Incorporating Probabilistic Assessment of Risks and Optimization Methods into Submarine Outfall Projects

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Abstract

Of all the sanitation infra-structures used nowadays, those encountered in the final step of the effluent treatment are of special importance mostly in countries where the coastline is extensively developed for housing, industry and other purposes, being almost inevitable that the chosen places for the final effluent disposal will be the sea and the estuaries.

Reality has revealed the existence of gaps in experience, information and means to carry out this type of structures in the best possible conditions. Reported accidents with such installations, including accidents in Portugal, highlighted that their good working conditions are of mandatory importance to the environment, population's welfare and economy.

This calls for the application of a risk management approach, based on methodologies that account for randomness and uncertainty, that incorporate all the existing information and data, that account for the probability of failure of the structures and its consequences and, finally, that will grant a cost optimization of the project.

The main goal of the project described in this paper is the development of a methodology and tools for application of probabilistic and optimization methods in the context of a risk management approach to the project of submarine outfalls. This represents an innovative research subject, both in Portugal and abroad.

The main objective of this paper is to present the methodology and the tools to be used throughout the project. The interim objectives include the presentation of a list of risks associated with the project of outfalls, identification of the failure modes for these structures and their ascription to ultimate, serviceability or operational limit states. The methodology is established suiting the needs for applying probabilistic and optimization techniques to the project of these structures.

Keywords

Submarine outfalls, risk assessment, probabilistic and optimization methods

INTRODUCTION

A maritime structure, such as a submarine outfall, 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.

The problem then is to define the particular features of the outfall system in such a way as to satisfy the conditions already established, i.e. to comply with the standards in force in the areas to be protected.

By taking into consideration both the quantities of the waste to be discharged and the local geographical and meteorological conditions, one can select a method which would give a solution with a smaller or greater degree of accuracy.

Moreover, the good working conditions of marine structures are of mandatory importance to the environment, to the welfare of populations and to the economy. 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.

Risk management in coastal and maritime engineering is necessary because a number of factors are uncertain, several are random, others cannot be controlled (e.g. rainfall) and others are cost factors that may be eliminated or minimized.

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, an analysis of the economic, social and environmental impact of the construction. However, in the absence of specific studies, the engineer needs guidelines for the specification of these values beforehand, thus allowing comparison of different project alternatives at different locations.

Current recommendations for projects of maritime structures (e.g. [ROM 0.0, 2002]) include the application of probabilistic and optimization techniques. However, their application has been restricted essentially to harbour and coastal protection structures (e.g. [Burcharth, 2000], [Oumeraci, 2001]) and conventional design practice for outfalls is still essentially deterministic. In this context, the methodology for risk management of the project of outfalls under development within the scope of this project is of paramount importance and is based on these techniques.

PLANS AND METHODS

In the domain of coastal and maritime engineering, the scientific progress in the last three decades made it possible to start shifting from a holly empirical knowledge (traditional approach) towards a more sophisticated and complete approach to reality (a very complex physical environment). As a result, many scientific tools that had been applied successfully in other engineering domains (such as offshore and structural engineering), have started being applied to coastal and maritime engineering as well. One of these tools is the risk management approach to the project of coastal and maritime interventions.

Project is here taken in a broad sense, i.e. it includes all stages of a project (conception, design, construction, exploitation, maintenance and repair) and all stakeholders that play an active role for its achievement (e.g. client, designer, contractor, state authorities, community representatives, insurer).

Risk management is the process of identifying, analysing and assessing risks to enable informed decisions on accepting, treating and/or controlling risks. Its utilization is increasing for the achievement of project objectives and for assisting in the decision-making processes.

This approach is largely dependent on the type of structure involved in the project and implies a detailed knowledge of its behaviour under environmental and man driven conditions. For some structural types, such as breakwaters and coastal protection works, the approach has already been developed, although it has not yet been fully implemented in current practice. For others, such as submarine outfalls, it has not yet been developed.

Furthermore, these high-cost projects, which are still approached in the traditional fashion, are eligible to be the object of an approach where risks are explicitly and systematically minimized or avoided, where the whole community of stakeholders is involved in its development to make a rational share of responsibilities for each risk, and where costs are optimized.

The aim of the research project described in this paper is to gather information on the physical behaviour of submarine outfall systems and on the methodologies for risk management of projects, to create a consistent methodology for the risk management of the project of submarine outfalls.
To accomplish this, it is necessary: (1) to prepare an inventory of risks associated with the project of outfalls and to identify the failure modes for these structures; (2) to establish a methodology for applying probabilistic and optimization techniques to their project; and (3) to develop computational tools for their probabilistic and optimized design, that will result in a set of recommendations to be applied to these projects.

AIM AND SCOPE OF THE PROJECT

The general calculation procedure applied in this work consists in methods to be applied in sequence, 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 procedure should begin by defining and situating the structure in time and space in terms of safety, serviceability, and use and exploitation. The definition of the following concepts is important: 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 [ROM 0.0, 2002].
In this paper, the procedure described is applied, on a preliminary level, to two presented case studies.

Limit States and Failure Modes

Limit state is a 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).

Failure mode is an 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. 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. Failure modes are either ascribed to ultimate or serviceability limit states for their verification.

Ultimate limit states are states that produce the collapse of the structure because of breakage or structural breakdown. 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.

Serviceability limit states are states that produce a reversible or irreversible loss of service and functionality due to a type of structural, aesthetic, or environmental failure or legal constraint. The failure mode can reduce the useful life and reliability of the structure that could be delayed or prevented by means of a suitable strategy conducive to the maintenance of the structure and its elements [ROM 0.0, 2002].

The failure modes, and corresponding limit states, considered in this study for each section of the submarine outfalls are:

For the submerged pipe

1 - Progressive collapse (ULS): caused by a) stress fluctuations in the pipeline due to: direct wave action; vibrations of the pipe system, e.g. due to vortex shedding (current, waves, wind, towing) or fluid flow; supporting structure movements; fluctuations in operating pressure and temperature; and buoyancy due to liquefaction; b) vertical instability due to hydrodynamic forces resulting from the action of near-seabed, wave-induced and steady currents on the pipe;

2 - Fracture (ULS/SLS): caused by impacts associated with activities of outside parties: ship anchors, fish operations, dropped object impacts, trawlers fishing;

3 - Fatigue (SLS): associated to environmental loads (winds, waves, currents, earthquakes, etc);

4 - Obstruction (SLS): consequence of low velocities of the effluent, flows that exceed outfall capacity, sedimentation and air entrapment due to curves in the pipe;

5 - Internal corrosion (SLS/OLS): scaling, bacterial action (H_2SO4, H_2S), velocities not self-cleansing.

For the diffuser

1 - Fracture (ULS): caused by impacts associated with activities of outside parties: ship anchors, fish operations, dropped object impacts, trawlers fishing;

2 - Obstruction (SLS): marine growth, sea water intrusion, entrance of solids in low flow cycles, trapped objects;

3 - Corrosion (SLS/OLS): by saline intrusion.

For the riser

1 - Rupture (ULS): dropped object impact, environmental loads, pipe displacement or foundation settlement.

2 - Obstruction (SLS): marine growth, sea water intrusion, entrance of solids in low flow cycles, trapped objects;

3 - Corrosion (SLS/OLS): by saline intrusion.

For the ring joints and anchor blocks

1 - Fracture (SLS): pipe displacement, overstressing, soil liquefaction, vertical instability.

In operational limit states the use and exploitation are reduced or temporarily stopped due to causes external to the maritime structure and installations, without structural damage.

Exceedance of the threshold value of agents of the physical environment (climatic agents) leading to interruption of the exploitation.

Unacceptable environmental effect or social repercussion: stoppage modes carried out to avoid damage to people, habitats and environment.

*Legal constraints: s*toppage modes carried out to fulfil legal requirements. E.g.: outflow of residual waters into the sea

Steps for Specifying Target Design Levels

As shown in **Error! Reference source not found.**, the procedure used to obtain the target design levels consists of three steps [Losada and Benedicto, 2005]:

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 nature

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 (GIN) of the subset (Figure 1). 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 [ROM 0.0, 2002].

The general intrinsic nature of the structure is established (in the absence of this specification by the developer of the maritime structure) as a function of the economic repercussion index (ERI) and the social and environmental repercussion index (SERI).

The economic repercussions and the social and environmental repercussions produced when the maritime structure stops functioning or reduces its operational level are specified by means of its operational intrinsic nature (OIN). This will be evaluated by selecting the mode from among the principal modes of operational stoppage, which gives the minimum operational level, and is established in terms of the operational index of economic repercussion (OIER) and the operational index of social and environmental repercussions (OISER).

Within the scope of the project the definitions of these indices, established in the ROM 0.0 for maritime structures, were reviewed and adapted to submarine outfalls, adding other relevant aspects and changing the weights of existing aspects and are presented in the following sections.

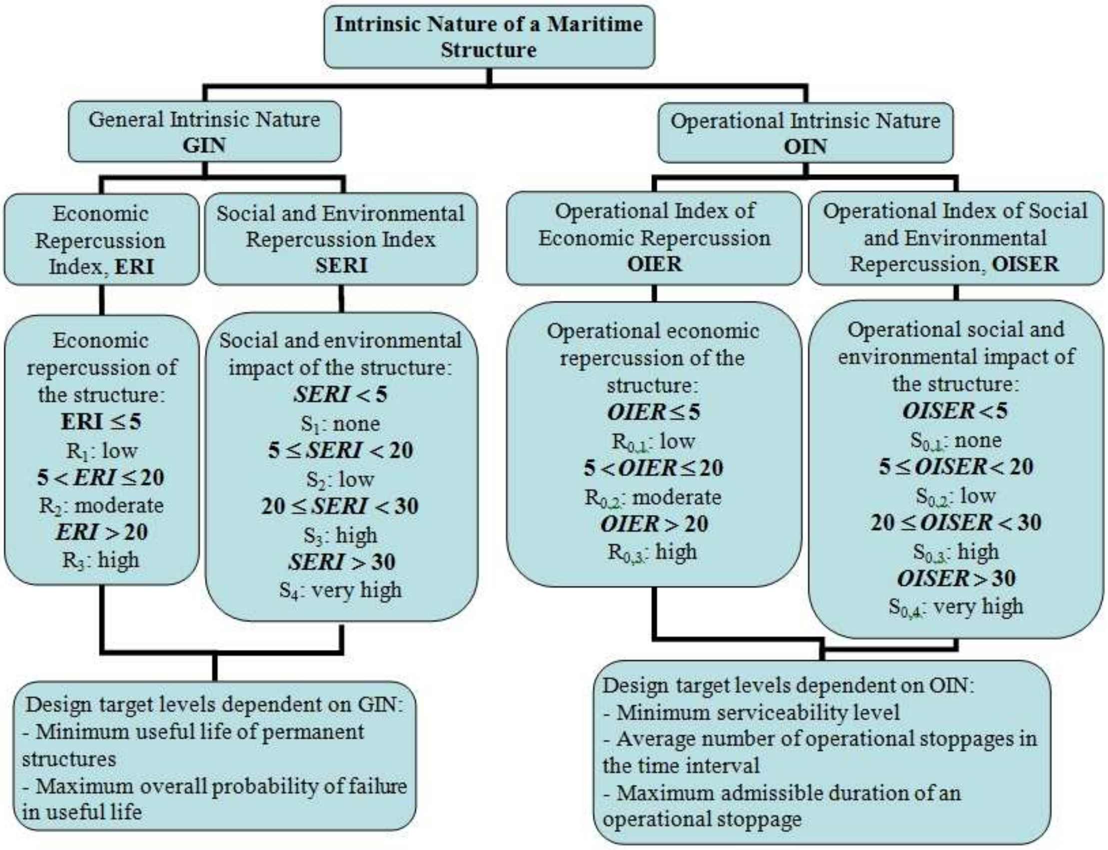


Figure 1. Intrinsic nature of a maritime structure [ROM 0.0, 2002]

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.

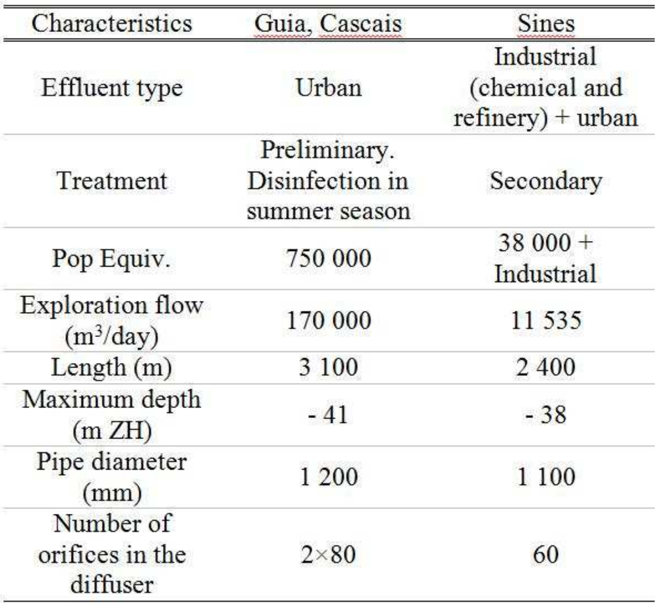
This results in the classification of the structure in terms of two values (R_i, S_i).

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, **Error! Reference source not**

found.. The next step is to describe the operational intrinsic nature of the maritime structure in terms of OIER and OISER values ($R_{0,i}$, $S_{0,i}$).

In the present work four Portuguese submarine outfalls were chosen to represent typical characteristics of these structures. This paper presents the case studies of Guia, in Cascais, the wider submarine outfall in Portugal, which serves four municipalities around Lisbon, and the submarine outfall of Sines, where an important petrochemical industry is installed. The main characteristics of these structures are summarized in Table 1.

Table 1. Submarine outfalls - case studies: main characteristics.



Characteristics	Guia, Cascais	Sines
Effluent type	Urban	Industrial (chemical and refinery) + urban
Treatment	Preliminary. Disinfection in summer season	Secondary
Pop Equiv.	750 000	38 000 + Industrial
Exploration flow (m^3/day)	170 000	11 535
Length (m)	3 100	2 400
Maximum depth (m ZH)	- 41	- 38
Pipe diameter (mm)	1 200	1 100
Number of orifices in the diffuser	2×80	60

Economic repercussion index

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 $\left(C_{RD}+C_{RI}\right)/C_0$, in which C_0 is an economic parameter of dimensionalization:
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 M Euros for the horizontal year in which the costs are valued. For Portugal it is assumed, in a first approximation, the value of 300 T Euros.

C_{RD} is the investment cost that corresponds 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 [ROM 0.0, 2002].

C_{RI} is the repercussion cost used to evaluate the 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 [ROM 0.0, 2002].

Approximate evaluation of C_{RI}/C_o

In those cases in which a detailed determination of C_{RI} is not carried out, either for reasons of excessive complexity due to 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 equation C(A+B), 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 [ROM 0.0, 2002].

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.

Submarine outfalls act mainly at a local level, so coefficient A is considered constant A=1, for all cases.

Despite the fact that this methodology is foreseen for maritime structures in general, it is found more suitable for submarine outfalls to consider a relation that takes into account the relevance of the submarine outfalls for the local strategic importance (B_L).

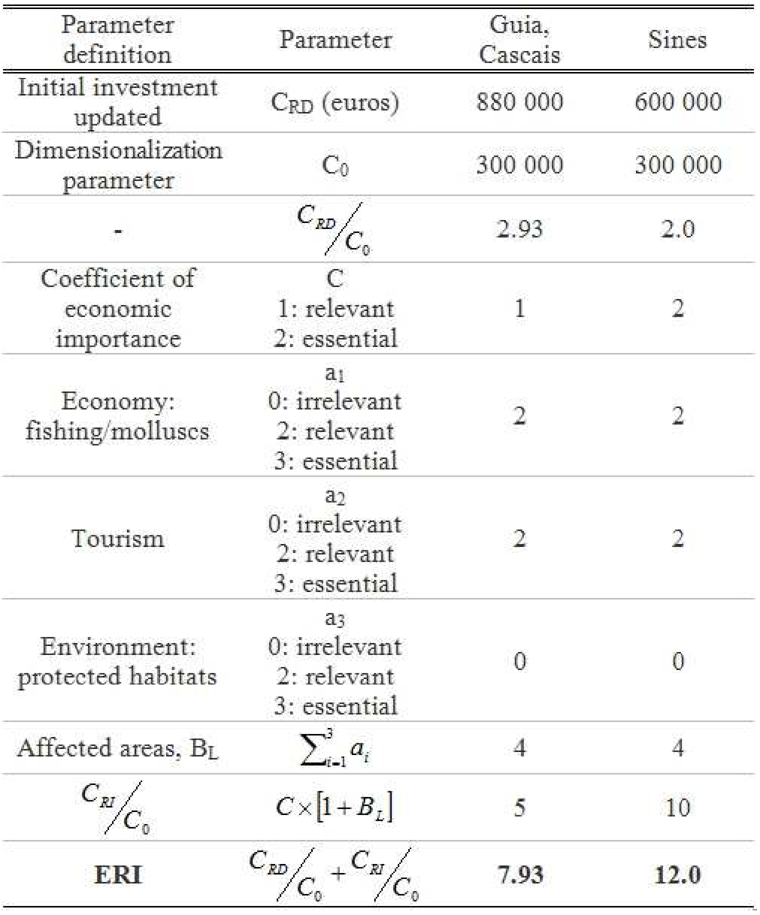
So, coefficient B is replaced by B_L, considering the relevance of the submarine outfall for:

a_1) Economy: fishing and molluscs (Essential (2), relevant (1), irrelevant (0));
a_2) Environment: sensitive habitats, flora and fauna (Essential (2), relevant (1), irrelevant (0));
a_3) Tourism: e.g. beaches and nautical sports (Essential (2), relevant (1), irrelevant (0));

At this point, $\frac{C_{RI}}{C_0} = C(1 + B_L)$.

The values of the parameters to evaluate the economic repercussion index (ERI), for the submarine outfalls of Guia and Sines are presented in Table 2.

Table 2. Values of parameters to evaluate the economic repercussion index (ERI) for the case studies



Parameter definition	Parameter	Guia, Cascais	Sines
Initial investment updated	C_{RD} (euros)	880 000	600 000
Dimensionalization parameter	C_0	300 000	300 000
-	C_{RD}/C_0	2.93	2.0
Coefficient of economic importance	C 1: relevant 2: essential	1	2
Economy: fishing/molluscs	a_1 0: irrelevant 2: relevant 3: essential	2	2
Tourism	a_2 0: irrelevant 2: relevant 3: essential	2	2
Environment: protected habitats	a_3 0: irrelevant 2: relevant 3: essential	0	0
Affected areas, B_L	$\sum_{i=1}^{3} a_i$	4	4
C_{RI}/C_0	$C \times [1 + B_L]$	5	10
ERI	$C_{RD}/C_0 + C_{RI}/C_0$	**7.93**	**12.0**

The obtained values of the ERI for both structures suggest that the economic repercussions of their destruction or total loss of exploitation capacity are moderate ($5 < \text{ERI} \leq 20$, **Error! Reference source not found.**).

Social and Environmental Repercussion Index

According to ROM 0.0 Recommendations 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 structure.

Factors evaluated are the possibility and scope of the following: ($SERI_1$) loss of human lives; ($SERI_2$) damage to the environment as well as the historical and cultural heritage; ($SERI_3$) 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 Environmenta Repercussion Index

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

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

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 (0), when injury to people is improbable;
- Low (3), when loss of human life is possible but not probable accidental and few people are affected;

- High (10), 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 (20), 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 (0), when damage is improbable;
- Low (2), if the damage is slight but reversible in less than a year or there is loss of elements of little value;
- Moderate (4), 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 (8), when damage to the ecosystem is irreversible and there is loss of important elements of historical and artistic value; and
- Very high (15), 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 (0), when there are no signs of any significant social disruption associated with the failure of the structure;
- Moderate (5), if there is a minimum degree of social disruption associated with high $SERI_1$ and $SERI_2$ values;
- High (10), if a minimum degree of social disruption is caused by a catastrophic $SERI_1$ value; and
- Very high (15), when there is a maximum degree of social high $SERI_2$ value disruption.

As far as submarine outfalls are concerned they should secure protection and enhance the status of aquatic ecosystems, minimizing the risk of human diseases, protecting environmental uses/values of the waters and considering their potential impact, directly or indirectly, on food chain processes. Consequently, subindex $SERI_1$ is changed to' impact on human health' and can be represented as:

$$SERI_1 = \left\lfloor \sum_{i=1}^{3} a_i + B \right\rfloor C$$

Where:

a) Direct: through bathing in contaminated waters and contact with contaminated sand;

a_1: skin irritations (irrelevant (0), relevant (1)); a_2: digestive problems (irrelevant (0), relevant (2); a_3: chronic diseases (irrelevant (0), relevant (5)).

b) Indirect: through the ingestion of fish and molluscs, B: (irrelevant (0), relevant (2)).

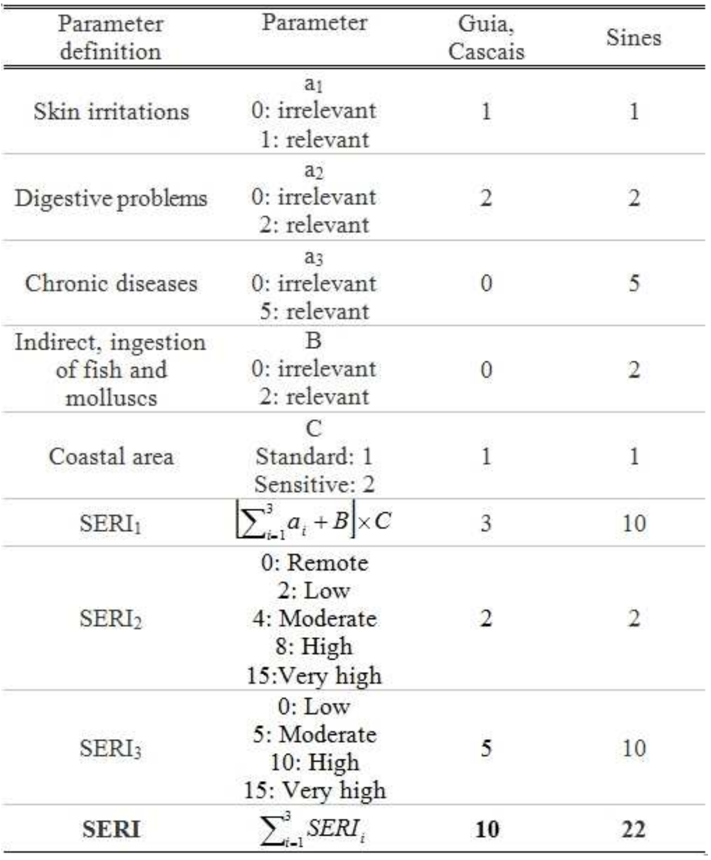
c) Coastal area, C: sensitive (2) and standard or less sensitive (1).

The Portuguese legislation, through Decreto-Lei n.º 152/97, considers coastal zones as 'sensitive' and 'less sensitive', Algarve included in first classification and the rest of the coast in the later.

The subindex $SERI_2$ is replaced by 'damage to the environment and habitats' since submarine outfalls have no effect on the historical and cultural heritage.

The values of the parameters to evaluate the social and environmental repercussion index (SERI), for the submarine outfalls of Guia and Sines are presented in Table 3.

Table 3. Values of parameters to evaluate the social and environmental repercussion índex (SERI) for the case studies.



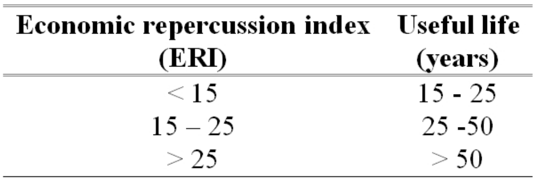
Parameter definition	Parameter	Guia, Cascais	Sines
Skin irritations	a_1 0: irrelevant 1: relevant	1	1
Digestive problems	a_2 0: irrelevant 2: relevant	2	2
Chronic diseases	a_3 0: irrelevant 5: relevant	0	5
Indirect, ingestion of fish and molluscs	B 0: irrelevant 2: relevant	0	2
Coastal area	C Standard: 1 Sensitive: 2	1	1
$SERI_1$	$\left\|\sum_{i=1}^{3} a_i + B\right\| \times C$	3	10
$SERI_2$	0: Remote 2: Low 4: Moderate 8: High 15:Very high	2	2
$SERI_3$	0: Low 5: Moderate 10: High 15: Very high	5	10
SERI	$\sum_{i=1}^{3} SERI_i$	**10**	**22**

These values of the SERI show that the social and environmental repercussions of the submarine outfalls destruction or total loss of operationality are low ($5 \leq SERI < 20$) for the Guia outfall and high ($20 \leq SERI < 30$) for Sines outfall, **Error! Reference source not found.**.

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 submarine outfall. This table has been developed based on the results obtained for the four case studies analysed within the scope of the project. As a first approximation, the useful life has been defined for three classes of the ERI.

Table 4. Minimum useful life



Economic repercussion index (ERI)	Useful life (years)
< 15	15 - 25
15 – 25	25 -50
> 25	> 50

STUDY UNDER DEVELOPMENT

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.

This characterization is under development for this study, with the aim to specify the operational intrinsic nature of submarine outfalls in terms of the operational index of economic repercussion and the operational index of social and environmental repercussion (**Error! Reference source not found.**).

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 [Losada and Benedicto, 2005]:

- Minimum values for the useful life of permanent structures (Table 4);
- 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;
- 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.

CONCLUSIONS

The aim of this work is to provide a procedure to decide on the target levels for submarine outfalls of all types and designs, whatever the materials, techniques, and elements used for these purposes. This procedure is based on a transformation of the classification for maritime structures, provided in the ROM 0.0 Recommendations, 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 submarine outfall and its importance to economy, tourism and environment, 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.

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