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Target reliability indices for existing quay walls derived on the basis of economic optimisation and human safety requirements

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General frameworks for reliability differentiation have evolved over time and are mainly developed for buildings. However, recommendations for the safety of existing quay walls are lacking. In this study, target reliability indices for assessing existing quay walls were derived by economic optimisation and by evaluating the requirements concerning human safety. In quay-wall design, some dominant stochastic design variables are largely time-independent, such as soil and material properties. The influence of time-independent variables on the evolution of the probability of failure was taken into consideration, since this affects the present value of future failure costs and the associated target reliability indices. The target reliability indices obtained for existing quay walls depend on the consequences of failure and the remaining lifetime. If the failure modes of a quay wall are governed by time-independent design parameters and the quay wall has already survived the early service period, the residual probability of failure is lower for an existing quay wall compared to a new structure. Hence, this should be considered in the determination of target reliability indices. The method to evaluate quay-wall reliability over time can also be used to assess other civil and geotechnical structures.

Keywords: target reliability index; existing quay walls; probability of failure; human safety; corrosion; human safety; past performance; risk acceptance criteria.

1. Introduction

Globally thousands of kilometres quay wall are situated along inland waterways, in city centres, in commercial port areas and even in flood defence systems. The reliability level of quay walls is generally determined in accordance with a certain design code or standard, such as ISO 2394 (2015), EN 1990 (2011) and JCSS (2001). In the Netherlands, the reliability differentiation of EN 1990 is directly applied to the design of quay walls (Gijt & Broeken, 2013). In this study, the target reliability index and target probability of failure are related as follows:

$$\beta = -\Phi^{-1}(P_{\mathrm{f}}) \tag{1}$$

where:

β = Target reliability index [-]

P_{f} = Target probability of failure[-]

In practice, target reliability indices can be derived by calibrating against previous design methods in order to maintain an existing reliability level (Böckmann & Grünberg, 2009). Another method establishes target reliability indices β* on the basis of economic optimisation by minimising the costs during the lifetime of a structure. Using this method, Rackwitz (2000) showed that the reliability optimum is largely influenced by the marginal costs of safety measures and the consequences of failure. The consequences of failure can take many different forms, such as loss of human life and social, environmental and economic repercussions (Diamantidis, 2017). The results obtained by Rackwitz (Table 1) formed the basis for the recommended target reliability indices in ISO 2394 (2015), the standard describing the general principles on structural reliability.

Table 1. Marginal costs of safety measures and annual target reliability indices for structural components (Rackwitz, 2000).

Marginal costs of safety measures	**Consequences of failure**		
	Insignificant	**Normal**	**Large**
High	2.3	3.1	3.7
Moderate	3.1	3.7	4.3
Low	3.7	4.3	4.7

Target reliability indices β^* derived on the basis of economic optimisation are acceptable provided that the risk-acceptance criteria concerning human safety have been met (Roubos, 2019). When many people are at risk, human safety requirements, often expressed by annual failure rates, will determine the acceptable reliability level (Steenbergen et al., 2015). ISO 2394 (2015) recommends to employ the life quality index (LQI) acceptance criterion and provides information with regard to the Social Willingness To Pay (SWTP) corresponding to the amount of money which should be invested into saving one additional life. In Fischer et al. (2012) and Fischer et al. (2019) the LQI acceptance criterion is defined in terms of the acceptable reliability level:

$$-\frac{\partial P_f(\beta_{acc;t_1})}{\partial \beta} \leq \frac{C_1(\gamma_S+\omega)}{\mathrm{SWTP}\cdot N_{F|f}} \qquad (2)$$

where

C_1 = marginal costs associated with a considered safety measure;

SWTP = Social willingness to pay for saving an additional life;

γ_S = Societal discount rate;

ω = annual rate of obsolescence;

$N_{F|f}$ = expected number of fatalities given failure.

$\beta_{acc;t_1}$= Annual reliability index representing the threshold of acceptance [-]

The target reliability indices presently in use were mainly developed for buildings (Vrouwenvelder, 2001) and bridges (Steenbergen, & Vrouwenvelder, 2010) assuming mainly fully time-variant reliability problems (Holický, 2011). Since the source of aleatory and epistemic uncertainty as well as consequences of failure could be very different for quay walls situated in port areas, Roubos et al. (2018a) derived target reliability indices for new quay walls. Clear guidance, however, how to evaluate the reliability of existing quay walls subject to corrosion (Figure 1) is still lacking.

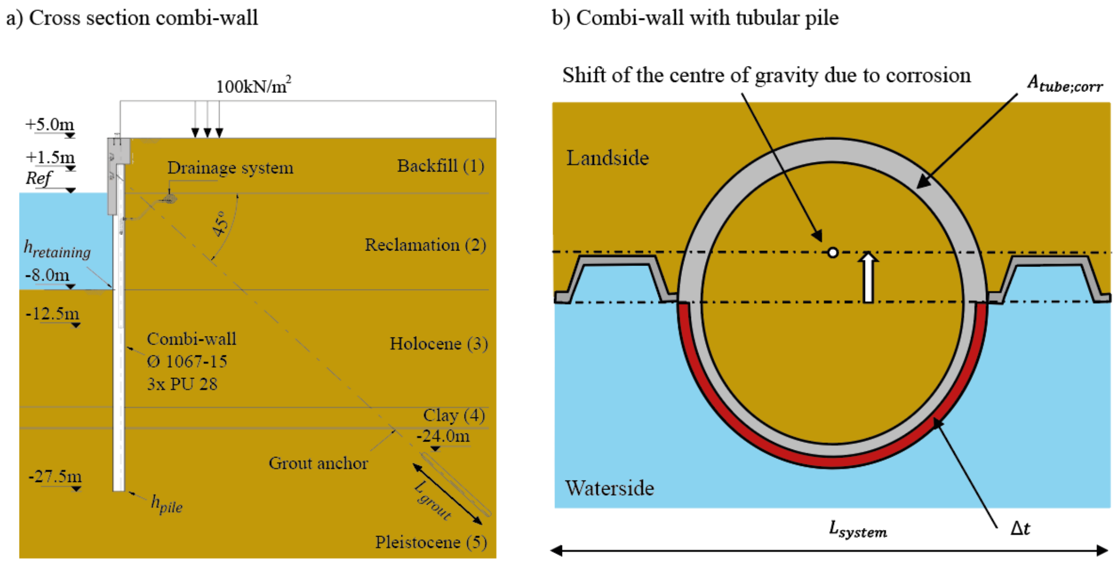


Figure 1. Typical dimensions of a quay wall, a combi-wall with grouted anchor (a), and the corrosion-induced loss of thickness Δt at the water side of the tube of the combi-wall system (b).

This study aims to provide guidance to code developers and engineers on deriving target reliability indices for assessing existing quay walls subject to degradation. The reliability optimum associated with 'repairs' of an existing quay wall was examined by economic optimisation. Subsequently, the reliability index for 'disapproval' of an existing quay wall was derived by evaluating the acceptable residual risk. In Roubos et al. (2018b), it is described how the LQI acceptance criterion can be used to determine reliability targets. In addition, the current paper presents an overview of annual target reliabilities presently in use throughout the world and target reliability indices are derived from different risk perspectives. In quay-wall design, the dominant stochastic design variables are largely time-independent, such as soil strength and material properties of steel (Appendix B), which influence the annual failure rate. Hence, a detailed Monte Carlo analysis was performed in combination with the analytical method of Blum to determine the evolution of the annual failure rate. The requirements concerning human safety were examined on the basis of the individual risk (IR) and life quality index (LQI) acceptance criterion. Furthermore, a sensitivity analysis was performed in order to derive insight into the parameters that influence the target reliability index, such as discount rates, remaining lifetime, marginal costs for safety investments and degree of damage in terms of monetary units or number of fatalities.

2. Reliability differentiation throughout the world

2.1 Annual target reliability indices

This section presents an overview of the reliability differentiation embedded in design codes and standards presently in use throughout the world. Target reliability indices are always related to a reference period of, for example, one year or fifty years. Within a one-year reference period, the effects of past performance and degradation can be appropriately taken into account, whereas this is fairly unpractical for longer reference periods. Since the remaining service life and the associated reference period are generally unknown a priori, using annual target reliability indices is preferred in the evaluation of the reliability of existing quay walls. Consequently, Table 2 presents an overview of the annual reliability targets recommended in literature. The classes A, B, C, D and E correspond to the reliability differentiation in ISO 2394 (2015).

Table 2. Overview of annual target reliability indices in literature

Codes & Standards	**Consequence classes**				
	A[2]	**B**[2]	**C**[2]	**D**[2]	**E**[2]
	Low	**Some**	**Considerable**	**High**	**Very high**
ISO 2394	Class 1	Class 2	Class 3	Class 4	Class 5
(2015)		4.2	4.4	4.7	
JCSS		Minor	Moderate	Large	
(2001)[1]		4.2	4.4	4.7	

Structural concrete	Small	Some		Moderate	Great
(2012) [1]	3.5	4.1		4.7	5.1
EN 1990		RC1		RC2	RC3
(2011)		4.2		4.7	5.2
Rackwitz	Insignificant		Normal	Large	
(2000) [1]	3.7		4.3	4.7	
DNV	Type I	Type I & II	Type II & III	Type III	
(1992)	3.09	3.71	4.26	4.75	
USACE	Average	Good			High
(1999)	2.5/3.0	4.0			5.0

[1]) The target reliability index presented in this table has been derived by assuming low relative costs of safety measures, which is questionable in case of assessing existing quay walls (Section 3).
[2]) The associated assessment criteria are included in Appendix A.

2.2 Reliability classes in quay-wall design

In the Netherlands, the reliability differentiation of EN 1990 is applied unaltered to the design of quay walls (Gijt & Broeken, 2013). The reliability of marine structures designed in accordance with the Det Norske Veritas (DNV, 1992) depends on structural redundancy and the presence of warning signals before failure.

In the United States, the American Society of Civil Engineers distinguishes four occupancy categories in (ASCE 7–16, 2016) representing the number of lives placed at risk by failure and annual probabilities of failure. The acceptable safety and the associated target reliability index are further differentiated for situations when failure is sudden or not sudden and does or does not lead to widespread progression of damage. These codes, however, prescribe lifetime reliability targets and do not explicitly provide annual target reliability indices.

In Canada, the design codes (NBCC and CHBDC) incorporate the consequence classes ‘low’, ‘typical’ and ‘high’ and reduce safety factors in the case of a detailed understanding of structural behaviour and a detailed site investigation (Fenton et al., 2016).

The technical standards and commentaries for port and harbour facilities in Japan (OCDI, 2009) evolved into a performance-based design approach (Nagao et al., 2009) that implements the basic principles of ISO 2394. For seismic performance verification, high (HR), intermediate (IR) and normal seismic (NR) resistance classes were developed. International sea container terminals and facilities that have an important role in emergency recovery materials after earthquakes are classified as HR facilities.

The Spanish recommendations for maritime structures, ROM 0.0 (2002), comply with EN 1990 and verify structural reliability, functionality and operability against failure and stoppage modes. The intrinsic nature of a maritime structure is expressed in terms of the social and environmental repercussion index (*SERI*) and the economic repercussion index (*ERI*) (Losada & Benedicto, 2005). Low and high/very high *SERI*-rated maritime works are assumed to correspond to RC1 and RC2 of EN 1990, respectively (ROM 0.5, 2008). ROM 0.5 noted that maritime works do not have an equivalent representation with RC3. *ERI* is used to determine the ‘minimum useful’ life. The Spanish code also includes lifetime reliability targets only.

The German recommendations for the design of waterfront structures, EAU 2012 (Grabe, 2012), distinguish safety classes for resistance and typical loading cases, but do not explicitly recommend target reliability indices.

Neither the British Standard (BS 6349-1-2, 2016) nor CIRIA (the UK’s Construction Industry Research and Information Association) (Cork & Chamberlain, 2015), (Gaba et al., 2017) prescribe a specific target reliability index.

2.3 Requirements concerning human safety

When many people are at risk, safety requirements, often expressed as annual failure rates, will determine the acceptable reliability level (Vrouwenvelder & Scholten, 2010; Steenbergen et al., 2015). Detailed overviews of available methods for quantitative risk measures of loss of life and accompanying thresholds are given by Jonkman et al. (2003) and Bhattacharya et al. (2001). The minimum annual failure rates for ultimate limit states derived by Fischer et al. (2012) – namely 3.1, 3.7 and 4.2 for high, medium and low relative life-saving costs, respectively – are implemented in ISO 2394 (2015). In the Netherlands, hydraulic structures that are part of a flood defence system are examined using risk-based methods (Jonkman & Schweckendiek, 2015). The maximum allowable risk is defined by frequency of inundation and socioeconomic damage. Reliability differentiation of failure modes of soil-retaining walls that are part of a flood defence system is applied by distinguishing specific safety classes and associated lifetime target reliability indices (STOWA, 2011; TAW, 2003).

3. Methods

3.1. Introduction

This section briefly discusses the methods used to establish target reliability indices for existing structures. Firstly, the reliability optimum $\beta^*_{\mathrm{repair}}$ for repairing an existing quay wall (Figure 2a) was derived by using the principles of economic optimisation as for new structures. The target reliability index $\beta^*_{\mathrm{repair}}$ is generally slightly lower than the reliability target for a new structure β^*_{new}, because the marginal safety costs are generally higher in case of repairing an existing structure or in other words it is generally more expensive to improve reliability in the event of an existing structure than to achieve the same improvement when designing a new structure (Sýkora & Holický, 2011; Sýkora et al., 2017). 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 'repairs' - denoted as $\beta_{LQI;repair}$ - was derived on the basis of the LQI acceptance criterion.

In this paper, the reliability minimum below which a structural member is insufficiently safe and should be repaired is denoted as '$\beta_{disapproval}$' (Sýkora et al., 2017). The reliability level for 'disapproval can be determined on the basis of economic optimisation as well as on minimum requirements concerning human safety. If the total costs for a repair – sum of capitalized risk and investments in safety measures of the repairs (Figure 2a) – are equal to the actual residual capitalised risk of the scenario 'doing nothing' (Figure 2b) the reliability threshold for repairing the existing structure can be found. The reliability thresholds derived on the basis of economic optimisation and the LQI criterion are denoted as $\beta^*_{disapproval}$ and $\beta_{LQI;disapproval}$, respectively. The main difference is that in the latter criterion the 'societal' costs were taken into consideration (Figure 2b). This is further explained in Section 2.4.

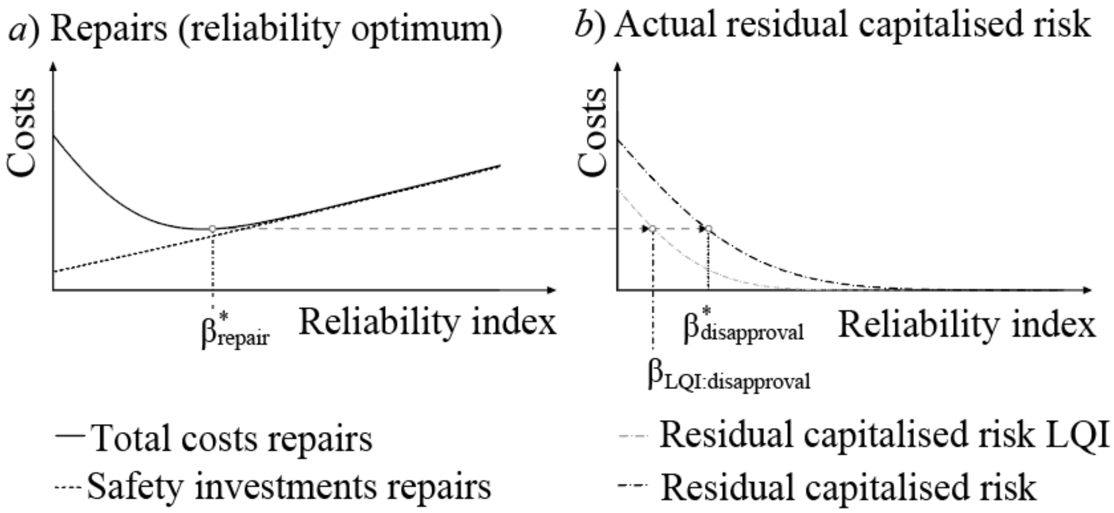


Figure 2. Comparison of the total costs – summation construction costs and associated capitalized risk - after repairing the existing structure (a) with the residual risk of the existing structure (b).

3.2 Failure mode

The reliability indices were ascribed to failure modes of structural components in accordance with modern design codes assuming that progressive damage is mitigated. Due to this assumption the failure probability of the majority of mutual dependent failure modes will become very small and their contribution in an overall fault tree analysis will hence be negligible or in other words the reliability level of a structural component is generally dominated by one specific failure mode. In this study, one simplified ultimate limit state was considered as a reasonable first approach.

$$Z_{yield}(z) = f_y - max\left(\frac{M_{wall}(z)}{W_{wall}(z)} + \frac{N_{tube}(z)}{A_{tube}(z)}\right) \qquad (3)$$

where,

Z_{yield} = structural limit state function [-];

f_y = yield strength of retaining wall [kN/m^2];

M_{wall} = bending moment in retaining wall [kNm/m];

N_{tube} = normal force in tube [kN/m];

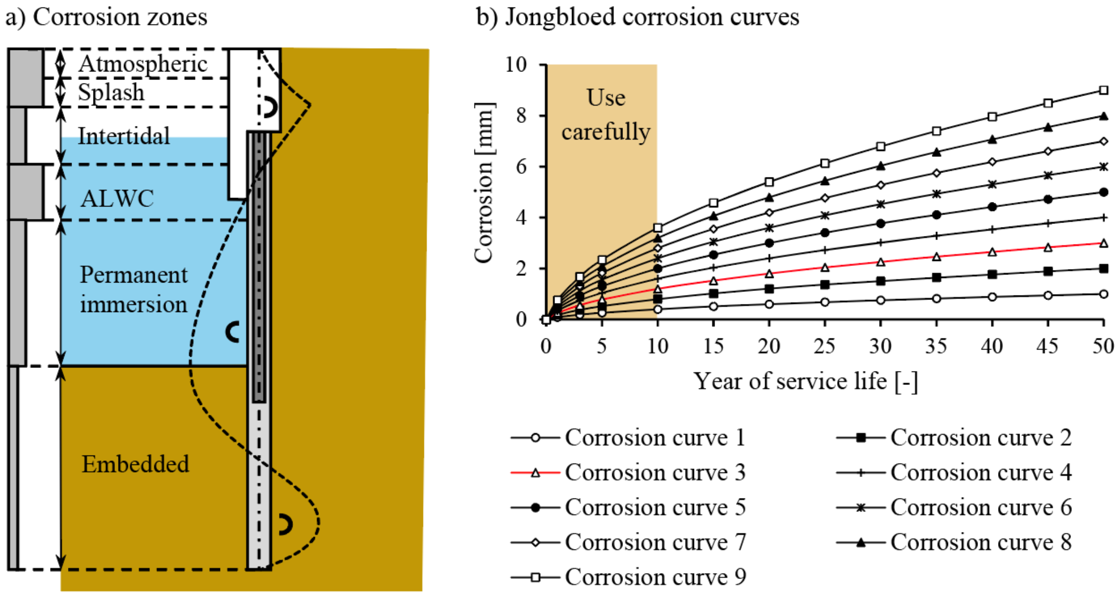
W_{wall} = section modules of retaining wall [m^3/m^1];;

A_{tube} = section area of tube [m^2/m^1];

z = depth [m].

The assumed ultimate limit state for structural failure is the yielding of the outer fibre of the soil-retaining wall.

If no system of cathodic protection is installed the quay wall is subject to a certain corrosion environment. The port of Rotterdam authority developed their own corrosion curves – which are based on detailed measurement campaigns – in order to assess the reliability of their quay walls (Voogt, 2014). It should be noted that different corrosion zones are distinguished across the height of the soil-retaining wall. In this study, the ‘Permanent immersion’ zone was of interest, because the stresses in the outer fibre prevail just above the harbour bottom (Figure 3). Corrosion curve 3 is considered in this study, since this curve represents the corrosion loss just above the harbour bottom for the quay walls in the west part of the port of Rotterdam.


a) Corrosion zones

b) Jongbloed corrosion curves

Figure 3. Typical corrosion zones (A) and the Jongbloed corrosion curves (B) (Roubos, 2019)

The stochastic model parameters considered in this study are listed in Appendix B. For detailed information about the distribution types the reader is referred to Allaix et al. (2017) and Roubos et al. (2019). The length of a quay wall was subdivided into equivalent sections for which failure events are independent. The associated proportional change in marginal safety costs and failure consequences (Section 3.4) was taken into account for an ′equivalent length’ L_{eq} along a quay wall. An inventory of past failures in Rotterdam (Allaix et al., 2017) showed that the failure length of the limit state under consideration was approximately 25-50m. In the calculations performed in this study, L_{eq} was assumed to be equal to 40m. In this study, 2D-Blum calculations were performed to evaluate the structural limit state function. Those calculations are representative of the ′equivalent length’ L_{eq}.

3.3 Modelling time-variant reliability

The risk profile of a quay wall evolves over time. This section discusses the method used to model the evolution of the probability of failure over time in order to determine the present value of future potential failure costs. Assuming that no failure has occurred in the previous years the annual failure rate of a quay wall equipped with a system of cathodic protection will decrease during its service life (dashed line in Figure 4a). A system of cathodic protection prevents deterioration of the steel construction components. Due to corrosion induced degradation the annual failure rate tends to increase (solid line in Figure 4a).

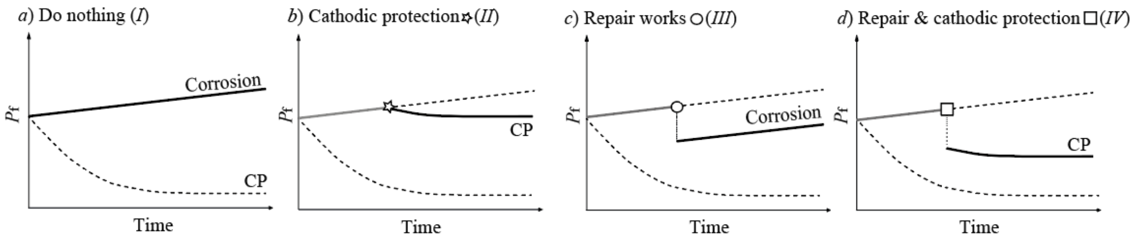


Figure 4. Typical evolution of annual failure rate for a quay wall subject to severe corrosion and different repair scenarios during the lifetime, e.g installation of a system of cathodic protection or repairing corrosion induced degradation.

The evaluation of the annual failure probability was examined for different scenarios. The probability of failure in year *i* was defined as the probability that failure occurs during year i, given that the structure survived the previous period $t_{survive}$.

$$P_{\mathrm{f;year\ i}} = \mathrm{P}\left(F_i | \overline{F}_1 \cap \overline{F}_2 \cap \ldots . \cap \overline{F}_{i-1}\right) \qquad (4)$$

where:

F_i = the event of failure during year *i* [-];

$\overline{F}_1, \overline{F}_2, \ldots., \overline{F}_{i-1}$ = the events of no failure in individual years until year *i* [-].

The probability of failure was estimated using the Monte Carlo method and performing 10×10^6 samples for each year of the service life. Hence, in total approximately 1.5 billion samples were taken. In each simulation, the soil properties are generated once, while a sample of the live load Q is generated for each year of the lifetime. The equivalent wall-thickness loss due to corrosion Δt_{eq} was modelled using corrosion curve 3 of Jongbloed (Figure 3), which represents the mean value of uniform and pitting corrosion combined. It should be noted that these curves, which are based on millions of wall-thickness measurements, exhibit higher corrosion rates when compared with other design guidance (Grabe, 2012; NEN-EN 1993-5, 2007). The uncertainty related to corrosion-induced degradation was estimated using field measurements from the port of Rotterdam (De Jong, 2018). The coefficients of variation found for distinctive corrosion environments

(Figure 3; Roubos, 2019) range between 0.1 and 0.5, which is in accordance with other literature (Allaix et al., 2018; Boero et al., 2012; Roubos et al., 2019). In the calculations performed in this study, a coefficient of variation of 0.5 was taken into consideration. Roubos (2019) shows that the effects of changing this coefficient of variation on the evolution of the failure rate is fairly low. Consequently, a lower value is not likely to influence the results of this study.

3.4 Cost minimisation

This section concerns the method used to determine target reliability indices using the principles of cost minimisation in accordance with the recommendations in literature (Rackwitz, 2000; Sýkora, & Holicky, 2011; Sýkora et al., 2017). The reliability indices for new structures β^*_{new} and repairs of existing structures β^*_{repair} were derived minimising the following 'total cost' function:

$$\min\{C_{\text{Total}} = C_{\text{Investments}} + C_{\text{CapitalisedRisk}}\} \quad (5)$$

in which,

$$C_{\text{Investments}}(\beta) = C_0 + C_m\,\beta \quad (6)$$

$$C_{\text{CapitalisedRisk}}(\beta) = C_{\text{f}} \sum_{n=1}^{t_{remaining}} \frac{P_{\text{f};n}}{(1+r)^n} \quad (7)$$

where,

$C_{\text{Investments}}$ = investments in safety measures [€];

$C_{\text{CapitalisedRisk}}$ = present value of future risk [€];

β = reliability index/ decision parameter [-];

$\beta*$ = optimal reliability index [-];

C_0 = initial construction costs independent of the reliability index [€];

C_m = marginal construction cost dependent on the reliability index [€];

$t_{remaining}$ = remaining lifetime [year];

$P_{f;n}$ = annual probability of failure [-];

r = real discount rate [-].

The investments in safety measures were divided into initial construction cost C_0 and marginal construction costs C_m. The initial construction costs C_0 often dominate structural investments (Gijt, 2010), but unlike C_m do not influence the reliability optimum for β^*_{new} or β^*_{repair} (Rackwitz, 2000). However, it should be noted that for assessing the reliability minimum – or in other words the reliability target for disapproval – of a quay wall this is the opposite: C_0 largely influences the target reliability index and the contribution of C_m is negligibly low (Section 4.2).

As explained in Section 3.2 the length of a quay wall was subdivided into equivalent sections for which failure events are independent. The associated proportional change in marginal safety costs was found by multiplying the ′equivalent length' to the fraction ΔC/Δβ representing the safety investments per metre:

$$C_m\,(x) = L_{eq}\frac{\Delta C(x)}{\Delta\beta(x)} \qquad (8)$$

where,

x = a vector representing changes in structural dimensions;

L_{eq} = equivalent length along a quay wall for which failure events are independent [m];

ΔC = change in costs of safety measures [€];

$\Delta\beta$ = change in reliability index [-].

The fraction $\Delta C/\Delta\beta$ assumed was in the range of 5% to 10% of the construction costs of structural components, which was in accordance with the study of Schweckendiek et al. (2007) and Roubos et al. (2018a). Table 3 lists the initial and marginal construction costs per scenario.

Table 3. Initial and marginal construction costs for L_{eq} = 40m (Section 3.2)

Scenario	C_0	C_m
Renewal	€360k[2]	€60k[2]
I) Do nothing	n.a.	n.a.
II) Prevention of corrosion (CP[1])	€50k	n.a.
III) Repairs	€100k	€120k
IV) Repairs & prevention (CP[1])	€150k	€120k

[1]) The quay wall will be equipped with a system of cathodic protection (CP)

[2]) The values are derived in Roubos et al. (2018a)

It should be noted that even if adequate safety measures are implemented there will always be a residual capitalised risk. The capitalised risk represents the present value of future costs and was established by assuming a real discount rate *r* (Sykora & Holický, 2011; Rackwitz, 2006). Fischer et al. (2013) showed that different discount rates could be used for private and social decision makers. In this study a discount rate of 3% was taken into consideration. Detailed information about the direct and indirect costs associated with failure can be found in Allaix et al. (2017) and Roubos et al. (2018a). The economic consequences of a structural failure ($Z_{yield} < 0$) are in the range of €1-5m.

3.5 Risk-acceptance criteria

Reliability indices derived on the basis of cost minimisation can be lower than the thresholds of acceptance. In this case, the reliability target must be based on the minimum requirements concerning human safety. This section discusses the evaluation of three risk-acceptance criteria, namely the individual risk per annum (IRPA) (Equation (9)), the localised individual risk per annum (LIRA) (Equation (10)) and the life quality index (LQI) acceptance criterion (Equation (2)).

$$\beta_{acc;t_1 IRPA} \geq -\Phi^{-1}\left(\frac{IRPA}{P_{\mathrm{Present}}(1-P_{\mathrm{Escape}})P_{d|\mathrm{f}}}\right) \qquad (9)$$

$$\beta_{acc;t_1;LIRA} \geq= -\Phi^{-1}\left(\frac{LIRA}{(1-P_{\mathrm{Escape}})P_{d|\mathrm{f}}}\right) \qquad (10)$$

where,

$IRPA$	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 [-];
$P_{d\|\mathrm{f}}$	Conditional probability that an individual being present will die given failure [-];
$\beta_{acc;t_1}$	Annual threshold of acceptance [-].

IRPA is generally used to assess work-related risks faced by particularly exposed individuals (NORSOK, 2001; Skjong et al., 2007) and is frequently used in decision-making processes, whereas *LIRA* represents the risk at a specific geographical location (Johansen, 2010). *LIRA* is mainly used in spatial planning and assessing external safety contours in the vicinity of hazardous installations or in the design of flood-defence systems (Jongejan et al., 2009; Jonkman et al., 2003; Vrijling, 2001; Vrijling et al., 1998).

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. Studying the background documents of the LQI target reliabilities (Fischer & Faber, 2012) showed that this criterion can also be evaluated by applying the principles of costs minimisation if the capitalized 'societal' risk is taken into consideration (Roubos et al., 2018a). The corresponding present value of societal losses, denoted by $C_{f;Societal}$, then depends on the SWTP and the expected number of fatalities $N_{F|f}$ and is used in Equation (7). In this study $N_{F|f} = 1$ was taken into consideration.

$$C_{\mathrm{f;Societal}} = \mathrm{N}_{F|f}\ \mathrm{SWTP} \tag{11}$$

where,

$C_{f;Societal}$	Societal failure cost [€];
$N_{F\|f}$	Expected number of fatalities [-].

In this study, a SWTP of 2-5M$ per life saved was assumed for the evaluation of the marginal lifesaving costs principle / LQI criterion, which is in accordance with the range suggested in ISO 2394 (2015). Note that it is not the purpose of the SWTP to assign a monetary value to human life, which is very controversial (Vrijling & Gelder, 2000). According to Rackwitz (2008) a monetary value of life does not exist.''...the value of human life is infinite and beyond measure ...''. Nonetheless, to apply the marginal lifesaving costs principle, it is necessary to define a quantitative threshold value for the costs per life saved to clearly distinguish between efficient and inefficient safety measures. The goal is to generate the largest life saving benefit possible with limited societal resources by focussing on efficient safety measures rather than wasting money for inefficient ones.

4. Results

4.1 Structural limit state

This section presents the target reliability indices obtained by economic optimisation and assessing the IRPA and LQI acceptance criteria. Not only the target reliability indices for ‘repair’ or ‘disapproval’ were derived, but also the reliability indices for ‘new’ quay walls in order to evaluate and interpret the results found. Table 4 shows that target reliability indices in accordance with the LQI and IRPA acceptance criteria are lower than the target reliability indices derived by economic optimisation. It should be noted that a discount rate of 3% was assumed. This value is often used by societal decision makers, such as port authorities or governmental organizations. Private decision makers, such as terminals or commercial companies, may consider higher discount rates which will lead to lower reliability targets (Section 4.2).

Table 4. Target reliability indices for new quay walls for Z_{yield} with t_{ref} = 50 years, r = 3%, C_f = €5m, $C_{f;societal}$ = €3m; C_0 = €360k; C_m = €60k.

New	**Economic optimisation** β^*_{new}	**LQI** $\beta_{LQI;new}$	**Individual risk** $\beta_{IRPA:10^{-6}}$
Annual in year 1	3.4	3.3	2.8
Annual in year 50	4.1	4.0	2.8
Reference period of 50 years	2.8[2]	2.6[1, 2]	n.a.[1]

[1])Requirements concerning human safety are generally set for a reference period of one year only.

[2]) Since soil properties largely dominate the amount of uncertainty and only have one realisation, annual failure rates are not constant. Consequently, failure events in subsequent years are to a certain extent dependent, and hence lower target reliability indices were found for a reference period of 50 years compared to a reference period of one year.

When the quay wall has survived a certain period of time, while being constantly subjected to corrosion, different strategies can be considered (Figure 4), such as installing a system of cathodic protection (scenario II) whether or not in combination with repairing corrosion induced degradation (scenario III and IV).

In this study, it was assumed that the quay wall has been subject to the corrosion rates of curve 3 (Figure 3) and has already survived the first 50 years of its 75-years' service life. Consequently, the reliability indices found are related to the remaining lifetime of 25 years. For non-deteriorating scenarios (II and IV) the target reliability indices of the first year are generally higher compared to the final year of the remaining service life, whereas for deteriorating scenarios (I and III) the target reliability indices of the final year are higher. In the event of a non-deteriorating quay wall retaining a large body of soil, its reliability target decreases over time due to the effects of past-service performance, since the amount of epistemic uncertainty decreases accordingly (Roubos, 2019).

Table 5 shows that the total costs – or in other words the capitalized risk – of the scenario 'Do nothing' (I) are lower than the total costs of repairs (III and IV). This indicates that repairs are not optimal from an economic perspective. The total costs of installing a system of cathodic protection without repairs (II) seems an interesting and efficient risk measure. However, scenario I and II can only be taken into consideration if the remaining probability of failure is acceptable or in other words meets the risk-acceptance criteria (Section 3.5).

Table 5. Reliability indices β^* and associated total costs for different scenarios: I) Do nothing; II) Install cathodic protection; III) Repairs; IV) Repairs and install cathodic protection (Figure 4).

	Scenario			
	I)	**II)**	**III)**	**IV)**
Annual in year 50	3.0	3.0	3.5	3.3
Annual in year 75	2.8	3.1	3.3	3.4
Remaining lifetime 25 years[1]	1.7	1.9	2.3	2.4
Total costs	€ 155k	€ 150k	€ 190k	€ 220k

1) The service life of the quay wall was assumed to be 75 years and the structures has already survived the first 50 years.

Table 5 shows that repairing the corroded quay wall (III or IV) is less efficient than equipping the quay wall with a system of cathodic protection and stop further degradation (II). If one still considers repairing the quay wall, the best repair strategy is: repairing the structure without installing a system of cathodic protection (III). The reliability indices for disapproval depend on the total costs associated with the intended repairs and are listed in Table 6. Similar to the results obtained for new structures the acceptable reliability indices according to the LQI acceptance criterion are again a little lower than the target reliability indices derived by economic optimisation. The influence of the input variables on the reliability indices is further discussed in the following section.

Table 6. Target reliability indices for repairs, disapproval and IRPA. C_f = €5m, $C_{f;societal}$= €3m; C_0 = €100k; C_m = €120k.

	Repairs		**Disapproval**		**Individual risk**
	β^*	β_{LQI}	β^*	β_{LQI}	$\beta_{IRPA:10^{-5}}$
Annual in year 50	3.5^2	3.3	3.0	2.8	1.9
Annual in year 75	3.3^2	3.1	2.7	2.6	1.9
Remaining lifetime 25 years^3	2.3^2	2.1^1	1.6	1.3^1	n.a.^{1}

1) Requirements concerning human safety are generally derived for a reference period of one year only.

2) Correspond to Scenario III in Table 5.

3) The service life of the quay wall was assumed to be 75 years and the structures has already survived the first 50 years.

4.2 Sensitivity analysis

The sensitivity analysis performed in this study aims to provide insight into the extent to which target reliability indices related to ‘repair’ or ‘disapproval’ of a quay wall are influenced by input variables, such as the discount rate, the construction costs, the failure costs and the remaining lifetime (Figure 5). The curves representing the annual and lifetime target reliability indices show generally a similar trend. It should be noted that the annual reliability indices presented represent the reliability in the final year of the remaining lifetime, because due to corrosion the indices of the final prevail over the first year of the remaining lifetime. The remaining lifetime equals 25 years except for the analysis in Figure 5e where the remaining lifetime is varied on the x-axis. While the target reliability indices for 'repair' are not influenced by the initial construction costs C_0, the target reliability indices for 'disapproval' slightly decrease for higher initial construction costs C_0 of the suggested repair strategy (Figure 5a). In addition, Figure 5b shows that the marginal safety investments C_m of repairs do not significantly influence the reliability index for 'disapproval'. In the event of a high risk profile, expressed in terms of high discount rates, there is less willingness to invest in safety measures, and hence lower target reliability indices were found (Figure 5c). The absolute value of the failure costs C_f significantly influence the target reliability indices (Figure 5d). Low failure costs ($C_f \leq$ €10m) as well as a short remaining lifetime ($t_{remaining} \leq 5$ years) resulted in an exponential decrease in the target reliability index.

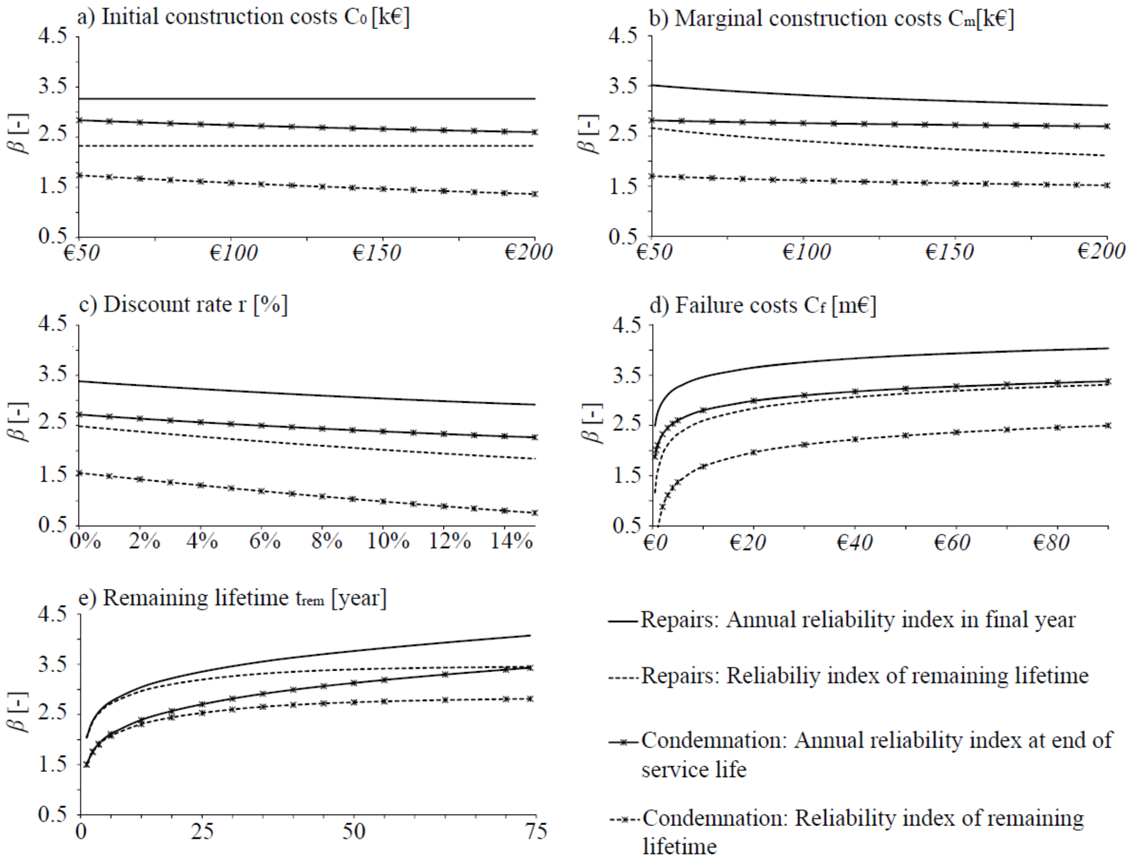


Figure 5. Sensitivity analysis β^*_{repair} for Z_{yield} of scenario III. The reference calculation is based on: t_{ref}=25; $t_{survive}$=50; r=3%; L_{eq} =40m; C_0 =€100k; C_m =€120k; C_f =€5m.

5. Discussion

The target reliability indices derived in this study are related to a one-year reference period. In addition, it is fairly practical to use annual target reliability indices when assessing existing quay walls, since otherwise an iterative procedure to determine the quay wall's remaining lifetime will be required (Roubos, 2019). In the case of new quay walls, however, the reference period is known. Consequently, both annual or lifetime reliability indices can be used in the design of new quay walls. Since the remaining service life of an existing quay wall is generally unknown a priori, using annual target reliability indices is preferred over reliability targets for longer reference periods in the evaluation existing quay walls. The evaluation of annual target reliability indices for existing quay walls can be performed by estimating the annual failure rates for the coming period. For non-deteriorating quay walls the first year of the remaining lifetime determines the acceptable risk, whereas in the event of corrosion-induced degradation the final year service life can be found. The results of this study show that target reliability indices for commercial quay walls determined by economic optimisation are a little higher, and hence prevail compared to reliability indices derived using the LQI acceptance criterion (Table 7) and the IRPA acceptance criterion (Table 6). In the event of a new quay wall, the optimal annual reliability target equals 3.4. Due to corrosion for instance, the reliability level of the quay wall will in time decreases. When the annual reliability target is lower than 2.7 it is highly recommended to repair the structure. However, once the decision is made to repair the structure the optimal annual reliability target for an efficient upgrade is 3.3.

Table 7. Overview annual target reliability indices for the structural limit state Z_{yield} in the event of new commercial quay walls, repairs and disapproval

	New	**Repairs**	**Disapproval**
β^*	3.4^1	3.3^2	2.7^2
β_{LQI}	3.3^1	3.1^2	2.6^2

1) This reliability index is related to the first year of the reference period.

2) Due to scenario III this reliability index is related to the final year of the reference period.

In this section, the target reliability indices were derived from different risk perspectives in order to compare them with the annual target reliability indices related to the consequence classes in ISO 2394 (2015). Economic optimisation was found to be the governing criterion for consequence class A, B and C (Table 8). It should, however, be noted that the marginal lifesaving cost principle was taken into account in the determination of total failure costs. Since the societal costs will become dominant in case of class C and D rather small differences between the LQI acceptance criterion and reliability indices found on the basis of economic optimisation. The relatively high societal costs also lead to fairly high reliability requirements of disapproval for class D. In addition, Table 8 generally 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 with ‘medium’ relative costs of safety measures. It is worth noting that the recommended target reliability indices are assigned to limit states of structural components and that the target reliability indices found are only valid if progressive failure is mitigated (Janssen, 2012; De Gijt & Broeken, 2013). It seems that reliability indices in accordance with the LQI acceptance criterion are a little lower than the target reliability indices derived by economic optimization for most of the commercial quay walls in class A and B. Although undoubtedly not all types of quay walls are covered, the examples listed in Table 9 will serve as a useful reference for categorising quay wall types for each consequence class (Roubos, 2019).

Table 8. Annual target reliability indices for different consequences classes of quay walls.

Criterion	**Consequence class**			
	A	**B**	**C**	**D**
	Low	**Some**	**Cons.**	**High**
$N_{F\mid f}$	**<1**	**<5**	**<50**	**<500**
C_f	**<€8m**	**<€50m**	**<€200m**	**<€1500m**
ISO 2394[1]				
Large[2]	-	3.1	*3.3*	*3.7*
Medium[2]	-	3.7	*4.2*	*4.4*
Small[2]	-	4.2	*4.4*	*4.7*
New[3]				
β^*	3.4	3.8	4.1	4.5
β_{LQI}	3.2	3.6	4.1	4.5
Repair[4]				
β^*	3.3	3.8	4.1	4.6

β_{LQI}	2.9	3.4	4.0	4.6
Disapproval[5]				
β^*	2.7	3.2	3.6	4.1
β_{LQI}	2.4	2.9	3.5	4.1
Individual risk acceptance criterion				
$IRPA=10^{-6}$	2.8	3.3	3.7	n/a
$IRPA=10^{-5}$	1.9	2.5	3.1	n/a
$LIRA=10^{-6}$	n/a	n/a	n/a	4.3[4]
$LIRA=10^{-5}$	n/a	n/a	n/a	3.4[4]

1) Target reliability indices are based on economic optimisation.

2) Relative costs of safety measures.

3) Input variables t_{survive}=0, t_{ref}=50, L_{eq}=40, C_0=€600k, C_m=€100k and STWP=3M€ (Roubos et al., 2018a).

4) Input variables for repairs t_{survive}=50, t_{ref}= $t_{\mathrm{remaining}}$=25, C_0=€200k, C_m=€200k €, and STWP=3M€.

5) This criterion is only active at a hazardous site/project location.

Table 9. Examples of quay wall types for the consequence classes of Table 8.

Class	**Examples of quay wall types**
A	Soil-retaining walls where the risk of fatalities is negligible or very low; quay walls are part of a terminal or port with functional redundancy.
B	Quay walls are part of a terminal or port without functional redundancy.
C	Quay walls in urban areas.
D	Quay walls for which failure will lead to the failure of other structures, such as chemical or power plants; soil-retaining walls that are part of secondary flood defence systems or dams; quay walls needed for recovery after earthquake damage or tsunamis; quay walls that facilitate cruise ships.
E	Soil-retaining walls that are part of a primary flood defence system, major dam or important sailing route.

6. Conclusions

The results of this study provided guidance on reliability differentiation for assessing structural limit states of existing commercial quay walls. The most important findings of this study are:

- The target reliability indices for commercial quay walls derived by assessing the IRPA and LQI acceptance criterion are slightly lower than the targets found by economic optimisation. Hence, target reliability indices can be derived on the basis of economic optimisation by accounting for societal failure costs via the marginal lifesaving cost principle.

- The target reliability indices of the structural limit state function seem to be largely influenced by the failure costs as well as the remaining lifetime. In the event of a quay wall equipped with a system of cathodic protection – preventing degradation of steel – the highest failure rates were typically observed in the first year of the remaining lifetime due to past performance, whereas in case of a quay wall subjected to corrosion the failure rate of the final year lifetime prevails. The annual target reliability index found for 'repair' was approximately 3.3 and for 'disapproval' approximately 2.7.

Since reliability methods have become more robust and efficient, it is expected that they will be used more frequently. However, it is quite remarkable that less effort has been put into customising target reliability indices for different types of civil engineering works. Consequently, the results of advanced reliability-based assessments have to be compared with fairly general reliability targets, which were derived predominantly for buildings. It is therefore recommended that design codes and standards, such as ISO 2394 (2015) and the Eurocodes (NEN-EN 1990, 2011), be improved in order to allocate appropriate reliability targets for quay walls and other civil engineering works.

Furthermore, in literature it is often not very clear whether targets are assigned to the structure as a whole or to structural components (Roubos, 2019). Since quay-wall systems are fairly long structures, it is recommended that that the safety costs and failure consequences as well as the model used to estimate the probability of failure all relate to the same failure event (Fischer et al., 2019). Consequently, the methods used can be used in evaluating structural components as well as the quay-wall system as a whole. However, quay walls that are part of a larger system, such as a primary flood-defence system or have multiple equal failure modes, should take account of the length effect (Janssen, 2012; STOWA, 2011; TAW, 2003) in the assessment of system reliability.

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Appendix A. Assessment criteria for classification

Table 10. Assessment criteria for each consequence class

Description	**Consequence class**				
	A	**B**	**C**	**D**	**E**
Qualitative	Negligible/ low	Some	Considerable	High	Very high

Human safety					
- Number of fatalities (ISO 2394, 2015)	$N \leq 1$	$N \leq 5$	$N \leq 50$	$N \leq 500$	$N > 500$
- Degree of warning (ASCE, 2016; DNV, 1992)	Progression of failure is not possible and people at risk are able to escape in time.	Redundant structural response and progression of failure is mitigated and failure is not sudden providing adequate warning signals.	Progression of failure is mitigated, but failure is sudden without providing warning signals.	Widespread progression of damage is likely to occur and failure is sudden without providing warning signals.	Widespread progression, induced by unexpected and sudden environmental disasters, is possible.
- Social and environmental repercussion index (ROM 0.0, 2002)	SERI ≤ 5	SERI ≤ 15	SERI ≤ 25	SERI ≤ 30	SERI > 30
Economic					
- Description (ISO 2394, 2015)	Predominantly insignificant material damages.	Material damages **and** functionality losses of significance for owners and operators **and** low or no social impact.	Material losses **and** functionality losses of societal significance, causing regional disruptions **and** delays in important societal services over several weeks.	Disastrous events causing severe losses of societal services **and** disruptions **and** delays at national scale over periods in the order of months.	Catastrophic events causing losses of societal services **and** disruptions **and** delays beyond national scale over periods in the order of years.
- Accessibility (Ligtvoet & Lei, 2012).	Very little hindrance to shipping, railway transport, pipeline systems	Small consequences for availability of navigation channels,	Short period of barricade with regard to navigation channels, railways, roads or	Damage to navigation channels, railways, roads or pipeline corridors.	Loss of main navigation channels, railways, roads or pipeline

	(Very short period, less than one day).	railways, roads or pipeline corridors. (Barricade measures for a period of one day).	pipeline corridors. (The availability is lower for a period of one week)	(The availability is lower for a period of weeks)	corridors. (Main transport routes are unavailable for a period of months)
-Ratio between direct and construction costs (JCSS ,2001)	≤1	≤2	≤5	≤10	>10
-Failure costs C_f (Roubos et al.,2018a)	<€8m	<€50m	<€200m	<€1500m	>€1500m
Environmental (ISO 2394, 2015)	Damages to the qualities of the environment of an order that can be restored completely in a matter of days.	Damages to the qualities of the environment of an order that can be restored completely in a matter of weeks.	Damages to the qualities of the environment limited to the surroundings of the failure event and that can be restored in a matter of weeks.	Significant damages to the qualities of the environment contained at national scale but spreading significantly beyond the surroundings of the failure event and that can only be partly restored in a matter of months.	Significant damages to the qualities of the environment spreading significantly beyond the national scale and that can only be partly restored in a matter of years to decades.
Reputation (Ligtvoet & Lei, 2012)	No negative attention in media and no damage to the image of the port.	Very short period of negative attention in local, regional and national media (>1 day).	Short and limited period of negative attention in local, regional and national media (>2	Period of negative attention in local, regional and national media (>week), Serious	Long period of negative attention in local, regional and national media (>month). Very

	Serious concerns among people living in the vicinity, local government, national government or external clients. Damage to image of a few stakeholders.	days). Serious concerns among people living in the vicinity, local government, national government or external clients. Damage to image of the port for some time.	concerns among people living in the vicinity, local government, national government or external clients. Damage to image of the port for some time.	serious concerns among people living in the vicinity, local government, national government or external clients. Permanent damage to image of the port.

Appendix B. Distribution functions and coefficient of variation of stochastic variables.

Table 11. Type of distribution and coefficient of variation used in the Blum-based reliability assessment (Roubos et al., 2019; Roubos, 2019)

Design parameter	Time-dependent	SI	X_k	μ	Distribution	V
Unit weight of soil γ_{sat}					Normal	0.05
- Backfill	No	kN/m^3	20.0	20.0		
- Reclamation sand	No	kN/m^3	20.0	20.0		
- Holocene sand	No	kN/m^3	20.0	20.0		
- Clay layer	No	kN/m^3	17.0	17.0		
- Pleistocene sand	No	kN/m^3	20.0	20.0		
Friction angle φ'_{rep}					Normal	0.10[2]
- Backfill	No	°	32.5	38.9		
- Reclamation sand	No	°	30.0	35.9		
- Holocene sand	No	°	30.0	35.9		
- Clay layer	No	°	22.5	26.9		
- Pleistocene sand	No	°	32.5	38.9		
Cohesion c'	No	kPa	5.0	6.9	Lognormal	0.20
Yield strength f_y	No	N/mm^2	485	510	Lognormal	0.07
Tube diameter D_{tube}	No	m	1.067	1.067	Normal	0.05[1]

Wall thickness t_{tube}	No	m	0.15	0.15	Uniform	0.05[1]
Corrosion Δt_{eq}	Yes	m	n/a	variable[3]	Normal	0.50
Outer water level (h_{OWL})	Yes	m	-0.84[4]	-0.84	Gumbel	0.20 m[5]
Ground water level (h_{GWL})	Yes	m	-0.34[4]	-0.34	Gumbel	0.25 m[5]
Annual maximum load Q_{t1}	Yes	kN/m^2	n/a	72.1	Gumbel	0.14
Lifetime maximum load Q_{t50}	n/a	kN/m^2	100	104.8	Gumbel	0.10

[1]) Based on production and execution tolerances, as well as project-specific acceptance criteria in the port of Rotterdam.

[2]) By analogy with NEN-EN 1997 (2004), considered at 5% strain rate (Huijzer & Hannink, 1995).

[3]) Depends on the selected corrosion curve.

[4]) Outer water level is based on low low water at spring tide (LLWS); the groundwater level depends on the position of the drainage system. Water loads were considered as non-dominant loads, in accordance with the design report.

[5]) Geometrical standard deviation Δ_a based on the water-level measurements.