

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Probabilistic safety analysis of anchored sheet pilings

L'analyse probabiliste des palplanches ancrées

L.DE QUELERIJ, Manager of Engineering, Fugro Geotechniek B.V., Leidschendam, Netherlands

SYNOPSIS: A level II type probabilistic analysis to verify the failure mode "rotation of a sheet piling about the anchor rod" is presented. The model is developed for a multi layered soil system and incorporates the stochastic character of both the soil properties, the water levels, surcharges and the dredge level. It is shown from some practical cases that the model is a useful tool to determine the failure probability of a selected sheet piling design and the associated partial coefficients for the soil, load and geometry parameters.

INTRODUCTION

Anchored sheet pile wall design is conventionally assessed by evaluating the possible failure modes. The main modes are:

- rotation of the sheet piling about the anchor rod;
- bending failure of the sheet piles;
- failure of the anchor rod, the wale or the anchor block;
- geotechnical instability of the total sheet piling-soil-anchor system;
- failure of the passive soil zone caused by seepage flow effects related to piping or boiling.

Overall safety factors (FS) are derived for each mode. It is generally accepted that a single FS value is not a uniform measure of the safety level. The same FS value may correspond to different safety levels, depending among others on the variability of the strength and loading parameters. Failure probability is a more consistent way of assessing the safety level. Recent national and international codes of practice in geotechnical engineering show an increasing use of (semi)-probabilistic evaluation methods.

According to these codes the failure modes are generally associated with limit states of the structure, while sufficiently safe design values of the input variables are determined by means of partial coefficients (PC). In current practice the PC method is referred to as a level I probabilistic method. If the failure probability is calculated explicitly the method is a level II (approximate) method or level III (exact) method.

According to the limit state approach, each failure mode is described by a relationship in which the basic strength, loading and geometric variables X_1 , X_2 , $X(1)$ are incorporated. This is the performance function $Z(X)$. The hypersurface given by:

$$Z(X) = 0 \quad (1)$$

is called the limit state surface or boundary. Those combinations of input parameter values which give $Z(X) > 0$ is called the safety region, whereas the condition $Z(X) < 0$ determines the failure region. The failure probability P_f is defined by:

$$P_f = \Pr(Z < 0) \quad (2)$$

The reliability index β is frequently used instead of the P_f ; β is defined by:

$$\beta = \mu(Z)/\sigma(Z) \quad (3)$$

in which $\mu(Z)$ and $\sigma(Z)$ denote the mean value and the standard deviation of the performance function $Z(X)$. Assuming a Gaussian distribution of Z , the relationship between β and P_f is given by:

$$P_f = \Phi(-\beta) \quad (4)$$

where Φ is the cumulative density function of a standard Gaussian variate.

PREVIOUS STUDIES

The design of sheet pile walls shows several attempts to model one or more failure modes using a level II method. Smith (1985) presented some examples of modelling the rotational failure mode of anchored sheet piles, according to a first-order-second-moment (FOSM) probabilistic approach.

Matakeyma and Yasuda (1987) presented results of a study of a braced excavation. Both toe failure and bending failure of the sheet piles and failure of the struts and wales were evaluated in terms of failure probability.

Piping failure around sheet pilings was been probabilistically modelled by Zyl and Han (1981) based on an empirical performance function.

The total stability of the sheet piling-soil-anchor system can be modelled by probabilistic analysis in a similar way to that used for slope stability (Li and Lumb, 1987).

Spiereburg and Calle (1987) have carried out studies to systematically model the geotechnical failure modes of the sheet piles and anchor. For one of these failure modes the model SHEPRO has been developed (de Quelerij and Bijmagne, 1987).

PROBABILISTIC MODEL SHEPRO

Computer program SHEPRO models the most common failure mode: rotation of the sheet piling about the anchor rod. The performance function $Z(X)$ is:

$$Z(X) = M_p/M_a - 1 \quad (5)$$

where M_p and M_a denote the total moments about the anchor rod on the passive and the active sides of the sheet piling. These moments are the results of all

forces. They include those exerted by the horizontal effective soil stresses and water pressures.

The stresses are calculated assuming that full active and passive pressure development over the whole wall length. In case of vertical sheet piling and horizontal ground surfaces the horizontal active and passive earth pressure coefficients K_a and K_p are given by Bowles (1968), based on Coulombs theory. K_a and K_p are a function of the angle of internal friction of the soil ϕ' and the angles of wall friction δ_a and δ_p on active and passive sides. It is assumed that δ_a and δ_p are complete correlated with ϕ' according to $\delta_a = \delta_p = 2\phi'/3$. The effect of cohesion c' on the active and passive earth pressures is counted for according to the Rankine solution (Bowles, 1968).

Surcharge loadings are also included (Hoesch, 1986). Water pressures can vary both linearly (hydrostatically) or non-linearly with depth.

The following variables are input as stochastic parameters:

- soil parameters: unit weight γ , angle of internal friction ϕ' , effective cohesion c' : for each soil layer;
- water : pressure depth profiles;
- surcharges : magnitude and location
- geometry : soil layer levels.

The earth pressure coefficients can either be calculated automatically or be treated directly as stochastic input parameters.

The location of the anchor point and the length of the sheet piling are considered to be deterministic parameters.

The soil layers on active and passive side of the wall are defined separately. The soil properties on active and passive side can be either completely correlated (i.e. the properties are the same on both sides; hence the correlation factor $r = 1.0$) or can be considered as independent variables ($r = 0.0$).

The model incorporates different types of probability density functions (PDF) for the basic variables. However, for clarity the examples presented herein all deal with a normal or Gaussian type of PDF.

The probabilistic module is based on an advanced type of FOSM analysis. The performance function is linearized by means of a Taylor series at the design point $Z(X) = 0$. The reliability index β is considered as an invariant; thus β does not depend on the format of $Z(X)$ (Li and Lumb, 1987).

The output module of SHEPRO provides the failure probability and the reliability index β . In addition, the relative contribution of the variability of the input parameters to the total variance of $Z(X)$ are tabulated.

COMPARISON PROBLEM

To verify the accuracy of the SHEPRO program a comparison was made with the iterative analytical calculations by Smith (1985) for a one layer soil problem.

A propped cantilever sheet-pile wall is driven through cohesionless soil. The groundwater level is at dredge level as shown in Figure 1. The sheet pile and water geometry are assumed constant. Thus there are only three basic variables that affect the stability: the soils unit weight γ and the earth pressure coefficients K_a and K_p .

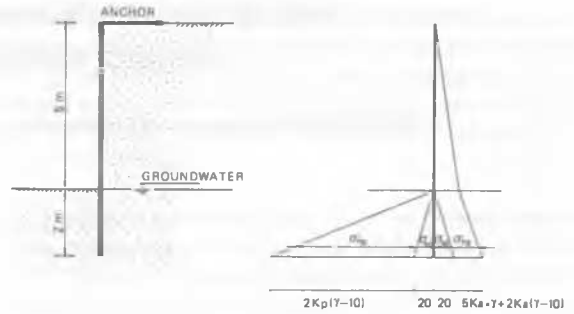


Figure 1. Example Smith: (a) wall details ; (b) stress distribution.

The basic variables and the results from the SHEPRO analysis are summarized in Table 1.

Table 1. Results SHEPRO Analysis Example Smith

Input					Output	
variable	mean	stand. dev.	units	corr. coef	design point	contrib. in % to variance of Z(x)
X(1)	$\mu(1)$	$\sigma(1)$		r	X(1)*	$\alpha(1)^2$
X(1): γ	20.0	1.0	kN/m ³	1.0	19.23	6.1
X(2): K_a	0.235	0.02	-	0.0	0.257	12.6
X(3): K_p	7.1	0.9	-	0.0	4.56	81.3
					$P_f = 8.7 * E^{-4}$	
					$\beta = 3.131$	

The SHEPRO results show very good agreement with those of Smith for both the design point values $X(i)*$ and the reliability index β . The same applies to the relative contribution of the variability of $X(i)$ to the total variance of $Z(X)$ as expressed in the factor $\alpha(1)^2$.

CASE STUDY

The banks of the Wessum-Nederweert Canal in the Netherlands are affected by waves generated by shipping. In order to prevent erosion an anchored sheet pile bank protection was designed. The construction aimed at retaining 4.50 m height of soil and the effect of surcharges q_1 and q_2 due to respectively traffic load and an elevation of the ground level on the land side. In addition a row of large trees, with a top height of 25 m, was present at a distance of 5 m from the sheet pile head. A 6 layer soil system is present (Figure 2).

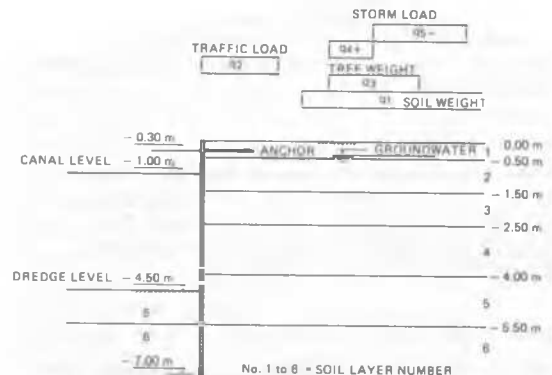


Figure 2. Sheet pile wall, Wessum-Nederweert Canal.

After the preliminary design, which was based on conventional stability analysis, was assessed the question arose whether storm loads on the trees could cause an additional risk.

To answer this probabilistic analyses were performed in which the tree weight is modelled by way of a vertical surcharge q3. The storm loading on top of the trees, inducing moment actions at the root level of the tree, were translated into two extra surcharges, a pressure surcharge (+) q4 and a tension surcharge (-) q5.

The surcharges, unit soil weight, friction angle of each soil layer, water levels and the dredge level were treated as stochastic variables (Table 2).

Table 2. Stochastic variables Wessum-Nederweert Canal

Variable X(i)	Sym- bol	mean μ(i)	stand. dev. σ(i)	unit	corr coef r.
X(1) : tree weight	q3	2.5	1.5	kN/m ²	-
X(2) : storm load +	q4	57.0	10.5	kN/m ²	-
X(3) : storm load -	q5	-12.0	2.0	kN/m ²	-
X(4) : unit weight	γ1	17.5	0.5	kN/m ³	-
to	to	to			
X(9) :	γ6	20.5			
X(10): friction	φ1	29.0	1.0	°	1.0
to angle	to	to			
X(15):	φ6	31.0	2.5		-
X(16): dredge level	dz	4.50	0.25	m	-
X(17): water level	gwa	-1.00	0.30	m	-
X(18): canal level	gwp	-0.40	0.15	m	-

In order to evaluate the effect of the trees analyses were performed both with (=standard case) and without trees and storm loading. In addition the effect of some design modifications were analysed. The results are summarized in Table 3. Only the basic variables which had a noticeable contribution to the variance of the performance function are shown.

Table 3. Results Wessum-Nederweert Canal

Variable X(i)	α(i) ² : contribution of X(i) to var(Z) in %				
	stan- dard	without tree	tree without storm	longer sheet pile	higher φ'6
X(3) : q5	1.1	-	-	0.8	1.2
X(15) : φ6	49.6	46.7	47.0	62.4	28.8
X(16) : dz	39.6	41.8	41.6	27.8	58.3
X(17) : gwa	0.9	1.2	1.1	0.8	1.2
X(18) : gwp	7.2	9.0	8.8	6.5	8.7
all others:	1.6	1.3	1.5	1.7	1.8
sum:	100.0	100.0	100.0	100.0	100.0
β	1.34	1.90	1.86	3.19	2.68
P _f	9.0xE-2	2.9xE-2	3.1xE-2	7.2xE-4	3.7xE-3

From the analyses it was concluded that the failure probability could increase a factor of 3 due to the storm loading on the trees. The effect of the tree weight was negligible. The uncertainties of the basic variables which dominate the variance of the stability are the friction angle of the passive soil layer at the toe of the wall, the canal dredge level and the groundwater level.

Since the reliability index of the standard design was lower than 2.5 to 3.0, which is generally accepted for permanent retaining structures, the effect of a longer sheet pile and the improvement of the passive soil zone (higher φ6) were analysed. The results are given in the right hand columns of Table 3. These design measures are the most effective means of increasing the reliability index to acceptably high levels.

PARTIAL COEFFICIENTS

According to the PC approach design values of the basic variables X(i) are derived by applying partial coefficients PC(i) to representative values of X(i). The partial coefficients should be selected in such a way that, given the variability of X(i) and its relative effect on the failure probability, the total safety level is sufficiently high.

From probability theory a direct relationship between PC(i) from level I and the failure probability from level II methods can be derived. If, for reason of clarity, the representative value of X(i) equals the mean value, this relationship can be described by:

$$PC(i) = 1 / [1 - \alpha(i) \cdot \beta \cdot V(i)] \tag{6}$$

where (i) refer to variable X(i) and V(i) denotes the coefficient of variation. The term α(i) denotes the sensitivity coefficient and counts for the relative effect of the variability of X(i) on the total failure probability and is given by:

$$\alpha(i) = \frac{\delta Z}{\delta X(i)} \cdot \frac{\sigma(i)}{\sigma(Z)} \tag{7}$$

$$\sum \alpha(i)^2 = 1 \tag{8}$$

where δZ/δX(i) denotes the partial derivative of Z with respect to X(i).

According to this relationship (equation 6) suitable PC(i) can be selected from level II probabilistic analyses. It is obvious that a higher PC(i) has to be applied if either α(i) or β or V(i) increases. From these parameters only the sensitivity coefficient α(i) is a structure related coefficient that can be calculated for a specified design by a level II analysis.

In order to obtain a better insight in the range of actual values α(i) of the main parameters considered in the sheet pile design a parametric study with the SHEPRO program has been performed. For a range of sheet piling structures to be applied in typical Dutch conditions (Spierenburg and Calle, 1988) the effect of the variability of the angle of internal friction φ', the effective cohesion c', the unit soil weight γ', the groundwater levels and the depth of dredging dz has been investigated.

A summary of some results is presented in Table 4. They are derived from a standard anchored sheet pile design with a retaining height of 5 m, an anchor depth of 1 m below ground level and penetration. The soil properties on those sides are assumed to be completely correlated. Both a single soil layer and a two soil layer system (denoted by the indexes 1 and 2) were considered. The values of the soil properties were assumed as μ(φ') = 25°, V(φ') = 0.10, μ(c') = 5 kN/m², V(c') = 0.20 and μ(γ) = 13.5 kN/m². The deviations from these values are given in Table 4.

Table 4. Calculated sensitivity coefficients $\alpha(1)$ and partial coefficients PC(1) from a parametric study.

Case	β	$\alpha(c')$	$\alpha(\phi')$	$\alpha(1)$ other	PC(c')	PC(ϕ')
one soil layer:						
standard	3.11	0.40	0.90	-	1.37	1.39
$V(\gamma') = 0.10$	2.89	0.42	0.89	0.16	1.33	1.35
$\sigma(dz) = 0.25$ m	2.22	0.34	0.68	0.66	1.18	1.18
$d = 3.0$ m	4.59	0.37	0.93	-	1.50	1.75
$V(c') = 0.30$	2.80	0.58	0.81	-	1.96	1.29
$\mu(\phi') = 20^\circ; \mu(c') = 8$	2.62	0.70	0.72	-	1.58	1.23
$\sigma(gwa, p) = 0.25$ m	2.81	0.39	0.82	0.41	1.28	1.30
two soil layers:						
$\phi'1, c'1$ standard	3.58	0.09	0.12	-	1.12	1.05
$\phi'2, c'2$ standard	-	0.42	0.90	-	1.43	1.47
$\phi'1, c'1$ standard	2.40	0.06	0.10	-	1.03	1.02
$\mu(\phi'2) = 35^\circ; c2 = 0$	-	-	0.99	-	-	1.31

Although the above parametric study does not exhaustively treat all type of conditions some general remarks with respect to the rotational failure mode of sheet piling structures can be forwarded.

The relative influence of the variability of ϕ' is high: $\alpha(\phi')$ varied from 0.7 to 0.99. This is due to K_p being strongly influenced by the wall friction angle δ and ϕ' ; a 10% variation of ϕ' implies a variation of the passive earth coefficient exceeding 20%. The sensitivity coefficient of c' depends strongly on the problem concerned and varies in the studied cases from 0.3 to 0.7.

The effect of the variability of the dredge line or the (ground) water levels is significant: $\alpha(dz) \approx 0.4$ to 0.65, whereas the effect of the variability of the unit soil weight is minor: $\alpha(\gamma') \approx 0.10$ to 0.20. The effect of variability of shear strength of the deeper soil layers on the failure probability is much greater than that of the top soil layers.

Codes of practice should provide partial factors that covers a wide range of structures. Since the sensitivity coefficient will depend on the problem concerned conservative partial factors should be chosen. To this purpose equations (6) and (7) may be used. These imply sensitivity coefficients in the order of $\alpha(c') = 0.7$ and $\alpha(\phi') = 0.95$ for the rotational failure mode.

CONCLUSIONS

In sheet pile wall design all possible failure modes and associated limit-states should be verified systematically. A failure probability is a better way of measuring the safety level than an overall safety factor. A set of partial coefficients of the main basic variables may be a good practical alternative to ensure an acceptable safety level, provided that these coefficients are adjusted to level II type probabilistic analysis.

The level II program SHEPRO enables probabilistic analyses of the rotational failure mode of sheet pile walls. This program incorporates the main basic geometry, surcharge and soil parameters as stochastic variables. From such analyses more insight can be obtained in the influence of the uncertainties of the different parameters for a specified sheet piling design.

From the parametric study of the rotational failure mode the required partial coefficients for the soil parameters may depend strongly on the design alternative concerned. For use in design codes it is therefore suggested that conservative values should be applied for sensitivity coefficients based on extensive parametric probabilistic studies. The codes should provide options to select more specific (i.e. less conservative) values of the partial coefficients. This is provided that these can be supported by level II probabilistic analyses.

ACKNOWLEDGEMENTS

The author would like to thank A. Jonker and J.G. Bastiaans of the Netherlands Ministry of Transport & Public Works for their support of this study.

The author is much indebted to Mr. S. Kay of Fugro McClelland Engineers B.V. for reviewing this paper and providing helpful comments.

REFERENCES

- Bowles, J.E. (1968). Foundation analyses and design, 268-280, McGraw-Hill Book Company, New York.
- Hatakegama, A. and Yasuda, N. (1987). Optimization of braced excavation using sheet piles by reliability-based design. Proc. ICASP 5, Vol 2: 893-900, Vancouver.
- Hoesch, (1986). Spundwand-Handbuch Berechnung (in German), Hoesch Stahl A.G., Dortmund.
- Li, K.S., and Lumb, P. (1987). Probabilistic design of slopes. Canadian Geotechnical Journal 24: 520-535.
- Quelerij, L. de, and Bijnagte, J.L. (1987). The effect of trees on anchored sheet piles; a probabilistic approach (in Dutch). Fugro Report No. D-0342, Leidschendam.
- Smith, G.N. (1985). The use of probability theory to assess the safety of propped embedded cantilever retaining walls. Geotechnique 35, no.4, 451-460.
- Spierenburg, S.E.J., and Calle, E.O.F. (1988). Safety of sheet piling structures, a probabilistic method for the determination of partial safety coefficients; (in Dutch). Report CO-247348/14, Delft Geotechnics.
- Zyl, D. van, and Harr, M.E. (1981). Seepage erosion analysis of structures. Proc. XICSMFE, Vol.3: 503-509, Stockholm.