A SEMI-PROBABILISTIC DESIGN PROCEDURE FOR SHEET PILES

METHODE PROBABILISTIQUE DE CONCEPTION DES PALPLANCHES

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SYNOPSIS: This paper reports the results of a study on the development of a probability based design procedure for sheet walls. Starting from an acceptable probability of failure or malfunctioning of the structure as a whole, target probabilities for the various individual failure mechanisms which play a role, have been derived using fault tree analysis. The acceptable probability of failure of the structure as a whole has been estimated by calibreation to rules of design, which are in use in nowadays pratice. This way it was aimed to derive a new code which more or less complies with current practice. By applying level II probabilistic analyses, target probabilities for the individual failure mechanisms have been translated into a system of partial safety factors, in line with the methodology adopted in the Eurocodes.

1 INTRODUCTION

Recent developments in the Netherlands impose the need for a design manual on sheet piling structures. In the first place new geotechnical design standards were introduced and coming into operation by the Dutch Building Law of 1992. These standards provide design requirements and calculation procedures for several types of geotechnical structures in accordance with the safety approach from the Eurocodes. However these standards specify only minor regulations for sheet piles. On the other hand the Dutch current practice for design of sheet piles show a great variety of rules, calculation methods and safety considerations.
Moreover technical developments regarding among others the effect of surcharge on sheet piles, probabilistic analyses and the use of finite element models were not yet accessible for the daily engineering practice.
Therefore public authorities, industry, contractors and consulting firms, brought together by the CUR (Dutch Civil Engineering Centre for Regulation and Codes), took the initiative to prepare a Design Manual on Sheet Piling Structures.
The Manual should provide information on the design requirements related to ultimate and serviceability limit states, the calculation methods for the concerning failure mechanisms, the site and laboratory investigations, the construction methods and guide lines for quality assurance and quality control.
Within the framework of this manual a study was performed by Delft Geotechnics and Fugro B.V. in order to support the development of a design procedure based on a consistent safety approach which fits into the semi-probabilistic system of the Eurocode.

2 SCOPE OF WORK

The aim of this study was to develop a set of probability based design rules for evaluating all the relevant failure mechanisms of a sheet pile structure. In engineering practice several potential failure modes are evaluated for the design of a sheet pile wall. The relevance of each mode depends on the particular circumstances of a project.

Safety requirements are evaluated in terms of the probability of failure P_f and the reliability index β. The following definitions and relationships apply:

$$P_f = P(Z < 0) \qquad (1)$$
$$\beta = \mu_Z / \sigma_Z \qquad (2)$$
$$P_f = \phi(-\beta) \qquad (3)$$

where $Z(x_1, x_2, .. x_n)$ is the performance function of the failure mechanism described by the basic geometry, soil, load and structural parameters x_i, μ and σ represents the mean value and the standard deviation and ϕ is the probability function of a standard Gaussian random variable.
The study consisted of the following successive phases:

- assessment safety categories represented by a required $\beta_{s;l}$ (s denotes index for the structure as a whole and l the safety category)
- translation of $\beta_{s;l}$ into the required reliability indexes $\beta_{f;i}$ (f denotes failure mechanism i) for the individual failure mechanisms using fault-tree analyses;
- translation of $\beta_{f;1}$ for one failure mechanism into a set of partial factors based on probabilistic level II type analyses, in which the relevant geometry, load, soil and structural material parameters are treated as stochastic variables;
- translation of $\beta_{f;i}$ for the other failure mechanisms (i > 1) into additional partial factors, if necessary;
- calibration of the derived set of partial factors with the current deterministic design practice by comparison of examples of recent sheet piling projects;
- development of a practical design code in which step by step the failure mechanisms are evaluated.

The aim is to develop a design code which is based on partial safety factors (margins), which replace the traditional overall factors. According to reliability theory, see Thoft-Christensen & Baker (1982) the partial factor $\gamma_{m;i}$ of variable x_i related to mechanism m is defined by:

$$\gamma_{m;i} = x_{i;rep} / x_{i;d} = (1 - k*V_i)/(1 - \alpha_i*\beta*V_i) \qquad (4)$$

where "rep" denotes representative value (5 pct quantile), "d" denotes the design value (which equals representative value divided by partial factor), V_i denotes coefficient of variation (equals standard deviation divided by mean value = σ_i/μ_i) and β denotes the required reliability index for the mechanism which is considered.

The coefficient α_i denotes the sensitivity coefficient, which reflects the relative effect of variability of x_i on the probability of failure and is defined as:

$$\alpha_i = \delta Z/\delta x_i * \sigma_i/\sigma_Z \quad (5)$$

where $\delta Z/\delta x_i$ denotes the partial derivative of Z with respect to x_i.

The sensitivity factors can be determined by Level II probabilistic analysis. In this study three typical sheet pile configurations have been analyzed and so typical values of α for each parameter were obtained.
The derived set of α factors and partial safety factors has been used for implementation of a design code. Different sets of partial safety factors are obtained for the various mechanisms which have to be evaluated in the design of a sheet pile wall. This would lead to a design procedure, in which the evaluation of different mechanisms would require different design values of the same soil parameters. For example, evaluation of toe stability, bending moment and anchor forces would require separate sets of input values of soil parameters and thus three calculation steps using the same numerical model. This would make render the process of designing a sheet pile wall tedious and impractical. So it was decided to use only one set of partial factors based on one mechanism (i.e. toe instability) to derive additional "overall type" factors for the evaluation of the other mechanisms.

3 TRADITIONAL APPROACH

Sheet pile wall design is conventionally assessed by evaluating the following failure modes:

1- toe instability: insufficient embedment depth leading to rotation of the wall;
2- plastic yielding of the sheet piles;
3a- large horizontal displacement of the anchor;
3b- insufficient strength of anchor rod leading to failure of the rod;
4- instability of the total sheet pile- soil-anchor system;
5- heave;
6- Bishop type overall instability;
7- piping.

Traditionally the failure mode associated with insufficient depth of embedment is evaluated by simple plastic models , for example Blum's method (EAU 1985). In this study the response of a sheet pile for given loading conditions is calculated using a Winkler model, considering a flexible beam supported by subgrade reaction. In this model the sheet pile wall is supported by horizontal springs and a concentrate load reflects the anchor force. The reaction of the springs, which are defined as elasto-plastic, depend on the local deformation of each spring. The application of this model for sheet pile walls has been outlined by Terzaghi (1955), as well as Rowe (1955). Many numerical programmes based on this concept have been developed.
In the conventional approach the dimensions (length, moment capacity and anchor resistance) are eventually found in one (final) calculation. For the length only a part of the maximum passive resistance near the toe may develop. The calculation with the required length results also in a bending moment and anchor resistance. In order to ensure an acceptable safety level these values are multiplied with an overall safety factor, which was traditionally in the order of 1.5. Traditionally a higher factor of safety is used for the design of the anchor rod.

Stability of the sheet pile-soil-anchor system is generally evaluated by the method of Kranz (EAU, 1985) assuming maximum shear mobilization along a straight sliding plane from the toe of the sheet pile wall till the toe of the anchor. Again conservative shear strength values and an overall safety factor (circa. 1.3) are being used.

Heave at the toe of a sheet pile wall that may occur in case of strutted piling walls with a relatively small depth of embedment in a soft cohesive soil is evaluated by bearing capacity formula (Terzaghi & Peck (1967). Starting with a pessimistic undrained shear strength a minimum overall safety factor is applied (circa 1.5).

The total stability of the excavation is generally evaluated with a Bishop type analysis.

Finally piping is evaluated by comparison of the actual creep ratio (= measure of the total seepage length) with the required ratio, empirically established by Lane (EAU 1985, Lane 1935).

In conclusion the current practice show a great variability of definitions of "conservative" values of soil parameters and overall safety factors. The actual or required safety in terms of failure probability is not defined. Neither it is clear if the different failure modes are designed at a comparable level of safety. The current design approach emphasizes the need for a consistent design approach based on well defined safety requirements.

4 FAULT TREE ANALYSIS

A fault tree provides an instrument to visualize and order the consequences of potential basic failure events which may lead to failure or malfunctioning of the structure as a whole. Figure 1 shows the fault tree which has been constructed for our study. It defines the top unwanted event "failure or malfunctioning", downwards tracing the underlying events which are potential causes, to a level at which one may recognize the basic events, i.e. the previously discussed failure mechanisms.

Evaluation of probability of top event:

Starting at the lowest level, the probabilities of occurrence of the basic failure mechanisms have to be determined. Then, one proceeds bottom up by analyzing the probabilities of "higher" events, taking into account the "and" /"or" character of combinations of lower events, or the conditional probabilities of an event, given the occurrence of a lower event. Very often, rigorous assumptions have to be made, for example concerning correlation among events which are combined in the fault tree, in order to avoid too much complexity of the analysis.

Assessment of target probabilities of failure:

When designing a probability based design code, a core task is to assess the acceptable probability of occurrence of the unwanted top event in one way or another. Then proceeding top down, this probability measure has to be "divided" over the events of the underlying level in the fault tree branches, etc., until the lowest levels have been reached. The process of division is far from unique. Most often it is a matter of trial and retrial to achieve a more or less consistent set of target probabilities for each of the fault tree events.

Several ideas to assess the acceptable probability of failure of the top event have been suggested in literature, among which economic optimization by probabilistic risk analysis and calibration to existing design codes and rules of practice.

Elaboration of an economical approach for some actual design may be complex, even for relatively simple structures. Therefore it has not been adopted in the present study.

Calibration to existing codes or design practice is indicated, if it is aimed to develop a new design code which more or less conforms with current practice. Such approach starts with the selection a set of hypothetical or really existing structures, so called test cases, designed according to the current rules of practice. Then by probabilistic analyses of potential failure mechanisms, probabilities of failure of the fault tree events can be evaluated. Though calculated probabilities of failure will in general differ from one test case to another, they provide us with a rough idea about which probabilities of failure are implicitly accepted by current practice. When designing a new code which is explicitly based on probabilistic principles, these probabilities serve as a starting point to assess the target probabilities associated with the fault tree events. Strictly speaking, each and every potential failure mechanism should be investigated this way, however, this is impractical and tedious. A pragmatic approach, which has been adopted in our study, is to calibrate only one important mechanism, and to assess the remaining target probabilities

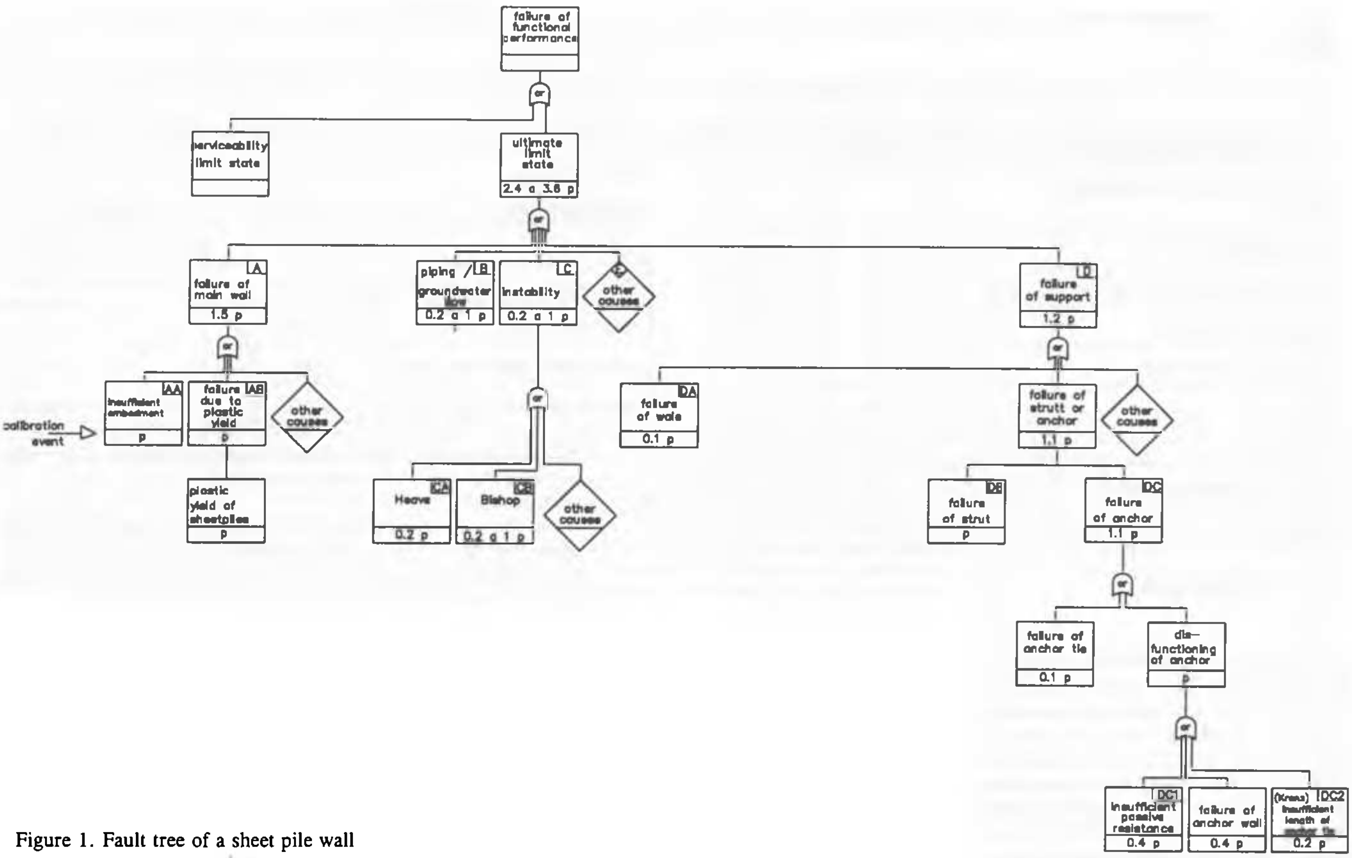

Figure 1. Fault tree of a sheet pile wall

of failure by heuristic and intuitive reasoning. As for the fault tree of figure 1 calibration analyses have been carried out for the mechanism "toe instability (insufficient embedment depth)" only, resulting in a target probability of failure (denoted by p in figure 1). From earlier studies (Spierenburg, 1989) it was concluded that there is no logic in assessing essentially different target probabilities for the mechanisms "plastic yield of the sheet piles" and "yield of support (strut or anchor)". Mechanisms, like for example "failure of anchor tie", "instability due to insufficient length of anchor tie (Kranz)" or "failure of wale" contribute to anchor failure, so target probabilities for these mechanisms should be assessed to consistent lower values. Target probabilities for other mechanisms, for example "piping" or "Bishop instability" have been assessed to values which are intuitively considered feasible. This way the event blocks of the various branches of the fault tree have been provided with target probabilities. Finally the resulting target probability for the top event has been evaluated by bottom up analysis of the tree, giving due consideration to correlation among the events.

5 PROBABILISTIC ANALYSIS OF MECHANISMS

The fault tree analysis shows that the probability of failure (or malfunctioning) of a sheet pile wall is dominated by three (main) failure mechanisms, i.e.

1- insufficient embedment depth,
2- structural failure of the wall elements by bending,
3- insufficient anchor resistance.

The three failure modes have been analyzed using a Level II probabilistic analysis. In the Level II methods the performance function Z is linearised in a suitable point. For the linearisation the (sensitivity) factors are introduced which reflect the influence of a certain parameter on the variations of the performance function. For this study the Level II general purpose code FORM, see Fiessler (1979), was used and an interface between the Winkler sheet pile programme and FORM was established.

In order to derive a range of possible α values three typical sheet pile configurations have been evaluated:

1 a canal lining
2 an excavation for a building pit
3 a quay wall

Each configuration was analyzed for a varying probability of failure. The influence of the following (stochastic) parameters has been evaluated.

1 soil strength		cohesion, angle of friction,
2 geometry		retaining height, water levels,
3 loads		overburden.

From the results the sensitivity factors for each parameter were derived. These sensitivity factors correspond to mechanism 1: toe instability. With these results partial safety factor for soil strength and the surface load and a margin for the geometrical parameters were calculated. These factors and margins depend on the required level of safety which is determined by the reliability index. Additional partial factors have been derived for the bending moment and the anchor force. These factors are introduced in order to incorporate the difference between the calculated moment or resistance, which are based on partial factors of mechanism 1, and the required values conforming to probabilistic analysis.

Probabilistic analysis have also been carried out for the remaining mechanisms as Kranz-type, Bishop-type instability and Piping. For these mechanisms the design procedure is the same as above. Partial factors and margins for mechanism 1 are used while an overall factor is derived to ensure the safety level for the particular mechanism.

Table 1. Reliability index of failure mechanisms for each safety category.

	I	II	III
Top event Reliability index β	2.5	3.4	4.2
Reliability indices partial mechanisms			
1 Toe instability	2.75	3.75	4.50
2 Moment capacity wall panel	2.75	3.75	4.50
3a Anchor resistance	2.75	3.75	4.50
3b Anchor rod strength	3.40	4.30	4.95
4 Kranz	3.25	4.15	4.80
5 Heave	3.25	4.15	4.80
6 Totaal (Bishop) stability	3.25	3.75	4.50
7 Piping	3.25	3.75	4.50

6 CALIBRATION

The result of the probabilistic analysis were a set of partial safety factors which depend on the reliability index. In order to chose the required level of safety a calibration was made against standard engineering practice. The three configurations have also been designed using a conventional approach. This resulted in a required embedment depth, which could be calibrated to a reliability index. In this way safety categories were defined. Using the fault tree the reliability index for each mechanism in each category could be calculated. The results for each category are given in Table 1. In Table 2 partial safety factors and margins for soil parameters, geometry and surface load are given. These factors should be applied to the characteristic values of the parameters i.e. the 5% lower boundary for the mean, based on a gaussian distribution.
A final calibration was made for a number of sheet pile walls from recent project which were designed with a traditional concept.

7 DESIGN PROCEDURE

As a result of the study a design procedure was proposed consisting of the following steps:

1. **Safety category**
   Determine safety category of the structure: I, II or III
2. **In-put parameters**
   Assess from the mean value and standard deviation the representative values (upper and lower) of the soil parameters (strength, stiffness, volume weight), anchor stiffness, load and geometry parameters.
3. **Minimum depth of embedment**
   Compute the minimum depth of embedment with a plastic soil model using the design values derived from the lower representative values and the concerning partial factors.
4. **Optimum sheet pile wall**
   Determine optimum depth of embedment (satisfying step 3) and sheet pile profile with a spring constant model using design values equal to the representative lower values of the parameters (all partial factors are 1.0)
5. **Control bending moment**
   Repeat the calculation of the optimum design from step 4 with the representative upper values of the spring constants. The maximum bending moment from 4 and 5 is taken as the representative bending moment. Check if the design bending moment (by applying the partial factor for the moment) does not exceed the design yielding moment (following from the partial factor for the sheet pile material: i.e. steel, concrete or timber)
6. **Control anchor**
   Select the maximum anchor force calculated in step 4 and 5 and repeat the most unfavourable calculation using the representative upper value of the anchor stiffness. The maximum calculated value from 4, 5 and 6 is taken as the representative anchor force.
   Check if the design anchor force (with the partial factors for the rod and the block respectively) does not exceed the design rod strength (including the factors for the rod material) and the anchor block resistance.
7. **Control deflexions**
   Select the maximum horizontal deflexion as the representative value from the calculations performed in step 4 and 5. Determine the design value of the deflexion using the partial factor for deflexion. Check if the design value does not exceed the maximum allowable deflexion.
8. **Control the remaining failure mechanisms**
   Check the remaining mechanisms using the design values of the basic variables in the concerning performance functions. This concern the models for overall stability (Kranz method), heave (Terzaghi) and piping (Lane).
   The representative value of the anchor force in the Kranz model should be taken as the maximum anchor force from step force from step 6.

Table 2. Partial safety factors γ

Safety category	I	II	III
Soil strength $X_d = X_{rep}/\gamma$			
cohesion	0.90	1.00	1.10
friction angle	1.05	1.15	1.20
Load $X_d = X_{rep}*\gamma$			
surface load	0.85	0.90	0.90
Geometry $X_d = X_{rep} \pm \gamma*\sigma_x$			
excavation height	1.60	2.20	2.60
groundwater level low side	1.30	2.70	1.10
groundwater level high side	0.66	0.85	1.50

The before described design steps fits very well within the current procedures of the daily engineering practice. It is felt that the new procedure leads to more balanced sheet piling structures where all the relevant failure mechanisms are evaluated at a comparable level of safety.

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