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Risk-based target reliability indices for quay walls

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ABSTRACT

Design codes and standards rely on generalised target reliability indices. It is unclear, however, whether these indices are applicable to the specific risk-profile of marine structures. In this study, target reliability indices for quay walls were derived from various risk acceptance criteria, such as economic optimisation, individual risk (*IR*), societal risk (*SR*), the life quality index (*LQI*) and the social and environmental repercussion index (*SERI*). Important stochastic design variables in quay wall design, such as retaining height, soil strength and material properties, are largely time-independent, whereas other design variables are time-dependent. The extent to which a reliability problem is time variant affects the present value of future failure costs and the associated reliability optimum. A method was therefore developed to determine the influence of time-independent variables on the development of failure probability over time. This method can also be used to evaluate target reliability indices of other civil and geotechnical structures. The target reliability indices obtained for quay walls depend on failure consequences and marginal costs of safety investments. The results were used to elaborate the reliability framework of ISO 2394, and associated reliability levels are proposed for various consequence classes. The insights acquired were used to evaluate the acceptable probability of failure for different types of quay walls.

1. Introduction

There are thousands of kilometres of quay wall along inland waterways, in city centres, in commercial port areas and even in flood defence systems throughout the world. The reliability level of quay walls is generally determined in accordance with a certain design code or standard, such as the Eurocode standard EN 1990 [60]. Table 1.1 shows an example of reliability differentiation for buildings by employing a risk-based approach that directly relates the target probability of failure and the associated target reliability index to the consequences of failure. The consequences of failure can take many different forms, such as loss of human lives and social & environmental and economic repercussions [17]. It should be noted that target reliability indices were mainly developed for buildings [102,99] and bridges [85] assuming fully time-variant reliability problems [35,53]. However, the source of aleatory and epistemic uncertainty [50] as well as the consequences of failure could be very different for quay walls in port areas [55].

In the Netherlands, the design handbooks for quay walls [29] and sheet pile walls [42] further elaborated the recommendations of the Eurocode standard, because examples of soil-retaining walls are lacking (Table 1.2).

Table 1.2 suggests that reliability differentiation is influenced to a certain extent by the retaining height of a quay wall. Although the retaining height is an important design parameter, it is not necessarily an assessment criterion for reliability. In port areas, 'danger to life' is fairly low [65] because few people are present and quay walls are ideally designed in such a way that adequate warning is mostly given by visible signs, such as large deformations [25,29]. In reality, however, the factors influencing reliability differ per failure mode [1,43]. Fig. 1 gives an impression of the types of quay walls built in the Port of Rotterdam.

The primary aim of this research was to provide code developers with material to establish target reliability indices for quay walls and similar structures in a substantiated manner. In addition, the secondary aim was that quay walls can be categorized into existing reliability classes by authorities, clients and/or practising engineers. The first part of the research was devoted to examining the reliability optimum by economic optimisation on the basis of cost minimisation. In quay wall

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Table 1.1
Consequence and reliability classes for civil engineering works in EN 1990 [60].

Consequence/Reliability Class	Description	Examples of buildings and civil engineering works	Reliability index	
			β_{t_1} [1]	β_{t50} [1]
CC3/RC3	**High** consequences for loss of human life *or* economic, social or environmental consequences **very great**	Grandstands, public buildings where the consequences of failure are high (e.g. a concert hall)	5.2	4.2
CC2/RC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where the consequences of failure are medium (e.g. an office building)	4.7	3.8[2]
CC1/RC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings and green houses)	4.2	3.3

[1] The annual (β_{t_1}) and lifetime reliability ($\beta_{t_{50}}$) indices only represent the same reliability level if limit state functions are time-dependent.

[2] This value is equal to the mean value derived by calibrating building codes [99].

Table 1.2
Reliability classes for quay walls in accordance with Quay Walls handbook [29].

Consequence/Reliability Class	Description consequences of failure	Examples of quay walls	Reliability index β_{t50}
CC3/RC3	Risk danger to life high Risk of economic damage high	Quay wall in flood defence/LNG plant or nuclear plant (hazardous goods)	4.2
CC2/RC2	Risk danger to life negligible Risk of economic damage high	Conventional quay wall for barges and seagoing vessels. Retaining height > 5 m	3.8
CC1/RC1	Risk danger to life negligible Risk of economic damage low	Simple sheet pile structure/quay wall for small barges. Retaining height < 5 m	3.3

design, the dominant stochastic design variables, such as retaining height, soil strength and material properties, that influence the risk profile and hence the willingness to invest in safety measures, are largely time-independent [81,107]. In this study a method was developed to determine capitalised risk and the associated reliability optimum. The second part of the research was focussed on assessing minimum requirements concerning human safety. A sensitivity analysis was performed in order to derive insight into the parameters that influence the reliability index, such as discount rates, time horizons, marginal costs of safety investments and degree of damage in terms of monetary units or number of fatalities. The results were used to elaborate the reliability framework of ISO 2394 [40,4] in order both to be consistent with most of the codes and standards currently used in quay wall design and to improve guidance on reliability differentiation.

2. Target reliability indices in literature

2.1. Principles of target reliability

Basic performance measures are frequently expressed as an allowable probability of failure on the basis of a limit state function [31]. International organisations, such as the International Organization for Standardization (ISO) and the Joint Committee on Structural Safety (JCSS), support reliability-based design and assessments of structures. ISO provided an international standard, ISO 2934 [40], in order to develop a more uniform and harmonised design approach regarding resistance, serviceability and durability. ISO 2394 formed the foundation for many design codes and standards, such as all guidelines complying with the Eurocodes [10,11,25,29,30,63,76] and technical standards and commentaries for port and harbour facilities in Japan [65]. Modern design codes define the probability of failure $P_f = P(Z \le 0)$ by a limit state function [43]. The target reliability index and target probability of failure are then related as follows:

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

in which:

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

Target reliability indices are always related to a reference period of, for example, one year or fifty years, as presented in Table 1.1. Eq. (2) is

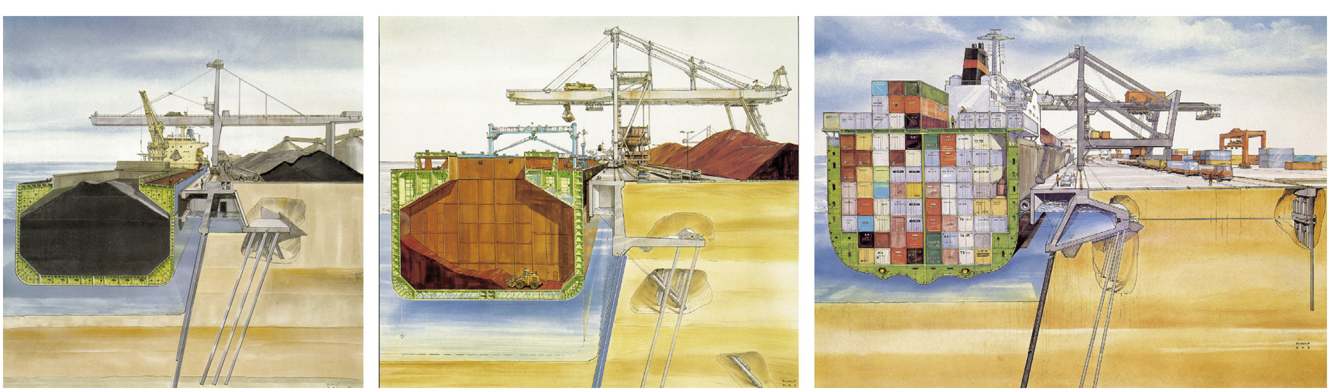

Fig. 1. Typical quay walls equipped with a relieving platform in the Port of Rotterdam [29]. Used by permission of the Port of Rotterdam Authority.

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