Kennisplan Natte Kunstwerken 2020

Bestaand object

Probabilistische Tools

Quantifying reliability of sheetpile walls

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In het **Kennisprogramma Natte Kunstwerken** (KpNK) werken Deltares, MARIN, Rijkswaterstaat en TNO samen aan de kennisontwikkeling om de vervangings- en renovatieopgave bij natte kunstwerken (stuwen, sluizen, gemalen en stormvloedkeringen) efficiënt en kostenbesparend aan te pakken.

Voor het kennisprogramma wordt er jaarlijks een inhoudelijk **Kennisplan** inclusief bijbehorend financieringsplan opgesteld. Andere partijen (zoals waterschappen en marktpartijen) worden nadrukkelijk uitgenodigd om deel te nemen.

Meer informatie over het Kennisprogramma Natte Kunstwerken vindt op www.nattekunstwerkenvandetoekomst.nl waar ook de onderzoeksresultaten ter beschikking worden gesteld.

De samenwerking binnen het Kennisprogramma Natte Kunstwerken vormt de uitwerking van de onderzoekslijn “Toekomstbestendige Natte Kunstwerken” binnen het **Nationaal Kennisplatform voor Water en Klimaat** (NKWK). Dit kennisplatform brengt Nederlandse overheden, kennisinstellingen en bedrijven bij elkaar om samen te werken aan pilots, actuele vraagstukken en lange termijn-ontwikkelingen op gebied van water- en klimaatvraagstukken.

Meer informatie staat op www.waterenklimaat.nl.

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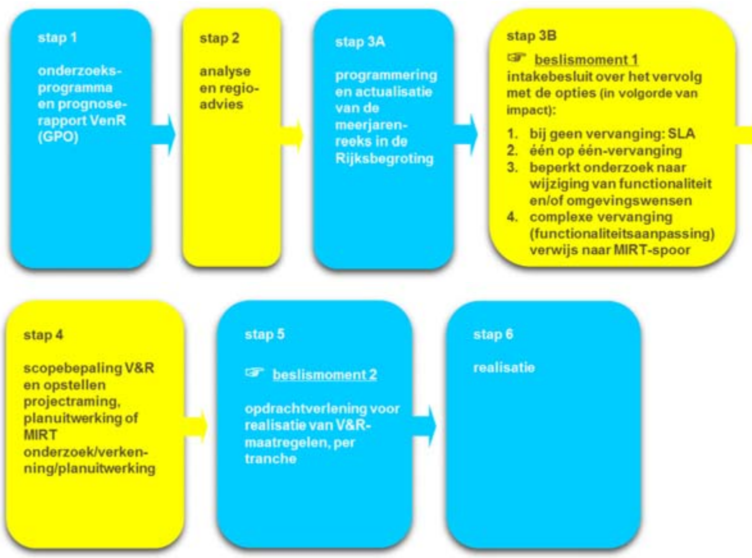
Voorwoord

Sluizen, stuwen, gemalen en stormvloedkeringen zijn belangrijke assets van beheerders zoals Rijkswaterstaat en de waterschappen. Een groot deel van deze natte kunstwerken bereikt komende decennia het einde van de (technische) levensduur waarvoor het is ontworpen. Er dient zich dan ook een aanzienlijke vervangings- en renovatieopgave van deze kunstwerken aan.

De laatste jaren wordt steeds meer gezocht naar mogelijkheden om levensduur van kunstwerken te verlengen, en om bij einde levensduur (noodzakelijke) ingrepen te koppelen aan gebiedsontwikkelingen en/of functionele-/netwerk ontwikkelingen. RWS heeft daartoe als asset manager een vernieuwde werkwijze voor het Vervanging en Renovatie (VenR) proces opgesteld, welke de basis vormt voor de inrichting van het kennisprogramma Natte Kunstwerken (zie onderstaand figuur).



Figuur 1. Vernieuwde RWS-werkwijze Vervanging en Renovatie.

In het kennisprogramma Natte Kunstwerken wordt kennis ontwikkeld die bijdraagt aan de verschillende stappen binnen deze vernieuwde VenR-werkwijze, met als focuspunten stap 1 prognoserapport en stap 2 regioanalyse en - advies. Het prognoserapport richt zicht op de (einde) technische levensduur, het regio-advies brengt met name in kaart de relatie object-netwerk-gebied.

Het onderzoek in het kennisprogramma vindt plaats langs de onderstaande 3 onderzoekssporen en heeft tot doel om een effectieve en efficiënte aanpak van de vervanging- en renovatieopgave en nieuwbouw van natte kunstwerken mogelijk te maken:

- bestaand object	- inzicht in (einde) technische levensduur - levensduurverlenging
- object-systeem	- inzicht in (einde) functionele levensduur en object-systeemrelaties
- nieuw(e) object/objectonderdelen	- toepassen innovaties - inspelen op toekomstige ontwikkelingen.

Sinds enkele jaren is er het Nationaal Kennisplatform voor Water en Klimaat (NKWK). Hieronder lopen diverse onderzoekslijnen. Eén van de onderzoekslijnen is Toekomstbestendige Natte Kunstwerken. Voor het praktisch laten functioneren van deze onderzoekslijn is er een Samenwerkingsovereenkomst Natte Kunstwerken en een Kennisprogramma Natte Kunstwerken opgesteld:

- Samenwerkingsovereenkomst Natte Kunstwerken. De partijen die momenteel binnen deze overeenkomst samenwerken aan onderwerpen op het gebied van natte kunstwerken (stuwen, sluizen, gemalen en stormvloedkeringen) zijn Deltares, TNO, Marin en RWS.
- In het kader van de bovengenoemde Samenwerkingsovereenkomst Natte Kunstwerken en de 3 onderzoekssporen van het Kennisprogramma Natte Kunstwerken wordt er jaarlijks een inhoudelijk Kennisplan Natte Kunstwerken inclusief bijbehorend financieringsplan opgesteld.

Naast de genoemde partijen zijn en worden andere partijen nadrukkelijk uitgenodigd om deel te nemen aan de Samenwerkingsovereenkomst en/of Kennisplan Natte Kunstwerken. Inzet kan zowel in kind en/of financieel zijn.

Resultaten uit het Kennisplan Natte Kunstwerken worden gedeeld met de gehele sector via onder andere de site www.nattekunstwerkenvandetoekomst.nl.

Het na dit voorwoord beschreven onderzoek en rapportage op het gebied van betrouwnbaarheidsanalyses voor de beoordeling van damwanden is uitgevoerd in het kader van het Kennisplan Natte Kunstwerken 2020.

Summary

Quantifying reliability of sheetpile walls

<u>Aanleiding</u>

In 2019 TNO and Deltares cooperated in the research about the use of Structural Health Monitoring (SHM) for system identification of sheet pile walls. The investigation led, among other results, to (i) the development of a sound and robust procedure for the design of the sensor layout, (ii) a remarkable gain in terms of structural reliability and (iii) a significant reduction of the computational effort by using adaptive surrogate models and advanced sampling methods for Bayesian inference.

Additionally, in 2019 a research within this Knowledge Program a research was conducted where TNO proposed a reliability framework to evaluate the evolution of the annual reliability of existing sheet pile walls through the design lifetime using a simplified model in Blum's method not taking into account the soil-structure interaction.

<u>Onderzoeksvraag en -opzet (WAT)</u>

The aim of the research done in 2020 is the evaluation of the added value of measuring the structural response of sheet pile walls and anchors. The added value is assessed in terms of the probability of failure with respect to the ULS conditions of yielding of the sheet pile wall and tension failure of the anchor. The following research questions were stated at the start of the project:

- given that corrosion affects the safety of sheet pile walls, how does the added value of system identification change during the lifetime?
- given information about the serviceability limit state (SLS) related behaviour of the wall, what could be concluded about the reliability of the wall and the anchors at the ultimate limit state (ULS)?
- given information about the SLS behaviour of the anchor, what could be concluded about the reliability of the wall and the anchors at the ULS?

<u>Onderzoek zelf (aanpak, methode; het HOE)</u>

Within this Knowledge Program TNO and Deltares investigate the effect of corrosion on the annual probability of failure of sheet pile walls by combining numerical models of the soil-structure interaction and reliability methods. Furthermore, reliability methods will be compared aiming at an efficient estimation of the reliability over the lifetime of the structures in addition to methods proposed in 2019. Last, the added value of measuring the structural response of sheet pile walls and anchors should be evaluated.

The foreseen activities are (in order of execution):

- Further development parameter identification tool prob_taralli
- Case definition

- Prior reliability assessment with respect to the ULS of yielding of the sheet pile wall and to the ULS of tension failure of the anchor
- Parameter identification
- Posterior reliability assessment with respect to the ULS of yielding of the sheet pile wall and to the ULS of tension failure of the anchor
- Reporting

Onderzoeksresultaten en synthese

The project plan, in hindsight, seemed to be a bit ambitious. Therefore, not all research questions stated at the start of the project are addressed in this report and should be further considered in future research. The activities described in this report are the case definition and the prior reliability assessment with respect to the ULS of yielding of the sheet pile wall using different implementations of FORM. Also, a plan of activities is proposed for the parameter identification, using a toolbox developed at TNO.

A case study is used that makes use of a nonlinear model also considering soil-structure interaction implemented in DSheetPiling additional to the simplified Blum's method used in 2019. The sheet pile case study is taken from (Post, 2019). Two implementations of FORM were compared for the prior analysis. The FORM analysis using the implementation in UQLab did not converge, while the analysis using the implementation by Prob2B did.

In addition, the effect of measurements of the residual thickness and outcomes of proof load tests on the annual reliability of sheet pile walls with respect to the ultimate limit state of yielding of the steel profile has been investigated. This work is an addition to the reliability framework to evaluate the evolution of the annual reliability of existing sheet pile walls through the design lifetime proposed in the work of 2019.

The work of 2020 therefore consists of two reports:

1. An extension of the report of 2019 adding the effect of measurements and outcomes of proof load tests on the annual reliability of sheet pile walls based on the simplified Blums model
2. The prior annual reliability analysis of sheet pile walls using a nonlinear model including soil-structure interaction and comparison of reliability methods.

This sheet accompanies report 2.

Evaluatie en vooruitblik

The prior reliability analysis for the case study and comparison of different reliability tools turned out to be more challenging and time-consuming than expected. Future research should continue with current analyses extending the comparison with AK-MCS and SDARS. Also the parameter identification and posterior reliability analysis should start once the prior reliability results for all 75 years are available.

The reliability analyses accounting for measurements of the residual thickness and outcomes showed a reliability gain. The outcomes of such analysis could be used for which information and at which point in time should be gathered from the structure for an optimal assessment of the structural reliability.

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TNO report

Quantifying reliability of sheetpile walls

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Contents

1 Introduction

The performance of existing quay walls and sheet pile walls reduces in time due to corrosion-induced degradation of the steel profiles. The safety verification of structures that do not belong to the primary flood defense system is currently based on limit state verifications at the semi-probabilistic level according to national and international codes. The aging of the structures poses the challenge of knowing the actual and future safety levels of a large stock of structures, in order to support decision making related to lifetime extension.

The reliability requirements and partial factors behind the actual codes are in most cases based on a reference period of 50 years. The current approach is not suited for the assessment of existing structures for several reasons. Due to degradation, the safety evolution in time for periods shorter than the design lifetime is of interest for asset management. Moreover, the reliability of retaining structures like sheet pile walls and quay walls, is in most cases governed by time-invariant parameters (e.g. soil parameters and model uncertainties), leading to a considerable effect of past performance on the structural reliability. The actual approach to safety assessment is not capable of considering the effect of past performance on the reliability prediction for the remaining lifetime, as well as the effect of load tests, monitoring and inspections.

The objective of the research is the definition and implementation of a reliability framework for existing sheet pile walls and quay walls based on a 1-year reference period. This framework aims at overcoming the limitations of the current approach to safety assessment that is mentioned above. The framework consists of probabilistic models of the parameters governing the structural reliability, the approaches for updating the reliability of the structural elements based on load tests, monitoring and inspections.

In 2019 the research started and a reliability framework to evaluate the evolution of the annual reliability of existing sheet pile walls through the design lifetime and beyond was proposed based on FORM analysis and the Equivalent Plane (EP) method. The framework has been tested on a simple case using Blum’s method to describe the structural behavior of the wall. Failure of the wall because of yielding has been considered.

The aim of the research done in 2020 is the evaluation of the added value of measuring the structural response of sheet pile walls and anchors. The added value is assessed in terms of the probability of failure with respect to the ULS conditions of yielding of the sheet pile wall and tension failure of the anchor. The following research questions were stated at the start of the project:

- given that corrosion affects the safety of sheet pile walls, how does the added value of system identification change during the lifetime?
- given information about the serviceability limit state (SLS) related behaviour of the wall, what could be concluded about the reliability of the wall and the anchors at the ultimate limit state (ULS)?
- given information about the SLS behaviour of the anchor, what could be concluded about the reliability of the wall and the anchors at the ULS?

A case study will be used that makes use of a nonlinear model also considering soil-structure interaction instead of the simplified Blum's method. Furthermore, reliability methods will be compared aiming at an efficient estimation of the reliability over the lifetime of the structures in addition to the FORM/EP-method used in 2019.

The prior reliability analysis for the case study and comparison of different reliability methods turned out to be more challenging than expected. The project plan, in hindsight, seemed to be a bit ambitious. Therefore, not all research questions are addressed in this report and should be further considered in future research. The activities described in this report are therefore:

- Case definition (chapter 2)
- Prior reliability assessment with respect to the ULS of yielding of the sheet pile wall and comparison of reliability methods (chapter 3)
- Plan of activities parameter identification (chapter 4)
- Conclusions and recommendations (chapter 5)

2 Case definition

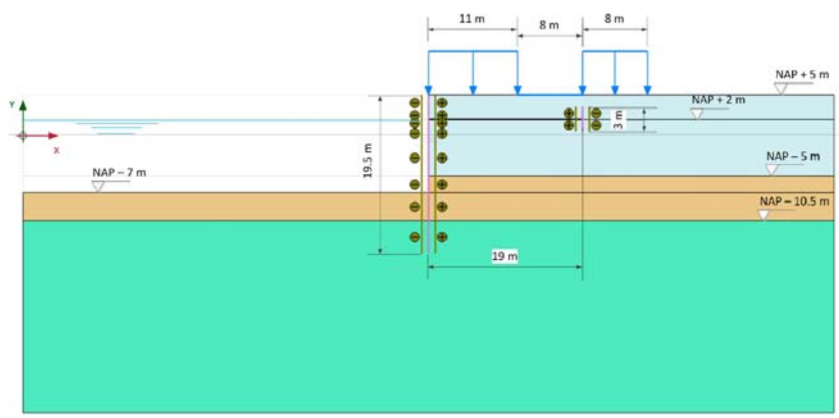
2.1 General

TNO worked on a case study with a sheet pile wall which allows for reliability updating using performance data. The sheet pile case study is taken from (Post, 2019). This model was set up in PLAXIS, but is transformed to DSheetPiling for this study by Deltares. A Deltares laptop was provided to TNO where the DSheetPiling model could be run for the purpose of the reliability assessment.

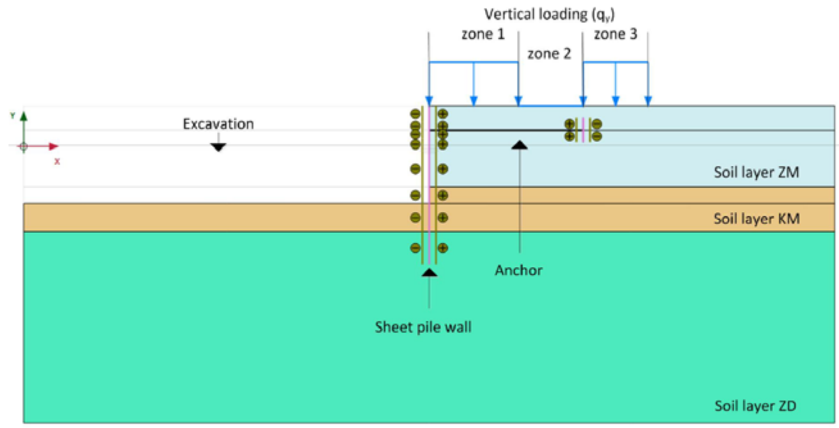
This chapter briefly describes the case study model defined by Deltares and the stochastic parameters for the reliability analysis. Regarding the case from (Post, 2019) some further adjustments, simplifications and additional information are used for this report. The input parameters for the model in DSheetpiling are adjusted so the results match the PLAXIS model in (Post, 2019) the best possible.

The case study is representative for a wall of a lock chamber in fresh water. Specific for this application are the high fluctuations of the water level, causing significant corrosion during the service life. The dimensions and elements of the case study retaining wall are presented in Figure 2.1.

In this research at start only failure of the sheet pile wall is considered as we want to evaluate the effect of increasing the lifetime and the introduction of thickness measurement data on the reliability of the wall. Failure of the anchor or soil structure is could also be considered next, but this was not yet realized in this research.



(a) Dimensions



(b) Elements

Figure 2.1: Schematisation of the case study retaining wall

2.2 Loads

Both the outside water level as the surcharge load are considered as random variables in this research. In Figure 2.1 three different zones for the surcharge loads are shown. However, in this research for simplicity we will consider only one uniform load on the surface. It is expected that this simplification has no big influence when only failure of the front wall is focused on. The expected value of the average water level is NAP+1.0 m. The expected value of the lowest water level, which is reached once in 50 years, is NAP – 1.0 m and the 'decimeringshoogte' is 0.3 m. From these characteristics an extreme value distribution for minima was derived. Both for a reference period of 50 years, but also translated to a reference period of one year.

2.3 Soil characterization

For the soil characterization the non-associative soil parameters are used. The parameters for the three different soil layers are presented in Table 2.1. The so called 'associative' soil parameters are used. With this approach we set the friction angle equal to the dilatancy angle. This approach will generate (more or less) same results as the 'equivalent' non-associative approach but will give more stable FE behavior and is thus preferred for automated (reliability) calculations.

Table 2.1: Soil parameters for the Mohr-Coulomb soil model (average values per layer)

Soil layer	**Material**	**γ [kN/m^3]**	**γ_{sat} [kN/m^3]**	**c_a' [kN/m^2]**	**φ_a* [˚]**	**R_{int} [-]**
1: SM	Sand, moderate	γ_{sat} - 2.0	20.7	0.0	38.9	0.90
2: CM	Clay, moderate	γ_{sat} - 2.0	17.4	14.8	26.9	0.67
3: SD	Sand, dense	γ_{sat} - 2.0	21.8	0.0	41.9	0.90

Further note:

- Cohesion for sand layers (SM and SD) set to zero in DSheetPiling.
- Dilatancy does not exist in DSheetPiling and is effectively zero (not in Table 2.1)
- The δ parameter in DSheetpiling is a measure for the friction between sheet pile wall and soil. δ is calculated as follows:

$$\delta_a^* = \tan^{-1}\left(R_{\text{inter}} \tan\left(\varphi_a\right)\right) \quad (2.1)$$

- The stiffness is modelled in a different manner in DSheetPiling. The average stiffness of the different layers is derived from CUR166 table 3.3. Fixed rations between k1, k2 and k3 of 1/0.5/0.25 and the same values for top and bottom of layer are used. The relevant parameters are given in Table 2.2.

Table 2.2: Stiffness values different soil layers (medium values per layer)

Soil layer	Material	k_1 [kN/m^3]	k_2 [kN/m^3]	k_3 [kN/m^3]
1: SM	Sand, moderate	20000	10000	5000
2: CM	Clay, moderate	4000	2000	1000
3: SD	Sand, dense	20000	10000	5000

2.4 Sheet pile wall and anchor

The sheet pile wall consists of AZ26 profiles, with properties according to Table 2.3. Only elastic behaviour of the wall is considered. Failure of the sheet pile is defined as exceedance of the yield strength.

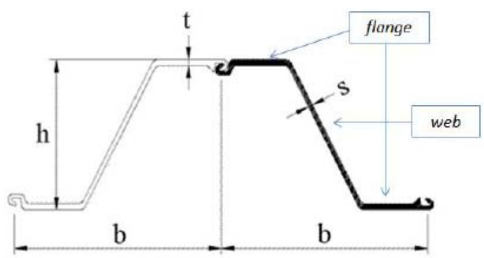


Figure 2.2: Sheet pile AZ26 profile [http://ds.arcelormittal.com]

Table 2.3: Sheet pile properties AZ26 profile

Parameter	Value
Width Z-element *b*	630 mm
Height *h*	427 mm
Thickness flange *t*	13 mm
Elastic section modulus W_{el}	2600 cm^3/m
Yield strength	240E3 kN/m^3

The anchor is also modelled in DSheetpiling (failure however is not considered). For the anchor rod an initial diameter of 63.4 mm is chosen with a yield stress of 355E3 kN/m^3. For the spacing between the anchors 1.6 m is chosen. The relevant properties for DSheetpiling are given in Table 2.4.

Table 2.4: Anchor properties in DSheetpiling

Parameter	Value
Anchor stiffness A_{anchor}	1942.5E-6 m^2/m
Yield force anchor	700 kN/m
Anchor length	19 m
Angle	0 degrees (horizontal anchor)

2.5 Corrosion

A uniform corrosion process is assumed and modelled by applying a reduced thickness. Different thickness reduction values exist for the different zones over the height and side of the sheet pile wall (contact with soil, water, air or both). In this study, however, only one zone is used. It is possible to add different corrosion zones to the DSheetpiling model.

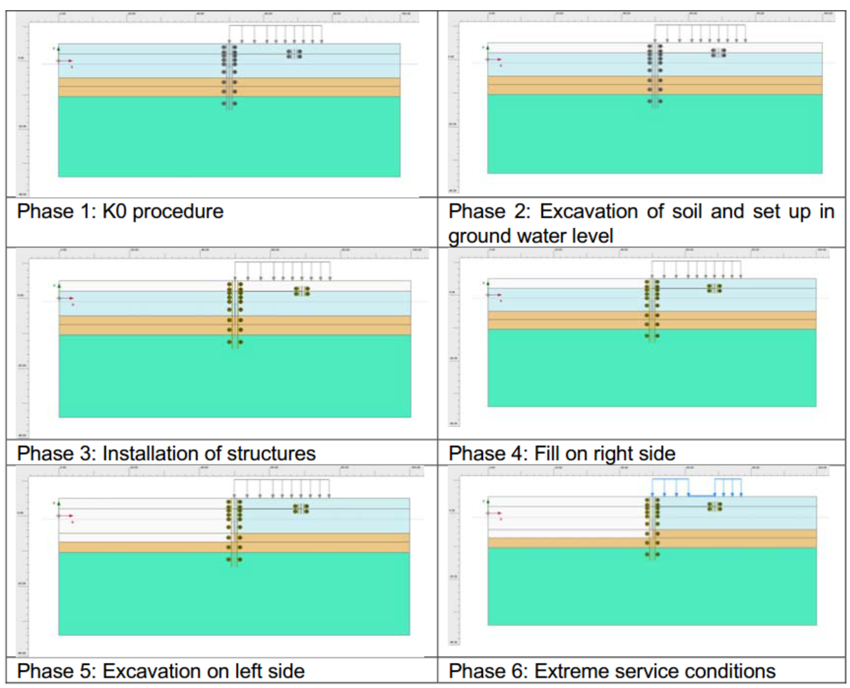
To calculate the stresses in the sheet pile wall the section modulus should be updated with the reduced thickness. This is performed using eq (2.2).

$$W_{corr} = (W_0 - 170\Delta t_i) \cdot 10^{-6} \ [\mathrm{m^3/m}] \tag{2.2}$$

We calculate in DSheetPiling always with uncorroded stiffness values, within the LSF evaluation we incorporate the corrosion. Effects are expected to be relatively small on structural forces and deformations.

2.6 Phasing

There are 6 phases distinguished and implemented in DSheetPiling (see Figure 2.3). For details on the construction phases see (Post, 2019).



Phase 1: K0 procedure

Phase 2: Excavation of soil and set up in ground water level

Phase 3: Installation of structures

Phase 4: Fill on right side

Phase 5: Excavation on left side

Phase 6: Extreme service conditions

Figure D.1 Screenshots of relevant phases

Figure 2.3: Construction phases implemented in DSheetpiling model

2.7 Stochastic properties

The stochastic properties of the parameters considered as random variables are given in Table 2.5. The other parameters relevant for the reliability calculation are considered deterministic. A reference period of one year is considered, which is relevant for the time-dependent variables.

Table 2.5: Stochastic properties for the reliability calculation

#	Soil layer	Parameter	Symbol	Unit	Distribution	Parameters
1	SM	Saturated soil weight	γ_{sat}	[kN/m^3]	Normal	μ = 20.7, CoV = 0.05
2	SM	Friction angle	φ_a*	[°]	Truncated normal [0,60]	μ = 38.9, CoV = 0.1
3	SM	Effective stiffness	k_1	[MN/m^3]	Lognormal	μ = 20.0, CoV = 0.3
4	CM	Friction angle	φ_a*	[°]	Truncated normal [0,60]	μ = 26.9, CoV = 0.1
5	CM	Stiffness	k_1	[MN/m^3]	Lognormal	μ = 4.0, CoV = 0.3
6	CM	Cohesion	c_a'	[kN/m^2]	Lognormal	μ = 14.8, CoV = 0.2
7	SD	Friction angle	φ_a*	[°]	Truncated normal [0,60]	μ = 41.9, CoV = 0.1
8	-	Lock bottom	z_{exc}	[+ m NAP]	Deterministic	-7.0
9	-	Water level	w_l	[+ m NAP]	Gumbel (minima)	Mean = -0.5685, Std = 0.1664
10	-	Load	q_y	[kN/m^2]	Truncated normal [0,100]	μ = 0.0, σ = 6.0
11	-	Thickness reduction	Δt	[mm]	Truncated normal [0,13]	μ = 4.65/75, CoV = 0.2

The parameters are uncorrelated apart from some of the soil parameters within one layer. The correlation for these parameters is given in the correlation matrix in Table 2.6.

Table 2.6: Correlation matrix of random soil parameters

#	Soil layer	Symbol	1	2	3	4	5	6
1		γ_{sat}	1	0.5	0.5			
2	SM	φ_a*	0.5	1	0.25		0	
3		k_1	0.5	0.25	1			
4		φ_a*				1	0.25	-0.65
5	CM	k_1		0		0.25	1	0.12
6		c_a'				-0.65	0.12	1

2.8 Limit state function wall failure

The research considers only structural forces and not deformations. A simplified approach is used to simply use the elastic capacity of the sheet pile wall. The limit state function becomes:

$$g = f_y - \frac{\left(\max\left|M_{DSheetpiling}\right|\right)}{W_{el}} \tag{2.3}$$

3 Prior reliability assessment

3.1 Methods annual reliability assessment

3.1.1 FORM

The First Order Reliability Method was performed both by the implementation in Prob2B and UQLab (Marelli, Sudret, & Schöbi, 2019). In Table 3.1 a comparison of the default and adjustable settings of both methods is provided.

Table 3.1: Possible settings in FORM implementations of Prob2B and UQLab

	Prob2B	**UQLab**
Algorithm	HLRF[1]	Improved HLRF (default), HLRF (optional)
Startingpoint	$U_i = 0$	$U_i = 0$ (default), possible to overrule
MaxIterations	100 (adjustable by 'itmax')	100 (adjustable)
Relaxation parameter	'relaxf' = 0.25[2]	Choice for next iteration sample cannot be influenced
DeltaU	0.3 (default) (adjustable by 'pertub')	10^{-3} (default), adjusted to 0.3
Gradient method	Centered (default)	Forward (default), adjusted to centered
Convergence criterion	Tolerance value on computed β and on limit state value in design point ('epsB' = 0.05 and 'epsZ' = 0.05)	Tolerance value on design point $\|U_{k+1} – U_k\|$ < 'StopU' = 10^{-4} and on limit state value $\|g(U_k)/g(U_0)\|$ < 'StopG' = 0.05
Programming language	Both implementations in Matlab and Python	Matlab

3.1.2 SDARS

SDARS is a response surface method using directional sampling. It is based on the Directional Adaptive Response surface Sampling (DARS) method described in (Waarts, 2000). In this method directional sampling is used to obtain a response surface which is fitted more accurately (more samples are taken) near the limit state and close to the origin in the u-space. One should be careful with non-convex and cross terms containing limit state functions. To use SDARS in the evaluation of failure of multiple years it should be possible to set the direction (prior estimation of reliability index, or λ-parameter) in which the algorithm should search for the design point. However, this functionality is not yet implemented in the current SDARS version callable through Python. This method is therefore not yet used in this report. The functionality is however, close to being implemented. This method could therefore be used in a future research project.

3.1.3 AK-MCS

Secondly, Adaptive Kriging Monte Carlo simulation is used to evaluate the annual reliability levels of the sheetpile wall. Adaptive Kriging Monte Carlo Simulation (AK-MCS) combines Monte Carlo simulation with adaptively built Kriging (a.k.a. Gaussian process modelling) metamodels. In AK-MCS, a Kriging metamodel surrogates the limit-state function to reduce the total computational costs of the Monte Carlo simulation. An adaptive experimental design algorithm is introduced to

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[1] Hasofer-Lind – Rackwitz-Fiessler algorithm

[2] 'Relaxf' is used to determine the next sample U_{k+1} = 'relaxf'*$U_{d,k}$ + (1-r)U_k, where $U_{d,k}$ is the estimated design value within the iteration.

increase the accuracy of the surrogate model. This is achieved by adding carefully selected samples to the experimental design of the Kriging metamodel based on the current estimate of the limit-state surface (g(x) = 0). The selection of the samples to evaluate next is based on a so-called learning function. New samples are added until a certain convergence criterion is met. Several learning functions and convergence criteria can be defined.

In this research the AK-MCS implementation (Marelli, Sudret, & Schöbi, 2019) of UQLab (Marelli & Sudret, 2014) is used. In UQLab an advanced option of AK-MCS is Adaptive PC-Kriging MCS (APCK-MCS). The default learning function is based on the U-function. It is defined for a Gaussian process as follows:

$$U(\mathbf{x}) = \frac{\left|\mu_{\hat{g}}(\mathbf{x})\right|}{\sigma_{\hat{g}}(\mathbf{x})} \tag{3.1}$$

$\mu_{\hat{g}}(\mathbf{x})$ and $\sigma_{\hat{g}}(\mathbf{x})$ are the prediction mean and standard deviation of $\hat{g}$. A misclassification happens when the sign of the surrogate model and the sign of the underlying limit-state function are not the same. The probability of misclassification is defined as:

$$P_m(\mathbf{x}) = \Phi\left(-U(\mathbf{x})\right) \tag{3.2}$$

The candidate sample is chosen as the sample that maximizes the probability of misclassification:

$$\mathbf{s}^* = \arg\min_{\mathbf{s}\in S} U(\mathbf{s}) \equiv \arg\max_{\mathbf{s}\in S} P_m(\mathbf{s}) \tag{3.3}$$

A convergence criterion related to the evaluated failure probability or reliability index is proposed.

The default input parameters for a AK-MCS analysis using UQLab are provided in Table 3.2.

Table 3.2: Default settings for AK-MCS implementation in UQLab

Parameter	Default value
Max samples	10^5
Samples per batch	10^4
Type of metamodel	Kriging (PC-Kriging also possible)
Learning function	U-function
Convergence criterion for adaptive experimental design (ED) algorithm	StopU (StopPf and StopBeta possible)
Number of samples added to ED for metamodel	10^3
Initial ED strategy	LHS
Number of samples in initial ED	Max(10,2*N) with N number of dimensions

The implementation of UQLab requires a MATLAB (MATLAB, 2019) installation. MATLAB could not be installed on the laptop provided by Deltares. However, the UQLab package and scripts necessary for the reliability analysis could be packaged into an executable to run the DSheetPiling case on the Deltares laptop. We have not yet been able to complete these AK-MCS analyses on the case study model, because debugging of the analysis is challenging in this workaround. It should be included in future research.

3.2 Results

3.2.1 FORM

3.2.1.1 Case study Blum

The implementation of UQLab requires a MATLAB (MATLAB, 2019) installation. MATLAB could not be installed on the laptop provided by Deltares. However, the UQLab package and scripts necessary for the reliability analysis could be packaged into an executable to run the DSheetPiling case on the Deltares laptop. To have more flexibility and control in trying out the UQLab implementation the prior reliability analysis using FORM was first performed using the case study defined in previous research (la Gasse & Allaix, 2019). This case study is based on the same input as the case study in (Post, 2019). Therefore, the results should be in a similar order of magnitude. The case study used in (la Gasse & Allaix, 2019) can run on a laptop which does have a MATLAB installation.

The reliability analysis was performed for the first year. The results are provided in Table 3.3. The analysis using the implementation in UQLab did not converge. This is also shown in Figure 3.1.

Table 3.3: Results FORM first year case study with Blum's model (la Gasse & Allaix, 2019)

	Prob2B	**UQLab**
β	4.86	4.99
P_f	5.96e-07	3.06e-07
Converged	Yes	no
g-value	-1.29	

In Figure 3.2 the computed sensitivity factors from the analysis using Prob2B were shown. The UQLab analysis did not yield sensitivity factors, because the analysis did not converge. The most important parameters for the first year seem to be: c_{CM}, φ_{SM}, φ_{CM} and f_y.

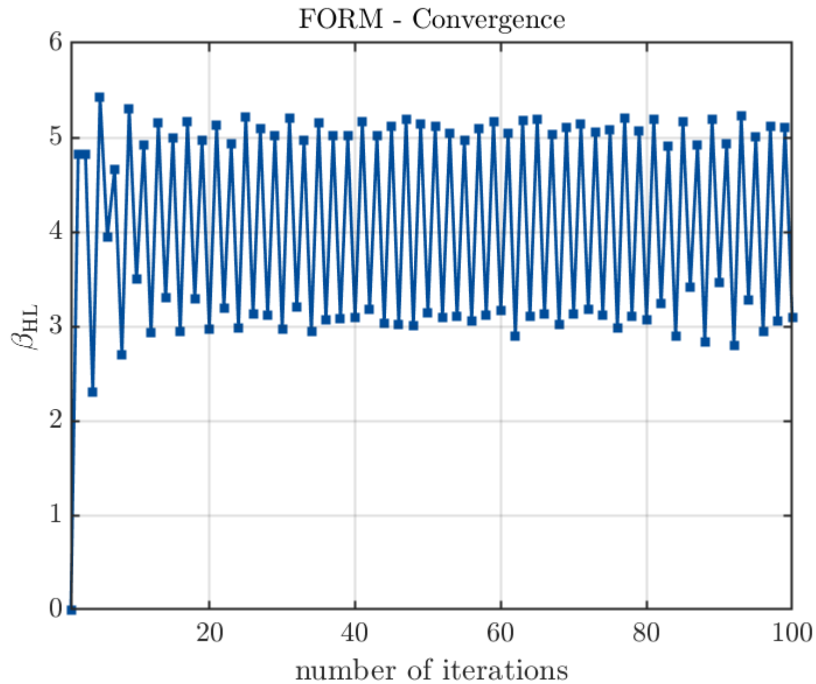

Figure 3.1: Convergence for β in UQLab FORM implementation

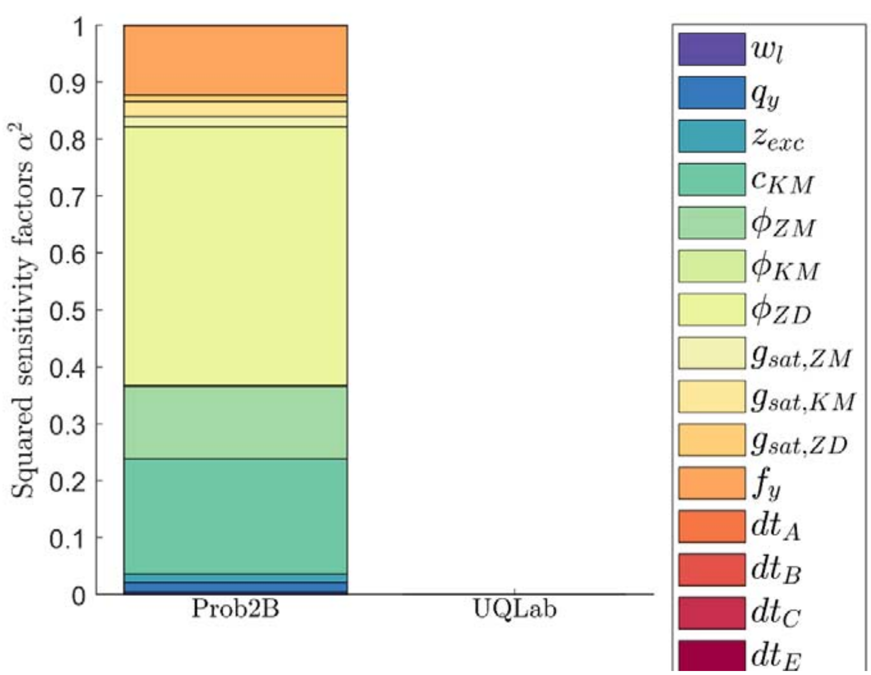

Figure 3.2: Sensitivity factors from FORM calculation year 1

Also the results for the last year of service life (75 years) are provided. They are compared to the reliability analysis in the first year. The reliability results are provided in Table 3.4. In Figure 3.3 shows the sensitivity factors for year 1 and year

75. The influence of other parameters becomes more dominant. The influence of c_{CM} and φ_{SM} is still substantial and the influence of f_y is similar between both years. However the influence of the thickness loss (zone C is only relevant for failure) is increased substantially, as expected.

Table 3.4: Reliability results year 1 and 75 using Prob2B FORM implementation

	Year 1	Year 75
β	4.86	2.01
P_f	5.96e-07	2.22e-02

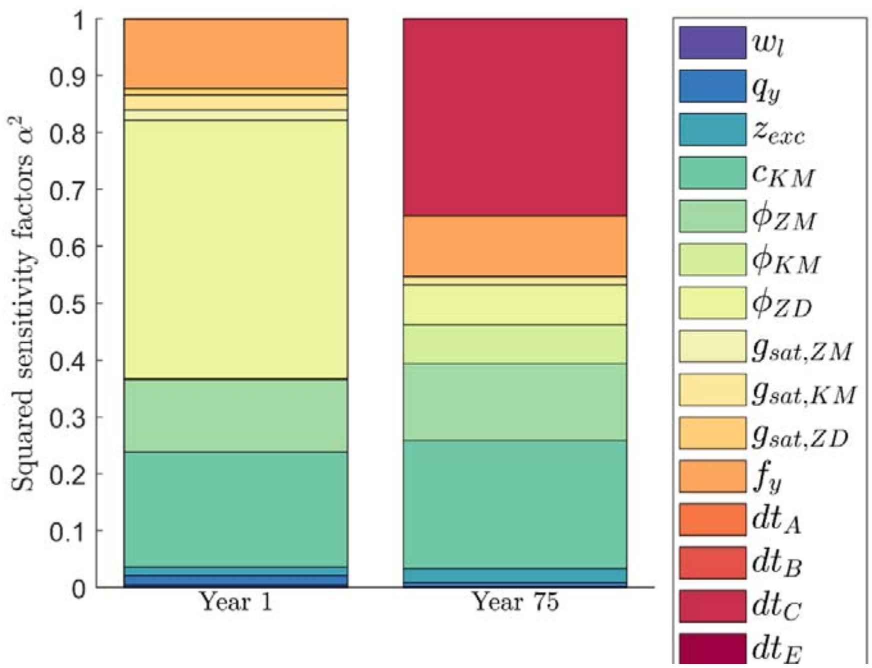

Figure 3.3: Sensitivity factors FORM analysis year 1 and 75 using Prob2B

3.2.1.2 *Case study DSheetpiling*

The case study model in DSheetPiling has also been evaluated using the FORM implementation of Prob2B (UQLab was not used as this provided non-convergence for the previous case). The run of every year requires about 1 hour of computation time (using DSheetPiling on a local desktop at Deltares, Delft, handled through a remote desktop connection for every sample). Therefore, the first 4 years of the sheet pile wall were analysed at first. The results are given in Figure 3.4 and Figure 3.5. This gives insight in the most relevant parameters in the analysis in the first years. The next step would be the analysis of the final year of the lifetime, year 75. Because of hardware problems, DSheetPiling could not be used for this analysis. The FORM reliability analysis using the hardware provided by Deltares takes about 55-60 minutes for every year of calculation.

For the first few years it seems that the most relevant parameters are φ_{SM}, and w_l. The influence of the different parameters compared between the Blum case and DSheetPiling case are very different. The reliability indices also differ a lot, as they are much higher than for the Blum case. This could partly be explained, because the Blum case has more stochastic parameters. One important parameter in the DSheetPiling case that is not considered stochastically is the yield strength of the sheet pile wall f_y.

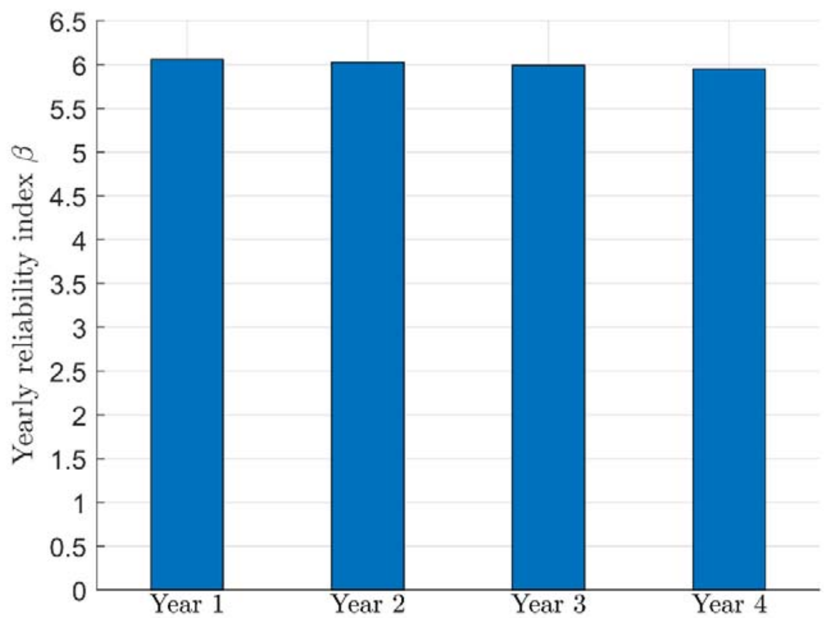

Figure 3.4: Reliability indices DSheetPiling case

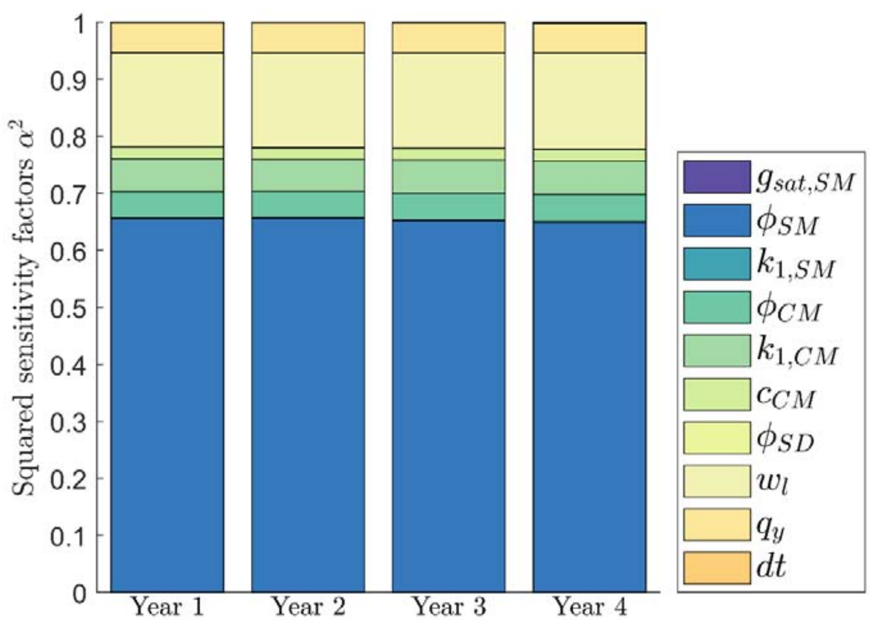

Figure 3.5: Sensitivity factors DSheetPiling case

4 Parameter identification

4.1 Tool description

A parameter estimation tool for statistical problems with a computationally demanding likelihood function (that is comparably expensive to evaluate as to simulate from it) has been developed at TNO. Part of the development was within this project. It is built to be able to contain:

- Model calibration → more accurate and informed structural analysis.
- Sensor layout design support.
- Damage identification.

Its main functionality is Bayesian inference for which it also contains functionalities as a log-likelihood builder, surrogate modelling (basic adaptive Gaussian process regression) and reliability analysis including three sampling techniques (not a replacement of traditional reliability methods but complementary).

4.2 Plan for DSheetPiling case study

The objectives of this activity are:

- to infer the parameters of the numerical model from measurements of the structural response at predefined points in time.
- to optimize the sensor layout
- to understand which parameters should also be measured (e.g. water level, water bottom level, surcharge load, residual thickness of the sheet pile wall)

The inferred parameters are:

- the soil parameters ((Chai, 2019) and (Post et al., 2019) can be used as a guidance for the choice of the parameters)
- the residual thickness of the sheet pile wall
- the residual area of the anchor

In this investigation, it is assumed that the data are gathered during a short period of time. Continuous monitoring of the response will not be considered.

In 2020 these activities have not yet been performed, because of challenges in the prior reliability analysis. The toolkit is available, but the prior reliability analysis results serve as a starting point and are required for the parameter identification. Therefore, it should be included in later research work.

5 Conclusions and recommendations

The aim of the research done in 2020 is the evaluation of the added value of measuring the structural response of sheet pile walls and anchors. The added value is assessed in terms of the probability of failure with respect to the ULS conditions of yielding of the sheet pile wall and tension failure of the anchor. The main research activities foreseen to achieve this aim were:

- Case definition
- Prior reliability assessment with respect to the ULS of yielding of the sheet pile wall and to the ULS of tension failure of the anchor and comparison of reliability methods
- Parameter identification
- Posterior reliability assessment with respect to the ULS of yielding of the sheet pile wall and to the ULS of tension failure of the anchor

The prior reliability analysis for the case study and comparison of different reliability tools turned out to be more challenging and time-consuming than expected. The project plan, in hindsight, seemed to be a bit ambitious. Therefore, not all research questions stated at the start of the project are addressed in this report and should be further considered in future research. The activities described in this report are the case definition and the prior reliability assessment with respect to the ULS of yielding of the sheet pile wall using different implementations of FORM. Also, a plan of activities is proposed for the parameter identification, using the developed toolbox at TNO.

A case study is used that makes use of a nonlinear model also considering soil-structure interaction implemented in DSheetPiling additional to the simplified Blum's method used in 2019. The sheet pile case study is taken from (Post, 2019). The case study is representative for a wall of a lock chamber in fresh water. Specific for this application are the high fluctuations of the water level, causing significant corrosion during the service life. The original case study was set up in PLAXIS, but is transformed to DSheetPiling for this research by Deltares. Regarding the case from (Post, 2019) some further adjustments, simplifications and additional information are used for this report. The input parameters for the model in DSheetpiling are adjusted so the results match the PLAXIS model in (Post, 2019) the best possible. A Deltares laptop was provided to TNO where the DSheetPiling model could be run for the purpose of the reliability assessment.

The prior reliability assessment started comparing FORM implementations in Prob2B and UQLab. In future research also a comparison with UQLab's Adaptive Kriging Monte Carlo simulation (AK-MCS) and TNO's adapted Directional Adaptive Response surface Sampling (SDARS) method should be made. The FORM analysis using the implementation in UQLab did not converge, while the analysis using the implementation by Prob2B did. This comparison was made using the simple Blum model used in 2019 (because in this way we did not need to use a Matlab executable on the Deltares laptop). The FORM implementation of Prob2B was therefore used on the DSheetPiling case as well.

The Blum case study resulted in a reliability index of 4.86 in the first year. The most important parameters for the first year seem to be: c_{CM}, φ_{SM}, φ_{CM} and f_y. In year 75 the computed reliability index is 2.01. The influence of other parameters becomes more dominant. The influence of c_{CM} and φ_{SM} is still substantial and the influence of f_y is similar between both years. However the influence of the thickness loss (zone C is only relevant for failure) is increased substantially in year 75, as expected.

The analysis using the DSheetPiling case for the first year yield a reliability index of 6.06. This is much higher than for the Blum case. This could partly be explained, because the Blum case has more stochastic parameters. One important parameter in the DSheetPiling case that is not considered stochastically is the yield strength of the sheet pile wall f_y. This should be considered in future research. For the first year it seems that the most relevant parameters are φ_{SM}, and w_l. The water level seems to have more influence in the DSheetPiling modelling as for Blum's model.

Future research should continue with current analyses extending the comparison with AK-MCS and SDARS. Also the parameter identification and posterior reliability analysis should start once the prior reliability results for all 75 years are available.

6 References

la Gasse, L., & Allaix, D. (2019). *Lifetime reliability analysis of a sheet pile wall.* KP Natte Kunstwerken 2019 - TKI updaten levensduur, TNO.

Marelli, S., & Sudret, B. (2014). UQLab: A Framework for Uncertainty Quantification in MATLAB. *The 2nd International Conference on Vulnerability and Risk Analysis and Management (ICVRAM 2014)* (pp. pp. 2554–2563). Liverpool, United Kingdom: University of Liverpool.

Marelli, S., Sudret, B., & Schöbi, R. (2019). *UQLab user manual – Structural reliability (Rare event estimation).* Zurich, Switzerland: Chair of Risk, Safety and Uncertainty Quantification, ETH Zurich.

MATLAB. (2019). *9.6.0.1072779 (2019a).* Natick, Massachusetts: The MathWorks Inc.

Post, M. (2019). *Case study. Kennisprogramma Natte Kunstwerken.* Deltares.

Waarts, P. (2000). Structural reliability using Finite Element Analysis - An appraisal of DARS: Directional Adaptive Response surface Sampling. Delft: Technische Universiteit Delft.