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Target reliability indices for existing quay walls derived on the basis of the LQI criterion

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ABSTRACT: General frameworks for reliability differentiation have evolved over time and are mainly developed for new buildings. However, recommendations for 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 Life Quality Index criterion (LQI). 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 development of the probability of failure was taken into consideration in this study, because this affects the present value of future failure costs and the associated target reliability indices. The reliability indices obtained in accordance with the LQI acceptance criterion were a little lower than the target reliability indices derived by economic optimization. The target reliability indices obtained for existing quay walls depend on the consequences of failure and the remaining service life. If failure modes of a quay wall are largely time-invariant and already survived the first period of the service life, the residual probability of failure is lower for an existing quay wall compared to a new quay wall. Hence, this should be considered in the determination of target reliability indices. The method of approach to assess the development of reliability over time can also be used for evaluating target reliability indices of other civil and geotechnical structures.

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 ISO2394 (2015), EN1990 (2011) and JCSS (2001). In the Netherlands the reliability differentiation of EN1990 is directly applied to the design of quay walls (Gijt & Broeken, 2013).

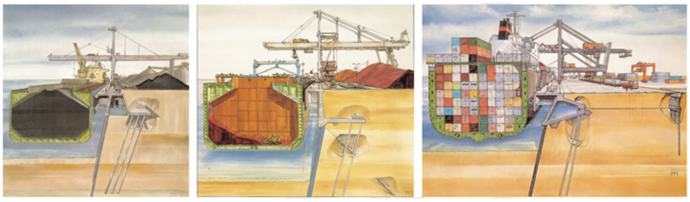

Figure 1. Typical quay walls in the port of Rotterdam (Gijt & Broeken, 2013) copyright Port of Rotterdam Authority.

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:

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

In practice, target reliability indices are often derived by calibrating with previous design methods in order to maintain an existing reliability level (Böckmann & Grünberg, 2009). 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). However, 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, 2018). Another method used establishes target reliability indices on the basis of economic optimisation by minimising costs. Rackwitz (2000) showed that the reliability optimum is largely influenced by marginal costs of safety measures and consequences of failure and formed the basis for the recommended target reliability indices in ISO 2394. However, target reliability indices derived on the basis of economic optimisation might not be acceptable with regard to requirements concerning human safety. When many people are at risk, safety requirements, often expressed by annual failure rates, will determine the acceptable reliability level (Steenbergen, et al, 2015). Detailed overviews of available methods for quantitative risk measures of loss of live and accompanying thresholds are given by Jonkman et al. (2003) and Bhattacharya et al. (2001). Minimum annual reliability indices for ultimate limit states on the basis of the LQI criterion were derived by Fischer et al. (2012) and are implemented in ISO 2394 (2015), the standard describing the general principles on reliability for structures. ISO 2394 recommends to employ the 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) the LQI acceptance criterion is defined in terms of the acceptable reliability:

$$-\frac{\partial \mathrm{P_f}\left(\beta_{\mathrm{acc;t_1}}\right)}{\partial \beta} \leq \frac{\mathrm{C_1}\left(\gamma_{\mathrm{s}}+\omega\right)}{\mathrm{SWTP}\cdot \mathrm{N_{F|f}}} \tag{2}$$

where C_1 = marginal costs associated with a considered safety measure; SWTP =Social willingness to pay; γ_s = Societal discount rate; ω = annual rate of obsolescence (lifetime buy vs design refresh); $N_{F|f}$ = expected number of fatalities given failure.

For assessing existing structures ISO 13822 and NEN 8700 specify other acceptable reliability indices recommending specific target reliabilities for 'renewal', 'repair' and minimum values for 'disapproval'. The recommendations of NEN 8700 were adopted in the handbook 'Urban quay walls' (Roubos & Grotegoed, 2014).

1.1 *Objective*

This study aims to provide guidance to code developers and engineers on deriving target reliability indices for assessing existing quay walls using the LQI acceptance criterion. The reliability optimum associated with 'repair works' was examined by economic optimisation on the basis of cost-minimisation. Subsequently, the reliability index for 'disapproval' of an existing quay wall was derived by an risk-based assessment using the LQI criterion. In quay wall design the dominant stochastic design variables are largely time-independent, such as retaining height, soil strength and material properties, which influence the annual failure rate. Hence, a detailed Monte Carlo analysis was performed in combination with the analytical method of Blum (1930) to determine the development of the annual probability of failure. The minimum requirements concerning human safety were examined on the basis of the LQI acceptance criterion. 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 METHODS

2.1 *Introduction*

This section briefly discusses the methods used to establish reliability indices for existing structures using the LQI acceptance criterion. Firstly the reliability optimum and minimum threshold for 'repair' (Fig. 2A) were derived by using the same principles as for 'renewal'. The target reliability index β^*_{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. 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 $\beta_{acc;repair}$ - was derived on the basis of the LQI acceptance criterion (Fig. 2B).

In this paper the reliability minimum below which the structural member is insufficiently safe and should be upgraded 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 repair works (Fig. 2A) – are equal to the actual residual capitalised risk of the scenario 'doing nothing' (Fig. 2B) the reliability threshold for assessing 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 (Fig. 2B). This is further explained in Section 2.4.

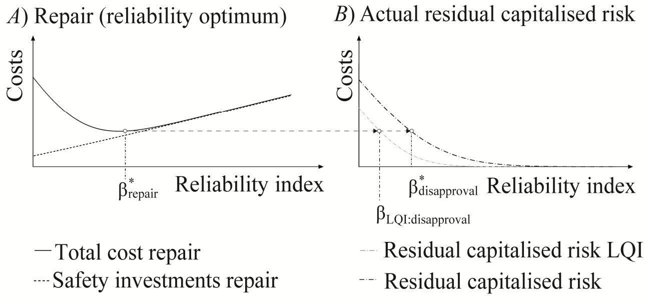

Figure 1: Comparison of the residual risk of the existing structure (right) with the total costs – summation construction costs and associated capitalized risk - after repairing the existing structure (left).

2.2 *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.

$$Z_{STR} = f_y - \left(\frac{M_{wall}}{M_{wall}} + \frac{N_{tube}}{A_{tube}}\right) \quad (3)$$

where, Z_{STR} = structural limit state function; f_y = yield strength of retaining wall; M_{wall} =bending moment in retaining wall; N_{tube} = normal force in tube; W_{wall} = section modules of retaining wall; A_{tube} = section area of tube.

The ultimate limit state for structural failure represents the stresses in the outer fibre of the soil-retaining wall. The limit state function was evaluated by coupling the Monte Carlo method to the analytical method of Blum.

If no system of kathodic 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 the quay walls in the port. It should be noted that different corrosion zones are distinguished over the height of the soil-retaining wall. In this study the ‘Permanent immersion’ zone was of interest, because the stresses in the outer fibre are fairly high just above the harbour bottom.

The stochastic model parameters considered in this study are listed in Table 1. For detailed information about the distribution types the reader is referred to Allaix et al (2017) and Roubos et al. (2018).

Table 1: Input variables probability analysis

Design parameter	**Symbol**	**Distribution**	**CoV**
Unit weight of soil	γ_{sat}	Normal	0.05
Soil strength	Φ	Normal	0.10
Yield strength	f_y	Lognormal	0.07
Tube diameter	D	Normal	0.01
Wall-thickness	T	Uniform	0.05
Live load	Q	Gumbel	0.20

In this study 2D-Blum calculations were performed. However, those calculations represent only a certain distance along a quay wall due to spatial uncertainty in resistance and loads (Roubos et al, 2018). Hence, the length of a quay wall was therefore subdivided into equivalent sections for which failure events are independent. The associated proportional change in marginal safety costs and failure consequences (Section 2.4) 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 two limit states under consideration was approximately 25-50m. In the calculations performed in this study L_{eq} was assumed to be equal to 40m.

2.3 *Modelling time-variant reliability*

The risk profile of a quay wall evolves over time. This section discusses the method used to model the marginal increase 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 kathodic protection will decrease during the first period of service. A system of kathodic protection prevents deterioration of the steel construction components. Due to corrosion induced degradation the annual probability of failure tends to increase (Fig. 3).

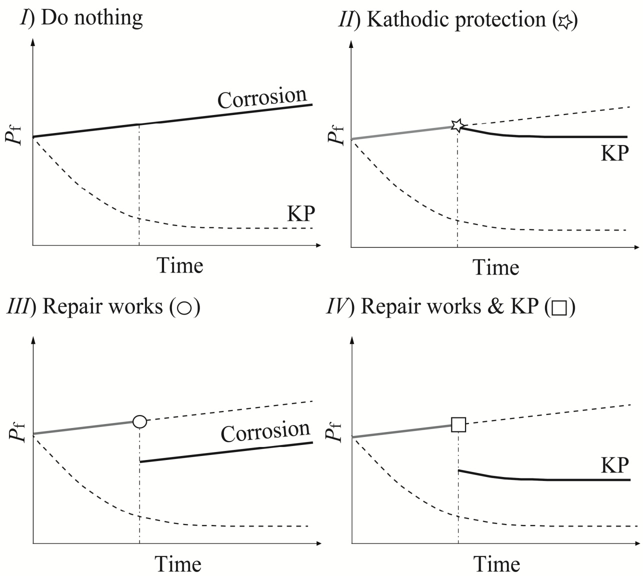

Figure 3: Development probability of failure over time for different scenarios.

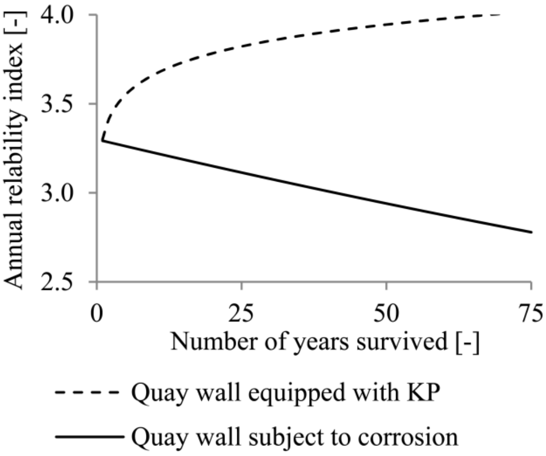

Figure 4: Development annual reliability index over time for a quay wall equipped and without a system of kathodic protection (KP)

Fig. 4 shows that if a quay wall has survived a certain time period, the annual probability of failure will decrease with time if a system of kathodic protection is installed. However, if no measures are taken the annual failure rate will increase with time, due to corrosion. The development of the annual failure probability was examined for different scenarios using the analytical method developed by Blum. The probability of failure of year *i* was defined as the probability that failure occurs during year *i*, given that the structure survived the previous period $t_{survive}$.

$$P_{f;\text{year } i} = P\left(F_i \mid \bar{F}_1 \cap \bar{F}_2 \cap .... \cap \bar{F}_{i-1}\right) \tag{4}$$

where: F_i = the event of failure during year *i*; (F_1, F_2, .. 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. Hence, in total approximately 1.5 milliard 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.

2.4 *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 repair works of existing structures β^*_{repair} were derived minimising the following 'total cost' function:

$$\min\{C_{\text{Total}} = C_{\text{Investments}} + C_{\text{CapitalisedRisk}}\} \tag{5}$$

in which,

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

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

where: $C_{\text{Investments}}$ = investments in safety measures ; $C_{\text{CapitalisedRisk}}$ = present value of future failure costs; β = reliability index/ decision parameter; β^* = optimal reliability index; C_0= initial construction costs independent of the reliability index; C_m = marginal construction cost dependent on the reliability index; $t_{\text{remaining}}$ = remaining lifetime; $P_{f;n}$ = 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 'renewal' or 'repair works' (Rackwitz, 2000). However, it should be noted that for assessing the reliability minimum – or in other words the 'disapproval' level – of a quay wall this is exactly the opposite: C_0 influence the target reliability index and C_m does not (see Fig 5).

As explained in Section 2.1 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:

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

where, x = a vector representing changes in structural dimensions; L_{eq} = equivalent length along a quay wall for which failure events are independent; ΔC= change in construction costs; $\Delta\beta$ = change in reliability index.

The fraction ΔC/Δβ 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. (2018).

Table 2: Initial and marginal construction costs for L_{eq} *=40m*

Scenario	**C_0**	**C_m**
Renewal	€360k	€60k
I) Do nothing	n.a.	n.a.
II) Prevention of corrosion (KP)	€50k	n.a.
III) Repair works	€100k	€120k
IV) Repair works & prevention (KP)	€150k	€120k

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. Detailed information about the direct and indirect costs associated with failure can be found in Allaix et al. (2017) and Roubos et al. (2018). The economic consequences of a structural failure (Z_{STR}<0) are in the range of €1-5m.

Studying the background documents of the LQI target reliabilities (Fischer, 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., 2018). The corresponding present value of societal losses, denoted by $C_{f;\text{Societal}}$, then depends on the SWTP and the expected number of fatalities $N_{F|f}$ and is used in Eq. (7). In this study a conservative estimate $N_{F|f}$ = 1 was taken into consideration.

$$C_{f;Societal} = N_{F|f}\ SWTP \tag{9}$$

where, $C_{f;Societal}$ = societal failure cost;

The monetary value of a human life can be determined on the basis of the Societal Willingness To Pay (ISO 2394, 2015). However to assign a monetary value to human life, on whatever basis, is a very controversial issue (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 ...''. In this study a SWTP of 2-5M$ was assumed for the evaluation of the marginal life saving costs principle / LQI criterion.

3 RESULTS

3.1 *Structural limit state*

This section presents the reliability indices obtained by economic optimisation and assessing the LQI acceptance criterion, which are related to the structural limit state function Z_{STR}. 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 3: Optimal reliability indices for Z_{STR} with t_{ref}=50, r=3%, L_{eq} =40m, C_f =€5m, $C_{f;societal}$=€3m; C_0 =€360k; C_m =€120k.

Renewal	β^*_{new}	$\beta_{LQI;new}$
Annual in year 1	3.4	3.3
Annual in year 50	4.1	4.0
Reference period	2.8	2.6

Table 3 shows that reliability indices in accordance with the LQI acceptance criterion are a little lower than the target reliability indices derived by economic optimization.

If we assume that the quay wall survived a certain time period – being constantly subjected to corrosion – different strategies can be considered, such as installing a system of kathodic protection (scenario II) whether or not in combination with repair works (scenario III and IV). In this section it was assumed that a quay wall had already survived 50 years and was subjected to corrosion. The total service life was estimated at 75 years, and hence the reliability indices found are representative for a reference period of 25 years. Table 4 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 repair works (III and IV). This indicates that repair works are not feasible from an economical perspective. The total costs of installing a system of kathodic protection without repair works (II) seems an interesting risk measure. However, scenario I and II can only be taken into consideration if the remaining probability of failure is acceptable.

Table 4: Reliability indices and associated total costs for different scenrios: I) Do nothing; II) Install KP; III) Repair works; IV) Repair works and KP.

	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
Reference period	1.7	1.9	2.3	2.4
Total costs	€ 155k	€ 150k	€ 190k	€ 220k

If one still considers repairing the quay wall, the best repair strategy is: repairing the quay wall without installing a system of kathodic protection (III). The reliability indices for disapproval depend on the total costs associated with the intended repair works and are listed in Table 5. Similar to the results obtained for 'renewal' 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 5: Reliability indices and total costs of scenarios

	β^*_{repair}	$\beta_{LQI;repair}$	$\beta^*_{disapproval}$	$\beta_{LQI;disapproval}$
Annual in year 50	3.5	3.3	3.3	3.2
Annual in year 75	3.3	3.1	3.4	3.2
Reference period	2.3	2.1	2.4	2.1

3.2 *Sensitivity analysis*

The sensitivity analysis performed in this study aims to provide insight into the extent to which target reliability indices related to 'repair works' 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 (Fig. 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 probability of failure in the final year of the reference period, because due to corrosion these indices are governing. The reference period equals 25 years except for the analysis in Fig. 5E in which the reference period is equal to the remaining lifetime. In contrast to the target reliability indices for 'repair', the target reliability indices for 'disapproval' are slightly influenced by the initial construction costs C_0 of the intended repair works (Fig. 5A), but are not influenced by the marginal safety investments C_m of these repair works (Fig. 5B). In the case 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 (Fig. 5C). The absolute value of the failure costs C_f significantly influence the target reliability indices

(Fig. 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.

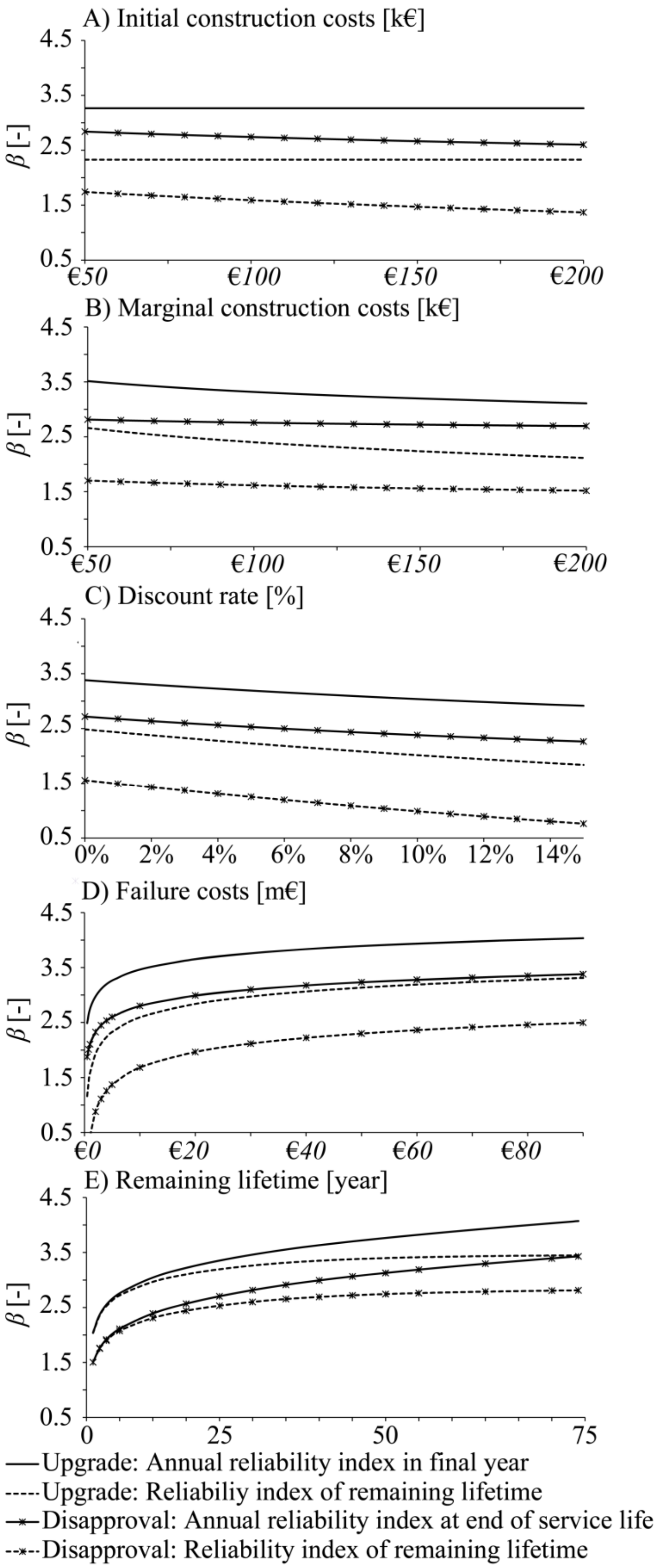

Figure 5: Sensitivity analysis ‘repair’and ‘upgrade’ for Z_{STR} of scenario III. The reference calculation is based on: t_{ref}=25; $t_{survive}$=50; r=3%; L_{eq} =40m; C_0 =€100k; C_m =€120k; C_f =€5m.

4 DISCUSSION

The results of this study show that target reliability indices for commercial quay walls determined by economic optimisation are a little higher, and hence governing compared to reliability indices derived using the LQI acceptance criterion (Table 6). However, it should be noted that not all risk-acceptance criteria with respect to human safety – such as individual risk and societal risk – are taken into consideration in this study.

Table 6: Overview risk-based optimal and acceptable reliability indices for Z_{STR} in case of new commercial quay walls, repair works and disapproval

	New		**Repair**		**Disapproval**	
	$\boldsymbol{\beta_{1year}}$	$\boldsymbol{\beta_{tref}}$	$\boldsymbol{\beta_{1year}}$	$\boldsymbol{\beta_{tref}}$	$\boldsymbol{\beta_{1year}}$	$\boldsymbol{\beta_{tref}}$
β^*	3.4^1	2.8	3.3^2	2.3	2.7^2	1.6
β_{LQI}	3.3^1	2.6	3.1^2	2.1	2.6^2	1.3

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.

The influence of the parameters used, such as discount rate, marginal safety investments, failure consequences, was evaluated by a sensitivity analysis (Section 3.2). The target reliability indices derived from economic optimisation and the LQI criterion were determined for different consequences of failure, in order to compare the results with the recommendations in codes and standards. Economic optimisation was found to be the governing criterion for consequence class A, B and C (Table 7 and Table 8). However, it should be noted that the marginal live saving cost principle was taken into account in the determination of total failure costs. Hence, the societal costs will become dominant in case of class C and D explaining the fairly small differences in reliability indices found. Table 7 also shows that the recommended annual target reliability indices for new quay walls are in the range of the guidance of ISO2394 (2015) and seem to correspond with ‘medium’ relative costs of safety measures, whereas Table 8 shows that the associated lifetime reliability indices for ‘repair works’ as well as in case of ‘disapproval’ are well in line with the recommended values of NEN 8700 (2012). 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), (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.

Table 7: Annual target reliability indices for different consequences classes of quay walls.

Criterion	**Consequence class**			
	A	**B**	**C**	**D**
	Low	**Some**	**Cons.**	**High**
$N_{F\|f}$	**<1**	**<5**	**<50**	**<500**
C_f	**<€8m**	**<€50m**	**<€200m**	**<€1500m**
ISO2394				
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]				
β^*	3.4	3.8	4.1	4.5
β_{LQI}	3.2	3.6	4.1	4.5
Repair[3]				
β^*	3.3	3.8	4.1	4.6
β_{LQI}	2.9	3.4	4.0	4.6
Disapproval[4]				
β^*	2.7	3.2	3.6	4.1
β_{LQI}	2.4	2.9	3.5	4.1

[1] Relative costs of safety measures

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

[3] Input variables for repair works $t_{survive}$=50, t_{ref}= $t_{remaining}$=25, C_0=€200k, C_m=€200k €, and STWP=3M€

[4] It should be noted that other criterions, such as the *IR* criterion and *SR* criterion could lead to higher reliability indices.

Table 8: Remaining lifetime target reliability indices for different consequences classes of quay walls.

Criterion	**Consequence class**			
	A	**B**	**C**	**D**
	Low	**Some**	**Cons.**	**High**
$N_{F\|f}$	**<1**	**<5**	**<50**	**<500**
C_f	**<€8m**	**<€50m**	**<€200m**	**<€1500m**
EN 1990/ NEN 8700				
Renewal	-	3.3	*3.8*	*4.3*
Repair	-	2.8	*3.3*	*3.8*
Disapproval	-	1.8	*2.5*	*3.3*
New[1]				
β^*	2.8	3.3	3.7	4.2
β_{LQI}	2.4	3.0	3.6	4.2
Repair[2]				
β^*	2.3	3.0	3.4	3.9
β_{LQI}	1.9	2.6	3.3	3.9
Disapproval[3]				
β^*	1.5	2.3	2.8	3.4
β_{LQI}	1.0	1.8	2.7	3.4

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

[2] Input variables for repair works $t_{survive}$=50, t_{ref}= $t_{remaining}$=25, C_0=€200k, C_m=€200k €, and STWP=3M€

[3] It should be noted that other criterions, such as the *IR* criterion and *SR* criterion could lead to higher reliability indices.

5 CONCLUSIONS

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

- The target reliability indices derived by assessing the LQI acceptance criterion were 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 using 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 service life. In case of a quay wall equipped with a system of kathodic protection – preventing degradation of steel – the first year of the remaining service life determines the annual target reliability index, whereas in case of a quay wall subjected to corrosion the final year of the reference period is of interest. The annual target reliability index found for ‘repair’ was approximately 3.3 and for ‘disapproval’ approximately 2.7. The associated remaining lifetime target reliability indices for ‘repair’ and ‘disapproval’ with a remaining lifetime of 25 years were approximately 2.3 and 1.6, respectively.
- The annual and lifetime reliability indices found are in the range of the guidance in ISO 2394, EN1990 and NEN 8700.

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