Target Design Levels for Maritime Structures

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Abstract: The main objective of a project is to verify the requirements and target levels for values of reliability, functionality, and operationality during the useful life of the structure. Such requirements should be provided by external studies carried out by the promoter. In their absence, the engineer has to specify requirements using his or her own criteria. This paper describes a procedure that defines the target levels for maritime structures in terms of their general and operational intrinsic natures. These natures are used to evaluate the importance of the structure as a function of the economic, social, and environmental impact produced in case of serious damage or a total loss of functionality and stoppage, respectively. This procedure gives recommendations for values of a structure's minimum useful life, joint probability of failure against the principal failure modes, adscribed to ultimate and serviceability limit states, minimum operationality, average number of admissible technical breakdowns, and maximum allowed duration of a stoppage mode.

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Introduction

A maritime structure is built for specific functions and is generally constructed to facilitate or create possibilities for economic activities within its immediate context. All of these factors generate social repercussions as well as having an impact on the environment. Moreover, the structure must be safe and reliable for the time that it remains in operation. Throughout its useful life it passes through different stages pertaining to its structure, form, and use and exploitation, depending on the spatiotemporal variation of the project factors.

For a variety of reasons, due to factors described in failure modes and operational stoppage, the structure may lose its resistance (loss of safety), structural capacity (loss of serviceability), and/or operational capacity (loss of exploitation). This may occur either suddenly or gradually, temporarily or permanently, or partially or totally. One of the main objectives of the project design is to ascertain if the proposed structure will be reliable with regard to safety, functional with regard to serviceability, and operational with regard to use and exploitation. For that reason, values or target levels of reliability, functionality, and operationality should be specified beforehand. The construction and maintenance costs of the structure as well as its use and exploitation depend on all of these elements during its useful life.

The specification of target levels is not a trivial task. Usually decisions regarding the project for a maritime structure are made on the basis of previous external planning studies, which include, among other things, an analysis of the economic, social, and environmental impact of the construction. However, in the absence of specific studies, the engineer needs guides for the specification of these values beforehand, thus allowing comparison of different project alternatives at different locations.

Review of Procedures to Choose Target Levels

When a target level is specified or reliability, functionality, or operational assessments have been performed, it must be decided if the values are acceptable. This is mainly done in the form of risk acceptance (tolerance) criteria by (1) comparing the probability of failure or stoppage with other risks in society and using these comparisons to infer acceptable or tolerable risk for structures; and (2) relating the consequences of the failure, which are encountered in regulators of hazardous industries (nuclear and chemical plants, etc.) (Stewart and Melchers 1997).

Other areas dealing with risk use the concept "as low as reasonably practical," the so-called ALARP principle (HSE 1999), which considers three ALARP regions: acceptable, unacceptable, and intermediate. Some degree of cost-benefit trade-off is unavoidable in order to reduce risks to the ALARP level.

Following CIRIA CUR (1991), the acceptable level should be given by the owner or society based on specific studies, particularly on socioeconomic optimization methods. A more general criterion for assessing acceptability of failure and stoppage is the cost-benefit analysis. A number of papers have been published, recently that deal with the evaluation of the optimal probability of failure or stoppage (Castillo 2004; Oumeraci et al. 2001).

In the absence of specific studies, there are few procedures an engineer can apply to specify the target levels. Even if studies happen to exist, not many procedures couple their recommendations with the engineering methods and tools to evaluate the structure's safety serviceability and use and exploitation.

The procedure given in the Maritime Navigation Commission Report WG28 (PIANC 2003) is a further step in the procedure proposed in the *Spanish Recommendations for Maritime Struc-*

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tures (ROM 0.2-90 1990). However, there are still aspects related to the economic, social, and environmental impacts that should be considered, namely, the determination of (1) a structure's useful life; (2) the assignment of the breakwater (to be discussed later) to a class; and (3) the target levels for use and exploitation.

Although a socioeconomic analysis is frequently carried out for most infrastructures in order to justify the investment, this analysis generally does not touch upon the quality of the structure or its capacity. This means that no relationship is specified between the dimensions of the structure and its probability of failure. For this reason, a new procedure has been developed that can be applied in the absence of more specific studies.

Aim and Scope of the Paper

This paper describes an engineering procedure by means of which the requirements and target levels of a maritime structure can be specified. First, we state our main objectives and procedure restrictions, define the concept of the intrinsic nature of a structure, and then outline a procedure that can be used to evaluate both the general and operational intrinsic natures of a structure. A classification of maritime structures in terms of these natures is then given. Second, in accordance with the structure's intrinsic nature, we propose recommendations for the following values: minimum useful life, joint probability of failure against the principal failure modes assigned to ultimate and serviceability limit states, minimum operationality, average number of admissible technical breakdowns, and maximum allowed duration of a stoppage mode (ROM 0.0 2001). The procedure described is then applied to the real case of the breakwater in the harbor of Motril, Spain. The appendix summarizes these data.

Specific Objectives and Procedure Restrictions

Hereafter a procedure is understood as a sequence of activities that must be carried out to attain a specific objective. Such a procedure should be

1. Unique for the specification of all values or target levels;
2. Based on simple, standard, accessible, and homogeneous information;
3. Easily applied by any engineer;
4. Not significantly affected by external interferences; and
5. Consistent.

In our opinion the procedure proposed in this article meets the first four requisites; the last is also fulfilled if engineers apply the same input to maritime structures with similar economic, social, and environmental impacts and obtain similar recommended values for the target levels. With a view to achieving this goal, values were proposed by senior engineers with ample experience and applied to a large number of cases on the basis of different inputs. The values assigned to the various aspects of the intrinsic nature formulae were determined and tested by a Commission, which consists of more than 50 Spanish maritime engineers.

Nevertheless, the reader should bear some very important conclusions in mind. The recommended target-level values should only be applied to maritime structures that are infrastructures of an industrial nature that have controlled access and are handled by people with experience. These values thus cannot be compared with those for the design of other civil works such as buildings and bridges, which are intensively used by humans.

The values assigned to the different aspects and the formulae used in evaluation of the structures' intrinsic natures have been tested in the framework of Spanish experience. However, this procedure can be easily adapted to any other country in the world by adding other relevant aspects or by changing the weights of the existing aspects. Since social perceptions tend to evolve over time, these values should be reviewed in the future.

Last but not least, observe that the recommended probability values should not be considered a relative frequency that can actually be measured or observed. Probability in the context of this paper can be understood in its Bayesian sense as an assessment of the degree of confidence or faith that the event in question 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.

Steps for Specifying Target Design Levels

As shown in Fig. 1, the procedure used to obtain the target design levels consists of three steps:

1. Evaluation of the indices of economic, social, and environmental repercussions that define the general and operational intrinsic natures of the structure;
2. Classification of the structure according to the indices obtained in step 1; and
3. Specification of the target design levels as a function of the classification of the structure.

General and Operational Intrinsic Natures

The general intrinsic nature *(GIN)* of a maritime structure is an indicator of the structure's importance. The GIN can be used to evaluate the economic, social, and environmental impact of serious structural damage/destruction or total loss of functionality, which is normally defined on the basis of a principal failure mode assigned to an ultimate limit state; in other words, it is reliability oriented. Moreover, the GIN of the structure can be established on the basis of a principal failure mode assigned to a serviceability limit state and thus will depend on the structure's functionality.

The economic, social, and environmental repercussions produced when the maritime structure stops functioning or reduces its operational level are specified by means of the structure's operational intrinsic nature (*OIN)*. This can be evaluated by selecting the mode from among the principal modes of operational stoppage, which gives the minimum operational level. It is the responsibility of the developer of the maritime structure (who may belong to either the public or private sector) to specify the general and operational intrinsic natures of the structure.

In the absence of a specific definition, the GIN of the maritime structure is established in terms of the following indices: the economic repercussion index (ERI) and the social and environmental repercussion index (SERI). Similarly, in the absence of a specific definition, the OIN is established in terms of the following indices: the operational index of economic repercussions (OIER), and the operational index of social and environmental repercussions (OISER). The definitions of the indices and their values can be approximately calculated as given in the sections that follow.

Classification of Maritime Structures

The second step in the procedure is to assign ERI and SERI values to the general intrinsic nature of the maritime structure. This results in the classification of the structure in terms of two values (R,S).

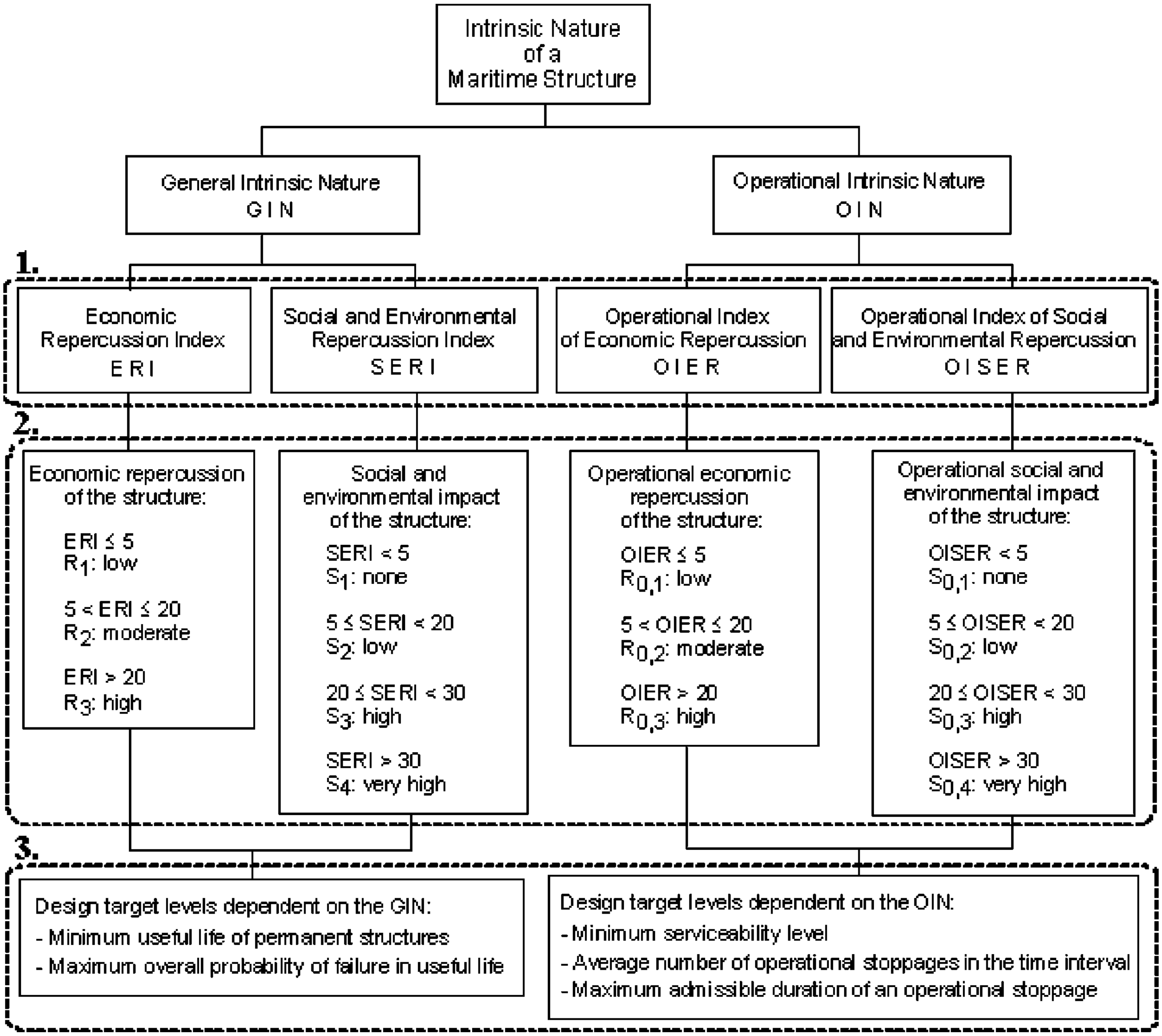

Fig. 1. Intrinsic nature of maritime structure

According to their ERI values, maritime structures can be divided into three groups. When they are classified according to their SERI values, they fall into four groups (Fig. 1).

The next step is to describe the operational intrinsic nature of the maritime structure in terms of OIER and OISER values. This results in the classification of the structure on the basis of two values (R_O,S_O).

Since the intrinsic nature (or its indices) is not precise but gives information regarding the importance of the structure, the resulting index values in the classification understandably have broad intervals. The bounds of the intervals have been defined by the Commission so that all of the many cases studied fit into the category to which they are expected to belong.

Economic Repercussion Index

The economic repercussion index (ERI) leads to a quantitative assessment of the foreseeable economic repercussions caused by the failure of the structure. The ERI is defined by the expression shown in Fig. 2, where the numerator ($C_{RD}+C_{RI}$) takes into account all the economic repercussions of the failure, while the denominator (C_0) is an economic parameter of dimensionalization.

The investment cost, C_{RD}, corresponds to the rebuilding/repair of the maritime structure so that it can regain its previous state. This value is determined for 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 equal to the initial investment, duly updated to the year in question.

The repercussions cost, C_{RI}, can be used to evaluate the economic repercussions that are the consequences of the economic activities directly related to the structure in the event of its destruction or total loss of exploitation capacity. 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. The cost is valued in terms of loss of gross added value 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. The cost is considered to occur 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 takes place a certain number of years after it begins to function. For the purposes

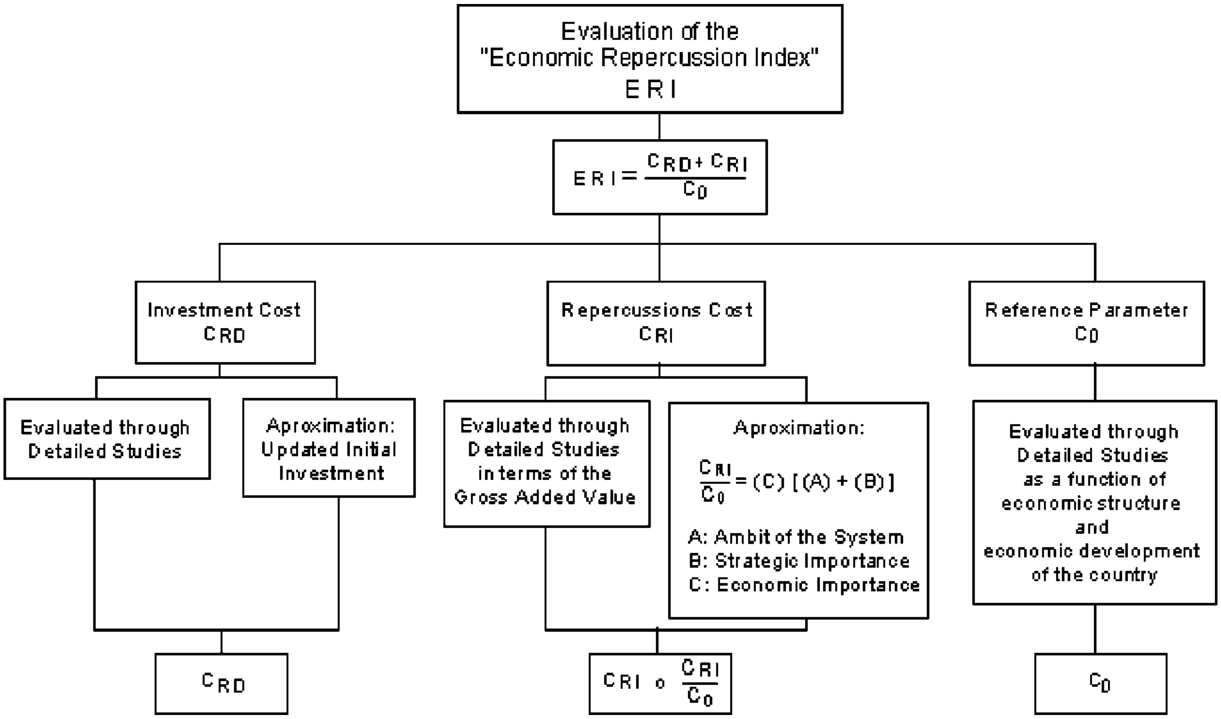

Fig. 2. Evaluation of economic repercussion index

of evaluation and unless there are reasons to the contrary, this time period is estimated to be 5 years. Analogously, the time period during which rebuilding takes place is 1 year.

The value of the economic parameter of dimensionalization, C_0, depends on the economic structure and level of economic development in the country where the structure is going to be built and consequently will vary over time. In Spain, for example, the value of C_0 that should be applied is $C_0=3$ million euros for the year in which the costs are valued. This value may be representative of the average unit investment cost per meter of a maritime structure in the country, that is, the average cost per meter of a dock at a water depth of 15 m.

Approximate Evaluation of C_{RI}/C_0

In those cases in which a detailed determination of C_{RI} is not carried out, either for reasons of excessive complexity because of the structure's size or because there are no previous studies upon which to base it, the value of the ERI can be qualitatively estimated by the equation $C(A+B)$ shown in Fig. 2, where A is the value of the context of the economic and productive system; B evaluates the strategic importance of the economic and productive system; and C represents the structure's importance for the economic and productive system for which it offers a service.

The role of C in the value of ERI is greater than that of A and B. If the structure is irrelevant for the economic and productive system for which it offers a service, its serious structural damage/destruction or total loss of functionality will not affect that system. These coefficients can be determined by assigning the values given in Table 1, according to the type of context involved.

Economic Repercussion Index of Breakwater of Motril

The most critical failure mode ascribed to an ultimate limit state is the sliding of the caisson; see the appendix, which gives information from which the following values can be obtained:

- C_{RD}: In the absence of detailed studies, this value is considered equal to the initial investment, duly updated to 5 years after the maritime structure is in full operation, which in this case is 2004, $C_{Rd}=15.7$ million euros;
- C_0: In Spain, $C_0=3$ million euros; and
- C_{RI}: Since a detailed determination of C_{RI} was not carried out, the value of the quotient C_{RI}/C_0 was evaluated by the approximation method:
- *Coefficient of the ambit of system (A)=2*, regional;
- *Coefficient of strategic importance (B)=5*, essential, since the goods handled are used in 40% of the industrial activity in the area; and
- *Coefficient of economic importance (C)=2*, essential, since it is the main entrance route of the products to the hinterland.

Sampling the values, the quotient $C_{RI}/C_0=14$ and the ERI $=19\leqslant 20$.

Social and Environmental Repercussion Index

The social and environmental repercussion index (SERI) leads to a qualitative assessment of the social and environmental repercussions produced in the event of the destruction or total loss of operationality of the maritime structure. Factors evaluated are the possibility and scope of the following: (1) loss of human lives; (2) damage to the environment as well as to the historical and cultural heritage; and (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.

Approximate Calculation of Social and Environmental Repercussion Index

The SERI is determined by the sum of three subindices:

Table 1. Parameters to Evaluate $C_{RI}C_0$

A		*B*		*C*	
Classification	Value	Classification	Value	Classification	Value
Local	1	Irrelevant	0	Irrelevant	0
Regional	2	Relevant	2	Relevant	1
National or international	5	Essential	5	Essential	2

$$\mathrm{SERI} = \sum_{i=1}^{3} \mathrm{SERI}_i$$

where $SERI_1$ evaluates the possibility and scope of the loss of human life, which is considered to fall into one of the following categories:

- *Remote*, when injury to people is improbable;
- *Low*, when loss of human life is possible but not probable (accidental) and few people are affected;
- *High*, if loss of human life is very probable but affects a relatively reduced number of people (for example, damage produced by a serious traffic accident); and
- *Catastrophic*, if loss of human life and injury to people is so serious and widespread that it affects the regional medical response capacity.

$SERI_2$ evaluates the damage to the environment and the historical and cultural heritage. Similarly, it is classified as

- *Remote*, when damage is improbable;
- *Low*, if the damage is slight but reversible (in less than a year) or there is loss of elements of little value;
- *Moderate*, if the damage is important but reversible (in less than 5 years) or there is loss of important elements of historical and artistic value;
- *High*, when damage to the ecosystem is irreversible and there is loss of important elements of historical and artistic value; and
- *Very high*, if damage to the ecosystem is irreversible, resulting in the extinction of protected species or the destruction of protected natural resources or of a large number of important elements of historical and artistic value.

$SERI_3$ evaluates social disruption. It is classified as

- *Low*, when there are no signs of any significant social disruption associated with the failure of the structure;
- *Moderate*, if there is a minimum degree of social disruption associated with high SERI_1 and SERI_2 values;
- *High*, if a minimum degree of social disruption is caused by a catastrophic SERI_1 value; and
- *Very high*, when there is a maximum degree of social high SERI_2 value disruption.

According to the description above, these coefficients can be determined by assigning the following values (Table 2):

Social and Environmental Repercussion Index of Breakwater of Motril

- $SERI_1=0$, remote, since access to the harbor installations is restricted and only authorized to harbor workers;
- $SERI_2=0$, no damage expected, since no elements of historical or artistic value are in the immediate vicinity; and
- $SERI_3=0$, no human injuries or damage to historical and artistic values expected.

From the above values, the failure of the Motril breakwater has a $\mathrm{SERI}=0<5$.

Table 2. Values of Parameters to Evaluate Social and Environmental Repercussion Index (SERI)

SERI_1		SERI_2		SERI_3	
Classification	Value	Classification	Value	Classification	Value
Remote	0	Remote	0	Low	0
Low	3	Low	2	Moderate	5
High	10	Moderate	4	High	10
Catastrophic	20	High	8	Very High	15
—	—	Very high	15	—	—

Operational Index of Economic Repercussions

The operational index of economic repercussions (OIER) quantitatively assesses the costs resulting from the operational stoppage of the structure. In those cases in which a detailed determination of costs is not carried out, either for reasons of excessive complexity because of the structure's size or the lack of previous studies, the value of the OIER can be qualitatively estimated as follows:

Approximate Calculation of Operational Index of Economic Repercussions

The OIER is determined by the following formula:

$$\mathrm{OIER} = F \cdot [(D) + (E)]$$

where *D* evaluates the simultaneity of the period of the demand affected by the structure and the period of agent intensity that defines the serviceability level; *E* characterizes the intensity of use of the demand in the time period being considered; and *F* characterizes the adaptability of the demand and the economic context for the operational stoppage. Evidently, if the demand adapts with no problems to the stoppage of the structure, the economic repercussions of the stoppage are negligible.

According to the above description, these coefficients can be determined by assigning the values given in Table 3.

Operational Index of Economic Repercussions of Breakwater of Motril

The stoppage mode that gives the minimum operational level is overtopping; see the appendix, which gives information from which the following values can be obtained:

- *Coefficient of simultaneity $D=2.5$*, partially simultaneous, since the harbor has traffic year round and the period of extreme waves occurs only on certain winter days. It is important to remark here that the procedure is flexible. Consequently, between the two options given by the ROM 0.0 (simultaneous or nonsimultaneous), an intermediate value can be chosen if there is sufficient reason for it.
- *Coefficient of intensity ($E=3$)*, intensive, because the use of the demand in the time period being considered.

Table 3. Parameters to Evaluate Operational Index of Economic Repercussions

D		E		F	
Classification	Value	Classification	Value	Classification	Value
Nonsimultaneous periods	0	Not intensive	0	High	0
Simultaneous periods	5	Intensive	3	Moderate	1
—	—	Very intensive	5	Low	3

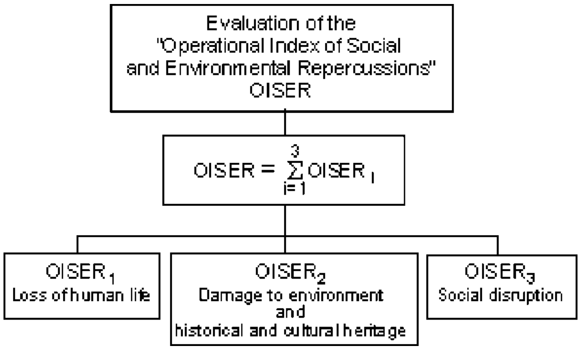

Fig. 3. Evaluation of operational index of social and environmental repercussions

- *Coefficient of adaptability (F=0)*, high adaptability, since there are two harbors, Malaga and Almeria, for the same hinterland and demand. If all of these values are inserted in the above formula, OIER $=0 \leqslant 5$.

Operational Index of Social and Environmental Repercussions

The operational index of social and environmental repercussions (OISER) leads to a qualitative assessment of the social and environmental repercussions 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; and (3) degree of social alarm produced.

In most maritime structures, the OISER is zero, given that once an operational stoppage occurs, any possible cause of environmental impact also disappears. However, the stoppage of certain structures, such as submarine outfalls and water intakes for electric power plants or water desalinization plants, can cause significant social and environmental repercussions.

Approximate Calculation of Operational Index of Social and Environmental Repercussions

The OISER is defined as the total sum of three subindices (Fig. 3). The procedure to follow is the same as that described for the approximate calculation of the SERI, taking into account that the cause of the repercussions is an operational stoppage of the maritime structure.

Operational Index of Social and Environmental Repercussions of Breakwater of Motril

Based on the information given in the appendix, this index is null because the three subindexes are null, and OISER $=0 \leqslant 5$.

Classification of Breakwater Enlargement of Harbor of Motril

If we consider caisson displacement as the worst failure mode ascribed to an ultimate limit state (ULS), and on the basis of the values of the indices obtained, the economic repercussion is moderate (R_2) and there is no significant social or environmental impact (S_1). When overtopping occurs, the economic repercussion is low (R_{01}) and there is no significant social or environmental impact (S_{01}).

Table 4. Minimum Useful Life

Economic repercussion index	Useful life (years)
<5	15
6–20	**25**
>20	50

Recommended Target Design Levels

Once the indices of repercussion are evaluated and the maritime structure is classified in terms of its general and operational intrinsic nature, the required target design levels are defined as a function of these natures. The following elements are defined in terms of the GIN of the maritime structure:

- Minimum values for the useful life of permanent structures;
- Maximum global probability of failure;
- Methods to verify the safety and serviceability levels against the failure modes assigned to the ultimate and serviceability limit states as well as the methods to verify its use and exploitation against the operational stoppage modes; and
- Plans of maintenance, visual inspection, sounding, and monitoring the structure.

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:

- Minimum operational level;
- Average number of operational stoppages; and
- Maximum duration of an operational stoppage.

The target design levels for Motril are marked in bold letters in each of the following tables. Although the corresponding tables are not given, enlargement should be verified by a Level I method to control relative sliding and rotation of the caisson.

Minimum Useful Life

The duration of a structure's useful life should be at least the value assigned in Table 4 in accordance with the ERI of the maritime structure.

Maximum Safety and Serviceability Probability of Failure

During its useful life, the maximum overall probability of failure will be adjusted to the values recommended in Tables 5 and 6. These values are merely guidelines.

Failure Modes Ascribed to Ultimate Limit States

The joint probability of failure $p_{f,\mathrm{ULS}}$ of a structure against the failure modes assigned to the ULSs cannot exceed the values assigned in Table 5 during its useful life.

Comments: Observe that the values in Table 5 are 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 impact index, going from low to high, and then to very high. For maritime structures whose social and environmental impact index is very high (S_4), the probability of exceedance is 10^{-4}, which is of 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 (Melchers 1999). The third column of the table 5 gives the minimum values of the reliability index.

Table 5. Maximum Overall Probability of Failure in Useful Life for Ultimate Limit States

Social and environmental repercussion index	$P_{f,\text{ULS}}$	β_{ULS}
<5	**0.20**	**0.84**
5–19	0.1000	1.28
20–29	0.0100	2.32
⩾30	0.0001	3.71

Note: ULS=ultimate limit state.

Most maritime structures, especially those affected by extreme sea states, usually have a low or very low SERI and are generally designed according to economic optimization procedures. These procedures, which should be applied to each structure, give adequate values regarding the probability of failure. The value indicated in Table 5 is a limit which, unless extremely well justified, should not be exceeded.

At the other extreme are structures whose SERI is high or very high (SERI>20). Therefore optimization criteria cannot 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.

Failure Modes Ascribed to Serviceability Limit States

The joint probability of failure $p_{f,\text{SLS}}$ of a structure against the principal failure modes assigned to the serviceability limit states cannot exceed the values in Table 6 during its useful life.

Comments: In maritime engineering it is not customary to calculate a structure against the failure modes assigned to the serviceability limit states (SLSs), 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 [see Goda and Takahashi (2001) for a state-of-the-art presentation]. It may take a while before enough theory and data are available so that the verification of the structure (as opposed to the modes assigned to the serviceability limit states) is as frequent as the verification of the modes assigned to ultimate limit states.

The recommended values of the joint probability of failure in Table 6 should be taken as indicative. Time and experience will eventually provide the necessary information to contrast and adjust these values.

Use and Exploitation Target Levels

Maritime and harbor installations usually 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, in some cases 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 is sufficient to verify only two of them since the third will be automatically fulfilled.

For more conventional structures in which the OISER<5, economic studies should be carried out to analyze the optimal operationality and number of operational stoppages. Nevertheless, it is advisable to limit *beforehand* the results that such studies can generate. This limit is specified in Tables 7 and 8.

Table 6. Maximum Overall Probability of Failure in Useful Life for Serviceability Limit States

Social and environmental repercussion index	$p_{f,\text{SLS}}$	β_{SLS}
<5	**0.20**	**0.84**
5–19	0.10	1.28
20–29	0.07	1.50
⩾30	0.07	1.50

Note: SLS=serviceability limit state.

Table 7. Minimum Operationality in Useful Life

Operational index of economic repercussions	$r_{f,\text{OLS}}$	β_{OLS}
⩽5	**0.85**	**1.04**
6–20	0.95	1.65
>20	0.99	2.32

Minimum Operationality

The operationality of the structure in accordance with the OIER should be higher than the values given in Table 7.

Comments: In accordance with the definition of the reliability index, $r_{f,\text{OLS}}=\Phi(\beta_{\text{OLS}})$ is the minimum operationality 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 (OISER<5). In these conditions the operationality may not be absolute (nominal guarantee of 100%), but somewhat less.

Average Number of Stoppages

In the time interval specified (usually a year), and for those cases in which it is not specified *beforehand*, 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 8.

Comments: In the event that the operational stoppage has social and environmental repercussions, $S_{O,4}$, 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, if this requirement is to be met, it will be necessary to duplicate the installation.

Maximum Duration of Stoppage

Once the stoppage has occurred, the probable maximum duration expressed in hours cannot exceed the value assigned in Table 9, in accordance with the OIER and OISER of the structure.

Table 8. Average Number of Operational Stoppages per Time Interval

Operational index of social and environmental repercussions	Number
<5	**10**
5–19	5
20–29	2
⩾30	0

Table 9. Probable Maximum Duration of Stoppage Mode (in hours)

Operational index of economic repercussions	Operational index of social and environmental repercussions			
	<5	5–19	20–29	⩾30
⩽5	**24**	12	6	0
6–20	12	6	3	0
⩾20	6	3	1	0

Comments: The maximum duration τ_{max} of a stoppage is the maximum period of time since stoppage occurs until the installations can be used again. If the stoppage is caused by nature (waves, wind, etc.), it is a random variable. A statistical descriptor of its distribution is the most probable value or mode. Except for specification to the contrary, the zero value of the probable maximum duration indicated in the table is an indication of the desire that no stoppage occur in the structure whose OISER is $S_{O,4}$. In such cases it is necessary to duplicate the installation in order to comply with this recommendation.

Additional Comments

Some important aspects related to the target design levels of the enlargement of the harbor of Motril are discussed in this section. Also mentioned are the introduction of the subset of a maritime structure as a way to consider the spatial lack of homogeneity of the field domain, the selection of the most critical failure mode of a subset, the definition of a principal failure mode, and the optimization of the design.

Project Target Levels

The enlargement of the harbor of Motril was projected and constructed before the publication of ROM 0.0. For this reason, the ROM 0.2-90 procedure was applied. The suggested minimum design lifetime for the harbor was $V=25$ years based on the following classification:

- Type of infrastructure: specific industrial installation; and
- Required security level (b): general interest and moderate risk of human life or environmental damage in case of failure.

The suggested maximum probability of failure during the useful life, based on the economic effects (average), level of damage (destruction), and unexpected human loss in case of failure, was $p_f < 0.15$.

Using the equation $p_f = 1-(1-1/T_R)^V$ for a return period of $T_R=230$ years, $p_f=0.10,(p_f<0.15)$, and from the extreme sea states regime at 15 m water depth, this return period corresponds to an expected probability of failure in a year, $p=0.0043$. The related sea state descriptors are

- Significant wave height at 15 m depth, $H_s=6.00$ m; and
- Wave peak period, $T_p=11$ s.Since no breaking waves were expected, Goda's (1985) formula was used, and therefore a design wave height of $H_c=1.8^{*}H_s=10.80$ m was considered.

As can be observed, the ROM 0.2-90 procedure directly associates the probability of exceedance of the agent (maximum sea state in a year) with the probability of failure of the structure. Moreover, it only considers one failure mode, that is, the most dangerous ascribed to a ULS.

The new procedure ROM 0.0 recommends the overall probabilities of failure in the structure's useful life for all the principal modes ascribed either to ultimate limit states (ULSs) or serviceability limit states (SLSs). Therefore, considering a set of mutually exclusive, collectively exhaustive $i=4$ principal modes of failure, and assuming that all of them have the same probability of occurrence and that the occurrence of one produces the failure of the structure, the actual probability of failure of the new breakwater of Motril in its useful life is $p_{f,\mathrm{ELU}}=\Sigma p_{\mathrm{mode},i}$ where $i=1, \ldots,4$ represents the failure mode. Consequently, the probability of one failure mode should be $p_{\mathrm{mode}}=0.05$.

Subsets of Maritime Structure

The ROM 0.0 procedure recommends obtaining the target design levels for each of the subsets of the maritime structure, and it defines a subset as "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 subjected to the same levels of action (initiated by the agents), and are a part of the same formal and structural typology."

Following these criteria, three subsets have been considered for the enlargement of the breakwater: (1) the transition between the old and the new breakwaters; (2) the main alignment of the breakwater for which the target design levels have been obtained in this paper; and (3) the head of the breakwater.

The same procedure has to be followed to obtain the target design levels of subsets (1) and (3), taking into account the specific characteristics of each. For example, in the case of the head of the breakwater, one should consider the possibility of a failure mode that causes the closure of the entrance channel due to failure, overturning of the head, or extraction of berm units.

Under these circumstances, general intrinsic nature of the breakwater's head will probably be higher than that of the main alignment. More restrictive target design levels for the head would thus be recommended. Notice that this recommendation is not related to our knowledge or the quality of the verification equation applied. For large structures built on an inhomogeneous domain because of soil properties, wave climate, or use and exploitation, the concept of subset can help to design optimal maritime structures.

Most Critical Failure Mode

The intrinsic nature of the subset is evaluated assuming that the most critical failure mode has occurred. For this purpose, the most critical failure is the mode that produces the greatest economic, social, and environmental damage. The selection of the mode should be carried out using good judgment and is usually done by senior engineers who have considerable experience in maritime structure and environmental analysis. In the case where two or more modes can be considered to be most critical, the intrinsic nature should be evaluated for all of them, the target design levels being the most restrictive.

It should be pointed out that the target levels obtained are based on a previous decision, a preliminary design, and usually limited information. It sometimes happens that in the final design new information comes to light that provides insights into new processes. Alternatively, the selected typology or environment may not behave as expected. In these cases the target level must be reevaluated to account for the new information.

Principal Modes of Failure

The procedure ROM 0.0 establishes the overall probability of failure in the useful life of a maritime structure for all the principal modes ascribed either to ultimate or serviceability limit states.

Principal failure and stoppage modes are those whose occurrence has significant consequences for the reliability, functionality, and operationality of the structure. Moreover, their probability of occurrence cannot be significantly decreased by increasing the construction cost (and therefore improving the design). Thus, a small increase in the size of the pieces of the main layer of a mound breakwater will not necessarily involve a significant decrease in its probability of failure, but will involve a great increase in the cost. Furthermore, the same increase in the pieces of the berm may involve a significant decrease in its probability of failure, but without much added cost. The comparison between the increase in cost and the expected reduction of the probability of failure is necessary to determine if a failure mode is principal or not.

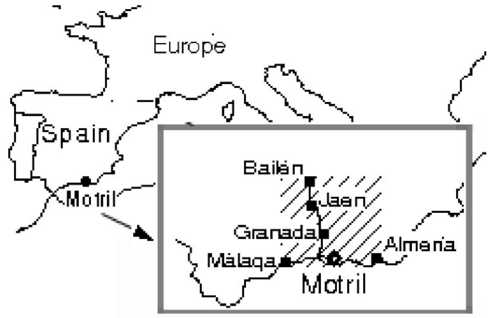

Fig. 4. Location of Motril

Economic Optimization versus Intrinsic Nature of Structure

The procedure described in this article begins with the evaluation of the general intrinsic nature of the structure according to the ERI and SERI, which are approximately determined by assuming the occurrence of the worst failure mode assigned to an ultimate or serviceability limit state. 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 are in the same interval of values as those estimated at the beginning of the project.

Moreover, different schemes of economic optimization can be established for the structure, 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 [Vrijling and Voortman (2001)].

An optimal economic analysis may give a different joint probability of failure and stoppage from the recommended values. The possible contradiction between the results of the verification and the economic optimization may occur because the joint probability of failure values recommended has 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 procedure will provide a source for the data 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.

Conclusions

The aim and scope of this paper are to provide a procedure to decide on the target levels for maritime and harbor structures of all types and designs, whatever the materials, techniques, and elements used for these purposes. The procedure is based on the classification of maritime structures in terms of their general and operational intrinsic natures. These indices evaluate the economic, social, and environmental consequences of the most severe failure and stoppage modes.

Depending on the type of maritime structure, the final step of the procedure provides values for the minimum useful life of the structure, the joint probability of failure against the principal failure modes assigned to ultimate and serviceability limit states, minimum operationality, the average number of admissible technical breakdowns, and the maximum allowed duration of a stoppage mode.

The procedure described is (1) common for the selection of the three target levels of safety, serviceability, and use and exploitation; (2) based on simple, standard, accessible, and homogeneous information; (3) valid for the management of engineering concepts; and (4) weakly affected by external interferences.

Appendix. Harbor of Motril

In this appendix we introduce some characteristics of the harbor of Motril and its surroundings that are important to obtain the project requirements and target design levels.

City and Surroundings of Motril

Motril is located on the southern coast of Spain between the cities of Almeria and Malaga (Fig. 4). It has approximately 50,000 inhabitants, who have a third-sector economy based on industrial activity, agriculture, fishing, and tourism.

The main activity of the harbor is related to oil, construction, and agricultural goods. Harbor traffic is constant year round, but due to the poor intermodal communications network of the harbor, its hinterland does not go beyond the limits of Andalusia (see shaded area in Fig. 4). The harbor is the main entrance route of

Fig. 5. Aerial view of harbor of Motril

the products to the hinterland, products that are used in approximately 40% of the activity developed in the area.

Weather Climate

The variations of the water level in the harbor are due to the meteorological and astronomical tides. The amplitude of the variations oscillates between 0.8 and 1.6 m. The most relevant maritime oscillations are due to wind waves, mainly those coming from the second and third sectors. The principal directions of those waves coming from the third sector are west and west-southwest, with a probability of 0.98 of not exceeding a significant wave height of 4.0 m (usually associated with a peak period of 11 s), and decrease their intensity as they move off to the southwest. For the second sector, the main direction of the waves is from the east, with a probability of 0.98 of not exceeding a significant wave height of 3.4 m (usually associated with a peak period of 10 s). Other incoming wave directions are less important.

Enlargement of Harbor of Motril

The project consists of the enlargement of the actual breakwater, the *Dique de Poniente*, and the construction of a north-northeast breakwater that will be almost perpendicular to the coastline and aligned with the head of the enlargement of the *Dique de Poniente* (Fig. 5).

The enlargement is 625 m long and oriented northwest-southeast. It consists of prefabricated reinforced concrete caissons, each 43.00 m long. The soil underneath the breakwater has been determined to be suitable for vertical breakwater foundations after some cleaning and preparation of the surface.

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