the physical environment. Other project factors show different temporal variability in a specific place. If adequate justification is given, other time intervals can also be defined.

Note *In order to account for the temporal evolution of soil behavior, two extremes are usually considered: a short-term state when the water has not been able to move (without drainage), and a long-term state when the interstitial water has reached a stationary regime. The duration of these two states depends on the type of soil and the state of the load.*

2.4.2.4 Project phase

Temporal sequence of project states during which the maritime structure or a subset of the structure has the same activity, even though it may have other secondary activities. The following can be considered to be project phases: surveys and project design, construction, useful life, maintenance, repair, and dismantling.

Note *The loading cycle is described in terms of the states which for all practical purposes, are time period units. Analogously, the project phase can be described in years. In this case, the year is the time interval unit. Time interval units are used in the statistical description of project factors.*

2.4.2.4.1 Surveys and construction project

The survey and construction project phase lasts from the beginning of the initial planning of the structure to the actual elaboration of the design, containing field and laboratory research, environmental impact studies, etc.

2.4.2.4.2 Construction phase

The construction phase lasts from the beginning of the construction until the commissioning of the structure, this latter being defined as the time starting from when the structure completely fulfills the function for which it was designed. Depending upon the activities to be carried out on the structure or any of its elements, it is possible to distinguish the following subphases of construction: fabrication, transport,installation, progress and constructional waitings, and others.

2.4.2.4.3 Useful life phase

All project states that can occur from the time that the structure completely fulfills the function for which it was designed until it is no longer in service is dismantled, or used for another purpose.

2.4.2.4.4 Maintenance and repair phase

Project phases which my be undergone by the maritime structure or one of its elements during the scheduled maintenance work, as well as unforeseen repairs. Depending on the actions to be carried out in the repair of the subset of the structure or of one of its elements, it is possible to specify the following subphases in the processes of maintenance and repair: preparation and dis-mantling,fabrication,transport,installation,progress and constructional waitings,as well as others.

2.4.2.4.5 Dismantling phase

Project states, which take place when the structure or any of its elements is being take down. In this phase, the following subphases may be distinguished: preparation and dismantling work,trans-port, deposit, abandonment, recycling or reutilization, and others.

2.4.2.4.6 Specification of other project phases

Other phases and subphases of the project may also be considered,which are in consonance with the particular characteristics of the structure. In such a case, it is necessary to establish,after due justification, the criteria and methods that will be used to verify safety, serviceability, and use and exploitation.

2.5 Provisionality and permanence

Maritime structures and their subsets are regarded as provisional or permanent in accordance with the criteria specified in the following sections:

2.5.1 Provisional structures

A structure is said to be provisional when it is due to remain at a certain site, without alterations regarding its safety, serviceability, and use and exploitation for a period of time, which, within the framework of these Recommendations is a time period of less than five years.

2.5.1.1 Project phase duration of provisional structures

The duration or life of the different project phases is defined by their necessity or functionality, and should be duly justified in the project.

2.5.1.2 Transformation of a project from provisional to permanent

In the event that a provisional maritime structure is to become permanent, the owner should design and verify the structure, taking into account the extension of its useful life in accordance with the general project criteria.

2.5.2 Permanent structures

Failing adequate justification or express recommendation being given to the contrary, a structure is considered permanent when it is due to remain at a certain site with the characteristics specified in the original project for a period of longer than five years.

2.5.2.1 Duration of the project phases

The duration of any of the project phases of permanent maritime structures is established on the basis of building,functional,economic, and administrative criteria.However, in some cases, it is not easy to specify a duration for the project phases,especially for the useful life phase. For those cases in section 2.1.3.1., the duration of the useful life of the project is a lower bound.

2.5.2.2 Useful life of the structure

The time period of the useful life phase is known as the useful life of the project or simply, useful life, V_S. Generally speaking, this term refers to the time period during which the structure fulfills the principal function for which it was designed.

2.5.2.3 Criteria used to determine useful life

The value of the useful life phase of the project, V_S is determined by the developer. However, this duration should fulfill the following criteria:

- In permanent maritime structures whose duration is determined by their use and exploitation, this time period will be taken as the minimum value of the useful life of the project.
- In those cases in which the duration is unknown or has not been defined, the useful life of the project (expressed in years) should, without further justification, be taken as not less than the value assigned to it in table 2.1., in accordance with the intrinsic nature of the maritime structure.
- For operational climatic reasons as well as for other reasons, the useful life of the structure can be defined in terms of other time intervals. In this case, the values in table 2.1 should be converted into units of the time interval being considered,adapting and duly justifying the equivalence between the two.
- When components of the same maritime structure are envisaged as having different starting up times, defining different project states, and the duration of any state is less than a certain number of years,(considered in these Recommendations as five),the same useful life should be applied to all stages of the construction.
- In those cases in which it is foreseen that after M years, the realization of a second stage might alter the significant values of some of the project factors, the duration of the useful life phase of the project is considered to be M years.In these Recommendations,M has to be larger than five years.

In those cases, the owner of the structure should do the following:

1. Plan and design the successive starting up time or foreseeable stages.

2.If a second stage of the structure is not implemented or is postponed,the relevant subset of the structure should be adapted so that it meets project requirements in regards to the extended useful life phase.

3. If the stage is implemented, it is necessary to verify that the required safety, serviceability, and use and exploitation level for the structures of previous phases are met. If necessary, a project of adaptation to previously built structures must be elaborated.

2.5.2.4 Extended useful life of a structure

The useful life of a maritime structure may be longer than the actual useful life of the project. In this case and if the structure continues to fulfill its function, whether this function is original or new, its extended useful life refers to the additional time during which the structure can keep on fulfilling its function, even though the safety, serviceability, and use and exploitation requirements are different from those for which it was originally built.

In these cases, the owner of the structure should design and verify the structure, taking into account its extended useful life in accordance with the general project criteria.

2.6 Project factor and design requirements

A design alternative of a subset is a response to the factors and the design requirements, among which can be included:

- Spatial (site) and temporal (project phases) domain
- Requirements for use and exploitation
- Geometry of the subset and the soil
- Properties (parameters) of the physical environment and construction materials
- Agents that can interact with the maritime structure and the environment, as well as the specific actions that they carry out.

Generally speaking,it is impossible to know the exact nature of the project parameters and variables that will affect each subset of the structure during its useful life. This also follows for their magnitude, and when relevant, their direction. It is therefore necessary to supply criteria for classifying the project factors,determining their values, and delimiting their spatial and temporal variability. The project factors and design requirements are described in Chapter 3.

2.7 General and operational intrinsic nature

Usually, decisions regarding the project for a maritime structure are taken on the basis of previous external planning studies, which include, among other things, an analysis of the economic, social, and environmental impact of building the structure. In these Recommendations, the general and operational intrinsic nature of a maritime structure are defined in consonance with those repercussions (see figure 2.3).

2.7.1 General intrinsic nature: definition

The importance of a subset of the maritime structure, as well as the economic, social, and environmental impact produced in the case of serious damage or destruction or total loss of service and functionality is evaluated by means of the general intrinsic nature of the subset. This intrinsic nature will be assessed by selecting the failure mode that gives highest value of repercussion from the principal modes assigned to the ultimate limit state and the serviceability limit state.

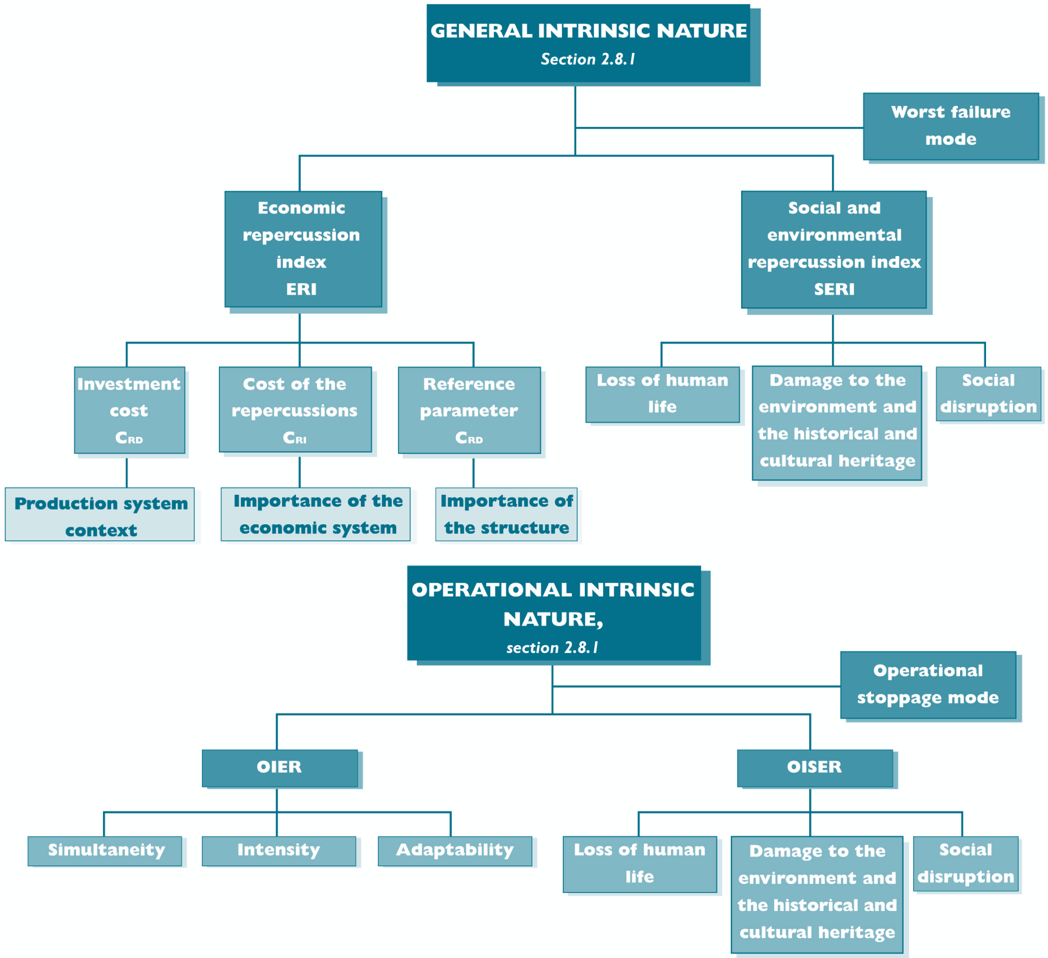


Figure 2.3: General and operational intrinsic nature of the subset of the structure

Note *The general intrinsic nature of a subset of the structure is normally defined on the basis of a principal failure mode assigned to an ultimate limit state. In other words, it is safety oriented. However, there are cases in which the intrinsic nature of the structure will be established on the basis of a principal failure mode assigned to a serviceability limit state, and thus will depend on its functionality.*

2.7.1.1 General intrinsic nature of the subset of the structure

All the subsets of the structure, whose destruction or total loss of functionality has similar economic, social, and environmental repercussions will have the same general intrinsic nature value. Those subsets of the structure whose failure implies significantly different repercussions will have a different general intrinsic nature value.

2.7.1.2 Subsets implemented in stages

When it can be foreseen that the maritime structure will be implemented in stages,each stage will have its own separate general intrinsic nature as long as the time elapsed between the starting up times of the different stages is greater than a certain number of years.Within the framework of these Recommendations, the minimum time period is five years. Otherwise, the subset of the structure will only have one general intrinsic nature.

2.7.1.3 Indices to determine the general intrinsic nature

It is the role of the developer of the maritime structure (who may belong to either the public or private sector) to specify the general intrinsic nature of the structure. In the absence of a definition, the general intrinsic nature of the structure is established as a function of the following indices:

- economic repercussion index (ERI)
- social and environmental repercussion index (SERI)

Note *The above two indices should be established a priori and as such, constitute an initial approximation to the general intrinsic nature of the structure. Consequently, they should be evaluated within the framework of a previous study. Both indices are obtained by assuming the occurrence of a failure mode related to the ultimate and serviceability limit states.*

2.7.1.4 Economic repercussion index (ERI)

This index leads to a quantitative assessment of the foreseeable economic repercussions caused by the rebuilding of the structure (C_{RD}),and the consequences for the economic activities directly related to the structure (C_{RI}) in the event of its destruction or total loss of exploitation capacity. The ERI is defined by the following formula in which C_0 is an economic parameter of dimensionalization:

$$IRE = \frac{C_{RD} + C_{RI}}{C_0}$$

2.7.1.4.1 Approximate evaluation of the ERI

In those cases in which a detailed determination of C_{RI} is not carried out, either for reasons of excessive complexity because of the size of the structure or because there are no previous studies to base it on,the value of the ERI can be qualitatively estimated by the methodology described in section 2.11.

2.7.1.5 Classification according to the ERI

In accordance with the value of the Economic Repercussion Index (ERI), maritime structures can be classified in three groups (R_i, i = 1, 2, 3):

- R_1, structures with low economic repercussion: ERI $\leq$ 5
- R_2, structures with moderate economic repercussion: 5 < ERI $\leq$ 20
- R_3, structures with high economic repercussion: ERI > 20

2.7.1.6 Social and environmental repercussion index (SERI)

This index leads to a qualitative assessment of the social and environmental repercussions produced in the event of the destruction or total loss of the operationality of the maritime struc-ture. Factors evaluated are the possibility and scope of the following: (1) loss of human lives; (2) damage to the environment as well as the historical and cultural heritage; (3) degree of social disruption produced, taking into account that the failure occurs after the economic activities directly related to the structure have been consolidated.

The SERI is defined as the sum total of the three subindices:

$$SERI = \sum_{i=1}^{3} SERI_i$$

In the above formula, $SERI_1$, is the subindex of the possibility and impact of the loss of human lives, $SERI_2$, the subindex of damage to the environment and the historical and cultural heritage; and $SERI_3$, the subindex of social disruption.

2.7.1.6.1 Approximate evaluation of the SERI

In those cases when it is impossible to carry out a detailed determination of the SERI, its values can be qualitatively estimated by the methodology described in section 2.11.

2.7.1.7 Classification according to the SERI

According to the value of the social and environmental repercussion index (SERI), maritime structures can be classified in four groups (S_i, i = 1, 2, 3, 4):

- S_1, structures with no social and environmental impact, SERI < 5
- S_2, structures with a low social and environmental impact, 5 ≤ SERI < 20
- S_3, structures with a high social and environmental impact, 20 ≤ SERI < 30
- S_4, structures with a very high social and environmental impact, SERI ≥ 30

2.7.1.8 Project criteria dependent on the general intrinsic nature

In the absence of specific studies, the following elements are defined in terms of the general intrinsic nature of the maritime structure:

- Minimum values for the useful life of permanent structures
- Maximum overall probability of the failure of a subset and the operational level
- Methods for verifying the safety and serviceability levels against the failure modes assigned to the ultimate and serviceability limit states, as well as the methods for verifying use and exploitation against the operational stoppage modes
- The plans of maintenance, visual inspection, sounding, and monitoring the subset of the structure.

2.7.2 Operational intrinsic nature: definition

The economic repercussions and the social and environmental repercussions produced when the maritime structure stops functioning or reduces its operational level is specified by means of its operational intrinsic nature. This will be evaluated by selecting the mode from among the principal modes of operational stoppage, which gives the minimum operational level.

2.7.2.1 The operational intrinsic nature according to the subset of the structure

The same operational intrinsic nature of the maritime structure is given to all the subsets of the structure, whose reduction or stoppage of the exploitation produces similar economic, social, and environmental repercussions. A different intrinsic nature can be associated with those parts of the structure whose operational stoppage produces different repercussions.

2.7.2.2 Indices for the specification of the operational intrinsic nature

It is the responsibility of the developer of the maritime structure (who may belong to either the public or private sector) to specify the operational intrinsic nature of the structure. In the absence of a specific definition, the operational intrinsic nature of a maritime is established in terms of the following indices:

- Operational index of economic repercussion (OIER)
- Operational index of social and environmental repercussions (OISER)

2.7.2.3 Operational index of economic repercussion (OIER)

The operational index of economic impact quantitatively assesses the costs resulting from the operational stoppage of the subset of the structure.

2.7.2.3.1 Approximate evaluation of the OIER

In those cases in which a detailed determination of costs is not carried out,either for reasons of excessive complexity because of the size of the structure or the lack of previous studies,the value of the OIER can be qualitatively estimated by the methodology described in section 2.11.

2.7.2.4 Classification according to the OIER

According to the value of the Operational Index of Economic Repercussion (OIER), maritime structures can be classified in three groups ($Ro_{,i}$, i = 1, 2, 3):

- $RO_{,1}$, structures with low economic repercussion:OIER = 5
- $RO_{,2}$, structures with moderate economic repercussion: 5 < OIER = 20
- $RO_{,3}$, structures with high economic repercussion: OIER > 20

2.7.2.5 Operational index of social and environmental repercussions (OISER)

This index leads to a qualitative assessment of the social and environmental repercussion produced in the event of an operational stoppage of the maritime structure. Factors evaluated are the possibility and scope of the following:(1) loss of human life;(2) damage to the environment as well as the historical and cultural heritage; (3) degree of social alarm produced.

The OISER is defined by the sum total of the following three indices:

$$OISER = \sum_{i=1}^{3} OISER_i$$

In the preceding formula,$OISER_1$, is the subindex of the possibility and impact of the loss of human lives; $OISER_2$, the subindex of damage to the environment as well as the historical and cultural heritage; and $OISER_3$, the subindex of social disruption.

2.7.2.5.1 Approximate evaluation of the OISER

In those cases in which it is impossible to make a detailed specification of the $OISER_i$, its values can be qualitatively estimated by the methodology proposed for the approximate calculation of the SERI (see sections 2.7.1.7.1 and 2.11.4).

2.7.2.6 Classification according to the OISER

According to the value of the Operational Index of Social and Environmental Impact (OISER),the subsets of the maritime structure can be classified in four groups ($S_{O,i,}$ i = 1, 2,3, 4):

- $S_{O,1}$, structures without any significant social and environmental impact, OISER < 5
- $S_{O,2}$, structures with a slight social and environmental impact, 5 ≤ OISER < 20
- $S_{O,3}$, structures with a significant social and environmental impact, 20 ≤ OISER < 30
- $S_{O,4}$, structures with a very significant social and environmental impact, OISER ≥ 30

Note *In the majority of maritime structures, the OISER has no value since, once the operational stoppage occurs, the cause of any possible environmental impact ceases to exist However, some structures, such as the submarine outfalls and water intake for electric plants or for desalinization plants can have significant social and environmental repercussions. In this case, the OISER ≠ 0, and its importance ought to be considered in the project in accordance with the operational intrinsic nature of the maritime structure.*

2.7.2.7 Project criteria dependent on the operational intrinsic nature

In the absence of detailed studies, and in accordance with the operational intrinsic nature of the maritime structure, the following criteria should be considered in a time interval, which is generally a year[9],

- minimum serviceability level
- average number of operational stoppages
- maximum duration of an operational stoppage

(9) In the majority of cases, the year is considered as the pulse unit or meteorological period. Working from the hypothesis that the outcomes of each year are statistically independent,the annual operational level also represents the operational level of the subset of the project during its useful life.

2.8 Verification procedure

One of the tasks in the project is to verify that the subset as a whole and all of its elements are reliable, functional, and operational during each of the project phases.Accordingly, a verification procedure is recommended that includes at least the following activities:(1) definition of the project factors and design requirements developed in Chapter 3;(2) selection of the limit states,definition of the failure and stoppage modes, formulation of the verification equation, work and operating conditions (WOCs), and establishment of the types of combination, explained in Chapter 4; (3) resolution of the verification equation and calculation of the probability of occurrence of each mode and set of modes in the project phase (see Chapters 5, 6,and 7).

2.8.1 Definition of the project design alternative and organization factors

Once the functional requirements of the structure are specified and their general intrinsic nature determined, it is necessary to geometrically define the design alternative, choose the project factors, and organize them by their origin and function, and temporal domain occurrence.

2.8.2 Limit states

Failure modes can be grouped into the following limit states: (1) ultimate limit states (ULS), which include failure modes that cause a loss of structural capacity or resistance; (2) serviceability limit states (SLS), which include the failure modes that induce a loss of serviceability because of shape and structural deterioration; (3) operational limit states (OLS), which include the stoppage modes that cause loss of use and exploitation without the occurrence of a structural or functional failure.

2.8.3 Verification equation

The occurrence of each of the modes is described in terms of a functional relation between project factors that is known as the verification equation. This equation can appear in different formats: global safety coefficient, safety margin, etc. If there is no verification equation or the existing one is unreliable, it is necessary to have recourse to laboratory or field studies as well as other techniques.

2.8.3.1 Safety and failure domains

States and failure domains are made up of sets of project states for which the verification equation takes values that are respectively higher or lower than a certain threshold value. If the verification equation is of the safety margin type, $S = X_1 - X_2$, where S is the safety margin and X_1 and X_2 are favorable and unfavorable sets of terms to avoid the occurrence of failure, then the safety domain is $S > 0$. The failure domain is made up of all of the project states for which $S \leq 0$. If the equation is of the global safety coefficient type, the safety domain is $Z > Zc$. The failure domain is defined by $Z \leq Zc$, where Zc is the minimum global coefficient allowed for the mode.

Note *The words safety and failure should be understood in their widest sense, as referring the capacity to meet or fail safety, serviceability and utilization requirements.*

2.8.4 Working and operating conditions (WOCs)

Failure modes can occur under different project states. These states can be grouped in WOCs, representative of the extreme manifestations of the predominant agents and of the functional requirements, as well as of the use and exploitation of the structure and of the installations. A WOC is a set of project states characterized by the occurrence of certain project factors in terms of their simultaneity and compatibility. Generally speaking, WOCs are specified in terms of predominant agents. In each project phase, activities can fall in the following groups: normal $WOCs_1$, extreme $WOCs_2$, and exceptional $WOCs_3$.

2.8.5 Types of combination

To begin with, it is sufficient to define three types of combination of factors and terms in the verification equation, namely: improbable or fundamental, frequent, and quasi-permanent or habitual.

2.8.6 Verification method

The verification method defines the criteria to do the following: (1) give values to the project factors and terms of the verification equation; (2) solve the equation; (3) define the failure criteria and, thus, declare in a certain time interval when the subset of the structure satisfies the safety and serviceability requirements.

Note

When a verification method for a failure or stoppage mode is applied,the result depends on the values of the project factors. Since the occurrence, magnitude and simultaneity of the project factors are difficult to foresee, the result of the verification equation should be treated as a random variable with a probability model.

In accordance with table 4.1. and the intrinsic nature of the structure, four verification methods are recommended.These methods are organized in three levels (Levels I, II, and III), which are described in Chapters 5 and 6.The Level I methods of verification do not give information about the probability of failure or stoppage, and as a result, its evaluation should be carried out by establishing certain hypotheses that are described in Chapter 5. Level II and III Verification Methods provide the probability of occurrence of the mode in the time interval.

2.9 Safety, serviceability, and use and exploitation

In each project phase, the structure as a whole and each of its subsets, components, subcomponents, etc. should meet the project requirements for safety serviceability, and exploitation (see figure 2.4).

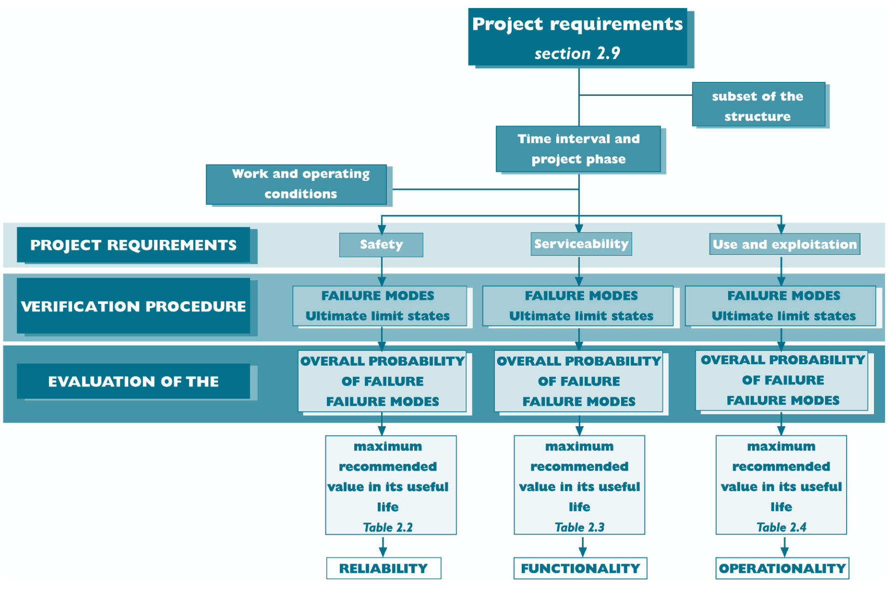


Figure 2.4: Project requirements: safety, serviceability, and exploitation

2.9.1 Safety

A subset of the structure is considered to be safe when it meets the safety requirements specified in the project and required by current regulations during the occurrence of all possible project states.

When a project state does not meet these safety requirements and the structure or one of its components lacks the capacity to respond adequately insofar as its structure or resistance is concerned, it is said to be unsafe or unreliable.

Generally speaking, the failure occurs in a short time period and can affect the subset of the structure as a whole or one of its components, subcomponents,etc. in the way or mechanism described by the failure mode. If the mode or modes are caused by the same agent, various failure modes can occur in the same time interval in such a way that the occurrence of one mode leads to or induces other modes.

2.9.1.1 Safety by subsets

The safety of the maritime structure will be verified in terms of its subsets or as a whole.

2.9.1.2 Safety of the subset in time

The safety of the subset of the structure should be verified in all of the project phases, always assigning the failure modes to the ultimate limit states. Accordingly, the project phase can be divided into time intervals of shorter duration.

2.9.1.3 Probability of failure against safety

The probability that a subset of the structure will not meet the safety requirements in a certain time interval because of the occurrence of a failure mode is generically known as probability of failure (against safety).

2.9.1.4 Reliability

(10) The complementary value of the probability p is 1-p.

Reliability is the complementary value[10] of the probability of failure in the project phase, against all of the principal failure modes assigned to all of the ultimate limit states. Within the context of this ROM, this probability is known as the overall probability of the subset against the ultimate limit states.

2.9.1.4.1 Maximum overall probability in ultimate limit states

In a subset of the structure and its useful life, the overall probability cannot be more than the value given in table 2.2 in accordance with the general intrinsic nature of the structure.

Note *Due to the geometric dimensions of the maritime and harbor structures, as well as to the spatial diversity of the factors affected, the structure should be verified by subsets in accordance with the definition given in section 2.2.9. Implicit in this procedure is the hypothesis of the statistical independence of the subsets of the structure. Consequently, the probability of failure in the whole structure as compared to all possible failure modes is the probability that at least one subset of the structure will be affected by the occurrence of at least one of the failure modes assigned to one of the ultimate limit states.*

2.9.2 Serviceability

A subset of the structure must fulfill the functional requirements regarding resistance and shape, specified in the project and required by current regulations for all the states that can occur in the project phases.

When these requirements are not met in a project state and the subset or one of its components does not have the capacity to behave properly, it is considered not to be fit for service. Usually, the failure occurs gradually over time and can affect the subset of the structure as a whole or some of its components, subcomponents, etc. in the way or mechanism described by the failure mode. If the failure or failures are caused by the same agent, various failure modes can occur in the time interval in such a way that a chain reaction is produced and one mode leads or induces another or other failure modes.

Note *The reduction or loss of serviceability can be caused by the loss of durability. Durability is the capacity of the subset of the structure and of the building materials to withstand, without deterioration or loss of the properties described and required of them in the project,the actions of the physical environment, soil, and construction as well as those pertaining to use and exploitation.*

2.9.2.1 Serviceability by subsets

This is verified in terms of its subsets, and, when applicable, in terms of the structure as a whole.

2.9.2.2 Serviceability of the subset in time intervals

This is verified in all project phases, considering the failure modes assigned to the serviceability limit states.Accordingly, the project phase can be divided in time intervals of shorter duration.

2.9.2.3 Probability of failure against serviceability

Probability that a subset of the structure fail to meet the serviceability requirements in a specific time interval because of the occurrence of a failure mode.

2.9.2.4 Functionality

Complementary value[11] of the probability of failure during the project phase against all of the principal modes of failure assigned to all of the serviceability limit states. In the context of this ROM, this is known as the overall probability of the subset against the serviceability limit states.

(11) The complementary value of the probability p is 1-p.

2.9.2.4.1 Maximum overall probability in serviceability limit states

In a subset of the structure and for its useful life, the overall probability cannot be greater than the value given in table 2.3 in accordance with the general intrinsic nature of the structure.

2.9.3 Use and exploitation

A structure or subset and its installations are in exploitation when they meet the use requirements specified in the project and required by current regulations.

When these requirements are not satisfied in a project state, or one the subcomponents lacks the capacity to behave properly, and without structural failure, the structure is considered not to be in exploitation or not to be operational.The operational stoppage generally occurs all at once because one of the project factors, namely one of the climatic agents exceeds one or several use and exploitation thresholds.When the cause is no longer present, the subset once again recovers its capacity to meet the exploitation requirements.

The form or way in which the stoppage is produced is described by an operational stoppage mode. If the stoppage is motivated by the same agent, stoppages can occur in various installations in the same time interval, setting off a chain reaction in such a way that the occurrence of one stoppage triggers another in the same or different installations.

2.9.3.1 Use and exploitation by subsets

The use and exploitation of the structure is verified in terms of its subsets, and, when applicable, in terms of the structure as a whole.

2.9.3.2 Use and exploitation of the subset in time intervals

This is verified in all of the project phases, taking into account the modes assigned to the limit states of the operational stoppage. Accordingly, the project phase can be divided into time intervals of shorter duration.

2.9.3.3 Probability of stoppage

The probability that a subset of a structure will fail to meet the use and exploitation requirements in a time interval because of the occurrence of a stoppage mode is generically known as the probability of operational stoppage.

2.9.3.4 Operationality

(12) The complementary value of probability p is 1-p.

Complementary value[12] of the probability of stoppage in the structure's useful life against all of the principal stoppage modes assigned to the stoppage limit states. In the context of this ROM, this probability is known as the operationality (or level of operationality) of the subset, against the stoppage limit states.

For a subset of the structure and a project phase, the level of operationality is the percentage of time that the structure and its installations are in exploitation, and thus fulfill the requirements of use and exploitation, whether or not they are actually being used.

2.9.3.4.1 Minimum level of operationality

In a subset of a structure and during its useful life, the level of operationality cannot be less than the value given in table 2.4 in accordance with the operational intrinsic nature of the structure.

2.9.3.5 Other evaluation measures of use and exploitation

Besides the level of operationality, the quality of utilization is evaluated in terms of the average number of stoppages in the project phase or other time interval, and the maximum duration of a stoppage mode.

2.9.3.5.1 Average number of stoppages

For a subset of the structure and a given time interval, the average number of stoppages is the number of times that on average the subset of the structure or its installations fails to fulfill exploitation requirements.

2.9.3.5.1.1 Average advisable number of operational stoppages

For a subset of the structure and a given time interval (generally, a year), the average number of stoppages due to the occurrence of all of the stoppage modes cannot exceed the values given in table 2.5.

2.9.3.5.2 Duration of a stoppage

Time that the stoppage lasts and, thus,the time that the subset of the structure or its installations fails to fulfill the requirements of use and exploitation.

Note *The duration τ of an operational stoppage is the time that elapses from the moment that the stoppage of the installations occurs until they are in use again. The duration is a random variable.*

2.9.3.5.2.1 Maximum advisable duration

The duration of each stoppage mode in the useful life project phase cannot be greater than the values given in table 2.6.

Note *The maximum duration τ_{max} of a stoppage is the maximum time that elapses from the moment that the stoppage of the installations occurs until they are in use again. The maximum duration is an extreme random variable. A statistical descriptor is the most probable maximum value, or mode.*

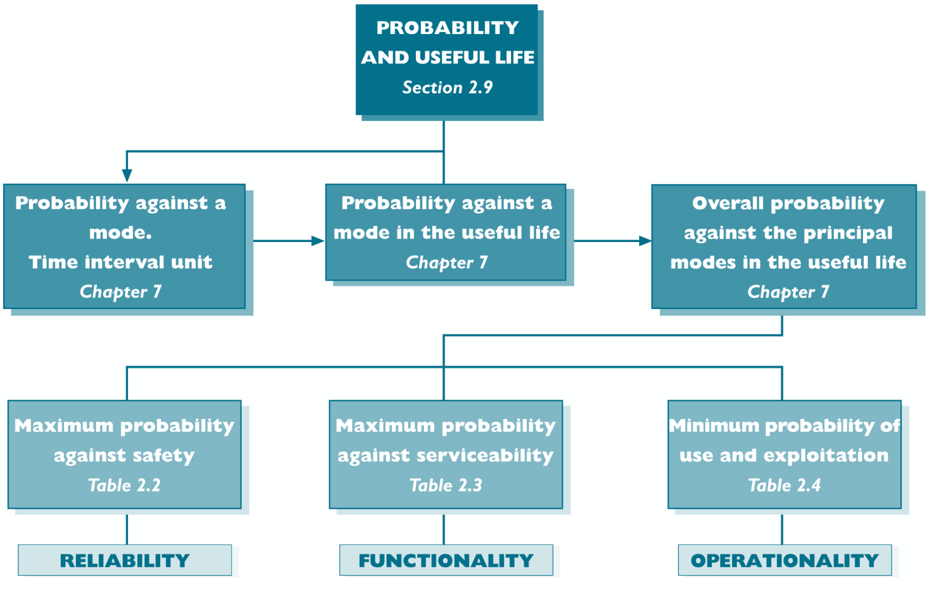


Figure 2.5: Calculation sequence of the overall probability of failure and stoppage.

2.9.4 Calculation of the overall probability of failure and stoppage

The calculation of the overall probability of failure and stoppage is carried out by the following sequence: (1) the probability of occurrence of a mode in the time interval unit; (2) the probability of occurrence of the mode in the project phase (generally, its useful life); (3) the overall probability of occurrence of all the modes assigned to the ultimate serviceability and operational limit states in the project phase. Figure 2.5 is a diagram of the sequence.

2.9.4.1 Diagram of the principal modes of failure and stoppage

A diagram of the principal modes is a simplification of the behavior of a subset and lists the different modes. Furthermore, the diagram can describe the relation between different modes in the case that such a relation exists. In this sense, a diagram can be serial, parallel or compound. (See Chapter 7).

Note *The subset of a structure is a part of the system that is designed and built to provide a set of services. In certain cases it is necessary to evaluate the joint probability of the system against the failure or stoppage modes. In this ROM no methods are proposed for the evaluation of this joint probability since in that case it would be necessary to define the failure trees that take into account the possible reactions of the system to a failure or a set of failures, which depend,among other things, on the services, installations, and organization of the system. In these Recommendations, the formulation of the joint probability of the failure is based on the independence of each subset of the structure in reference to its safety, serviceability, and use and exploitation, and is known as the overall probability of failure. It is a pragmatic approach, which, in all likelihood,will be changed in the near future.*

2.9.4.2 Safety and failure domains

This type of domain is made up of the sets of project states for which the verification equation takes greater or lesser values in relation to a given threshold value. If the verification equation is of the safety margin type, the safety domain is $S > 0$.The failure domain is formed by all project states for which $S \leq 0$. If the equation is of the global safety coefficient type, the safety domain is $Z > Z_c$.The failure domain is defined as $Z \leq Z_c$, where Z_c is the minimum global coefficient for the mode.

2.9.4.3 Time interval unit

Temporal framework for which statistical information and probability models of the project factors and terms are available, and in which it is possible to solve the verification equation and evaluate the probability of failure or stoppage.

2.9.4.4 Probability of occurrence of a mode in the time interval unit

This probability is calculated by evaluating the probability that the result of the verification equation will be in the failure domain.The probability of failure against the mode A_{ij}, $p_{Aij} = Pr[S_{Aij} \leq 0]$, where i = 1, ...,M are the modes assigned to each one of the j = 1, ...,N ultimate, serviceability or operational limit states.

Note *If a verification equation is lineal and the X_1 and X_2 are normally distributed and independent, S is also a Gaussian variable.The failure domain is defined as $S \leq 0$. If S is a normal variable with a mean μ_S, and a standard deviation σ_S, the reduced variable $\beta = \frac{0-\mu_S}{\sigma_S}$, is known as the reliability index.The probability of failure $p_{Aij} = Pr[S \leq 0]$, can be obtained from the Gaussian distribution function $\Phi(\beta)$, $p_{Aij} = 1 - \Phi(\beta) = \Phi(-\beta)$, and the reliability of the structure or subset against the mode is $r_{Aij} = \Phi(\beta) = 1 - \Phi(-\beta)$.Moreover, the reliability index can be calculated for non-lineal verification equations with terms that are not random Gaussian variables.The technique to follow is described in Chapter 6 and is included in the methodology of Level II.*

2.9.4.5 Probability of occurrence of a mode in the project phase

Once the probability of occurrence of a mode is known for a time interval unit, its probability of occurrence is determined for the project phase, divided into a finite number of time interval units.

2.9.4.6 Overall probability and diagram of modes

The overall probability of occurrence of principal modes is calculated according to the methodology described in Chapter 7.The modes are grouped in a serial, parallel or compound diagram or chain of failure, assigned to ultimate and serviceability limit states,as well as the level of operationality against the principal stoppage modes assigned to the operational limit states.In the event that sufficient statistical data is available, other calculation methods can be used to arrive at the overall probability.

Note *As explained in Chapter 7,this overall probability is an approximation to the joint probability of failure or stoppage of the subset of the structure.*

2.10 Recommended values

This section gives recommendations for values of the minimum useful life, maximum overall probabilities of failure against safety, serviceability, and use and exploitation, average number of stoppages, and the maximum duration of a stoppage (see figure 2.6).

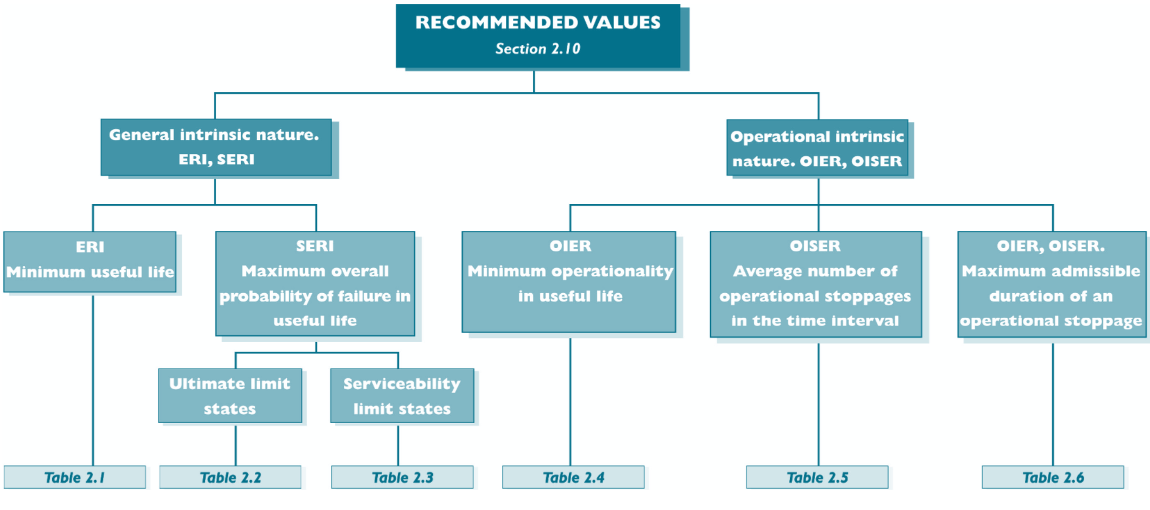


Figure 2.6: Recommended values in accordance with the general and operational intrinsic natures of the subset .

2.10.1 Minimum durations

In those cases in which the duration of the project phase has not been specified a priori, the following minimum durations will be considered.

2.10.1.1 Minimum useful life

The duration of the useful life project phase V_m, is, at the least, the value assigned in table 2.1 in accordance with the economic repercussion index (ERI) of the maritime structure.

Table 2.1: Useful life

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

2.10.1.2 Duration of the construction phase

In the determination of the duration of this phase, the relevant technical and economic resources, as well as the construction processes, which have been established to build the maritime structure, are taken into account. In all of those structures, whose construction process involves the strengthening of the soil (foundations, filling, and core of materials), the minimum duration of the corresponding subphase should be of sufficient length to reduce subsequent deformations to levels that can be tolerated by the maritime structures resting on them.

2.10.1.3 Duration of the dismantling phase

As a rule, the duration of this phase should not be greater than the duration of the construction phase of the structure. When the structure has been built in different stages, the duration of each phase should not exceed the sum of the durations of the construction phases of each stage.

2.10.2 Maximum overall probability of failure in the useful life of the structure

In each subset of the structure and during its useful life, the maximum overall probability of failure will be adjusted to the values recommended in Tables 2.2 and 2.3. These values are merely guidelines and can be modified in the other more specific Recommendations.

Note

In Chapter 7 it is suggested that studies be carried out for the economic optimization of the subset of structure. One of the results of this analysis is the overall probability of failure associated with the optimal economic typology of the subset. Since the values in Tables 2.2 and 2.3 have been determined on the basis of criteria that are not economic, it should not be surprising to find certain differences between the strict application of the values in Tables 2.2 and 2.3 and that obtained on the basis of the economic analysis explained in section 7.7. In any case, the numbers in these tables are experimental, and thus, their validity is transitory until the application of this procedure supplies sufficient data for their definitive adoption or modification.

The value of the probability should not be understood necessarily as a relative frequency that can actually be measured or observed. Probability in the context of the ROM Program can be understood in its Bayesian sense as an assessment of the degree of confidence or "faith" that this will actually occur, taking into account all of the unforeseen factors that might come into play. As such, it can be regarded as an aid in any decision process.

2.10.2.1 In ultimate limit states

The overall probability of failure $p_{f,\ ULS}$, of the subset of the structure, against the failure modes assigned to the ultimate limit states cannot exceed the values assigned in table 2.2 during its useful life.

Table 2.2: Maximum overall probability in the useful life for ultimate limit states.

SERI	< 5	5 -19	20 -29	≥ 30
p_{fELU}	0.20	0.10	0.01	0.0001
β_{ELU}	0.84	1.28	2.32	3.71

Note *The members of the technical committee have tried to make the values in table 2.2 in consonance with technical uses in other branches of civil engineering. In this sense, the maximum probability of failure progressively changes in magnitude in tandem with the social and environmental repercussion index,going from low to high, and then to very high. For maritime structures whose social and environmental repercussion index is very high (s_4),the probability of exceedance is 10^{-4}, which is the order of magnitude of the maximum probability of failure permitted in buildings and public works with a high risk of loss of human lives.*

In accordance with the definition of the reliability index, $r_{f,ELU} = \Phi(\beta_{ELU})$,should be the minimum reliability of the subset of the structure in its useful life, against the principal failure modes assigned to the ultimate limit states.

The majority of maritime structures, especially those affected by waves, usually have a low or very low SERI index, and generally are designed according to economic optimization procedures as recommended in this ROM.These procedures, which should be applied to each structure, lead to the obtaining of suitable values regarding the probability of failure.The value indicated in the preceding table is a limit which, unless extremely well justified, should not be exceeded.

At the other extreme, there are structures within the context of the ROM Program, whose SERI index is high or very high (SERI> 20).Therefore optimization criteria can not be applied to them,but rather they must be designed with all possible safety guarantees in the same way as structures destined for public use. The theoretical probability of failure indicated is purely for referential purposes, and will only be applicable in certain formal verifications carried out with probabilistic techniques.

2.10.2.2 In the serviceability limit states

The overall probability of failure $p_{f,EIS,}$ of the subset of a structure against the principal failure modes assigned to the serviceability limit states cannot exceed the values in table 2.3 during its useful life.

Table 2.3: Maximum overall probability of the useful life phase for the SLS.

SERI	< 5	5 -19	20 -29	≥ 30
p_{fELS}	0.20	0.10	0.07	0.07
β_{ELS}	0.84	1.28	1.50	1.50

Note *In civil engineering it is not customary to calculate a subset of a structure against the failure modes assigned to the serviceability limit states mostly because of the insufficient modeling capacity of the time evolution response. Furthermore, the quantity of available data, whether from the laboratory or the real world, is clearly insufficient. It may take awhile before there is enough theory and data so that the verification of the subset, as opposed to the modes assigned to the serviceability limit state, is as frequent as the verification of the modes assigned to ultimate limit states. In order to achieve this objective, which will doubtlessly* *result in more reliable and functional maritime structures, it is necessary to establish strategies of visual inspection,sounding, and monitoring that can produce data for the comparison of different theoretical approaches. In the meantime, for the sake of descriptive coherence and criteria of functionality and maintenance of the structure, it is helpful to include this verification modality in a general calculation procedure.*

Until more reliable information is available, the values of the overall probability of failure have been obtained on the assumption that the reliability index varies in proportion to the intervals of the SERI. As a result, the recommended values of the overall probability of failure in table 2.3 should be taken as indicative. Time and experience will eventually give the necessary information to contrast and adjust these values.

In accordance with the definition of the reliability index, $r_{f,ELS} = \Phi\ (\beta_{ELS})$ *should be the minimum functionality of the subset of the structure as opposed to the principal failure modes assigned to the serviceability limit state in its useful life.*

2.10.2.3 Provisional starting up time

In the event that the structure provisionally enters into service during the construction phase, the overall probability of failure will be what is specified in the project.In all other cases,it will be equal or inferior to the probability given in table 2.2 and 2.3.

2.10.3 Use and exploitation of the subset in the useful life

In these Recommendations, the exploitation of the subset of the structure can be specified in terms of minimum levels of operationality, the average number of stoppages, and the maximum duration of a stoppage permitted. In reference to the first item on the list, the minimum level of operationality should be achieved in the time period specified as a result of previous economic studies.As for the second item,the average number of stoppages has to be fulfilled in a time interval generally linked to social and environmental factors,and its determination should naturally take such factors into account. Finally, the maximum duration permitted should be analyzed in a time interval that depends on the economic result and the cycle of demand. Until more information is available, the interval used for the calculation of the three measurements will be one year.

Note *The three measurements or indicators of exploitation (i.e. level of operationality, average number of stoppages, and maximum duration) fulfill different objectives, and in each case should be applied (one, two, or all three) when they are relevant to the exploitation of the project.The level of operationality should be obtained from studies regarding the economic profitability of the installation, and therefore, is related to the time interval during which these studies have been carried out.In contrast,the average number of stoppages has its justification principally in the social and environmental repercussion of the stoppage itself, and so the time interval should be defined on the basis of this information. Finally, the maximum permitted duration of the stoppage affects economic factors and the cycle of demand,as well as social and environmental aspects. Consequently, all of this information should be taken into account when defining the time interval.*

Habitually, maritime and harbor installations have an environmental and economic cycle of one year, which naturally means that the operationality and average number of stoppages will be analyzed for this same interval. However, there are cases in which the cycle can be seasonal.The probable maximum duration is conditioned by various factors, and generally, this duration should not exceed a certain value during the useful life phase. If the three measurements show the recommended values for the year, it will be sufficient to verify only two of them since the third will be automatically fulfilled.

2.10.3.1 Minimum operationality

In the useful life, and when it has not been specified a priori, the operationality of the subset against the principal modes assigned to the stoppage limit states in normal WOCs has to be at least the value assigned in table 2.4 in accordance with the OIER, the operational index of economic repercussion of the subset.

TablE 2.4: Minimum operationality in the useful life

OIER	≤ 5	6 - 20	> 20
Operationality, $r_{f,ULS}$	0.85	0.95	0.99
β_{OLS}	1.04	1.65	2.32

Note *In accordance with the definition of the reliability index, $r_{f,ELO} = \Phi(\beta_{ELO})$ is the minimum operationality of the subset of the structure, against all of the principal failure modes assigned to the operational limit states in its useful life. Normally, operational stoppage does not have noticeable social and environmental repercussions (SERI < 5). In these conditions the operationality may not be absolute (nominal guarantee of 100%), but somewhat less. The most convenient level of operationality can be derived from economic studies, but it is not recommendable to exceed the limits specified in this section.*

2.10.3.2 Average number of stoppages

In the time interval specified (usually, a year), and for those cases in which it is not specified a priori, the average number of occurrences N_a, of all the modes assigned to the stoppage limit states, will be at the most, the value specified in table 2.6.

Table 2.5: Average number of operational stoppages per time interval

SERI	< 5	5 -19	20 -29	≥ 30
Number	10	5	2	0

Note *In the event that the operational stoppage has social and environmental repercussions $s_{0,4}$, no such stoppage should occur in the time interval, unless there is adequate justification. The installation should thus be kept operational except in the event of extraordinary or unforeseen conditions. In some cases, in order to meet this requirement, it will be necessary to duplicate the installation*

For more conventional structures in which the SERI < 5, economic studies should be carried out to analyze the optimal number of operational stoppages. Nevertheless, it is advisable to limit a priori the results that such studies can generate, and this limit is specified in the table.

2.10.3.3 Maximum duration of a stoppage

In the useful life and for those cases in which it has not been specified a priori, the probable maximum duration expressed in hours, once the stoppage has occurred, cannot exceed the value assigned in table 2.6, in accordance with the OIER and OISER of the subset of the structure.

Table 2.6: Probable maximum duration of a stoppage mode (hours)

	OISER			
OIER	< 5	5 - 19	20 - 29	≥ 20
≤ 5	24	12	6	0
6 - 20	12	6	3	0
≥ 20	6	3	1	0

Note *Duration is a random value. The total time of stoppage because of the occurrence of a mode in the project phase, whose life is V independent time intervals (e.g. years) is equal to* $V*p_i$ *where* p_i *is the probability of occurrence of the mode in the given time interval. The average number of stoppages due to the occurrence of this mode in V is* $N_{m,i} = V*p_i/\tau_{m,i}$ *, where* $\tau_{m,i}$ *is the average duration of the stoppage. The average duration can be obtained from the distribution function of the stoppage threshold in the time interval (see ROM 0.4 for wind velocity). If the stoppage modes are independent, the total stoppage time due to the occurrence of M modes in V is equal to* $V * \Sigma_M\, p_i$*, where* p_i *is the probability of the occurrence of the stoppage mode i in the time interval. The average number of stoppages of the subset in V time intervals is* $N_m = \Sigma_M V*p_i / \tau_{m,i} = V\, \Sigma_M (p_i / \tau_{m,i})$

The maximum duration, τ_{max} *of a stoppage is the maximum time that passes from when the stoppage occurs until the installations can be used again. It is an extreme random variable. A statistical descriptor of this distribution is the most probable value or mode. The zero value of the probable maximum duration is an indication of the desire, except for specification to the contrary, that no stoppage occur in the subsets of the structure whose OISER is* $s_{0,4}$*. In such cases in order to comply with this recommendation it is necessary to duplicate the installation.*

2.10.4 Other permissible values

The recommended values for the joint probability of failure and operationality are specified for the overall life, which generally is expressed in terms of a number of years.

Note *If the year is set as the time interval unit and, if it is possible to regard the successive time intervals (years) as independent,then that statistical property can be used to simplify the calculation of the overall probability of failure and of the operationality of the subset. However, on other occasions it may be necessary to evaluate the probability of failure or stoppage in other time intervals. An example of this type of behavior is a breakwater during a storm (defined as a sequence of sea states) or the operationality of a pier during the tourist season, or the season of the year when Muslim immigrants who live and work in Europe cross the Straits of Gibraltar by ferry to return to Africa for their vacation period.In such cases, the developer or person responsible for the exploitation of the structure should specify the utilization requirements of the structure for that specific period of time.*

2.11 Annex: Calculation of the indices of repercussion

The evaluation of the economic, social, and environmental importance of the subset of a structure is based on its general and operational intrinsic nature. It is the responsibility of the owner or developer of the maritime structure (who may belong to either the public or private sector) to specify the intrinsic nature of the structure. In the absence of a specific definition, the intrinsic nature is determined as a function of the ERI and SERI, whose value can be approximately calculated according to the methodology described in the following sections.

2.11.1 Cálculo aproximado del IRE

Approximate calculation of the ERI

$$ERI = \frac{C_{RD} + C_{RI}}{C_0}$$

In the above formula, C_{RD} quantitatively values the economic repercussions produced by the reconstruction of the structure; C_{RI} values the repercussions caused by the cessation or inadequacies of the economic activities directly related to the structure or those foreseen to have taken place in the event that the structure has been destroyed or has suffered a loss of operationality; C_0 is the parameter of dimensionalization. These costs are determined by using the following criteria:

2.11.1.1 Cost C_{RD}

Investment cost corresponding to the rebuilding of the maritime structure to its previous state, in the year in which the costs due to the consequences of the economic activities directly related to the structure are calculated. In the absence of detailed studies, this cost can be considered to be equal to the initial investment, duly updated to the year in question.

2.11.1.2 Cost C_{RI}

Economic repercussions caused by the consequences of the economic activities directly related to the structure. These activities refer to services offered after the structure has begun to function as well as to services demanded because of damage to the goods being protected. This cost is valued in terms of loss of Gross Added Value (GAV), at market prices during the time period that the rebuilding is supposed to take place after the destruction or loss of operationality of the structure, considering that this happens once the economic activities directly related to the structure are consolidated.

In the absence of detailed studies, the consolidation of economic activities directly related to the structure occurs after a certain number of years have passed after it begins to function. For the purposes of these Recommendations and unless there are reasons to the contrary, this time period will be five years. Analogously, the time period during which rebuilding takes place will be one year.

Note *The GAV is what the set of economic activities contributes to an economy and represents the difference between inputs and outputs of the associated production process associated with the set of activities. This difference is made up of the employed labor force and the business surplus generated. In macroeconomic accounting and in accordance with the European Audit System, the GAV is calculated as the sum of the wages of salaried workers (salaries, gross salaries, and social contributions) and the gross surplus of the amortizations. For its valuation at market prices, it is necessary to add the taxes linked to the production (gross taxes minus subsidies).*

2.11.1.3 Cost C_O

The value of this economic parameter of dimensionalization depends on the economic structure and the level of economic development in the country where the structure is going to be built. Consequently, it will vary over time.

In Spain, for example, the value of C_0 that should be applied is C_0 = 3 Meuros for the horizontal year in which the costs are valued.

2.11.1.4 Approximate evaluation of C_{RI} / C_O

In those cases in which a detailed determination of C_{RI} is not carried out either because of its disproportionate complexity, or the absence of previous studies, the quotient C_{RI} / C_0, can be qualitatively estimated, in the following equation:

$$C_{RI}/C_0 = (C) * [(A)+(B)]$$

In the above equation, (A) is the value of the context of the economic and production system;(B), the strategic importance of the economic and productive system; and (C), the structure's importance for the economic and productive system for which it offers a service. These coefficients can be determined in the following way:

2.11.1.4.1 Coefficient of the ambit of the system (A)

The context of the productive system for which the maritime structure offers a service is evaluated by assigning the following values according to the type of context involved:

- Local, (1)
- Regional, (2)
- National/International, (5)

2.11.1.4.2 Coefficient of strategic importance (B)

The importance of the structure for the economic and productive system for which it offers a service is evaluated by assigning the following values, depending on whether it is considered:

- Irrelevant, (0)
- Relevant, (2)
- Esential, (5)

2.11.1.4.3 Coefficient of economic importance (C)

The importance of the structure for the economic and productive system for which it offers a service is evaluated by assigning the following values, depending on whether it is considered:

- Irrelevant, (0)
- Relevant, (1)
- Esential, (2)

2.11.2 Classification according to the ERI

In accordance with the value of the Economic Repercussion Index (ERI), maritime structures are divided into three groups: R_i, i = 1, 2, 3:

- R_1, structures with low economic repercussion: ERI $\leq$ 5
- R_2, structures with moderate economic repercussion: 5 $<$ ERI $\leq$ 20
- R_3, structures with high economic repercussion: ERI $>$ 20

2.11.3 Approximate calculation SERI

The SERI is defined by the sum total of three subindices:

$$ISA = \sum_{i=1}^{3} ISA_i$$

In the above formula, $SERI_1$ is the subindex of the possibility of the loss of human lives; $SERI_2$, the subindex of damage to the environment and to the historical and cultural heritage; and $SERI_3$, the subindex of social disruption. These indices are evaluated according to the methodology described in the following sections:

2.11.3.1 Calculation of the subindex $SERI_1$

Subindex of the possibility and impact of the loss of human life. The following values are assigned according to their possibility and scope[13],

- Remote (0): injury to people is improbable
- Low (3): loss of human life is possible, but not probable (accidental), and few people are affected.
- High (10): loss of human life is very probable, but affects a relatively reduced number of people[14]
- Catastrophic (20): loss of human life and injury to people is so serious and widespread that it affects the regional medical response capacity.

(13) In the evaluation of this subindex it is important to take into account the existence or lack of system and evacuation procedures for the installation.

(14) For example, damage produced by a serious traffic accident..

2.11.3.2 Calculation of the subindex $SERI_2$

Subindex of damage to the environment and the historical and cultural heritage. The following values are assigned according to the possibility, persistence and irreversibility of damages to the environment and the historical and cultural heritage:

- Remote (0): Damage to elements of great historical and artistic value is improbable.
- Low (2):Damage is slight,but reversible (in less than a year) or loss of elements of little value.
- Moderate (4): Damage is important, but reversible (in less than five years) or loss of important elements of historical and artistic value.
- High (8): Damage to the ecosystem is irreversible, and loss of important elements of historical and artistic value.
- Very high (15): Damage to the ecosystem is irreversible, implying the extinction of protected species or the destruction of protected natural resources, or a large number of important elements of historical and artistic value.

Note *Irreversible damage is normally that which cannot be remedied, and in the event that recovery is possible, the ecosystem takes more than five years to return to its original state.*

2.11.3.3 Calculation of the subindex $SERI_3$

Subindex of social disruption. The following values are assigned according to the intensity of the social disruption produced:

- Low (0): No signs of any significant social disruption associated with the failure of the structure.
- Moderate (5): Minimum degree of social disruption associated with high $SERI_1$ and $SERI_2$ values.

- High (10): Minimum degree of social disruption caused by a catastrophic $SERI_1$ value and a very high $SERI_2$ value.
- Very high (15):Maximum degree of social disruption.

2.11.4 Classification according to the SERI

In accordance with the value of the SERI, maritime structures can be classified in four groups (S_i, i = 1, 2,3, 4):

- S_1, structures with little significant social and environmental impact: SERI < 5
- S_2, structures with a low social and environmental impact: 5 ≤ SERI < 20
- S_3, structures with a high social and environmental impact: 20 ≤ SERI < 30
- S_4, structures with a very high social and environmental impact: SERI ≥ 30

2.11.5 Calculation of the operational intrinsic nature of the subset

It is the responsibility of the developer of the maritime structure (who may be from either the public or private sector) to specify the general operational intrinsic nature of the structure. In the absence of a specific definition, this intrinsic nature is established according to the operational index of economic repercussion (OIER) and the operational social and environmental impact index (OISER), as described in section 2.7.

2.11.6 Approximate calculation of the OIER

The Operational Index of Economic Repercussion is evaluated by means of the following equation:

$$OIER = (F) * [(D)+(E)]$$

In the preceding formula (D),(E) and (F) evaluate the simultaneity, intensity and adaptability of the uses concurrent with the stoppage situation.These coefficients can be determined in the following way.

2.11.6.1 Coefficient of simultaneity (D)

This coefficcent characterizes the simultaneity of the period of the demand affected by the structure and the period of agent intensity that defines the serviceability level.This simultaneity is evaluated in terms of the following types of periods:

- Non-simultaneous periods (0)
- Simultaneous periods (5)

2.11.6.2 Coefficient of intensity (E)

This coefficient characterizes the intensity of use of the demand in the time period being considered, according to the following categories:

- Not intensive (0)
- Intensive (3)
- Very intensive (5)

2.11.6.3 Coefficient of adaptability (F)

This coefficient characterizes the adaptability of the demand and the economic context to the operational stoppage, in terms of the following values:

- High level of adaptability (0)
- Moderate level of adaptability (1)
- Low level of adaptability (3)

2.11.7 Classification according to the OIER

In accordance with the value of the Operational Index of Economic Repercussion (OIER), maritime structures can be classified in three intervals ($R_{O,i}$, i = 1, 2,3):

- $R_{O,1}$, structures with low operational economic repercussion: OIER ≤ 5
- $R_{O,2}$, structures with moderate operational economic repercussion: $5 <$ OIER ≤ 20
- $R_{O,3}$, structures with high operational economic repercussion: OIER > 20

2.11.8 Approximate calculation of the OIER

The OISER is defined as the sum total of three subindices:

$$OISER = \sum_{i=1}^{3} OISER_i$$

In the preceding formula, $OIER_1$ is the subindex of the possibility and scope of the loss of human life;$OIER_2$ is the subindex of damage to the environment as well as the historical and cultural heritage;and $OIER_3$, the subindex of social disruption.The procedure to follow is the same as that described in section 2.11.3. for the approximate calculation of the SERI.

2.11.9 Classification according to the OISER

According to the value of the operational index of social and environmental repercussions (OISER), the subsets of the maritime structure can be classified in four groups ($S_{O,i}$, i = 1, 2, 3, 4) in the subset of:

- $S_{O,1}$, structures with no significant social and environmental impact, OISER < 5
- $S_{O,2}$, structures with little social and environmental impact, $5 \leq$ OISER < 20
- $S_{O,3}$, structures with high social and environmental impact, $20 \leq$ OISER < 30
- $S_{O,4}$, structures with a very high social and environmental impact, OISER ≥ 30

Note *In the majority of maritime structures, the OISER is zero, since once an operational stoppage occurs, any possible cause of environmental impact also disappears. However, certain structures, such as submarine outfalls and water intakes for electric plants or water desalinization plants, can cause significant social and environmental repercussions. In this case, the OISER* $\neq S_{O,4}$, *and its importance should be considered in the project in accordance with the operational intrinsic nature of the maritime structure.*

CHAPTER 3
Project Requirements

3 PROJECT REQUIREMENTS

3.1 Introduction

The site and the structure can be divided into subsets, which are representative of the spatial variability scales of the project factors.Analogously, the duration of the different project phases can be divided into time intervals. which are representative of the temporal variability scales of the project factors.In a project state, any outcome of the subset of the structure and its context is considered to be stationary from a statistical viewpoint. In each project phase, the structure passes through a sequence of project states characterized by the different values of the project factors

The project of a structure should respond to project requirements, such as the following:

- Spatial (site) and temporal (project phases) domain
- Requirements for use and exploitation
- Geometry of the subset and the soil
- Properties (parameters) of the physical environment and the materials
- Agents that can interact with the maritime structure and the environment, as well as the specific actions that they carry out.

The project must verify that in every project state, all requirements pertaining to safety, serviceability, as well as use and exploitation are satisfied. However, it is impossible to verify each and every one of the states of the subset of a structure primarily, because no one can know with any certainty when they will occur. Moreover, there is no way of knowing which project parameters and variables operate in each state, nor for that matter, their magnitude and direction.As a result, it is necessary to specify criteria for classifying and giving values to the project factors, while taking into account their spatial and temporal variability.

3.1.1 Chapter contents and organization

This chapter describes the parameters that characterize, for a certain site and time interval, the geometry of the construction and soil, properties of the physical environment, air and water, prop-erties of the soil and building materials.It also describes the variables characterizing agents and actions, such as loads, deformations, and imposed movements, which can affect the safety, serviceability, and use and exploitation of the maritime structure.The set of all of these parameters,agents, and actions is known as the set of project factors.This description and characterization are carried out by taking into account the uncertainty involved, and in particular, by quantifying the spatial and temporal variability of the different project factors.

The chapter begins with the description of the project parameters, followed by the description of agents,which are classified according to their origin and function.The project factors are categorized according to their temporal variability, and the different value types that can be assigned to them are defined. Criteria are also given to classify a factor as deterministic or random, and statistical classes membership is specified that permits the development of types of combination. Finally, the chapter describes studies of the factors that should be included in every project.Figure 3.1. is a schematic outline of the contents of chapter 3.

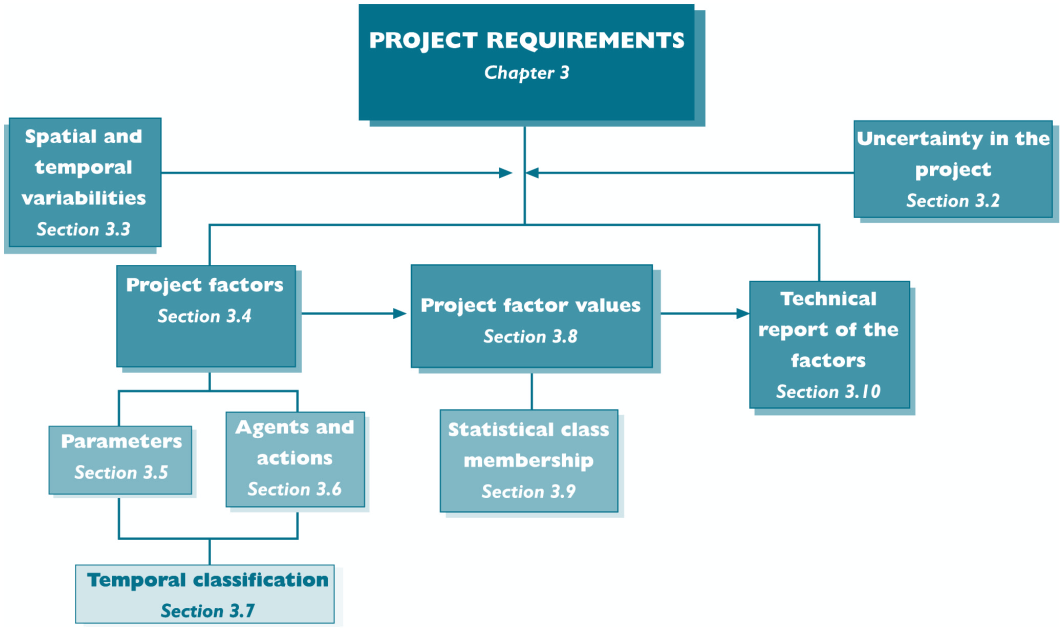


Figure 3.1: Chapter 3. Organization and contents

3.2 Uncertainty in the project

The decision concerning which value to assign to a project factor implies uncertainty. If the assigned value is expected to only have slight variations on a large magnitude, and if those variations are not significant for the safety, serviceability, and exploitation and use of the structure, uncertainty can be ignored.This means that an appropriate value can be adopted, and one can either suppose that it remains constant or that the value follows a known law in the time interval.

Conversely, if one of the previous conditions is not fulfilled.it is necessary to explicitly address the uncertainty of the project factors and the verification,and elaborate a study to this effect (see section 3.10) in which the following levels of uncertainty should be considered (see Figure 3.2):

3.2.1 Sources of uncertainty

In any project of a maritime structure, uncertainty can be produced, among other things, by the occurrence of the phenomenon (e.g.waves,wind, etc.),data,statistical treatment, and model used.

3.2.2 Uncertainty of the phenomenon

The extreme outcomes of the majority of the agents of the physical environment in a time interval are infrequent occurrences,which must be quantified.They also vary considerably in space.The occurrence and the magnitude or value of the project factor are uncertain from a temporal as well as a spatial perspective, and one way of dealing with this is by applying probability theory.

3.2.3 Uncertainty in the data

The majority of the magnitudes have a variability inherent in the event, which is either being observed or measured.This variability can be said to be independent of the accuracy of measurement.Furthermore, the measurement process itself adds a certain variability, which can be reflected as a bias,caused by a systematic error in the instrument, by the measurement process itself, or randomly. It is important to make sure that the instruments are calibrated in order to reduce the uncertainty to acceptable limits.

3.2.4 Statistical uncertainty

One of the principal sources of uncertainty is the limited information available regarding the quantity being measured.Given that considerations of time and economy constrain the quantity of data that can be collected, this limitation is a source of uncertainty regarding the event being studied. It is necessary to consider the influence of this uncertainty on the adopted value of the project factor.

3.2.5 Uncertainty of the model

The verification equation or laboratory test used to analyze the behavior of the structure against certain agents can only represent part of the physical phenomena participating in the event.Any model is a limited or restricted version of reality, and as such, does not accurately reflect it.As a result, the conclusions obtained from the application of the model naturally show a certain margin of error or uncertainty.This uncertainty is also present in the probability model, since such a model is based on a restricted quantity of information. It is thus necessary to consider the influence of this uncertainty in regards to the adopted value of the project factor and in the result.

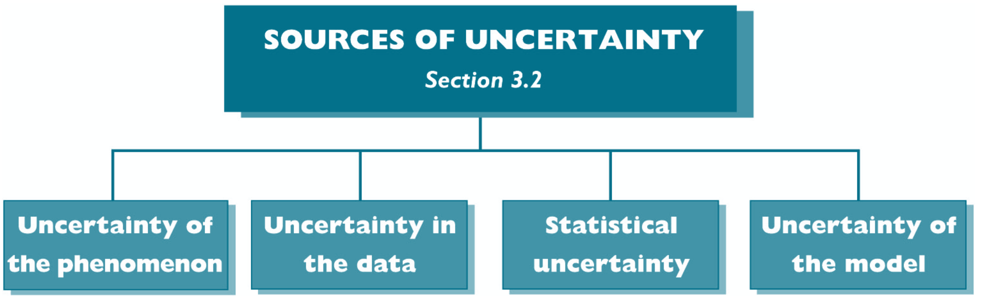


Figure 3.2: Sources of uncertainty in the project

3.3 Spatial and temporal variabilities

The project of a maritime structure, the same as any other type of public works, is based on models derived from mathematics and physics.These models are used to design and predict the behavior of the structure during its useful life and also to quantify the phenomena (physical,chemical, etc.) that affect it. In order to apply these models, it is necessary to have information about the project factors that participate either directly or indirectly in such processes. Consequently, one of the first steps in the project is the definition of the subsets of the structure and of the time intervals for which the project factors can be considered statistically homogeneous and stationary.

3.3.1 Spatial variability of the project factors

The magnitude (and direction) of the project factors can vary throughout the structure. In this case, the structure is divided into subsets in which the project factors can be regarded as statistically homogeneous random variables, and their value (magnitude and/or direction) is associated with the probability that it will be exceeded in the subset. Value and probability of exceedance are related by means of the distribution function of the random variable.

3.3.1.1 Correlation and spatial interpolation between subsets

Sometimes there are mathematical and physical models available that can evaluate a project factor in some of the subsets in which the site has been divided. Other times, project factor measurements are available in nearby sites or in other subsets. This information can be used to specify the value of the project factor in other subsets.

In order to do this, whenever possible, it is advisable to establish between the different subsets the spatial correlation of the parameters of the probabilistic models and the nominal values assigned, following statistical techniques[1], such as the spatial correlation function, the semivariogram, or the spatial correlation coefficient. Moreover, the application of these techniques permits the realization of spatial interpolations in which there is no available data concerning the project factor or factors.

(1) In this respect, it should be pointed out that in theory, the application of these statistical procedures for the study of the variability of a project factor in a subset requires that the homogeneity hypothesis be fulfilled in the mean, covariance function, statistical isotropy, and ergodicity.

3.3.2 Temporal variability of the project factors

In a subset of the structure, the magnitude (and direction) of the project factors can vary in the time interval. In this case, the project phase is divided into time intervals in which the project factors can be considered to be statistically stationary random variables, and their value (magnitude and/or direction) is associated with the probability of being exceeded in the time interval. The value and probability of exceedance are related by means of the distribution function of the random variable.

3.3.2.1 Temporal correlation, regression, and multivariate analysis

In order to apply a verification equation of a failure mode, it is necessary to define the set of project factors that can simultaneously act in the project (limit state). It is convenient to take into account the dependence of one or various factors on the predominant project factor, or simply analyze the interdependence of the various project factors. For this reason, in the first case, statistical regression techniques should be used, and in the second, techniques of multivariate analysis[2].

(2) It should be understood that these techniques are developed to study the interdependence of project factors and not to establish a priori a cause-effect relation between them.

3.3.3 Determinism and randomness

In a certain subset and time interval, a project factor can be considered deterministic or random, depending on its variability with respect to a representative value and the sensitivity of the result of the verification equation to this variability.

To this effect, in the subset of the structure and within each time interval, the temporal variability of the project factor can be delimited by means of a confidence interval, whose extremes are the quantiles, α and $(1-\alpha)$, of the density function, respectively. As a general rule, the value of $\alpha = 0.05$.

In the case that the temporal variability is small and that the sensitivity of the verification equation result is not significant for the value of the probability of occurrence of the mode, the project factor can be considered deterministic and its value known. Otherwise, the project factor will be considered as a random variable with distribution function that can be marginal, conditional or joint with other project factors.

Note *The term* known *includes the cases in which the value is calculated on the basis of a fixed mathematical expression of one or more variables (e.g. variables representing the spatial and temporal coordinates) or is a nominal value.*

3.4 Project factors

Project factors are a set of parameters, agents, and actions which help to define and verify the safety, serviceability, and exploitation and use of the structure and its context (see Figure 3.3). The magnitude (and direction) of the project factors and consequently, the response and shape of the structure and its level of use and exploitation over time.

3.4.1 3.4.1 Specification of the project factor

During the verification process of a design alternative, and when required, each project factor should be classified as a parameter, agent, or action according to the method, verification equation, available data, or other reasons.

Note *The classification of a factor as project parameter or agent and action depends on its purpose. For example, in the determination of the weight of the concrete block main layer of a breakwater, among the factors involved are the geometric dimensions of the block, its density and the wave height. In the safety verification (ultimate limit states) of the structure in the useful life, it can be assumed that the density of the concrete is known. It can thus be classified as a project parameter, and will be thus considered during the entire verification process.*

However, in certain cases it may be necessary to verify the evolution of the block's weight during the useful life of the structure. This weight can vary because of changes in the block's shape due to impacts, erosion, and rounding of block edges, surface modifications caused by the adherence of biological elements, loss of compactness, increase of porosity, etc. Some of these events can produce temporal variations in the density value of the concrete, which cannot be known a priori. In order to take into account the way this may influence the safety of the structure, the density of the concrete is considered to be an agent (of the material). It should thus be verified that in the project phase the density is not lower than the threshold value, marking the occurrence of a failure. This failure mode should be as-signed to a serviceability limit state.

3.5 Project parameters

(3) Although the soil is an agent of the physical environment,it is defined separately from the other agents of the physical environment because of its importance in the project and because traditionally its definition and characterization differ from those of air and water.

Project parameters define the geometry of the structure and the soil, as well as the properties of the physical environment[3]. Figure 3.3 is a schematic outline of the contents of this section.Project parameters can be divided into the categories below.

3.5.1 Geometrical parameters

These parameters define the geometry of the various structural elements of the maritime structure, as well as their location in the territory.

3.5.2 Physical environment, soil, and materials parameters

These parameters identify and define the properties and characteristics of the physical environment, soil, and building materials.

3.5.2.1 Classification

These parameters can be classified in the following subgroups:

- Identification parameters permit identification and recognition.
- State parameters specify the state of the physical environment, soil, and material.
- Mechanical parameters define the mechanical behavior of the maritime structure.
- Other parameters help to describe specific behaviors.

Note *The purpose of classifying the project parameters is to help establish the properties of the physical environment, soil, and building materials, as well as to organize the databases in such a way as to make them easily accessible and capable of incorporating new information. Furthermore the classification of a factor as a parameter or as an agent and action will help to compare different project design alternatives.*

3.5.2.2 Interference with the structure and the environment

In the identification and characterization of the project parameters, foreseeable changes should be allowed for, especially those regarding the properties of the physical environment and the soil, induced by the presence of the maritime structure and the human and industrial activities taking place.

3.5.2.2.1 Influence on the durability

(4) Section 8.2 of the Spanish Instrucción de Hormigón Estructural *itemizes specific types of environmental exposure associated with the deterioration processes of reinforced iron and concrete.These types constitute the guidelines in the analysis of the durability of the properties of certain project parameters.*

In this regard, it is necessary to consider the influence of the physical environment to which the building materials and soil will be subject,and which can produce the deterioration of their properties, and thus negatively affect their durability[4].

3.5.3 Soil parameters

For each design alternative, the properties of the soil should be defined, taking into account their spatio-temporal variability, based on the results of geotechnical research,geological studies, available data, etc.

Note *To allow for changes due to the evolution of the soil properties, geotechnical studies usually consider soil conditions from two standpoints: (1) short-term, when no water movement is possible (no drainage); (2) long-term, when interstitial water movement has become permanent.The terms short-term and long-term are also used to describe climatic phenomena. For purposes of greater clarity, in section 2.4 on time intervals, the terms short duration and long duration are used to describe the temporal variability of the project factors.*

3.5.3.1 Some parameters of the soil

(5) The R.O.M.0.5 gives a detailed description of the parameters soils and rocks.

Relevant examples of this type of parameter[5] are the following:

1. Identification parameters identify certain characteristics on the basis of which different types of soil can be classified in groups (layers or levels) with similar behavior, such as the mineralogical composition of the rocks, granulometry and plasticity of the fine part of the soils.

2. State parameters define the soil state at the time corresponding to the project situation. They pertain to its compactness and humidity (natural humidity and degree of saturation). Examples of state parameters are interstitial pressure and the suction in semi-saturated soils (air pressure minus the air pressure in the pores of the soil).

3. Mechanical parameters define soil behavior against outside effects.These include undrained shear strength in cohesive soils, resistance parameters of the Mohr-Coulomb model in effective stress patterns, deformability parameters of the soil skeleton (elasticity modules, Poisson modulus in elastic models or compression and numbness indices in the edometric model), as well as the parameters that govern the movement of interstitial water (permeability, e.g. when Darcy's Law is applicable).

4. Other parameters define soil behavior in specific situations, e.g. expansivity, dispersivity, weathering, aggressiveness, etc.

3.5.4 Air and water parameters

Bearing in mind their spatio-temporal variability, air and water properties are defined for each project design alternative on the basis of the data available, the results of climatic research, analytical or numerical models, testing, etc.

3.5.4.1 Some air and water parameters

(6)This section includes the properties of the water in the physical environment in which the structure is built and gives service. It does not include other properties required in the building process, e.g. the production of concrete.

The following air and water[6] parameters should be considered:

1. Identification parameters define the components of the air and the water as well as their contents in substances and particles.

2. State parameters define the state of the fluid and its components (e.g.temperature, salinity, density, presence of nutrients, organic matter, etc.)

3. Mechanical parameters define the behavior of the fluid according to changing stress patterns (e.g.kinematic viscosity: υ_c, Poisson's modulus,sound propagation velocity, specific heat,etc.)

4. Other parameters define the behavior of the fluid in specific conditions (e.g. in turbulent conditions, by means of eddy viscosity ε_r, dispersion coefficients, etc.)

3.5.5 Building materials parameters

Bearing in mind their spatio-temporal variability, it is essential to define the properties of the materials for each design alternative on the basis of data available or current regulations, analytical or numerical models, testing, etc.

3.5.5.1 Representative parameters

The materials parameters may be classified as follows:identification parameters,state parameters, mechanical parameters, and specific parameters.The following materials are some of those that should be considered:

1. Natural blocks or rock
   - Identification: origin, mineralogical composition, granulometry
   - State: void index, degree of saturation, specific weight, degree of meteorization
   - Mechanical:compressive strength,indirect tensile strength, angle of internal abrasion, deformability
   - Specific: resistance to wetting-drying cycles, corrosion resistance, resistance to salt attack, etc.

2. Concrete
   - Identification:type of concrete, composition
   - State:specific weight,compactness, permeability, absorption
   - Mechanical: characteristic compressive strength at 28 days, tensile strength, longitudinal deformation module (instantaneous and deferred), Poisson's coefficient
   - Specific: shrinkage and creep behavior, resistance to wetting-drying cycles, surface erosion, resistance to rapid loading-unloading cycles, corrosion, docility, etc.

3. Steels
   - Identification: grade of steel and composition
   - State:specific weight
   - Mechanical:elastic limit, unit breaking stress, breaking shrinkage
   - Specific: corrosion resistance, behavior in wetting-drying cycles and loading cycles, experimental relationship of the unit stress and the elastic limit under breaking conditions, etc.

4. Other materials: pavements, metals, etc.

Note *Spanish regulations governing the properties required for building materials are set out in the following recommendations, standards, and instructions (amongst others):*

- Instrucción de Hormigón Estructural *(EHE)*

- *Steel for construction*
- *ROM 0.1: description and characterization of building materials (forthcoming)*

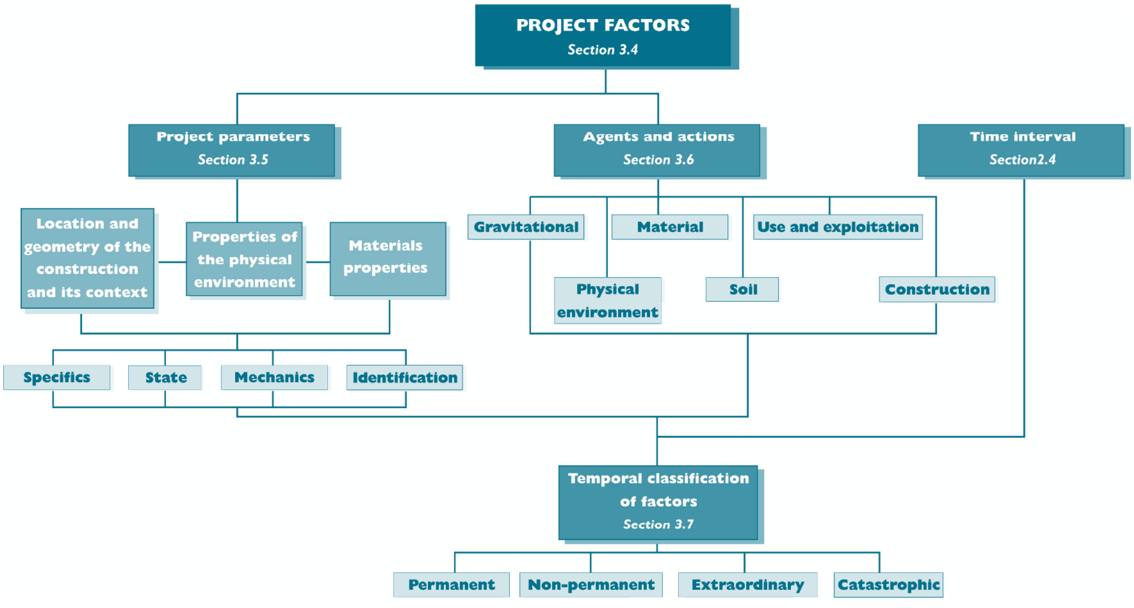


Figure 3.3: Classification of project factors according to the origin and function, and behavior over

3.6 Agents and actions

(7) In contrast to a patient, the agent performs the action instead of suffering its effects. The agents initiate the action (an activity) in the structure, its components, and context.

Agent is any entity that can act on or significantly affect the reliability, functionality[7], and operationality of a maritime structure and its context.

Action is any effect that an agent can produce in the structure and its context as a result of their mutual interaction. Consequently, the term *action* encompasses such notions as force, load applied to the structure, stress-induced movements, stress-related deformations, etc.

Note *The agent is defined independently of the typology of the structure or element.In contrast,when defining an action (whether it be a load,movement or any outcome of stress) not only must the agent be taken into account, but also the structure, its geometrical characteristics (mass, volume, and shapes), the materials used to build it,as well as the site where it is located.In each of its outcomes, the action is the result of the interaction between the agent and the structure.*

The presence or absence of certain agents and their possible effect on the structure will depend on the site, subset,typology of the structure, and time interval involved.According to the typology of the structure, the physical environment, and the materials, these agents may or may not produce effects on the structure, such as loads or forces, stress-related movements and deformations, etc.

These actions are evaluated by means of one or various terms in the verification equation.The verification equation of a failure or stoppage mode is a function of one or various project factors.The values of the factors that intervene in the terms can be simultaneous and compatible.To help establish which factors are simultaneous with compatible values, the agents and thus, the project factors are organized and classified according to their origin and function.

3.6.1 Classification by origin and function

(8) This classification is heterogeneous and far from exhaustive, but is useful as a means of establishing a working methodology. Furthermore, it maintains the most accepted classification of agents in engineering circles.

The project agents can be classified[8] according to origin and function (see Figures 3.3 and 3.4):

- Gravitational, q_g
- Physical environment, q_f
- Soil, q_t
- Use and exploitation, q_v
- Materials, q_m
- Construction, q_c

Note *In the present Recommendations, agents appear in small letters, while actions (whether they be loads, deformations, etc.) appear in capital letters.*

3.6.1.1 Other agents

Apart from the above-mentioned agents, other agents can also be considered In accordance with the specificity of the structure, and if they are duly justified.

3.6.2 Gravitational agent (q_g)

(9) These actions are generally considered as being produced by the gravitational agent. Nevertheless, gravitational force is explicitly present in other actions whose origin can be identified with the occurrence of another agent, e.g.the pressure impulse or force produced by waves on a sea wall.

This type of agent is associated with the direct action of the force of gravity. Such agents can cause two types of actions: own weight $Q_{g,1}$, and load or dead weight $Q_{g,2}$[9].

Note *Within the context of these Recommendations, dead weight is the load produced by the weight of the various structural elements. Static loads correspond to the weight of elements, which are not load-bearing in the structural sense, but which form a permanent part of the load-bearing structure, e.g. road surfaces, marine accretions, etc. Marine accretions develop over time so that in certain conditions the dead weight may prove to be a non-permanent action.*

3.6.3 Physical environment agents (q_f)

Agents of this type stem from the physical context in which the structure is located and may be classified in the following categories:

1. Climatic, q_{fc}
2. Hydraulic, q_{fh}
3. Seismic, q_{fs}
4. Bio-geochemical, q_{fb}
5. Thermal, q_{ft}

3.6.3.1 Climatic agents (q_{fc})

Outcomes associated with atmospheric patterns are known as atmospheric climatic agents. Conversely, those which are outcomes of sea patterns are known as maritime climatic agents. Climatic actions are those due to the direct action of agents of climatic origin on the load-bearing structure or on non-structural elements.

Every design project for a maritime structure should contain an annex entitled "A study of climatic agents",with the data and methods used in the description and evaluation of the climatic agents involved.This also should include a description of the laboratory tests, field studies as well as the data used.

3.6.3.1.1 Atmospheric climatic agents ($q_{fc,i}$, i = 1, 2, 3)

These agents can be classified in the following categories:

- Air at rest, atmospheric pressure, and permanent, uniform air movement, $q_{fc,1}$
- Varied and variable air movement, $q_{fc,2}$; e.g. wind, spatio-temporal variations of atmospheric pressure, etc.
- Precipitation:rain, snow, and ice, $q_{fc,3}$

3.6.3.1.2 Maritime climatic agents ($q_{fc,i}$, i = 4, 5, 6)

These agents can be classified in the following groups:

- Water at rest and permanent uniform water movement, $q_{fc,4}$
- Varied and variable water movement, $q_{fc,5}$, e.g.currents, spatio-temporal variations of density, etc.
- Oscillatory movements[10], short period (3 <T(s)[11] < 30), intermediate period (1/2 < T(min) < 120), large period (T(h) > 2), $q_{fc,6}$

(10) The period intervals specified here are purely indicative. In each case, each oscillatory band is defined according to its verification objective.

(11) T is a representative period of the oscillatory movement.

3.6.3.1.3 Hydraulic agents ($q_{fh,i}$, i = 1, 2)

These agents include those associated with the presence of fluids, liquids or gases, which are not related to climatic, maritime, and atmospheric agents, either at rest or in variable movement.

- Fluid at rest, $q_{fh,1}$
- Fluid in movement, $q_{fh,2}$

Note *When hydraulic agents are associated with the use and exploitation of the subset of the structure or of the installations, they will be considered to be agents of use and exploitation. For example, the fuel oil in a deposit is a fluid that is unrelated to climatic agents, and which should be regarded as an agent of use and exploitation. In other cases, such as soil, the fluid at rest or in permanent movement is a hydraulic agent of the physical environment.*

3.6.3.3 Seismic agents ($q_{fs,i}$, i = 1, 2 and 3)

These agents are those associated with seismic movements,They can produce oscillations in structures,causing actions which can be classified in the following categories:direct loads ($Q_{fs,1}$);stress-induced movements or vibrations ($Q_{fs,2}$); stress-induced deformations ($Q_{fs,3}$).

3.6.3.4 Bio-geochemical agents ($q_{fb,i}$, i = 1, 2)

These agents include those bio-geochemical processes that can cause spatio-temporal variations in the project factors ($q_{fb,1}$), with the possibility of also causing stress-induced deformations and alterations to the geometry of the structure, as well as to the soil ($q_{fb,2}$).

3.6.3.5 Thermal agents ($q_{ft,i,}$ i = 1, 2)

These agents can cause spatial thermal gradients ($q_{ft,1}$),and temporal thermal gradients ($q_{ft,2}$) in the structure and its materials, as well as in the physical environment and the soil.

3.6.4 Soil agents ($q_{t,i}$, i = 1 and 2)

The soil is considered an agent when it gives rise to actions such as pressure and other stresses, movements or deformations of the various elements of a load-bearing structure.These actions can be ordered according to whether the action is direct ($Q_{t,1}$) (e.g. stresses against the sea walls) or indirect, due to soil movements ($Q_{t,2}$) (e.g. the effects of parasites on piles)

3.6.5 Use and exploitation agents ($q_{v,i}$, i = 1, 2 and 3)

These agents stem from the normal use and exploitation of the load-bearing structure, such as the storage of goods ($q_{v,1}$), and the movement of goods and traffic ($q_{v,2}$).This includes the handling, transport,and the operationality of the ship ($q_{v,3}$),such as the docking,mooring,careening,and the launching and beaching of the ship.

3.6.6 Agents associated with building materials ($q_{m,i}$, i = 1 and 2)

These agents are those associated with the physical, mechanical, chemical, thermal, and biological behavior of the building materials, which can cause changes in their properties, and thus result in actions affecting the structure or any of its elements. Purely for the sake of convenience, these agents can be classified as thermal ($q_{m,1}$) or rheological ($q_{m,2}$),.

Note *Certain thermal agents arise from the chemical and thermo-dynamic processes which occur in the building materials used, e.g.concrete, to acquire its resistance characteristics. Analogously, rheological agents are produced by the development over time of the properties of the material. These agents can cause at least three types of action,namely loads, movements, and stress-induced deformations. Due to their origin,their magnitude depends on the passing of time and the type of material involved.*

3.6.7 Construction agents (q_c)

These agents include the various processes which, in the course of the building,fabrication, transport, assembly and disassembly, repairing or dismantling of the structure or one of its elements, can cause any type of action (instantaneous, temporary, transitory, permanent or residual) on the structure.

For each of the design alternatives, a study of the construction should be carried out, which considers the procedures and elements necessary for the implementation of the structure (e.g. construction, repair or dismantling).

If actions are foreseen that will significantly affect the safety of the structure, this should be verified as indicated in section 4.6.

3.6.7.1 Modifications in the building method

If the construction method adopted for the structure is different from the method specified in the project and actions are foreseen that will significantly affect its safety, this should be verified according to the procedure described in this ROM.

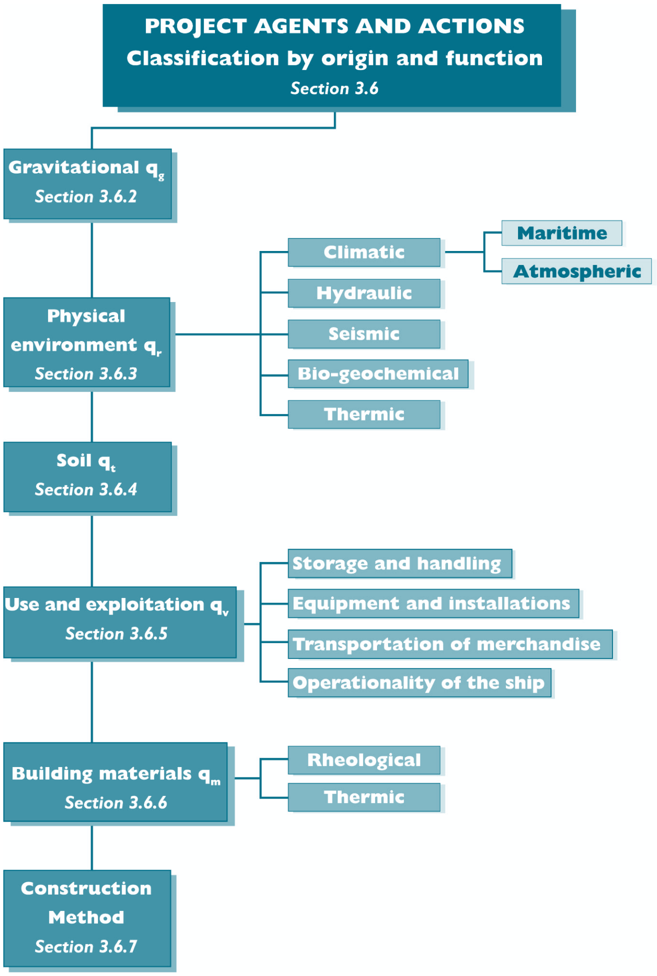


Figure 3.4: Classification of the agents and actions according to their origin and function.

3.7 Temporal classification

In order to select the project factors which in a given time interval may simultaneously appear in the verification equation of a mode, it is advisable to use the temporal classification of agents and actions according to the following criteria:

Note *Temporal classification is applied to agents and their actions, but it can also be used to classify the project parameters when temporal variability is being considered. Thus, as a general rule, temporal classification can be applied to all of the project factors.*

3.7.1 Classification criteria

In each time interval, whether it be of short duration, long duration or a project phase, the project factors can be classified according to the following criteria:

1. probability of exceeding a representative threshold value of the project factor and whose occurrence may be significant for the safety, serviceability, and exploitation of the structure, its elements, and context.

2. persistence of the exceedance of that threshold level

3.7.1.1 Classification of the project factors.

In a given time interval of duration T_L, depending on their probability of exceeding the threshold level and of the persistence of exceedance, the project factors can be classified in the following categories (see Figures 3.3):

- Permanent
- Non-permanent
- Extraordinary
- Catastrophic

3.7.1.1.1 Permanent project factors

Factors whose probability of occurrence is equal to one and whose average time of occurrence or action t_m, is roughly equal to the duration of the time interval, i.e. $t_m \approx T_L$.

3.7.1.1.2 Non-permanent project factors

Factors whose probability of occurrence is close to but always less than one and whose average time of action, t_m, is less than the duration of T_L, i.e. $t_m < T_L$.

3.7.1.1.3 Extraordinary project factors

(12) The characteristic value and the predominant project factor are defined in section 3.7.l.

Project factors whose possibility of occurrence during the time interval under consideration is considerably less than one and less than the probability of exceeding the characteristic value of the predominant factor[12], and whose average time of action t_m, is much less than the duration T_L, i.e. $t_m << T_L$.

3.7.1.1.4 Catastrophic project factors

Factors whose probability of occurrence during the time interval under consideration is much less than one and also less than the probability of exceeding the characteristic value of the predominant project factor. Their average time of action, t_m, is much less than the duration T_L, i.e. $t_m << T_L$.

Note *As a general rule, extraordinary project factors are associated with the extreme WOCs, while catastrophic project factors are associated with exceptional WOCs.*

3.7.2 Summary of temporal classification

Based on the previous sections, the temporal classification of project factors is outlined in table 3.1.

Table 3.1: Temporal classification of project factors

Duration	Probability of exceedance		
	Prob ≃1	Prob < 1	Prob << 1
$t_m \approx T_L$ (1)	Permanent		
$t_m < T_L$	Non-permanent		
$t_m << T_L$		Extraordinary(2)	Catastrophic(3)

Notes on table 3.1.

1. *T_L represents the duration of the time interval relevant for the temporal classification.*
2. *The probability of exceedance should also be less than the probability of exceeding the predominant project factor.*
3. *The probability of exceedance should be much less than the probability of exceeding the predominant project factor.*

3.7.3 Occurrence of a project factor

The permanent project factors are active during the whole time interval.However, non-permanent, extraordinary or catastrophic project factors are active only at certain times during the time interval. In some cases, it is possible to predict the point in the time interval when a project factor will appear. However, when it cannot be predicted, this also means that neither the duration nor the magnitude of the project factor can be predicted either. As a result, the appearance as well as the value of these factors must be regarded as random variables, and in each case, a probability model should be adopted to describe the point when the project factor appears in the time interval.

Note *It is often possible to regard the instant that a non-permanent, extraordinary or catastrophic project factor appears as a random variable according to the uniform distribution in the time interval. In other words, its appearance at any other point in the time interval is equally probable. However, in specific cases, e.g.the occurrence of exceptionally violent storms or "unusual" events, this simplification may not be correct.*

3.7.3.1 Appearance of a factor as an unusual event

The appearance of certain project factors, generally related to natural processes in extreme conditions, such as climatic agents of the physical environment or the arrival of ships, can be regarded as a statistically rare event. This appearance can be described by a Poisson distribution, whose parameter is the average number of occurrences of the factor in a given time interval.

3.8 Project factor values

These Recommendations define several project values, depending, among other things, on the verification method (e.g. nominal value, representative value, upper and lower characteristic value, maximum and minimum value, design value, verification value, etc.). The value of the project factor can be nominally assigned, based on a probability model or some other procedure, such as previous experience, predesign laboratory testing, etc. (see Figure 3.5)

Note *The value of a project factor can be determined by using a probability model in the following way: On the basis of one or various samples and by means of statistical inference, a probability model is obtained, and a project factor is selected. This process is inductive since from one or various samples, the behavior of the whole population is induced, a probabilistic model inferred, and based on this model, its behavior predicted.*

Other times, the value of the factor can be nominally determined or selected in accordance with a pre-design, calculation, experience, previous data, or because it is established in current Regulations. In this case, a probability model can be proposed, which should be verified once the maritime structure is implemented. On the basis of this model, other values of the project factor can be specified, as described in the following section. This procedure is deductive, since once the distribution function of the project factor is assumed, this and the other assigned values can be verified by means of field work.

In this section, different project factor values are defined, which are used in the verification procedure, as described in Chapter 4.

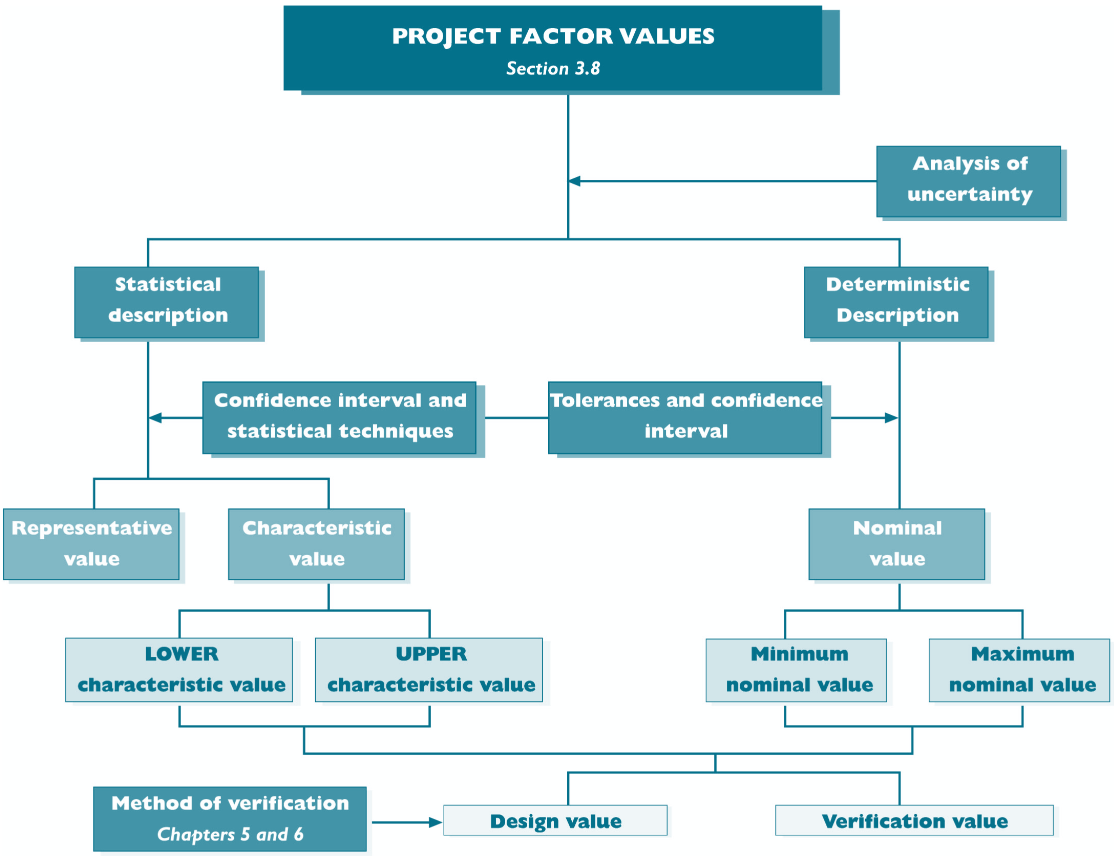


Figure 3.5: Project factor values

3.8.1 Value defined using a probability model

When the project factor value is selected from the distribution function of the population, it corresponds to a quantile or a statistical descriptor of the function in question. Among others, the following values should be considered.

3.8.1.1 Representative value

This is the value of the quantile which provides an order of magnitude of the value that the project factor can take in the verification of failure modes.

3.8.1.2 Characteristic value

This value is the principal representative value of the project factor.

3.8.1.2.1 Upper and lower characteristic value

For project factors bounded within a confidence interval, the extreme values of the interval are known respectively as the upper and lower characteristic value.

3.8.1.2.2 Confidence interval

Unless expressly stated otherwise in the Recommendations and Standards, the upper and lower characteristic values of a project factor are determined as the extreme values of the minimum confidence interval, $(1 - \alpha) = 0.90$.

3.8.2 Value without a probabilistic model

This project factor value is defined by non-statistical procedures,such as previous experience, pre-design,calculations, current regulations, etc.

Note *In principle, the value selected does not have a statistical meaning, even though it quantifies a project factor that may be random.This procedure can be used to give value to the project parameters related to geometric elements, materials parameters, agents of use and exploitation,such as a load distribution by a crane, storage load, etc.,or project factors whose real value is not known until the structure is implemented. For this reason, once the structure is implemented, it must be verified by measurements taken during field work to see if the value assigned to the factor is correct.*

3.8.2.1 Nominal value

The nominal value is the value allotted in the definition of the project factor[13] in all those cases in which the value is not selected on the basis of a distribution function. For all practical purposes, this nominal value is the representative project factor value.

(13) In geometric parameters, this is the dimension of the element to be built.In parameters related to materials, it can be mechanical strength,etc.

3.8.2.1.1 Probabilistic model based on the nominal value

When necessary or when established in the Recommendations and Standards, either on the basis of previous experience, analytical or numerical derivation, or simply as a working hypothesis, a probabilistic model or distribution function of the project factor can be adopted, which permits the definition of other values of the project factor. In this case, it will be necessary to define the relation between the nominal project factor and the statistical parameters of the probability model.

The definition of other values of the project factor, such as the characteristic values, should be in keeping with the recommendations set down in section 3.8.1.2 and those following it.

3.8.3 Minimum and maximum values

In the cases in which project factors, such as geometric parameters, properties of the construction materials,certain use and exploitation agents,etc. should comply with maximum and minimum values, which depend, among other things, on the failure or stoppage mode to verify, the limit state and WOCs, its determination should be in keeping with the following:

When the project factor is defined by means of a probability model, the maximum and minimum values are statistically determined as upper and lower characteristic values of the confidence interval or by order statistics. When the project factor has been defined by means of a nominal value, it is necessary to provide the relation between this value and the maximum and minimum values, or assume a distribution function of the factor and define them by means of a confidence interval or as order statistics. Generally speaking, the confidence level will be not less than 0.90.

Note *These values can either be established by the developer of the structure or imposed by the official Regulatory Guidelines*[14]

(14) *Article 30.5 of the Spanish* Instrucción de Hormigón Estructural *(EHE) delimits the compressive strength of the concrete.*

3.8.4 Design value

This value is used in the evaluation of the verification equation of the failure or stoppage mode. The procedure to follow for the assignment of the design value of the project factors depends on the verification method, and is described in Chapters 5 and 6 of these Recommendations. This value is defined in terms of the distribution function, of one of its quantile values, or of the nominal value, according to whether it corresponds to a project factor with or without a probability model, respectively.

The project factors which, in the time interval and the subset of the structure, take values delimited within a confidence interval, and whose participation in the occurrence of the failure mode is not significant, can be assigned a fixed design value, independently of the verification mode. For these purposes, these project factors will be considered deterministic.

3.8.5 Verification value

The nominal value assigned to a project factor and the probability model adopted can be verified by means of samples taken in field studies in those cases specified in these or other Recommendations and Standards. Other project factors defined according to a probabilistic model can also be verified.

To this end, verification values for the project factor are generally specified, defining an interval or range in which sampling values of a certain confidence level should be included. In all cases, unless expressly stated otherwise, this level will not be less than 0.90. The maximum and minimum values of the interval can be defined in terms of: (1) tolerances or deviations from the representative value in the interval; (2) quantiles of a distribution function. In this case, the upper and lower characteristics of the project factor are adopted as maximum and minimum values.

To verify the project values defined by a nominal value, the relation is established between the nominal value and the parameters of the distribution function adopted and the maximum and minimum values of the confidence interval.

Note *The decision to adopt a certain project factor value carries with it consequences of various types (economic, social, environmental, etc.). Since the decision is based on a limited quantity of data, it is affected* *by statistical uncertainty, and thus entails a certain degree of risk.As a result, in order to decide the project factor value, it is necessary to have statistical tools available, capable of quantitatively measuring the uncertainty associated with this decision.*

3.9 Statistical Class Membership

A project factor, whether a parameter, agent or action,can take values with a wide range of variation. If this variability is described statistically, the possible values taken by the project factor can be organized around a mean value (and so belong to a distribution or mean regime) or alternatively, they can be organized around upper or lower values belonging to the distribution of values (an extreme regime).

In any of these ranges (mean and extreme) of maximum and minimum values,and according to the magnitude of the values that can be taken in reference to a centered range value, three types of values can be defined: (1) values of the lower tail; (2) centered values; (3) values of the upper tail (see Figure 3.5).

These classes are applied in the verification method,and particularly in the method of partial coefficients to establish the compatibility of the values of the factors and terms which intervene in the verification equation in each type of combination.

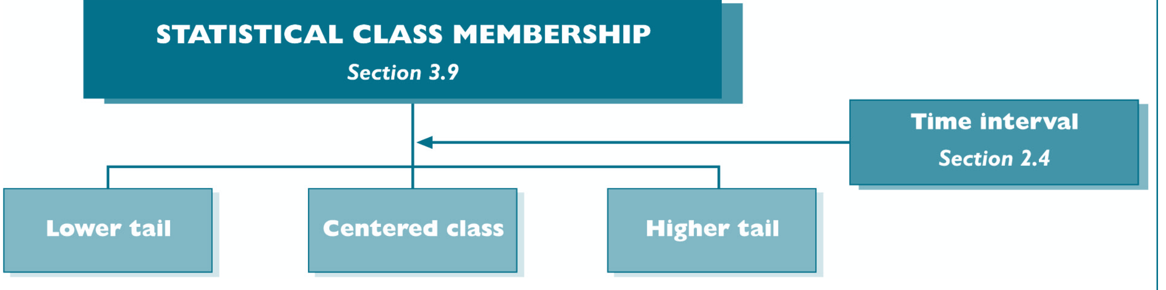


Figure 3.6: Statistical class membership

3.9.1 Class of the lower tail

This class of values belongs to the values of the lower tail of the corresponding distribution function. It thus represents the project factor values or term with a high probability of being exceeded in the time interval under consideration.The inferior nominal value belongs to this class.

3.9.2 Centered class

This class of values includes the values of the central zone of the corresponding distribution function. It thus contains the values ordered around the mean value, mode, and median of the distribution. In other words, it includes the values ordered around the most probable values that the factor or term can take in the time interval.The average nominal value belongs to this class.

3.9.3 Class of the upper tail

This class contains the values of the upper tail of the corresponding distribution function.It therefore represents the project factor values or term with a low probability of being exceeded in the time interval.The upper nominal value belongs to this class.

Note

The three classes of values are defined in a time interval. As a result, in the case of a factor or term with a statistical description, the distribution function to be applied in the definition of each class should be statistically representative of the factor or term in the time interval, the WOC, and the limit state to which the verified mode is assigned.

According to certain hypotheses, it can be assumed that in a sea state, the wave heights follow a Rayleigh distribution with the root mean square wave height H_{rms} *as descriptor. This value is a centered value of the waves that can occur in the sea state (or time interval). As a result, the waves whose height is around the root mean square wave height, belong to the class of centered values. If* $H_{rms} = 3m$, *the probability of this value being exceeded is:* $Pr(H > H_{rms}) = 1 - Pr(H \leq H_{rms}) = 1 - e^{-1} = 0.63$. *The probabilities of the significant wave height not being exceeded,* $H_S \cong \sqrt{2} H_{rms}$ *and* $H_{\frac{1}{20}} \cong 2.07\, H_{rms}$, *are 0.87 and 0.99, respectively. Clearly the latter wave height is very far removed from the centered value, and thus, the evaluation of its probability of being exceeded, which is derived from the distribution function of the average values, is not statistically correct. At the lower extreme, the probability of wave height* $H_{rms}/4$, *not being exceeded is equal to 0.06. Wave heights inferior to this one are in the lower tail of the Rayleigh distribution function.*

The wave height values in the range $0.25H_{rms} \leq H \leq 1.5H_{rms}$, *belong to the centered class of wave heights in a sea state or time interval. The wave height values in the range* $1.5H_{rms} < H \leq 3H_{rms}$, *belong to the class of the upper tail of wave heights in a sea state. Analogously, the values in the range* $0 \leq H < 0.25H_{rms}$, *belong to the class of the lower tail of the wave heights in a sea state. Neither of these tails is statistically well represented by the Rayleigh distribution function.*

If the occurrence of consecutive waves are regarded as independent events, the maximum waves of a sea state follow a Rayleigh distribution to the N^{th} *power, where N is the number of waves in the sea state. The mode or most probable value of the maximum wave heights for 10000 waves is 9.1 m, and for 500 waves is 7.6 m. These wave height values belong to the centered class of the maximum wave heights in a sea state. In a sea state, the upper and lower tails can also be defined in much the same way as the "average" wave heights. The ranges of values are not absolute and depend on the variability of the factor or term and the variability of the distribution function.*

In the case of the description of the significant wave height for a time period of one year, at least two distributions can be defined: the distribution of average values (wave regime) and the distribution of extreme values (storm regime). In both regimes three classes of values can be identified: (1) centered values; (2) values of the upper tail; (3) values of the lower tail. Moreover, if each year is considered independent, it is possible to calculate the distribution function for the useful life of the structure. Similarly, there are the same three classes of values in this regime as well: (1) centered values; (2) values of the upper tail; (3) values of the lower tail.

The same role played by the upper tail for certain factors is played by the lower tail for others. For example, the lower tail represents the periods of drought for the agent, precipitation. When focusing on the worst values for drought, it is necessary to work with the distribution function of minimum values. In this case, the minimum tail of this distribution has centered values as well as values assigned to the upper and lower tails. The lower tail supplies the minimum precipitation conditions.

In those cases in which the values of the tails are associated with extremely low or high probabilities of not being exceeded, it is necessary to adjust the tails with a suitable distribution function. Finally, it should be stressed that the existence of centered values does not necessarily imply the existence of an upper or lower class of values. For example, this occurs in the case of the gravitational agent, the element's or structure's own weight which, in the majority of cases figures in the verification equation with values belonging to the centered class. It can also occur with agents that are limited by threshold values, such as wind velocity and the study of its action on a crane under normal WOCs.

3.10 Technical report of the factors

For each of the project factors and in particular, for the agents in the classification according to origin and function, a Technical Report should be written and included in the project. This Technical Report should list the processes of occurrence of the agent, and if relevant, its effects on the physical environment,soil, building materials, and geometry of the structure. It also includes all the information necessary to justify its participation in the project, the data used along with the data source, and possibly, the field and laboratory studies carried out.

Furthermore, this report will include the evaluation of the actions caused by the agent, and which affect the structure and its immediate context. In this respect, the specific Recommendations should be followed.

3.10.1 Recommended table of contents

The following subjects, among others, should be included in the study:

1. Use and exploitation factors
2. Physical environment factors
3. Soil factors
4. Factors associated with construction processes
5. Factors associated with the behavior of building materials

3.10.2 Data sources

The data source of the project factors should be specified, whether the value adopted is deterministic or random. Alternatively, if the data is the object of collected field work, then the techniques used must be described in detail (measurement techniques, recording and analysis of data, as well as the methodology applied in the statistical inferences).

3.11 Annex: Examples of values

This annex describes different aspects of the values of the agent and action parameters,which may be helpful in the application of the recommendations presented in this chapter.

3.11.1 Project parameter values

In a subset of the structure and a given time interval, it is necessary to specify the project parameter values which define the geometry of the site and the subset, as well as the properties of the physical environment,soil,and building materials,in accordance with the recommendations in section 3.8 and the following sections, for certain specific aspects.

3.11.1.1 3.11.1.1 Geometrical parameters

These parameters define the dimensions of the site, physical environment, and soil,as well as the dimensions of the elements of the maritime structure. In the first case, the geometric values are defined along with the error associated with the measurement or distribution function.In the second case, a nominal value is defined, and after adopting a distribution function or tolerance, tolerable deviations are specified in the element under construction.These deviations should be verified in the structure.

3.11.1.1.1 Measured geometrical value

Unless more detailed information is available, it is assumed that the measured geometrical parameters of the physical environment and soil follow a Gaussian distribution with a mean value, V_μ, the value contained in the drawings, and a tolerable deviation equivalent to "δ %" of the mean value estimated in the measurement process. The value of δ depends on the geometrical parameter under consideration and on the method of measurement used, which should be specified in the section of the Technical Report describing the field study.

Based on this information, the representative geometrical value is specified,and if necessary, characteristic geometrical values can also be defined, taking into account the margin of error associated with the measurement process.

3.11.1.1.2 Geometric verification value

The criteria described in the previous section can also be applied to the real geometrical parameters of the element that are subject to experimental verification. In this case, it is necessary to comply with the specifications regarding tolerable deviations.

3.11.1.1.3 Representative geometrical value of the project

The drawings should be elaborated with the geometrical value to be implemented in the structure. This is the nominal value.

3.11.1.1.4 Characteristic geometrical value of the project

Unless expressly stated otherwise, the characteristic geometrical value is the nominal value. In those cases in which the characteristic values defined are different from the nominal value, these are defined according to the typical deviation.

3.11.1.1.5 Tolerable deviation in geometric parameters

(15) σ is the standard deviation of the geometrical measurement.

The admissible deviation of the geometrical measurement should be specified in terms of tolerance, Δ, or a variation coefficient[15], σ / V_μ. In any case, the value should be consigned in the construction design or in the technical requirements, though for safety's sake, they should be included in both.

The tolerance should be specified in the same units as the geometrical measurement or by a certain percentage of it. It should indicate the magnitude of the admissible deviation in respect to the nominal value. The interval of admissible variation in the measurement is defined by means of the positive or negative sign.

The variation coefficient has no dimension, but in the same way as the tolerance, its sign permits the definition of the interval of admissible variation of the measurement. Unless expressly stated otherwise, the nominal value will regarded as the mean value, V_μ, of the geometrical parameter.

Note *Generally speaking, when specifying tolerance, the tolerance should be generous enough to permit the construction of the element or the maritime structure. If possible, it should also be sufficiently small so that the deviation pertaining to the nominal value not significantly affect the safety and operationality of the structure. Otherwise, it will be necessary to take into account the specifications about the verification with other characteristic values given in the second paragraph of the following section. Moreover, the magnitude of the tolerance should be able to be verified by available methods of control.*

3.11.1.1.6 Geometric design value

Unless expressly stated to the contrary, it is assumed that the value of the geometrical dimensions of the structure and soil, applied in the verification calculations, is that included in the construction drawings. In certain cases, when carrying out the verification, it may be necessary to apply other characteristic values, which are determined by modifying their value by means of the admissible tolerance, Δ, or the variation coefficient, increasing or decreasing it, depending on whether or not it is favorable to the verification.

3.11.1.2 Soil parameters

(16) See Part II of the ROM 0.5.

As a rule, the soil parameters vary both spatially and temporally at the site. As a result, their value is determined by field and laboratory studies, as described in the ROM 05. The depth and extension of the geotechnical research depend, among other factors, on: (1) the expected horizontal and vertical heterogeneity of the soil; (2) the intrinsic nature of the maritime structure; (3) the typology and plant layout of the maritime structure[16]. In the degree possible, the information obtained should be susceptible to statistical analysis. Nevertheless, in the verification of certain failure modes in maritime structures, the parameters of soil can fulfill the criteria recommended for their application as deterministic.

3.11.1.2.1 Representative value

Unless expressly stated otherwise, it is assumed that the representative value of the soil properties is the mean value, V_μ of the results obtained in the geotechnical study.

When a geotechnical study is not necessary or when there is not sufficient data available to be statistically processed, the representative value of the parameter of the soil is the nominal value, V_n, defined on the basis of the data from a geotechnical survey supplemented by previous experience, spatial correlation, or other criteria. If necessary, a probability model of the parameter or parameters of the soil can be assumed.

Once the representative values of the parameters of the soil in the different subsets or zones have been determined, the spatial correlation between the values of the different subsets should be studied.

3.11.1.2.2 Characteristic value

This value is obtained on the basis of the distribution function of the parameter, whose spatial domain of the application has to be delimited.Alternatively, the characteristic value is the nominal value.

3.11.1.2.2.1 Upper and lower characteristic value

When the distribution function of the project parameter is known, the upper and lower characteristic values can be determined, in the same way as the extreme values of a confidence interval, whose level will be at least 0.90.

In those cases in which the property's distribution function is not known, in which the representative value of the soil parameter has been defined by a nominal value, and in which it is necessary for the verification calculations, the upper and lower characteristic values can be determined according to the nominal value and coefficients supplied for the most usual soil parameters in the ROM 0.5.

3.11.1.3 Value of the air and water parameters

As a rule, the value of the air and water parameters follow the climatic cycles. For this reason,they should be described by statistical methods applied to the data collected in field work. Nevertheless, in the verification of some of the failure modes of the maritime structures, the air and water parameters can fulfill the criteria recommended to be applied as deterministic.

3.11.1.3.1 Representative value

Unless expressly stated otherwise, it is assumed that the representative value of the properties of air and water is the mean value, V_{μ} of the distribution functions obtained through statistical inference from the sample.

When it is not necessary to carry out a field study or if there is not enough data available for statistical processing, the representative value of the air or water parameter will be a nominal value, V_n, defined on the basis of survey data in the zone, backed up by previous experience, spatial correlation, or other criteria. If necessary, a probability model for air and water can be assumed.

Once the representative values for the air and water parameters in the different regions or zones have been determined,the spatial correlation between values belonging to the different zones will be studied.

3.11.1.3.2 Characteristic value

This value is obtained from a distribution function for the parameter, whose domain should be bounded. Otherwise, the characteristic value is the nominal value.

3.11.1.3.2.1 Upper and lower characteristic value

When the distribution function of the air or water parameter is known,the upper and lower characteristic values can be determined in the same way as the confidence interval whose level will be at least 0.90.

In those cases in which the distribution function of the property is not known and the representative value of the parameter has been defined by a nominal value, the upper and lower characteristic values can be determined, assuming a distribution function based on spatial correlation, analytical and statistical models, etc, which should be verified in the corresponding field studies.

3.11.1.4 Value of the materials parameters

As a rule, the value of the parameters that identify and characterize the construction materials are not known until the building materials are manufactured, whether they are prefabricated in a factory or elaborated at the site. In both cases, the value of the parameter implemented is a random variable that can vary both spatially and temporally.

However, in the verification of some of the failure modes of the maritime structures, the materials parameters can fulfill the recommended criteria to be applied as deterministic.

3.11.1.4.1 Parameters of materials elaborated industrially

When it is a question of materials elaborated industrially and subject to quality control, the value of the materials parameters is determined and guaranteed by the manufacturer, who provides the distribution function, the upper and lower characteristic values of the confidence interval or level, or the tolerances regarding the nominal value.

In the first case, the determination of the representative and characteristic values, should be carried out following current regulations, or in the absence of these, following the general criteria given in section 3.8. In the second case, the representative value is usually specified in the current regulations, but if no regulations are available, the representative value is either the upper or lower characteristic value, depending on which is relevant for the verification. In the third case, tolerances are applied to define the confidence interval, in the same way as in the previous section.

3.11.1.4.2 Parameters of materials elaborated at the site

The value of the parameter specified in the project before its implementation is the nominal value.

3.11.1.4.2.1 Representative value

The nominal value of the materials parameter is regarded as the representative value.

3.11.1.4.2.2 Characteristic value

The characteristic value is the principal representative value of the building material. Unless expressly stated to the contrary, it is the nominal value.

3.11.1.4.2.2.1 Upper and lower characteristic value

Unless expressly stated otherwise in Standards and Regulations, the upper and lower characteristic value of the implementation of a materials parameter is the quantile of 0.95 and 0.05 of the distribution function. Between these two values a confidence interval of 0.90 is defined.

Since it is impossible to know the distribution function of the parameter before its implementation, in order to specify characteristic values, it is necessary to assume a distribution function based on analytical or statistical models according to current regulations.The distribution function adopted should be verified by means of a field study. In any case, the relation between the nominal value and the descriptors of the distribution function should be specified.

3.11.1.4.3 Durability and value of the materials parameters

Regarding durability, in the determination of the nominal value or other representative values, it is necessary to consider the evolution of the properties of the material exposed to the effects of agents of the physical environment,particularly, loading and unloading cycles with frequencies analogous to those of the oscillations of the sea and wind (gusts) and cycles of wetness-dryness,similar to those produced by the astronomical tide and other long-period oscillations.This analysis can be carried out by using experimental techniques or analytical and numerical models,duly contrasted or consigned in the Recommendations or relevant Standards.

Note *Relevant here are the specifications in table 8.2.2 "General classes of exposure related to the corrosion of steel reinforcements" and table 37.3.2b "Minimum strengths compatible with the durability requirements"in the Spanish* Instrucción de Hormigón Estructural *(EHE).*

3.11.1.5 Other parameter values

Unless expressly stated to the contrary, the value of other project parameters is determined,using the same criteria in this section.

3.11.1.6 Spatial and temporal variability of the parameters

In reference to spatial and temporal variability, the recommendations in section 3.3 should be taken into account.

3.11.2 Agent values

In a subset of the structure and for a given time interval, the determination of the values of agents and actions on the maritime structure and its context should be in consonance with the recommendations in section 3.8 as well as the those in following sections regarding certain more specific aspects.

3.11.2.1 Value determined by a probability model

As a general rule, the majority of the agents,particularly those related to the physical environment and the soil, should be defined on the basis of the distribution function of the population, according to the criteria developed in section 3.8.

3.11.2.1.1 Representative value

This type of value supplies an order of magnitude which the agent can take in the verification of the failure mode.

3.11.2.1.2 Characteristic value

This value is the principal representative value of the agent.

3.11.2.1.2.1 Upper and lower characteristic value

For project factors defined within a confidence interval,the maximum and minimum values of the domain are known as the upper and lower characteristic values. Generally speaking, for agents of the physical environment, the upper characteristic value is the quantile of 0.95 of the mean distribution function or the extreme distribution function. The lower characteristic value may be a threshold value or simply zero, i.e. the non-occurrence of value. Other times,the lower characteristic value can be the value of the quantile of 0.05.

3.11.2.1.3 Value of agents without a probability model

The gravitational agents of use and exploitation, as well as those associated with construction are quantified by means of nominal values defined in the current regulations, previous experiences or other duly contrasted procedures.In these cases,the agent values are determined by following the recommendations in section 3.8. on project factors defined by a nominal value.

3.11.2.1.4 Spatial and temporal variability of agents

Relevant to this type of variability, are the recommendations in section 3.3.

3.11.3 Action values

The value of the action is obtained by a functional relation of one or various predominant agents[17], other agents, and a certain number of project parameters, or by research studies in Nature or a physical model.This evaluation depends on whether the project factors have been defined by distribution functions or nominal values.An action is generally represented mathematically by one or more terms of a verification equation. Its evaluation should be in consonance with the recommendations in section 3.8 and those in the following sections for more specific aspects.

(17) The predominant agent and by extension, the predominant project factor, is that which primarily determines the occurrence of the failure mode.

3.11.3.1 Value determined by a probability model

The distribution function of an action can be obtained by laboratory tests or field studies, a physical model,or by means of mathematical calculation.In this case, based on the distribution function of the project factors that intervene in the calculation of the action, it is possible to obtain the distribution function of the action,either analytically or numerically. Once the distribution function of the action has been found, its upper and lower characteristic values can be determined, following the criteria recommended in section 3.8.

3.11.3.1.1 Probability model of the action with a predominant agent

If only one predominant agent, whose function is known,intervenes in the action,then the probability can be approximated through the distribution function of the predominant agent, giving to the other factors values compatible with value of the predominant agent.

Once the distribution function of the action has been found, its upper and lower characteristic values can be determined, following the criteria recommended in section 3.8.

3.11.3.2 Nominal value of the action

In certain cases, the nominal value of the action is defined in the current regulations by conditions imposed by the exploitation, previous experiences and other duly contrasted experiences. In these cases, it is advisable to follow the recommendations in section 3.8 to determine other values of the action,particularly, the characteristic values, maximum and minimum,etc.

When the nominal value of the agent is not known, but can be quantified by means of a function of the project factors, all of which are defined by their nominal value, it can be assumed that the value obtained is a nominal value of the action.

3.11.3.3 Spatial and temporal variability of the action

When this type of variability is under consideration,it is advisable to follow the recommendations in section 3.3.

CHAPTER 4
Verification Procedure

4 VERIFICATION PROCEDURE

4.1 Introduction

A verification procedure ascertains when and in what way a subset of a structure no longer fulfills the project requirements in a project phase. For this reason, such a procedure consists of a sequence of acts that can be applied to decide whether or not the project is reliable and functional against all the ultimate failure and serviceability modes, as well as operational against all stoppage modes.

4.1.1 Objectives of the procedure

The project of a maritime and harbor structure, implemented in accordance with these Recommendations, should show that in each of the project phases, each subset of the structure satisfies the requirements regarding safety, serviceability, and use and exploitation in consonance with the values recommended in section 2.10.

Note *Section 2.10 defines the requirements regarding safety, serviceability, and use and exploitation of a subset of a structure. Also defined is the probability that these requirements (i.e. reliability, functionality, and operationality) will be satisfied in a given time interval.*

4.1.2 Activities included in the verification process

These activities are the following: (1) choice of a work method; (2) description of the failure or stoppage mode, which generally takes the form of a verification equation; (3) ordered sequence of the project factors that can explicitly or implicitly appear in the terms of the equation; (4) criteria to determine the compatible values of terms and to establish types of combination for a given set of WOCs; (5) verification method to evaluate the probability of the occurrence of a mode, and the overall probability of the presentation of other principal modes.

4.1.3 Chapter organization and contents

This chapter begins with an explanation of the objectives of the general procedure and a description of the method of the limit states. Then comes an account of the possible formats of the verification equation, the global safety coefficient and the safety margin, as well as the organization of the project factors. This is followed by the description of WOCs, and the criteria for the combination of the factors and terms of the verification equation. The next section presents the verification methods of the failure or operational stoppage modes that are applied in these Recommendations, and which are discussed at greater length in Chapters 5 and 6. Finally, a summary is given of the criteria that can be applied to evaluate the probability of the occurrence of a mode and the overall probability of all the modes. These criteria are further developed in Chapter 7. Figure 4.1 is a schematic outline of the contents of this chapter.

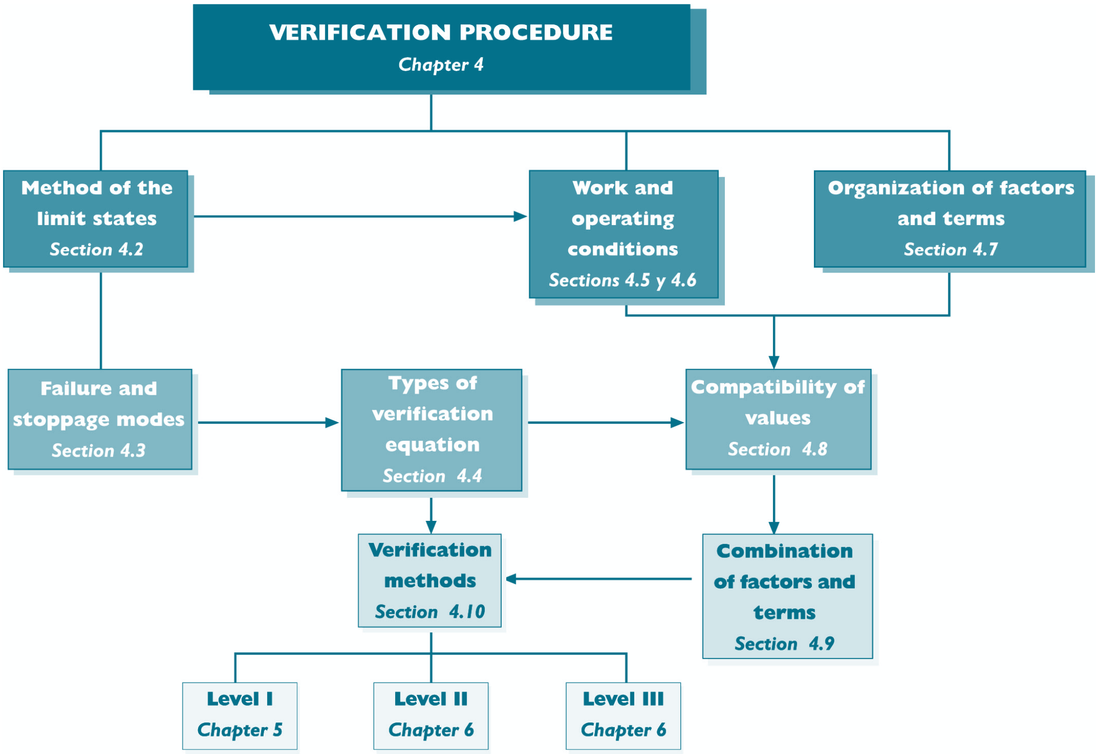


Figure 4.1: Chapter 4. Organization and contents

4.2 Method of the limit states

The duration of each of the project phases which the structure undergoes (i.e. construction, useful life, maintenance and repair, and dismantling) can be divided into a sequence of project states. The project state defines and describes the behavior of a subset of a structure in a given time interval. During its occurrence, the shape and structural response and the exploitation of the subset are assumed to be stationary processes.

The objective of the project design is to verify that the subset of the structure fulfills the project requirements in each and every one of the states. With a view to simplifying the verification of a subset of the structure, only some of all the possible project states are verified, namely those that represent limit situations of the subset from the viewpoint of structure, shape, and use and exploitation. It is precisely for this reason that these states are known as limit states, and the work method is known as the method of the limit states.

Three sets of limit states can be defined. The first two are known as ultimate limit states and serviceability limit states, respectively. The states that describe the use and exploitation of the subset are called operational limit states (see Figure 4.2).

4.2.1 Definition of a limit state

Project state in which the combination of project factors produces one or various failure or operational stoppage modes. These modes all occur in the same way, or are caused by the same mechanism.

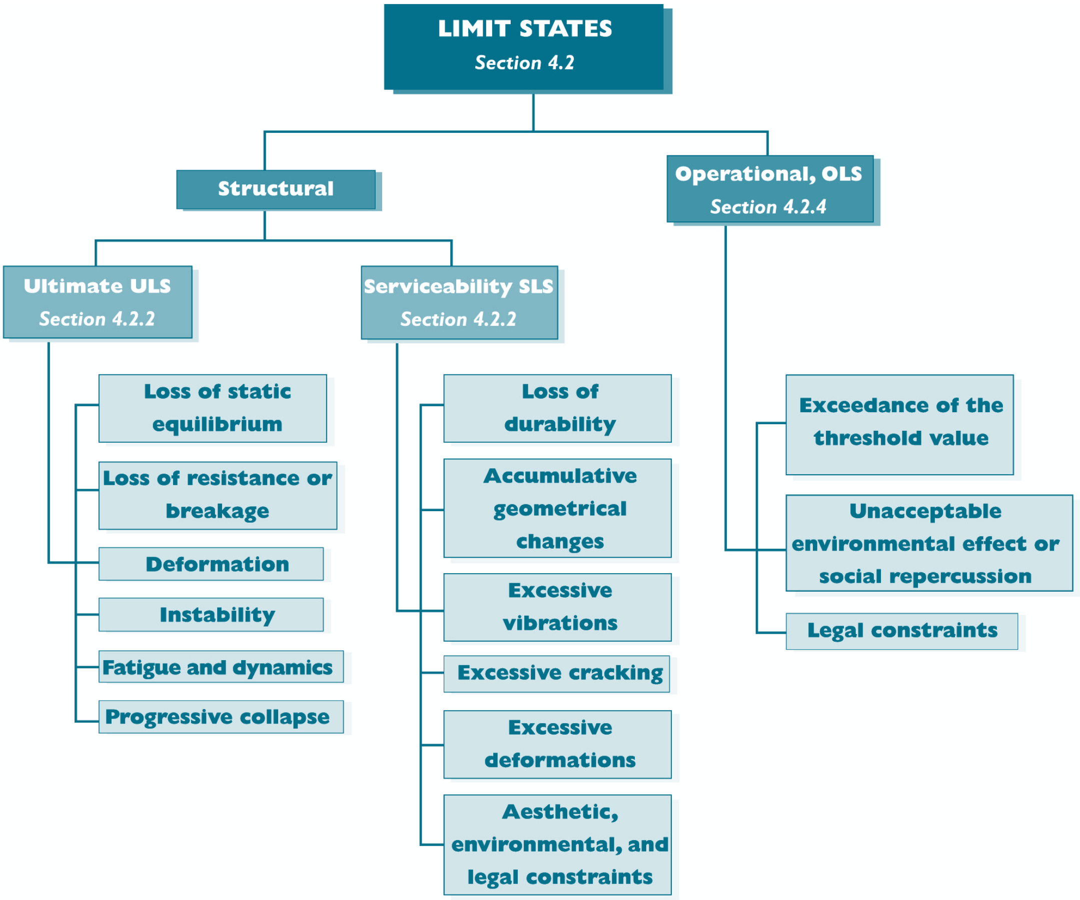


Figure 4.2: Ultimate limit states, serviceability limit states, and operational limit states

4.2.1.1 Types of limit states

There are two types of limit states: (1) those affecting the safety and serviceability of the maritime structure, which define the failure modes affecting the previously mentioned aspects of the structure;(2) those associated with the use and exploitation of the maritime structure in which there is no structural failure. In other words,once the cause of the stoppage has disappeared, the structure again fulfills its use and exploitation requirements.

The limit states related to shape and structural safety requirements are organized in ultimate limit states and serviceability limit states.

4.2.2 Ultimate limit states (ULS)

Those states that produce the collapse of the structure either because of breakage or structural breakdown of the structure or any part of it. They include all failure modes, which may be caused by the following:

1. Loss of static equilibrium of all or part of the structure, considered as a rigid, solid entity
2. Excessive deformation, breakage, loss of stability in all or part of the structure
3. Accumulation of deformation, progressive cracking, fatigue and dynamics

4.2.2.1 Classification of the ultimate limit states

(1) With a view to maintaining the conceptual coherence of these Recommendations with other Regulations and Instructions, this classification follows the criteria specified in the Spanish Instrucción de Hormigón Estructural *(EHE).*

Whenever significant, the following ultimate states[1] should be taken into consideration in each project phase:

- Loss of static equilibrium
- Loss of resistance or breakage
- Deformation
- Instability
- Fatigue and dynamics
- Progressive collapse

In consonance with the particularities generally related to the project factors, the lay out and typology of the structure, as well as the safety of the structure and its context, other ultimate limit states can also be proposed, whose specification should conform to the definition given in section 4.2.2.

Note *In certain maritime structures, the ultimate limit states are often associated with the occurrence of climatic agents, such as waves and wind, which can produce static and dynamic actions. In the latter cases, the structure may oscillate, forced by the agent, and in some cases may even resonate. A resonant oscillation occurs when the principal oscillation period of the agent or its action coincides with the principle mode response of the structure. In this event, the oscillation amplitudes can be unlimited, at least in theory. Otherwise the oscillations are forced, and usually stop rapidly after the agent causing it, stops.*

Furthermore, the failure of the structure has a probability of occurrence. In the case of failure modes due to wind waves, all of the sea states have a certain probability of producing damage since, in all of them, there is a probability that waves larger than calculated will occur. However, only the most energetic sea states contribute significantly to the probability of failure. For this reason, it is convenient to specify a threshold sea state. Then, it can be assumed that any sea state exceeding this threshold level will significantly contribute to the probability of failure.

This concept can be extended to all of the agents whose occurrence is associated with a probability. As a result, threshold values of state descriptors can be defined whose exceedance can produce significant values in the probability of occurrence of the failure mode.

4.2.2.1.1 Loss of static equilibrium

This group includes all of the failure modes associated with the loss of static stability of the structure as a whole and its individual elements, considered as a rigid body. The verification equation should apply only when the idealization of a rigid solid is representative of the WOCs of the entire structure, thus the method of Rational Mechanics can be applied.

Note *The loss of static equilibrium can occur because the resistance to friction or overturning has been exceeded. In this limit state it is possible to include, among others, the following failure modes: rigid overturning, sliding, deformation, floating, etc.*

4.2.2.1.2 Loss of resistance or breakage

This group includes all the failure modes that can occur when the maritime structure reaches its resistance capacity or when there is excessive plastic deformation in one or several (or parts of sections) of the structure's individual elements. This state must be assessed for the sections of the different structural elements.

Note *The loss of resistance of the section can occur because of tensiles, shears, torsion, or punching. Amongst the modes that can be included in this limit state are the following: failure of the structural section, sliding, or loss of bearing capacity under the crown deep soil sliding circle, etc*

4.2.2.1.3 Instability

This group includes all of the failure modes associated with the local or global deformation of the structure or in one of its elements, which can lead to its loss of resistance.

Note *The instability of the structural element can result in its being bent, dented, and warped. This limit state will be verified in the sections of the different elements of the structure, generally by studying the element's capacity to withstand the actions caused by its deformations, applying second-order models.*

4.2.2.1.4 Fatigue and Dynamics

This group includes the failure modes produced under dynamic loads that act on an element or the soil.

Note *Fatigue in many maritime structures is usually associated with the occurrence of marine and climatic atmospheric agents. The failure is produced by the loss of resistance of the section, and thus can be caused by tensiles, shears, and torsion. In maritime structures, a classic example is breakage because of fatigue of slender pieces of the main layer, such as dolos, acropods, etc.*

Although, fatigue generally results in the loss of resistance of the structure, given the peculiarities of its processes, such fatigue is normally regarded as a limit state, which is independent of the loss of resistance.

4.2.2.1.5 Deformation

This group includes the failure modes in which the structure in its totality or one of its elements, experiences changes in its geometry that do not guarantee the safety of the structure.

Note *This limit state includes the failure modes of the maritime structure, related to its deformation or that of one of its elements, which occur in time intervals of lesser duration than the useful life of the structure. In this case, the deformation is a rational index of the immediate failure of the structure or one of its elements because of loss of resistance. The geometrical changes considered in deformation limit states provoke important modifications in the shape of the structure, converting it into a different one from the structure initially designed, and for this reason, with a different structural behavior from that assumed in its verification.*

In this limit state, the following failure modes, among others, can be included: erosion of the toe berm, sediments and deformations of the soil or the main layer, settlements of a pile in a structure, etc.

In the case of the breakwater, the action of the storm design can cause the lifting out of pieces, deforming the main layer and modifying its geometry. This "new" slope is different from the one originally designed in that its interaction with the incoming waves is also different; it produces a moving off towards the sea, a change how and where the waves break.

In section 4.2.3 serviceability limit states are defined and among them, those associated with accumulative geometrical alterations which, like ultimate limit states by deformation, lead to a structural failure because of geometrical changes, incompatible with the safety of the structure. This serviceability limit state is achieved by the use and exploitation of the structure in the physical environment during its useful life.

4.2.2.1.6 Progressive collapse

This limit state includes the progressive and conditioned sequence of failure modes of one or various elements of the structure, which lead to its eventual collapse. This occurs either by transforming the structure into a mechanism or by altering the geometry and resistance dependencies of the different structural elements.

Note *The progressive collapse of the structure is defined by means of serial, parallel or compound failure sequences (trees). In the first case, each structural element failure is followed by another one, and so on until the structure collapses, though the occurrence of one mode can cause the failure of the structure. The parallel sequence specifies failure subsequences of elements along independent lines. In order for the structure to collapse, all of the modes belonging to one of the parallel failure lines must occur. Finally, the mixed sequence consists of combinations of the serial failure sequences, some of which may divide into parallel sequences, continue with another serial sequence, etc.*

4.2.3 Serviceability limit states, SLS

States that produce a reversible or irreversible loss of service and functionality in all or part of the maritime structure, due to a type of structural, aesthetic, or environmental failure or legal constraint. When these states are permanent, repairs become necessary so that the maritime structure can recover its ability to meet the project requirements. These limit states can be reached during the useful life of the structure as a consequence of its use and exploitation, as well as its location in the physical environment.

In these serviceability limit states, all failure modes are considered, which reduce or constrain the use and exploitation of the structure, and which can signify a reduction of the useful life and the reliability of the residual life of the structure, due to the following:

1. Deterioration of the properties of the building materials or soil
2. Excessive deformations or vibrations in the structure of the use and exploitation of the structure
3. Accumulative geometrical changes

4.2.3.1 Classification of the serviceability limit states

In each project phase, the following limit states, when significant, should be verified:

- Loss of durability
- Accumulative geometrical changes
- Excessive vibrations
- Excessive cracking
- Excessive deformations
- Aesthetic, environmental, and legal constraints

In consonance with the particularities of the structure, associated with the project factors, the layout and typology, as well as the structure's functionality and context, other serviceability limit states can be proposed in accordance with the definition given in section 4.2.3.

Note *The failure modes of the structure, assigned to the serviceability limit states, are not usually reached as the result of a pathology, but rather because of the progressive deterioration of the structure's resistance capacity and shape, associated with the properties of the building materials and the soil.*

Differentiating between ultimate limit states and serviceability limit states is often difficult. Two essential criteria are the type of failure and temporality. When the modality of failure is a pathology, or if it is produced by the action of one or various agents during a time interval of a much lesser duration than the useful life of the structure, the failure mode should be assigned to an ultimate limit state. Otherwise, it should be assigned to a serviceability limit state.

If the occurrence of the failure mode can be delayed or prevented by means of a suitable strategy conducive to the maintenance of the structure and its elements, the mode usually belongs to a serviceability limit state.

Furthermore, in the same way as ultimate limit states, agents also have threshold values, which once exceeded, significantly contribute to the probability of failure. For this reason, it is convenient to define these threshold values for the analysis of serviceability limit states. In certain cases, upper and lower higher threshold values should be defined. The latter could be associated with the occurrence of reversible failure modes (e.g. reversible cracking), while the former could be related to irreversible failure modes.

4.2.3.1 Loss of durability

Durability is the capacity of the structure and its construction material to withstand, with no significant alterations in the technical specifications required in the project, the actions of the agents of the physical environment, soil, construction, and use and exploitation, during each of the project phases. This deterioration is different from that caused by the actions considered in the structural or operational analysis.

Note *This limit state includes all modes characterized by progressive deterioration in structure, shape, aesthetic considerations, etc. of the maritime structure or one of its elements. Among the failure modes included in this state are the following: reversible cracking, corrosion, abrasion, loss of impermeability and porosity, water absorption, diffusion of gases and ions, combined action of sulfate and magnesium ions, etc.*

4.2.3.2.1.1 Standards of good practice

It is often difficult, if not impossible to establish a reliable equation that permits the verification of a failure mode, assigned to a limit state of loss of durability. In these cases, it is advisable to apply criteria and standards of good practice for the design, implementation, and exploitation of the structure. A maritime structure can be said to be durable if these standards of good practice are applied correctly.

Note *One way of assuring the durability of the concrete of a floating caisson is to reduce its permeability. For this reason, it is necessary to have a low water-cement relation, adequate cement content, properly vibrated, and in which sufficient hydration is allowed. If all of these norms are correctly applied, the concrete of the floating caisson can be said to fulfill the requirements of loss of durability.*

4.2.3.2.2 Accumulative geometrical alterations

This category includes the situations reached by the structure or one of its elements in which an accumulation of geometrical changes are generated, which reduce the possibility of or prevent the serviceability requirements specified in the project from being fulfilled.

Note *Examples of failure modes that can be included in this state are the following: deformations and erosions of the surface caused by crown overtopping, longitudinal or transversal variations of the depth in a navigation channel because of accumulation or erosion, tunneling in the docks or other type of structure, washing of fills caused by the wind waves or the astronomical tide, settlements in pavements, etc.*

The longitudinal and transversal variations of the depth in a navigation channel can illustrate the assignment of a failure mode to an ultimate limit state or a serviceability limit state. For example, a navigation channel can be subject to two wave regimes, a dominant one and a prevailing one, directionally different.The beginning of movement and the transportation of sediments towards the navigation channel is produced once a certain threshold value for the significant weight height and the mean period is exceeded.

The occurrence of prevailing sea states with values superior to the thresholds provokes accumulative geometrical changes of the depth in the navigation channel, which occur progressively, and are generally irreversible. These variations can be controlled with an adequate conservation strategy.The failure mode, progressive loss of the depth in the navigation channel, should be assigned to the serviceability limit state because of accumulative geometrical alterations.

Moreover, the maximum design sea state, belonging to a set of dominant sea states, can cause the transport of a sufficient volume of sediments, which rapidly or "instantaneously" reduce the depth in the navigation channel below the minimum required value in the project.The recovery of the depth of the project can only be achieved through the complete dredging of the accumulated sediment.The failure mode, instantaneous or rapid loss of the depth in the navigation channel should be assigned to the ultimate limit state, deformation.

4.2.3.2.3 Excessive vibrations

This state characterizes the situations reached by the structure or one of its elements in which the amplitude or vibration frequency produces damage in the elements or installations.

Note *One example of the failure modes assigned to these limit states are damage in the floating ramps because of the impact of ship during the operations of loading and unloading, vibrations in the crown because of the impact of the waves, which produces the breakage of the concrete and the exposure of the frameworks, vibrations in a building or bridge because of the effect of the wind,which limits access to them or the transit of vehicles, sheet piling in the proximity of existing structures, on diaphragm seawalls, affected by the action of waves, etc.*

4.2.3.2.4 Excessive cracking

This state characterizes the conditions for which the geometric dimension of the fissure, though reversible can induce failures in the behavior of building material or other covered materials.

Note *The visual inspection (in terms of length,width, and direction) of the fissure or crack is common practice in civil engineering.This analysis is useful in the evaluation of the evolution of these cracks over a period of time. Generally, two types of situation can occur. In the first, the fissure opens and closes according to the loading of the elements under extreme conditions. In this case the duration of the extreme conditions is limited and the risks derived from the opening of the crack are relatively insignificant.In the second case it is necessary to evaluate the consequences of the temporal opening of the crack.*

In this regard, it must be underlined that the cracking cannot be considered a state of breakage because the steel-making stress is sufficiently distant from its elastic limit.When the loads disappear, the crack closes up, and as a result, the cracking is a short-term reversible state. Generally, the maximum width of the crack should be fixed according to the aggressiveness of the environment and actions, as well as their duration.

For example, in the case of a wall made of reinforced concrete which, loaded by the oscillations of the sea, opens and closes fissures during the most violent storms. The frequency and duration of these storms is so short that the attack of the sea on the frameworks is usually insignificant. If the crack opens in the most frequent sea states, then the exposure time during the useful life of the structure may be sufficient, if it is not taken into account, to cause the corrosion of the frameworks and the deterioration of the structure.

In the second situation, the crack may continually progress during the useful life of the structure. In this case, it is necessary to calculate when one of the geometrical dimensions of the crack exceeds the previously established failure criteria.

4.2.3.2.5 Excessive deformations

States in which deformations are produced, which, without being accumulative, can endanger the functionality of the subset of the structure or one of its elements.

Note *This state can be produced in a floating beam for a crane railway that presents deformations greater than the tolerances for the use and exploitation of the crane, which have been specified by the supplier.*

4.2.3.2.6 Aesthetic, environmental and legal constraints

Limit states in which the structure does not fulfill the serviceability requirements because of losses regarding its shape, attractiveness, environment, or legality.

Note *Some of the failure modes assigned to these limit states are excessive deflections in prefabricated elements, deformations of the front dock beam, etc.*

4.2.4 Operational limit states, OLS

Limit states in which a structure's use and exploitation is reduced or temporarily stopped due to causes that are external to the maritime structure and its installations without the existence of structural damage to the structure or any of its elements. Generally, the exploitation is stopped in order to avoid this sort of damage to the structure or unacceptable environmental and social consequences. Once the external cause disappears, the structure and its installations totally recover the exploitation requirements of the project.

In operational stoppage limit states, all modes should be considered which can cause the following:

1. Temporary reduction of the reliability and functionality of the maritime structure and its installations
2. Temporarily unacceptable environmental effects and social repercussions

4.2.4.1 Classification of the OLS

Whenever significant in each project phase, it is important to take into account the following operational stoppage limit states because of:

- Exceedance of the threshold value of one or various agents
- Unacceptable environmental effect or social repercussion
- Constraints

According to the particularities related to the project factors, layout, and typology of the structure, the exploitation of the subset and the context,other operational stoppage limit states can be proposed, whose definition should be in consonance with that given in section 4.2.4.

Note *All public works have a certain probability of operational failure. This is due to physical environment effects, as occurs, for example at airports, roads, etc. It is impossible to build a structure that guarantees exploitation during all of its useful life. For this reason, it is necessary to define operational limit states. In maritime structures, the magnitude of the environmental agents, in particular, climatic agents (i.e. high waves, wind, and fog) determines their operationality. Once the environmental agents and their actions exceed a certain magnitude, known as the threshold magnitude, the structure and its installations should stop operating to avoid damage themselves, the user or the physical environment. Once the agent or its action fall below the threshold value, the service may be resumed.Operational limit states, therefore, do not cause damage to the maritime structure, but are established to avoid this occurring.*

The operational limit states evaluate the exploitation and management conditions of the maritime structure, and thus should be analyzed and evaluated in the project.

It is advisable to draw up a User and Operations Manual for the structure to inform the technician responsible of the operational limit states and stoppage modes.

4.2.4.1.1 Exceedance of the threshold value of the agents

This operational limit state includes the stoppage modes caused by the exceedance of the threshold value of one or various agents of the physical environment,particularly the climatic agents.

Note *This limit state is intrinsic to the location of the maritime structure in the environment, since it is not economically viable to design a structure that can maintain its level of exploitation during the whole of its useful life for any magnitude of the agents of the physical environment and their actions. This state includes all the operational stoppage modes that the agents of the physical environment can cause in the structure or its installations.*

For example, after a certain wind speed threshold is surpassed,the crane's exploitation level and loading capacity are reduced until it reaches a certain superior threshold value, after which it must cease to operate. According to current Spanish legislation, the crane should cease to operate as soon as the prescribed wind speed threshold is surpassed.A similar case happens when the boat pitching, rolling or surging becomes too violent, causing the loss of control of loading and unloading operations. When such conditions occur, it is best to interrupt the exploitation.

Sometimes the exploitation is interrupted because the ship cannot arrive at the dock because of the presence of fog. When there is a lack of visibility, it is advisable to wait before docking.

4.2.4.1.2 Socially unacceptable environmental effect or social repercussion

This operational limit includes the stoppage modes carried out to avoid damage to people, the historical and cultural heritage, and to the environment.

Note *In certain bulk unloading docks, it is necessary to limit the volume and time of unloading in the presence of winds of a certain direction in order to minimize the spreading of suspended particles. It should be underlined that on many occasions these stoppage modes arise after various years of service because of the evolution of social attitudes and behavior, urban development around the harbor area, passing of new legislation, etc.*

4.2.4.1.3 Legal constraints

This operational limit state includes stoppage modes carried out to fulfill legal requirements.

Note *In the same way as the previously mentioned limit states, on many occasions the stoppage modes assigned to this state occur after the structure has been operating over a period of several years, when new legislation is passed, or when the application limits of existing legislation is modified.A case in point is the legislation regarding the outflow of residual waters into the sea, which over the years has substantially reduced the admissible level of outflow of polluted waters into the sea.*

4.3 Failure and stoppage modes

A mode describes the form or mechanism in which the failure or the operational stoppage of the subset of the structure or one of its elements is produced.

4.3.1 Characterization of a mode

To characterize a failure or operational stoppage mode, it is necessary to define the following:

1. Form or mechanism in which it is produced
2. Project factors that can simultaneously participate in its occurrence
3. Form of verification: (1) equation describing the form or the mechanism and the functional relation between the project factors that participate in the mode; or (2) experimentation
4. The hypothesis for the application and the range of validity of the equation or experimentation

4.3.2 Assignment of a mode to a limit state

The modes that can occur in a similar way or by the same mechanism will be assigned to the same structural or operational limit state.

The assignment of a mode to one of these types will be given in the specific Recommendations. Otherwise, the mode will be assigned according to the following criteria: (1) the limit state with the worst possible verification; (2) the limit state that best describes the work carried out by the predominant agent, triggering the mode; (3) according to the verification equation to be applied.

Note *The assignment of a mode to one of these limit states is not unique, since the same mode can belong in more than one state. For example, the lifting out of pieces of the main layer of a breakwater can be assigned to two ultimate limit states: loss of static equilibrium and accumulated deformation.*

In the first case, the extraction of individual pieces or units (such as a rigid solid) of the main layer, whether concrete block,quarry stone, tetrapod,etc.,occurs when the friction and interlocking forces between units are surpassed. In such conditions a failure is assumed to happen when an absolute or relative number of units has been extracted from the layer.

In the second case, the geometrical variation (accumulated deformation) of the first layer of the main layer due to the lifting out of units is taken into consideration. In these conditions, a failure is assumed to occur when pieces of the second layer are directly exposed, and therefore, can be extracted by the wave action. In each case the verification equation should quantify what defines the failure or the criterion of failure: (1) number of extracted units; or (2) the geometrical deformation of the main layer. If the verification equations are representative of the phenomena that they quantify, the result of the verification should be the same. In the previous example, both expressions represent different failure criteria, whose quantification is carried out by experimentation in the physical model, and thus, both are related since they are based on the same data model. Either one can be used.

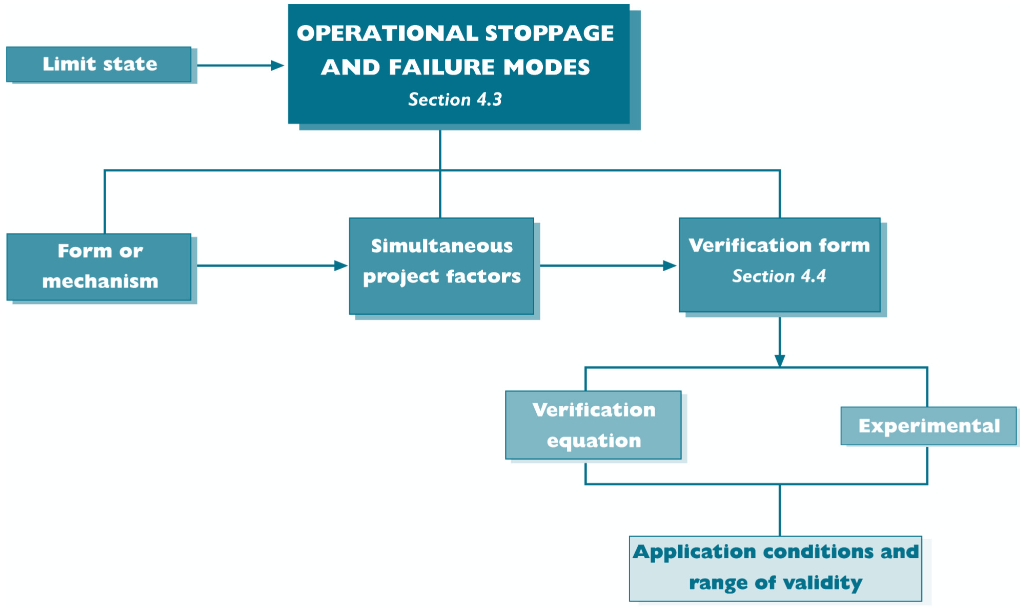


Figure 4.3: Failure and stoppage modes and verification procedures

4.4 Types of verification equation

It is necessary to establish a verification equation for each failure mode assigned to an ultimate or serviceability limit state and for each operational mode belonging to an operational limit state. The verification equation is formed by a set of terms. Generally speaking, this equation is a state equation, and therefore, it is applied with the hypothesis that the outcomes of the set of project factors are stationary and uniform from a statistical point of view.

4.4.1 Terms of the equation

Terms formed by a combination of mathematical operations of project factors, parameters, agents, and actions. The word term is therefore used in the mathematical sense. Accordingly, each term can be formed by other terms.

4.4.1.1 Favorable and unfavorable terms

Terms can be classified as favorable (X_1), and unfavorable (X_2). Favorable and unfavorable terms are those that contribute in a favorable or unfavorable way to the non-occurrence or the prevention of the failure mode, respectively. The favorable or unfavorable participation of a project factor depends on the mode being analyzed. This behavior cannot be generalized to other modes.

4.4.1.2 Temporal classification of terms

Following the criteria elaborated in section 3.7, the terms of the verification equation can be classified as permanent,non-permanent,extraordinary, or catastrophic, according to the probability of exceedance and the persistence of the threshold level of the relevant project factor in the term.

4.4.2 Recommended formats

These Recommendations suggest two formats for the verification equation: Global Safety Coefficient and Safety Margin. Traditionally in Engineering,the verification of the fulfillment of safety requirements of a structure in relation to a failure mode is carried out through the global safety coefficient.

4.4.2.1 Global Safety coefficient (Z)

Quotient of favorable terms (X_1) and unfavorable terms (X_2).

4.4.2.1.1 Minimum safety coefficient

Generally speaking,in order to consider that the structure or element has been favorably verified against the mode, the safety coefficient should be greater than a given minimum value: $Z > Z_c$.

Note *The minimum value (Z_c) of the safety coefficient depends, among other things, on the intrinsic nature of the structure, the failure mode, the limit state of the WOCs, and the combination type. Each ROM gives the values that should be applied in each case. If $Z > Z_c$, then the design can accepted or favorably verified, at least from the point of view of safety, serviceability, or use and exploitation. This does not imply, however, its validity from an environmental, social or economical point of view.*

4.4.2.2 Safety Margin

Difference between favorable terms (X_1) and unfavorable terms (X_2)

4.4.2.2.1 Minimum safety margin

In order for the structure or element to be favorably verified against the mode, it should fulfill S>0.

Note *In the case of maritime structures, the structure of the verification equation is established with pairs of terms that can represent, for example, actions due to wind waves and unit weight,approach rate of cargo vessels and capacity of the dock, calculated tension and acceptable tension, wave run-up and the freeboard of the dike, etc..*

In the case of water rising about the dike, it is necessary to define a freeboard (F_c) and the height of the water tongue overtopping the crown (R_w).The freeboard (F_c) is the geometric design parameter, e.g. the height with regard to a fixed reference level and apart from expected deviations during the construction phase, takes a determined and fixed value known a priori.

The height of the layer of water (R_w) depends on the characteristics of the structure, such as porosity, geometry, etc., and the characteristics of wind waves and mean water level. If the project requirement or failure criteria is such that water does not overtop the structure, the verification equation is expressed with a safety margin format $S = F_c - R_w > 0$, or with a safety coefficient format $Z = F_c/R_w > Z_c; Z_c > 1$.

4.4.3 Value of the terms of the verification equation

The verification equation is a state equation. Consequently, the project factors that participate in it,can take nominal values or be statistical variables.The value of the terms of the equation depend on the verification method which is selected, depending on the general intrinsic nature of the structure.

Note *In the preceding example about overtopping, the verification is carried out in a sea state. The predominant agent is the wind wave. Each wave is defined according to its height, period, and direction. In a sea state it is assumed that the water surface vertical displacement respecting a mean level of reference is a stationary process, and statistically homogeneous in the subset of the structure. It is possible to proceed deterministically, selecting nominal values for the height, period, and direction of the waves. Nevertheless, it is also feasible, and generally more correct,to assume that the height, period, and direction of each individual wave are random variables that are described by a probability model.*

When the description is deterministic, the answer to the verification equation is if there is $S \leq 0$, or not $S > 0$, overtopping.If the description is probabilistic, it is also possible to obtain the probability of overtopping events in a given sea state.

4.4.4 Other forms of verification

It will occasionally be necessary to verify a subset by means of experiments carried out at the site or in the laboratory.These techniques are not described in these Recommendations.In such cases for the acceptance of the verification and the evaluation of the probability of occurrence of one or all of the modes, the experimental results should be analyzed in the same way as the project factors and the terms of the verification equation.This means observing all the aspects associated with uncertainty, and describing it, if relevant, in terms of probability models.

Note *The result of an experiment also carries an uncertainty which should be evaluated. For this reason, it is necessary and convenient to repeat the experiment a sufficient number of times to obtain a statistical representative sample.*

4.5 Work and operating conditions (WOCs)

A maritime structure is built to fulfill certain requirements, which include supplying the necessary means and conditions to carry out normal operations of use and exploitation, as well as to withstand, without damage or structural deformation, extreme (or extraordinary) actions caused by the mutual interaction of the structure and its immediate environment.The project states that characterize those conditions and means are known as WOCs (see Figure 4.4).

4.5.1 Definition

A work and operating condition is a set of project states characterized by the simultaneous occurrence with compatible values of certain project factors.WOCs are generally specified on the basis of predominant agents.

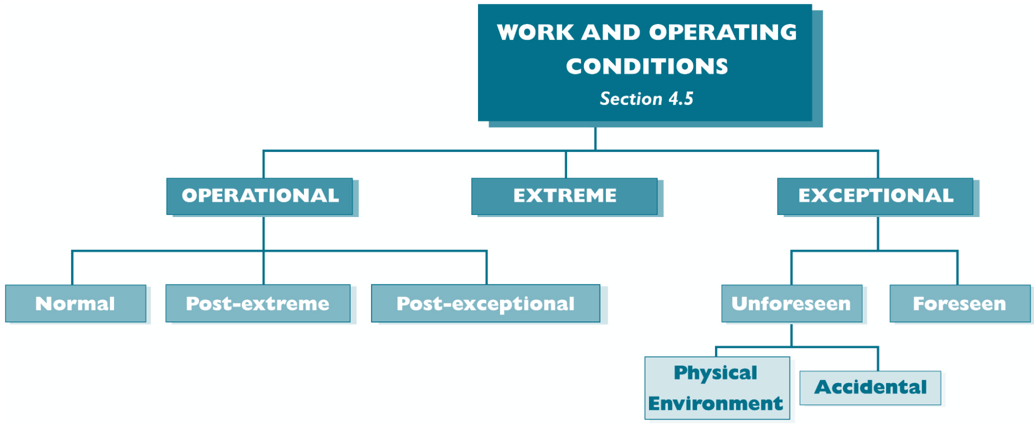


Figure 4.4: WOCs

4.5.2 Recommended WOCs

For each project phase and time interval, the following WOCs will be considered, WOC_i, (i = 1, 2, 3). (See table 4.1)

Table 4.1: WOCs in the verification procedure

	Work and operating conditions
WOC_1	Operational
WOC_2	Extreme
WOC_3	Exceptional

4.5.2.1 Normal operational conditions (WOC_1)

These conditions include the project states that habitually occur and during which the maritime structure offers the service for which it has been designed. Predominant agents are usually those of use and exploitation though other agents can simultaneously act as well. To guarantee the operationality of the operating structure, compatible values of simultaneous agents (though different from the predominant ones) must be specified and delimited. When they surpass threshold values, it is assumed that the maritime structure is temporarily out of service and a breakdown mode occurs. Apart from normal conditions, the following operational WOC will also be considered:

4.5.2.1.1 Post-extreme operational ($WOC_{1,2}$)

When partial deformations of the structure or one of its elements is possible, post-extreme operational WOCs should be considered in order to verify that the maritime structure as a whole and each of its elements, including the foreseen partial deformation, fulfill the necessary safety, serviceability, and exploitation requirements in the operational WOC_1.

4.5.2.1.2 Operational, post-exceptional conditions ($WOC_{1,3}$)

These conditions occur after the appearance of exceptional WOCs. If they have been foreseen, the structure as a whole and each of its elements should satisfy the necessary safety, serviceability, and exploitation requirements in the project for all of the WOCs.

4.5.2.2 Extreme conditions (WOC_2)

These conditions include the project states associated with the most severe actions due to project factors.The predominant agents, which in maritime structures are generally climatic environmental factors can take extreme (or extraordinary) values. In these circumstances, the structure is generally out of service. Moreover, agents of use and exploitation are not simultaneous with climatic environmental agents, or else their compatibility values are insignificant.

Note *The following are regarded as extreme values: (1) those associated with a "reasonable" probability of occurrence in a given time interval;(2) those that are physically possible;(3) those that are statistically representative of the data; (4) those that are consistent with the initial hypotheses.*

4.5.2.3 Exceptional conditions (WOC_3)

These conditions are the set of project states associated with certain project factors that have the following: (1) very low probability of exceedance, always much lower than the probability of occurrence of the predominant project factor values that define extreme WOCs; (2) an unexpected or accidental occurrence; (3) an occurrence due to unforeseen reasons, use and exploitation, or exceptional work and operating conditions. The following exceptional conditions can be defined:

4.5.2.3.1 Unforeseen exceptional conditions ($WOC_{3,1}$)

These conditions include unforeseen conditions of the physical environment as well as accidental unforeseen conditions. These conditions should be specified in terms of extraordinary project factors and of a reduced number of simultaneous agents, limiting their values by compatibility criteria. The reduction of the number of simultaneous agents as well as the limiting of compatible values should be carried out according to the intrinsic nature of the maritime structure.

4.5.2.3.2 Unforeseen environmental conditions ($WOC_{3,1,1}$)

These conditions are the set of project states associated with the outcomes of marine dynamics, atmospheric dynamics,or other actions of the physical environment of an extraordinary, but foreseeable level. Given these conditions, partial failures of the maritime structure or one of its elements are possible.

4.5.2.3.3 Accidental unforeseen conditions ($WOC_{3,1,2}$)

These conditions include project states caused by an accident or incorrect use of the installation. Given these conditions, the structure may not be in service and partial failures in the structure or one of its elements may occur.

4.5.2.3.4 Exceptional foreseen conditions ($WOC_{3,2}$)

These conditions include project states caused by a use or exploitation necessity. Such project states are planned and under control, but may demand the reinforcement of the maritime structure or one of its elements. When this exceptional situation has disappeared, the structure and each of its elements should satisfy the safety, serviceability, and the use and exploitation requirements. Simultaneous agents and their compatibility values with the structure and the duration of the time interval in which the foreseen exceptional WOCs concur and can be specified in advance.

4.5.2.3.5 Specification of exceptional work and operating conditions

As long as present legislation does not stipulate otherwise, exceptional WOCs will be defined by the developer, according to the intrinsic nature of the structure, characteristics of the physical environment,and typology of the installations protected by the structure.

Note *Generally speaking, exceptional WOCs are produced by the presentation or consideration in the project of unusual and unforeseen project factors.*

4.6 Work and operating conditions and limit states

In each subset of the structure and for each project phase, the verification of the failure modes assigned to ultimate and serviceability limit states, and of the operational stoppage modes are carried out for a priori WOCs, according to the general and operational intrinsic nature of the maritime structure. (See Figure 4.5).

4.6.1 WOCs to verify

In each project phase it is necessary to verify the safety, serviceability, and use and exploitation of the subset for the WOC, marked with a "YES" in table 4.2:

Table 4.2: WOCs and limit states

Work and operating conditions		Limit states		
		Ultimate	Serviceability	Operational
Operational	Normal	Yes	Yes	Yes
	Post-extreme/exceptional	(2) and (5)	(1),(2) and (5)	(1) and (4)
Extreme		Yes	Yes	No
Exceptional	Unforeseen	(3)	(3)	No
	Foreseen	(3)	(3)	(2)

Table 4.2: Notes

1. *After the occurrence of extreme conditions, it is necessary to verify if the subset is functional and operational.*
2. *The operational conditions are those required by the exceptional situation foreseen.When these conditions are no longer present,the structure should satisfy normal and extreme WOCs.*
3. *During the occurrence of exceptional WOCs (WOC_3), it is necessary to verify that the damage levels specified in the project are not exceeded.*
4. *After the occurrence of exceptional WOCs, it is necessary to verify that the requirement of partial operationality specified in the project objectives are satisfied,and that the structure is functional against the failure modes assigned to the serviceability limit state of permanent damage.*
5. *After the occurrence of exceptional WOCs, it is necessary to verify that the structure is reliable against the failure modes assigned to the ultimate limit state of progressive collapse.*

4.6.2 WOCs and ultimate limit states

As a general rule, and unless expressly stated otherwise, apart from the recommendations in table 4.1 (section 4.6.1), it is necessary to verify that the maritime structure is safe against the failure modes of the ultimate limit states during the project phases and for the WOCs in table 4.3.

Table 4.3: WOCs and ultimate limit states

Work and operating conditions		Project Phase		
		Construction	During Useful Life	Repairs
Operational	Normal	Yes (1)	Yes	Yes (1) and (3)
	Post-extreme/exceptional	No	(2)	(3)
Extreme		Yes	Yes	(3)
Exceptional	Unforeseen	(4)	(4)	(3) and (4)
	Foreseen	(5)	(5)	(3) and (4)

Table 4.3: Notes

1. *Only when there is a partial starting up and for the verification of the elements that participate significantly in the processes of construction and repair.*
2. *When modifications of project factors are being considered*
3. *To be specified in the repairs and dismantling project*
4. *Only when exceptional conditions are defined*
5. *When foreseen exceptional conditions occur*

4.6.3 WOCs and serviceability limit states

Generally speaking, and unless expressly stated otherwise, apart from the recommendations in table 4.1 (section 4.6.1),it is necessary to verify that the structure is safe against the failure modes of the serviceability limit state during the project phases and for the WOCs given in table 4.4.

Table 4.4: WOCs and serviceability limit states

Work and operating conditions		Project Phase		
		Construction	During Useful Life	Repairs
Operational	Normal	Yes (1)	Yes	Yes (1) and (3)
	Post-extreme/exceptional	No	(2)	(3)
Extreme		(1)	Yes	(3)
Exceptional	Unforeseen	(4)	(4)	(3) and (4)
	Foreseen	(5)	(5)	(3) and (5)

Table 4.4: Notes

1. *Only when there is a partial starting up and for the verification of the elements that participate significantly in the processes of construction and repairs.*
2. *When modifications in the project factors are envisaged.*
3. *To be specified in the repairs or dismantling project.*
4. *Only when exceptional conditions are defined.*
5. *When foreseen exceptional conditions occur.*

4.6.4 WOCs and operational limit states

Generally speaking and unless expressly stated otherwise, the maritime structure should be in use and exploitation at least during it useful life in normal operational $WOCs_1$ (table 4.5). For reasons of use and exploitation,the structure can be in exploitation in other WOCs.In this case, such conditions should be specified in the project.

Table 4.5: Notes

1. *Only when there is a partial starting up and for the verification of the elements that participate significantly in the processes of construction and repair.*
2. *If it is required and specified in the project.*
3. *If it is required during the repairs and dismantling.*
4. *Only when exceptional conditions are defined.*
5. *When foreseen exceptional conditions occur.*

Table 4.5: WOCs and operational limit states

Work and operating conditions		Project Phase		
		Construction	During Useful Life	Repairs
Operational	Normal	Yes (1)	Yes	Yes (1) and (3)
	Post-extreme/exceptional	No	(4)	(3)
Extreme		No	(2)	(3)
Exceptional	Unforeseen	No	(4)	(3) and (4)
	Foreseen	(5)	(5)	(3) and (5)

4.7 Organization of factors and terms

In each subset of the structure and for all the verification methods applied, it is convenient to reduce the number of project factors which participate in terms of the verification equation. In the case of probabilistic methods,if the overall distribution function of the factors is known,the organization of the factors is implicit in the same method.

It is unfortunate that this function is rarely known,and thus, the organization a priori, of the project factors helps simplify the application of probabilistic verification methods.

In the case of deterministic verification methods,organization is extremely necessary and strongly recommended. Figure 4.5 offers a schematic outline of a sequence for the organization of factors and terms applicable to any verification method,and which is specified by means of the sequential selection of the project factors that can simultaneously participate in the occurrence of a failure mode.

Note *In the following sections, the organization criteria to be applied are specified for project factors as well as for the terms of the equation.They are applied to one group or the other, depending on the information and data. However, the organization by factors or by terms is not exclusive or redundant, but rather complementary.*

4.7.1 Organization schema

The project factors and the terms of the equation should be organized according to the following schema:

1. General project criteria: phase and WOC
2. Time interval and structural subset
3. Work method, limit state, and failure mode
4. Factors and term of the verification equation

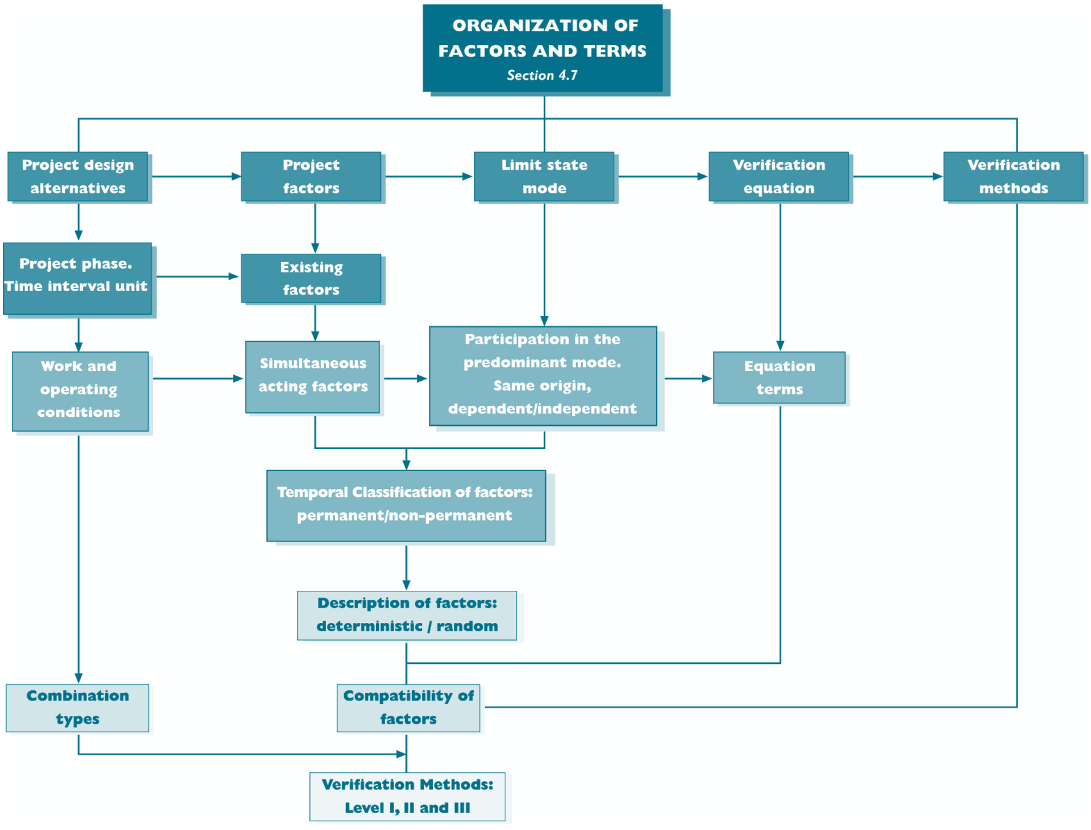


Figure 4.5: Organization of factors and equation terms

4.7.1.1 According to the work phase and condition

(2) This definition is complementary with the definition of non-significant factor. In this case the reasons for classifying a factor as acting are both physical and operational, irrespective of the failure mode analyzed and the predominant factor.

The project factors in a given phase can generally be classified, according to the physical and operational reasons,as existing or non-existing project factors[2]. Each of these categories can be subdivided in acting and non-acting project factors, depending on the WOCs being considered

Note *An earthquake can be regarded as a non-existing factor in maritime structures implemented on the Cantabrian coastline, whereas it should be considered an existing factor in structures on the coast of Almería. However, an earthquake can be declared non-acting in the project construction phase, due to the short duration of this phase, but at the same time be regarded as an existing factor in the useful life of the structure. Moreover, in normal operational WOCs, the earthquake can be considered an existing and non-acting factor. Nevertheless, this factor can be regarded as both an existing and acting factor in extreme WOCs.*

4.7.1.2 According to time interval

In each of the project phases, WOC, and time interval in which the structure and its elements are to be verified, the factors or terms are organized according to the following schema:

4.7.1.2.1 Simultaneous

Factors,which can coexist in a given time interval since there are no natural or operational causes or other reasons to make this impossible. Factors that act, appear together or interact in the same sense are said to be concurrent.

4.7.1.2.1.1 Permanent and non-permanent

Permanent and non permanent groups of factors are derived from the set of simultaneous factors or terms. The classification of a factor as permanent or non-permanent depends on its persistence during the time interval.

4.7.1.3 According to the limit state and mode

These factors or terms, taken from the set of existing, acting, simultaneous, permanent and non-permanent factors or terms for each limit state and mode, are defined according to their magnitude or the significance of their participation in the occurrence of the mode.

4.7.1.3.1 Predominant

Factors which have a determining effect on the occurrence of the mode, and thus, are decisive in the typology, spatial location, geometrical dimensions, shapes, and function of the structure or a subset of the same.

4.7.1.3.1.1 Factors related to the predominant factor

From the remaining factors, subgroups of factors or terms are defined, which have the same origin as the predominant factor, or are statistically or functionally dependent on it, as well as those which are independent. Within the latter group, subgroups of factors and terms are also defined, which have the same origin or are statistically or functionally interdependent, as well as those which are totally independent.

4.7.1.4 According to the verification equation

These subgroups are defined from the set of simultaneous and acting, permanent and non-permanent factors, according to their relative magnitude and their respective type of participation in the occurrence of the mode.

4.7.1.4.1 Non-significant factors in respect to the predominant

Factors are considered to be non-significant when their effect or variability of effect on the structures as a whole or one of its elements is barely perceptible, compared to the effect produced by the dominant factor.

Note *When the term of the verification equation in which a factor participates is less than "n %" of the magnitude of the predominant term, its effect is said to be non-significant. The value of n depends on the intrinsic nature of the maritime structure, the project phase, and the WOC involved. Its values are given in the specific Recommendations.*

4.7.1.4.2 Favorable and unfavorable factors

Of the sets of terms that can be present in the verification equation, those that prevent the occurrence of the failure mode are known as favorable terms, and those that promote its occurrence are known as unfavorable[3].

(3) The classification of the project factor or term as favorable or unfavorable is not absolute and can depend on the mode, limit state, WOC, as well as the project phase.

Note *In certain cases, a factor that normally is a project parameter simultaneously appears in both the set of favorable and unfavorable terms.*

Although factors and terms can belong to the subset of existing, simultaneous and acting, permanent and non-permanent, and favorable and unfavorable, their values in the verification equation should be compatible. The following sections develop criteria to specify the compatibility of factors and terms.

4.8 Compatibility of values

The values of the project factors and terms, their magnitude, and, when relevant, their direction, which co-exist either directly or indirectly in a verification equation, ought to be mutually compatible. Compatible values are those that are "in harmony" with others which simultaneously participate in the verification equation, and therefore during the occurrence of the failure mode. When the mode is verified by applying a deterministic method, it is necessary to regulate the compatibility of the values of factors and terms. In the probabilistic methods, the compatibility of values is a result of the method. However, in many cases, the terms of the verification equation contain deterministic and random factors. For this reason, the analysis of the compatibility of values is always convenient.

The compatibility is analyzed, taking into account the statistical class membership of the values of the terms defined in section 3.9 (lower tail, centered, and higher tail).

Once the organization of factors and terms that can intervene in a mode has been carried out, equivalences are established between statistical classes of the different terms.

4.8.1 Equivalence between classes

On the basis of the class membership of the predominant factor or term, the range of compatible values can be determined for each of the subsets in accordance with the following criteria.

For the subset of factors and terms of the same origin and which are functionally or statistically dependent on the predominant factor, the equivalent class is obtained by applying the functional or statistical relation to the set of possible values of the predominant term.

Regarding the equivalent class for the subset of factors and terms independent of the predominant factor, the compatibility is carried out based on its physical nature, chemical composition, construction process, etc. In any case, the equivalence between classes should be taken into account for all mutually dependent terms or factors, using one of these classes as a reference for the others, and determining their equivalents as described in the previous paragraph.

Such equivalences should be specified for each time interval and for all statistical descriptions: centered as well as maximum and minimum values.

4.8.1.1 Elimination of the equivalent class

Finally, for each of the equivalent classes obtained, it is necessary to eliminate the values that the factor or term cannot take because it is limited or prevented from doing so because of natural or operational causes, or other reasons.

4.8.2 Other statistical classes

If adequately justified, other statistical classes can be defined, in which simultaneous factors and terms that can participate in the occurrence of a mode are included. Once this new class is defined, its equivalence can be established with the predominant term, and its values delimited.

4.9 Combination of factors and terms

In a subset of the structure, a failure or stoppage mode can occur in any state and WOC during the project phase. Nevertheless, during the useful life of the maritime structure, the modes assigned to ultimate limit states are less probable during extreme and exceptional WOCs, while the modes assigned to serviceability and operational stoppage limits states have a greater possibility of occurring during normal WOCs.

It is not necessary to verify each and all of the project states that can happen during each of the project phases and WOCs, but only those for which the probability of occurrence is significant. The participation in the verification equation of the different factors and terms, as well as their respective values is established for certain combinations, which are specified in combination types that are formed by factors and terms which can simultaneously participate in the occurrence of a failure mode.

Note *The combination of factors and terms for the verification of a mode in a given time interval can be formulated deterministically according to Turksta's rule. The simplest way to establish the combination is generally by adding simultaneous terms without noting their probability of occurrence in the time interval, or the compatibility of their values. It can be assumed that the failure mode can occur because of the presentation of one of the two predominant and independent project factors (i = 1, 2) and that each one of them participates in the term $X_{2,i}$. As a result, the maximum value of term X_2, is:*

$$\max (X_2) = \max (X_{2,1}) + \max (X_{2,2})$$

This simplification can understandably produce overdesign structures. Consequently, a more reasonable result is the following:

$$\max (X_2) \approx \max [(\max X_{2,1} + X^*_{2,2}); (\max X_{2,2} + X^*_{2,1})]$$

In other words, the unfavorable term of the mode is selected from among the following values: (1) the maximum value associated with the predominant factor (i = 1), added to the value of the term associated with the predominant factor (i = 2), when the maximum value of the latter occurs; (2) the maximum value of the term associated with the predominant factor (i = 2) added to the predominant factor (i=1), when the maximum value of the latter occurs. This result can be generalized for n unfavorable terms.

$$\max (X_2) \approx \max [(\max X_{2,i} + \sum_{j=1}^{n} X^*_{2,j})],\ j \neq i;\ i = 1, ..., n$$

The difficulty now lies in determining the maximum value of $X_{2,i}$ *and its concurrent values,* $X^*_{2,j}$, *which depend on the verification method. In the Level I deterministic method (e.g. partial coefficients method), the maximum value is generally the characteristic value associated to the quantile of 95%, while* *the accompanying values depend on the combinations types as established in the following sections.*

By applying probabilistic verification methods (i.e. Level II and III), the combination of term values which supplies, at least in theory, the worst failure probability, can be obtained. In practice, however, either because of the lack of statistical data or because of the difficulty and complexity of the calculation involved, the number of states to be verified should be reduced. This is done by previously defining certain combination types. In any case, it is advisable to follow the method outlined in section 4.7 to establish the compatibility of factors and terms.

4.9.1 Combination types

(4) *These classifications mean exactly what their name implies:* habitual *is what is done by habit, use or custom;* quasi-permanent *is something that is so frequent as to be almost permanent;* frequent *is something that is often repeated; and* improbable *is something that is unlikely.*

Three types of combination of factors and terms can be defined: improbable or fundamental, frequent, and quasi-permanent or habitual[4] (See Figure 4.6).

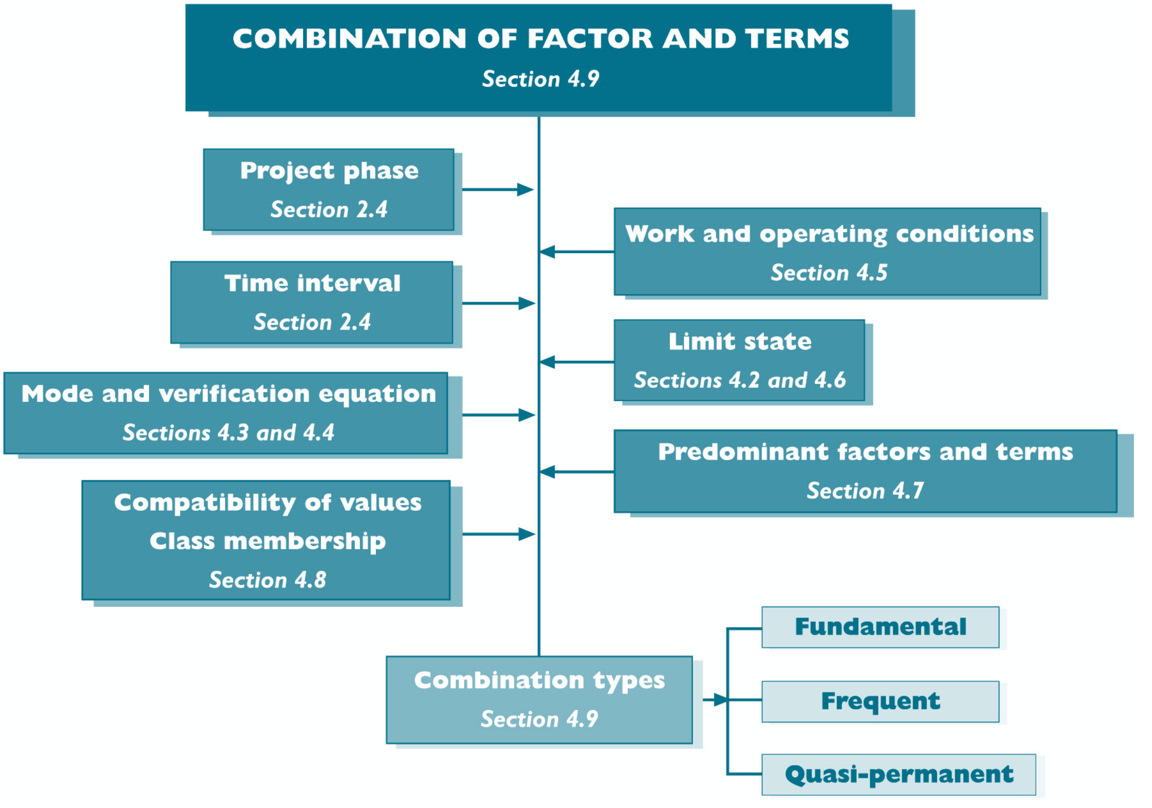


Figure 4.6: Combination of factors and equation terms

4.9.1.1 Improbable or fundamental combinations

These combinations describe the occurrence of predominant project factors or terms, whose range of values belongs to the upper tail (or in some cases to the lower tail), combined with the occurrence of other factors or terms belonging to the centered class and the lower tail. Consequently, few factors or terms participate in this combination type, apart from the predominant factor and those dependent on it, with values belonging to the centered class, and rarely to the lower tail.

4.9.1.2 Frequent combinations

These combinations describe the occurrence of predominant project factors or terms with values corresponding to the centered class, combined with other factors and terms, some of which are of the lower tail, and various of the centered class. Given that the predominant values belong to the centered class,this type increases the number of simultaneous and compatible project factors and terms that participate in the verification of the mode. This combination is applied in those cases in which there are factors and terms with operational thresholds.

4.9.1.3 Quasi-permanent or habitual combinations

These combinations describe the occurrence of predominant project factors with centered values, combined with project factor and term values,some of the centered class and others of the lower tail.The objective here is to use this type of combination to substantially increase the number of factors and terms that participate in the verification. None of them have values of the upper tail.

Note *The names of these combination types are different from those used in the ROM 0.2 and in the Spanish* Instrucción de Hormigón Estructural *(EHE). In the former, the three combination types are called serviceability limit states. In contrast, in the EHE, the classification names proposed for serviceability limit states are improbable, frequent, and quasi-permanent.This ROM adds the classification name fundamental, for those combinations that are highly unlikely, improbable or infrequent, and habitual to the quasi-permanent combination types.Whatever their name, the three combination types have a similar context of application, at least for the verification of the serviceability limit states. However, there is no reason that the same combination types cannot be applied to verify ultimate limit states and operational stoppage limit states.The use of one type of application for all of these states should have the benefit of making the combinations of terms and factors in the verification of a design alternative more homogeneous, and therefore more comparable.*

4.9.2 Sequence to construct a combination type

Once a project phase and a limit state is defined, the mode assigned to it is verified for different combination types of factors and terms.These combination types can be mapped out by identifying the following.

1. Predominant factors and factors of the same origin, and dependent on the predominant
2. Independent factors
3. Classification of (1) and (2) in permanent and non-permanent factors and extraordinary and unexpected factors (when they exist)
4. Classification of (3) in favorable and unfavorable

For each predominant factor, i, the WOCs are verified, whether they be operational $WOCs_1$, extreme $WOCs_2$, or exceptional $WOCs_3$, (when such conditions exist). For each of these categories, the following combinations are also considered:(1) fundamental;(2) frequent;(3) quasi-permanent. In this way, to each project phase, limit state, and failure mode, it is possible to assign the combination types represented by the following sets of three numbers: (i, WOC_1,1), (i, WOC_1, 2), (i, WOC_1, 3), (i, WOC_2, 1), (i, WOC_2, 2), (i, WOC_2,3), and if relevant, (i, WOC_3,1), (i, WOC_3,2), (i, WOC_3,3).The letter i represents the predominant term and the two other elements indicate the WOCs, and the combination types. If sufficiently justified, some of these sets or combination types may not be verified.

Note *Some of these combinations are very rare. This is the case for (i, WOC_2, 3), (i, WOC_3, 2), (i, WOC_3, 3) and, thus, they will normally not be considered.*

As a general rule, following the ROM 0.2-90, section 4.2.2, combination types of more than two terms due to agents of use and exploitation and more than two terms due to environmental agents will not be jointly worked out.

4.9.3 Combination types to consider

In reference to the construction and useful life project phases and the ultimate, serviceability, and operational stoppage limit states, the following combinations types should be taken into account:

4.9.3.1 Combination (i, WOC_1, 1)

This combination type considers the failure mode against the threshold values of the terms of the physical environment, which are generally compatible with other terms (e.g. use and exploitation) that can be predominant. Generally speaking, this hypothesis is applied to modes assigned to ultimate limit states. When applied to WOCs, it verifies the mode against the presentation of maximum values of the terms of use and exploitation. These values depend on the exploitation regime. The threshold values of the terms are generally associated with infrequent, but not extreme occurrences. For this reason, their determination should be carried out based on the class of centered values.

4.9.3.2 Combination (i, WOC_2, 1)

This combination type considers the presence of various simultaneous and independent terms in relation to other simultaneous terms. When applied to extreme WOCs, it verifies the mode against the presentation of the maximum values of predominant terms. Generally speaking, this hypothesis is applied to the modes assigned to ultimate limit states. The values of the terms or predominant factors belongs the class of values of the upper tail (or sometimes, to those of the lower tail).

4.9.3.3 Combination (i, WOC_3, 1)

This combination type considers terms associated with the extraordinary or unexpected factor. When applied to exceptional WOCs, it verifies the mode against the presentation of extraordinary values of the predominant factor, simultaneously with other terms, which can be considered as belonging to the centered class or to the lower tail, depending on the duration and the duration of the exceptional project state. The extraordinary values of the factors and terms usually belong to the upper tail.

4.9.3.4 Combination (i, WOC_2, 2) and (i, WOC_1, 3)

This combination type considers various factors and terms of different origin. When applied to WOCs, it verifies the mode against the presentation of centered values of terms of use and exploitation that depend on the exploitation regime, with threshold values of the terms associated with factors of the physical environment. This hypothesis is generally applied to modes assigned to the serviceability and operational limit states.

Note *Combination types should be regarded as guidelines to simultaneously define project factors and terms that can participate in the different project states and their compatible values. In the partial coefficients method, the hypothesis of combination is part of the method, since the terms of the equation are affected* *by a compatibility coefficient. In this way, this method tries to make compatible the ranges of values assigned to the project factors that participate in the different terms.*

In probabilistic verification methods, if there is a joint distribution function of the project factors, it will not be necessary to establish combination types. This situation is far from being a reality since, in the best of cases, what is available is the joint distribution function of certain terms, the marginal distribution function of others, and the nominal values of others. In such cases, the combination types can help to verify a failure mode and evaluate the probability of failure. Similarly to a deterministic approach,it is possible and convenient to establish the simultaneity and compatibility of project factors.

4.10 Verification and methods

These Recommendations propose the following verification and calculation methods to verify the maritime structure against a failure mode assigned to an ultimate or serviceability limit state, and a stoppage mode assigned to an operational stoppage limit state (see Figure 4.7):

- Level I Methods
  1. Global safety coefficient [1]
  2. Partial coefficients [2]

- Level II and III Methods
  3. Statistical moments and optimization techniques, Level II [3]
  4. Integration and numerical simulation, Level III,[4]

4.10.1 Level I Methods, [1] and [2]

These include the global safety coefficient method [1] and the partial coefficients method [2]. In both methods, project factors and the values of the terms in the verification equation are usually specified by deterministic criteria.

In the partial coefficients method, the terms of the equation are multiplied by coefficients that weigh their simultaneity and compatibility, as well as the favorable or unfavorable participation in the occurrence of the mode.

In the global safety coefficient method,the favorable and unfavorable terms are not affected by any weighting coefficient,though they should be affected by compatibility coefficients.The safety coefficient is where all the aspects related with the uncertainty of the verification process are concentrated, except the uncertainty associated with the combination type.

However, at least in the context of maritime structures, the determination of the values of the agents of the physical environment should be carried out as much as possible by means of probabilistic criteria.

Note *The word deterministic should be understood in the sense that the project factors and the results are essentially treated as deterministic variables. However, this does not mean that there are no factors that are treated as random variables (e.g. the compression and tensile resistance of concrete, the wave height and period,the wind speed, etc.*

4.10.1.1 Evaluation of failure criteria

A project design alternative is considered to fulfill the project requisites against a failure mode in a given time interval, when safety coefficient,Z exceeds a minimum value, Z_c, which is given in the specific Recommendations,and in the case of the partial coefficients method,when the safety margin satisfies S > 0.

4.10.1.2 Result of the application of Level I Methods

The result of the application of Level I Verification Methods is a value indicating the behavior of the subset against the mode.

4.10.2 Level II Methods, [3]

The verification equation is formulated in terms of the safety margin. To apply this method, it is necessary to know for the time interval the distribution and covariance function (or establish a work hypothesis regarding them, particularly in reference to the statistical independence of the verification equation).The verification equation is defined according to the first-order statistical moments, and functional transformations. It is formulated in terms of reduced and independent Gaussian variables.

In this system of variables,the probability of failure is associated with the minimum distance of the origin of the coordinates in relation the failure surface, G = 0, which is a verification equation in the safety margin format. For this reason, the result is generally approximate.

4.10.2.1 Evaluation of failure criteria

The verification equation is of the safety margin type. Thus, the subset generally fulfills the project requirements against the mode when S > 0.

4.10.2.2 Result of the application of the Level II Verification Method

The result of the application of a Level II Method is the value of the terms and the project factors and the probability of failure against the mode.

4.10.3 Level III Verification Methods, [4]

To apply a Level III procedure it is necessary to know the joint distribution functions of the project factors that participate in the terms of the equation within the time interval.The solution is obtained by integrating a multidimensional function in the failure domain.This integration is generally a complex task.Thus, the probability of failure and the values of the project factors can be obtained by means of numerical simulation techniques (e.g. Monte Carlo).

4.10.3.1 Failure criteria

The verification equation is generally of the safety margin type. As a result,the project situation is regarded as verified against the mode when S > 0.

4.10.3.2 Result of the application of the Level III Verification Method

The result of the application of a Level III Method is the distribution function of the safety margin of the subset in the time interval. When this function is integrated in the failure domain, $S \leq 0$, the probability of failure of the subset against the mode is obtained.

4.10.4 Verification method and intrinsic nature of the subset

In Table 4.6, the following methods are recommended to verify the safety, serviceability, and use and exploitation requirements of a project design alternative against a failure or operational stoppage mode, according to the general intrinsic nature of the subset of the maritime structure.

In the following chapters these methods are described and their application in the context of maritime structures is developed.

Table 4.6: Verification method recommended in accordance with the intrinsic nature of the subset of the structure

	SERI			
ERI	s_1	s_2	s_3	s_4
r_1	[1]	[2]	[2] and [3] or [4]	[2] and [3] or [4]
r_2	[2]	[2]	[2] and [3] or [4]	[2] and [3] or [4]
r_3	[2] and [3] or [4]	[2] and [3] or [4]	[2] and [3] or [4]	[2] and [3] or [4]

Note *The global safety coefficient method is perhaps the most well known method, but it is also less precise in the evaluation of factors and terms, which is in many cases, associated with lack of information. At higher levels in the classification, more precise and probably more accurate results can be obtained, but there is also less experience in the application of the method. As a result, the method recommended in the table should be understood as the minimum to be used. However, if sufficient information is available and the engineer is experienced in its application, the structure might be verified by a method of a higher level.*

In those cases in which the application of two methods leads to contradictory results, it is advisable to opt for the result that is most in consonance with accumulated experience and available data.

4.10.4.1 Structures with a high general intrinsic nature

The structures whose general intrinsic nature is $[r_3, \geq s_1]$ and $[\geq r_1, \geq s_3]$, should be verified at least by the partial coefficients method as well as another of a higher level.

Note *The difficulties regarding the verification by the partial coefficients method of maritime structures subject to the actions of random predominant factors are due to the fact that weighting and compatibility coefficients were not initially defined by this format. For this reason, specific Recommendations propose duly contrasted weighting and compatibility coefficients.*

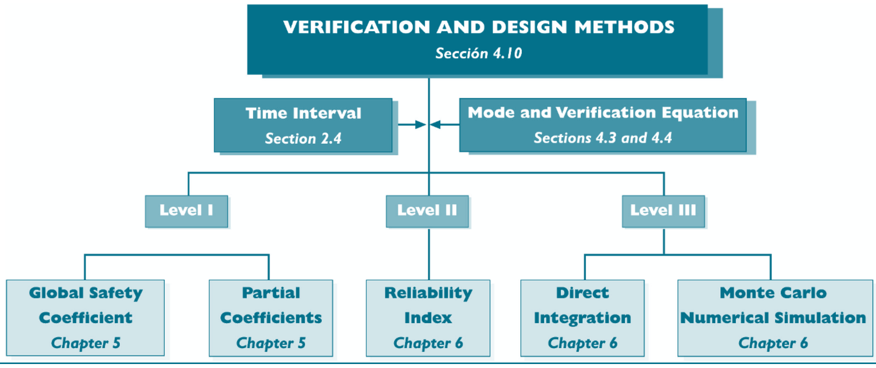


Figure 4.7: Verification Methods in the ROM program.

4.11 Probability and useful life

The calculation procedure ought to verify that the subset will satisfy the safety and serviceability requirements in its useful life. It should have an overall probability of failure that does not exceed the values given in Tables 2.3 and 2.4, according to the general intrinsic nature of the subset, and which satisfies the use and exploitation requirements with an operationality level higher than the value in table 2.5, according to the operational intrinsic nature of the subset.

Note *In these Recommendations,* mode *refers to the occurrence of a failure (in structure or shape) assigned to one of the ultimate or serviceability limit states and the occurrence of an operational stoppage assigned to one of the operational limit states. "Probability of occurrence or presentation of the mode" in the time interval refers to the probability of failure as well as the probability of operational stoppage.*

4.11.1 Probability and time interval

The evaluation of the probability of the failure against a mode in the useful life phase depends on the verification method and on the format of the verification equation. This equation is expressed according to the state variables, and thus, the probability of failure or stoppage of the subset against the mode depends on the temporal evolution of the values of the terms. As a result, it is necessary to know the probability models that permit the quantification of the uncertainty of the terms in the project phase. This information is generally not available. The definition of the time interval unit is of use in attaining this objective.

4.11.2 Time interval unit

Period of time in which it is possible to know or infer the probability model of the state descriptors of the project factors and the terms of the equation. The duration of the interval unit is usually associated with climatic variability or the economic criteria and exploitation. The time intervals and useful life can be assumed to be sequences of the time unit intervals. Any of the time intervals defined in section 2.4 can act as a time interval unit.

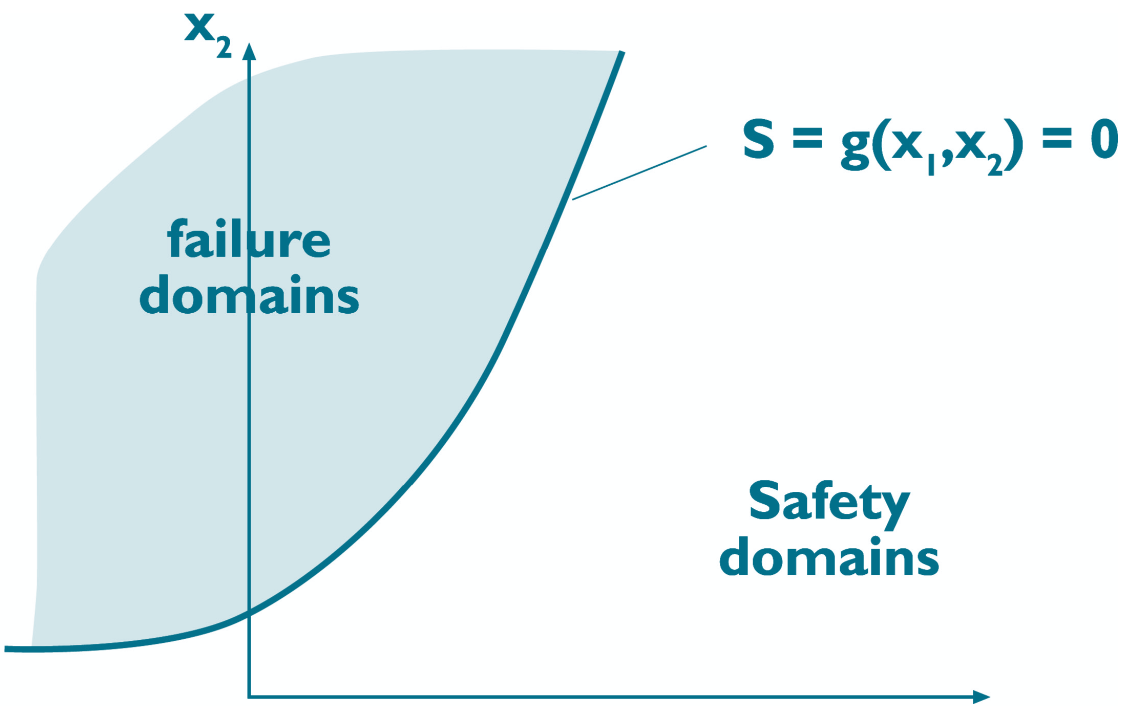
Note *The useful life can usually be defined in years, and knowing the annual variability of the climate on the Spanish coast, the year can be the time interval unit. Useful life is thus defined in V time interval units or years. Assuming the statistical independence between successive years, it is possible to calculate the probability of the subset against the mode during the useful life of the structure.*

4.11.3 Safety and failure domains

The verification equation is resolved in the time interval unit. The safety and failure domains (see Figure 4.8) are the sets of project states. for which the verification equation takes values that are respectively higher or lower than a certain threshold value. If the verification equation is the safety margin type, i.e. $S = X_1 - X_2$, where W is the safety margin and X_1 and X_2 are the sets of favorable and unfavorable terms, then the safety domain is $S > 0$. The failure domain is formed by project states for which $S \leq 0$. If the equation is the global safety coefficient type, the safety domain is $Z > Z_c$. The failure domain is defined by $Z \leq Z_c$, where Z_c is the minimum global coefficient for the mode.

Note *The words* safety *and* failure *should be understood in their widest sense, and as a reference to the fulfillment or failure to fulfill requirements regarding safety, serviceability, and use and exploitation.*

Figure 4.8: Definition of safety and failure domains.



CHAPTER 5
Level I Verification Methods

5 LEVEL I VERIFICATION METHODS

5.1 Introduction

Verification methods are used to check when and in what way a subset of a structure no longer meets project requirements, due to the occurrence of a failure or operational stoppage mode assigned to limit states and subject to a WOC that can arise during a given project phase. A verification equation represents and quantifies the occurrence of the mode. The verification methods described in this chapter are known as Level I Methods, which encompass the global safety coefficient method as well as the partial coefficients method.

Once the project phase, limit state, WOC, and combination type have been selected, term values and the results of the verification equation can be obtained by following the work sequence described for each of these two methods.

However, these methods do not supply information regarding the probability of project requirements. The calculation of this probability could be carried out independently, and should take into account the probability of the presentation of the predominant project factor in the occurrence of the mode.

Chapter 6 describes Level II and Level III Verification Methods. These methods, beside verifying the subset against the mode, provide under certain conditions, the probability of failure.

5.1.1 Contents of Chapter 5

The present chapter begins by describing the global safety coefficient method, one of the most frequently used in civil engineering. This is followed by a description of the partial coefficients method, applied in the ROM 0.2-90, in the Spanish Regulations for concrete, *Instrucción de Hormigón Estructural* (EHE) and in many other Standards and Regulations. Figure 5.1 provides a schematic outline of the organization and contents of this chapter.

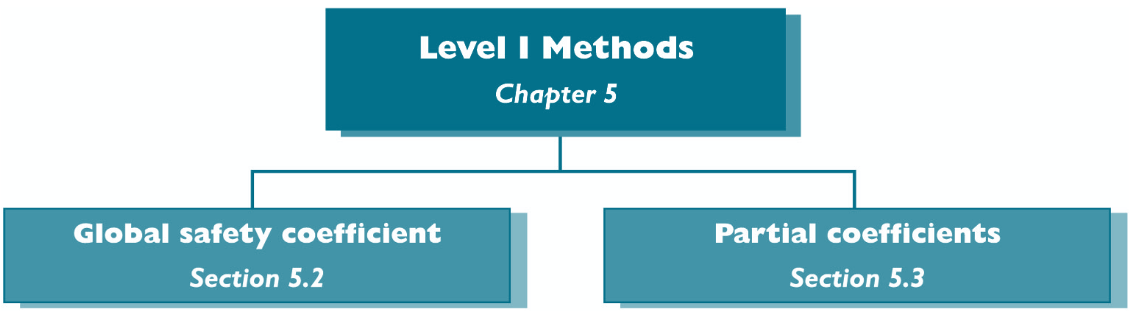


Figure 5.1: Chapter 5. Organization and contents.

5.2 Global safety coefficient method

This verification method is applied when the subset of the structure has a low intrinsic nature $[r_I, s_I]$ or when the scope of the work carried out belongs to a preliminary study. The sequence used in the application of this verification method is the one given in figure 5.2:

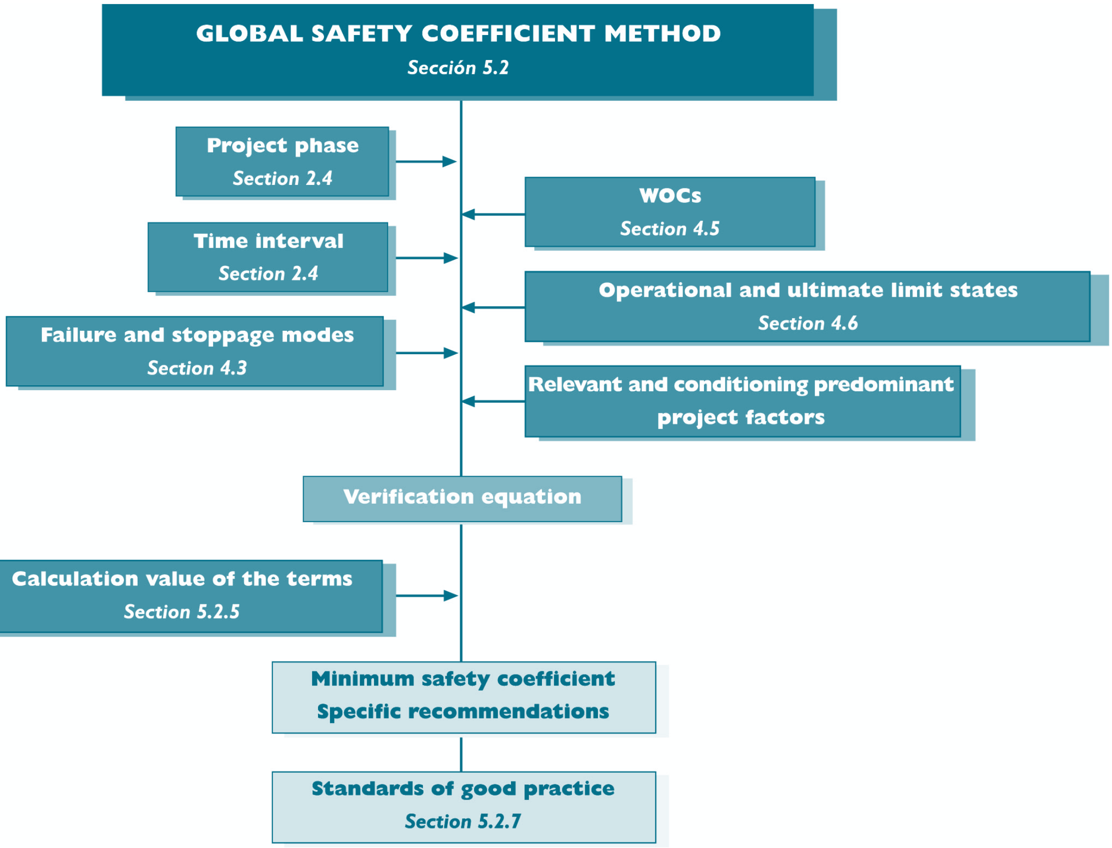


Figure 5.2: Application sequence of the global coefficient method.

5.2.1 Definitions

The verification equation is evaluated through the global safety coefficient method, and this result is compared with a given coefficient (Z_c), known as the global safety coefficient.

5.2.1.1 Verification equation

The format of this equation is of the safety coefficient type $Z = X_1/X_2$, The numerator generally contains favorable terms that prevent the occurrence of the mode, while the denominator contains unfavorable terms. X_1 and X_2 can be combinations of various terms.

5.2.1.1.1 Verification condition

It is generally accepted that the failure or operational stoppage mode will not occur when $Z \geq Z_c$ is fulfilled, where Z_c is a minimum acceptable value called the global safety coefficient.

The value of the coefficient Z_c is the means by which uncertainty (both known and unknown) associated with the calculation process, availability of data,validity of the equation, etc. should be evaluated. Experience has sanctioned minimum safety coefficient values for certain typical failure modes. Some of these can be found in technical regulations, guides, and recommendations.

Note *The term of the equation generally represents the action of a project factor (e.g.an agent, and can be a force, load, movement, etc.). Sometimes a favorable or unfavorable term represents the action of more than one factor, including agents and parameters.*

In this method all deterministic terms are usually considered, though there are other options for the cases in which certain factors or terms are random.Among such alternatives are the centered and characteristic safety coefficients. These coefficients can be useful in the verification of modes, whose occurrence exclusively depends on terms that have a probability model. Nonetheless, when this information is available, it is advisable to apply Level II and III Verification Methods.

$$Z_E = \frac{E[X_1]}{E[X_2]}$$

where $E[X_1]$ and $E[X_2]$, respectively represent the average values of the favorable and unfavorable terms[1]. In all cases, this centered value should be equal or superior to the value recommended for each typology of the maritime structure. The characteristic safety coefficient Z_k is:

$$Z_k = \frac{X_{1,k}}{X_{2,k}}$$

where, $X_{1,k}$, and $X_{2,k}$ are respectively the characteristic values of the favorable and unfavorable terms[2].

When they are defined on the basis of a mean value, μ, and its variation coefficient C_v, favorable terms are expressed by their lower characteristic value, while unfavorable terms are expressed by their upper characteristic value in such a way that the characteristic safety coefficient is expressed by:

$$Z_k = \frac{\mu_{x1}\,(1-k_{x1}\,V_{x1})}{\mu_{x2}\,(1-k_{x2}\,V_{x2})}$$

In this equation the upper and lower extremes of the confidence intervals are associated with the quantile values of 95% and 5%, respectively.

(1) Z_E is a useful approximation to the safety coefficient. This centered coefficient is generally different from the mean value of the coefficient of X_1 and X_2, $E[X_1/X_2] \neq E[X_1]/E[X_2]$.

(2) Analogously, the characteristic value of the quotient is not equal to the quotient of characteristic values

5.2.1.1.2 Equation format

The verification equation of the principal modes and the minimum safety coefficients are given in the specific Recommendations. Its application should generally follow the sequence described in the following sections to determine the factors and terms.

Alternatively, if a verification equation is applied that was originally obtained with the global safety coefficient, the same criteria and hypotheses with which it was proposed should be respected, particularly those aspects referring to the dimensional units of the terms.

If the verification equation to be applied was not originally obtained with this format, and no information is available concerning the order of magnitude of the value of the coefficient, a Level II or III Verification Method should be used to obtain this value in accordance with section 6.10.

5.2.1.2 Principal verification mode

Types of mode that experience has shown to be the most important and demanding from a structural and operational viewpoint.As a result,they can be said to constrain the typology of the subset and are described in the specific Recommendations.The occurrence of any of these modes causes the failure or stoppage of the subset of the structure with the resulting economic, social, and environmental repercussions, which can be classified by means of economic, social, and environmental repercussion indices, such as the ERI, SERI, OIER,and OISER.

The principal modes assigned to ultimate, serviceability, and use and exploitation limit states are those considered in the evaluation of the overall probability of failure during the useful life of the maritime structure.

Note *The dock of Levante in the Puerto de Almería (Harbor in Almería, Spain) is made of concrete blocks. It is a dock for passenger vessels. One of the project objectives is to verify that the structure as a whole and each of its elements do not incur in any of the principal failure modes. For ultimate limit states, the principal modes are sliding between the rows of concrete blocks and berm, overturning as a rigid body, total loss of global stability, loss of soil-bearing capacity, and liquefaction under seismic action.The occurrence of some of them have economic, social, and environmental repercussions which, evaluated in accordance with section 2.8, give the dock a general intrinsic nature within the interval of $6 < ERI \leq 20$; $5 \leq SERI < 20$.*

Furthermore, any element of the dock, such as the bollards and fenders, can fail, but this occurrence does not have significant consequences for the reliability, functionality, and operationality of the subset of the structure. For this reason, this type of failure is not considered to be principal, and although the probability of such an occurrence in the useful life of the structure should be specified and delimited, it does not enter into the calculation of the overall probability of the subset (see Chapter 7).

5.2.1.3 Project factors

The application of the global safety coefficient method is based on the following project factors:

5.2.1.3.1 Predominant factor in the mode

Any factor whose occurrence triggers the occurrence of the mode.

5.2.1.3.2 Relevant factors of the term

Factors which: (1) characterize the response, the geometry of the structure and the properties of the physical environment, as well as the soil, and its materials; (2) give meaning to and justify the presence of the term in the verification equation; (3) are usually the most influential[3] in the value of the term.

(3) Influential refers to the effects of the project factor on the absolute value and variability of the term.

5.2.1.3.3 Conditioning and conditioned factors

Factors that do not directly participate in any term of the verification equation, but can condition the value of other factor or factors, and thus, the value of the term in which they participate.The factors thus affected are known as conditioned factors, and their values should be compatible with the values of the conditioning factors. If the conditioned factor is predominant in the mode, the conditioning factor should be treated as predominant.

Note *The subset of the structure is often found in shallow waters, where the wave height is generally delimited by the depth.This may not explicitly appear in the verification equation,as for example, in the Iribarren* *formula for the calculation of the weight of main layer units. To verify this weight, the value of the depth should be chosen as though it were a predominant factor, and thus, as belonging to the upper tail of the distribution function. The sea water depth is regarded as a conditioning project factor and wave height (H) is the conditioned factor.*

5.2.2 Limit states, work and operational conditions, and combination types

Generally speaking, the global safety coefficient method can be applied to verify the modes assigned to ultimate and operational limit states.

Unless expressly stated otherwise, in each project phase, extreme WOCs and all limit states are verified, according to section 4.6.2 by applying the combination types in section 4.9.

Note *This method can also be applied to serviceability limit states, though in the majority of cases, the verification equations of the failure modes assigned to these states are in the safety margin format, which implies previously transforming the equation to that format (see section 6.5). When relevant, and with due justification, this method can be applied to exceptional WOCs.*

5.2.3 Factor and term values

The value of factors and terms is generally determined by considering the same hypotheses and criteria with which the verification equation to be applied was obtained. In the majority of cases, each term of the verification equation is a mathematical expression of the project factors, quantified by its nominal values.

5.2.4 Project factor values

To determine these values, it is advisable to follow the recommendations in Sections 3.7, 3.8 and 3.9. Furthermore, the following subsections concern factors of the physical environment and soil as well as conditioning factors.

5.2.4.1 Value of factors of the physical environment

In the absence of specific regulations or statistically representative data, factors of the physical environment, parameters, and agents are represented by a nominal value or a mean value. Alternatively, it is possible to define upper and lower characteristic values of the factors of the physical environment based on their distribution function.

5.2.4.1.1 Value of the conditioning factor

To obtain the representative value and design value of the conditioning factor, it should be treated in the same way as the term and factor/s conditioned by it.

5.2.5 Value of the terms of the equation

This value is determined according to the recommendations in section 3.10. Generally speaking, the value of favorable and unfavorable, permanent and no-permanent terms is nominal.

5.2.5.1 Value of the favorable and unfavorable terms of the physical environment

When the agents of the physical environment are obtained on the basis of a probability model, upper and lower characteristic values can be defined. In all cases,the value of the term associated with agents of the physical environment depends on the favorable or unfavorable sense of its participation in the verification equation.

5.2.5.2 Value of the terms controlled by soil resistance capacity

Generally speaking, and in the absence of specific regulations or statistically representative data, the properties of the soil are represented by nominal or average values.These values are determined according to the specifications in the ROM 0.5, or in other specific Recommendations, Standards, and Regulations. In all cases, the criteria with which the applied formulation was obtained should be strictly observed.

5.2.5.3 Value of the permanent terms[4]

(4) For the definition of permanent term, *see section 4.4.1.2*

When the permanent term is the weight of the structural elements, it has only one value, which is defined by the nominal value and calculated from the geometrical dimensions of the element and the average specific weight of the materials.

When the permanent term represents the materials' non-structural weight, maximum and minimum nominal values are determined, which can be upper and lower characteristic values.

The permanent values, whose maximum and minimum values do not differ in more than 5%, can have a nominal value that is equal to the average value of the two nominal values.

5.2.6 Design value of the terms

Value applied in the evaluation of the verification equation.The design value of each term is obtained by multiplying its nominal value by the compatibility coefficient.The determination of the value of this coefficient is carried out,using the same criteria as for the partial coefficients method (see sections 5.3.6.1 and following ones).

The uncertainties of the project, with the exception of those associated with the compatibility and combination of terms, are quantified by means of the minimum value of the global safety coefficient (Z_c).The greater these uncertainties are, the greater the value of the safety coefficient.

5.2.6.1 Reducing coefficient applied to mechanical properties

(5) The reduction coefficient multiplies the value of the mechanical property. For this reason, $c_r \leq 1$.

The values of the project parameters that express mechanical properties of the material, and which appear in unfavorable terms, are reduced by means of the reducing coefficient[5] (c_r).As a general guide, the value of the corresponding coefficient is that specified in tables 5.6 and 5.7, observing the given limitations in their application.

5.2.7 Standards of good practice and conditions of application

When the verification of the mode is carried out, applying the global safety coefficient method, it is necessary to bear in mind its limitations, above all, the criteria with which the values of the factors and the terms are determined. For this reason, when applying the global safety coefficient, it is also necessary to consider the standards that for years have regulated its use. Furthermore, during both the project and the construction phase, its utilization should be accompanied by standards of good practice, which should be scrupulously observed.

5.2.8 Summary of the global safety coefficient method

The following is a summary of the most important criteria in the application of the global safety method in the verification of the failure and operational stoppage modes:

- This method is applied to the structure or small subsets of the structure $[r_l, s_l]$ or in previous studies and analysis.
- It can be applied in the verification of all modes of ultimate and serviceability limit states,and of operational stoppage states.
- In all cases,it is necessary to verify types of term combinations corresponding to operational and extreme WOCs (see section 4.6), and when applicable, those corresponding to exceptional WOCs as well.
- The minimum acceptable safety coefficients are those recommended in the specific ROM for each typology, mode, WOC, limit state, and combination type.
- The terms take nominal values. In the case of agents of the physical environment, the value of the term can be determined based on the predominant agent's probability of exceedance.
- The terms of the verification equation are taken into consideration and the value is determined, strictly following the criteria with which the verification equation was established.
- The term compatibility coefficients are adjusted to comply with the recommendations regarding the partial coefficients method.
- The properties of the building materials used should be adjusted to comply with current regulations.When no such regulations exist, the nominal value should be used.The mechanical properties are reduced by means of a reducing coefficient, c_r.
- It is advisable to scrupulously follow standards of good practice in the project and during the construction process.
- This method should not be applied without sufficient experience or in those situations that are clearly an extrapolation of the state of the art.

Note *The verification of a vertical dike against the ultimate limit state, loss of static equilibrium, has three principal failure modes: sliding and overturning as a rigid body and plastic overturning.When the purpose for the dike is the creation of a protected zone, one of the predominant agents is the wind waves. If the dike is built in water deep enough to guarantee that no wave breaks and with sufficient freeboard to avoid overtopping,the incident waves are reflected in the dike and the interference of the incident and reflected wave trains produces standing waves. Such waves produce horizontal pressures on the front wall,and subpressures or vertical pressures on the foundation of the dike which, once integrated horizontally and ver-*

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tically, provide the horizontal force (FH) and the vertical force (FV) upon the dike. Generally, the maximum and minimum values of the horizontal force on the front wall of the dike are produced beneath the crest and through the standing wave, respectively.

One of the most widely used laws of horizontal and vertical pressure was proposed by Goda in 1973, and ever since, it has been generally used in Japan, though with certain modifications, for the calculation of vertical dikes. Pressure laws depend on the wave height with the participation of a range of different coefficients, which take into account the period of the waves, the oblique incidence of the incident sea swell, the depth on the berm, the height of the crown of the dike, etc.

Following the determination of the pressure laws, failure modes, sliding, and overturning as a rigid body can be verified by applying the global safety coefficient method with the practical criteria with which it was originally proposed. These are the following:

Global safety coefficient against sliding:

$$Z_{d,c} = \frac{\mu\,(Mg - F_V)}{F_H} = \frac{X_1}{X_2}$$

Global safety coefficient against overturning as a rigid body:

$$Z_{c,v} = \frac{Mgs - M_V}{M_H} = \frac{M_1}{M_2}$$

In both, M is the mass of the vertical dike per unit length at the still water level; μ, is the friction coefficient between the dike and its foundation; s is the horizontal distance between the center of gravity of the dike and the point of rotation; g is the gravitational acceleration; and M_H and M_V are the exterior moments of the horizontal and vertical forces, respectively; X_1 and X_2 and M_1 and M_2 are the favorable and unfavorable terms of the verification equation of the sliding mode and the overturning mode as a rigid body, which are applied with a weighting coefficient equal to the unit a recommended in the global safety coefficient method. Since the waves are the only predominant agents and no other agents are taken into consideration, it is not necessary to consider the term compatibility coefficients.

Horizontal and vertical forces should be calculated with a wave height $H_{mx} = 1.8\ H_s$, where H_s, is the significant wave height of the "design" sea state. The value 1.8, which multiplies the significant wave height, though it has a statistical basis, is really adopted as the result of experience. Consequently, the wave height, H_{mx}, can be said to be defined by an estimated "nominal" value with a statistical basis. It can be shown that the most probable value or mode of the maximum wave height in a sea state with N waves is approximately $H_{mx} \cong (0.706\sqrt{\ln N})H_s$ *; if* $N \cong 750$ *waves,* $0.706\sqrt{\ln N} \cong 1.8$.

According to the method, the period associated with the calculated wave height is the significant period, i.e. $T_{mx} = T_s$*. This decision has a statistical basis, since the largest waves of the sea state have on average a period equal to the significant period. However, there are large waves in the sea state that can occur with greater or lesser periods than the significant period.*

Furthermore, the nominal value of the friction coefficient is normally μ = 0.6, and the emerged and submerged calculation of the weights of the dike is carried out by adopting specific average weights (e.g. 2300 kg/m^3 for the crown reinforced concrete, 2100 and 1100 kg/m^3 for the caisson reinforced concrete filled with sand, emerged and submerged respectively, and 1030 kg/m^3 for the sea water. Finally, the crown will be topped at a height of 0.6 H_s, over the design still water, and the height over the bottom and width of the berm will be such that the waves will not break.

Having adopted these criteria, the value of the global safety coefficients to the sliding and the overturning will not be less than 1.2, or more specifically, $Z_{c,d} > 1.2$ *y* $Z_{c,v} > 1.2$.

5.3 Partial coefficients method

The partial coefficients method is recommended for the verification of the failure and operational stoppage modes of the maritime structures, whose general intrinsic nature lies in the interval, $[r \geq r_2, s \geq s_1]$, (see table 4.6). This method can be applied by following the sequence described in figure 5.3.

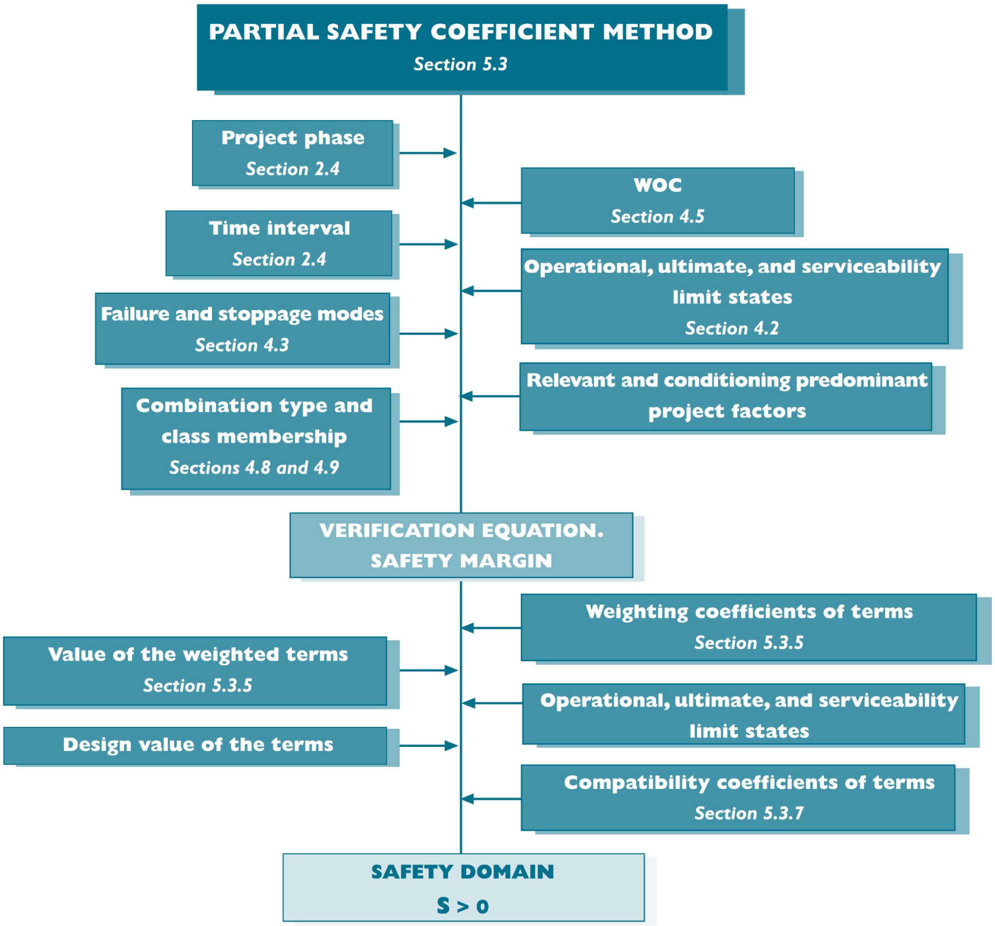


Figure 5.3: Application sequence of the partial coefficients method

5.3.1 Definitions

The partial coefficients method evaluates the verification equation written in the safety margin format, and affects the terms by means of partial coefficients that weight and make terms compatible[6]. The result is then compared with a value of the safety margin that is generally S = 0. This section describes the criteria for assigning values to the terms and the partial coefficients.

(6) In the partial coefficients method the terms are weighted. However on some occasions, if properly justified, agents that participate in the term can be weighted too.

5.3.1.1 Verification equation

This equation is generally established by the difference between favorable and unfavorable terms that participate in the mode. In other words, it is an equation of the safety margin format, which is usually written in the following way:

$$S = \sum_{i=1}^{I} a_i X_{1,i} - \sum_{j=1}^{J} b_j X_{2,j} = \sum_{i=1}^{I} X_{1,i,d} - \sum_{j=1}^{J} X_{2,j,d}$$

In the preceding equation, a_i and b_j are partial coefficients that weight and compatibilize the characteristic value of the I favorable terms ($X_{1,I}$) and of the J unfavorable terms ($X_{2,j}$). $X_{1,i,d}$ and $X_{2,j,d}$ are the I and J design values of the terms, also known as favorable and unfavorable, respectively. S is the safety margin

Note *$X_{1,i}$ and $X_{2,j}$ are the terms of the equation and can represent any project factor, parameter, agent, action, structural reaction, or reaction of the physical environment, soil or functional relation between them. $X_{1,i}$ and $X_{2,j}$ can represent magnitudes of diverse types (physical, mechanical, chemical, biological, etc.). All terms ought to have the same units, which are those that take the safety margin S. Subindices 1 and 2 identify favorable and unfavorable terms, respectively. The letter "d" identifies the design value of the term.*

5.3.1.1.1 Verification condition

In order for the subset of the structure to be verified against the failure or operational stoppage mode, the result of the verification equation should be $S > 0$.

5.3.1.1.2 Equation format

The verification equation of the principal modes and the weighting and compatibility coefficients of the different typologies of maritime structures are given in the specific Recommendations. As a general rule, its application should follow the sequence described in the following sections.

Alternatively, if a verification equation is applied that was originally obtained with the partial coefficients format, the same criteria and hypotheses with which it was proposed should be respected, particularly in regards to the dimensions of the terms.

If the verification equation to be applied was not originally obtained with the partial coefficients format and no information is available regarding the order of magnitude of the coefficients, a Level II or Level III Verification Method should be applied to obtain the partial coefficients in accordance with section 6.10[7].

(7) These coefficients are provided in the specific Recommendations. If they are not specified, the engineer should determine them, following the procedure established in Chapter 6.

5.3.1.2 Project factors

In the application of the partial coefficients method, the following project factors play an important role.

5.3.1.2.1 Relevant term

Regarding the project factors appearing in each term, there is one (or even several) that can: (1) characterize the action or response, the geometry of the structure and the properties of the environment, the soil, and the building materials; (2) give meaning and justify the presence of the term in the verification equation; (3) be the most influential in the value of the term. This factor is known as the relevant term.

5.3.1.2.2 Conditioning factor

There are cases in which a conditioning factor does not directly participate in any term of the verification equation, but rather conditions the value of another factor, and consequently, the value of the term in which the latter participates. The value of this conditioned term should be compatible with the values of the conditioning term.If the conditioned factor is predominant in the mode, the conditioning factor should be considered predominant.

Note *In this regard,see the note on section 5.2.1.3.3.*

5.3.2 Limit states, WOCs, and combination types

The partial coefficients method can be applied to verify the subset of the structure against the modes assigned to ultimate, serviceability, and operational limit states.

Unless expressly stated otherwise, in each project phase, extreme and operational WOCs,as well as ultimate, serviceability, and operational limit states should be verified according to section 4.6.2, applying the combination types given in section 4.9.When necessary, exceptional WOCs should also be verified.

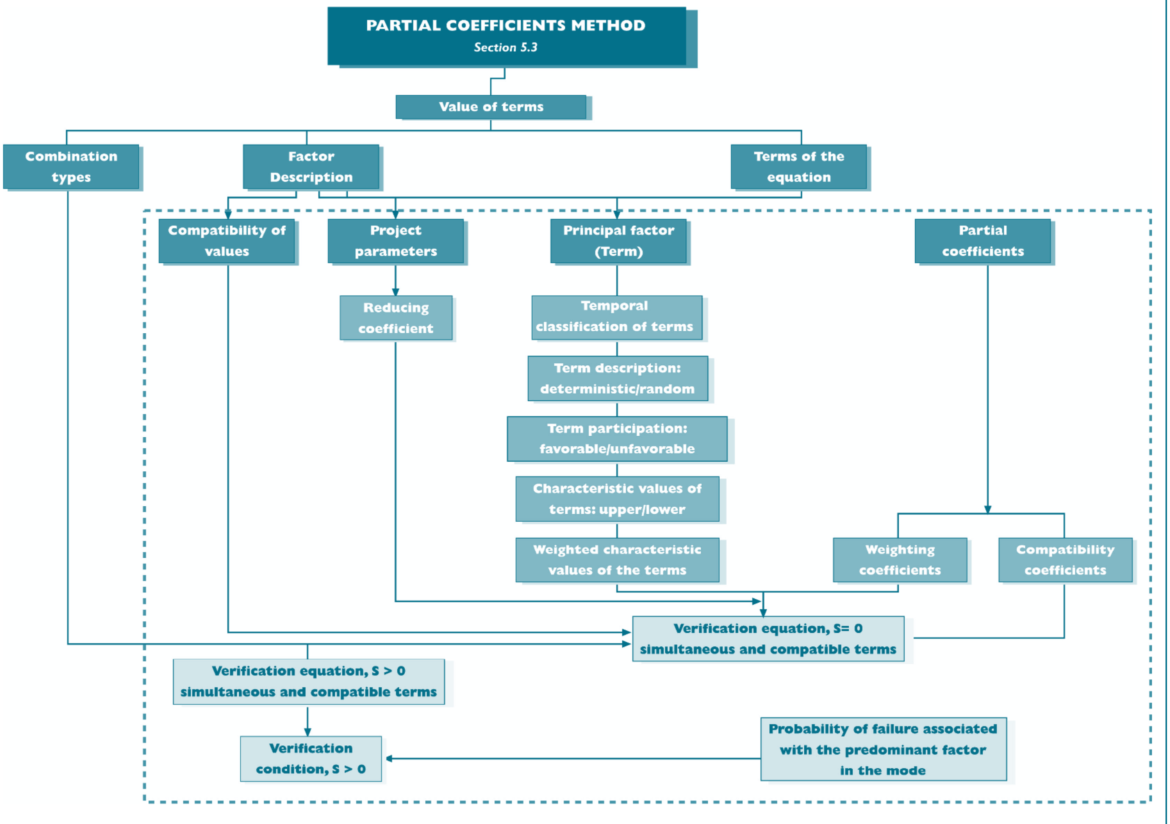


Figure 5.4: O rganization of factors and terms in the partial coefficients method..

5.3.3 Sequence to obtain the design value of an equation term

This calculation can be itemized in three partial sequences (see figure 5.4): (1) calculation of the characteristic value of the terms, $X_{1,i}$ and $X_{2,j}$; which depend on the way the term participates in the occurrence of the mode; (2) calculation of the characteristic weighted value of the terms by applying the weighting coefficients ($p_{1,i}$ and $p_{2,j}$); (3) application of the compatibility coefficient $\Psi_{1,i}$ and $\Psi_{2,j}$ to obtain the design value of the term.This coefficient depends on the compatibility class to which the term and the combination type belong. Moreover, the terms that contain project parameters that quantify properties of the physical environment,building material, and soil should include a reducing coefficient c_r applied to each parameter that lessens its characteristic value.

Note

(8) In order to maintain the same application criteria as the other two coefficients, in these Recommendations the reduction coefficient multiplies the parameter value, and as a result,should be less than or equal to the unit.

The partial coefficient $a_{l,i}$ for the favorable term is calculated by $a_{l,i} = p_{l,i}\Psi_{l,i}$; Furthermore, if the term has a project parameter that quantifies its resistance capacity, its magnitude should then be multiplied by a reducing coefficient[8], $c_r \leq 1$. The design value of $X_{l,i,d}$, of the term, $X_{l,i}$, is finally obtained by the following expression $X_{l,i,d} = p_{l,i}\,\Psi_{l,i}X_{l,i}$.

There are important differences between this method and the global safety coefficient method. In the latter, the value of the term is generally a nominal value, which furthermore is the design value of the term without being affected by weighting coefficients. In the partial coefficients method,the value of the term is determined on the basis of the characteristic values which, by definition, are quantiles of the distribution model. Only when there is enough information, can nominal values be used. Moreover, the design value of each of the terms is obtained by applying weighting and compatibility coefficients that allow the simultaneous occurrence of agents and parameters in the occurrence of a failure mode to be delimited deterministically. As a result, the application of this method is more complex, but on the other hand, it is expected to provide higher "quality" and confidence in the result.

The criteria used to compatibilize term values and their application have a certain ambiguity, and thus may sometimes seem subjective. This section develops a set of criteria for this compatibilization. At the end of this chapter there is a brief summary of other Level I Verification Methods, which to a certain extent, lie halfway between the two methods described in these Recommendations.

5.3.4 Term value of the equation

In the majority of cases, the term value of the verification equation is obtained from a mathematical expression of project factors,parameters,and agents. These expressions generally are provided in Recommendations, Standards, and Regulations. In other cases, the term value can be obtained either in the field, or in the labs, or directly by experimentation.

5.3.4.1 Term value according to the project factors

One of the following situations can arise: (1) all the project factors are defined by a nominal value without a probability model; (2) certain project factors, such as the relevant one, have a probability model and others have a nominal value without a probability model; (3) all the project factors have an associated probability model (individual or joint). In any of these three situations, it is convenient to define the principal factor of the term.

5.3.4.1.1 All factors are defined by nominal values: case (1)

The value of the term is obtained by taking the nominal values of all the factors. To this end, the relations of functional and statistical dependence between different project factors are taken into account in accordance with the organization given in section 4.7.

Note

This usually occurs in terms related to gravitational agents, agents of use and exploitation, and soil agents.

5.3.4.1.2 The relevant factor has a probability model: case (2)

In this case, the distribution function of the term should be analytically or numerically obtained from the distribution function of the relevant factor, while taking into consideration the joint, conditional or marginal distribution functions of the project factors with a probability model.

To determine the values of the remaining factors, the relations of functional and statistical dependence between different project factors are taken into account in accordance with the organization given in section 4.7, and whether or not they have a probability model.

Since in certain cases,obtaining the probability model of the term can be difficult, complicated or impossible, approximations can be considered,as described in the following subsection:

Note *In the determination of the value of the term, it is necessary to take into account its value class: upper tail, centered or lower tail. Class membership depends on the combination and the role played by the term in the verification equation: predominant, of the same origin, dependent or independent. This is the case for those terms associated with the occurrence of agents of the physical environment. For sea states, for example, if it is predominant in the occurrence of the mode and if the structure is being verified in extreme WOCs, the probability model is an extreme regime, and its value generally belongs to the upper class. If it is not predominant, but accompanies another term associated to an agent of the physical medium (e.g. an earthquake), its value belongs to the upper tail of the annual average regime.*

If the term due to the sea swell is not predominant and a normal WOC is being verified, the probability model is an annual average regime that properly represents the threshold exploitation level of the sea state. Its value generally belongs to the centered class.

5.3.4.1.2.1 Simplifying the way of obtaining the probability model

When the other project factors, apart from the relevant one can be considered deterministic or when their variability does not significantly contribute to the variability of the characteristic value of the term, their value can be a nominal value or the most probable value. In any case, relations of functional and statistical dependence among the different project factors should be taken into account according to the organization specified in section 4.7.

This simplification cannot be applied to those factors whose value is imposed for other sets of Regulations and Instructions.

Note *When this simplification is applied, it is advisable to study the variability of the characteristic values of the term for different nominal values, especially for those that are defined by maximum and minimum values. If significant deviations from the term value are obtained from the study, it is necessary to carry out the calculation using more accurate methods or define the project factors by means of appropriate probability models.*

5.3.4.1.3 All the factors have a probability model: case (3)

In this case, the statistical function of the term can be obtained, either analytically or numerically, on the basis of the conditional and marginal distributions of the project factors. Sometimes, it is necessary to posit the independence of project factors. To this end, relations of functional and statistical dependence between the different project factors must be taken into account according to the organization specified in section 4.7.

Note *The term value is determined for each of the classes according to the combination type and the role played by the term in the verification equation of the mode.*

If all the project factors participating in the term have a probability model, it is advisable to carry out the verification by means of a Level II or Level III probabilistic method.

5.3.4.2 Term value by means of specific experimentation

In some cases, the term value is obtained by means of specific experimentation of some of the project or term factors. To determine the term value, the recommendations in Chapter 3 should be followed, regarding the treatment of experimental data,experimental uncertainty, and probability models.

5.3.4.3 Directly determined term value

On other occasions, the term value is determined on the basis of previous experience, available data, or simply the best possible estimate. To determine the design value, it is advisable to bear in mind the considerations in Chapter 3 regarding sources of uncertainty and their evaluation by means of a probability model.

5.3.5 Characteristic value of the term

Generally speaking, the verification equation is resolved by giving characteristic values to terms affected by the weighting and compatibility coefficients.Unless there is sufficient justification given, the upper and lower characteristic values of the term are quantiles of the 0.95% and 0.05% of its probability model.

When the term is calculated by a nominal value, case (1),the upper and lower characteristic values can be the maximum and minimum values, or a single value, such as the mean, the most probable value, etc. according to the recommendations in section 3.7,as well as in other Recommendations, Standards, and Regulations.

Furthermore, the following aspects should be taken into consideration:

5.3.5.1 Characteristic value of favorable and unfavorable terms

In all possible situations,the characteristic value of the term depends on the favorable or unfavorable direction of its participation in the verification equation. Generally speaking, the value of a favorable or unfavorable term is respectively an upper or lower characteristic value obtained from its probability model.

When the term is defined by a nominal value without a probability model, this will be the only characteristic value, unless maximum and minimum nominal values are available, in which case, these will be considered the upper and lower characteristic values.

5.3.5.2 Characteristic value of the permanent terms

When the permanent term is the weight of the structural elements, the characteristic value is a single value, defined on the basis of a nominal value and calculated by means of the geometric dimensions of the element and the average specific weight of the materials.

When the permanent term represents their non-structural weights, the maximum and minimum nominal weights are determined, and considered upper and lower characteristic values. On most occasions, the lower value can be assumed to be equal to zero.

Regarding permanent terms whose maximum and minimum nominal values do not significantly differ, the characteristic value can be equal to the average value of both nominal values.

5.3.5.3 Characteristic value of non-permanent terms

These terms generally have an upper and lower characteristic value, though the lower characteristic value can be zero or so small as to be non-significant. This will not be so, unless there is justification to the contrary, for terms due to factors whose origin and function are associated with the physical environment, soil, and building material.

5.3.5.4 Characteristic value of terms due to factors of the physical environment

These terms have upper and lower characteristic values, and should be defined on the basis of their distribution function, or if this is not possible, the distribution function of the relevant project factor. In any case, the probability model should be representative of the occurrence of the term in the time interval in which the mode and combination types are being verified.

5.3.5.5 Characteristic value of terms due to soil factors

The characteristic values of the terms are determined according to the specifications in the ROM 0.5, or in other specific Regulations.

5.3.5.6 Characteristic value of terms due to use and exploitation factors

Whenever possible, the terms of use and exploitation are defined by means of probability models, which are the basis of the definition of the upper and lower characteristic values. Alternatively, the term values can be nominal. The maximum nominal value specified in the project or required by specific Regulations, Standards, and Recommendations can be the upper characteristic value. The lower characteristic values are zero or possibly a minimum nominal value for those factors that must always exceed a certain threshold.

5.3.5.7 Characteristic value of terms due to building materials factors

Whenever possible, when determining the characteristic values of building materials,it is advisable to take into consideration their temporal evolution during the useful life of the structure by means of analytical, numerical, and probability models. If characteristic values of building material parameters participate in the models, and there are no laws to regulate them, these values are regarded as the average values. Alternatively, upper and lower characteristic values can be determined on the basis of maximum and minimum nominal values, which represent the temporal evolution of the term.

5.3.5.8 Characteristic value of terms due to construction factors

Generally, only the upper characteristic values of the terms induced by the construction process are considered. These can be maximum nominal values for the unfavorable terms. The lower characteristic value is generally a minimum nominal value, which unless expressly stated otherwise, is equal to zero.

Note *Once the characteristic value of each term of the verification equation is known, whether it be a random value of the probability model or a nominal value, the next step in the application of the partial coefficients method is the determination of the weighting coefficients ($p_{1,i}$ and $p_{2,j}$). The objective of these coefficients is to reduce or increase the terms according to: (1) type of participation in the occurrence of the mode; (2) type of classification (temporal or based on the origin of the participating project factors); (3) limit state; (4) WOC; and (5) project phase.*

5.3.6 Determination of the weighting coefficient of the term

The weighting coefficient of each term should conform to the specifications in the Recommendations or in other Regulations and Standards. Alternatively, the weighting coefficient is calculated, taking into consideration its dependence on the following aspects (see figure 5.5):

- Aspects pertaining to general project criteria
  - Project phase: construction, useful life, maintenance and repair, and dismantling
  - WOCs: operational, extreme, and exceptional

- Aspects pertaining to the nature of the limit state
  - Ultimate, serviceability, and operational limit state

- Aspects pertaining to the term and its project factors
  - Temporal classification: permanent, non-permanent
  - Classification according to origin or function
  - Type of participation of the term: favorable and unfavorable

- Aspects pertaining to the verification equation

Note *It should be stressed that the verification equation of a failure or stoppage mode is obtained after a theoretical derivation, dimensional analysis, experiment, etc., which sets down criteria and constraints for its application in reference to project factors as well as terms. This equation generally entails uncertainty, and exclusively represents the conditions for which it has been obtained. Consequently, when a verification equation is to be applied, it is necessary to know with accuracy the scope of its validity and the means and criteria for its use.*

For example, if the equation has been derived and contrasted in a global coefficient format, its application to the partial coefficients method should be carried out by applying specific weighting coefficients, which can be obtained according to the recommendations in section 6.4. In all these cases, the dimension of the terms of the original verification equation is taken into account to preserve the weighting of the different terms in the verification equation in their new format.

5.3.6.1 Basic weighting coefficient

To help determine the weighting coefficient, a basic weighting coefficient is defined, whose value is determined according to the aspects listed in the previous section. The value of this coefficient is considered valid except if a different value is specified in Regulations and Standards.

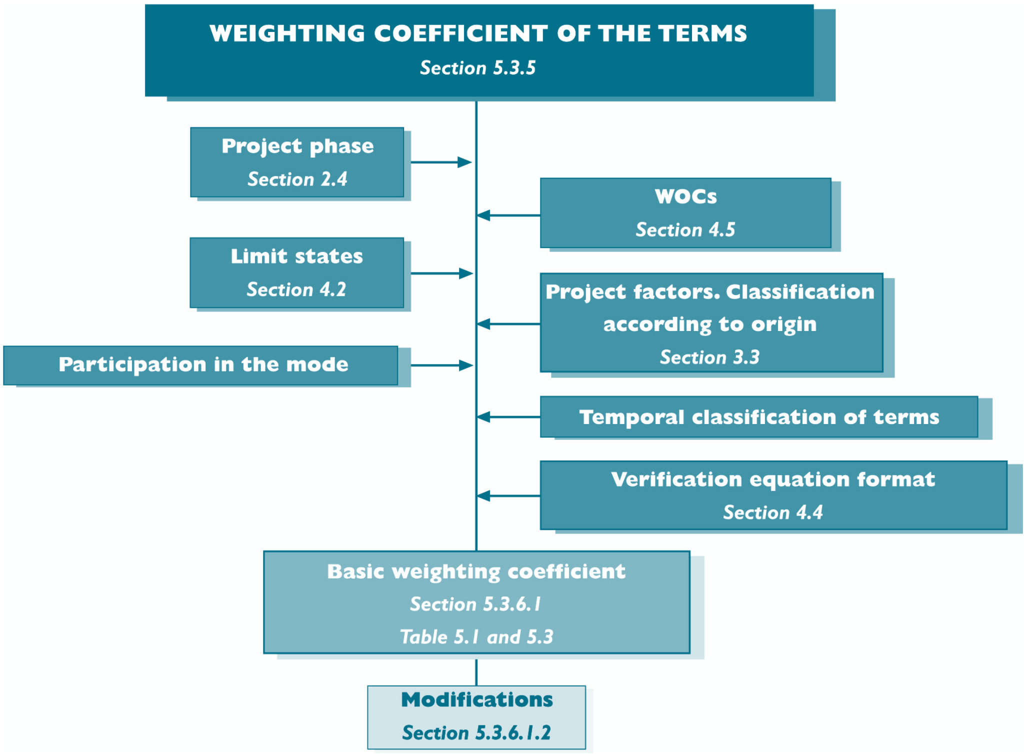


Figure 5.5: Calculation sequence for the basic weighting coefficient

5.3.6.1.1 Useful life, operational and extreme WOCs

Once the useful life, operational and extreme WOCs, and ultimate limit state have been selected, the weighting coefficient of the term only depends on the following characteristics of the project factors: (1) classification according to temporality or to the origin of the factors; (2) favorable or unfavorable participation in the occurrence of the mode, according to the following tables 5.1,5.2, and 5.3.

Table 5.1: Basic weighting coefficient.All terms except deformation and soil

Type of participation	Favorable, $p_{1,i}$	Unfavorable, $_{p2,j}$
Permanent	1.00	1.35
Non-Permanent	1.00	1.50

Tabla 5.2: Basic weighting coefficient.Terms associated with deformation factors

Type of participation	Favorable, $p_{1,i}$	Unfavorable, $_{p2,j}$
Permanent	1.00	1.35
Non-Permanent	0.90	1.20

Tabla 5.3: Basic weighting coefficient.Terms associated with soil factors

Type of participation	Favorable, $p_{1,i}$	Unfavorable, $_{p2,j}$
Permanent	1.00	1.35
Non-Permanent	0.90	1.20

Table 5.3 note *The basic weighting coefficient of 1.50 for unfavorable and non-permanent terms associated with soil factors is purely indicative. In each case the value adopted satisfies the most demanding conditions established in current regulations and specific Recomendations.*

Note *These values can be applied when the verification equation has been derived for the partial coefficients format. In other cases, specific weighting coefficients should be obtained.*

It is advisable to maintain the habitual value of the weighting coefficient (i.e. 1.50) for the permanent terms associated with the soil factors that represent soil actions in the structural calculation of the walls. When those terms represent soil weight, they can be weighted with the coefficient of 1.35.

However, for the analysis of failure or stoppage modes whose occurrence is controlled by the soil-resistance parameters, the weighting coefficients must be those indicated in the ROM 0.5 or the specific documents of the ROM Program.

5.3.6.1.2 Modification of the basic weighting coefficient

The basic weighting coefficient of table 5.1 is applied in the verification of the modes assigned to the ultimate limit states for the operational and extreme WOCs,and the useful life. For other limit states and WOCs, the following weighting coefficients are used:

5.3.6.1.2.1 Modification because of the limit state

The weighting coefficients for the verification of failure modes assigned to the serviceability limit states and stoppage modes assigned to the operational limit states are equal to the unit for all terms, independently of their type of participation and temporal classification.

5.3.6.1.2.2 Modification because of the WOC

In reference to the verification of modes in exceptional, unforeseen or foreseen WOCs for the ultimate and serviceability limit states,as well as for the operational limit states,the value of all the weighting coefficients can be equal to the unit for all terms, independently of their type of participation and classification according to their origin.This modification should not be applied to permanent terms.

5.3.6.1.2.3 Modification because of the project phase

In reference to the verification of modes during the construction project phase, the weighting coefficients can be reduced for all WOCs, limit states, and origin of terms, according to the characteristics of the structure and the construction process, as long as the specifications in other Standards, and Regulations are complied with.This modification is not valid for permanent terms.

The weighting coefficients in the verification of modes in other project phases should be determined in each case according to their specificity.

In any case, unfavorable weighting coefficients can never be less than the unit, and favorable ones can never be greater than the unit.

Note *Once the characteristic value of each term of the verification equation,either as a quantile of the probability model or a nominal value, and the weighting coefficient $p_{1,i}$ and $p_{2,j}$, are known, the next step in the application of the partial coefficients method is the determination of the compatibility coefficients of the terms $\Psi_{1,i}$ and $\Psi_{2,j}$. The objective of these coefficients is to compatibilize the values of the terms according to a combination type, the classification according to temporality and the origin of the project factor, limit state, WOC, and project phase.*

5.3.7 Term compatibility

The compatibility coefficient of each term should be adjusted so that it complies with specific Recommendations in this regard or with other Regulations and Standards.Alternatively, the compatibility coefficient is calculated, taking into consideration its dependence on the following aspects (see figure 5.6):

- Aspects pertaining to general project criteria
  - Project phase: construction, useful life, serviceability, maintenance and repair, and dismantling
    - WOCs:operational, extreme, and exceptional

- Aspects pertaining to the nature of the limit state
  - Ultimate, serviceability, and operational limit states

- Aspects pertaining to the term and its project factors
  - Type of participation: favorable and unfavorable
    - Statistical class membership: centered, lower tail, upper tail
    - Participation in the equation: predominant, same origin or dependent on it, and independent
    - Temporal classification of the term: permanent and non-permanent
    - Classification according to term origin and function
    - Description of the term: deterministic or random

- Aspects pertaining to the verification equation
  - Proposed format

5.3.7.1 Compatibility coefficient for permanent terms

The compatibility coefficient of permanent terms, both favorable and unfavorable, are in all cases equal to the unit.

5.3.7.2 Compatibility coefficient for non-permanent random terms

(9) The criteria and some of the recommended values were initially proposed in the ROM 0.4-95.

The compatibility coefficient of these terms is the unit,as long as they are determined on the basis of their probability model and according to the following subsections[9].

5.3.7.2.1 Compatibility coefficient of the predominant term

The compatibility coefficient of the predominant term is equal to the unit as long as the term value is taken from the extreme regime (upper tail). It is also necessary to take into account the fulfillment of the overall probability of failure and operationality, as described in Chapter 7.

5.3.7.2.2 Compatibility coefficient of the remainder of the terms

The compatibility coefficient of the other unfavorable terms, both non-permanent and random, which are not dependent on the predominant,though simultaneous and concurrent with it,is equal to the unit, as long as the term value is determined with the following criteria according to combination type.

- Fundamental combinations, (i,WOC_2,1): the value of the concurrent term is the quantile of the probability of not exceeding 0.70, taken from the extreme regime, centered class. In the case of work and operating conditions (i,WOC_1,1), it is the operational threshold value.

- Frequent combinations,(i,WOC_2,2):the value of the concurrent term is the quantile value of the probability of not exceeding 0.85 (centered class), taken from the mean regime of not exceeding 0.50-0.60, (centered class),which is taken from the extreme regime. In the case of operational work and operating conditions (i,WOC_1,2),it is the operational threshold.

- Quasi-permanent combinations (i,WOC_1,3) and (i,WOC_2,3): the value of the concurrent term is the quantile value with the probability of not exceeding 0.50-0.60 (centered class),of the mean regime or the quantile with the probability of not exceeding 0.25 (class of the lower tail), of the extreme regime. In each case, the criteria to be adopted should be that which best represents the normal and extreme operational WOCs that are being verified.

Note *The probability values of not exceeding 0.85, 0.70, 0.60, 0.50 and 0.25 have been previously established in order to begin the application of probabilistic criteria in the partial coefficients method.To correctly determine the probability values of non-exceedance of other terms, apart from the predominant, the recommendations in section 6.5. should be applied.*

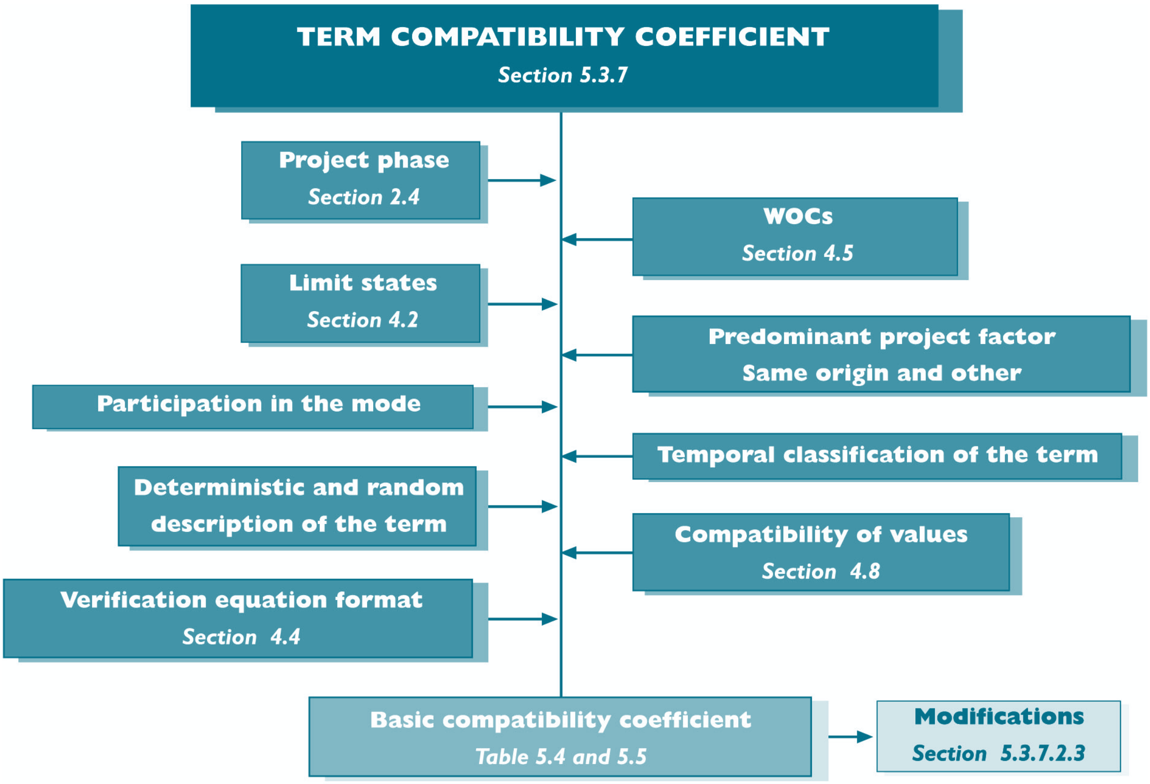


Figure 5.6: Calculation sequence for the basic compatibility coefficient.

5.3.7.3 Compatibility coefficient for non-permanent deterministic terms

The basic or modified compatibility coefficient for these terms is determined as specified in the following sections. Firstly, the basic coefficient is determined and then, if necessary, the modified coefficient.

5.3.7.3.1 Basic compatibility coefficient

The basic compatibility coefficient is determined according to the following aspects:

5.3.7.3.2 Useful life phase, operational and extreme work and operating conditions

Once the useful life, extreme and operational WOCs,and all the ultimate, serviceability and stoppage limit states have been selected,the compatibility coefficient only depends on:(1) classification according to temporality and to the origin of project factors; (2) combination type; (3) type of participation of the term in the occurrence of the mode: predominant, dependent on it, independent.

In this case, the value of the compatibility Ψ coefficient is taken from table 5.4.The subindex p refers to a predominant term or one that depends on the predominant, whereas the superindex 0 refers to the participation in the fundamental combination.The super indices 1 and 2 refer to the frequent and quasi-permanent combinations.

Table 5.4: Compatibility coefficient according to term participation.

Participation	fundamental	frequent	quasi-permanent
Predominant and dependent	Ψ^0_p	Ψ^1_p	Ψ^2
Independent	Ψ^0	Ψ^2	Ψ^2

The compatibility coefficients Ψ^0, Ψ^1 and Ψ^2, appear in table 5.5, organized in terms of the origin and function of participating factors.

Table 5.5: Basic compatibility coefficient according to term origin

	fundamental		frequent		quasi-permanent
Origin	Ψ^0_p	Ψ^0	Ψ^1_p	Ψ^2	Ψ^2
Gravitational force	1.0	1.0	1.0	1.0	1.0
Physical environment	1.0	0.7	0.3	0.2-0.0	0.2-0.0*
Soil	1.0	1.0	1.0	1.0	1.0
Use and exploitation	1.0	0.7	0.6	0.5-0.0	0.5-0.0*
Building materials	1.0	1.0	1.0	1.0	1.0
Construction	1.0	1.0	1.0	1.0	1.0

Note

According to the ROM 0.2-90,section 4.2.2, it will rarely be necessary to compatibilize two terms due to use and exploitation agents with two terms associated with agents of the physical environment. For this reason, in consonance with that Regulation and the Spanish Instrucción de Hormigón Estructural *(EHE), it is advisable to apply the coefficient,* Ψ^1_p*, to the predominant term, and the compatibility coefficient,* Ψ^2*, to the remainder of the concurrent frequent terms.*

Note that the compatibility coefficient does not depend on the way the term is related to the failure, and thus equally affects favorable as well as unfavorable terms.

The compatibility coefficient for the frequent and quasi-permanent combination types, which affects the terms of the agents of the physical environment as well those of use and exploitation, is defined by means of an interval in order to delimit its value and permit its participation in the different combination types.

5.3.7.3.3 Modification of the basic compatibility coefficient

The basic compatibility coefficient in tables 5.4 and 5.5 is applied to all the terms with a deterministic description for the verification of modes assigned to all the limit states for the operational and extreme WOCs in the useful life phase.

5.3.7.3.4 Modification according to the WOC

Unless expressly stated otherwise, in the verification of modes for both foreseen and unforeseen exceptional WOCs for the ultimate and serviceability limit states, as well as for the operational limit states, the compatibility coefficient of the terms unrelated to the extraordinary or catastrophic factor can correspond to a frequent or quasi-permanent combination type, according to whether it is predominant, dependent, or independent, respectively.

5.3.7.3.5 Modification according to the construction phase

Unless expressly stated otherwise, in the verification of modes during the construction phase, the compatibility coefficient of the terms non-related to the predominant factor can correspond to a quasi-permanent combination type.

5.3.8 Design value of project parameters

The value of the project parameters that participate in a term of the verification equation is determined according to the specific Regulations and Recommendations in this regard.

Alternatively, its determination is carried out according to the specifications in the following subsections.

5.3.8.1 Characteristic value of the geometrical parameters

If the project parameter is a geometrical magnitude, its characteristic value is the nominal value defined in the drawings. This will generally be the value applied in the calculation of the term. If deviations are expected, which can have a significant effect on the verification of the mode, upper and lower characteristic values can be defined, based on admissible tolerances or a probability model. In these cases, the term is calculated with the term that most unfavorably contributes to the verification of the mode.

5.3.8.2 Characteristic value of property parameters of identification and state

Unless expressly stated otherwise, the characteristic values of the parameters that define properties of identification and state of the soil, air, and water are determined according to the recommendations in chapter 3, and in specific Standards and Recommendations to this effect.

Such values are normally determined on the basis of their probability model, considering the median, mean or mode value, depending on the case. In other cases, a nominal value that is representative of the average behavior of the parameter in the time interval can be used as the characteristic value.

5.3.8.3 Characteristic value of the parameters that define mechanical properties

In most cases, the characteristic values of the parameters that define mechanical properties of soil and building materials, in particular, are determined in accordance with the recommendations in chapter 3 and should comply with the Standards and Regulations. Two characteristic values are generally determined, an upper one and lower one, associated with two quantiles of the distribution function.

Note *According to the Spanish* Instrucción de Hormigón Estructural *EHE,the characteristic value of the concrete resistance and compression and tensile steel resistance are the quantiles corresponding to a probability of 0.05.The upper and lower characteristic values of the concrete resistance are the quantiles associated with the probability of exceedance of 0.95 and 0.05 respectively. In other cases, for example, when the specific weight of the concrete is a state descriptor, its characteristic value is the mean value.*

5.3.8.3.1 Reducing coefficient of the mechanical properties

The characteristic value of the parameters that define mechanical properties and the behavior of the materials and soil is affected by a reducing coefficient c_{rm}, that causes it to decrease in value. This depends on the following aspects of the general verification procedure:

- Aspects pertaining to general project criteria
  - Project phase: construction, useful life, maintenance and repair, dismantling
    - WOC: operational, extreme, exceptional

- Aspects pertaining to limit states
  - Ultimate, serviceability, and operational limit states

- Aspects pertaining to the term
  - Statistical class membership: centered,upper tail, and lower tail

- Aspects pertaining to the project factor
  - Parameter of mechanical properties of building material and soil
    - Environmental parameters: treatment, variability, and repercussion in the verification
    - Control level of the material implementation: intense, normal, and reduced

- Aspects pertaining to the verification equation
  - Proposed format

5.3.8.3.1.1 Basic reducing coefficient

In the determination of this coefficient, it is necessary to define the basic reducing coefficient, whose value can be specified according to criteria described in the previous section.

Table 5.6: Basic reducing coefficient: properties of the materials

Resistance of building material	Work and operating conditions	
	operational and extreme	exceptional
concrete	0.65	0.70
framework steel	0.85	1.00
construction steel	1.00	1.00
connectors E.M.	0.75	0.90
wood	0.70	0.90
quarries	1.00	1.00
elasticity modulus	1.00	1.00
rigidity modulus	1.00	1.00
Poisson coefficient	1.00	1.00
thermal dilation coefficient	1.00	1.00

Table 5.7: Basic reducing coefficient: soil properties

Parameters	Work and operating conditions	
	operational and extreme	exceptional
Effective friction angle	0.80	1.00
Effective cohesion	0.65	1.00
Undrained shear resistance	0.70	1.00
Resistance to compression	0.70	1.00

5.3.8.3.1.1.2 All phases and WOCs, as well as ultimate limit states, intensive material implementation

(10) These values are analyzed in greater detail in the ROM 0.5.When there is a conflict between values, the ones in the specific Recommendations should be used.

For the verification of ultimate limit states in extreme, operational, and exceptional WOCs in all project phases and when the control level of the implementation is normal, the reducing coefficient of the characteristic value of the mechanical parameter of the building materials and the soil should conform to tables 5.6 and 5.7[10]:

5.3.8.3.1.2 Modification of the basic reducing coefficient

The basic reducing coefficients in tables 5.6 and 5.7 are applied to the favorable terms in the verification of the modes assigned to ultimate limit states for operational, extreme, and exceptional WOCs as well as all project phases. The following modifications will be adopted for other limit states and WOCs.

5.3.8.3.1.2.1 Modification of unfavorable terms

For all building materials and soil properties, the reducing coefficient of the parameters belonging to an unfavorable term is equal to the unit.

5.3.8.3.1.2.2 Modification according to limit state

The reducing coefficient of the materials and soil parameters in the verification of modes assigned to the serviceability and operational limit states is equal to the unit, independently of the term in which they participate.

5.3.8.3.1.2.2.1 Modification for the ultimate limit state of fatigue

For all building materials, the reducing coefficient for the verification of fatigue limit states is equal to 0.80 for operational and extreme WOCs, and equal to the unit for extraordinary WOCs.

5.3.8.3.1.2.2.2 Modification for the ultimate limit state of progressive collapse

For all building materials, the reducing coefficient for the verification of limit states of progressive collapse is equal to 0.90 for operational and extreme WOCs, and equal to the unit for extraordinary WOCs.

5.3.8.3.1.2.3 Modification according to the control level of the construction

(11) See EHE,article 95

Three control levels of the implementation are taken into consideration[11]: intensive, normal, and reduced.Depending on the control level adopted,the value of tables 5.6 and 5.7 can be multiplied by the following correction coefficient in table 5.8.

Note *In the Spanish* Instrucción de Hormigón Estructural *(EHE), three control levels of the construction of the concrete are considered: intense, normal, and reduced.The level depends on the number of tests and the sampling frequency. According to the level, a reducing coefficient is proposed that affects the mechanical properties of the building material.This Recommendation generally adopts this criteria.*

Table 5.8: Modification of the basic reducing coefficient according to the quality control of the construction.

Intense	Normal	Reduced
1.00	0.90	0.85

5.3.9 Summary of the criteria to determine partial coefficients

Generally speaking, the criteria to determine partial weighting and compatibility coefficients depend on the following aspects:

- Aspects pertaining to general project criteria
  - Project phase: construction, useful life, maintenance and repair, dismantling
    - WOC: operational, extreme, extraordinary

- Aspects pertaining to limit states
  - Ultimate, serviceability, operational limit states

- Aspect pertaining to the equation and the term:
  - Participation in the equation: predominant, dependent, independent
    - Term description: probabilistic model, deterministic value
    - Contribution to the failure:favorable or unfavorable
    - Statistical class membership: centered, upper tail, and lower tail
    - Type of combination

- Aspects pertaining to the project factor
  - Temporal classification[12]: permanent,non-permanent
    - Classification according to origin or function[13]
    - Type of factor: parameter, agent.

- Aspects pertaining to the construction of the structure
  - Control level of the material construction: intensive, normal, reduced

- Aspects pertaining to the verification equation
  - Proposed format

(12) This classification depends on participating agents, the most unfavorable of which is used for the verification.

(13) The classification of the term is the same as of the principal agent.

Note *According to the previous list, there are forty different aspects that should be taken into account when determining the partial weighting and compatibility coefficients that participate in a verification equation. The tables in this section, the software based on this ROM. 0.0, as well as the values specified in other Regulations and Recommendations will hopefully facilitate the application of the partial coefficients method.*

5.3.10 Design value of the term

These values are obtained by multiplying the term, $X_{1,i}$ and $X_{2,j}$ by the weighting coefficient, p, and the compatibility coefficient Ψ. For each mode, the design value of the term depends on the value of those coefficients, $a_i = p_i \Psi_i$ y $b_j = p_j \Psi_j$, which, in turn,depend on the limit state, WOC, combination type, and project phase. Moreover, the mechanical properties of the material are multiplied by a reducing coefficient, c_{rm}.

5.3.10.1 Verification and combination type

The general layout of the verification equation in safety margin format for the ultimate limit states can be found below:

$$S = \sum_{i=1}^{I} a_i X_{1,i} - \sum_{j=1}^{I} b_j X_{2,j} = \sum_{i=1}^{I} X_{1,i,d} - \sum_{j=1}^{I} X_{2,j,d}$$

Depending on the combination type, this equation can be the following:

- Fundamental combination (improbable or infrequent):

$$\sum_{i=1}^{I} X_{1,i,d} = p_{1,1} X_{1,1} + \Psi_0 p_{1,2} X_{1,2} + \ldots$$

$$\sum_{j=1}^{J} X_{2,j,d} = \Psi_{0,p} p_{2,1} X_{2,1} + \Psi_0 \left(p_{2,2} X_{2,2} + p_{2,3} X_{2,3} + p_{2,4} X_{2,4} + \ldots\right)$$

In other words, one of the predominant terms is designated as the principal fundamental term, while the other predominant terms are regarded as fundamental. Rarely will it be necessary to combine more than two predominant terms of the physical environment or more than two terms of use and exploitation, or more than one predominant term of the physical environment and another one of use and exploitation.

- Frequent combination

$$\sum_{i=1}^{I} X_{1,i,d} = p_{1,1} X_{1,1} + \Psi_1 p_{1,2} X_{1,2} + \ldots$$

$$\sum_{j=1}^{J} X_{2,j,d} = \Psi_{1,p} p_{2,1} X_{2,1} + \Psi_2 \left(p_{2,2} X_{2,2} + p_{2,3} X_{2,3} + p_{2,4} X_{2,4} + \ldots\right)$$

In the above equation, one predominant term is considered frequent, and the rest of the independent predominant terms and the non-predominant terms are considered quasi-permanent. It is sometimes necessary to combine more than two predominant terms of the physical environment with more than two terms of use and exploitation.

- Quasi-permanent combination

$$\sum_{i=1}^{I} X_{1,i,d} = p_{1,1} X_{1,1} + \Psi_2 p_{1,2} X_{1,2} + \ldots$$

$$\sum_{j=1}^{J} X_{2,j,d} = \Psi_2 \left(p_{2,1} X_{2,1} + p_{2,2} X_{2,2} + p_{2,3} X_{2,3} + p_{2,4} X_{2,4} + \ldots\right)$$

In other words, all the predominant terms, those dependent on the predominant, independent terms, and non-predominant terms are regarded as quasi-permanent.

In serviceability and operational limit states,the weighting coefficients are equal to the unit for all types of combination.

Note *In the case of the verification of the failure mode, sliding as a rigid body of a dock built with a caisson on a quarry basement in normal operational WOCs during the useful life of the structure, the following agents can be considered:*

Gravitational agent:Action,Own Weight, P_p

Soil agent:Action, E_T*, horizontal force of the soil*

Agents of use and exploitation:

Storage:Action, E_T*, horizontal force of the load*

Loading and unloading elements, crane: Action, H_G*, horizontal force and* V_G*, vertical force*

Boat docked:Action, H_B*, bollard force,* H_D*, and (horizontal) pressure against the fender*

Own weight is a permanent action and the rest are non-permanent.Actions or terms associated with own weight,the weight of the crane, and the pressure against the fender are regarded as favorable, whereas all the rest are regarded as unfavorable. Predominant agents and actions are those caused by the soil and the storage loading.

- *Verification equation*

The horizontal sliding mode is written in the safety margin format.

$$S = \sum_{i=1}^{I} a_i X_{1,i} - \sum_{j=1}^{I} b_j X_{2,j}$$

Terms

Favorable vertical terms: $X_{1,1} = P_p; XI_{,2} = V_G$

Favorable horizontal terms: $X_{1,2} = H_D$

Unfavorable vertical terms: none

Unfavorable horizontal terms: $X_{2,1} = E_T; X_{2,2} = E_S; X_{2,3} = H_G; X_{2,4} = H_B$

- *Basic weighting coefficients:*

Useful life, operational and extreme WOCs, and ultimate limit state

Terms

favorable permanent terms: P_p, $p_{1,1} = 1.00$

favorable non-permanent terms: V_G, $p_{1,2} = 1.00$

unfavorable permanent terms: E_T, $p_{2,1} = 1.35$

unfavorable permanent terms: E_S, $p_{2,2} = 1.50$; H_G, $p_{2,3} = 1.50$; H_B, $p_{2,4} = 1.50$

- *Combination type: Fundamental*

Predominant soil agent

Basic compatibility coefficient:

Useful life, operational and extreme WOCs.

Predominant term due to the action of the soil, $\Psi^0_p = 1.00$

Other independent simultaneous agents:

storage loading, crane and boat, $\Psi^0 = 0.70$

Gravitational agent: $\Psi_I = 1.00$

The verification equation for the sliding mode, assigned to an ultimate limit state in normal operational WOCs with the fundamental combination type during the useful life project phase is:

$$S = \mu(p_{1,1}\, P_p + \Psi^0\, p_{1,2} V_G) - \{(\Psi^0_p\, p_{2,1} E_T + \Psi^0\, p_{2,2} E_S) + \Psi^0\, (p_{2,3}\, H_G + p_{2,4}\, H_B)\}$$

$$S = \mu(P_p + 0.7V_G) - \{(1.35\, E_T + 0.7 * 1.50\, E_S) + 0.7\, (1.50\, H_G + 1.50\, H_B)\}$$

Note that the soil and the storage loading are considered to be both permanent and unfavorable terms, and as a result, the weighting coefficient is 1.35 and 1.50, respectively. However, the compatibility coefficient for each of them is different.The term,due to the soil,has a predominant agent coefficient,while the coefficient of loading is that of a simultaneous and compatible agent.

5.4 Annex: Other Level I Verification Methods

There are also other methods besides the global safety coefficient method and the partial coefficients method. One of them is known as the method "design load and resistance factor", proposed by Ravindra and Galambos (1978), which, as a general rule is applied in the USA, with the safety verification format of the ACI. In this method, the criteria for the combination of terms and the determination of the weighting and compatibility coefficients are regulated and must be complied with.

For buildings, four types of loads (terms) are defined that should be verified, although there is no guarantee that they are sufficient for certain special situations. In this respect, the following loads (actions) are considered:dead weight and the heaviest live loads,due to wind and snow in the useful life of the structure.These loads are quantified in terms of their average (maximum) weight, and are weighted and compatibilized by means of a specific coefficient for each one of them,known as the weight factor. The four types of load combination are: (1) live and dead loads; (2) dead loads, wind, and live loads affected by a coefficient that transforms the average maximum weight in a "sustained" load, which in these Recommendations is a frequent value; (3) dead loads,"sustained" live loads, and snow; (4) wind and minimum dead load.

In the four cases,the verification condition is that the superposition of the loads, affected by a load factor, must be less than the nominal resistance affected by a resistance factor.

The method that is most similar to the partial coefficients method is the one presently used in Canada for the verification of building structures, NRCC and CSA. Their structure is analogous to the design factor of the ACI in that there is only one resistance factor. However, it significantly increases the number of load combinations. Furthermore, it includes compatibility coefficients for the loads due the concurrent factors of the physical environment. The value of the compatibility coefficient for the first factor is equal to 1, whereas the two following factors can have values of 0.7 and 0.6, respectively.The weighting coefficients are determined according to the value of a coefficient or factor of importance which is used to measure the importance of the failure in the structure.

Finally, there is the method proposed by the European Committee of Concrete (ECC), which is the one that most resembles the partial coefficients method, as described in these

Recommendations. This method defines the following elements: (1) partial coefficients and reducing coefficients of the resistant properties of the building materials, which are applied with characteristic values; (2) weighting coefficient and compatibility coefficient of the loads that affect in each case the characteristic values. The verification equation is an inequality in which resistant terms are compared with load terms.

Different weighting and compatibility coefficients are proposed for ultimate and serviceability limit states. Loads are classified as fundamental and accidental for the verification of ultimate limit states, and as frequent, quasi-permanent, and infrequent for the verification of serviceability limit states. Furthermore, different compatibility coefficients are applied to the most unfavorable loads and the other loads that are different from the dead and live loads. Such loads are applied with maximum and minimum values affected by the weighting coefficients that depend on the type of participation in the result of the verification equation.

Table 5.9: Compatibility coefficients, CEB (1976)

Limit state	Load	Ψ_1	Ψ_i, i >1
Ultimate	Fundamental	1.0	A
	Accidental	B	C
	Infrequent	1.0	B
Serviceability	Quasi-permanent	C	C
	Frequent	B	B

The values of A,B and C depend on the type of building and agent according to the following table:

Table 5.10: Compatibility coefficients 2, CEB (1976)

	A	B	C
Houses	0.5	0.7	0.4
Offices	0.5	0.8	0.4
Other buildings	0.5	0.9	0.4
Car-parks	0.6	0.7	0.6
Wind	0.55	0.2	0.0
Snow	0.55 and 0.4		

Each method leads to a different number of verifications. Thus, for example, a building, subject to live and dead loads, wind and snow, which verified by the design factor method (USA), results in four load combinations. In contrast, the same building verified by NRCC and CEB methods result in fourteen and thirty-two load combinations, respectively. The partial coefficients method, as described in these Recommendations, leaves the number of verifications open. This number mainly depends on the experience of the person applying it, who determines the number and type of combinations to be verified.

CHAPTER 6
Level II and III Verification Methods

6 LEVEL II AND III VERIFICATION METHODS

6.1 Introduction

For a given project design alternative and time interval, the safety serviceability, and exploitation requirements of the maritime structure should be verified against all the modes assigned to ultimate, serviceability, and operationality limit states. Level II and III Verification Methods can be used to check the subset of the structure against a mode and evaluate its probability of occurrence in the time interval. These methods are described in this chapter.

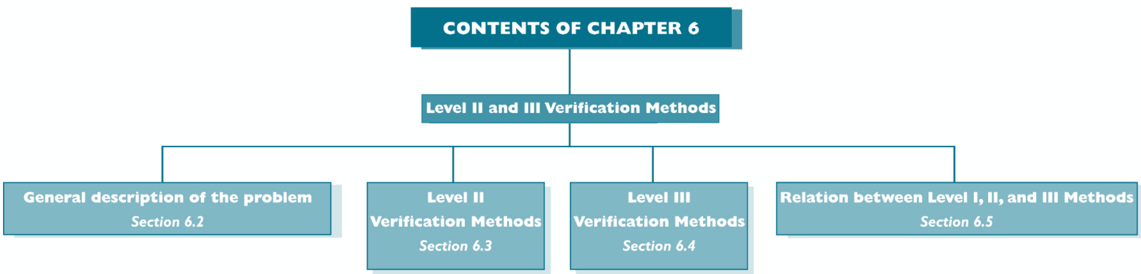
6.1.1 Chapter organization and contents

The first part of this chapter is a general formulation of the problem: calculation of the probability of the failure or stoppage mode occurring in a subset of the structure in a given time interval. The following is a description of a Level II Verification Method, elaborated on the basis of second-order statistical moments, mean, and variance.

This method can be applied with various orders of approximation. The most popular of these is that derived by linearizing the verification equation. It is thus known as a first-order or first order reliability method approximation (FORM). This is followed by a description of Level III Verification Methods, which include the simulation methods. Regarding the latter, this ROM proposes a method based on the Monte Carlo algorithm. Figure 6.1 is a schematic outline of the sections of this chapter and their relations.

Note *In the second part of the Recommendations, one of the chapters describes the theoretical aspects of Level II and III Verification Methods, which justify the contents of the chapter, as well as statistical formulations that can be used in the application of these Recommendations.*

Figure 6.1: Chapter 6. Organization and contents



6.2 General description of the problem

The n project factors which may participate during the occurrence of a failure of stoppage mode of a subset of a structure are defined by the n-dimensional vector X $(X_1, X_2, \ldots X_n)$, and their joint density function in the time interval $f_{X1 \ldots Xn}(x_1, \ldots x_n)$. The verification of the mode, $S = G(X_1, X_2,$

...X_n) = 0, defines a critical hypersurface in the n-dimensional space, such that S = G > 0 is the safety domain and S = G ≤ 0 is the failure domain. In a time interval T_L, the probability of occurrence of the mode i,denoted by $p_{f,i}$, and the reliability, $r_{f,i}$, can be calculated by means of the following n-multiple integrals:

$$p_{f,i}(T_L) = \int_{G(x_1,x_2...x_n)\leq 0} ... \int f_{x_1,x_2...,x_n}(x_1,x_2...,x_n)\,dx_1 dx_2 ... dx_n$$

$$r_{f,i}(T_L) = 1 - p_{f,i} =$$

$$\int_{G(x_1,x_2...x_n)>0} ... \int f_{x_1,x_2...,x_n}(x_1,x_2...,x_n)\,dx_1 dx_2 ... dx_n$$

The evaluation of the integral or the probability of failure can be carried out by means of direct integration (though this is rarely possible), numerical simulation (e.g. Monte Carlo, Level III) or by transformation of the participating variables into independent Gaussian variables (Level II). (See figure 6.2).

6.2.1 Application and limitations

Before applying any verification method, one must know the verification equation that quantifies the occurrence of the failure mode. Once the project phase, limit state, WOC, and combination type have been selected,the term values and the result of the equation can be obtained by following the work sequence described for each of the Level II and III Verification Methods.

It is assumed that the density and distribution functions, as well as statistical descriptors of the project factors do not change during the interval in which the mode is verified. In a parallel way,

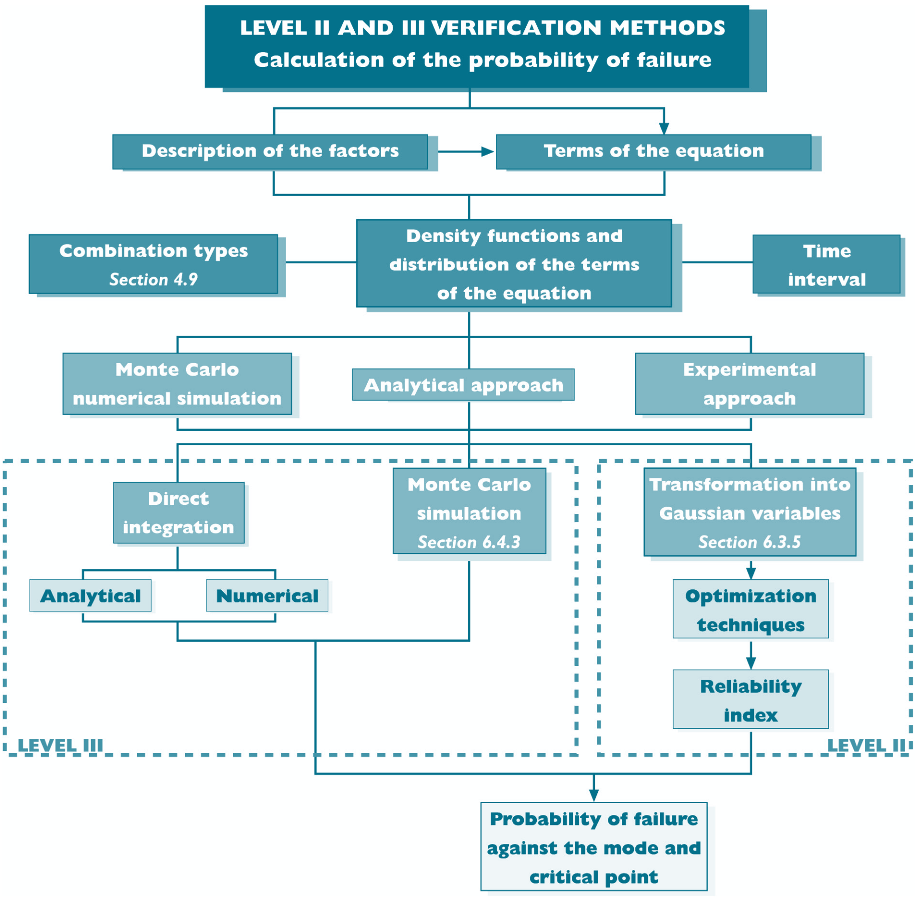


Figure 6.2: Level II and III Verification Methods

the verification equation used to analyze the mode can be regarded as valid in the time interval. In other cases, it is necessary to divide the time interval into smaller intervals in which the process involved can be considered stationary.

6.2.2 Joint probability of failure in the useful life phase

In consonance with the intrinsic nature of the maritime structure, Chapter 2 proposes maximum values for the probability of failure of the structure against the principal modes, assigned to the ultimate and serviceability limit states (see tables 2.3 – 2.5), and for the minimum operationality against the principal stoppage modes that can occur in the useful life project phase. Chapter 6 develops methods to analyze the probability of occurrence of one mode in a time interval. Based on this information, the calculation of the overall probability of the subset is carried out according to the recommendations in Chapter 7.

6.3 Level II Verification Method

A Level II Verification Method is recommended for the verification of failure modes and operational stoppage modes of maritime structures whose general or operational intrinsic nature is in the interval $[r \geq r_3, s \geq s_2]$ o $[r=r_3]$ o $[s \geq s_3]$, (see table 4.6). Figure 6.3. is a schematic outline of the sequence of activities for the application of a Level II Verification Method.

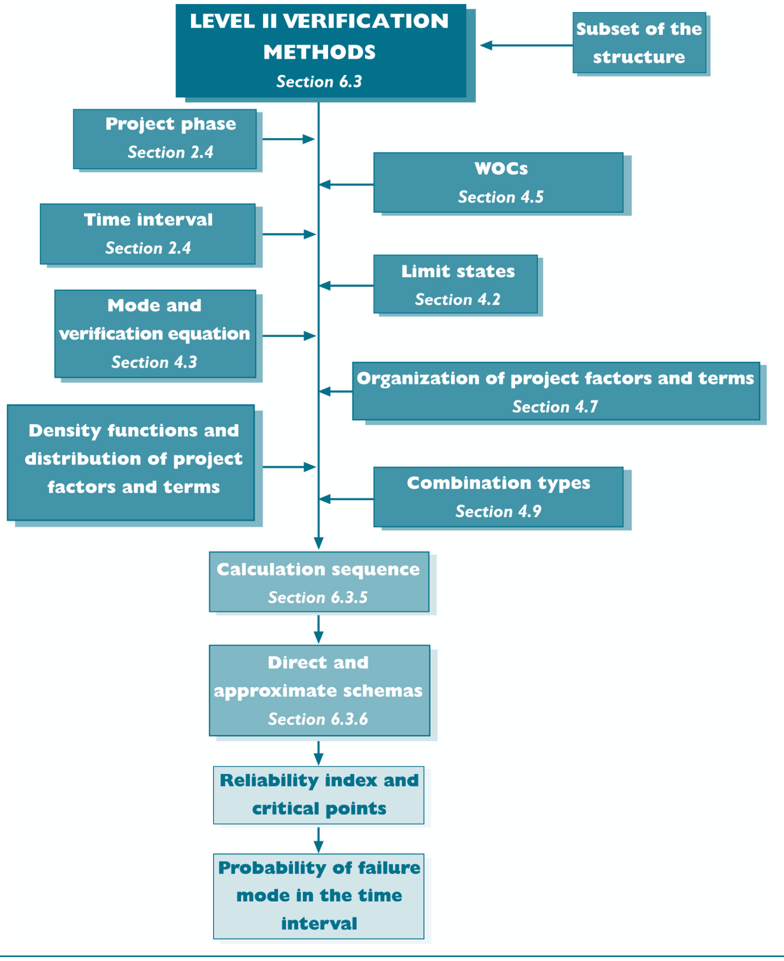


Figure 6.3: Application sequence of a Level II Verification Method

6.3.1 Introduction and definitions

With this method the probability of failure can be obtained by evaluating the minimum distance between the origin of the coordinates and the failure or stoppage surface, defined by the verification equation, $G(X_1,X_2, ..., X_n)=0$.Generally speaking, the project factors are random variables, whose density and distribution functions are known.

Note *Unlike Level I Verification Methods, in which certain parameters, such as the mechanical properties of building materials and soil, should take a reducing coefficient associated with the characteristic value (if they participate in the unfavorable term), Level II and III Verification Methods statistically describe the parameters in the same way as the other project factors. Furthermore, the equation terms are not affected by weighting and compatibility coefficients as occurs in the partial coefficients method (Level I).*

Given that sometimes the verification of a mode is associated with many project factors, it is convenient to maximally simplify the number of variables to be considered.

6.3.2 Organization of the project factors

This is a continuation of the organization of project factors proposed in section 4.7. For each project phase and time interval,factors are selected, and on the basis of the WOC involved,the set of simultaneously participating project factors is specified. Consequently, for each limit state and failure mode, the set is configured according to the participation of the factor in the occurrence of the failure mode. First come the predominant factor and those of the same origin, which are dependent on the predominant.They are followed by the independent factors,and within this category, those of the same origin which are mutually dependent, and finally, project factors that are totally independent.This set is the basis for the definition of combination types (see section 4.9).

6.3.3 Verification equation

Generally, the verification equation takes the safety margin format.The criteria, hypotheses, and dimensions of the terms with which it was originally proposed must be preserved.

Note *Furthermore, the application of a Level II Verification Method necessarily entails knowing the probability model of each term of the equation.*

6.3.3.1 Value of the factors with a probability model

The organization of project factors is specified according to the availability of information and summarized in the joint, conditional, and marginal distribution functions of the different project factors. In those cases in which the conditions established in section 3.5 are fulfilled, the factor can be regarded as deterministic.

6.3.3.2 Value of the factors without a probability model

Certain factors, because of their intrinsic nature or because no statistical information is available concerning them, will not have a probability model, and will thus take a nominal value. In any case, in order to be able to generalize both the method and its results, the nominal value should be associated with a probability model which,if sufficiently justified,should be a normal,lognormal,or other type of model, chosen according to the nominal value and its possible dispersion.

Note *If the nominal value is an average value, a Gaussian model should be associated with it after a typical deviation is estimated. If the nominal value is a minimum or maximum value, the probability model can also be normal. However, in this case, the nominal value is the value of an upper distribution quantile, (0.90, 0.95, 0.99) or a lower distribution quantile (0.01, 0.05, 0.10). By estimating the typical deviation, the average value of the Gaussian distribution function is obtained.*

The same process can be used when the project factor belongs, for example, to the upper tail,and can be assigned a Gumbel distribution function. In such cases, the two distribution parameters can be estimated, and on the basis of this calculation, any other value can be obtained.

6.3.3.3 Correlation between factors or terms

In the application of a Level II Verification Method, the following types of correlation between factors or terms should be considered:

6.3.3.3.1 Uncorrelated or weakly correlated factors or terms

When the correlation coefficient between two factors or terms is less than 0.2, [$\rho XiXj < 0.2$], the two variables can be considered statistically independent, and the joint density function is equal to the product of the marginal density functions.

6.3.3.3.2 Strongly correlated factors or terms

When the correlation coefficient between two factors or terms is greater than 0.8, [$\rho XiXjj > 0.8$], the two variables can be considered totally dependent to the extent that the value of one of them can be replaced by the proper value of the other one.

6.3.3.3.3 Correlated factors or terms

When the correlation coefficient of two factors or terms lies in the interval [$0.2 \leq \rho_{X_iX_j} \leq 0.8$], they should be treated as such, applying the method of transformation suggested (see 6.4.3.4).No reducing coefficient should be applied.

6.3.3.4 Reducing coefficient of the project parameters

The project parameters have the same statistical treatment as any other project factors. This would include their possible functional and statistical relation with other factors.

6.3.4 Joint, conditional, and marginal distribution function of the terms

Whenever possible, the distribution function of terms should be obtained analytically so that the probability of occurrence of the mode can be calculated by direct integration in the domain of the density function of the safety margin. When this is not feasible, the method described in the following sections should be used.

Note *When there is insufficient statistical information regarding the terms of the equation,it is convenient to specify the relevant factor of each term, since this can be the source for the density function of the term. At the same time, the nominal or deterministic values of the other factors that participate in the terms should also be considered, according to sections 5.3.1.2 and 5.3.4.1.2.*

6.3.5 Combination types

Until more statistical information is available regarding the joint distribution functions of project factors participating in the verification of a mode, a Level II Verification Mode can be applied, while taking into account the classes of values and combination types of terms recommended in sections 4.7, 4.8 and 4.9. They can be used to reduce the number of factors and terms, and in consequence, the necessity of a joint distribution functions of factors or terms.

6.3.6 Calculation sequence

The Level II Verification Method, the solution to the problem described in section 6.2, is obtained by minimizing a function subject to certain restrictions. This calculation can be carried out directly. Nevertheless, in some cases, it is necessary to use approximation techniques as described in this section.

To find a solution, these Recommendations propose an iterative schema in which the data specified in the previous sections is used to obtain project factor values of the critical point of the surface of the failure and the associated probability.

The calculation sequence includes: (1) the transformation of the variables that participate with a probability model in reduced, uncorrelated Gaussian variables; (2) the transformation of the verification equation to the new variables; (3) the calculation of the minimum distance of the origin of coordinates to the surface of the failure represented by the verification equation. This sequence is specified in calculation schemas that are presented in the following sections:

Note

In step (1) it is decided what the tails of the probabilistic distribution are like. This can have an important influence in the result, especially when the reliability index is high. For this reason, it is recommended that for projects with a high SERI index (SERI > 20), their safety should be verified along with some Level I Verification Method.

Moreover, in recent years with the development of computers, optimization problems with restrictions can be directly resolved by using software packages, which in many cases are of public domain. When such numerical techniques are established in the context of civil engineering, the approximation proposed in the following sections will not be strictly necessary.

6.3.6.1 Results of the application of the method

The result of the application of the method is: (1) the critical point of failure expressed in reduced and original variables; (2) the reliability index and the probability of failure or stoppage; (3) the sensitivity indices of the factors.

6.3.6.2 Deterministic project factors according to the sensitivity indices

The sensitivity index varies falling between [–1, 1]. Its value provides an indication of the relative importance (or contribution) of the factor (or term) variability in relation to the probability of occurrence of the mode. If the contribution is small (sensitivity index close to zero) compared with that of other factors, the factor can be considered deterministic, and depending on each case, it is possible to work with a representative value, mean, mode, upper or lower characteristic value, nominal value, etc.

6.3.7 Calculation schemas

Whenever possible, the calculation of the minimum distance can be carried out by directly applying numerical optimization techniques. However, in other contexts, approximation techniques can be used, particularly, first-order approximation techniques that linearize the surface of the failure around the critical point.In such cases,Level I or III Verification Methods can be used to obtain an initial assessment of the critical point. Afterwards, on the basis of this information, the linear approximation of Level II can be applied.

6.3.7.1 Direct schema

When the calculation can be made by optimization techniques,all random variables should be previously transformed into uncorrelated random Gaussian variables.The work schema is the following:

1. Transformation of variables $(X_1, X_2, ..., X_n)$, into reduced normal variables $(Y^*_1, Y^*_2, ..., Y^*_m)$, $m \leq n$
2. Expression of the verification equation, $G(X_1, X_2, ..., X_n) = 0$, in reduced variables, $g(Y^*_1, Y^*_2, ..., Y^*_m) = 0$
3. Estimation of an initial critical point by using other methods,(Level I or III),or a root of the verification equation, or previous experience.
4. Application of an optimization algorithm

6.3.7.2 Schema in the case of a non-linear verification equation

(1) See section 6.3.2.3

The verification equation , $G(X) = 0$, is not linear, and the terms, X_i, $i = 1, ...n$, are not uncorrelated normal random variables[1], an iterative schema can be applied which implements the following steps:

1. Transformation of variables $(X_1, X_2, ..., X_n)$, into uncorrelated reduced normal variables, $(Y^*_1, Y^*_2, ..., Y^*_m)$, $m \leq n$, (i.e applying the Rosenblatt transformation)
2. Expression of the verification equation, $G(X_1, X_2, ..., X_n) = 0$, in reduced variables, $g(Y^*_1, Y^*_2, ..., Y^*_m) = 0$
3. Estimation of an initial critical point, generally, a root of the equation
4. Development of a Taylor series ($g = 0$) around that root, only taking the linear term
5. Calculation of the reliability index β and the sensitivity indices α_i
6. Calculation of a new critical point
7. Continuation with the iteration until the results are stabilized

Finally, it is advisable to effectively verify that the critical point satisfies the verification equation.

6.3.8 Calculation codes with Level II Verification Methods

Since most of the time a Level II Method should be applied using numerical techniques,in the second part of these Recommendations along with the management program and guide, numerical codes are included that help the evaluation of the probability of the occurrence of a mode. This is done once the verification equation, project factors,and the joint, conditional,and marginal distribution functions have been defined. When this is the case, a calculation schema should be used that is in consonance with the surface irregularity of the failure.

Note *As shown in the following section,one of the Level III Verification Methods uses the Monte Carlo numerical simulation technique. Although this technique is very powerful, it limits the number of random project factors. The reason for this limitation resides principally in the computation time. One way of resolving this problem is to apply the Level II Verification Method to obtain the sensitivity index of the factors. The value obtained with this method can then be adopted for those that are less relevant. In this way the number of random project factors (which usually should not be greater than five) is reduced.*

6.4 Level III Verification Methods

A Level III Verification Method is recommended to verify failure and operational stoppage modes of the maritime structures, whose general or operational intrinsic nature is in the interval, $[r \geq r_3, s \geq s_2]$ o $[r = r_3]$ o $[s \geq s_3]$, (see table 4.6). Figure 6.4 is a schema of the sequence of activities to be carried out in the application of a Level III Verification Method.

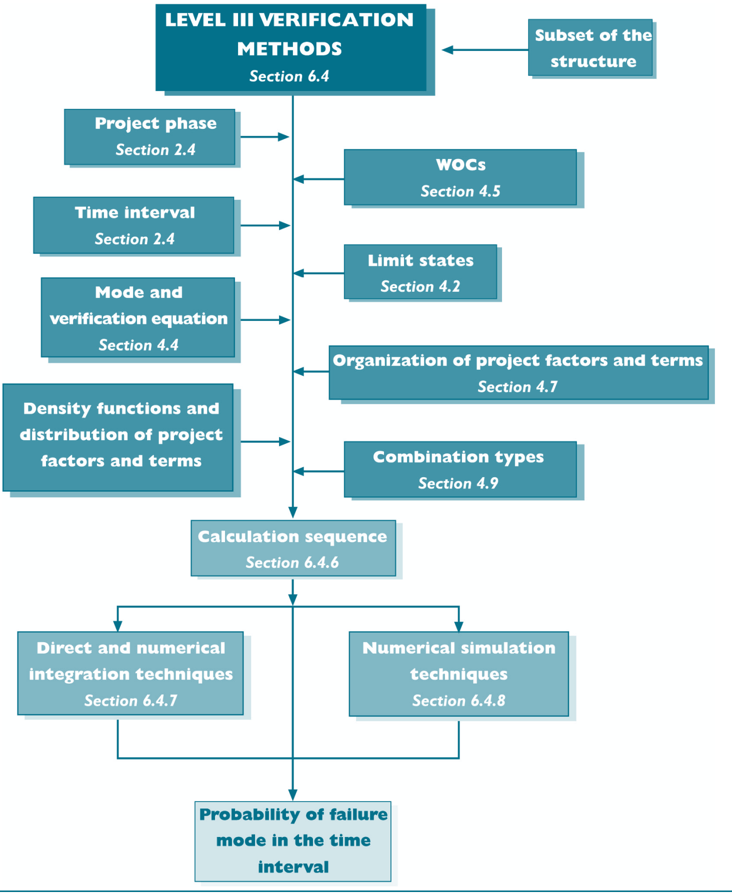


Figure 6.4: Application sequence of a Level III Verification Method

6.4.1 Introduction and definitions

Level III Verification Methods are those methods that solve the integral to evaluate the probability of failure, either by means of integration or simulation techniques. Generally speaking, the integration necessary to obtain the probability of failure can only be carried out analytically in certain cases. Consequently, Level III procedures are normally composed of numerical techniques, applied to the integration process in itself as well as to the integrand or the definition of the failure domain.

When the joint density function cannot be integrated either analytically or numerically, the values of the verification equation terms can be numerically simulated, obtaining the density function of the safety margin.This simulation can be carried out by using the Monte Carlo technique

6.4.2 Organization of factors

The organization of factors is that proposed in section 4.7. For each project phase and time interval existing factors are selected, and on the basis of the WOC, the set of simultaneously participating project factors is created.Afterwards, for each limit state and failure mode, the set is organized according to the participation factor in the occurrence of the failure. First come the predominant factor and those of the same origin, which are dependent on the predominant. They are followed by the independent factors, and within this category, those of the same origin which are mutually dependent,and finally, project factors that are totally independent.This set is the basis for the definition of combination types (see section 4.9).

Note *Since the joint density function of the project factors participating in each of the terms is usually not available, and the simulation technique requires many hours of computation, it is advisable to use the organization of factors to define terms and factors that are independent, dependent, of the same origin as the other factors or terms, but particularly as the predominant factor.*

6.4.3 Verification equation

The verification equation is generally established in the safety margin format, taking into account the criteria, hypotheses and dimensions of the terms with which it was originally proposed.

Note *Moreover, in order to apply a Level III Verification Method,one must know the probability model of each project factor participating in the equation or of each term in the verification equation.*

6.4.3.1 Value of the factors with a probability model

The organization of project factors is specified according to the availability of information and summarized by the joint, conditional, and marginal distribution functions of the different project factors. In those cases in which the conditions established in section 3.5 are fulfilled, the factor can be regarded as deterministic.

6.4.3.2 Value of the factors without a probability model

Certain factors, because of their intrinsic nature or because no statistical information is available concerning them, will not have a probability value, and will thus take a nominal value. In any case, in order to be able to generalize the method and its results,the nominal value should be associated with a probability model which, if sufficiently justified, should be a normal, lognormal, or other type of model, chosen according to the nominal value and its possible dispersion.

6.4.3.3 Correlation between factors or terms

In this respect,the recommendations concerning the application of the Level II Verification Method should be followed (see section 6.3.3.4ff).

6.4.3.4 Reducing coefficient of the project parameters

The project parameters are subject to the same statistical treatment as any other project factor. This includes their possible functional and statistical relations with other factors. No reducing coefficient should be applied.

6.4.4 Joint, conditional, and marginal distribution function of the terms

Whenever possible, the distribution functions of the terms should be obtained analytically in such a way that the probability of occurrence of the mode can be calculated by direct integration. In other cases,the method described in the following sections should be used.

Note *When there is insufficient statistical data about the equation terms, it is convenient to specify the relevant factor of each term since on the basis of this factor, it may be possible to obtain the density function of the term. This can be done by considering the representative or deterministic values of the other factors that participate in the equation, as described in sections 5.3.1.2 and 5.3.4.1.2.*

6.4.5 Combination types

Until there is more statistical information available pertaining to the joint distribution functions of the project factors participating in the verification of a mode, the Level III Verification Method should be applied, taking into consideration the classes of values and term combination types recommended in sections 4.7, 4.8 and 4.9. They are the means by which the number of factors and terms can be reduced, and as a result, the necessity of using the joint distribution functions of all the factors and terms.

6.4.6 Calculation sequence

In any of its modalities, the Level III Verification Method is generally solved numerically. In these Recommendations a sequence is outlined,which,based on data specified in previous sections,provides the values of factors belonging to the critical point of the surface of failure and its associated probability.

The calculation sequence includes:(1) the determination of the joint density and distribution functions of the project factors according to their organization. This can be carried out, either analytically or by simulation; (2) the determination of the joint density and distribution functions of the terms of the equation based on the distribution function of all participating factors. This can be done either analytically or by simulation; (3) Calculation of the probability of failure by numerical integration or simulation.

6.4.6.1 Results of the application of the method

The results of the application of the method are the following:the critical point of failure and the probability of failure or stoppage mode of the structure or one of its elements against a mode assigned to a limit state, presented during a project phase in a WOC for a combination type. Based on this information and by means of a sensitivity analysis, it is possible to study the contribution of each factor and term to the result.

Note *In those cases in which there is little statistical data or failure surfaces with multiple extremes, it is advisable to first carry out an approximate calculation of the critical point of failure by means of the Monte Carlo simulation,considering the relevant factors of each term as random variables.The values of the variables associated with the critical point can be used as initial values in the iterative schema of calculation of the Level II Verification Method.In this way, both Level II and III Methods are complementary and their utilization can permit an optimization of the implementation times, as well as a deeper knowledge of the behavior of the subset of the structure.*

6.4.7 Techniques of numerical integration

Whenever possible, the probability of failure is obtained by the analytical integration of the density function of the safety margin. Consequently, it is necessary to obtain this function analytically, based on the density functions of the terms of the verification equation.This calculation generally leads to an n-multiple integral.

The n-multiple integral may be solved by means of n simple integrals,bearing in mind the possible statistical independence of the terms. In these cases the integrals can generally be solved analytically.When this is not possible, numerical methods can used.These have to be contrasted methods, for example, the Simpson rule, quadrature, polynomial techniques, etc.

6.4.8 Monte Carlo simulation

The value of an integral can be obtained by applying the Monte Carlo simulation technique. For this reason, the following aspects, which are related to the generation of uniform random numbers, size of the sample , and convergence of the method, should at least be considered.

Note *To assess the probability of failure, it is necessary to know the range of values for which the failure condition is fulfilled, in other words, $G(x) \leq 0$.The estimate of p_f can be improved by adjusting a distribution function only to the points x, for which the failure condition is fulfilled.The failure is generally produced for values of the variable found in the tail of the distribution function.This is where the adjustment is normally more complicated because of the lack of data and the behavior of the random variable in the distribution tail.This is particularly important when one is working with values belonging to the upper or lower tail.The adjustment of the tails is always a critical aspect in the utilization of a numerical simulation method.*

6.4.8.1 Generation of random numbers

(2) An introduction to the theorem is given in Part II,which is published in another volume.

The generation of uniform random numbers based on any distribution function is in accordance with the theorem of the integral transformation of probability[2].

Note *Generally speaking, the generation of random numbers with uniform distribution (0,1) can be done by means of a lineal generator based on the recursive calculation of whole numbers k_1, k_2, ...within the inter-*

val (0,m – 1), on the basis of which, the value of u would be the following:

$$u_{i+1} = \frac{k_{i+1}}{m} = u_i - ent\left[\frac{u_i}{m}\right]$$

$$u_i = \frac{ak_i + c}{m}$$

In the above, a and c are the multiplicator and the increment, respectively. The results depend on the magnitude of the constants a, c, and m.

This generation is deterministic in the sense that the series is repeated with a certain period or cycle not greater than m. To begin the generation process, it is necessary to specify a, c, m, and the first value, k_0, taking into consideration that m should be as large as possible, c and a should be sufficiently large and not have any factors in common, while k_0 can be of any value between 0 and m–1. Once these values are specified, the complete series can be predicted. Since it is a question of pseudo-random numbers, the process can be regarded as deterministic. However, the resulting series of numbers, u_i, ($i \leq m$) is adjusted to a uniform distribution, and are stochastically independent.

6.4.8.1.1 Other aspects related with generation

It is frequently necessary to generate random numbers of discrete or joint distributions. In such cases, the following is advisable:

6.4.8.1.1.1 Generation of discrete variables

Unless there is sufficient justification, the discrete variable (x_i) corresponding to the random number (u_i), is obtained by applying the inverse transformation of the accumulated probability function, $F(x_i)$ (obtained as a sum of probabilities). This transformation limits the interval of values of u, $[F_X(x_i - 1) < u \leq F_X(x_i)]$ where x_i, is the value of the random number. When duly justified, other generation techniques can be applied.

6.4.8.1.1.2 Generation of mutually dependent variables

If n terms in the verification equation are mutually dependent, the generation of random numbers can be carried out in cascade, taking into account their joint, marginal, and conditional distribution functions.

6.4.8.1.1.3 Other generation methods with continuous variables

When it is difficult to obtain the inverse function $x = \Psi(u)$ of a distribution function $u = F_X(x)$, and it is impossible to derive it by analytical methods (as happens with normal, lognormal, beta, and gamma distributions), other generation techniques can be applied, such as the Box Muller or the rejection and decomposition method. In any case, the demands of uniformity and the independence of the sample should always be verified.

6.4.8.1.2 Adjustment of the distribution function, $F_X(x)$

In all these cases, it is advisable to adjust the distribution function to the domain or region in which the failure is going to occur, as well as to optimize the parameters through adjustment techniques.

6.4.8.1.3 Verification of the uniformity and statistical independence of the sample

In all cases,it should be verified that the sample generated follows a uniform distribution,and that its numbers are stochastically independent.

6.4.8.2 Number of samples required

Once a level of significance α, is chosen, and an error ε, the minimum size of the necessary sample N can be obtained by evaluating the following equation:

$$N = \frac{z^2_{\frac{\alpha}{2}}(1-p)}{\varepsilon^2 p}$$

In the above, $z_{\alpha/2}$, is the value of the reduced normal variable that is exceeded with a probability of (1 - α/2)%,and p is the probability that the mode will occur. Since p is unknown before the simulation is carried out, it is necessary to make an assessment of p a priori.

Note *When α =5%, (which is the equivalent of an accumulated probability of exceedance in the case of α/2 of 97.50%) ε = 0.05, and, p = 0.1, N > 13400.*

6.4.8.2.1 Size of the sample and convergence

On many occasions, it is advisable to draw the successive evaluations of p_f, and the estimate of their variance in accordance with the size of the sample N.This curve should be descending and its oscillations (i.e. the stability of the calculation) should be reduced as the size of the sample increases. In all cases, it is convenient to use information a priori concerning the problem to be solved, especially data conducive to mapping out the area of failure.

6.4.9 Calculation program for Level III Variation Methods

Given that in the majority of cases,the application of a Level III Variation Method should be carried out by using numerical techniques,in part II of these Recommendations, along with the help program, certain numerical codes are described. Once defined the verification equation, project factors, and their joint, conditional, and marginal distribution functions for each project phase, limit states, WOC, and combination type, they should facilitate the evaluation of the probability of occurrence of the mode,.

In each case, the information available determines the type of application involved: numerical integration of the density function or the simulation of the density function of the safety margin and of each of the terms of the equation.

6.5 Relation between Levels I, II, and III

The incorporation of Level II and III Verification Methods is still closely related to applied research. The majority of the verification equations of the failure and operational stoppage modes were obtained for their application with Level I Verification Methods, more specifically, the global safety coefficient method.The transition from this verification equation format to that of safety margin should not modify the previously acquired and verified safety standards. For this reason,it is necessary to establish general criteria for the adequation of one equation format to the other.

6.5.1 Determination of the weighting coefficients

In the specific Recommendations, verification equations are provided that should be used in each of the failure or stoppage modes. In the case that the equation is in the global safety coefficient format and there is no information pertaining to its application in the partial coefficients format, weighting coefficients must then be obtained. Once defined the project design alternative, subset of the structure, project phase, limit state, WOC, and combination type necessary to obtain weight-ing coefficients, the following procedure should be followed:

Generally speaking,what one tries to obtain is a relation between the coefficients of a verification equation expressed according to the characteristic values of the project factors,sensitivity indices, and reliability index, resulting from the application of a Level II Verification Method.This relation is used to minimize the root mean square error of the reliability index in question. If this is not feasible, a numerical procedure can be applied that follows the sequence described in the sections that follow.

Note *One of the objectives of the specific Recommendations is to provide partial coefficients for the verification of failure modes whose equation does not have that format.When these coefficients do not exist and the subset must be verified by the partial coefficients method, the value of the coefficients must be determined by the engineer, according to the criteria described in this section.*

6.5.1.1 Non-unicity of the weighting coefficients

In any case, it must be stressed that a change of equation format can modify the relation between terms.As a result, one should work, whenever possible, with dimensionless terms and verify that in all cases,the relation between values is preserved in all equation formats.The partial coefficients obtained are only valid for the conditions in which they have been calculated,and their application should be justified in each case. Other techniques or equation formats may produce different partial coefficients.

6.5.1.2 Sequence for the calibration

In the calibration process the sequence below can be followed:

1. Definition of the failure criteria,the probability of failure, or the reliability index of the mode
2. Organization of the project factors and definition of the classes of values
3. Application of the global safety coefficient method (if relevant)
4. Application of the partial coefficients method defining the weighting coefficients
5. Application of a Level II or III Verification Method with the equation in safety margin format

6. Minimization of the mean square root error of the difference between the probability of failure obtained and the probability of failure desired.

7. Comparison and analysis of the result with that obtained by means of the global safety coefficient.

8. Application of the same analysis for the other principal failure modes

9. Verification of the overall probability of the subset

The minimization is carried out on the basis of weighting coefficients. Such coefficients can be expressed in accordance with the predominant factor of the mode, or the principal factor of the term and its probability model. It is necessary to take into account that objectives of a ROM Project are evaluated by means of the overall probability of failure and operationality of the subset of the structure. Consequently, one should obtain the weighting coefficients for each of the verification equations of the principal failure modes of the subset.

Note *The preceding sequence includes the verification of the overall probability of the subset. This explicitly shows that calibration is not absolute, but rather associated with each subset of the structure, and consequently with its intrinsic nature. The specific Recommendations provide the values of the weighting coefficients to be applied in the different subsets of the structure.*

In 1992, the PIANC WG-12 Committee, formed expressly for this purpose, obtained partial coefficients for the verification of the failure mode, extraction of pieces of the main layer of a breakwater. Two weighting coefficients were defined, one affecting the unfavorable term, whose principal factor is the significant wave height and the other affecting the favorable term that weights the response of the breakwater.

Both coefficients are expressed by a formula that depends in the first case on the significant wave height and the uncertainty of its determination, and in the second, on the probability of failure. The calibration was carried out by a dimensional equation. These values are only indicative.

6.6 Annex: Calculation of overtopping with a Level II Method

The breakwater under consideration is an "Iribarren type" dike with a sloping breakwater tan β, and a freeboard F_c, measured from the still water level (SWL). When a wave reaches the dike, the tongue of water runs up the breakwater with the possibility of overtopping the breakwater. For large freeboards, $Fc \geq 1.2\ H_s$, one way of verifying the occurrence of the overtopping is to calculate the run up R_u, measured from the mean water level (MWL), which would reach the tongue of water for the previously mentioned wave for a hypothetically unlimited slope (see figure 6.5).

Losada (1985), on the basis of experimental results and a dimensional analysis, proposes the following formula to calculate R_u,

$$\frac{R_u}{H} = A_u(1 - e^{B_u I_r}) \qquad (6.1)$$

In the formula, A_u and B_u are coefficients that depend on the type of pieces; H is the wave height;

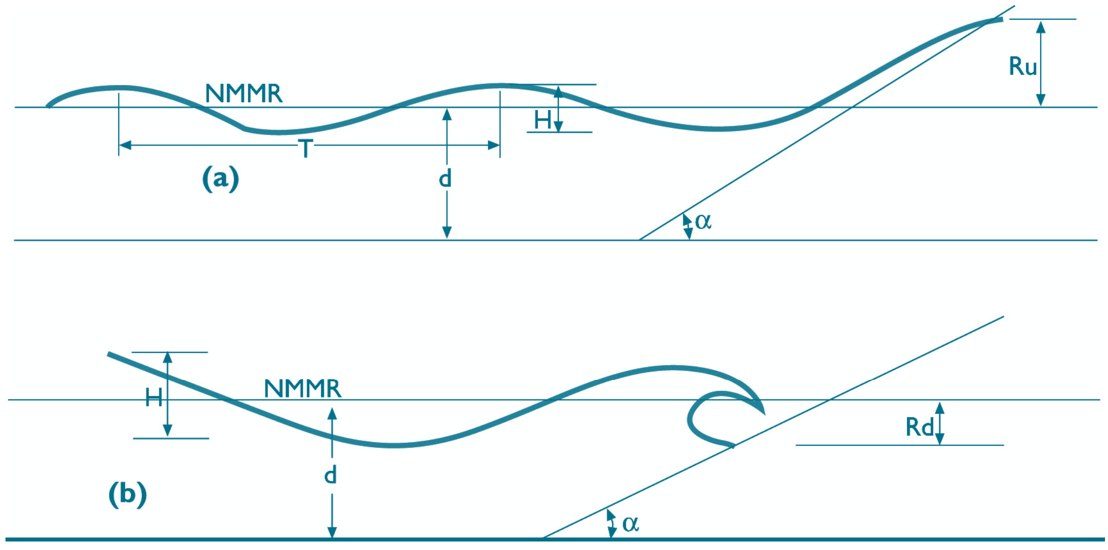


Figure 6.5: Definition of variables

and I_r is the Iribarren number:

$$I_r = \frac{\tan\beta}{\sqrt{\frac{H}{L}}} \tag{6.2}$$

which in deep water can be calculated as:

$$I_r = 1.25T\frac{\tan\beta}{\sqrt{H}} \tag{6.3}$$

In such conditions, the overtopping can be verified by using the equation in the safety margin format:

$$S = F_c - R_u = 0 \tag{6.4}$$

For those parameter values for which S is a non-negative number, no overtopping is produced.

In this example, the freeboard, F_c, and the breakwater slope, tan β, are assumed to be deterministic variables with nominal values F_c =10(m), tan β =1/1.5. A_u and B_u are independent Gaussian random variables of mean values μ_a =1.05, μ_b = - 0.67 and typical deviations σ_a =0.21, σ_b = 0.134 respectively. In a sea state defined by a significant wave height, H_s =5(m), zero up crossing mean period, T_z =10 (s), the wave heights and periods are jointly distributed according to the Longuet-Higgins distribution (1975), of parameters H_s, T_z, and ν = 0.25, whose density function is:

$$f(T,H) = 2L(\upsilon)\exp(u(T_*,H_*))\frac{H_*^2}{\upsilon T_*^2\sqrt{\pi}}\frac{1}{H_sT_z} \tag{6.5}$$

In the above T_* = T/Tz, H_* = H/H_s and L(ν), u(T_*, H_*) have the following expressions:

$$L(\upsilon)=\left[\frac{1}{2}\left(1+\frac{1}{\sqrt{1+\upsilon^2}}\right)\right]^{-1} u(T_*,H_*)=-H_*^2\left[1+\frac{1}{\upsilon^2}\left(1-\frac{1}{T_*}\right)\right] \quad (6.6)$$

As a result, the verification equation is the following:

$$G(A_u,B_u,T,H)=F_c-HA_u(1-e^{B_u l_r})=0 \quad (6.7)$$

Partial derivatives of the function G, whose expressions are necessary in the calculation of the probability of failure by means of the approximation method to the first order are the following:

$$\frac{\partial G}{\partial A_u}=-H\left(1-e^{B_u l_r}\right) \quad (6.8)$$

$$\frac{\partial G}{\partial B_u}=HA_u l_r e^{B_u l_r} \quad (6.9)$$

$$\frac{\partial l_r}{\partial T}=1.25\frac{\tan\beta}{\sqrt{H}} \quad (6.10)$$

$$\frac{\partial l_r}{\partial H}=-1.25T\tan\beta\,\frac{1}{2}H^{\frac{3}{2}} \quad (6.11)$$

$$\frac{\partial G}{\partial T}=HA_uB_u\frac{\partial l_r}{\partial T}e^{B_u l_r} \quad (6.12)$$

$$\frac{\partial G}{\partial T}=-A_u\left(1-e^{B_u l_r}\right)+HA_uB_u\frac{\partial l_r}{\partial H}e^{B_u l_r} \quad (6.13)$$

The initial approximation of the failure point is:

$$X^{(0)}=\left(A_u^{(0)},B_u^{(0)},T^{(0)},H^{(0)}\right)=(1.05,-0.67,10.0,4.5) \quad (6.14)$$

In the first step, the random variables are transformed into reduced normal variables equivalent to the original variables in the neighborhood of the point $X^{(0)}$.

The transformation of the variables A_u and B_u is immediate and valid for all the iterations.

$$Y_1=\frac{A_u-\mu_a}{\sigma_a};\quad Y_2=\frac{B_u-\mu_b}{\sigma_b} \quad (6.15)$$

Regarding the transformation of the variables T and H,the Rosenblatt transformation is used,looking for the reduced normal $Y_3^{(0)}$ and $Y_4^{(0)}$ equivalent to the original variables T and T and H|T (H conditioned to T)in the neighborhood of the point $X^{(0)}$. These variables are:

$$Y_3^{(0)} = \Phi^{-1}\left[F_T(T)\right] \quad Y_4^{(0)} = \Phi^{-1}\left[F_{H|T}(T)\right] \tag{6.16}$$

In the above equation, F_T is the marginal distribution function of T and $F_{H|T}$ is the distribution of H, conditioned to T

The means and variances of $Y_3^{(0)}$ and $Y_4^{(0)}$ are:

$$\sigma_3^{(0)} = \frac{\phi\Phi^{-1}\left[F_T\left(T^{(0)}\right)\right]}{f_T\left(T^{(0)}\right)} = \frac{\phi\Phi^{-1}[0.4884]}{0.2064} = \frac{\phi(-0.0291)}{0.2064} = 1.9320$$

$$\mu_3^{(0)} = T^{(0)} - \Phi^{-1}\left[F_T\left(T^{(0)}\right)\right]\sigma_3^{(0)} = 10 - 0.019 \cdot 1.9649 = 9.9627 \tag{6.17}$$

$$\sigma_4^{(0)} = \frac{\phi\Phi^{-1}\left[F_{H|T}\left(H^{(0)}\right)\right]}{f_{H|T}\left(H^{(0)}\right)} = \frac{\phi\Phi^{-1}[0.5697]}{f_{H|T}\left(H^{(0)}\right)} = \frac{\phi(-0.1755)}{0.1623} = 2.4205$$

$$\mu_4^{(0)} = H^{(0)} - \Phi^{-1}\left[F_{H|T}\left(H^{(0)}\right)\right]\sigma_4^{(0)} = 4.5 - 0.1366 \cdot 2.4363 = 4.1672$$

In the above equation f_T is the marginal density function of T, $f_{H|T}$ is the function of H conditioned to T; and ϕ and Φ are the Gaussian density and distribution function, respectively.

In these new coordinates, the approximation to the failure point is:

$$Y^{(0)} = \left(\frac{A_u^{(0)}-\mu_a}{\sigma_a}, \frac{B_u^{(0)}-\mu_b}{\sigma_b}, \Phi^{-1}\left[F_T\left(T^{(0)}\right)\right], \Phi^{-1}\left[F_{H|T}\left(H^{(0)}\right)\right]\right)$$
$$= \left(0, 0, \Phi^{-1}[0.4884], \Phi^{-1}[0.5697]\right) = (0, 0, -0.0291, 0.1755) \tag{6.18}$$

The Jacobian matrix of the transformation evaluated in $Y^{(0)}$ is,

$$J^{(0)} = \begin{bmatrix} \frac{\partial Y_1}{\partial A_u} & 0 & 0 & 0 \\ 0 & \frac{\partial Y_2}{\partial B_u} & 0 & 0 \\ 0 & 0 & \frac{\partial Y_3^{(0)}}{\partial T} & 0 \\ 0 & 0 & \frac{\partial Y_4^{(0)}}{\partial T} & \frac{\partial Y_4^{(0)}}{\partial H} \end{bmatrix} = \tag{6.19}$$

The partial derivatives of the function

$$= \begin{bmatrix} \frac{1}{\sigma_a} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma_b} & 0 & 0 \\ 0 & 0 & \frac{f_H}{\phi\left(y_3^{(0)}\right)} & 0 \\ 0 & 0 & \frac{\partial F_{H|T}}{\partial T}\frac{1}{\phi\left(y_4^{(0)}\right)} & \frac{\partial F_{H|T}}{\partial H}\frac{1}{\phi\left(y_4^{(0)}\right)} \end{bmatrix} = \begin{bmatrix} 4.7619 & 0 & 0 & 0 \\ 0 & 7.4627 & 0 & 0 \\ 0 & 0 & 5.09 & 0 \\ 0 & 0 & -0.2153 & 0.4105 \end{bmatrix} \tag{6.19}$$

$$g^{(0)} = (Y_1, Y_2, Y_3, Y_4) = \left(A_u(Y_1), B_u(Y_2), H(Y_3^{(0)}), T(Y_4^{(0)})\right) \tag{6.20}$$

are obtained by inverting the matrix J:

$$\begin{bmatrix} \frac{\partial g}{\partial Y_1} \\ \frac{\partial g}{\partial Y_2} \\ \frac{\partial g}{\partial Y_3^{(0)}} \\ \frac{\partial g}{\partial Y_4^{(0)}} \end{bmatrix} = J^{-1} \begin{bmatrix} \frac{\partial g}{\partial X_1} \\ \frac{\partial g}{\partial X_2} \\ \frac{\partial g}{\partial X_3} \\ \frac{\partial g}{\partial X_3} \end{bmatrix} = J^{-1} \begin{bmatrix} -4.1763 \\ 1.3352 \\ -0.0895 \\ -0.8751 \end{bmatrix} = \begin{bmatrix} -0.8770 \\ 0.1789 \\ -0.1757 \\ -2.2242 \end{bmatrix} \tag{6.21}$$

The verification equation in normalized coordinates $g^{(0)}$ (Y) linearized in the neighborhood of the point $Y^{(0)}$ is,

$$g_L^{(0)}(Y_1, Y_2, Y_3, Y_4) = a_0 + a_1 Y_1 + a_2 Y_{21} + a_3 Y_3 + a_4 Y_4 \tag{6.22}$$

In the preceding equation, the coefficients a_i are given by:

$$a_1 = \frac{\partial g}{\partial y_1 | X^{(0)}} = -0.8770$$

$$a_2 = \frac{\partial g}{\partial y_2 | X^{(0)}} = 0.1789$$

$$a_3 = \frac{\partial g}{\partial y_3 | X^{(0)}} = -0.1757$$

$$a_4 = \frac{\partial g}{\partial y_4 | X^{(0)}} = -2.2248$$

$$\begin{aligned} a_0 &= g^{(0)}\left(Y^{(0)}\right) - \left(a_1 y_1^{(0)} + a_2 y_2^{(0)} + a_3 y_3^{(0)} + a_4 y_4^{(0)}\right) \\ &= G\left(X^{(0)}\right) - \left(a_1 y_1^{(0)} + a_2 y_2^{(0)} + a_3 y_3^{(0)} + a_4 y_4^{(0)}\right) \\ &= 5.61 - (-0.3071) = 5.9220 \end{aligned} \tag{6.23}$$

The first approximation to the value of β, is the reliability index $\beta^{(1)}$, of the function $g_L^{(0)}$

$$\beta^{(1)} = \frac{a_0}{\sqrt{a_1^2 + a_2^2 + a_3^2 + a_4^2}} = \frac{5.9220}{2.4039} = 2.4635 \tag{6.24}$$

The sensitivity indices of $g_L^{(0)}$ are:

$$a_1^{(1)} = \frac{-0.8770}{2.4039} = -0.3648 \qquad a_2^{(1)} = \frac{0.1789}{2.4039} = 0.0744$$

$$a_3^{(1)} = \frac{-0.17570}{2.4039} = -0.0731 \qquad a_4^{(1)} = \frac{-2.2248}{2.4039} = -0.9252 \tag{6.25}$$

The following approximation to the failure point is the point $Y^{(1)}$ obtained as a critical point of the function $g_L^{(0)}$ based on the values of $\beta^{(1)}$ and $\alpha_i^{(1)}$,

$$Y^{(1)} = -\beta^{(1)}\left(\alpha_1^{(1)}, \alpha_2^{(1)}, \alpha_3^{(1)}, \alpha_4^{(1)}\right) = (0.8987, -0.1833, 0.1801, 2.264) \quad (6.26)$$

which in the original coordinates is:

$$\begin{aligned} X^{(1)} &= (0.210 \cdot 8987 + 1.05,\ 0.134(-0.1833) - 0.67, \\ &\quad F_T^{-1}(\Phi(0.1801)),\ F_T^{-1}(\Phi(2.264)) \\ &= (1.2387, -0.6946, 10.3276, 10.795) \end{aligned} \quad (6.27)$$

In the second iteration,the same procedure is followed with $X^{(1)}$ as with $X^{(0)}$.Table 6.1 shows the values obtained in each iteration, and figure 6.6 shows the evolution of the different parameters that are calculated in the iterative process.In ten iterations,the process has been stabilized,showing the speed of the convergence.

The sensitivity indices of B_u and T are α_2 =0.161, α_3 = - 0.190. Since they are relatively small, this indicates that the contribution of their variability to the occurrence of the failure is less than that of the variables A_u and especially H, whose respective sensitivity indices are α_1 = - 0.498 and α_4 = - 0.831.The reliability index is β =2.010 and the probability of failure is $p_f = \Phi(-\beta) = 0.022$. Finally, the critical design point obtained is:

$$A_u = 1260 \quad B_u = -0.713 \quad T = 10.782 \quad H = 9.033 \quad (6.28)$$

Table 6.1: Application results of the Level II Verification Method: Reliability index and probability of failure; n is the number of iterations; G is the value of the verification equation.

n	$A_u^{(n)}$	$B_u^{(n)}$	$T^{(n)}$	$H^{(n)}$	$G(x_i)$	β	P_f
0	1.05	-0.67	10 4.5				
1	1.239	-0.695	10.328	10.795	5.615	2.463	0.007
2	1.274	-0.727	10.953	8.801	-1.204	2.006	0.022
3	1.253	-0.709	10.730	8.986	-0.012	1.966	0.025
4	1.255	-0.713	10.755	8.989	0.104	1.979	0.024
5	1.254	-0.712	10.749	8.991	0.062	1.978	0.024
6	1.259	-0.713	10.772	9.177	0.067	2.029	0.021
7	1.263	-0.715	10.806	9.029	-0.160	2.019	0.022
8	1.260	-0.713	10.782	9.037	-0.067	2.010	0.022
9	1.260	-0.713	10.783	9.030	-0.032	2.008	0.022
10	1.260	-0.713	10.782	9.033	-0.030	2.010	0.022

Table 6.2: Application results of the Level II Verification Method: Sensitivity indices; n is the number of iterations.

n	$\alpha_1^{(n)}$	$\alpha_2^{(n)}$	$\alpha_3^{(n)}$	$\alpha_4^{(n)}$
0				
1	-0.365	0.074	-0.073	-0.925
2	-0.531	0.213	-0.225	-0.789
3	-0.491	0.147	-0.183	-0.839
4	-0.492	0.161	-0.188	-0.834
5	-0.492	0.159	-0.186	-0.836
6	-0.491	0.159	-0.186	-0.836
7	-0.503	0.165	-0.194	-0.826
8	-0.497	0.160	-0.190	-0.832
9	-0.498	0.161	-0.191	-0.830
10	-0.498	0.161	-0.190	-0.831

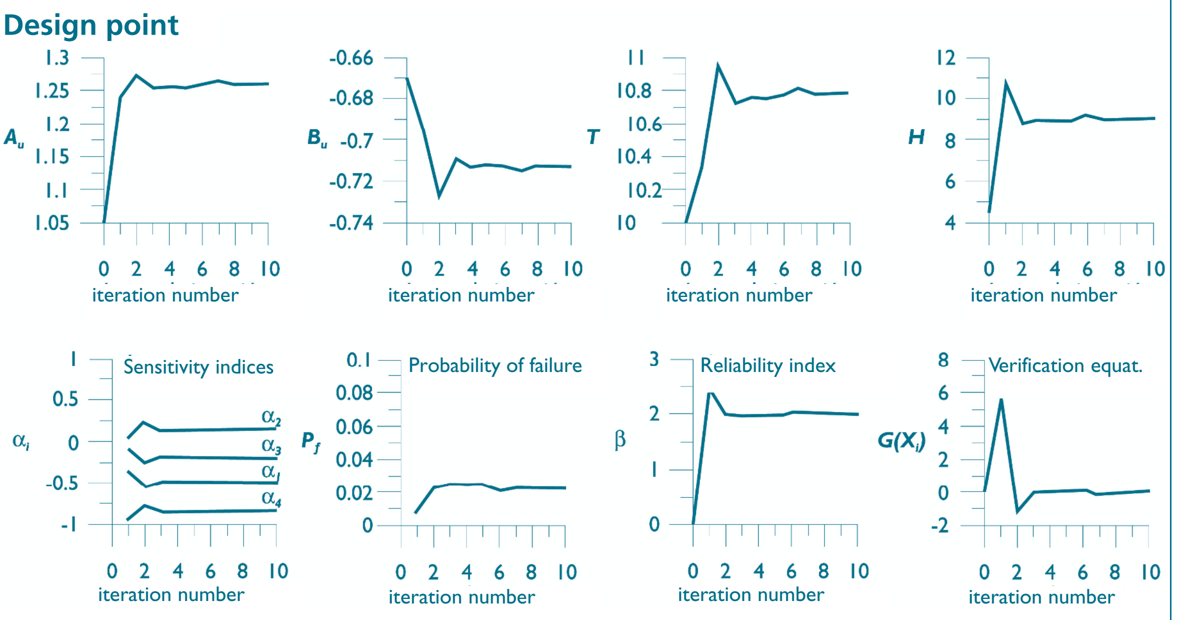


Figure 6.6: Results of the application of the Level II Method: H in m and T in s.

6.7 Annex: Verification in the Eurocodes and the Spanish EHE

This ROM proposes three levels of verification methods: Level I Methods, which include the global safety coefficient method and the partial coefficients method; Level II Methods, based on the statistical moments and optimization techniques; and Level III Methods, based on integration and numerical simulation techniques.

The utilization of one or various of these methods is determined in table 4.6 according to the intrinsic nature of the maritime structure. The partial coefficients method is the one most universally used since it is recommended in all cases except for one, corresponding to projects of lesser importance. In these cases, the global safety coefficient method can be applied. In important structures with a high intrinsic nature, it is advisable to use a Level II or III Verification Method too.

This procedure, which establishes four calculation methods differs from that followed in the majority of Standards, which only establish Level I Methods, generally the partial coefficients method. This difference is justified by the limitations inherent in the method itself that do not permit a relation to be obtained between the project factor values, the weighting, compatibility and correction coefficients, and the values of the probability of failure.

Since the ROM 0.0 recommends probabilities of failure and stoppage, which are fixed according to the specific nature of each project (in the same way as the ROM 02.90, though at that time the purpose was only to fix the values of certain predominant factors) the specific ROMs must now establish procedures that facilitate the specification of such relations. Section 6.5 presents the general outline of how to determine that relation.

6.7.1 Eurocodes

In the Eurocodes the general treatment of the problem can be found in Annex A of Part I: Eurocode I Project Bases "Project Criteria and Actions in Structures" It contains information and technical support regarding the partial coefficients method.Although this Annex is informative, its criteria should be followed for the verification of structures, as long as the existing Eurocode guidelines are not considered adequate for the corresponding case (as happens in many Maritime and Harbor Structures).

In this Annex, which is literally transcribed below, and which basically focuses on safety, the value of the partial coefficients should depend on the degree of uncertainty in the actions, resistances, geometrical data and models, and the type of construction and limit state considered.

There are two ways of determining the numerical values of the partial coefficients:

a) by calibration based on the long and successful history in construction.This is the basic principle of the majority of the coefficients proposed in the Eurocode.

b) by the statistical evaluation of experimental data and field observations.This ought to be carried out within the reliability theory.

For practical purposes these two can be combined.More specifically, a simple statistical (probabilistic) approximation normally lacks sufficient data. As a result, there is always the possibility of recurring to traditional project methods. The most important reason for using the traditional method is the long and successful history of the places where it has been applied.From this viewpoint, statistical methods should be used in tandem with the more traditional method.

Figure A.1 (included here as figure 1) presents a general vision of different verification methods and interactions between these methods. Probabilistic verification procedures can be subdivided into two main classes:Exact methods and first-order reliability methods (FORM),sometimes called Level III and Level II Verification Methods, respectively. In both methods, the reliability is measured by the probability of failure p_f of the failure modes considered and for the appropriate reference period.These values are calculated and compared with a predetermined value p_{f0}. If the probability of failure is $p_f < p_{f0}$, then the maritime structure is considered unsafe.

In accordance with figure A.1, the safety elements of the partial coefficients method (Level I) can be obtained in three ways:

a) by calibration based on the long and successful historical and empirical project methods
b) by the calibration of probabilistic methods
c) as a simplification of FORM, using the (calibrated) method of the design value, as described in A.3 (section 3 of this Annex)

The present generation of Eurocodes is initially based on method (a), and corrected with method (c) or similar methods, complemented by studies carried out in the project field.

6.7.2 The Spanish Regulations for Concrete, EHE

The basic design criteria upon which these Regulations are based can be found in Chapter II “Principios Generales y Método de los Estados Límites” [General Principles and Limit States Method], in which the commentaries of article 6.1 “Principios” [Principles] states that the Limit State procedure, based on the previous determination of partial safety coefficients correspond to a Level I method.

There are basically two procedures for the determination of partial safety coefficients:

a) By calibration with the design values of the variables used in the calculation of existing structures

b) By the statistical evaluation of experimental data in the framework of application of probabilistic methods.

Reliability is defined as the capacity of the structure to fulfill, with a predefined probability, a function under certain conditions. In a way, this corresponds with the probability of the absence of failure and can be quantified by means of the reliability index β, defined as described in the part of this chapter about the Level II Verification Method. The only problem is how to interpret the global probability of failure since this concept is not explained in the EHE. It only states that this type of probability does not correspond to the real frequency of structural failures.

The EHE defines the probability of failure and the reliability indices mentioned there (β = 3,8 for ultimate limit states and β =1,5 for serviceability limit states) by means of nominal safety values that are the basis for the "development of strict and coherent rules for the design of maritime structures".

ROM 0.0. In this ROM 0.0, the methods, specific values of the β reliability indices, and probabilities of failure have been taken in the cases where there was information (i.e. the cases mentioned in the EHE and the Eurocodes). This guarantees that they will be all be treated in the same way and eliminates the possible objection to their utilization.

Because of the special nature of maritime and harbor structures, whose probabilities of failure are generally admitted to be greater than those of other civil engineering structures, their verification using the three Levels recommended in the ROM 0.0 is not only advantageous, but indispensable.

CHAPTER 7
Probability of Failure and Operationality

7 PROBABILITY OF FAILURE AND OPERATIONALITY

7.1 Introduction

In Chapters 5 and 6 methods were proposed to verify compliance with requirements of safety, serviceability, and use and exploitation for a subset of the structure in a given time interval (e.g. a sea state). This chapter develops methods to determine: (1) the probability that a mode will occur in a time interval of generic duration T_L; (2) the probability that the principal modes will occur in T_L. Therefore, it could be regarded as a way to evaluate the reliability, functionality, and operationality in the useful life of the structure.

To evaluate the joint probability of failure, the principal failure and stoppage modes should be organized in diagrams. The diagram is used to order the most probable causes or ways that a subset can cease to be reliable, functional or operational, but it does not mention the relation between modes. Consequently, the diagram is not an element for the management and exploitation of the subset of the structure, but rather for the evaluation of an upper bound of the joint probability of failure and the establishment of strategies of maintenance and repair.

Nevertheless, all the subsets of the structure are a part of the harbor's system of services and functions. To calculate the system's probability of failure, failure trees must first be developed. Such trees are the means by which strategies can be defined to maintain the levels of safety, serviceability, and use and exploitation of the harbor system, once the failure or stoppage mode has occurred. These Recommendations do not consider either the failure trees or their relation with the decision-making process in a harbor system.

7.1.1 Chapter organization and contents

The chapter begins with a brief introduction regarding the temporal evolution of the values of the terms in a verification equation, and the statistical techniques for their description. These techniques are proposed to determine the probability of the subset against a mode in a time interval of duration T_L, (e.g. the useful life of the structure).

After this introduction, the diagrams of modes are defined, and the calculation of the overall prob-ability of occurrence is developed for the different types of diagrams. In a parallel way, the analysis of the exploitation of the subset is specified in terms of the calculation of the operationality level and the average number of operational stoppages. This is followed by the presentation of a simplified method, which can be applied to maritime and harbor structures with ERI $\leq$ 20 and SERI $<$ 20.

The final sections of the chapter briefly describe techniques for the optimization of harbor and maritime structures by means of an economic cost-benefit analysis. They also discuss other criteria, which can be used to evaluate the best and most viable solution, and which are complementary with the economic method.

Finally, it describes various tools, which can be used to update the reliability, based on the data obtained by using visual inspection,sounding and monitoring techniques.Criteria are proposed for deciding when to make repairs according to the temporal reduction of the reliability, functionality, and operationality of the subset of the structure. Figure 7.1 is a schematic outline of the contents and organization of chapter 7.

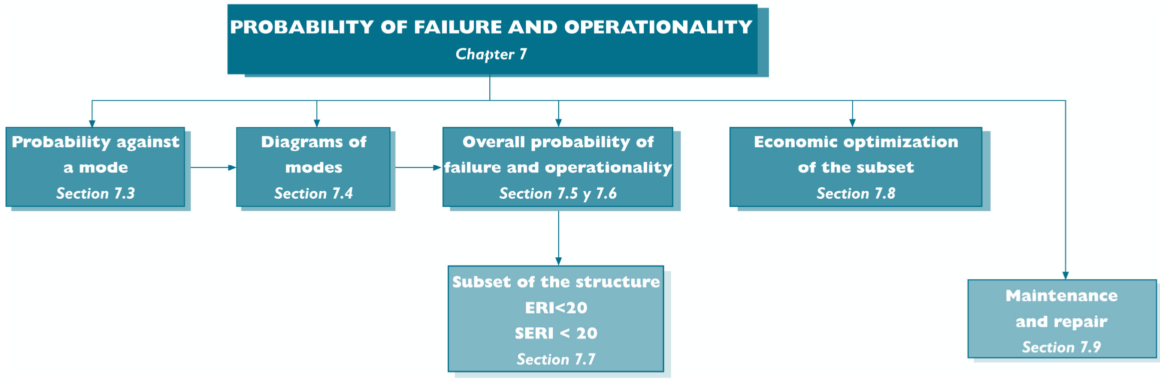


Figure 7.1: Chapter 7: Organization and contents

7.2 Basic concepts

The verification equation is usually established by the difference between a favorable and unfavorable term. The value of the unfavorable term, $X_2(t)$, changes over time, going from relative maximums to minimums, according to the temporal variability of the participating project factors. Figure 7.2 shows a curve representing this temporal evolution, which is known as the curve of states of X_2. The value of the favorable term X_1 also varies over time. Figure 7.3 shows the curve of states of the favorable term X_1.

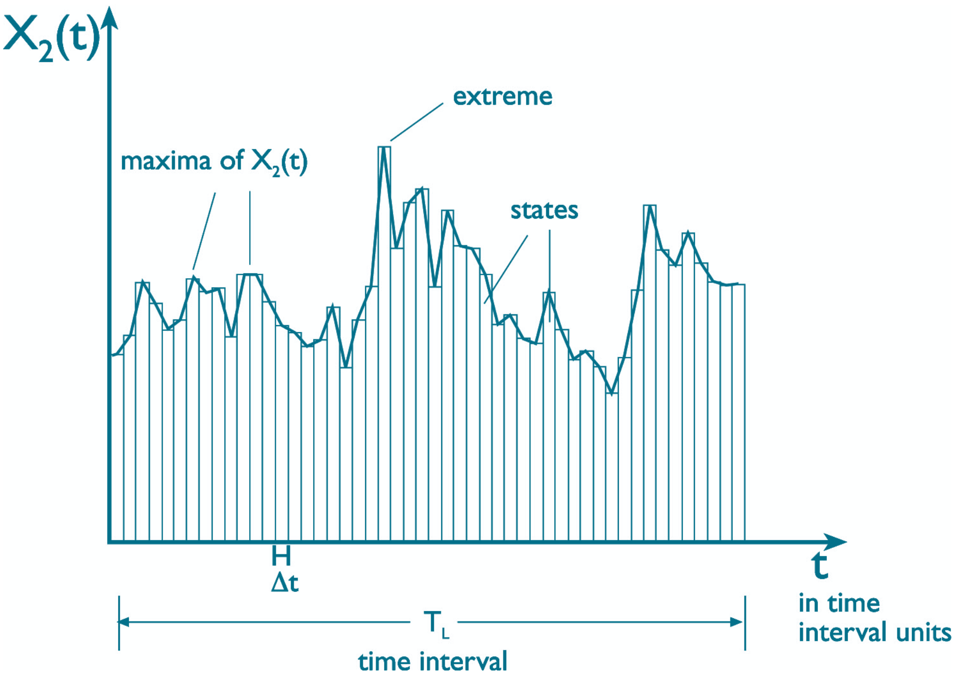


Figure 7.2: Temporal evolution of the unfavorable term.

The failure or stoppage mode occurs when the X_2 curve of states crosses X_1. In that state, after the subset enters into operation, the failure criterion, defined by the safety margin domain $S(t) \leq 0$, will happen when one of the peaks or maximum points of X_2 (t) intersects the curve of X_1.

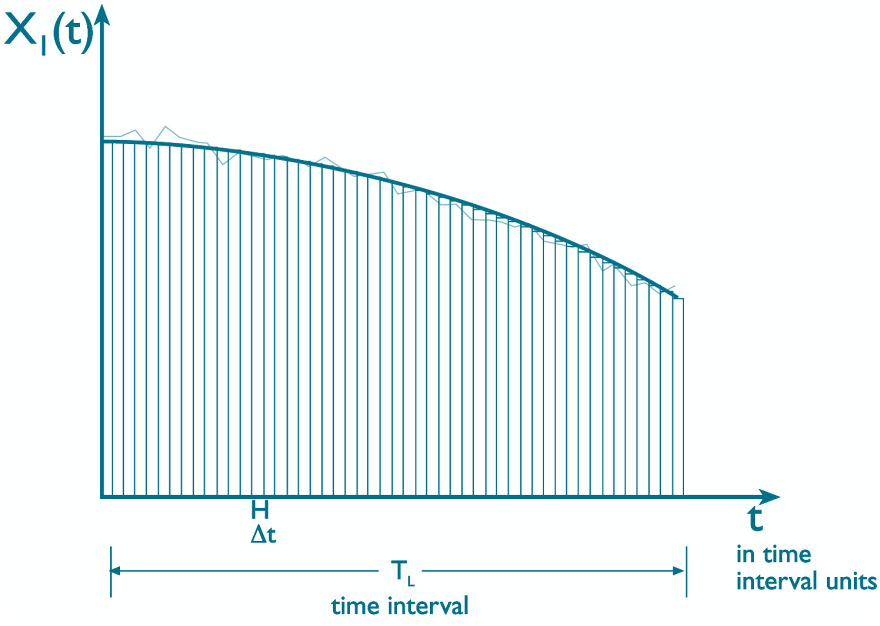


Figure 7.3: Temporal evolution of the favorable term

From this point of view, the probability that $S(t) \leq 0$ for the first time in T_L can be obtained by calculating the probability that one of the maximum values of the variable of state X_2 will exceed the value of the variable of state X_1, in time interval T_L (see figure 7.4). If the subset of the structure is well designed, the occurrence of an intersection of the state curves or a negative value of the safety margin will be an event that will happen only very rarely.

7.2.1 Probability of the peaks of X_2 in T_L

When they first appear, the magnitude and number of peaks of X_2 in T_L are random, and thus should be described in terms of probability models, which can be obtained from the density and distribution functions of the factors that participate in the term.

Whenever possible, the probability of occurrence of the mode in the time interval T_L is directly calculated on the basis of the distribution functions of the project factors and terms in the interval T_L, applying any of the methods of chapter 6.

7.2.2 Presentation of the peaks of X_2 as a Poisson process

The fact that the first occurrence of the mode is related to the peaks of the unfavorable term (or the relevant agent causing it) (or the relevant agent causing it) facilitates the analysis of the temporal sequence of the peaks in T_L as a Poisson process.To be able to apply such a model,there are two necessary conditions: (1) the number n of peaks of X_2 in T_L should be large; (2) the probability of the presentation of a peak in T_L should be small.

When a peak of X_2 occurs, only two things can happen,either $X_2 \geq X_1$, or $X_2 < X_1$. In the first case, the mode occurs, and in the second case, it does not; p represents the probability that the mode will occur, whereas 1-p represents the probability that it will not. In other words,a Bernoulli process can be used to describe what happens when there is a peak.

7.2.3 Number of peaks in T_L

During the time interval T_L, a number n_L of peaks can appear, which will generally be a random number. From this point on, there are two possibilities: (1) the number of peaks can be regarded as a known value or; (2) the number of peaks can be regarded as a random variable.

7.2.3.1 The number of peaks in T_L is a known value

If the time interval T_L is divided into regular intervals, and in each one, a maximum peak is selected, a sample is obtained of $n_L = T_L$, the peaks of X_2 (or of the relevant agent causing it). The extreme regime of X_2 or of the agent is obtained by adjusting a probability model to nL peaks. X_2 can thus be assigned the value of a quantile of this regime, whose probability of exceedance is p. Such a description can be made when useful life or the time interval T_L is expressed in years. Each year is a time interval unit, and in each one, a maximum peak is selected (see figure 7.5).

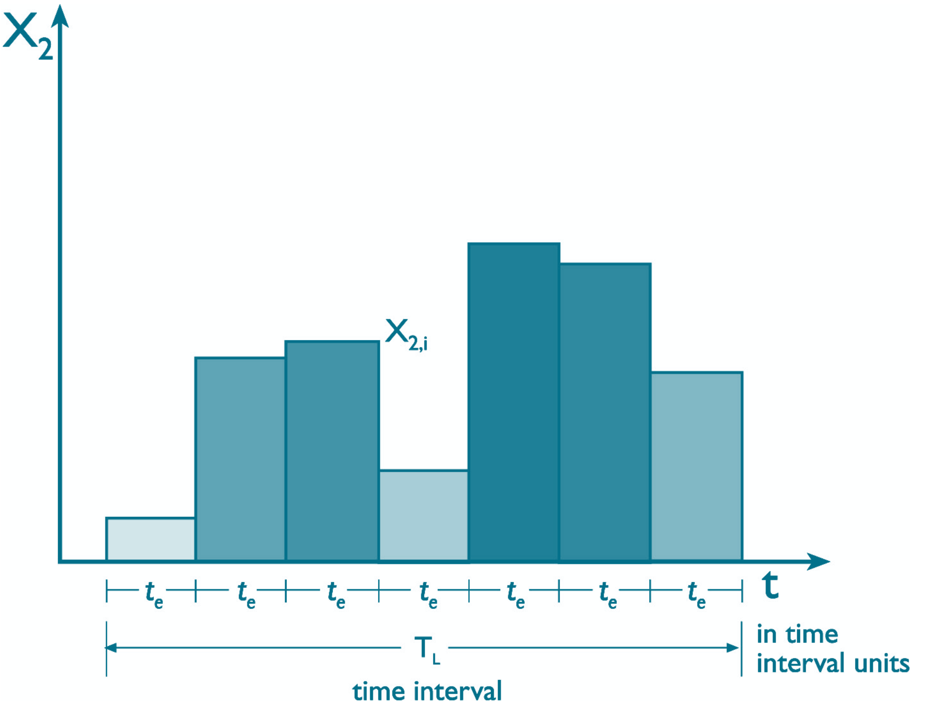


Figure 7.4: Peaks of the unfavorable term. One peak is selected for each of the regular time intervals

If it is assumed that what occurs in each time interval unit is independent of what happens in the others, it is possible to obtain the probability of occurrence of at least one failure in T_L.

$$P_{f,T_L} = 1 - (1-p)(1-p)\ldots(1-p) = 1 - \prod_{n=1}^{n=T_L}(1-p)$$

Since p is usually a small number and n_L a large number, this expression can be approximated by:

$$P_{f,T_L} \simeq 1 - \exp(-pT_L) \simeq T_L p$$

Note *Usually, there is not enough information available to obtain a statistically representative sample of n_L annual peak values. For this reason, this approximation often requires an important extrapolation of the extreme regime. Since in the measurement period various peaks usually occur in a year, a more efficient approach can be applied by regarding the number of peaks in T_L as a random variable.*

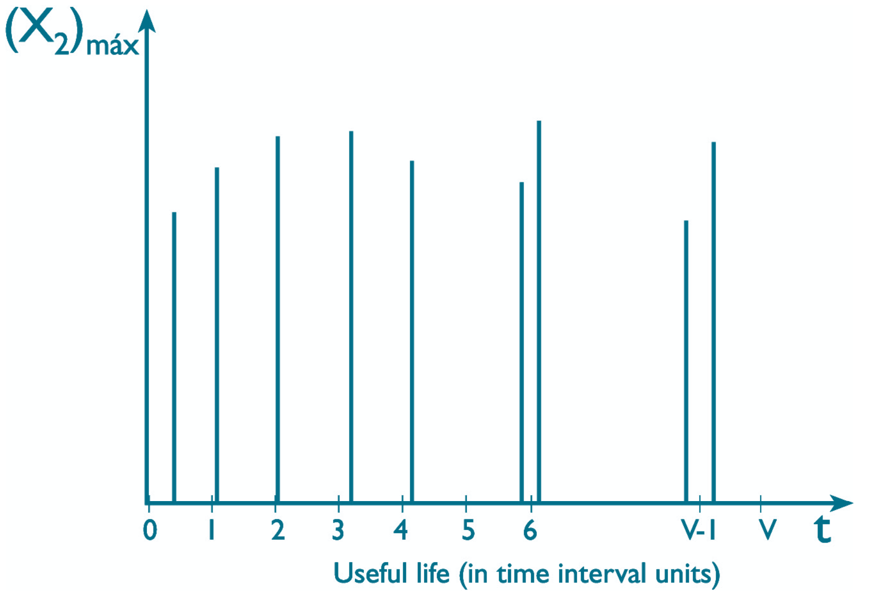


Figure 7.5: Peaks of the agent or term, which have been selected in the time interval

7.2.3.2 The number of peaks in T_L is a random variable

In this case, instead of working with a peak per year, the event peak of X_2 is used.The sample should be made up of n_p independent events that do not overlap. It is thus necessary to define a threshold value of $X_2(t)$, such that between two consecutive points of intersection at the threshold value, one ascending and the other descending,one maximum peak occurs.In this way, the state curve associated with a peak will not overlap with the state curve of the following one (see figure 7.6).Let p_u be the probability of exceedance of the threshold level.If the measurement period t_p is sufficiently long, the average number of events of the Poisson process is $\nu = n_p p_u$.

A subinterval of time can be defined $\Delta t = t_p/n_p$ which fulfills the following conditions:

1. The probability that more than one event will occur in the subinterval is null.
2. Each time interval behaves like a Bernoulli process.
3. Consequently, the occurrence of a failure in any of the subintervals is independent of the occurrences in other subintervals.
4. The probability that the failure event will occur in a subinterval is constant.

Given the above conditions,the number or rate of occurrences of the failure per time unit is defined by $\lambda = \nu/t_p$.Taking into account the definitions of subinterval, Δt, and of the Poisson parameter $\nu = n_p p_u$, the result obtained is $\nu \Delta t = p_u$. In other words,the probability of occurrence of a peak in a subinterval is p_u.

The probability of r peaks or maximum values of X_2 in T_L is obtained by the following equation:

$$p_r(r;\lambda,T_L) = \frac{(\lambda T_L)^r \exp(-\lambda T_L)}{r!}; \qquad r = 0,1,2,....$$

Its distribution function is :

$$F\left[s;\lambda,T_L\right]=\sum_{r=0}^{s}p_r(r;\lambda,T_L)$$

Note *The parameter λ does not have to be constant in the time interval, and the preceding model can be extended to intervals in which λ varies.*

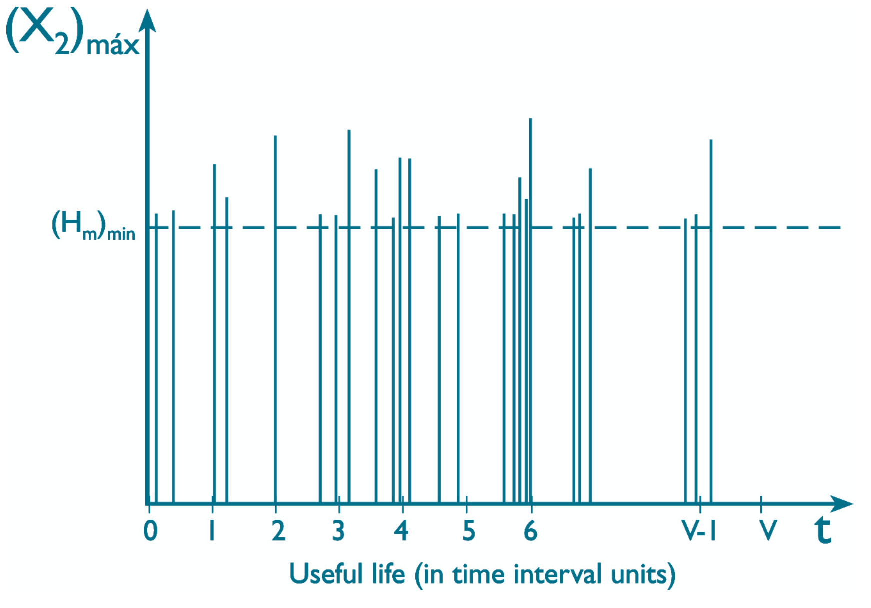


Figure 7.6: Random number of peaks of the agent or term (or the relevant agent causing it) in the time interval.

The appearance of each of these peaks brings with it the probability that $X_2 \geq X_1$. The adjustment of a probability model to the n_p peaks results in the regime of peaks or maximum values of X_2 or of the agent. X_2 can be assigned the value of a quantile of the probability model whose probability of exceedance is p_p. In that event, the probability of failure in the time interval T_L is:

$$P_{f,T_L}=\sum_{r=0}^{r=\infty}p_r(r;\lambda,T_L)\left\{1-(1-p_p)^r\right\}=\sum_{r=0}^{r=\infty}\frac{(\lambda T_L)^r\exp(-\lambda T_L)}{r!}\left\{1-(1-p_p)^r\right\}$$

For very small values of λ and very large values of T_L, the expression can be approximated by the following:

$$P_{f,T_L}\simeq 1-\exp\left(-\lambda T_L p_p\right)\simeq 1-\exp\left(-\frac{n_p p_u}{t_p}T_L p_p\right)$$

This approximation should only be applied if the number of peaks n_p, and the measurement period t_p, are large.

Note *When the determination p_p is based on the peak distribution function of a statistical descriptor (e.g. significant wave height), it is necessary to take into account the probability of the exceedance of the value of the descriptor. Therefore, p_p is the probability conditioned to the appearance of a peak $p_p(|H_s = h)$, This results in the following equation:*

$$P_p=\int_{H_{s,u}}^{\infty}P_p(|H_s=h)f_{H_s}(h)dh$$

In the above, f_{Hs} (h), is the density function of the peak regime of H_s. This calculation is also necessary in order to arrive at the probability of occurrence p, at regular time intervals, as described in the preceding section.

7.3 Probability against a mode in T_L

This section describes the procedure used to calculate the probability of occurrence of a failure or stoppage mode $p_{m,TL}$ in a time interval of duration T_L, which in general is the minimum useful life, $V_m = T_L$, recommended in table 2.2 in accordance with the economic repercussion index (ERI).

7.3.1 Probability of failure based on sufficient statistical information

If there is a large database available, which can be used to obtain the distribution functions of the terms of the verification equation in the time interval T_L, the probability of occurrence of the mode $p_{m,TL}$ is calculated by directly applying one of the Level II or III Verification Methods.

Note *Today in Spain, thanks to the network of oceanographic data, there are records of sea states available along the Spanish littoral. However, there is still not sufficient data available to cover a useful life spanning a period of 50 years, for example. In these circumstances, the data can be ordered by taking the year as the time unit interval and inferring the distribution functions of the maximum sea states. This can be done either by taking one per year to obtain the storm regime, or the maximum values higher than a certain threshold value to obtain the peak regime exceeding a given threshold, etc.*

These techniques can also be applied to time intervals of less than a year. For example, it is possible to obtain distribution functions for seasons, loading cycles, etc. Project factors due to use and exploitation and non-related to the physical environment, can also be treated in the same way.

In time and if measurement processes remain precise and accurate, a large data base will soon be available, which will allow the direct determination of the probability of occurrence of a mode in any time interval T_L without the necessity of additional hypotheses.

7.3.2 Probability of failure based on limited statistical information

In such cases, the probability $p_{m,TL}$ of the subset against the mode m in a time interval of duration T_L is calculated by assuming certain statistical properties of the time interval unit and of the number and values of the peaks that can occur in any of them, according to the information in the following sections.

7.3.2.1 Maximum values of X_2 at regular time interval units

Whenever possible, the duration T_L is divided into regular and independent time interval units of duration Δt. It also can be assumed that the favorable terms are constants in T_L, and that the peak of the unfavorable term is the extreme value. Thus, there is one in each of the Δt time interval units. If $p_{m,\Delta ti}$ represents the probability that in time interval unit i, an event m $((X_2)_p \geq X_I$ will occur, and assuming that what happens in each unit is independent of what happens in the others, then the probability $p_{m,TL}$ that in T_L the event $(X_2)_p \geq X_I$ will occur at least once is the following:

$$p_{m,T_L} = 1 - \prod_{i=1}^{i=n} \left(1 - p_{m,\Delta t_i}\right)$$

In the preceding equation, n $=T_L/\Delta t$ is the number of events in T_L and $1 - p_{m,\Delta ti}$ is the probability that event $(X_2)_p \geq X_1$ will not occur in the time interval i.The probability $p_{m,\Delta ti}$ can be determined by a Level II or III Verification Method.In the case of the application of a Level I Verification Method, $p_{m,\Delta ti}$ should be assumed to be equal to the probability of exceedance of the predominant factor in Δt_i, or if duly justified, other techniques can be used, such as experimental ones.

If the probability $p_{m,\Delta ti}$ is equal in all of the time intervals Δt, and equal to $p_{m,\Delta t}$, then:

$$p_{m,T_L} = 1 - \left(1 - p_{m,\Delta t}\right)^{T_L}$$

If the product $p_{m,\Delta t}T_L$ takes small values, the preceding expression can be approximated asymptotically by:

$$p_{m,T_L} \approx 1 - \exp\left(-p_{m,\Delta t} T_L\right) \approx p_{m,\Delta t} T_L$$

Note *This approximation can be applied when the useful life of the structure is divided into years and when the year is considered to be the time interval unit. In that case, p is the probability of occurrence of the extreme value in the year, which can be obtained from the extreme regime of* X_2.

7.3.2.2 Probability of failure in T_L with a random number of peaks

(1) *For this to be possible, certain hypotheses must be fulfilled.*

In these cases, it can generally be assumed that the number n of maximum values or peaks of X_2, which can occur in time interval T_L is a random number whose probability model is the Poisson function of parameter ν,the average number of peaks in T_L. For homogeneous processes ν is assumed to be constant[1] in T_L.

The number of peaks n_p is calculated by defining a threshold value for X_2 or for the agent, as described in section 7.2.3.2, on the basis of a data sample obtained in a time interval of duration t_p. The time interval unit $\Delta t = t_p/n$, is defined, and the average rate of occurrences of peaks in the time interval unit is, $\lambda = \nu/t_p$, where $\nu = n_p p_u$.

The probability of occurrence of a peak in the time interval unit is $p_u = \lambda\Delta t$, and the probability of failure in the time interval T_L can be calculated by the following equation:

$$p_{m,T_L} = \sum_{r=0}^{r=\infty} p_r(r;\lambda,T_L)\left\{1-(1-p_p)^r\right\} = \sum_{r=0}^{r=\infty} \frac{(\lambda T_L)^r \exp(-\lambda T_L)}{r!}\left\{1-(1-p_p)^r\right\}$$

In the above, r is the number of peaks that can appear in T_L, and p_p is the probability that the mode will occur, once the peak has been produced.This value is determined on the basis of the peak regime obtained from the sample of n_p peaks measured in t_p.

For very small values of λ and very large values of T_L this expression is approximated by the following:

$$p_{m,T_L} \simeq 1 - \exp\left(1 - \lambda T_L p_p\right) = 1 - \exp\left(-\frac{n_p p_u}{t_p} T_L p_p\right)$$

This approximation should not be applied if the database of the number of peaks n_p, and the period of measurements t_p are not statistically large enough for their extrapolation to time interval T_L.

Note *The peak regime is known as the POT (peaks over threshold) regime, which is different from the regime of extreme sea states where a peak is considered the greatest value per regular time interval unit. When the time unit is a year, the regime of extreme sea states in Spain is called* Régimen de Temporales *(Storm Regime).*

7.3.3 Return period of a mode

The probability of the occurrence of the failure in the regular time interval unit i, $p_{m,\Delta ti}$ represents the average frequency of occurrence of that event in the time interval.If all the time intervals have the same probability of occurrence, $p_{m,\Delta ti}= p$, the return period,or number of interval units, which on average should elapse until the first failure occurs, is calculated by $T_R = 1/p$.

Note *If the useful life is $T_L = V = 25$ years, the year is the time unit interval, and if the probability of failure of the subset against the mode in V is equal to or less than $p_{m,V} \leq 0.1$, the return period is $T_R = V/p_{m,V} = 250$ years.*

7.3.4 Threshold values and probability against a mode

To determine the probability of occurrence of a mode in the time interval,it is necessary to select the peak event of X_2 by defining a threshold value that fulfills the conditions established in section 7.2.3.2.The threshold value depends on whether the mode is assigned to a serviceability or ultimate or operational limit state.

7.3.4.1 Threshold value in ultimate limit states

For each subset of the structure and for each failure mode assigned to an ultimate limit state, a threshold value of the unfavorable term of the verification equation can be defined, such that values greater than it significantly contribute to the probability of the failure of the subset against this mode. In this case, it is known as the threshold value of the failure mode assigned to an ultimate limit state.

The specific Recommendations provide the method to delimit the failure mode, the significant probability of failure, as well as the threshold value.

Note *When the probability of the failure of the subset is evaluated against a mode assigned to an ultimate limit state, only those states should be considered, which are associated with the exceedance of a certain threshold value of the predominant factor, for which there is a significant probability of structural and shape deterioration. For the purposes of this type of calculation,probabilities with values less than 10^{-4} are not considered significant.*

The force and moment with which the waves load a pile depends, among other project factors, on the height and period of the successive waves in the sea state. Often, the sea state considered is a maximum sea state, and what is calculated is the probability that the force or moment will exceed in the state a certain design value. However, the sea state is part of a loading cycle or a storm, which is made up of a sequence of sea states, whose significant wave height is less than that of the maximum. In each of these states, there is a certain probability that the force or moment will exceed the design value. A threshold value of the significant wave height can be defined according to that of the maximum sea state.Any value lower than this threshold can be considered non-significant in regards to its contribution to the probability of the failure against the mode in the structure's useful life.

7.3.4.2 Threshold value in serviceability limit states

For each subset of the structure and failure mode, it is possible to define a threshold value of the unfavorable term of the verification equation,such that values greater than the threshold value significantly contribute to the probability of the subset against that mode. This value is known as the threshold value of the failure mode assigned to a serviceability limit state.

The specific Recommendations provide the method to delimit the significant probability of failure and the threshold value for each failure mode.

Note *When the probability of failure of the subset is evaluated against the mode assigned to a serviceability limit state, it is only necessary to consider the states associated with the exceedance of a certain threshold value of the predominant factor, for which the probability of structural and shape deterioration is significant. For the purposes of this type of calculation, probabilities with values less than 10^{-3} are not considered significant.*

The force and instantaneous moment with which the waves load a pile of reinforced concrete can reach a value such that a fissure is produced in the construction material. Once the action is reduced so that it is less than a certain value, the fissure closes. In such cases, it is generally more convenient to make the calculation with representative statistical descriptors of the sea state (e.g. significant wave height) since working with instantaneous values is complicated. It is then possible to define a threshold value of the significant wave height, above which fissures are produced in the concrete. Once the duration of the exceedance of the threshold value is known, the time of the useful life the structure is calculated during which the fissure remains open, and the consequences are evaluated.

7.3.4.3 Threshold value in operational limit states

For each subset of the structure and for each stoppage mode, a threshold value of the unfavorable term of the verification equation can be defined so that any values surpassing the threshold contribute in a significant way to the loss of operationality of the subset against the mode. This value is known as the threshold value of the mode assigned to an operational limit state.

Note

When the probability of failure of the subset is evaluated against the mode assigned to an operational limit state, it is only necessary to consider the states associated with the exceedance of a certain threshold value of the predominant factor, for which the probability of stoppage is significant. For the purposes of this type of calculation, probabilities with values less than 10^{-2} are not considered significant.

Let us assume that the stoppage should be carried out when the average concentration of a certain polluting agent released in a time interval during the exploitation exceeds a certain value. The concentration depends on the conditions of advection and dispersion of the physical medium where the contamination substance is introduced. These conditions are associated with the velocity of the current and the wave height, which depend on the phase of the astronomical tide and the sea state, respectively. Various combinations can arise in which the probability that the concentration will exceed the permitted value is significant. It is thus possible to define the maximum significant wave height and the minimum tidal amplitude for which the probability of occurrence of the average threshold concentration of stoppage in the useful life is significant.

7.4 Diagrams of modes

To evaluate the overall probability of failure of all the modes, the subset is said to constitute a system composed of a set of elements,subelements,etc.The modes can affect one or various elements;they can occur individually o all together; they can lead to other modes,etc.The subset can fail because of the occurrence of one mode or several, individually or sequentially until the structure collapses.The way that the behavior of the subset is analyzed against the modes is by means of failure and stoppage trees.This analysis is complex since it is necessary to consider certain aspects of the system in which the subset of the structure is located. Consequently, in these Recommendations the analysis of the failure and stoppage modes is carried out by means of diagrams of mutually exclusive modes[2]. This permits the approximation of the overall probability of the occurrence of failure or stoppage in a simpler way (see figure 7.7).

(2) These modes cannot occur simultaneously.The presentation of one of them excludes the others.

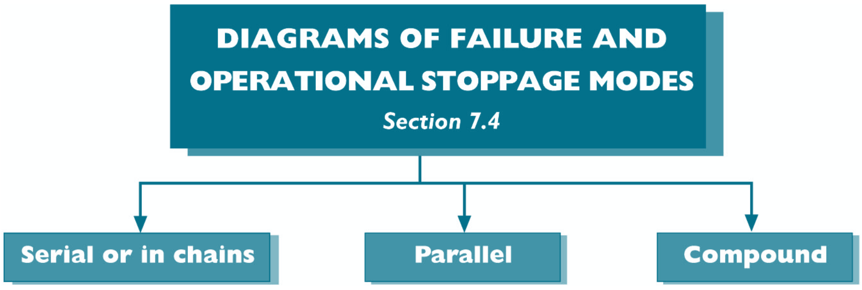


Figure 7.7: Diagram of failure and stoppage modes

7.4.1 Organization in diagrams

In order to evaluate the overall probability of the subset against the failure and stoppage modes, the modes are ordered in diagrams.A diagram is a simplified representation of the behavior of a subset and is an exhaustive collection of mutually exclusive modes.

Note

According to this definition, the subset of the structure fails or ceases to operate because of the occurrence of one of the modes of the collection, and for this reason, it is said to be complete. Moreover, when the occurrence of one of the modes excludes the simultaneous occurrence of the others, the modes are said to be mutually exclusive.

It should be noted that the calculation of the probability of failure by means of failure diagrams instead of failure trees excludes the progressive collapse, which ought to be avoided by applying standards of good practice.

7.4.2 Types of diagrams

These modes are ordered in one of the following three configurations: series, parallel, and compound.

7.4.2.1 Serial diagrams

In this type of diagram, the modes form a sequence or chain connected in a series.The subset of the structure fails or ceases to operate when at least one of the modes occurs.

7.4.2.2 Parallel diagram

This type is formed by parallel series of diagrams. The subset of the structure fails or ceases to operate only when all the chains fail or stop one after the other. The failure or stoppage of each of the chains is produced if at least one of its modes occurs.

7.4.2.3 Compound diagram

This type is formed by chains of serial and parallel diagrams, which, in turn, can generate other serial or parallel chains, and so on, successively.

Note

A simplified example of a subset of a structure with a serial diagram is a breakwater with a crown with the following failure modes: armor units extraction or sliding or overturning of the crown or erosion of the under toe. This diagram presents the failure modes as independent events. The occurrence of one of them causes the failure of the structure. In the calculation of the probability of the failure, the subset is said to fail when at least one of the diagram modes occurs.

The diagram does not represent sequences of correlated failure modes, for example, failures that trigger the others so that they occur sequentially until the structure collapses. Let us assume that in the previous example, due to the occurrence of the failure mode erosion of the under toe the following sequence of failure modes is produced:

erosion of the under toe => erosion of the berm => global sliding of the main layer => sliding of the crown.

In this case the modes occur sequentially, each depending on the other. The sequence is an indication of how the subset collapses. For this type of analysis, a failure tree should be used because the diagram is not sufficient.

From the point of view of the failure of the subset, and because it is a question of working with diagrams, what is analyzed is the probability that any of the following failure modes will occur: the erosion of the toe, erosion of the berm, global sliding of the main layer, or the sliding of the crown. Nevertheless, once the dependence between modes is known, the cost of reconstruction and the deficits resulting from loss of exploitation can still be evaluated by means of an cost-benefit analysis, which takes into account the possible sequence of failures.

The operational stoppage of a dock that has two mooring or docking lines for the same type of service, one in each direction, can be represented by means of a parallel diagram consisting of two chains of stoppage modes, one for each of the lines. Each is made up of a series of stoppage modes, such as wind speed of a certain direction higher than the threshold, water surface oscillation of the sea surface higher than the threshold, etc. The stoppage of one of the docks does not imply the stoppage of the other because of their difference in orientation and shelter.

7.4.3 Modes considered in the overall probability

Diagrams of modes help to evaluate the overall probability of the subset of the structure. Among the possible modes, there are some that are known as principal modes. Their occurrence can produce an important breakdown or stoppage resulting in the total cessation of the harbor operations, something that naturally entails significant economic, social, and environmental repercussions. These are the modes that should be considered when evaluating the joint probability of failure.

The assessment of the economic, social, and environmental repercussions due to the occurrence of one of these principal modes should produce repercussion indices with value in the same interval as the one adopted to define the intrinsic nature of the maritime structure.

Note *To evaluate the overall probability of failure of a dock of mass concrete blocks in Almería,it is necessary to consider failure modes, such as sliding between the rows of concrete blocks, overturning,liquefaction and deep sliding.However, failure modes that will not be included are the shearing breaker of a bollard or the breakage of a fender when a vessel is docking, unless this failure results in the non-probable sinking of the dock.*

7.5 Overall probability of failure

Once selected a subset of the structure and a time interval of duration T_L, which generally is its useful life, the overall probability of failure against safety and serviceability of the subset is calculated by grouping in diagrams the principal failure modes, assigned to ultimate and serviceability limit states. For each group, the calculation of the joint probability, which depends on the type of diagram, is obtained by applying the formulations presented in the following sections (see figure 7.8).

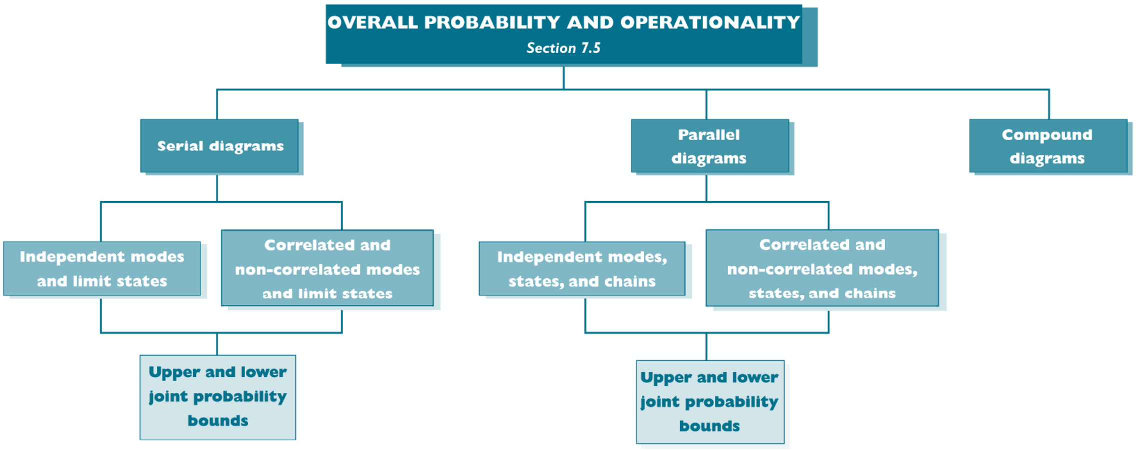


Figure 7.8: Calculation of the overall probability in the useful life.

Note *The complementary value of the overall probability of failure against the modes ascribed to the ultimate limit states is the reliability of the subset.The complementary value of the overall probability of failure against the modes assigned to the serviceability limit states is the functionality of the subset.*

7.5.1 Serial diagrams

If A_{ij}, i =1, ...M_j, represents each of the i failure modes assigned to the ultimate or serviceability limit state j =1,...N, in a serial diagram,the structure is said to fail when at least one of the modes occurs in the time interval T_L.

7.5.1.1 M_j mutually exclusive modes of limit state j

If $Pr[A_{ij}]=p_{ij,TL}$, is the probability that the mode A_{ij} will occur in the time interval T_L, and assuming that the failure modes in the diagram are mutually exclusive, the probability of failure of the subset against the failure modes i =1, ..I, assigned to limit state j can be calculated by the following equation:

$$p^*_{j,T_L} = \sum_{i=1}^{I} p_{ij,T_L}$$

In the above, $p^*_{j,TL}$, is the probability that at least one of the i failure modes in T_L will occur.

If the complementary events of the modes are statistically independent events, the probability of failure can also be calculated by the following equation:

$$p^*_{j,T_L} = 1 - \prod_{i=1}^{i=I} (1 - p_{ij,T_L})$$

In the preceding equation,(1 - $p_{ij,TL}$) is the probability that the failure mode i, assigned to the limit state j will not occur.

If it is also assumed that the set of ultimate and serviceability limit states make up a collection of mutually exclusive states, the overall probability of the failure of the subset against all the previously mentioned limit states j = 1, ...,J is calculated by the following:

$$p_{f,T_L} = \sum_{j=1}^{j=J} \sum_{i=1}^{i=I} p_{ij,T_L} = \sum_{m=1}^{m=M} p_{m,T_L}$$

In the above equation, M = I + J is the total number of principal failure modes, assigned to ultimate and serviceability limit states,whereas $p_{m,TL}$ is the probability of occurrence of mode m in T_L.

When T_L is the useful life of the structure, the overall probability of failure $p_{f,TL}$ should be less than or equal to the value given in tables 2.3 and 2.4 for the ultimate limit states and the serviceability limit states, respectively.

If the complementary events of the failure modes are also considered to be statistically independent, the probability of failure can be calculated by the following equation:

$$p_{f,T_L} = 1 - \prod_{j=1}^{j=J} \prod_{i=1}^{i=I} (1 - p_{ij,T_L}) = 1 - \prod_{m=1}^{m=M} (1 - p_{m,T_L})$$

Note *When all the failure modes in the serial diagram, assigned to the ultimate limit states are mutually exclusive, the overall probability of the subset of the structure is:*

$$p_f = \Pr[S_1 \cup \ldots \cup S_M] = 1 - \Pr[S_1^C S_1^C \ldots S_M^C]$$

$$\Pr[S_1 \cup \ldots \cup S_M] = \Pr[S_1^C] + \Pr[S_2^C] + \ldots + \Pr[S_M^C] = \sum_{m=1}^{m=M} p_m$$

In the preceding equation,Pr $[S_m] = p_m$, $m = 1, \ldots, M$ *the superscript c indicates the complementary event. If in addition, the complementary events of the modes are statistically independent, this gives rise to the equation below:*

$$\Pr[S_1^C S_2^C \ldots S_m^C] = \Pr[S_1^C]\Pr[S_2^C] \ldots \Pr[S_M^C] = \prod_{m=1}^{m=M} (1 - p_m)$$

This results in the following:

$$p_f = 1 - \prod_{m=1}^{m=M} (1 - p_m) = \sum_{m=1}^{m=M} p_m$$

If the events are mutually exclusive and their complementary events are statistically independent, the probability of failure of the subset of the structure can be evaluated in either of the two ways since:

$$\Pr[S_1^C S_2^C]\Pr[S_1 \cup S_2] = 1$$

The complementary events are not statistically independent.

$$Pr\left[S_1^C S_2^C\right] \geq Pr\left[S_1^C\right] Pr\left[S_2^C\right]$$

$$1 - Pr\left[S_1^C S_2^C\right] \leq \left(1 - Pr\left[S_1^C\right]\right)\left(1 - Pr\left[S_2^C\right]\right)$$

$$p_f = \sum_{m=1}^{m=M} p_m \leq 1 - \prod_{m=1}^{m=M} (1 - p_m)$$

In other words, the probability of failure that is calculated by independent complementary events is an upper bound of the probability of failure.The reliability or functionality of the subset of the structure against the modes assigned to the limit state j is $r_{TL} = 1 - p_{f,TL}$, *i.e. the probability that none of the i failure modes assigned to the ultimate limit states will occur.*

In section 4.3 a relation of ultimate and serviceability limit states was proposed. For the purpose of the calculation of the probability of failure, that relation is a complete collection of mutually exclusive limit states.

7.5.1.2 When there are modes that are not mutually exclusive

In some cases it is not possible to assume that the complete collection is made up of mutually exclusive modes. In that case, the overall probability of failure of the subset $p_{f,TL}$ is calculated on the basis of the existing relation between different modes:independent,correlated,and non-correlated.

7.5.1.2.1 Positively correlated modes in all the limit states

(3) The modes are positively correlated when, once the agents appear, the probability of occurrence varies in the same direction.

In the case that all the modes of the diagram are positively correlated[3], the overall probability of the failure of the subset of the maritime structure is calculated by the following:

$$p_{f,T_L} = 1 - r_f = \max\left(p_{m,T_L}\right)$$

In the preceding equation, $\max(p_{m,TL})$ indicates the greatest probability of failure among all those possible, and $p_{m,TL}$ is the probability of occurrence of one of the m = 1, ..,M modes assigned to one of the limit states.This result will be applied to ultimate as well as serviceability limit states.

7.5.1.2.2 Correlated and non-correlated modes

In these cases there is no general rule, and the ease with which a result is obtained depends on the number of modes and their relation,as described in the note below.

Note

If there are only two failure modes (A and B) assigned to limit state j, and they are positive or negatively correlated, the joint probability of failure of the subset of the structure with the serial diagram (i.e. that at least one of the two failure modes, A or B, will occur) is the following:

$$Pr[A + B] = Pr[A] + Pr[B] - Pr[A * B]$$

*In the above equation Pr[A * B] is the probability that two failure modes A and B will occur simultaneously.*

*For the independent failure modes A and B, Pr [A * B] = Pr [A] * Pr [B].Logically, as more failure modes come into the picture, the calculation of the probability becomes more complex. In many cases, it is difficult, if not impossible to obtain. For this reason,these Recommendations propose approximate calculation methods or methods to obtain an interval of this probability.*

It should be noted that the null correlation coefficient is only an indication that there is no linear relationship between modes, though there can be a quadratic relation, for example.

7.5.1.2.3 Upper and lower bounds of the overall probability

When some of the modes of the serial diagram are correlated and others are non-correlated or independent, the joint probability of failure of the subset in the time interval T_L should be found in the interval whose extremes are:

- Lower bound of the overall probability of failure

$$\left(p_{f,T_L}\right)_{inf} \geq \max\left(p_{m,T_L}\right)$$

- Higher bound of the overall probability of failure

$$\left(p_{f,T_L}\right)_{sup} \leq 1 - \sum_{m=1}^{m=M}\left(1 - p_{m,T_L}\right)$$

7.5.2 Parallel diagrams

Let B_{kji}, i=1,...M_{kj} be each of the i failure modes assigned to the serviceability or ultimate limit state, j =1, ...N_k of each of the k = 1, ...,K chains of a parallel diagram.The subset of the structure fails when all the serial diagrams fail,and the diagrams fail when at least one of the i modes assigned to one of the j states of the chain fails.The probability of failure of the structure or subset $p_{f,TL}$ in the time interval T_L is calculated on the basis of the relations between the different failure modes in each chain in the series:independent,correlated,and non-correlated failure modes.If $Pr[B_{kji}]=p_{kji,T_L}$ is the probability that a failure mode B_{kij} will occur in the time interval T_L, the overall probability of the parallel diagram is calculated in one of the following ways:

7.5.2.1 Mutually exclusive M_{kj} modes and N_k limit states of the chain k

If the modes and limit states are mutually exclusive, the probability of failure in the chain k is calculated by the following equation:

$$p_{f,k,T_L} = 1 - \sum_{j=1}^{j=J}\sum_{i=1}^{i=I}\left(1 - p_{kij,T_L}\right) = 1 - \sum_{m=1}^{m=M}\left(1 - p_{km,T_L}\right)$$

In the above, p_{km,T_L} is the probability of occurrence of one of the m = 1, ...,M, failure modes in the chain k, assigned to the ultimate or serviceability limit states.

7.5.2.2 Overall probability of failure of the subset with a parallel diagram

The overall probability of failure $p_{f,TL}$ of the subset with a parallel diagram made up of K chains in a series,consisting of mutually exclusive failure modes and limit states is calculated by the following:

$$p_{f,T_L} = \prod_{k=1}^{k=K}\left\{1 - \sum_{m=1}^{m=M}\left(1 - p_{km,T_L}\right)\right\} = \prod_{k=1}^{k=K} p_{f,k,T_L}$$

Note *In order for the failure of the subset to occur, all of the chains must fail with at least one failure mode in each. The reliability is calculated by* $r_{f,T_L} = 1 - p_{f,T_L}$.

These formulas can be applied in the case of ductile failures in which the resistance capacity of each element is maintained until all of them fail. In other words, it is assumed that neither a total nor partial progressive collapse takes place.

7.5.2.2 When there are modes that are not mutually exclusive

In some cases, it is not possible to assume that the complete collection is composed of mutually exclusive modes. In that case, the overall probability of failure of the subset, p_{f,T_L} is calculated on the basis of the existing relation between the different modes: independent, correlated, and non-correlated.

7.5.2.2.1 Correlated modes

When some of the chains of the parallel diagram have correlated and non-correlated modes to evaluate the overall probability of the failure of the subset, the recommendations in sections 7.3.2 should be applied to each.

7.5.2.2.2 Upper and lower bounds of overall probability

When the modes in the parallel diagram are of various types:correlated,non-correlated,and independent, the joint probability of failure of the subset of the structure is contained in the interval defined by:

- Lower bound of overall probability

$$\left(p_{f,T_L}\right)_{inf} > \prod_{k=1}^{k=K} p_{f,k,T_L}$$

- Higher bound of overall probability

$$\left(p_{f,T_L}\right)_{sup} \leq \max\left(p_{kji,T_L}\right)$$

7.5.3 Compound diagram

The overall probability of the structure or subset of the structure against failure modes, assigned to ultimate and serviceability limit states and described by a compound diagram is evaluated in each case, according to recommendations in the preceding sections for each of its chains.

7.5.4 Sensitivity of the joint overall against certain failure modes

It is advisable to analyze the sensitivity of the overall probability of failure against certain failure modes whose probability of occurrence is drastically reduced with slight modifications in the geometry of the subset or one of its elements, and whose economic repercussion in the structure is not significant.

Note *In breakwaters, one of the functions of the toe berm is to uphold the main layer, whose failure can make the structure collapse. This berm is usually located at a depth that is approximately equal to the* *design wave height measured from the equinoctial average low tide. In such conditions, the weight of the pieces of the berm is not great, and its placement does not usually require the use of big cranes. For this reason, if the weight of one of these pieces is increased by 50%, this does not make construction more complicated or more expensive. However, it can reduce the probability of failure in more than one order of magnitude.*

7.6 Operationality

After a subset of the structure and a time interval T_L, which generally is a project phase, have been selected, the calculation of its operationality is carried out according to the diagram type of the stoppage mode, and using the formulations and considerations described in section 7.5.

When the time interval used is a year and the duration of the project phase is expressed in years considered as independent intervals, the operationality of the phase is equal to the operationality of an average year.

7.6.1 Average number of operational stoppages

In the case of a serial diagram and mutually exclusive modes, the average number of operational stoppages are calculated as the sum of the average number of stoppages of each of the modes. In the case of parallel diagrams, the average number of stoppages are calculated for each of the sequence of chains that make up the parallel diagram.

Note *The average number of stoppages due to the occurrence of a mode i in V time intervals is the following.* $N_{m,i} = V * p_i / \tau_{m,i}$. *In the preceding equation,* $\tau_{m,i}$ *is the average duration of the stoppage and* p_i, *the probability that the stoppage will occur in the time interval. The average duration can be obtained on the basis of the distribution function of the stoppage mode in the time interval (see the ROM 0.4).*

If the stoppage modes are independent, the total stoppage time produced by the occurrence of M modes in V is equal to $V * \sum_M p_i$; *the average number of stoppages of the subset in V time intervals is* $N_m = \sum_M V * p_i / \tau_{m,i} = V \sum_M p_i / \tau_{m,i}$

7.6.2 Maximum duration of each mode

In a serial diagram, the probable maximum duration is independently calculated for each of the modes,and should not exceed the recommended values in table 2.7.

7.7 Subsets with ERI ≤ 20 and SERI < 20

In those cases in which it is advisable to use a Level I Verification Method to verify a subset of a structure whose general intrinsic nature is ERI ≤ 20 and SERI < 20, it is sufficient to evaluate its safety against the principal failure modes.The calculation of the probability of failure should be carried out as described in the following sections.

7.7.1 Probability of the appearance of a mode

The modes belong to the set of the principal modes assigned to the ultimate limit states and are caused by the occurrence of an agent in the physical environment. In these cases, the probability of failure p_{n,T_L} of the subset of the structure against the mode n can be approximated by the probability of the exceedance of the value of the predominant agent.

7.7.1.1 Return period of a principal mode

It is the average time T_R expressed by the number of time intervals which elapse between two consecutive exceedances of a value of the random variable. Assuming that the events that occur in each time interval are independent and if the distribution function of the variable X is defined in the time interval by $F_X(x) = Pr[X \leq x]$, the period of recurrence can be expressed by the following equation:

$$p_n = \left[1 - F_X(x)\right] \quad T_R = \frac{1}{1 - F_X(x)} = \frac{1}{p_n}$$

Note *According to these hypotheses, the probability of failure of the structure or subset in the useful life V (time intervals) against the principal mode caused by the exceedance of the value of the predominant project factor X is the following:*

$$p_{n,V} = 1 - \left[F_X(x)\right]^V = 1 - \left(1 - \frac{1}{T_R}\right)^V$$

The useful life of the structure is generally defined in years, and thus, the defining time interval $F_X(x)$ is the year. In the case of a breakwater subject to the action of extreme sea states $X=(H_s)_{max}$, where $(H_s)_{max}$ is the maximum sea state of each year, $F_X(x)$ is the regime of extreme sea states or storm regime. The extreme distribution function is generally represented by Φ.

7.7.2 Overall probability of failure in T_L

The overall probability of failure of the subset of the structure in T_L, against the modes n = 1, ..., N is calculated, assuming that these are mutually exclusive in a serial diagram, as represented in the following equation:

$$p_{f,T_L} = 1 - \sum_{n=1}^{n=N} (1 - p_{n,T_L})$$

Note *The reliability r_f of the subset of the structure is obtained by using the formula $r_f = 1 - p_f$. The maximum value of p_f should be in accordance with the recommended values in table 2.3, overall maximum probability of failure of the subset against the modes assigned to the ultimate limit states.*

7.7.2.1 Return period and overall probability of failure

If the principal modes are mutually exclusive and the events occurring in the time interval units (i.e. a year) are regarded as statistically independent, the inverse of the return period T_{RC} of the subset of the structure whose useful life is V, can be approximated by the sum of the inverses of the return periods of each failure mode, as long as they are sufficiently large.

$$\frac{1}{T_{RG}} \simeq \frac{1}{T_{R1}} + \frac{1}{T_{R2}} + \ldots + \frac{1}{T_{RI}}$$

If the principal modes are mutually exclusive or statistically independent, the approximation is exact.

7.8 Economic optimization of the subset

According to the intrinsic nature of the structure, levels of reliability, functionality, and operationality are recommended that should satisfy a subset during the useful life project phase. These levels are general rules, and sometimes for a variety of reasons, it is convenient and necessary to obtain other solutions by taking into account both the probability and the cost that is an optimal economic solution. This analysis can be carried out on the basis of one factor (e. g. geometric parameter) or various. The first case is known as a univariate analysis, whereas the second is known as a multivariate analysis.

The economic optimization of the structure can be carried out against the overall probability of occurrence of the modes assigned to ultimate, serviceability or operational limit states (see figure 7.11). The first two have to do with an economy of failure, and therefore, the economic optimum should be in consonance with the general intrinsic nature of the structure as defined by the ERI and SERI. The optimization against the operational limit states corresponds to the economy in full operation.

Different schemas of economic optimization can thus be established for the subset, depending on the optimization of the cost of the construction phase, the cost of the subset in the useful life phase, the cost of the two phases together against the ultimate and serviceability limit states, the cost-benefit with different constraints related to the exploitation of the subset, or even considering the costs of construction, maintenance and repairs.

Consequently, to resolve the problem of the optimization, it is necessary to define the objective function as well as the constraints. This analysis can be used to specify strategies for repairs, maintenance, and when relevant, economic profitability.

7.8.1 Optimization, reliability, and functionality

The optimal economic solution for the subset of the structure against the reliability or functionality by means of a univariate analysis is carried out by obtaining the minimum value of the total cost of the subset and bearing in mind the cost of repairs and the social and environmental repercussions that may be caused by the possible failure modes. These costs should be expressed in accordance with the project factor selected for the optimization of the subset.

The result of the calculation is the magnitude of the project factor, the joint probability of failure, and the optimal total cost of the subset in the time interval (generally the useful life of the structure).

Note *In Spain optimization studies are being carried out for the section type of the vertical dikes and mound breakwaters, taking the significant wave height of the maximum sea state as the independent optimization variable. This type of study is generally applied, considering only one failure mode, for example, the extraction of main layer units or the sliding of the foundation. The extension of these methods to include other mutually exclusive failure modes is relatively simple.*

At other times, it is convenient to use a geometric parameter of the subset of the structure to economically optimize the alternative against safety, serviceability or operationality limit states. A case in point is the freeboard of the crown wall that protects installations, goods, and people.

7.8.1.1 Economic optimization and intrinsic nature of the structure

The project design of a structure begins with the evaluation of the general intrinsic nature of the structure according to the ERI and SERI indices, which are approximately determined by assuming the occurrence of the worst failure mode assigned to an ultimate or serviceability limit state. Based on the values of these indices, recommended values are defined, among which are those of the useful life of the structure and the overall probability of failure.

In the majority of cases, since only a few principal failure modes provide guidelines for the design of the structure, the ERI and SERI of the verified project design alternative is in the same interval of values as those estimated at the beginning of the project. However, it can happen that the optimal economic solution has an overall probability of failure that differs from the recommended value in tables 2.3 and 2.4. In these cases, the developer of the structure should decide on the solution to be adopted, though it is advisable to choose the one associated with the smallest probability of failure.

7.8.2 Optimization and operationality

The cost of building the structure can be optimized against its operationality by applying the same criteria described in the previous section and by considering the operational stoppage modes. In a similar way, the initial evaluations of the OIER and OISER should be verified to make sure that they are coherent with the results obtained for the project design alternative adopted, and also to make sure that the economic optimum does not have lower operationality levels associated with it.

Note *The possible contradiction between the results of the verification and the economic optimization may occur because the overall probability of failure values recommended in tables 2.3 and 2.4 have been established by criteria of uniformity with other civil works, previous experience and subjective considerations that may not be relevant to other structures. In the coming years, the application of this ROM will provide a source of data that is necessary for the correct calibration of values in the previously mentioned tables. In all likelihood, that calibration will provide a better concordance between the results of the application of the calculation procedure and those of the optimization studies.*

7.8.3 Socioeconomic optimization

A cost-benefit analysis generally includes other aspects beside those presented in the previous section. These aspects are related to the evaluation of the consequences of the failure of the subset and the actions to be taken when such a failure occurs, as well as the marginal investments to be made. For this reason, it is necessary to consider the project factors of the subset as well as other factors pertaining to budget restrictions, technical and socioeconomic aspects, and what is known as qualitative safety. This term encompasses various subjects, such as the evaluation of management structures established for the structure and subset, as well as the monitoring and tracking of the structure's behavior , etc. The existence or inexistence of these elements significantly influences the determination of costs.

7.8.3.1 Objective function

The socioeconomic optimization criteria propose the maximization of the objective function ($B - C_T$) of the subset of the structure throughout all of the project phases. These include its construction, useful life, maintenance, repair, and dismantling, where B is the total cost/benefit of the subset of the structure and C_T, the total cost of the project, including its construction, stocks to improve the qualitative safety, insurance, corrective measures, financial costs, maintenance, and the probable cost associated with the occurrence of failure. In this type of study, it is possible to consider the maximization of the objective function, subject to as many restrictions as desired, including the reliability, functionality, and operationality, a maximum construction cost or an annual maintenance cost.

Objective Function: $Máx\ [B(x) - C_T(x)]$

$X\ (x_1, x_2, \ldots, x_n)$

Restrictions: $C_T\ (x) < C_{max}$

$E(x) < E_{max}$

$p_{f,ELU} < [p_f]$, ***Table 2.2***

$p_{f,ELS} < [p_f]$, ***Table 2.3***

$p_{f,ELO} < [p_f]$, ***Table 2.4***

If the value of the vector x causes any variation in the initial failure and operationality scenario, as defined by the ERI, SERI, OIER, and OISER, the objective function should be optimized again with the new values of the probability of failure and stoppage associated with the new values of the repercussion indices. As a result, the optimization should follow a recursive method.

In all cases, the optimization of the objective function should be coherent with the *Manual de Evaluación de Inversiones de Puertos del Estado* [Investment Evaluation Manual of Puertos del Estado].

7.9 Maintenance of structures and installations

Every productive system with a set of structures and installations should have a global maintenance strategy. This is the case of the public organism, Puertos del Estado, which is in the process of defining the criteria and maintenance strategies for the set of structures and installations, which are not the object of this ROM.

7.9.1 Conservation of the subset of the structure

All maritime and harbor structures designed in accordance with these Recommendations should include a Study and Maintenance Plan during their useful life, coordinated with the general criteria and structures for the maintenance of the productive system, which specifies those aspects not included in global maintenance strategies.

7.9.1.1 Maintenance Plan

This is the document that reflects the maintenance actions to be carried out during the useful life of the structure so that it will continue to comply with project demands.This Plan envisages short-term,medium-term,and long-term actions.The scope and contents of the Plan are defined according to the general intrinsic nature of the structure and are described in the specific Recommendations.

7.9.1.2 Maintenance and economic optimization

One of the methods of establishing a Maintenance Plan is by means of a minimization process of the total cost, defining the cost of the objective function, total investment, and maintenance planning

$$C_T(x) = C_I(x) + \sum_t C_{t,Rep}(x) + \sum_t C_{t,Mant.}(x)$$

according to the vector of project factors x, subject to budget restrictions because of external effects (Visual Inspection and Monitoring Plan), reliability and functionality.

Note *Even when all the restrictions pertaining to the budget,external effects and reliability and functionality are complied with, this optimization process can result in a smaller investment than the one foreseen as well as greater expenditures.*

7.10 Monitoring structures and installations

Every productive system with a set of structures and installations should have a strategy of visual inspection, sounding, and monitoring.This is the case of the public organism, Puertos del Estado, which is in the process of defining the criteria and strategies[4] of the set of its structures and installations,which are not the object of this ROM.

(4) In these Recommendations inspection refers to visual observation. Sounding refers to the short-term measurement taken with instruments in situ of a certain project factor; finally, monitoring refers to the permanent installation of equipment for the continuous measurement and recording of project factors.

7.10.1 Visual inspection, sounding, and monitoring

Once the construction of the subset is finished and its useful life begun, the behavior of the materials and other project factors may be subject to visual inspection, sounding and monitoring.

7.10.2 Visual inspection, sounding, and monitoring plan

The scope and contents of the plan should be defined in consonance with the general intrinsic nature of the structure and are described in the specific Recommendations.

7.10.2.1 Objectives of the plan

The objectives of the visual inspection, sounding, and monitoring are: (1) to verify the probability values and models of the project parameters as well as of the agents and actions. When relevant, this also may include the analysis of their incidence in the overall probability of failure and the operationality level of the project; (2) to decide when to carry out maintenance and repair actions; (3) to generate a database which in the reasonably near future will permit the establishment of the probability models for certain project factors, the development of new verification equations, and evaluation methods of the probability of failure.

7.10.2.2 2.2 Contents of the plan

In order to attain the previous objectives, the visual inspection, sounding, and monitoring plan should at least define the following aspects:

1. Temporal and spatial extension
2. Cadence of the inspections
3. Project factors inspected
4. Visual observation and sounding method, and when relevant, the measurement and recording method
5. Temporality: permanent and non-permanent

7.11 Failure of existing structures

Because of the intrinsic randomness of the parameters and the project variables,the reliability and functionality of all maritime structures inevitably decrease over time, and this leads to the occurrence of a failure.

7.11.1 Uncertainty and revision of the overall probability of failure

The overall probability of the structure, calculated by any of the methods recommended is not free of uncertainty. For this reason,once the subset has entered into service, the evaluation of the overall probability of failure should be revised in accordance with the information that is being gathered, mainly pertaining to the maximum values of the agents of the physical environment. It can thus be assumed that the reliability in the structure's useful life $r_{f,v} = 1 - p_{f,v}$, is a variable with a probability model (e.g. the beta function).

7.11.2 Regressive calculation of the behavior of the subset

Once the subset of the structure has begun to operate, a natural deterioration gradually begins to take place. Processes of visual inspection, sounding, and monitoring provide data, which is real information concerning the physical agents acting upon the structure. On the basis of this information, it is necessary to verify the deterioration of the structure together with the number of occurrences and magnitude of the presented agents.Other elements to verify are if the evaluation of the overall probability of failure is in accordance with the project design, and if the maintenance of the subset is effective.

To evaluate the residual behavior of the subset against the modes, the functions of survival, danger and reliable life can be applied.

Note *The survival time is the time elapsed from when the structure began to operate or its most recent repairs made until the expected time of the first failure occurrence.The reliability function is the probability that the subset will not fail in at least t time intervals from the time it becomes operational.The danger function is the conditional probability that the subset will fail in the following time interval, even after behaving adequately in previous time intervals from the time it first became operational or the time when it was last repaired.Reliable life is the time necessary for the reliability of the subset (complementary value of the overall probability of failure) to decrease until it is less than the recommended reliability.*

7.11.3 Repairing the subset

Until more information is available, it is generally necessary to begin repairs on the subset when the estimated value of the probability of the failure against one of the modes assigned to a limit state for the rest of the time units of the structure's useful life is less than the probability corresponding to the project time unit or when the analysis derived from the visual inspection and sounding of the subset indicate that repairs should be carried out.

7.11.4 Dismantling

When the subset of the structure has ended its useful life or when its safety and serviceability are not guaranteed by maintenance and repair, it should be dismantled.

7.12 Annex: Example of an overall probability calculation

The example described here is that of a vertical dike with three principal failure modes or sample elements: s_1: sliding; s_2: overturning; s_3: berm erosion. These elements along with the null event 9 form a complete collections, and consequently, are the sample space of failure modes $\Omega_s = \{s_1, s_2, s_3, \vartheta\}$.

7.12.1 Sequence of events

Based on these sample elements, it is possible to make up a collection of possible failure mode events by means of the combination of sample elements, including complementary events.

The most basic events are those that contain each of the failure modes and their corresponding complementary events: $S_1(s_1)$, S_1^c, $S_2(s_2)$, S_2^c, $S_3(s_3)$ y S_3^c. Assuming that the probability of each of these failure modes in one year is $Pr[S_1] = 0.050$,$Pr[S_2] = 0.001$ y $Pr[S_3] = 0.010$,if each event and its complement are regarded as mutually exclusive, it holds that $Pr\,[S_1^c] = 0.950$, $Pr\,[S_2^c] = 0.999$ and $Pr\,[S_3^c] = 0.990$.The formulation of other events is based on the union and the intersection of events.More specifically, the event that overturning or sliding or the erosion of the berm occur in the space of a year is the union event, $S_1 \cup S_2 \cup S_3$, and the event that none of these failure modes occur is the complement of the union $\vartheta = \{ S1 \cup S2 \cup S3 \}^c$, which is equal to the intersection of the complementary events $\vartheta = \{S_1^c\ S_2^c\ S_3^c\}$.

7.12.2 Mutually exclusive failure modes

In the case that the failure modes, S_1, S_2 and S_3, are mutually exclusive, their intersections are null and cannot occur simultaneously. The possible states that a vertical dike can undergo in a time interval (a year) are the following: (1) the wall has slid; (2) the wall has overturned; (3) the berm has eroded; (4) no failure has occurred. Bearing in mind that the probability of all possible events should be equal to the unit and based on available data,the probability that in a year, no failure will occur is the following:

$$Pr[S_1^c S_2^c S_3^c] = Pr[\vartheta] = 1 - 0.061 = 0.939$$

In these circumstances, a complete set of events, Ψ, is formed by combinations of the following events:

$$\Psi = \{S_1, S_2, S_3, S_1^c\ S_2^c\ S_3^c\}$$

On the basis of this information it is possible to calculate:

1. The probability that the dike will fail because of sliding, overturning, or erosion of the berm in a year.

$$p_{f,1} = Pr[S_1 \cup S_2 \cup S_3] = \Sigma^3_{i=1}\ Pr[S_i] = 0.050 + 0.001 + 0.010 = 0.061$$

As shown,this probability can be calculated by means of the probability of the complement of the union of the event or of the intersection of complementary events.

$$p_{f,1} = 1 - Pr[\{S_1 \cup S_2 \cup S_3\}^c] = 1 - Pr[\{S_1^c\ S_2^c\ S_3^c\}] = 0.061$$

The probability that no failure will occur in a year is $1 - p_{f,1} = 0.937$. It is convenient to verify that the complementary events of the failure modes are not statistically independent, given the following:

$$Pr[S_1^c]\ Pr[S_2^c]\ Pr[S_3^c] \neq Pr[\{S_1^c\ S_2^c\ S_3^c\}]$$

2. The probability that the dike will fail in 25 years because of one of these three failure modes is:

$$p_{f,25} = \{Pr[S_1 \cup S_2 \cup S_3]\}_{25años} = 1 - (1 - p_{f,1})^{25} = 1 - \{1 - Pr[S_1 \cup S_2 \cup S_3]\}^{25} = 0.7927$$

7.12.3 The overturning and the erosion of a berm are not mutually exclusive

It has often been observed that the vertical dike overturns once the berm has eroded.In this case, the conditioned probability of the dike overturning after the berm has eroded is not null. If $Pr[S_2 \mid S_3] = 0.5$, and the probabilities of the occurrence of wall sliding and overturning and berm erosion,considered as individual failure modes,are those previously adopted,a complete collection of events Ψ is formed by the combination of the following failure modes:

$$\Psi = \{S_1, S_2, S_3, S_1^c\ S_2^c\ S_3^c\}$$

The probability of the intersection event overturning and berm erosion is obtained according to the conditional probability:

$$Pr[S_2 S_3] = Pr[S_2 \mid S_3]\ Pr[S_3] = 0.50 \cdot 0.010 = 0.0050.$$

With this information it is possible to obtain the following:

1. The probability that the dike will fail because of sliding,or because of the overturning or erosion of the berm in a year:

$$p_{f,1} = Pr[S_1 \cup S_2 \cup S_3] = \sum_{i=1}^{3} Pr[S_i] - Pr[S_2S_3] = 0.0610 - 0.0050 = 0.0560.$$

The probability that the dike will not fail in a year is 0.944.As in the previous case,

$$p_{f,1} = 1 - Pr[\{S_1 \cup S_2 \cup S_3\}^c] = 1 - Pr[S_1^c\, S_2^c\, S_3^c] = 0.0560$$

and the complementary events of the failure modes are not statistically independent.

2. The probability that the dike will fail in 25 years because of one of the tree failure modes.

$$p_{f,25} = 1 - (1 - p_{f,1})^{25} = \{Pr[S_1 \cup S_2 \cup S_3]\}_{25años} = 1 - (1 - p_{f,1})^{25} = 1 - \{1 - Pr[S_1 \cup S_2 \cup S_3]\}^V = 0.7632$$

7.12.4 The overturning and the erosion of the berm are statistically independent

When statistical independence is assumed, the collection of events is the same as in the previous case, but the conditional probability of overturning, if the erosion of the berm has occurred, is $Pr[S_2 \mid S_3] = Pr[S_2]$, and the probability of the intersection event is $Pr[S_2S_3] = Pr[S_2]\,Pr[S_3]$.The probability that the dike will fail because of sliding or because of the overturning or berm erosion in a year is 0.06099; the probability that it will not fail in a year is $1 - p_{f,1} = 0.9390$, and the probability that it will fail in 25 years because of one of the three modes is $p_{f,25} = 0.7926$.

7.12.4 The overturning and erosion and the sliding and erosion are not mutually exclusive

Another case to consider is when the probabilities of the occurrence of overturning and sliding, conditioned by the occurrence of the erosion of the berm, and overturning, conditioned by the previous occurrence of sliding and the berm erosion are not null:

$$Pr[S_2 \mid S_3] = 0.50; \quad Pr[S_1 \mid S^3] = 0.25$$

Furthermore, this includes the probability that the dike will overturn,conditioned by the previous erosion of the berm and sliding, $Pr[S_2 \mid S_1S_3] = 0.80$ y $Pr[S_1S_2] = 0.0001$

Applying the definition of the conditional probability and taking into consideration individual probabilities of S_1, S_2 and S_3, the following is obtained:

$$Pr[S_2S_3] = 0.0050; \; Pr[S_1S_3] = 0.0025;$$
$$Pr[S_2S_1S_3] = Pr[S_2 \mid S_1S_3]\, Pr[S_1 \mid S_3]\, Pr[S_3] = 0.0020$$

In these circumstances, a complete collection of events Ψ is formed by the combination of the following failure modes:

$$\Psi = \{S_1, S_2, S_3, S_1S_2, S_1S_3, S_2S_3, S_1S_2S_3, S_1^c\, S_2^c\, S_3^c\}$$

In this case, the probability that the dike will fail in a year because of overturning or sliding, or because of the erosion of the berm is represented by the following expression:

$$p_{f,1} = Pr[S_1 \cup S_2 \cup S_3] = \sum_{i=1}^{3} Pr[S_i] - Pr[S_1S_2] - Pr[S_1S_3] - Pr[S_2S_3] + Pr[S_1S_2S_3] = 0.0554$$

The probability that the dike will not fail in a year is 0.9445, and the probability that it will fail at least once because of the occurrence of one of the failure modes, sliding, overturning or erosion of the berm is $p_{f,25} = 0.7601$.

As can be observed, the failure modes, overturning and sliding, continue to be mutually exclusive.

7.12.6 Probability of failure of different possible event combinations

The last case is similar to the actual behavior of a vertical dike faced with the action of the climatic agents with three interrelated principal failure modes. For this reason, the following subsections try to answer some questions that complete the analysis of the probability of failure of the dike in 1 and 25 years, and which can help to define strategies of maintenance and repair.

- Questions:

1. Probability that the dike will fail because of the simultaneous occurrence of the three failure modes.
2. Probability that the dike will fail because of the occurrence of two failure modes: sliding and erosion of the berm (overturning and erosion of the berm, sliding and overturning).
3. Probability that the dike will simultaneously fail because of one of the combinations of two of the three failure modes
4. Probability that once sliding has occurred that the dike will fail because of overturning and erosion of the berm.

- Answers:

1. Simultaneous occurrence of the three failure modes.

$$p_{f(3),1} = Pr[S_1S_2S_3] = Pr[S_2 \mid S_1S_3]\, Pr[S_1S_3] = 0.80 \cdot 0.25 \cdot 0.010 = 0.0020$$

$$p_{f(3),25} = 1 - (1 - p_{f(3),1})^{25} = 0.0048$$

2. Simultaneous occurrence of two failure modes.

$$\text{sliding and erosion: } \{Pr[S_1S_3]\}_1 = 0.0025; \ \{Pr[S_1S_3]\}_{25} = 0.0607$$

$$\text{overturning and erosion: } \{Pr[S_2S_3]\}_1 = 0.0050; \ \{Pr[S_2S_3]\}_{25} = 0.1178$$

$$\text{sliding and overturning: } \{Pr[S_1S_2]\}_1 = 0.0001; \ \{Pr[S_1S_2]\}_{25} = 0.0025$$

3. Occurrence of at least one of the possible combinations of two failure modes.

$$p_{f(2),1} = Pr[(S_1\, S_2\, S_3^c) \cup (S_1\, S_2^c\, S_3) \cup (S_1^c\, S_2^c S_3)] = Pr[S_1\, S_2\, S_3^c] + Pr[S_1\, S_2^c\, S_3] + Pr[S_1^c\, S_2^c S_3]$$

$$p_{f(2),1} = Pr[(S_1\, S_2\, S_3^c) \cup (S_1\, S_2^c\, S_3) \cup (S_1^c\, S_2^c S_3)] = 0.0075$$

The probability that one of the combinations of the two possible failure modes will occur at least once in 25 years is:

$$P_{f(2),25} = 1 - \{1 - Pr[(S_1\ S_2\ S_3^c) \cup (S_1\ S_2^c\ S_3) \cup (S_1^c\ S_2^c S_3)]\}^{25} = 0.1716$$

4. Probability that the dike will fail because of erosion and overturning, once a fail-ure caused by sliding has occurred.

$$Pr[S_2S_3 \mid S_1] = \frac{Pr[S_1S_2S_3]}{Pr[S_1]} = 0.040$$

7.12.7 Complete collection of mutually exclusive events

Assuming that in extreme WOCs, the vertical dike can only fail because of sliding, overturning and berm erosion,(s_1, s_2 and s_3) so that these sample elements form a complete collection, the space of the failure modes should be formed by the combination of these sample elements. The three individual failure modes are known as S_1, S_2 and S_3. After following the procedure described in the preceding sections, the values below have been obtained for the probability of failure in a year:

$$Pr[S_1]_1 = 0.045;\ \ Pr[S_2]_1 = 0.020;\ \ Pr[S_3]_1 = 0.050;$$

If these failure modes are mutually exclusive, the joint probability of failure of the subset of the structure in a useful life of 25 years because of one of the three failure modes is $p_{f,ELU} = 0.9528$. This very high probability can be reduced in different ways. The cost of the protection of the toe berm generally does not increase very much when the size of the elements of protection is increased. In this way, it is possible to obtain that $Pr[S_3]_1 \approx 0$, which results in $p_{f,ELU} = 0.8137$. In these conditions, it is necessary to reduce an order of magnitude the probability of occurrence of the modes S_1 and S_2, ($Pr[S_1]_1 = 0.0045$; $Pr[S_2]_1 = 0.0020$), in order to satisfy the probability required in Table 2.3. $p_{f,ELU} = 0.1504$.

7.12.8 Collection of events that are not mutually exclusive

If the individual events are not mutually exclusive, the calculation becomes more complex because it is necessary to consider certain combinations of events, which previously have not been regarded as significant. It is assumed that the overturning and sliding are mutually exclusive. This means that if overturning occurs, then sliding cannot. As a result, the intersection $S_1S_2 = \varnothing$ and $Pr[S_1S_2] = 0$, in the same way as the sliding and the erosion of the berm, $S_1S_3 = \varnothing$. However, the erosion of the berm and the overturning can occur simultaneously, $S_2S_3 \neq \varnothing$, and the probability that the overturning will occur when there has been erosion of the berm is $Pr[S_2 \mid S_3] = 0.20$. This results in the following:

$$Pr[S_2S_3] = Pr[S_2 \mid S_3]\ Pr[S_3] = 0.20 * 0.050 = 0.010$$

In this case, the space of mutually exclusive events contains the following combinations of events, S_2S_3, $S_2S^c_3$, $S^c_2S_3$, given that now,

$$Pr[S_2S^c_3] = Pr[S^c_3 \mid S_2]\ Pr[S_2] = \{1 - Pr[S_3 \mid S_2]\}\ Pr[S_2] = \{1 - Pr[S_3S_2]\ Pr[S_2]\}\ Pr[S_2] = 0.010 \neq Pr[S_2]$$

The space of mutually exclusive events is formed by:

$$\Psi_S = \{S_2S_3,\ S_2S^c_3,\ S^c_2S_3,\ S_1S^c_2S^c_3,\ S^c_1S^c_2S^c_3\}$$

The probability that at least one of the failure events S_1, or S_2, or S_3 will occur is the probability of the union of mutually exclusive events,including failure events:

$$Pr[(S_1S^c_2S^c_3) \cup (S_2S_3) \cup (S_2S^c_3) \cup (S^c_2S_3)] = Pr[S_1S^c_2S^c_3] + Pr[S_2S^c_3] + Pr[S_3S^c_2] + Pr[S_2S_3]$$

in such a way that the probability of non-failure (i.e. the occurrence of event $S^c_1S^c_2S^c_3$, now can be written in the following way:

$$Pr[S^c_1S^c_2S^c_3] = 1 - Pr[(S_1S^c_2S^c_3) \cup (S_2S_3) \cup (S_2S^c_3) \cup (S^c_2S_3)]$$

With the help of a Venn,it is easy to show the probability of occurrence of at least one of the failure events S_1, or S_2, or S_3 is,

$$Pr[S_1 \cup S_2 \cup S_3] = Pr[S_1] + Pr[S_2] + Pr[S_3] - Pr[S_2S_3] = 0.1050$$

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