

ON THE DEVELOPMENT OF NEN8994: ASSESSMENT OF EXISTING SHEET PILE AND QUAY WALLS BASED ON PAST SERVICE PERFORMANCE

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A history of good past service performance can help to safely extend the service life of existing structures. However, reliability assessments accounting for past performance can be time consuming when evaluating the remaining service life of earth retaining structures such as sheet pile walls and quay walls. Therefore, a national standard NEN8994 is currently being developed in the Netherlands which enables a semi-probabilistic safety assessment. The code should ensure safe life extension of existing sheet pile and quay walls and should account for the effects of survival under lifetime loading. This article discusses the factors that affect reliability and thus remaining service life over time and addresses the aspects and conditions relevant to responsible assessment of safety, including proven strength.

Keywords: assessment of existing structures, past service performance, reliability, code development.

1. Introduction

As infrastructure ages and reaches the end of the intended lifespan, asset management starts to aim at safely extending the remaining technical lifespan. For several reasons (such as efficiency and sustainability) there is a growing demand to apply innovative methods such as reliability-based safety assessments. One of the innovations is to incorporate past service performance information in safety assessments to improve the estimates of reliability and remaining lifetime (e.g. Roubos et al., 2020; Laghmouchi, 2021; Van der Krogt, 2022, Van der Zon, 2024). Past service performance, or simply the proven strength, or survival information, refers to the fact that a structure has functioned successfully without failure up to the point of the assessment.

Incorporating the proven strength accumulated under the experienced loads into safety assessment of structures can reduce time-independent uncertainties like soil properties, which are uncertain due to a lack of knowledge. This improves the reliability estimates and hence updates the estimated residual lifetime. Whilst the method offers the opportunity to safely extend the lifespan of structures, it also imposes additional requirements and conditions to such assessments. For example, it comes with the responsibility to investigate the current state of the structure and to substantiate the survived conditions. This article discusses the effects that affect the reliability at the end of the lifetime and thus remaining service life. Furthermore, it addresses the relevant aspects and conditions to responsibly assess the safety including proven strength, all being part of current code developments to the Dutch code NEN8994.

Section 2 first considers the development of the reliability over the life span, substantiated by results from earlier case studies in section 3. Furthermore, section 4 goes into the details and considerations about the safety assessment and the conditions to apply the concept of proven strength, and section 5 concludes on the next steps.

2. Reliability over the lifetime

Geotechnical structures, such as quay walls and sheet pile walls, are typically designed for an intended service life of 50 or 100 years. During this period, structures undergo several phases that affect their reliability, for example due to physical processes such as loading and degradation which affect the strength, behavior, and performance of the structure and the soil.

Additional data and updated knowledge may lead to different insights regarding the reliability over the life span. From the Bayesian perspective, reliability (or the probability of failure) is not a fixed quantity or frequency,

but a degree of belief about the failure of the structure (e.g. Baecher, 2003). In case of geotechnical structures, the probability of failure is largely determined by uncertainty arising from limited knowledge about quantities which are nearly constant over time yet uncertain, such as soil properties.

Quay walls are typically loaded by the weight of the soil and top load behind the quay. In the initial years after construction the reliability may increase due to strengthening effects in the soil (e.g. shear strength increases due to soil consolidation). Furthermore, the quay wall is subjected to loads such as a water level or top loading during the lifetime. Successfully bearing these loads is an observation of proven strength, which can be used to update the uncertainty of geotechnical properties to values more favorable than initially estimated. Incorporating this effect using Bayesian reliability analysis might reduce time-independent uncertainties and increase reliability.

Over time, the structure will start to degrade, for example, due to corrosion of sheet pile steel. As a result, the reliability decreases. Yet, each year that the structure does not show any signs of distress is another piece of survival information. Eventually, degradation will reduce the reliability of the structure until it falls below the target reliability threshold, see Fig. 1. The target reliability threshold should be defined in terms of a reliability index with a reference period of 1 year to make it easier to estimate the remaining service life. Regarding the latter an initiative has been taken by ECJRC (2024).

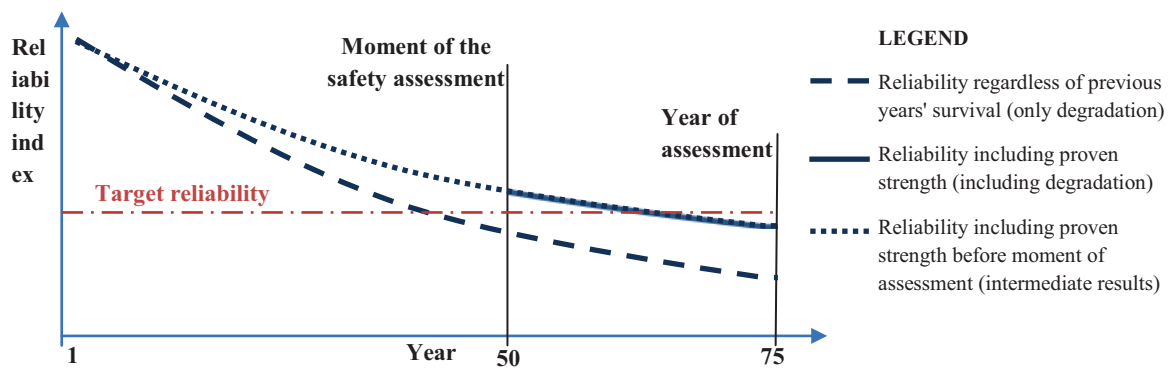


Fig. 1. Schematic representation of the reliability of a quay wall structure with degradation and proven strength over time.

3. Time dependent reliability calculations

The effects of proven strength and degradation on the reliability of quay walls have been investigated through time-dependent reliability analyses, see Van der Krogt (2022) and Smartport (2023). The results of dozens of variations provided insight into the influence of proven strength and corrosion over time of steel (combined) sheet pile walls. The results show the time-dependent development of reliability (failure probability) and the influence of the uncertainty of different parameters on the probability of failure, see an example of the latter in Fig. 2.

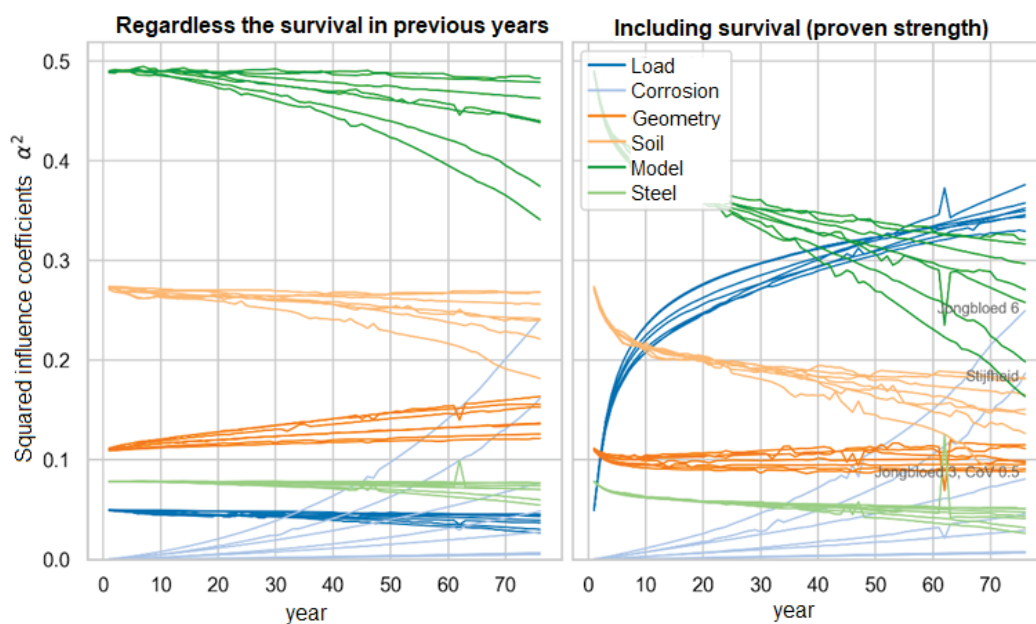


Fig. 2. Squared probabilistic influence coefficients α^2 over time, summed per category. Multiple probabilistic calculations for different variations are shown. Limit state of steel stress exceeding the yield stress of sheet pile wall. Figure from (Smartport, 2023).

The main findings of that study are:

- At the beginning of the lifetime, the failure probability is largely influenced by model uncertainty and geotechnical uncertainty. Over time, the impact shifts towards degradation uncertainties (left graph in Fig.2).
- Survival under loads anticipated in the design reduces the uncertainty in time-invariant parameters like soil, model, and geometry, decreasing their impact on failure probability over time. The relative influence of time-variant uncertainties such as loads increases (right graph in Fig.2).
- Towards the end of the service life, the influences of loads and degradation uncertainties on the failure probability increase, while the impact of strength parameter uncertainties decreases. Thus, the uncertainties of loads, corrosion, and corrosion prediction models become more critical parameters in determining the remaining lifetime.
- Most reduction in uncertainty for time-invariant parameters occurs within the first 30 years after construction. After this period, changes in influence coefficients are minimal, making the results applicable for assessing structures of 40-60 years old.
- The influence of time-dependent variables, like loads and degradation, can change significantly over time. However, over a 15-year period, changes in influence factors and case-specific partial factors remain limited, making the results most applicable for a remaining service life of up to 15 years from the assessment point.

The results show that, due to proven strength, the probabilistic design point is different for existing structures and new structures and implies that a more efficient semi-probabilistic safety assessment method might be possible for the assessment of existing structures including the effect of past performance and degradation.

4. Code development

4.1. Semi-probabilistic assessment method

A semi-probabilistic assessment method for existing structures thus ideally accounts for the shift over time of probabilistic influence coefficients from strength to load and degradation. Besides, the 'gain' of proven strength in terms of a higher reliability due to uncertainty reductions should also be accounted for. To that end, the derivation of partial factors is done based on the (case-specific) probabilistic design point values. If the partial factors would be derived from the influence coefficients only, the uncertainty reduction would not be accounted for.

Based on the definition of partial factors (e.g. $\gamma = X_k / X_d$ in case of material strengths and soil parameters, where X_k is the characteristic value and X_d is the value at the probabilistic design point), case-specific partial factors have been calculated for all cases and all parameters. A calculation with these partial factors, would result in a failure probability as close as possible to the target values when the unity check (u.c.) is equal to 1.0. The results of that analysis (summarized in Table 1) form the basis for a semi-probabilistic safety assessment format for these structures including the effect of past performance.

The effect of adjusted partial factors on the design value of the friction angle is demonstrated through a simplified example. According to current regulations, the partial factor for the friction angle is set to 1.0, resulting in a design value of $X_d = \tan^{-1}(\tan(X_k) / 1.0) = 30^\circ$ for $X_k = 30^\circ$. If the partial factor is adjusted to 0.9, the design value increases to $X_d = \tan^{-1}(\tan(X_k) / 0.9) = 32.7^\circ$. This represents a significant increase, highlighting the sensitivity of the design value to changes in the partial factor.

The selection of partial safety factors in the context of structural safety, however, requires careful alignment with existing standards and a thorough analysis of the necessary safety margins. For example, the factors need to align with fixed values from established codes such as Eurocode 3 (for steel design values) and in this specific context the NEN 6766 for corrosion. Furthermore, adopting fixed partial factors from other codes, should not go together with a deficiency of safety margins or overly conservatism. Moreover, it is undesirable for design values to exceed the expected value (mean), which can occur if partial factors lower than 1 are applied. The ultimate goal is to find a balance between reliability and simplicity, ensuring that the safety of the design is not compromised. This step is currently undertaken.

Table 1. Range of case-specific partial safety factors for different parameters for disapproval CC1 and CC2 (annual reliability index ranging from 2.8-3.3)(Smartport, 2023).

Parameter	Representative value	Range of partial safety factor
Friction angle	Characteristic (5%-percentile)	0.85-0.95
Effective cohesion	Characteristic (5%-percentile)	1.0*
Volumetric weight	Characteristic (5%-percentile)	0.9-1.0
Modulus of subgrade reaction	Characteristic (5%-percentile)	0.6-0.7
Yield stress steel	Characteristic (5%-percentile)	1.0
Top load	Characteristic (2%-percentile)	1.3
Model uncertainty		1.0-1.15 (bending moment) 1.2 (buckling) 1.05-1.2 (anchor force) 1.05-1.25 (passive soil resistance)
Corrosion	Characteristic (5%-percentile)	1.75 (tube thickness) 1.35 (anchor radius)
Water level		Exceedance probability 1/20 per annum
Ground water level		Exceedance probability 1/4 per annum

*) conservative value

4.1. Application conditions

Incorporating proven strength in the assessment thus offers opportunities for a safe extension of service life through adjusted safety factors. However, the application of proven strength poses additional requirements to the application of this method regarding different aspects, as explained below.

To assess the remaining lifespan, one needs to determine the year when a structure no longer meets the reliability requirements. Working with reference periods of multiple years is then cumbersome. Considering a reference period of 1 year is more versatile since it is independent of the current age and the remaining lifespan of the structure. Therefore, the reliability requirements for failure and renovation from the Dutch code for assessment of existing structures NEN 8700 have been translated from 15 years to a 1 year reference period, being 2.8, 3.3, and 4.0 per annum for CC1, CC2, and CC3, respectively.

To be able to utilize proven strength from surviving loads, it is important that relevant ultimate limit states such as yielding or buckling of the steel wall have not been exceeded. For application of the assessment method, it is necessary to substantiate that this is not the case. This can be done, for example, by collecting data that confirms there are no serious structural defects, such as cracks or unusual deformation, which could indicate redistribution of forces and near failure.

To rely on a history of proven strength, the structural behavior of the structure may not have changed significantly over the lifetime and towards the future, except for degradation. This is how it was assumed in the case studies. Specifically, this refers to an unchanged structure (i.e., that no renovations have been or will be performed that change structural strength or behavior), and the same probability distribution of loads and water levels, for example.

A proper assessment also requires accurate knowledge of the current state of the structure. This includes understanding of the ground-structure behavior and degrading factors like corrosion and soil erosion. A sufficient schematization of the ground and structure is required, and measurements of the soil properties and structural elements should be accurate and realistic, to avoid wrongly estimating the structure's strength. Particularly for steel sheet piling and quay walls, corrosion of the wall thickness should be measured with sufficient spatial and temporal frequency. Likewise, the underwater bottom must be regularly measured and maintained, for example, by repairing scour holes or using soil protection.

The proposed assessment approach is useful in situations where a structure has a track record of good performance, providing valuable insight into the remaining service life. However, caution is necessary in cases where brittle failure mechanisms dominate or when the structure is near continuous or progressive failure. In these situations, relying solely on past performance without additional preventive measures – such as structural reinforcement, real-time monitoring, or early-warning systems – may lead to unsafe conditions. For many geotechnical structures, however, brittle behavior is typically not a concern, as a certain degree of deformation is required to develop shear strength.

5. Conclusion

Time dependent reliability analysis including past performance provides insight in the influence of different uncertainties on the failure probability. The probabilistic design point values reflect the uncertainty reduction, which offers opportunities to adjust partial safety factors. For a responsible application and safe extension of

service life, there are some additional requirements. The most important are that the current and future operational conditions do not differ significantly from the past, and that survival is substantiated by adequate information on the past performance and investigations about the current condition.

The proposed assessment approach provides valuable insight into the remaining service life of existing sheet pile walls and quay walls, but requires caution in cases where brittle failure dominates, and when early signs of distress such as cracks or deformation are absent. It is emphasized that incorporating past performance is one of the tools that can be used to substantiate the safe lifetime extension. It should not be neglected to pay sufficient attention to the schematization of the construction and uncertainties, and to understand the ground-structure behavior. All above aspects will be part of the NEN8994 code currently under development.

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