Reliability analysis of piles and pile groups based on dynamic load testing

Jimmie Andersson
ELU Konsult, Sweden, Jimmie.Andersson@elu.se

Gary Axelsson
ELU Konsult, Sweden

Anders Beijer-Lundberg,
ELU Konsult, Sweden

ABSTRACT
In Sweden, pile design of end-bearing piles is predominately based on high strain dynamic load testing. The design value is calculated using a partial factor design approach in accordance with the Eurocode. This approach is entirely based on the failure load of single piles. However, a pile group is normally a redundant, statically indeterminate structure, where failure of the geotechnical bearing capacity for one pile does not lead to total failure of the whole pile group. If the pile group carries a stiff structure, the advantage of load redistribution can be utilized to transfer loads between piles.
A comprehensive study was undertaken to examine whether a design in accordance with the Eurocode gives reasonable results for pile groups. This was assessed using a reliability-based design according to the First Order Reliability Method, "FORM". Both individual piles and pile groups were analysed according to the FORM-model and compared to the current design regulations. A case study was conducted based on data from high strain dynamic testing of piles. A comparison of the design was carried out according to the Eurocode and the FORM-analysis. The pile groups were modelled as a parallel system consisting of ductile elements and including the correlation between the piles.
The main results show that the measured variation in bearing capacity greatly affects the safety factor when comparing the FORM-analysis and the Eurocode. Furthermore, the correlation between piles is an important factor that has a major influence on the safety factor. When comparing single piles, the design according to the FORM-analysis yields safety factors of the same magnitude as the Eurocode. However, if the correlation between piles is small to intermediate, the results clearly show that a significant reduction in safety can be utilized for pile groups.
Keywords: Reliability analysis, Pile groups, High strain dynamic testing, β-method, FORM-analysis, Eurocode

1 INTRODUCTION

Major parts of Sweden are covered by glacial soils, frequently consisting of soft clays on top of relatively compact till and hard rock. End-bearing piles are installed by driving or drilling in areas with limited clay coverage. The pile tip of such piles is designed to reach the till or the rock layer. This method provides a stiff resistance, resulting in an end-bearing pile. The bearing capacity of the pile therefore mainly consists of the bearing resistance of the till or rock layer at the pile base. Because of the high strength of the soil or the rock located at the pile base, these piles are subjected to very high loads.

The geotechnical end-bearing capacity is normally very high on either till or crystalline rock. However, the very low shear strength of the clay means that the structural capacity with regard to buckling, normally calculated according to the method presented in Bernander & Svensk (1970), also has to be checked. The geotechnical bearing capacity is normally determined using high strain dynamic testing with the CASE-method and, in some cases, also CAPWAP-analysis. The end-bearing capacity of these piles typically displays some variation, as a result of the natural variability of the soil or rock beneath the pile toe. Some parts of the total variability may be due to variations in the transferred energy from the hammer during high strain dynamic testing.

When designing in accordance with the Eurocode, these variabilities are accounted for by the use of what is called "correlation coefficients" (ξ_5 or ξ_6). The ξ_5 is used together with the measured mean value and the corresponding partial coefficient. The ξ_6 is used together with the minimum measured value together with the corresponding partial coefficient. The mean value will govern the design value for piles with a calculated coefficient of variation (*COV*) for the measured pile bearing capacity less than 10-12 %. Whereas the minimum measured value will govern the design value for a coefficient of variation above this (Frank et al., 2004). In this way, the Eurocode strives towards handling the variability in the measured pile capacity, preventing either too unsafe or too conservative designs. The reader is referred to EN 1997-1 for more details regarding the design of piles conforming to the Eurocode.

A reliability analysis of singular piles and pile groups has been carried out in the current paper. The method used is a First Order Reliability Method (FORM) and is called the β-method. From the β-method partial safety factors can be calculated and calibrated. The partial safety factors obtained from the β-method have been compared with those obtained using partial coefficients according to the Eurocode. Both the original Eurocode as well as the Swedish national annexes have been compared with the reliability analysis. Furthermore, the effects of piles placed in pile groups have been evaluated using the β-method.

2 THE Β-METHOD FOR PILES

2.1 General formulation of the model

The β-method is a First Order Reliability Method (FORM) that can be used to evaluate the safety and probability of failure for different structures. The method requires knowledge of the probability distribution of the different model parameters, as well as knowledge of the coefficient of variation (*COV*) and the mean value (μ).

The method also includes the safety-index β. The safety-index is directly linked to the probability of failure and by that means a measurement of how safe a structure is. In the current paper, the chosen β-value for the performed analysis as a whole is 4.3, which is the specified value according to the Swedish national annexes (Boverket, 2015; Trafikverket, 2011).

A yield function is needed to perform FORM-analysis. The yield function is an analytical solution for the problem:

$$f = R - S \tag{1}$$

Where f is the yield function, R is the bearing capacity and S is the applied load. Failure will occur for $f \leq 0$.

A transformation is made to the standardized normal distribution according to Hasofer & Lind (1974). The newly-obtained standardized normal distribution can be expressed as:

$$Z_i = \alpha_i \cdot \beta \tag{2}$$

Where Z_i is the standardized normally distributed variable and α_i is the weighting factor for that variable. The weighting factor for each variable in the yield function can be calculated as:

$$\alpha_i = \frac{\frac{\partial f}{\partial Z_i}(\beta\bar{\alpha})}{\sqrt{\sum_{k=1}^{m}\left(\frac{\partial f}{\partial Z_k}(\beta\bar{\alpha})\right)^2}} \tag{3}$$

Where $\bar{\alpha}$ is a unit vector containing all weighting factors. As mentioned earlier, failure occurs when:

$$f(\alpha_1 \cdot \beta, \ldots, \alpha_m \cdot \beta) = 0 \tag{4}$$

Equation (3) and (4) can then be used to solve α_i and β by iteration. The design value obtained can then be calculated as:

$$x_i^* = \mu_i \cdot e^{-\alpha_i \cdot \beta \cdot COV_i} \tag{5}$$

Where x_i^* is the design value for variable i and μ_i is the mean value for variable i. The partial safety factor can then be calculated as:

$$\gamma_i = \frac{x_{k,i}}{x_i^*} \tag{6}$$

Where γ_i is equal to the partial safety factor for variable i and $x_{k,i}$ is the chosen characteristic value (normally μ_i).

2.2 *FORM-analysis for piles*

A pile group is normally a redundant structural system, e.g. Poulus (2005). The geotechnical bearing capacity for a pile in non-cohesive soil subjected to compression can be simplified as a perfect elastic-plastic behaviour, where increased loading leads to settlements without losing the bearing capacity of the pile (Fleming et al., 2009). This idealization, along with the empirical experience that pile groups normally are redundant structures, make it possible to model a pile group as a parallel system consisting of ductile elements.

In the current paper, a method originally created for lime-cement columns by Bergman (2015) has been adapted to single piles and pile groups. This adapted method takes into account that several uncertainties exist when high strain dynamic testing is used to verify the geotechnical bearing capacity. The uncertainties that the method takes into account are the measured coefficient of variation for the bearing capacity ($COV_{R,m}$), the measurement uncertainty which is always present when measuring (COV_{mf}). The bearing capacity of the pile is measured with a high strain dynamic method, e.g. the CASE-method outlined in Gravare et al., (1980), or the CAPWAP-method, discussed in Rausche et al., (1985). The uncertainty originating from this transformation is called the transformational uncertainty (COV_{tr}). Furthermore, the fact that not all piles are tested introduces another uncertainty, which involves the number of piles tested (N). This uncertainty is considered utilizing the methods described in Ang & Tang (2007). All of the uncertainties are considered log-normally distributed and recommended for material properties as well as model uncertainties in Eurocode 7, Appendix C, (Eurocode 7, 1997).

An interconnected pile group can be modelled as a parallel system consisting of ductile elements; the correlation between the different piles will affect the overall probability of failure for the pile group. This is explained by the fact that the mean value for the group will vary less than that of the different piles, as explained by Lo & Li (2007). Zhang et al., (2001) give the following formula which accounts for the possible variance reduction due to the pile-group:

$$COV_G = \frac{COV_{RS}}{n}\sqrt{n + \sum_i^n \sum_j^n \rho_{ij}} \quad , i \neq j \tag{7}$$

Where COV_G is the coefficient of variation for the pile group, COV_{RS} is the coefficient of variation for the piles, n is the number of piles in the group and ρ_{ij} is the correlation between pile i and j.

The variance reduction is dependent on the number of piles in the pile group. This, together with the information presented above, can be combined into the following equation in order to describe the total uncertainty in the system:

$$COV_{R,G} = \sqrt{\begin{array}{c}\left(COV_{R,m}^2 - COV_{mf}^2\right) \cdot \\ \left[\frac{1}{N} + \frac{1}{n^2} \cdot \left[(n^2 - n) \cdot \rho + n\right]\right] \\ + \frac{COV_{mf}^2}{N} + COV_{tr}^2\end{array}} \tag{8}$$

Where ρ is the average correlation between the piles in the group. Equation (8) is based on the principle of how coefficients of variations may be added, as presented by Goodman (1960).

3 COEFFICIENT OF VARIATION FOR DRIVEN CONCRETE PILES

A database containing over 600 high strain dynamic test results from 110 piling projects in Sweden has been analysed. The database was described and partly analysed in Axelsson et al., (2004). The database contains concrete piles driven to refusal in till. The piles were driven until 0-20 mm of sinking per 10 blows was obtained. The fall height and driving equipment may differ between projects. The main dimensions are 235 mm and 270 mm square piles. The number of tested piles in each project ranges from 2 to 12, as can be seen in Figure 1.

The calculated mean value of the $COV_{R,m}$ for these 110 projects is 10,5 %. As can be seen in Figure 1, most of the piles fall below the $COV_{R,m}$ of 20 %. The percentage of projects with the $COV_{R,m}$ below 10 % is 57 % and the $COV_{R,m}$ below 12 % is almost 73 %. The partial safety factors according to the Eurocode are calibrated to make the mean value control the design value when $COV_{R,m}$ is below 10-12 %. When $COV_{R,m}$ is above 10-12 % the lowest measured value will determine the design value (Frank et al., 2004).

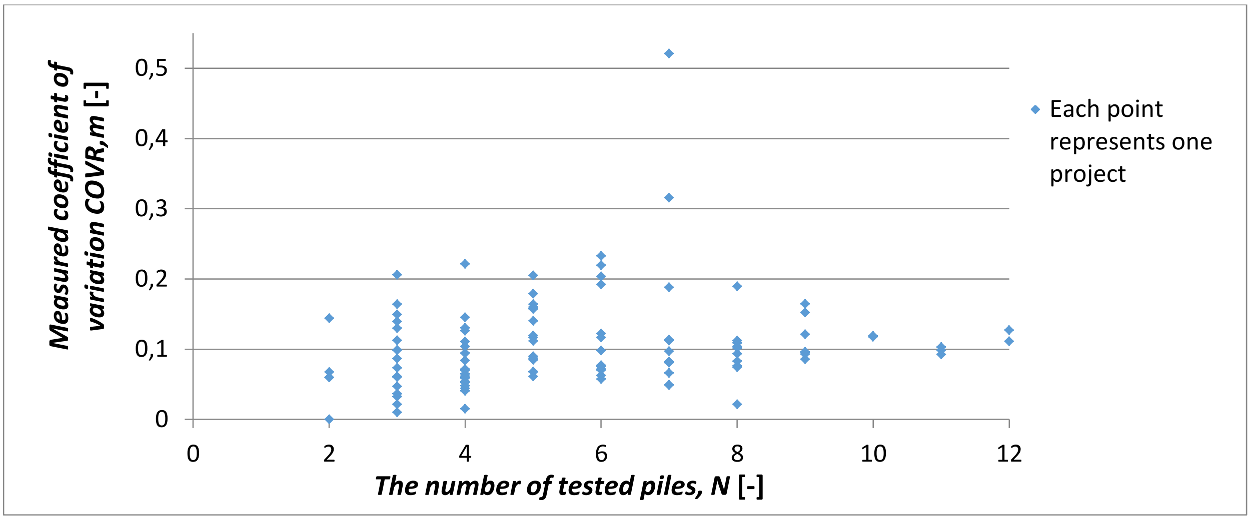

Figure 1: Measured coefficient of variation for concrete piles driven to refusal in till plotted against the number of tested piles. Each point represents one project.

4 ANALYSIS

4.1 General data for analysis

Reliability analysis with the FORM method was carried out with several uncertainties, as presented in Table 1.

Table 1: Coefficient of variation for the uncertainties in eq. (8).

	$COV_{R,m}$	COV_{mf}	COV_{tr}
CAPWAP	10 %	5 %	5 %
CASE	10 %	5 %	7,5 %

The number of tested piles as well as the number of piles in the group may vary between the different analyses and these are clearly specified. The choice of $COV_{R,m}$ in Table 1 is based on the reviewed database, Axelsson et al., (2004), as well as the limit where the Eurocode design values alternates from the mean value to the min value (Frank et al., 2004). COV_{mf} reflects that the ram may be aligned differently during the different blows - thereby reducing or increasing the energy in the blows. This has been estimated to vary between 3-5 %. In this paper 5 % is used. Measurement errors are always present when measuring is carried out. The choice of values for COV_{tr} is based partly on the model uncertainty of CAPWAP compared to static load tests in a study by Likins (1996).

4.2 Comparison between β-method and Eurocode for singular piles

A comparison between the β-method (FORM-analysis) and the Eurocode as well as both Swedish national annexes (Boverket (2015) and Trafikverket (2011)) has been carried out for both CAPWAP- and CASE-methods. Details on performance and evaluation of these methods may be found in Gravare et al., (1980) and Rausche et al., (1985).

Figure 2 shows that the required total safety factor according to the Eurocode results in the smallest total safety factor for both CASE and CAPWAP methods. When studying the results from the CASE-method, it is obvious that the β-method is the most favourable design method for this pile type design in Sweden. However, when comparing the CAPWAP-method, the Swedish national annexes are more favourable than the β-method.

In a comparison with the Eurocode, it should however be noted that the loads in Sweden are approximately 10 % lower for safety class 2. By increasing the Eurocode´s partial coefficient with approximately 10 %, comparable total safety factors for the bearing capacity are obtained. The strength of the group effect is related to the correlation between the piles.

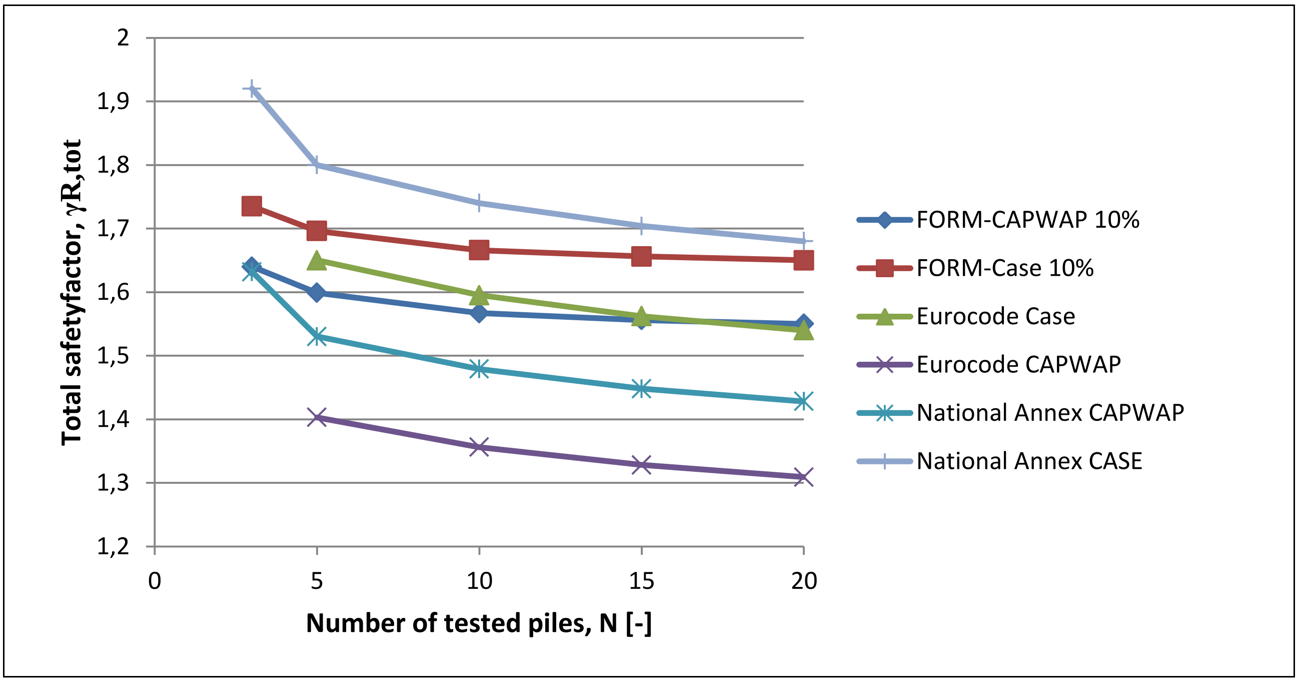

Figure 2: The total safety factor plotted against the number of measured piles.

A parametric study of how the correlation in the bearing capacity of the piles affects the total safety factor has been conducted. The number of tested piles was 5 and the correlation was varied between 0 and 1. The analysis was based on the CAPWAP-method (Rausche et al., 1985), which was used to evaluate the bearing capacity of the piles. Several different pile group sizes were tested.

As can be seen in Figure 3, the correlation coefficient ρ greatly affects the required total safety factor for the group. The required total safety factor is reduced from approximately 1.6 down to 1.39 or 1.34, depending on the size of the pile group. The ratio between ρ=1.0 and ρ=0 varies between 1.19 and 1.14, depending on the pile group size.

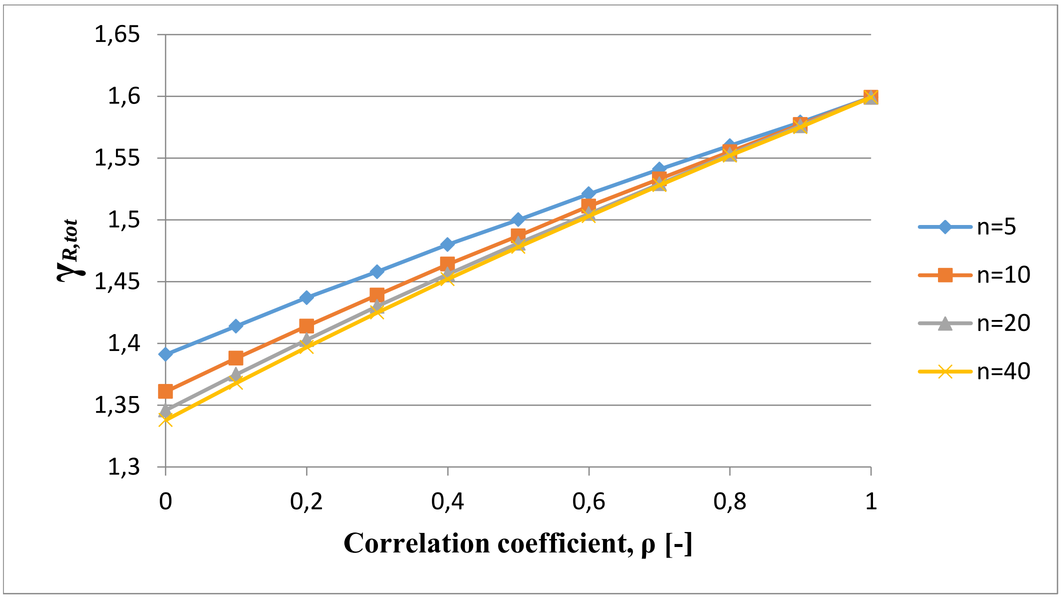

Figure 3: Total safety factor plotted against the correlation coefficient for different pile group sizes

4.3 Selected cases

Two cases have been chosen from the database in order to study how the original Eurocode (EN-1997-1) and the Swedish national annexes (SS-EN 1997-1) compare with the β-method. One case has a low coefficient of variation and the other has a higher coefficient of variation and record both where the mean value and the min value govern the design value. The two cases are named Case 1 and 2 respectively, and the test data is presented in Table 2 and Table 3. Case 1 is titled "Järnvägsbro över Vegeån" and is located close to Landskrona in the southern part of Sweden. The measurements were carried out during June 1996. The pile driving crane was of model "Junttan". The weight of the hammer was 5 tonnes and the fall height was 0.3 m.

Table 2: The measured pile capacity for Case 1

Pile No.	Measured capacity [kN]
1	1980
2	1850
3	1980
4	2060
5	1770
6	1760
7	1770

Table 3: The measured pile capacity for Case 2

Pile No.	Measured capacity [kN]
1	2050
2	2200
3	1840
4	1880
5	1990
6	1830
7	1530
8	1730
9	1770
10	2450
11	2070
12	2190

Case 2 is located at Bro, Gallsäter in the Höga Kusten area in the middle of Sweden. The measurements were carried out during January 1996. The pile crane was again a "Junttan". The hammer weight was 4 tonnes and the fall height was 0.4 m.

In Case 1 the measured coefficient of variation is 0.066. In Case 2 this is 0.127. The measured mean and min values for Case 1 are 1881 kN and 1760 kN respectively. For Case 2 the corresponding values are 1960 kN and 1530 kN respectively. The ratio between the measured min and mean value is 0.78 for Case 2.

4.4 Cases: Singular piles

The calculated total safety factors for the resistance obtained from the FORM-analysis (β-method) for Case 1 and 2 are presented in Table 4 below.

Table 4: The total safety factor for the resistance obtained from the FORM-analysis.

	Case 1	***Case 2***
CAPWAP	1.35	1.76 (1,38)*
CASE	1.47	1.85 (1,45)*

**Recalculated to the total safety factor for the resistance related to the minimum value*

It should be noted that when using the β-method, it is always the mean value and coefficient of variation that will control the design value. When using the Eurocode, the measured minimum value may control the design value. The total safety factors for Case 1 and Case 2 are presented in Table 5 and Table 6 respectively.

Table 5: The total safety factor for Case 1 (resistance), calculated using the Eurocode (EN-1997-1) and the national annexes

Case 1	**National annexes**	**Eurocode**
CAPWAP	1.51	1.38
CASE	1.78	1.63

When the FORM-analysis is compared with the Eurocode and the national annexes, it is clear that in Case 1, the FORM-analysis yields lower total safety factors for the resistance than the Swedish national annexes. The Eurocode's stated values will yield a slightly lower total safety factor for the resistance. When comparing the loads from the Eurocode with the Swedish national annexes, the loads are approximately 10 % smaller for the national annexes compared to EN 1997-1.To get a comparable total safety factor, the load according to the Eurocode would have to be increased with approximately 10 %.

Table 6: The total safety factor for Case 2, calculated using the Eurocode (EN 1997-1) and the national annexes

Case 2	**National Annexes**	**Eurocode**
CAPWAP	1.31*	1.20*
CASE	1.54*	1.43*

**Total safety factor for the resistance related to the minimum value*

Note that for Case 2, the measured minimum value is used to obtain the presented total safety factor. The total safety factors obtained from FORM-analysis can be recalculated to the total safety factor related to the min value by multiplication of the earlier calculated ratio (0.78) between min and mean value to 1.38 for CAPWAP and 1.45 for CASE.

The above presented analysis was performed assuming a deterministic load. If a live load with a *COV* of 30 % and a dead load with a *COV* of 10 % are introduced, the total safety factor obtained from the β-method will change. For this example, a ratio between live load and dead load of 0.2 is used. The obtained total safety factor from the FORM-analysis including variation of the load is presented in Table 7 below. This shows that a load model is required in order to obtain a correct total safety factor for the resistance. However, the results obtained with a deterministic load will be on the safe side.

Table 7: The total safety factor obtained from FORM-analysis (resistance) with variation of the load included in the analysis.

	Case 1	***Case 2***
CAPWAP	1.23	1,62 (1,27)*
CASE	1.34	1,71 (1,34)*

**Recalculated to the total safety factor for the resistance related to the minimum value*

4.5 Cases: Pile group

The positive effect of an interconnected pile group (i.e ξ may be divided by 1,1) is <u>not</u> taken into consideration when the design value is based on high strain dynamic testing according to the Eurocode (Frank et al., 2004). However, the group effect may be taken into consideration when using the calculations based on geotechnical investigation or static load tests (not logical at all). When using high strain dynamic testing in accordance with the Swedish national annexes it is on the other hand possible to use the positive effect of an interconnected pile group. The results are independent of the numbers of piles in the group. The correlation coefficients (ξ_5 and ξ_6) are divided by 1.1 to account for the group effects. Table 8 and 9 show the total safety factor calculated according to EN 1997-1 and the Swedish national annexes.

Table 8: Calculated total safety factors for Case 1 with regard to group effects.

Case 1	**National Annexes**	**Eurocode**
CAPWAP	1.37	1.38
CASE	1.62	1.63

Table 9: Calculated total safety factors for min values - Case 2 with regard to group effects.

Case 2	**National Annexes**	**Eurocode**
CAPWAP	1.20*	1.20*
CASE	1.40*	1.41*

**Should be used with the minimum measured value to obtain total safety factors for the resistance*

The pile group under analysis consists of 9 piles. Table 10 shows the results obtained from the FORM-analysis, with regard to group effects and pile group size.

Table 10: Calculated total safety factor from the FORM-analysis with an assumed correlation between the piles.

	Case 1 ρ=0.5	***Case 1 ρ=0***	***Case 2 ρ=0.5***	***Case 2 ρ=0***
CAPW	1.31	1.28	1.23*	1.10*
CASE	1.44	1.41	1.31*	1.18*

**Recalculated to the total safety factor for the resistance related to the minimum value*

As shown, Case 1 is affected less by the group effects than Case 2, simply due to the lower measured $COV_{R,m}$.

5 DISCUSSION

The 110 projects where driven concrete piles driven to refusal in till have been analysed, show that the limits and partial safety factors (partial coefficients, correlation factors and model factors) used by the Eurocode and the Swedish national annexes are reasonable for concrete piles at normal coefficients of variation. It is important to note that this analysis is based on concrete piles driven to refusal in till. However, a more precise installing method, such as drilling into the bedrock would probably yield a significantly lower $COV_{R,m}$ than that of driven piles. Piles drilled to and into the bedrock will most likely show less variability if the bedrock is of good quality – which is generally the case in Sweden. Assuming the same correlation coefficients in the Eurocode (ξ_5 or ξ_6) for piles showing different levels of measured coefficient of variation may result in either an unsafe or a conservative design. This is not reflected in the current design methods, resulting in a considerable variation of reliability depending on the soil conditions.

As shown from the two cases presented above, when considering the correlation coefficient for different piles in a group, the total safety factors for the resistance are reduced to very low levels. With regard to Case 2, the total safety factor for the resistance gets very low when the correlation between the piles is taken into consideration. For Case 2, the ratio between the minimum and the mean measured values are rather low. This greatly affects the converted total safety factor for the resistance. When the coefficient of variation is the same, but the quotient between the minimum and average measured value is higher, the total safety factor in relation to the minimum value will be higher.

The Eurocode is calibrated for a coefficient of variation of 10-12 %, in which the mean value controls the design value. This implies that piles with a lower coefficient of variation will be designed with a conservative approach. The codes need to be designed in this manner to avoid overtly complicated design schemes. However, using FORM-analysis or any other Reliability Based Design method, it is always possible to design for the current situation and soil variability. The model and soil uncertainties are possible to treat in a systematic fashion for both loads and uncertainties in bearing capacity without the risk of over- or underestimating the bearing capacity, provided that the uncertainties are estimated correctly. However, estimating the transformation error reflected in COV_{tr} is not easy. Even static load testing will contain a transformation error due to the short testing time. The transformation error will affect the calculated total safety factor for the resistance. For normal Swedish conditions, the measured geotechnical bearing capacity of the pile is normally on the safe side due to the small movement (set) of the pile toe during loading. This raises the question whether the transformation error needs to be taken into account since the measured geotechnical bearing capacity of the pile is lower than the actual fully mobilized capacity.

The presented cases show that the group effects resulting from the pile system correlation are less prone to affect the bearing capacity when the coefficient of variation for the bearing capacity is low. The possible reduction of the variance caused by taking the correlation between different piles into account is greater for pile groups with a larger coefficient of variation.

The current FORM-model does not take other significant factors into account. First, the bias is not considered when evaluating the geotechnical bearing capacity through high strain dynamic testing. When the piles are driven to full refusal where the measured set of the pile is none or small, the measured capacity from high strain dynamic testing is typically on the safe side (bias). The model does not take this effect into account. The pile needs to settle around 3-4 mm for its total bearing capacity to be fully activated. Zhang et al., (2001) present bias-factors for high strain dynamic testing. Zhang et al., (2005) have shown how much bias in the failure criterion can affect the calculated probability of failure. High strain dynamic testing is correlated towards Davisson´s failure criterion, which is a conservative failure criterion for piles. This could thereby be handled using bias-factors.

The presented model does not account for the variability of the loading conditions. A fully correct FORM-analysis should include the variability of the load effects, since a deterministic load model results in a conservative estimate of the system reliability. This is explained by the formulation of the weighting factors, α, that is a unit vector. If the load is not included, the weighting factor for the bearing capacity will become 1. Including the load in the yield function of the FORM-model, the resulting total safety factor for the bearing capacity is bound to be lower as is shown in Table 7 above. It can clearly be seen that the obtained total safety factor for the bearing capacity is affected when taking into account the uncertainties in the load.

To promote reliability based design through FORM-analysis or other methods, a load model consisting of mean values as well as the coefficient of variations for different loads need to be specified in the codes. The load model should also state which probabilistic distribution function is to be used and whether the loads should be modelled as normally distributed or log-normally distributed loads.

According to the authors´ knowledge with regard to Nordic conditions, the correlation between different piles has not been evaluated for end-bearing piles. Since the correlation greatly affects the evaluated total safety factor for the resistance, different pile types present an interesting area for further investigation. Chen and Zhang (2013) have analysed the correlation coefficient for piles driven in clay designed from CPT-tests. The correlation coefficient, which varies between 0.27 and 0.41 for the tested piles, is also shown to affect the probability of failure. It should however be noted that piles driven in clay and end-bearing piles may show significantly different correlation coefficients.

In this paper, the uncertainties with regard to the transformation error used were the values used when calibrating the Swedish national annexes. However, these factors influence the calculated total safety factor for the resistance and should therefore be investigated more thoroughly. The same applies to the uncertainty with regard to the measurement error which, in this paper, has been assumed to be 5 % for concrete piles driven to refusal in till.

In order to fully utilize the group effects, the superstructure supported by the pile foundation has to be able to transfer loads from the weaker piles to the stronger. In addition to this, it has to be investigated how many piles are able to work together. This is of particular importance if inclined piles are used in the designed pile group. In larger pile groups, it may be the case that all the piles are not able work together.

6 CONCLUSION

The reliability-based design method (FORM) has been used to analyze a database of end-bearing piles. The reliability of the piles with the current design method (Eurocode and national annexes) was compared with the β-method, including both model and transformation errors. The analysis shows that there is a difference between the current design method and the presented β-method. The current design method does not take the soil variability into account, resulting either in low or high reliability compared to the reliability-based design methods. When comparing the bearing capacity of piles in groups it is shown that the required safety factor for the resistance of a pile group is reduced with the increasing number of piles in the group. This is highly affected by the correlation between the piles in the group, which for end-bearing piles are relatively unknown. Reduced correlation between the piles reduces the probability of failure for the group, thus reducing the required total safety factor for the resistance. This is accounted for in the Swedish national annexes when using high strain dynamic testing but not in the Eurocode itself. The paper suggests some practical steps to improve the use of reliability-based design in order to control the safety and efficiency of interconnected pile groups in practical design.

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