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Target reliability indices for quay walls, jetties, and flexible dolphins

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ABSTRACT

Structural codes rely on generalised target reliability indices, which are mainly derived for buildings. It is unclear, however, whether these indices are applicable to the specific risk-profile of quay walls, jetties, and flexible dolphins. In this study, target reliability indices for marine structures were derived from various risk acceptance criteria, such as economic optimisation, individual risk, societal risk, the life quality index and the social and environmental repercussion index. This article uses a method to determine reliability targets distinguishing time-dependent and time-independent variables, because some important stochastic design variables in the design of marine structures, such as soil and material properties, are largely time-independent. The assessment framework of ISO 2394, taking into account social, economic and environmental impact, has proven to be a solid basis for reliability differentiation. The method of approach considered in this paper can also be used for evaluating target reliability indices of other geotechnical structures.

INTRODUCTION

Globally numerous quay walls, jetties and flexible dolphins are situated in commercial port districts and along inland waterways. The reliability level of these marine structures is generally determined in accordance with an applicable design code or standard, such as Eurocode Standard EN1990 (2011), ISO 2394 (2015), and JCSS (2001). Typical annual reliability targets are listed in Table 1. Modern design codes define the probability of failure $P_f = P(Z \leq 0)$ by a limit-state function (JCSS, 2001). The target reliability index and target probability of failure are then related as follows:

$$\beta_t = \Phi^{-1}(P_{\mathrm{f};t}) \tag{1}$$

in which:

β_t Target reliability index [-]

$P_{f;t}$ Target probability of failure[-]
Φ^{-1} Inverse of the standard normal cumulative distribution function [-]

Table 1: Overview of annual target reliability indices in literature (Roubos et al., 2018)

Codes & Standards	**Application**	**Consequence classes**				
		A **Low**	**B** **Some**	**C** **Considerable**	**D** **High**	**E** **Very high**
ISO 2394 (2015)	All	Class 1	Class 2 4.2	Class 3 4.4	Class 4 4.7	Class 5
JCSS (2001) [1]	All		Minor 4.2	Moderate 4.4	Large 4.7	
Structural concrete (2012) [1]	Concrete	Small 3.5	Some 4.1		Moderate 4.7	Great 5.1
EN 1990 (2011)	All		RC1 4.2		RC2 4.7	RC3 5.2
Rackwitz (2000) [1]	Bridges	Insignificant 3.7		Normal 4.3	Large 4.7	
DNV (1992)	Marine	Type I 3.09	Type I & II 3.71	Type II & III 4.26	Type III 4.75	
USACE (1997)	Geotech.	Average 2.5/3.0	Good 4.0			High 5.0

[1]) Reliability indices are derived by assuming low relative costs of safety measures

In recent code calibration tasks, target reliability indices are often derived by calibrating them with previous design methods in order to maintain an existing reliability level. It should be noted that target reliability indices were mainly developed for buildings (Vrouwenvelder, 2001) and bridges (Steenbergen, & Vrouwenvelder, 2010) assuming fully time-variant reliability problems (Holický, 2011). The methods neglect the effects of uncertainty on time-independent parameters, such as material properties, self-weight, model uncertainty, and gross errors, which might dominate the failure probability in the first years. For quay walls, jetties and flexible dolphins the source of aleatory and epistemic uncertainty as well as consequences of failure could be very different from buildings and bridges (Roubos et al, 2018).

This study aims to provide guidance to code developers and engineers on deriving target reliability indices for new and existing marine structures.

METHODS

Principles of economic optimisation

This section briefly discusses the methods used to establish target reliability indices for new and existing structures. Figure 1 shows that reliability indices are influenced by the efficiency of safety investments and failure consequences. The optimal reliability index β^* can be obtained by minimising the sum of investments in safety measures and the accompanying capitalised risk. However, the target reliability indices derived on the basis of economic optimisation might not be acceptable with regard to requirements concerning human safety (ISO 2394, 2015). These reliability indices are denoted as β_{acc}. The reader is referred to the paper of Roubos et al. (2018) for a detailed description of the methods used.

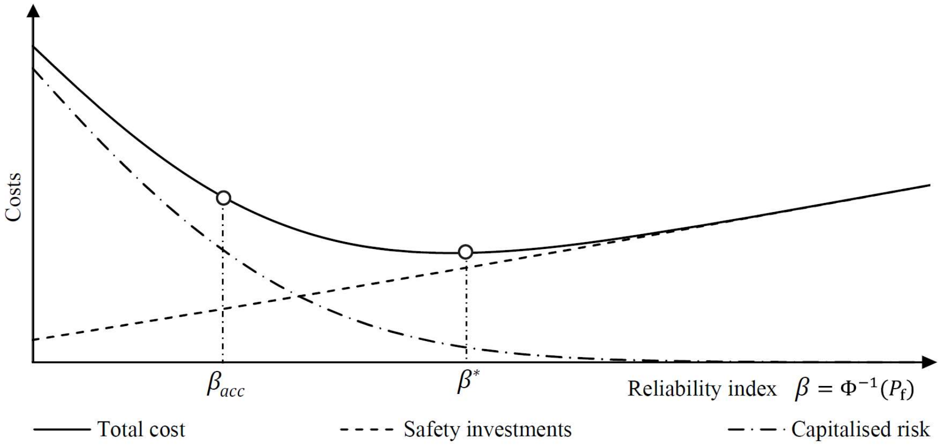

Figure 1: Principles of cost minimisation, optimal reliability index β^* derived by economic optimisation and acceptable reliability minimum β_{acc} derived by assessing human safety

Largely time-dependent limit state functions indicate that failure events are to some extent correlated. Sýkora et al. (2017) suggest using a ‘basic’ period in order to account for dependency of failure events, which in this study is denoted as t_{eq}; in other words, the ′equivalent′ period for which failure events are assumed to be independent in subsequent years. We however emphasize that this ‘basic period’ does not have a real meaning but is only used as an equivalent measure to define independent time blocks. The cumulative lifetime probability of failure was determined using the following equations, which formed the basis for the method used (Roubos et al., 2018):

$$P_{\mathrm{f};t_{ref}} = 1 - \left(1 - P_{\mathrm{f};t_1}\right)^{n_{eq}} \tag{2}$$

$$\beta_{t_{ref}} = \Phi^{-1}\left[\Phi(\beta_{t_1})^{n_{eq}}\right] \tag{3}$$

$$n_{eq} = \frac{t_{ref}}{t_{eq}} \tag{4}$$

in which:

$P_{\mathrm{f};t_{ref}}$ Probability of failure in the interval [0, t_{ref}) [-]

$P_{\mathrm{f};t_1}$	Probability of failure in the interval [0, t_1] [-]
n_{eq}	Number of equivalent periods during the reference period [-]
$\beta_{t_{ref}}$	Reliability index of reference period t_{ref} [-]
β_{t_1}	Reliability index of a one-year reference period [-]
t_1	Reference period of one year [year]
t_{eq}	Equivalent period for which failure events are independent in subsequent years [year]

The reliability optimum and minimum threshold for ‘repair’ (Figure 2A) were derived by using the same principles as for ‘renewal’. The target reliability index $\beta^{*}_{\mathrm{repair}}$ is generally slightly lower than the reliability target for ‘renewal’, because the marginal safety costs are generally higher in case of repairing an existing structure. In this study, the initial construction costs for repair works/upgrades were assumed to be lower and the marginal costs were assumed to be higher than new marine structures (Roubos et al., 2018). The optimal reliability indices - expressed by β^{*} - were obtained by minimising the sum of investments in safety measures and the accompanying capitalised risk. The reliability minimum for ‘repair’ - denoted as $\beta_{\mathrm{acc;repair}}$ - was derived on the basis of the LQI acceptance criterion (Figure 2B).

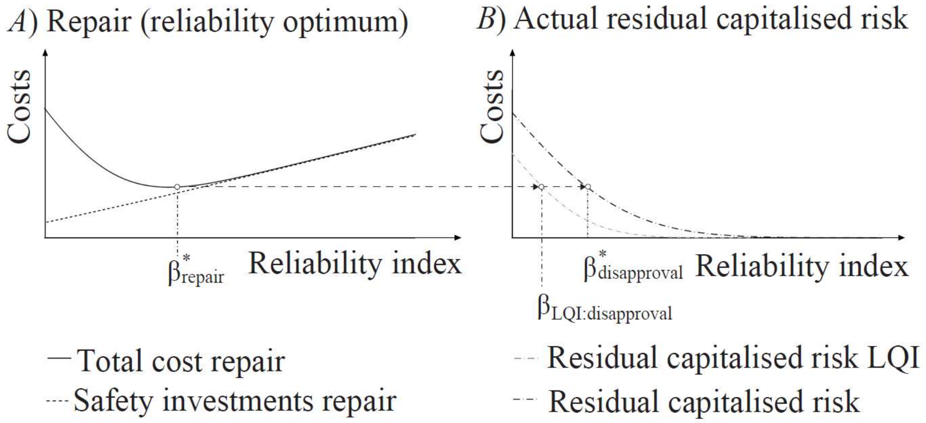

Figure 2: Comparison of the residual risk of the existing structure (right) with the total costs – summation construction costs and associated capitalized risk - after repairing the existing structure (left).

Risk-acceptance criteria

The optimal reliability indices derived on the basis of cost minimisation have to be higher than the thresholds of acceptance. This section presents the evaluation of three risk-acceptance criteria, namely the individual risk (*IR*) criterion (Equation 6 and 7), the societal risk (*SR*) criterion (Equation 8), and the life quality index (*LQI*) acceptance criterion (Equation 9).

$$\beta_{acc;t_1 IRPA} \geq -\Phi^{-1}\left(\frac{IRPA}{P_{\text{Present}}\left(1-P_{\text{Escape}}\right)P_{d|\text{f}}}\right) \tag{5}$$

$$\beta_{acc;t_1;LIRA} \geq= -\Phi^{-1}\left(\frac{LIRA}{\left(1-P_{\text{Escape}}\right)P_{d|\text{f}}}\right) \tag{6}$$

$$\beta_{acc;t_1;SR} \geq= -\Phi^{-1}\left(AN_{F|\text{f}}^{-k}\right) \tag{7}$$

in which:

$IRPA$	Annual probability that a specific individual or hypothetical group member will die due to exposure to hazardous events [-]
$LIRA$	Annual probability that an unprotected, permanently present individual will die due to an accident at a hazardous site [-]
P_{Present}	Probability that a specific individual will be present [-]
P_{Escape}	Probability of a successful escape [-]
$P_{d\|\text{f}}$	Conditional probability that an individual being present will die given failure [-]
$\beta_{acc;t_1}$	Annual threshold of acceptance [-]
$P_{\text{f}_{acc;t_1}}$	Acceptable annual probability of failure [-]
$N_{F\|\text{f}}$	Expected number of fatalities [-]
A	Acceptable risk for one fatality [-]
k	Slope factor of the F–N curve [-]

ISO 2394 (2015) recommends employing the LQI acceptance criterion and provides information with regard to the social willingness to pay ($SWTP$), which corresponds to the amount of money that should be invested in saving one additional life. The reader is referred Faber et al. (2011) and ISO 2394 for further information. In Fisher et al. (2012), the LQI acceptance criterion is defined by Equation (5). However, Roubos et al. (2018) showed that this criterion can also be evaluated by applying the principles of cost minimisation if the capitalised ‘societal’ risk is taken into consideration.

$$-\frac{dP_{\text{f}}\left(\beta_{acc;t_1}\right)}{d\beta} \leq \frac{C_1(\gamma_s+\omega)}{G_{\text{x}}N_{F|\text{f}}} = \frac{C_1(\gamma_s+\omega)}{SWTP \cdot N_{F|\text{f}}} \tag{8}$$

where:

C_1	Marginal costs associated with a considered safety measure life expectancy [€]
G_x	$SWTP$ for a unitary change in mortality [€]
γ_s	Societal discount rate [-]
ω	Annual rate of obsolescence [-]
$SWTP$	Social Willingness To Pay to safe one additional human life [€]

RESULTS

The target reliability indices derived in this study were determined from several risk-acceptance criteria. This section presents the reliability indices found for an arbitrary $t_{eq} \geq 20$ using the assessment criteria described in Roubos et al. (2018) , which represent the robustness of the structure as a whole (Table 2 and 3). This means that the expected consequences of a specific failure mode will generally be lower due to some additional measures for improving system robustness. Hence, direct failure consequences mainly involve the replacement of the structural parts that show damage, and the indirect consequences are associated with a more serious follow-up event (e.g. cascading effect leading to the collapse other components or failure of a hazardous installation causing a significant explosion). In addition, Table 4 shows the results for t_{eq} in the range of 1 to 50 in order to illuminate its impact on the target reliability indices.

The target reliability indices derived from economic optimisation and the LQI acceptance criterion were determined for different consequences of failure, in order to compare the results with the recommendations of ISO 2394 (2015). Economic optimisation was found to be the prevailing criterion for class A, B and C. However, it should be noted that the social willingness to pay ($SWTP$) in accordance with the marginal live saving cost principle was taken into account in the determination of total failure costs (Table 2). When the societal costs become fairly dominant, e.g. in case of class C and D, a smaller difference in reliability indices was found between the two criteria. Table 2 also shows that the recommended annual target reliability indices for new quay walls are in the range of the guidance of ISO 2394 (2015) and correspond to ‘medium’ relative costs of safety measures.

Since reliability targets are always related to a certain reference period, it shall be noted that this study presents annual reliability indices, rather than lifetime reliability indices, which is in accordance with the recommendations of ISO 2394 (2015), Rackwitz (2001), and with Roubos et al. (2018). Furthermore, the *LIRA* and *SR* criteria seem only relevant for failures with consequences that reach far beyond the marine structure site itself, for instance if installations with hazardous materials are affected. Consequently, they are not included in the recommended values, but should be considered separately when applicable. Table 2 shows that the recommended annual target reliability indices are in the range of the guidance of ISO 2394. Sticking to the convention of presenting the results as annual reliability indices shall not interpret that the effect of time-independency is not important of negligible. In contrast, it is noteworthy that the recommended target reliability indices represent structures that are largely dominated by time-independent uncertainty, such as the structural and geotechnical failure modes of marine structures (Roubos et al., 2018); This is partly caused by the phenomenon that the efficiency of safety measures as well as failure consequences significantly differs per limit-state function. For additional information the reader is referred to Roubos et al. (2018).

Table 2. Annual target reliability indices for consequence classes of largely time-independent limit state functions for new structures ($t_{eq} \geq 20$).

Criterion	**Type**	**Consequence class**				
		A	**B**	**C**	**D**	**E**
		Low	**Some**	**Considerable**	**High**	**Very high**
$N_{F\|\mathrm{f}}$		**<1**	**<5**	**<50**	**<500**	**≥500**
C_f		**<€8m**	**<€50m**	**<€200m**	**<€1500m**	**≥ €1500m**
ISO 2394 (2015)	Large [1]	-	*3.1*	*3.3*	*3.7*	-
	Medium [1]	-	*3.7*	*4.2*	*4.4*	-
	Small [1]	-	*4.2*	*4.4*	*4.7*	-
Economic optimisation[2,3]		2.8	3.4	3.8	4.3	excl.[5]
LQI criterion[2,3]		2.5	3.0	3.7	4.3	excl.[5]
IR criterion	$IRPA=10^{-6}$	2.8	3.3	3.7	n/a	n/a
	$IRPA=10^{-5}$	1.9	2.5	3.1	n/a	n/a
	$LIRA=10^{-6}$	n/a	n/a	n/a	4.3[4]	excl.[5]
	$LIRA=10^{-5}$	n/a	n/a	n/a	3.4[4]	excl.[5]
SR criterion	A=0.01; k=2	n/a	3.4	4.5	5.4	excl.[5]
	A=0.1; k=1	n/a	2.1	2.9	3.5	excl.[5]
Recommended values	**($n_{eq} \ll t_{ref}$ or $t_{eq} \geq 20$)**	**2.8**	**3.4**	**3.8[6]**	**4.3[6]**	**excl.** [5]

[1] Relative costs of safety measures.

[2] Dominant design variables are considered to be time-independent ($n_{eq} \ll t_{ref}$ or $t_{eq} \geq 20$).

[3] Input variables $t_{ref} = 50$, $C_0 = €0.6$m, $C_m = €0.1$m and $SWTP = €3$m (Roubos et al., 2018).

[4] This criterion is only active at a hazardous site/project location.

[5] It is not possible to provide general recommendations. A project-specific study is recommended.

[6] Verify whether *LIRA* or *SR* criteria are active.

Furthermore, Table 3 lists the reliability indices for new structures, upgrades and 'disapproval' related to economic optimisation and the LQI acceptance criterion. The reliability indices found using economic optimisation are higher than derived on the basis of the LQI criterion. The target reliability indices for upgrades are lower than for new structures; This caused by the higher marginal construction costs C_m and the fact that the structure already survived de first period of service. The influence of C_m was examined by performing a sensitivity analysis.

Table 3: Annual target reliability indices for different consequences classes for largely time-invariant limit states of marine structures ($t_{eq} \geq 20$)

Criterion	**Type**	**Consequence class**				
		A	**B**	**C**	**D**	**E**
		Low	**Some**	**Considerable**	**High**	**Very high**
$N_{F\|f}$		**<1**	**<5**	**<50**	**<500**	**≥500**
C_f		**<€8m**	**<€50m**	**<€200m**	**<€1500m**	**≥ €1500m**
ISO2394 (2015)	Large[1]	-	*3.1*	*3.3*	*3.7*	-
	Medium[1]	-	*3.7*	*4.2*	*4.4*	-
	Small[1]	-	*4.2*	*4.4*	*4.7*	-
New[2]						
Economic optimisation		2.8	3.4	3.8	4.3	excl.[4]
LQI-criterion		2.5	3.0	3.7	4.3	excl.[4]
Repair works/Upgrade[3]						
Economic optimisation		2.2	3.0	3.4	4.0	excl.[4]
LQI-criterion		<2	2.5	3.3	4.0	excl.[4]
Disapproval						
Economic optimisation		<2	2.0	2.5	3.2	excl.[4]
LQI-criterion		<2	<2	2.4	3.2	excl.[4]

1) Relative costs of safety measures

2) Input variables t_{ref}=50, C_0=€600k, C_m=€100k and *STWP*=3M€.

3) Input variables for repair works $t_{survive}$=25, $t_{remaining}$=50, C_0=€200k, C_m=€200k €, and *STWP*=3M€ (Roubos et al., 2018).

4) It is not possible to provide general recommendations. A project specific study is recommended.

Sensitivity analysis

This section presents the influence of some important assumptions on the target reliability indices found, such as t_{eq} =20 or that C_m and C_0 equal €200k. Table 4 shows that target reliability indices for time-independent failure modes (t_{eq} = 1) are higher than partly time-dependent failure modes. Furthermore, the differences between slightly time-dependent and fully time-independent reliability problems are fairly small for new structures, whereas for upgrades and disproval this differentiation seems still relevant. In addition, Table 5 illustrates that the marginal costs of safety measures influence the reliability targets in case of an upgrade, whereas the initial construction costs of an upgrade influence the reliability level related to disproval.

Table 4: Influence t_{eq} on the annual target reliability indices for different consequences classes on the basis of economic optimisation β*

Criterion	**Consequence class**				
	A	**B**	**C**	**D**	**E**
	Low	**Some**	**Considerable**	**High**	**Very high**
$N_{F\|f}$	**<1**	**<5**	**<50**	**<500**	**≥500**
C_f	**<€8m**	**<€50m**	**<€200m**	**<€1500m**	**≥ €1500m**
New[1]					
Time-dependent $t_{eq} \geq 1$	3.5	4.0	4.3	4.8	excl.[3]
Largely time-dependent $t_{eq} \geq 10$	3.0	3.6	4.0	4.5	excl.[3]
Slightly time-dependent $t_{eq} \geq 20$	2.8	3.4	3.8	4.3	excl.[3]
Slightly time-independent $t_{eq} \geq 30$	2.8	3.4	3.8	4.3	excl.[3]
Largely time-independent $t_{eq} \geq 40$	2.7	3.3	3.7	4.2	excl.[3]
Time-independent $t_{eq}=50$	2.6	3.3	3.7	4.2	excl.[3]
Repair works/Upgrade[2]					
Time-dependent $t_{eq} \geq 1$	3.3	3.8	4.2	4.6	excl.[3]
Largely time-dependent $t_{eq} \geq 10$	2.7	3.3	3.7	4.2	excl.[3]
Slightly time-dependent $t_{eq} \geq 20$	2.2	3.0	3.4	4.0	excl.[3]
Slightly time-independent $t_{eq} \geq 30$	<2	2.7	3.2	3.8	excl.[3]
Largely time-independent $t_{eq} \geq 40$	<2	2.3	2.8	3.5	excl.[3]
Time-independent $t_{eq}=50$	<2	<2	<2	2.7	excl.[3]
Disapproval					
Time-dependent $t_{eq} \geq 1$	2.3	3.0	3.4	3.9	excl.[3]
Largely time-dependent $t_{eq} \geq 10$	<2	2.4	2.9	3.4	excl.[3]
Slightly time-dependent $t_{eq} \geq 20$	<2	2.0	2.5	3.2	excl.[3]
Slightly time-independent $t_{eq} \geq 30$	<2	<2	2.3	2.9	excl.[3]
Largely time-independent $t_{eq} \geq 40$	<2	<2	<2	2.6	excl.[3]
Time-independent $t_{eq}=50$	<2	<2	<2	<2	excl.[3]

[1] Input variables $t_{ref}=50$, C_0=€600k, C_m=€100k and $STWP$=3M€.

[2] Input variables for repair works $t_{survive}=25$, $t_{remaining}=50$, C_0=€200k, C_m=€200k €, and $STWP$=3M€ (Roubos et al., 2018).

[3] It is not possible to provide general recommendations. A project specific study is recommended.

Table 5: Influence C_m and C_0 on the annual target reliability indices for upgrades and disapproval respectively.

Criterion	**Consequence class**				
	A	**B**	**C**	**D**	**E**
	Low	**Some**	**Considerable**	**High**	**Very high**
$N_{F\|f}$	**<1**	**<5**	**<50**	**<500**	**≥500**
C_f	**<€8m**	**<€50m**	**<€200m**	**<€1500m**	**≥ €1500m**
Repair works/Upgrade[1]					
C_m=€100k	2.6	3.2	3.6	4.1	excl.[2]
C_m=€200k	2.2	3.0	3.4	4.0	excl.[2]
C_m=€300k	2	2.8	3.2	3.9	excl.[2]
Disapproval					
C_0=€100k	*<2*	2.1	2.6	3.2	excl.[2]
C_0=€200k	*<2*	*2.0*	*2.5*	*3.2*	excl.[2]
C_0=€300k	*<2*	*<2*	2.5	3.1	excl.[2]

[1] Input variables for repair works $t_{survive}=25$, $t_{remaining}=50$, $C_{0;ref}$=€200k, $C_{m;ref}$=€200k, and $STWP$=3M€ (Roubos et al., 2018).

[2] It is not possible to provide general recommendations. A project specific study is recommended.

DISCUSSION

At present, Eurocode standard EN1990 (2011) presents annual reliability indices β_{t_1} (Table 1), which were derived from the lifetime target reliability indices $\beta_{t_{50}}$ assuming independency between the annual failure events. In the case of correlated annual failure events – due to dominant time-invariant actions and resistance – the annual reliability indices β_{t_1} in Table 1 are overly conservative; this is e.g. the case for marine structures dominated by geotechnical actions. Failure consequences can take many different forms, such as loss of human life or social–environmental and economic repercussions (Diamantidis, 2017). Civil engineering structures normally serve an economic purpose, and if they fail or malfunction this will be associated with economic loss. For port structures this is by definition not different, however the adverse economic effects may dampen or vanish when a port or terminal has overcapacity. Significant economic repercussions are not very likely in large ports, since it is often possible to mitigate damage within the overcapacity of a terminal or port cluster and terminals are often connected by pipeline corridors or road or railway networks. Substantial economic damage is more likely for ports and terminals without redundancy. Another example of berths with functional redundancy are berths functioning as public wharfs (Roubos, 2018), but for those loss of human life is an important factor.

CONCLUSION

The results of this study provide guidance on reliability differentiation for assessing limit states of marine structures, such as quay walls, jetties, and flexible dolphins. The most important findings are:

- The assessment framework of ISO 2394 provides a solid foundation for reliability differentiation. It can be optimised by including reliability problems that are time-variant. However, this framework will become more consistent and interpretable if it is further extended with detailed information about the type of failure, the likelihood of warning signals, the presence of functional and structural redundancy, and the damage to the image of a port or terminal.
- The reliability targets derived by assessing the LQI acceptance criterion were slightly lower than the targets found by economic optimisation. Hence, target reliability indices for marine structures can be derived on basis of economic optimisation in combination with the marginal lifesaving cost principle.
- The target reliability indices for ‘renewals’ and ‘upgrades’ seem to be largely influenced by failure costs and marginal construction costs, whereas the reliability target related to ‘disapproval’ is also influence by the initial construction costs of repair works.

- The target reliability indices are significantly influenced by the extent to which failure events are correlated. Assuming independent failure events introduces fairly conservative reliability targets. It was found that its effect on reliability targets for upgrades and disapproval is even higher than for renewals.
- The annual reliability indices found are in the range of the guidance in ISO 2394.

When defining target reliability indices for marine structures, and presumably for all other geotechnical structures, one should be very careful using the general guidance developed for buildings and bridges, because the degree and source of aleatory and epistemic uncertainty differ, as do the consequences of failure. It is strongly recommended to account for damage to the reputation of a terminal or port, because marginal safety costs appeared to be quite low compared to the total construction costs and expected benefits. A further study with regard to the influence of time-independent design variables and the efficiency of safety measures for individual failure modes is highly recommended if one wants to improve assessments with respect to reliability and safety.

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