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Relationship between the construction costs and the reliability index of quay walls

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Abstract. Structures, such as quay walls, have to meet a particular level of safety. Consequently, in the Eurocode standards, three reliability classes are distinguished, each corresponding to a target reliability index and set of partial factors. In this study, more insight is acquired into the relationship between the quay wall's construction costs and the associated reliability index β . It appeared that the marginal costs of safety investments of quay walls are fairly low and in the same order of magnitude of the uncertainty of the estimate of the construction costs. Hence, it seems that the current reliability classes, as defined in the Eurocode standards, are non-efficient for quay walls. In addition, this study investigates the influence of the partial factors and three failure mechanisms on the construction costs and the reliability index. It was concluded that for the considered cases, the soil's angle of internal friction strongly influences the construction costs and the β of the quay wall. Furthermore, it follows that economic optimisation in the probabilistic design of quay walls is possible by increasing the target reliability index of the failure mechanism 'insufficient passive soil resistance' and decrease the target reliability index of 'yielding of sheet pile profile'.

1. Introduction

Ports are essential for international maritime transport, handling over 80 per cent of the global trade by volume [1]. Accommodating vessels in ports several types of structures can be used, such as quay walls, wharves, jetties or dolphins for instance. In this respect, quay walls are used very commonly. In the Netherlands, a considerable number of kilometres of quay walls have been built already. Structures, such as quay walls, have to meet a target reliability level. Consequently, in the Eurocode standard EN 1990 [2], three reliability classes (RC) are introduced based on the potential consequence of failure of the structure (table 1). For each of these reliability classes, the maximum tolerable probability of failure is defined, corresponding to a target reliability index (β). The target reliability index determines for each of the reliability classes a set of partial factors, which are defined in the National Annexes of the Eurocode standards. The partial factors defined in the Dutch National Annex [3] and CUR 211 [4] act on the loads, the material characteristics and the geometrical variables of the design.

Generally, quay walls are designed in a semi-probabilistic manner according to one of these reliability classes, using the corresponding set of partial factors. Roubos et al. [5] suggest that the



marginal costs of safety investments for quay walls are fairly low. It is therefore questionable whether the current reliability classes and the corresponding set of partial factors are efficient for quay walls. This gave rise to the present study.

Table 1. Consequence and reliability classes for civil engineering works as defined in EN 1990 [2].

Consequence/ Reliability Class	Description		Examples	Reliability index β_{t50}
	Consequence with respect to loss of human lives	Economic, social and environmental consequences		
CC1/RC1	Low	Small or negligible	Agriculture building where people do not normally enter (e.g. depositories or greenhouses)	3.3
CC2/RC2	Moderate	Considerable	Home and office buildings, public buildings with moderate consequences of failure (e.g. offices)	3.8
CC3/RC3	High	Very large	Tribunes, public building where the consequences of failure are high (e.g. concert halls)	4.3

1.1. Objective of this article

The objective of this article is to present the acquired insight into the relationship between the construction costs and the reliability index β of quay walls. The relationship between the construction costs and the reliability index β is determined by the marginal costs of safety investments of quay walls, given specific functionality and boundary conditions of a quay wall. The most important factors of the marginal costs of safety investments are the partial factors. Therefore, the influence of the partial factors on the construction costs and on the reliability index β is estimated afterwards. Eventually, the influence of three of the critical failure mechanisms on the construction costs is evaluated as well.

1.2. Scope and limitations

This study mainly focusses on frequently applied types of quay walls in the Port of Rotterdam:

- A double anchored combi-wall;
- A combi-wall with a relieving platform.

The considered double anchored combi-wall has a retaining height of about 17 m and is located in the Waalhaven of the Port of Rotterdam. The combi-wall equipped with a relieving platform has a retaining height of about 24 m and is located on Maasvlakte 1 of the Port of Rotterdam. In figure 1 the double anchored combi-wall is depicted, next to the combi-wall with a relieving platform in figure 2.

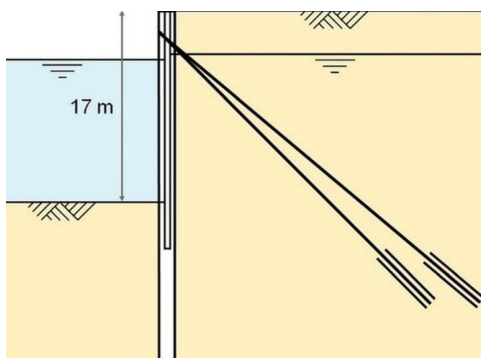


Figure 1. Double anchored combi-wall.

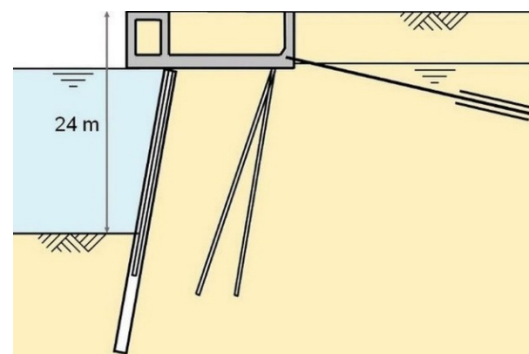


Figure 2. Combi-wall with a relieving platform.

Reliability calculations are performed for the double anchored combi-wall since the estimated β 's are fairly high (≥ 7); this is because the investigated failure mechanisms are not governing. The critical variables of the considered failure mechanisms and the present governing failure mechanisms are equal. It is therefore expected, that the influences of the considered failure mechanisms on the construction costs will be comparable when they are governing. However, this is still uncertain.

2. Methodology

For both quay walls, figure 3 shows the research steps. Firstly, the two quay walls were designed in accordance with RC1, RC2 and RC3 based on the starting points and design principles, using the subgrade reaction method for the double anchored combi-wall and using the Finite Element Method (FEM) for the combi-wall with a relieving platform. The subgrade reaction method is based on the principle that the soil is schematised by a system of uncoupled springs. For this approach the software package D-Sheet Piling was used. The FEM divides the structure in a finite number of small elements, which are interconnected by nodes. The partial differential equations that describe the constitutive relations, are discretized and approximated in the nodes. This finally results in displacements and stresses for the entire considered structure. For this approach the software package Plaxis 2D was used. Both quay walls have been designed in accordance with the Handbook of quay walls, CUR 211 [4] and the Eurocode standard for geotechnical structures, NEN-EN 9997-1 [3]. In these codes design approach 3 was used. Here the partial factors were applied to the load or the load effects and to the soil properties.

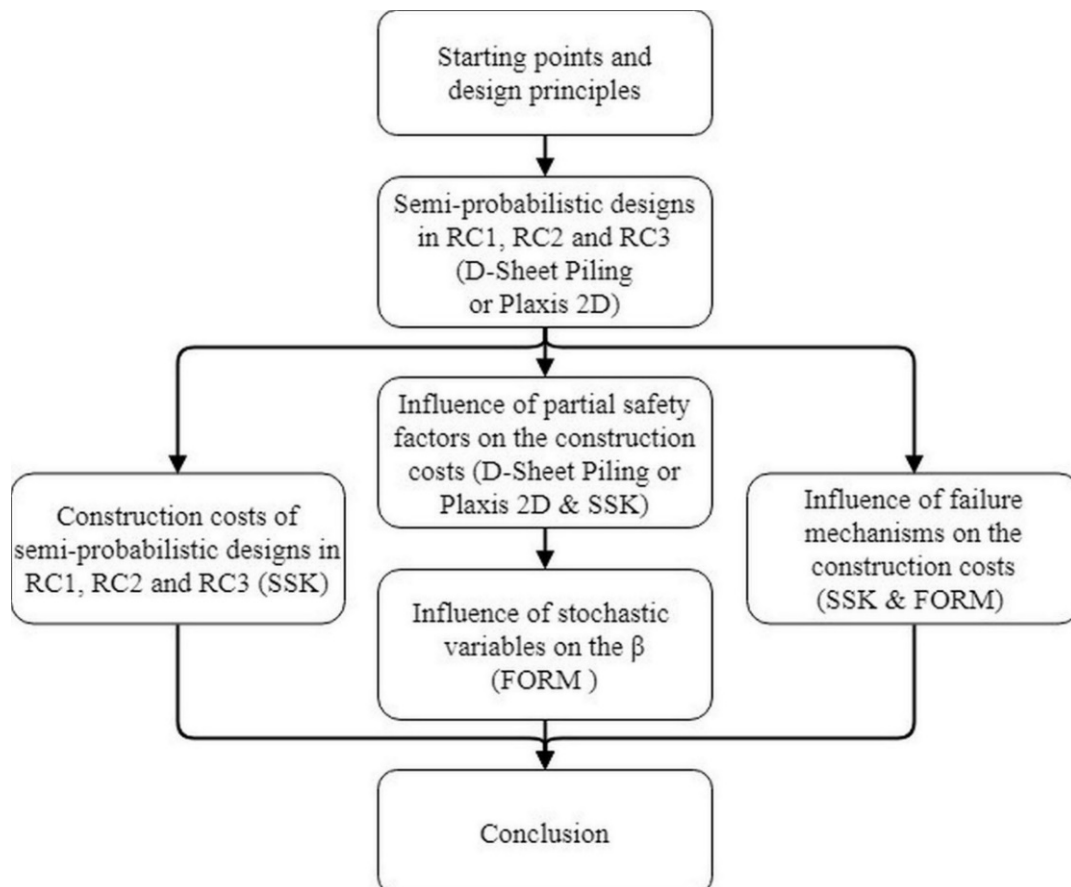


Figure 3. Flow diagram of research steps.

Thereafter, the construction costs for these semi-probabilistic designs were determined in a deterministic manner. The direct construction costs of the quay wall and the cost influenced by the reliability class were considered. The costs were estimated using a standard cost estimate system (SSK-

method), which is widely used in the Netherlands. With this methodology the construction cost differences between quay walls designed with a different reliability index β were calculated, together with a first estimate of the relationship between the construction costs and target β -values.

Furthermore, the influences of the partial factors on the construction costs of both quay walls were quantified. These partial factors are defined in the NEN-EN 9997-1 [3] and distinguish the reliability classes. Via a sensitivity analysis, the sensitivity of the construction costs of the quay wall to every partial factor was determined. From this analysis, the influential partial factors concerning the construction costs of quay walls were determined.

For the double anchored combi-wall the reliability calculations were performed for three of the critical failure mechanisms, in order to obtain the importance factors (α) of the stochastic variables. The α -values are a measure of the relative importance of the particular stochastic variable to the reliability index β per failure mechanism. Reliability-based analyses were performed on the basis of the First Order Reliability Method (FORM), while modelling the quay wall using D-Sheet Piling. FORM is a level II reliability method, approximating the probability of failure of designs based on the design point of the limit state function. The design point is the failure point with the highest probability density, so most probably failure occurs in this point [6]. A restriction of the reliability interface of D-Sheet Piling is that correlations between variables cannot be implemented. Furthermore, not all parameters can be modelled stochastically. Finally, model uncertainties are not taken into account. With the help of probabilistic level III methods more reliable results would be produced because the probability of failure could then be calculated more exactly. However, FORM is considered as a good alternative of level III methods because it requires less mathematical computations and generally gains accurate results [6]. Using this software, reliability calculations can be performed for three failure mechanisms, which are collected in table 2.

Table 2. Considered failure mechanisms with their corresponding structural component.

Failure mechanism	Structural component
Insufficient passive soil resistance (GEO)	Length of tubular piles [m]
Yielding of sheet pile profile (STR)	Section modulus of tubular piles [mm^3 / m]
Yielding of anchor rod (STR)	Steel area of anchor rod [mm^2]

In addition, the influence of the three failure mechanisms on the construction costs of the double anchored combi-wall was estimated. First, the influences of the structural components, corresponding to these failure mechanisms, on the construction costs were determined using a sensitivity analysis varying the dimensions of these components. In table 2 also the structural components corresponding to the three considered failure mechanisms are given. For every relevant situation of the sensitivity analysis, the reliability index of the failure mechanisms has been estimated for the double anchored combi-wall using the reliability interface of D-Sheet Piling. The influences of the failure mechanisms on the construction costs were estimated by combining the influences of the structural components on both the construction costs and the reliability index. For the combi-wall with relieving platform, only the influence of the structural components on the construction costs was evaluated.

3. Results

3.1. Semi-probabilistic designs in RC1, RC2 and RC3

When designing the quay walls, the vertical bearing capacity of the tubular piles of the combi-walls has been verified conform NEN-EN 9997-1 [3]. In 2017, this code has reduced the point load bearing capacity with 30%. Initially in this study, the combi-wall with a relieving platform was designed using the pre-2017 verification. Subsequently, the combi-wall was also designed using the post-2016 verification, including the 30% points resistance reduction. In this manner, it was possible to compare both case studies, in order to be consistent with the double anchored combi-wall. In the comparison of

both types of quay walls, the results of the designs using the post-2016 bearing capacity verification were used since this verification is currently in use.

3.2. Construction costs of designs in RC1, RC2 and RC3

This study has estimated the construction costs for the quay walls designed in accordance with the reliability classes RC1, RC2 and RC3. Table 3 shows the results of the construction costs of the semi-probabilistic designs in RC1, RC2 and RC3. In table 3 also the relative increase in construction costs compared to the design in RC1 are given.

Table 3. Construction costs of semi-probabilistic quay wall designs in RC1, RC2 and RC3.

Type of quay wall	Construction costs [€/m]			Relative increase in construction costs compared to RC1 [%]	
	RC1	RC2	RC3	RC2	RC3
Double anchored combi-wall	€ 17,380.-	€ 17,570.-	€ 17,980.-	1.3%	3.7%
Combi-wall with a relieving platform	€ 35,540.-	€ 36,020.-	€ 36,840.-	1.1%	3.4%

From table 3 it follows that the relationship between the construction costs and the reliability target β of both quay walls are generally comparable and the marginal costs of safety investments are relatively low. These differences in construction costs between the reliability classes are in the same order of magnitude of the uncertainty of the estimate of the construction costs. For both quay walls, the construction costs difference increases between the designs in RC2 and RC3, suggests that the relationship between the construction costs and β increases for higher β -values. The increase in construction costs of quay structures in higher reliability classes is dominated by the enlarged diameter and wall thickness of the tubular piles of the combi-wall, mostly due to the local buckling verification of the combi-wall.

The influence of the reliability class on the construction costs can be expressed in the fraction $\Delta C/\Delta\beta_{\text{target}}$, in which ΔC is the relative change in construction costs [%] and $\Delta\beta_{\text{target}}$ the absolute change in target reliability index [-]. Between RC1 and RC2 the fraction $\Delta C/\Delta\beta_{\text{target}}$ is about 2.2-2.7% and between RC2 and RC3 about 4.6-4.7%. These estimated values are significantly lower than the values of about 5-10% suggested by Roubos et al. [5] and Schweckendiek et al. [7]. It is emphasised that the fractions $\Delta C/\Delta\beta_{\text{target}}$ are based on the target β -values as defined in the EN 1990 [2] and these β -values may be different for different designs.

3.3. Influence of partial factors on the construction costs

Through a sensitivity analysis the sensitivity of the construction costs of the quay walls to every partial factor was determined, representing the influence of each factor. The influence of the partial factors on the construction costs can be expressed in the fraction $\Delta C/\Delta\gamma$, in which ΔC is the relative change in construction costs [%] and $\Delta\gamma$ the absolute change in partial factor value [-]. An overview of the fractions $\Delta C/\Delta\gamma$ is given in table 4.

Table 4. Influence of partial factors on the construction costs of quay walls.

Partial factor	γ	$\Delta C/\Delta \gamma$ [%]	
		Double anchored combi-wall	Combi-wall with a relieving platform
Internal friction angle of soil	$\gamma_{\phi'}$	17.8%	45.0%
Cohesion of soil	$\gamma_{c'}$	0.6%	0.3%
Surface load	$\gamma_{Q, \text{surface}}$	5.0%	2.9%
Bollard load	$\gamma_{Q, \text{bollard}}$	0.6%	0.3%
Crane load	$\gamma_{Q, \text{crane}}$	-	1.5%

3.4. Influence of stochastic variables on the β of the double anchored combi-wall

From the reliability calculations importance factors α^2 -values were derived, representing the contribution of the stochastic variables to the reliability index β per failure mechanism. In table 5 the α^2 -values of the stochastic variables are given, which follow from the reliability results of the double anchored combi-wall designed in accordance with RC2. Some stochastic variables can be directly linked to particular partial factors and their influences on the construction costs and on the β are compared below.

From the results of table 4 and table 5 follows that the $\gamma_{\phi'}$ greatly affects the construction costs, just like the internal friction angle of soil ϕ' dominates the contribution to the β of all three failure mechanisms. The influence of the partial load factor $\gamma_{Q, \text{surface}}$ on the construction costs is reasonable, and comparable to the contribution of the surface load to the β of the failure mechanisms ‘yielding of sheet pile profile’ and ‘yielding of anchor rod’. In additionally, material factor for cohesion $\gamma_{c'}$ has a small influence on the construction costs. The same holds for the contribution of c' to the β of the three considered failure mechanisms. It can be concluded that in the initial phase of a quay wall design, the determination of ϕ' strongly influences the construction costs and the β of the quay wall, in contrast to c' . Therefore, geotechnical investigation determining the ϕ' can be very valuable.

Table 5. Contribution of stochastic variables to the β of three failure mechanisms of the anchored combi-wall in RC2. Due to rounding errors, the α^2 -values of the variables together per failure mechanism is not exactly 100%.

Stochastic variable	α^2 [%]		
	Insufficient passive soil resistance	Yielding of sheet pile profile	Yielding of anchor rod
ϕ' [°]	92.2%	78.1%	78.1%
c' [kN/m ²]	1.2%	3.4%	0.3%
Surface load [kN/m ²]	2.2%	10.3%	19.6%
Water level [m NAP]	0.9%	3.1%	1.4%
Surface level [m NAP]	3.2%	5.0%	0.5%

3.5. Influence of failure mechanisms on the construction costs of the double anchored combi-wall

For the double anchored combi-wall the influences of the structural dimensions on the β were estimated and combined with their influences on the construction cost. The influences of the failure mechanisms were found by plotting the reliability results against the relative increase in the construction costs in figure 4. The linear trendlines in figure 4 indicate a first estimate of the influences of the failure mechanisms on the construction costs.

It appeared that the influences of the failure mechanisms ‘insufficient passive soil resistance’ and ‘yielding of anchor rod’ on the construction costs are relatively low. Consequently, the reliability index β of the quay wall can be increased economically by increasing the length of the tubular piles of the combi-wall, the steel sectional area of the anchor rod or the soil strength. Due to these influences, economic optimisation in the probabilistic design of quay walls is possible by increasing the target β of

the failure mechanism ‘insufficient passive soil resistance’ and decrease the target β of ‘yielding of sheet pile profile’.

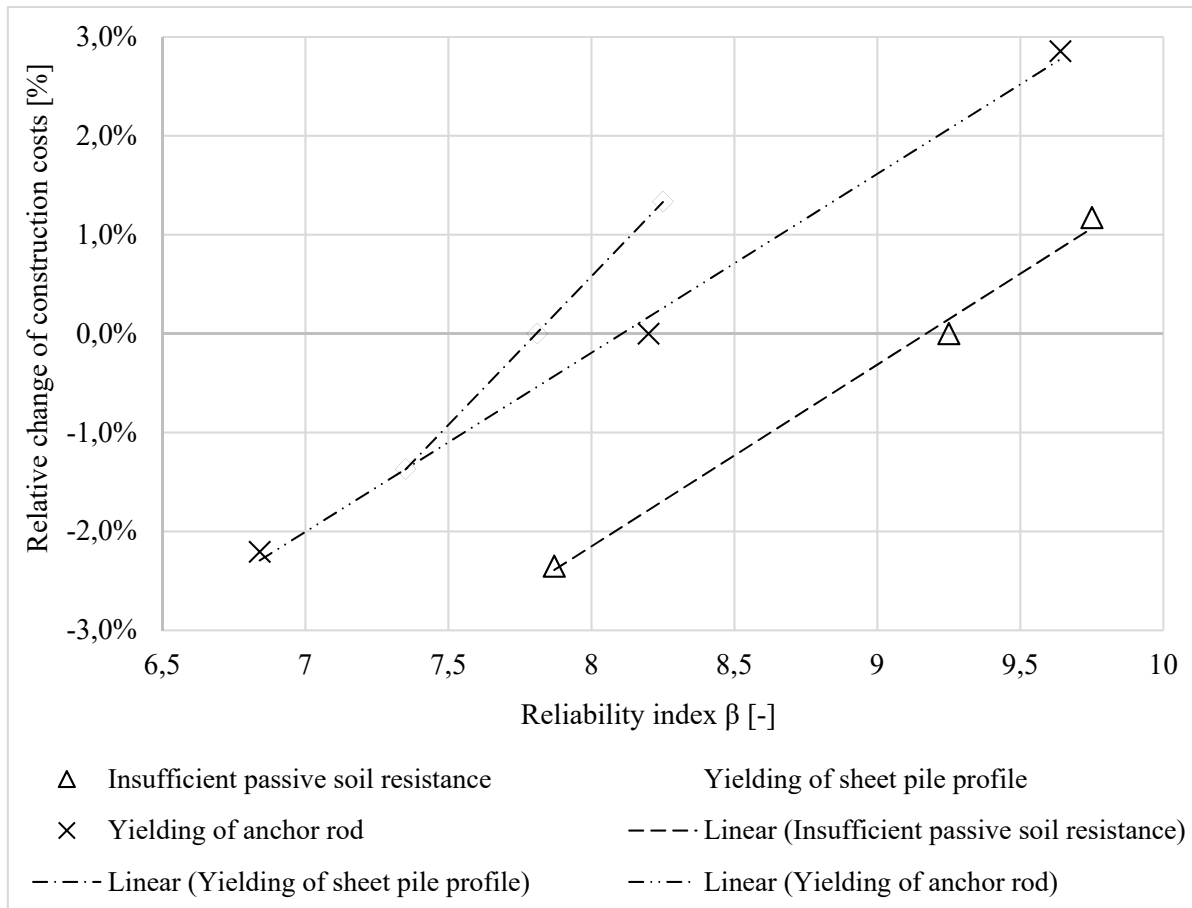


Figure 4. Influence of failure mechanisms on construction costs of the double anchored combi-wall.

4. Conclusion

The results show that the marginal costs of safety investments of quay walls are fairly low. This means that the reliability level of a quay wall can be upgraded with relatively low investment costs. When selecting a reliability class, it is recommended to consider the potential consequences carefully, because the expected benefits considering a lower reliability class, are quite low. Therefore, it can be valuable to select a higher reliability class to prevent potential damage to the reputation of a terminal or port because of failure of the quay wall.

In addition, it followed that the differentiation in construction costs between the reliability classes is about one order of magnitude less than the differentiation of the construction costs of quay walls in practice [8]. This differentiation in construction costs between the reliability classes are in the same order of magnitude of the uncertainty of the estimate of the construction costs. Therefore, it seems that the current reliability classes and the corresponding set of partial factors, as defined in the NEN-EN 9997-1 [3] and CUR 211 [4], are non-efficient for quay walls.

From the reliability results of the double anchored combi-wall followed that the reliability differentiation between the reliability classes in practice is smaller than defined in the EN 1990 [2]. Recent research by Van der Wel [9] and Roubos et al. [10] already suggested that the steps between the current partial factors defined in the NEN-EN 9997-1 [3] are too small. It is questionable whether this current set of partial factors is corresponding to their defined target β -values for RC1 and RC3.

5. Recommendations

In the determination of the construction costs, the influence of the execution classes (EXC) is neglected in this study. Further research would be required into the relationship between the construction costs and the reliability index, considering the influence of the EXC's on the construction costs as well. The EXC's specify a classified set of requirements for the execution of the works related to the quay wall construction. The requirements of the EXC's are specified in order to ensure adequate levels of mechanical resistance and stability, serviceability and durability. Considering the influence of the EXC's on the construction costs will most probably lead to larger differences between the construction costs of the designs in RC2 and RC3.

From the reliability results of this study and recent research by Van der Wel [9] and Roubos et al. [10] followed that the reliability differentiation between the reliability classes in practice is smaller than defined in the EN 1990 [2]. It is questionable whether this current set of partial factors is corresponding to their defined target β -values for RC1 and RC3. The partial factors are validated to their target β of RC2, in contrast to RC1 and RC3. Therefore, it is advised to validate and possibly adjust the partial factors for designs in RC1 and RC3.

The estimated influences of the failure mechanisms on the construction costs do not correspond to the distribution of target β -values between the failure mechanisms, defined in the CUR 211 [4]. Therefore, it is possible that redistribution of the target β -values of the fault tree of the CUR 211 [4], leads to economic optimisation in the probabilistic design of quay walls. In this case, it is possible that the cost of the quay wall decreases, but the overall β of the quay wall remains constant. From this study follows that it is attractive to increase the target β of the failure mechanism 'insufficient passive soil resistance' and decrease the β of 'yielding of sheet pile profile'. Further research would be required in order to determine the optimised target β 's, considering other critical failure mechanisms as well.

The obtained β 's for these failure mechanisms of the double anchored combi-wall are very high (≥ 7) because these failure mechanisms are not governing in the design verifications. In the development of probabilistic design of quay walls, it is essential that reliability calculations can be performed for the governing failure mechanisms; 'insufficient bearing capacity of tubular piles', 'local buckling of combi-wall' and 'soil mechanical failure of anchorage'.

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