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Reliability targets for geotechnical structures in the Eurocode framework

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Summary

This report provides background information and supporting material for reliability requirements for geotechnical structures, specifically focusing on the target values for the reliability index (or equivalently, the target probability of failure) for different reference periods, i.e. 50 years or annual. This work was carried out within the SITO program of Deltares with the aim of informing choices for the second-generation Eurocodes.

Target reliabilities are investigated in this report from various angles:
1. Investigating reliability levels achieved with Eurocode designs, with an emphasis on the difference between 1-year and 50-year reference period.
2. Evaluating risk criteria (individual, economic and group risk).
3. Literature.

With regards to reliability target values for geotechnical structures designed within the Eurocode framework, we conclude the following:
- The reliability target value of β_T = 3.8 (CC2) for a reference period of 50 years in EN 1990, originally derived for bridges and buildings, also seems appropriate for geotechnical structures from various perspectives, namely (a) reliability theoretical calibration, (b) considering risk acceptance both economical and risk to life and (c) considering the ranges of reliability requirements in other codes of practice.
- For an annual reference period, the corresponding annual reliability index ranges from 4.0 to 4.6, depending on the relative influence of the variable load. Most geotechnical problems have a low influence of variable loads and will tend towards the lower bound values, say 4.0 to 4.3.

The contents of this report have served the formulation of guidance for reliability-based design and assessment of geotechnical structures in the Eurocode framework as published in JRC (2024a).

Contents

1 Introduction

1.1 Rationale and goal

The second generation of Eurocodes is under development. With more focus on risk-based design principles. An important anchor of the Eurocodes are the target reliabilities that define minimal required probabilities of failures. These inform e.g. partial factors or can directly be used as a target in a probabilistic analysis. The target reliabilities in Eurocode 7 (Geotechnical design) have traditionally been the same as for other structures. However, geotechnical structures can have different characteristics than other structures. Hence, there was the need for more substantiation of target reliability for geotechnical structures.
This report provides background information and supporting material for reliability requirements for geotechnical structures, specifically focusing on the target values for the reliability index (or equivalently, the target probability of failure) for different reference periods, i.e. 50 years or annual. This report is carried out with the SITO program of Deltares. The scope of this report is to record the approach and outcomes such that it can be reproduced without providing in-depth analysis of the results.

1.2 Approach

The first line of reasoning (Chapter 2) deals with the reliability levels achieved by geotechnical designs using different theoretical and empirical sources; the second line of reasoning (Chapter 3) contemplates risk acceptance criteria to derive reliability targets. Furthermore, an overview of relevant literature and related codes of practice is given in Chapter 4. Lastly, Chapter 5 provides contextual information on observed failure frequencies.

1.3 Application outcomes

The contents of this report have served the formulation of guidance for reliability-based design and assessment of geotechnical structures in the Eurocode framework as published in JRC (2024a).

2 Reliability levels achieved with Eurocode designs (calibration study)

2.1 Background reliability targets

The technical report JRC (2024b) describes the reliability backgrounds of the Eurocodes, where a rationale for the recommended partial load factors in Annex A of EN1990 (Eurocode 0) is presented. EN1990 presents the target reliabilities for different consequence classes (CC), for both a 1-year and 50-year reference period. For structures such as bridges and buildings, the relation between the partial factor design approach and target reliability (β) is relatively well established. However, for geotechnical structures this has not been verified extensively.

JRC (2024b) clarifies that the target values on the Eurocode were originally derived for buildings and bridges, while a reliability-based calibration study in the same report suggests that they may also be applicable to geotechnical structures (as shown for spread foundations and for piled foundations, see Section 2.1). This report aims to support this further, based on the following steps:

a) By evaluating a generic limit state function (LSF) and corresponding partial factor format. Similarly to the calibration shown in the reliability background document of the Eurocode (JRC, 2024b), but with geotechnical specific input – Section 2.1.
b) By relating reliability indices of different reference periods taking into account the correlation of failure events between years – Section 2.2.
c) And with literature review of studies where reliability computations of geotechnical structures are compared with geotechnical (mostly Eurocode-based) designs – Chapter 4.

The technical report JRC (2024b) shows the results of the reliability-based calibration (β-values for 50 years), for various materials. For each loading type and each material the using partial factors according to the Eurocodes are used. Figure 2-1 indicates that for pile foundations and spread foundations approximate the target reliability index of β_T = 3.8 for CC2 with a reference period of 50 years rather closely. The 50-year reference period is choses as starting point since this is the basis of EN1990, the 1-year reference period results are back-calculated (with some assumptions) based on the 50-year reference period.

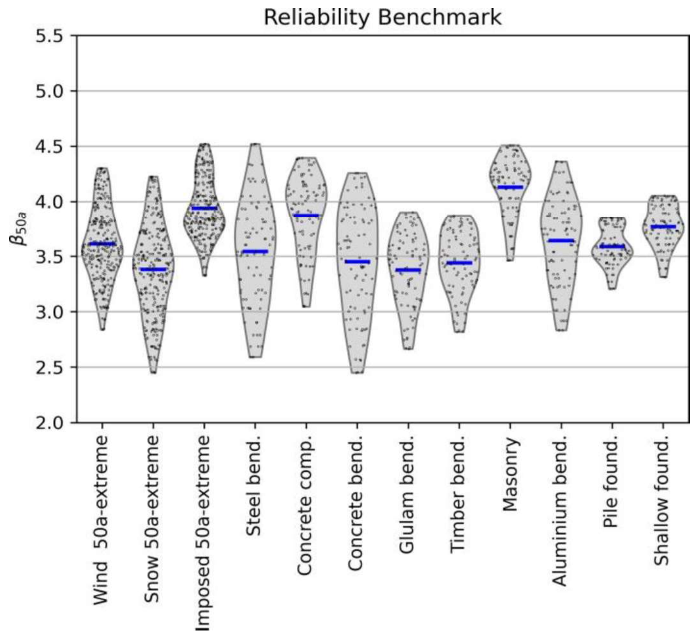


Figure 2-1: Reliability-based calibration, i.e. β-values for 50 years, for each loading type and each material; calculations based on design format EN 1990 using partial factors according to the Eurocodes (JRC, 2024). The target reliability index for CC2 is 3.8.

2.2 Definitions and input data

Hereunder, we carry out the same the reliability-based calibration exercise as in JRC (2024b)[1] with geotechnical 'generic' input in order to cover for a wider range of geotechnical structures. A couple of sensitivity analysis are then carried out, which aim to further assess if the reliability targets reported in the Eurocodes are also applicable to geotechnical structures. The generic format used for the analysis, as well as the geotechnical specific input, are described below:

- Generic limit state function (LSF):

$$g(X) = \theta_R \, p \, R - \theta_e \left[(1-a_Q) \, G + a_Q \, \theta_Q \, Q \right] \tag{1}$$

- Corresponding design equation:

$$p \, R_k / \gamma_R = \gamma_G (1-a_Q) \, G_k + \gamma_Q \, a_Q \, Q_k \tag{2}$$

- Unity-check (UC):

$$UC = [\gamma_G (1-a_Q) \, G_k + \gamma_Q \, a_Q \, Q_k] / [p \, R_k / \gamma_R] \tag{3}$$

for which the definitions are given in Table 1. The main difference between a 1-year and 50-year reference period is the definition of the load. In a safety verification, the UC should be larger than 1.0. Computation have been made with the Probabilistic Toolkit (PTK) of Deltares.

[1] For simplicity here we avoid distinction between self-weight and other permanent loads by only using one term G, since the distinction is not so relevant for geotechnical structures.

Table 2-1: Input used to carry out the reliability-based calibration for geotechnical structures (similar to JRC, 2024).

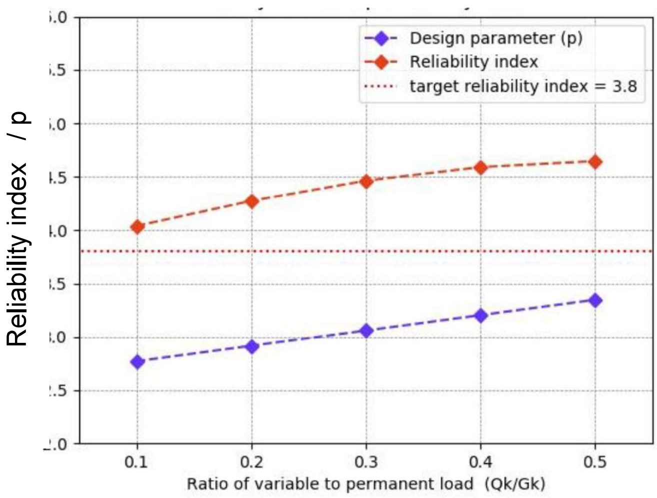
Variable	Definition	Uncertainty
p	Design parameter (adjusting resistance for UC=1)	-
θ_R	Resistance model uncertainty	Logn(1.0, 0.15)
R	Resistance	Logn(1.0, 0.15) Characteristic value = R_k = 5% quantile = 0.77
θ_e	Load effect model uncertainty	Logn(1.0, 0.10)
G	Permanent load (incl. self-weight)	Normal(1.0, 0.10) Characteristic value = G_k = mean = 1.0
θ_Q	Variable load model factor	Logn(1.0, 0.10)
Q	Variable load (imposed)	50 years: Gumbel(1.0, 0.15) Char.= Q_k = 98% quantile = 1.39 1 year: Gumbel(0.54, 0.15) Char.= Q_k = 98% quantile = 0.93
a_Q	Ratio of variable to permanent load (characteristic: Q_k/G_k)	[0.1 - 0.5]
γ_R	Partial resistance factor	1.50
γ_G	Partial load factor	1.35 (CC2, DC1)
γ_Q	Partial load factor	1.50 (CC2, DC1)

2.3 Results for 50 years reference period

The following steps are taken in the analysis:

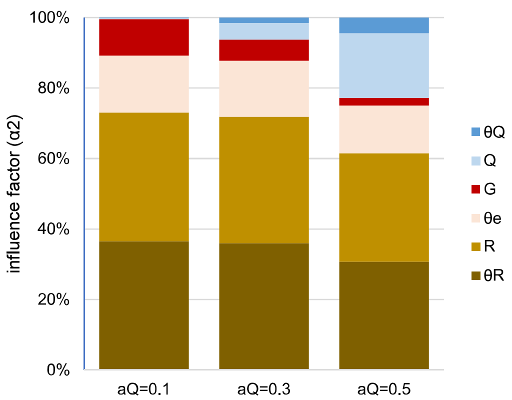
a. Apply design equation eq. (3) to obtain p such that UC=1, with characteristic values and partial factors, incl. sensitivity analysis on aQ).
b. Run reliability analysis with obtained p.
c. Compare result with Eurocode target β = 3.8.
d. Check resulting influence coefficients (α).

The results are presented in the figures below and further discussed in Section 2.4.



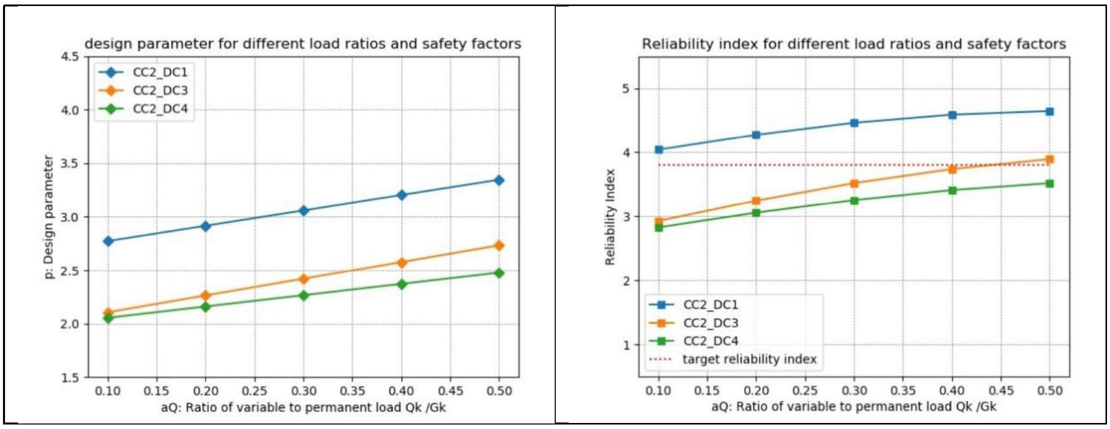
a_Q	0.1	0.2	0.3	0.4	0.5
p	2.77	2.92	3.06	3.20	3.35
β_{50y}	4.0	4.3	4.5	4.6	4.6
β_{1y}	4.2	-	5.0	-	5.4

Figure 2-2: Relability index for 50 years reference period as function of a_Q=Q_k/G_k (variable load ratio).



50y	θ_R	R	θ_e	G	Q	θ_Q
a_Q=0.1	37%	37%	16%	10%	0%	0%
a_Q=0.3	36%	36%	16%	6%	5%	2%
a_Q=0.5	31%	31%	14%	2%	18%	4%

Figure 2-3: Influence factors for reference period 50 years as function of aQ=Qk/Gk (variable load ratio).



Factors CC2 +	DC1	DC3	DC4
γ_G	1.35	1.0	1.0
γ_Q	1.50	1.30	1.11

Figure 2-4: Sensitivity analysis to set of safety factors (with UC = 1). DC stands for ‘design case’.

2.4 Discussion reliability results (reference period 50 years)

Depending on the ratio of variable to permanent load, the reliability index achieved for a reference period of 50 years can vary between 4.0 and 4.6, both higher than the target reliability index of 3.8.

The influence factors (α^2) of the different random variables depend also on the on the ratio of variable to permanent load (a_Q). However, the uncertainty in the resistance parameters (both R and θ_R) are dominant, being between 61% and 73% for the lowest and higher load ratios respectively. As expected, the higher the ratio, the higher the variable load and thus the higher the influence of this uncertainty.

2.5 Results for 1-year reference period

The main difference with the 50-year reference period is that the load is scaled to a 1-year reference period. It is aimed to compare two approaches to design a geotechnical structure: 1) by directly using the 50-year reference period and 2) by first using a 1-year reference period combining this to a 50-year reliability, while incorporating the year-to-year correlation that exist due to the strength variables that are constant in time.

The following steps are taken in the analysis:

a. Scale variable load (Q) to 1 year reference period assuming independence between years.
b. Apply design equation eq.(1) to obtain p (with characteristic values and partial factors), where partial factors correspond to CC2 for a 1-year reference period.
c. Run reliability analysis (incl. sensitivity analysis on a_Q).
d. Combine resulting probability of failure (P_f) for 50 years, including correlation between years.
e. Compare result with Eurocode target β = 3.8 for 50 years.
f. Repeat steps a. to f. by adjusting p such that β = 3.8.

The results of the various steps are shown below.

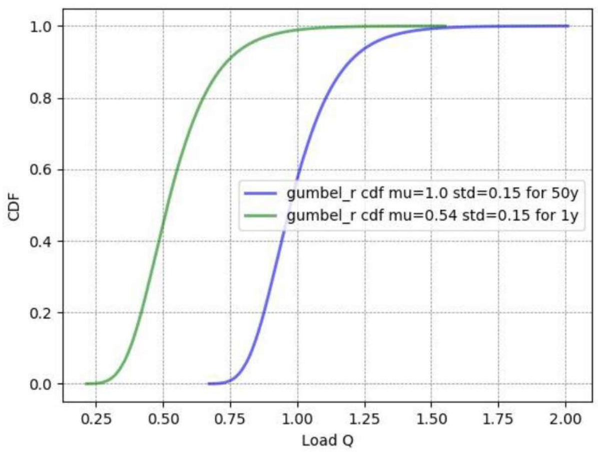
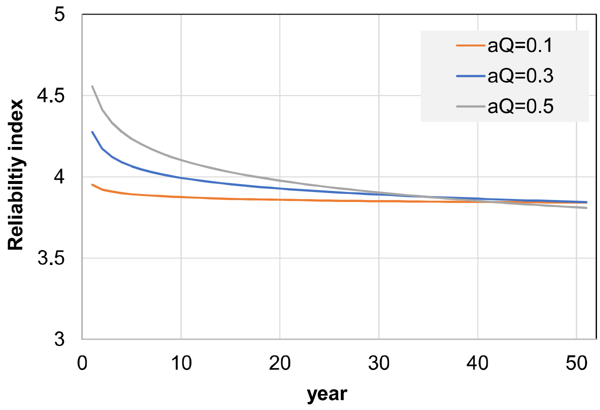


Figure 2-5: Gumbel distribution of the variable load Q scaled from reference period of 50 years to 1 year.



beta-results (PTK)			
Ref period	a_Q=0.1	a_Q=0.3	a_Q=0.5
1 year	4.0	4.3	4.6
50 years	3.84	3.84	3.81
p =	2.6	2.55	2.65

Figure 2-6: Cumulative reliability index from 1 year to 50 years, resulting in 3.8 for 50 years.

2.6 Discussion reliability results (reference period 1 year)

In order to end up with a reliability index of 3.8 (CC2) for 50 years, the annual reliability index needs to be higher. Depending on the relative importance of the variable load (a_Q) the corresponding annual reliability index ranges from 4.0 to 4.6 in the relevant range of a_Q. That being said, most geotechnical problems have a low influence of variable loads and will tend towards the lower bound values. Furthermore, especially for low aQ and thus a relative low influence of the load, there is limited difference between the 1-year and 5-year reference period, indicating high correlation between years. Which is opposite to EN1990 which assumes independence between years.

3 Reliability targets based on risk acceptance criteria

Optimum reliability indices can be derived by various risk acceptance criteria, for example human safety, societal risk, and economic risk - or combinations thereof. The following sections elaborate on how to derive such reliability targets, and what ranges of optimum targets are typically found for various geotechnical structures, based on reasonable assumptions.

With respect to the number of fatalities N_f, the reliability target (expressed as a consequence class, CC, in Eurocode) is typically governed by:

- Low N_f: individual risk (IR) [CC1b].
- Medium N_f: economic risk [CC2].
- High N_f: societal risk [CC3+].

3.1 Minimum reliability based on risk to life

Risk to life (also human safety, or individual risk, IR) can pose a criterion for the minimum level of safety of a geotechnical structure or failure mode.

The individual risk of fatality P_f is defined as $P(D) \cdot P(f|D)$, where $P(D)$ is the annual probability that damage occurs, and $P(f|D)$ the probability of fatality given this damage. $P(f|D)$ can be described as $1 - P_{escape}$ or in words the probability there is no escape. Following the definition, the individual risk can be written as:

$$IR \leq P(D) \cdot P(f|D)$$

For a typical range of acceptable risk (IR_{acc}) from 10^{-4} to 10^{-6}, and various conditional probabilities for fatality, target reliabilities range roughly between 2.0 and 5.0, see Table 3-1. For a generally acceptable probability of loss of life of 10^{-5} per year (10^{-4} is probability of a random person in the general population dying per year , so a max. 10% increase), a target reliability of 4.0 seems reasonable (or even conservative) for a 1-year reference period. The corresponding β_T for reference period of 50 years is lower than 3.8.

Table 3-1 Annual target reliability for individual risk for different values for the acceptable risk and the probability of death conditional to structural failure.

Annual target reliability $\beta_{T,IR}$		**$P(D\|F)$**			
		1	**0.1**	**0.01**	**0.001**
IR_{acc} (annual)	**10^{-6}**	4.8	4.3	3.7	3.1
	10^{-5}	4.3	3.7	3.1	2.3
	10^{-4}	3.7	3.1	2.3	1.3

3.2 Economically optimal reliability targets

In many situations, it is worthwhile to adopt higher reliability targets than the minimum targets for individual risk. For example, when investments for safety outweigh the risk reduction, a higher target reliability is cost-effective. Economically optimum targets can be derived by a cost-benefit-analysis minimizing the sum of investments for safety and the capitalized risk.

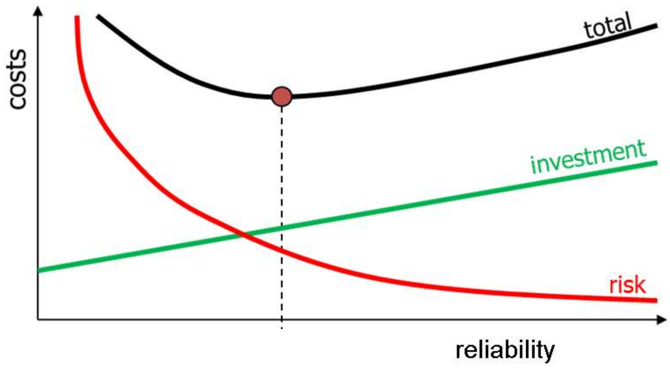


Figure 3-1 Economically optimum targets defined as the minimum of total cost (black line) that is the sum of risk (red) and investment (green).

We analyzed the sensitivity for the optimum annual target reliability for a range of failure costs (from 5M€ to 5000M€), and investment costs (from 20k€ to 500k€ to attain a 1.0 higher reliability index), see Figure 3-2.

We chose the discount rate 0.03 per year and assumed an 'equivalent time' $t_{eq} = 20$ to translate 1-year to 50-year reference periodes. This represents a virtually resistance-dominated (time-invariant) problem, with still a small contribution of variable load uncertainty (time-dependent), which is a reasonable assumption for geotechnical failure modes, see Chapter 2. For CC2, we estimate failure costs in the range of 50-500 million Euros (upper bound?), for which the reliability target roughly gets into the range of 3.5-4.0.

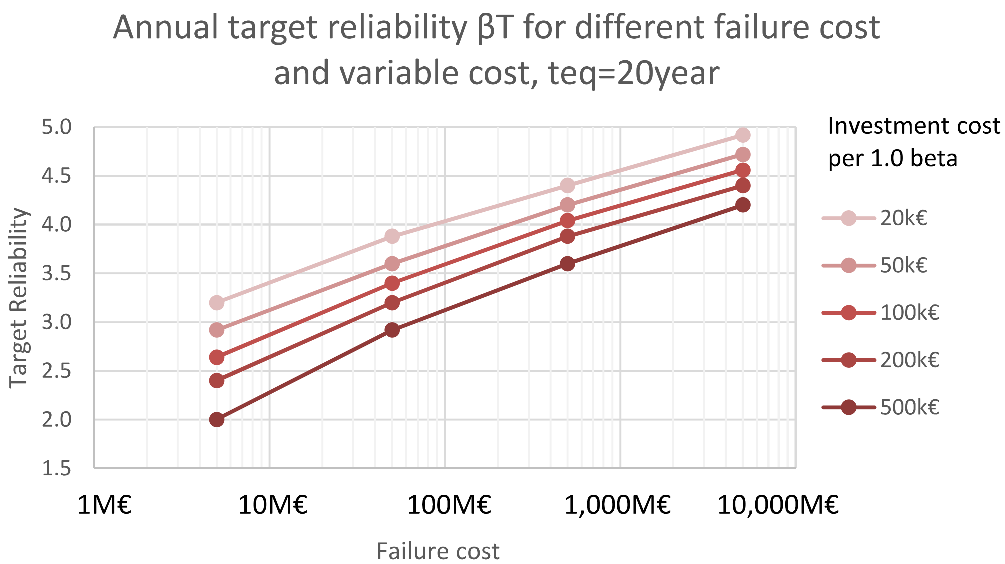


Figure 3-2 Annual target reliability for economic optimization of risk for different values of failure cost and variable investment cost.

3.3 Societal risk considerations

Failures with a larger number of people at risk of life are less acceptable from a societal point of view. Therefore, target reliabilities for the structure are higher for higher expected number of fatalities. F-N curves (that plot probability F that larges number N die) can be used to determine reliability targets for societal risk. The societal risk (group risk) is calculated by:

$$SR = R_{acc} \cdot N_{f|D}^{-k}$$

Here, R_{acc} is the acceptable risk for one fatality, and $N_{f|D}^{-k}$ the expected number of fatalities given damage or failure. The factor k is the slope factor of the F-N curve, representing risk-neutrality (k=1) or risk-averseness (k>1, e.g. k=2).

From a sensitivity analysis with typical ranges for the acceptable risk per person and the slope factor follows that reliability targets for societal risks mainly govern (i.e. result in stricter targets than individual or economic risk) in situations where many people are exposed to death.

Table 3-2 Target reliability based on group risk for k =1.

Annual target reliability $\beta_{T,SR}$ $k = 1$		$N_{f\|D}$			
		1	**10**	**100**	**1000**
R_{acc}	10^{-3}	3.1	3.7	4.3	4.8
	10^{-2}	2.3	3.1	3.7	4.3
	10^{-1}	1.3	2.3	3.1	3.7

Table 3-3 Target reliability based on group risk for k =2.

Annual target reliability $\beta_{T,SR}$ $k = 2$		$N_{f\|D}$			
		1	**10**	**100**	**1000**
R_{acc}	10^{-3}	3.1	4.3	5.2	6.0
	10^{-2}	2.3	3.7	4.8	5.6
	10^{-1}	1.3	3.1	4.3	5.2

3.4 Relevant literature

In the table below, several examples of authors who derived target reliability based on various risk criteria.

Table 3-4 Literature on target reliability for geotechnical structures.

What	Source	Remark
Target reliabilities Quay walls	Roubos (2019)	Target reliabilities based on risk criteria. Cost most important driver. Annual target reliabilities of 2.8 (STR) and 3.5 (GEO)
Temporary scaffold structures	Vereecken e.a. (2020)	Temporary (scaffold) structures and its effect on target. Target reliabilities of 2,3 – 3,1 for loss of life considerations; 2,5 –3,5 for economic considerations
Target reliabilities	TNO (2021)	Target reliabilities sheet piles, including proven strength. Existing and renewal. Target reliabilities ranging from 1.8 – 4.4.

4 Reliability targets in related codes of practice

For some (geotechnical) structures, specific reliability targets have been formulated in the pertinent codes of practice. See Table 4-1 for examples. For more examples, refer to Roubos (2019).

Table 4-1: Examples of codes and standards specifying or recommending reliability targets.

Code or standard	Reference	Remarks
ENW, flood defences, Netherlands	ENW (2017)	Annual target failure probabilities of flood defense segments (systems) ranging from 10^{-2} to 10^{-6} ($\beta = 2.3\ to\ 4.8$).
USBR, dams, USA	FERC (2015)	Annual targets based on FN-Curves including individual risk and group risks, with target failure probabilities ranging from 10^{-4} to 10^{-6} ($\beta = 3.7\ to\ 4.8$).
ISO 2394, General	ISO (2015)	Annual target reliabilities for structures of 4.2 to 4.7 depending on consequence class.
Probabilistic Model Code, General	JCSS (2001)	Annual target reliabilities for structures of 4.2 to 4.7 depending on consequence class.
USACE, Geotechnical, USA	USACE (1999)	Annual geotechnical target reliabilities.
ASCE, structures, USA	ASCE (2010)	Lifetime target reliabilities for structures of 2.5 to 4.5 depending on consequence class.
OCDI, maritime, Japan	OCDI (2009)	Lifetime target reliabilities for marine structures of 2.19 to 3.65 depending on consequence class.
CUR 166, sheet piles, NL	CUR 166 (2012)	Lifetime target reliabilties sheet piles of 2.5 – 4.2.
CUR 211, quay walls, NL	CUR 211 (2013)	Lifetime target reliabilties quay walls of 3.3 -4.3.

We observe ranges of reliability index very similar to the target values in EN 1990, namely 3.3 (CC1) – 4.3 (CC3) for a reference period of 50 years, depending on the consequences of failure. Notice that where annual values are mentioned, these tend to be naturally somewhat higher (see 2.4 and 2.5).

5 Observed failure frequencies and design reliability estimates

Observed failure frequencies and calculation-based reliability estimates of geotechnical structures and designs are summarized in Figure 5-1. These provide further context for the reliability targets in (geo)structural design.

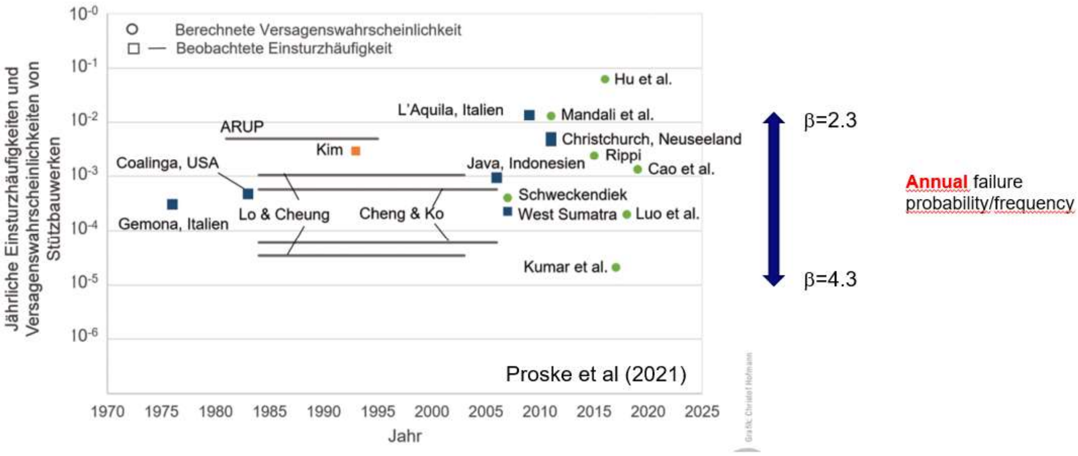


Figure 5-1: Observed failure frequencies and calculation-based reliability estimates of geotechnical structures and designs (based on Proske et al, 2021).

While the data exhibit a rather wide range in terms of the reliability index (roughly 2.3-4.3), the lower range contains mainly failure cases, often with exceptional loading (e.g. strong earthquakes). The ‘normal’ failures and the design studies tend to be in the upper range.

Notice that observed failure frequencies cannot directly be compared to calculated reliability indices due to hidden safety elements in calculation models and design approaches (see JRC, 2024b).

6 Conclusions

With regards to reliability target values for geotechnical structures designed within the Eurocode framework, we conclude the following.

The reliability target value of $\beta_T = 3.8$ (CC2) for a reference period of 50 years in EN 1990, originally derived for bridges and buildings, also seems appropriate for geotechnical structures from various perspectives, namely (a) reliability theoretical calibration, (b) considering risk acceptance both economical and risk to life and (c) considering the ranges of reliability requirements in other codes of practice.

For an annual reference period, the corresponding annual reliability index ranges from 4.0 to 4.6, depending on the relative influence of the variable load. Most geotechnical problems have a low influence of variable loads and will tend towards the lower bound values, say 4.0 to 4.3.

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