An Approach for Assessing Geotechnical Reduction Factors for Pile Design

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Summary: Design of piles in Australia is based on the Australian Piling Code, AS 2159 – 1995. For geotechnical design of piles for the ultimate limit state, it is necessary that the designer selects an appropriate geotechnical reduction factor, ϕ_g, which is applied to the estimated ultimate geotechnical capacity. The Code tabulates various ranges of ϕ_g, depending on the method of analysis employed, the level of testing, and other conditions pertaining to the project. Selection of ϕ_g requires a good measure of judgement from the designer. This paper describes an approach for making a more rational selection of ϕ_g. It employs, in a simplistic manner, elementary reliability concepts and calibrates the level of uncertainty with commonly-employed overall factors of safety. It then derives geotechnical reduction factors from these overall safety factors. A process is then described for quantifying the level of uncertainty and risk for a particular project into an overall risk rating, which is then used to select an appropriate value of ϕ_g. The application of the method is illustrated with respect to a high-rise development in South East Asia.

INTRODUCTION

In the Australian Piling Code AS 2159-1995 (termed hereafter "the Piling Code"), when designing for the ultimate limit state (i.e. against failure of the piles), the following criterion must be satisfied for geotechnical failure, i.e. failure of the supporting soil or ground:

$$R_g^* \geq S^* \quad (1)$$

where R_g^* = geotechnical design strength (capacity), S^* = design action effect (a combination of factored loadings applied to the pile or group).

R_g^* is computed from the estimated ultimate geotechnical strength R_{ug} via a geotechnical reduction factor ϕ_g, so that:

$$R_g^* = \phi_g \cdot R_{ug} \quad (2)$$

R_{ug} is obtained via conventional calculation methods involving summation of shaft and base resistances of the pile, with allowances being made for such factors as group effects and cyclic and dynamic loading. Alternatively, it may be obtained by means of static load tests or by interpretation of dynamic pile load tests. The designer has the important responsibility of selecting an appropriate geotechnical reduction factor, ϕ_g, in Equation 2. The Piling Code tabulates ranges of ϕ_g, depending on the method of estimation of R_{ug} and the circumstances of the project (for example, the proportion of piles tested and the extent of ground investigation). Unfortunately, there can be some liberal interpretation of the appropriate value of ϕ_g to use for particular cases, and some designers may tend to be overly bold.

There appears to be some need to develop a more systematic approach to the selection of ϕ_g which allows some measure of engineering judgement but requires a proper assessment of the risks involved with a particular site and project. This paper sets out such an approach and employs elementary reliability theory, together with collective world-wide experience to arrive at appropriate ϕ_g values. In calibrating the proposed values of ϕ_g, reference will be made to commonly used overall factors of safety, which until recently, have been universally used for pile design. In this way, use can be made of experience and practice in many parts of the world.

SUMMARY OF COMMONLY USED OVERALL FACTORS OF SAFETY

Overall factors of safety have usually been based on experience and precedent, although some attempts have been made to relate safety factors to statistical parameters of the ground and the foundation type. A review of design practice around the world indicates that the range of values of factor of safety typically is 2.0 to 3.5, although there are some instances of values outside this range. Some of the more modern codes and recommendations distinguish between factors of safety based on mean values of resistance from load tests and minimum values, e.g. Eurocode 7-1.

INCORPORATION OF RELIABILITY CONCEPTS FOR ASSESSING FACTORS OF SAFETY

Relating Reliability Index to Overall Factor of Safety

Some simple concepts can be applied to assist in the assessment of factors of safety, and the general approach can be summarized as follows:

- The reliability index β, can be considered as a "normalized" factor of safety which has been normalized against the variability of the input parameters (Li et al, 1993);
- β can be related to the probability of failure, P_f. Assuming that the random variables are normally distributed, the following relationship holds:

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

  where $\Phi(\ )$ is the cumulative distribution function of a standard normal distribution.
- The reliability index can be related to the overall factor of safety (FS), the coefficient of variation of the loads (COVf), and the coefficient of variation of the resistance (COVq), with adequate accuracy, using the following approximation of Rosenblueth and Esteva (1972):

$$\beta = \ln(FS) / [COVf^2 + COVq^2]^{0.5} \qquad (3)$$

Thus, from the above relationship, the probability of failure can be linked to the variability of loads and resistances, and to the overall factor of safety.

Target Reliability Index

As a matter of sound design principle, it would appear appropriate to design for a target reliability index (i.e. a target probability of failure), and to adjust the factor of safety in accordance with the variability (i.e. the level of uncertainty) of the loads and resistances.

Target values of reliability index β have been suggested by a number of authors, for example, Barker et al (1991), Wu et al (1989), Meyerhof (1970), Paikowsky (2002), Kulhawy and Phoon (2002). There appears to be general agreement that, where piles are used in groups, the redundancy afforded by a pile group should allow a smaller reliability index (and hence a larger probability of failure) to be tolerated than when piles are used as isolated foundation elements. There are also indications that smaller values of reliability index may be relevant to driven piles than to bored piles, reflecting the larger levels of uncertainty generally present with the latter pile type. On the basis of the inferences from the published information, it would appear that reasonable target values for the reliability index may as follows:

- For pile groups with 4 or less piles per cap: $\beta = 3.0$
- For pile groups with 5 or more piles per cap, and the cap in contact with the ground: $\beta = 2.5$

PROCEDURE FOR ASSESSING RISKS, AND AN APPROPRIATE FACTOR OF SAFETY AND GEOTECHNICAL REDUCTION FACTOR

Factors Affecting Risk

There are several factors which affect the risk of failure of a foundation, and which should be taken into account when assessing an appropriate factor of safety for the design of pile foundations. Some of the more significant factors are as follows:

- The geological complexity of the site;
- The extent of ground investigation;
- The amount and quality of relevant geotechnical data;
- Method of assessment of geotechnical parameters for design;
- Amount of in-situ pile load testing;
- The method of utilizing the in-situ test data;
- The method of design adopted;
- Experience with similar foundations in similar geological conditions;

- The level of construction control;
- The level of performance monitoring during and after construction.

It would seem reasonable to expect that some assessment of each of these factors could be made in order to arrive at a rational basis for selecting an appropriate factor of safety for design. The level of redundancy is also a key factor, as indicated above, and hence should be given particular consideration. An approach that incorporates these issues is set out in the following section.

Risk Rating Scheme

A five-point risk rating scheme is suggested, as set out in Table 1. To assist in selecting an appropriate level of risk for each of the risk factors above, Table 2 gives some guidelines for the two extreme cases of very low risk (rating = 1 in Table 1) and very high risk (rating = 5 in Table 1). Weighting factors (either 1 or 2) are included to allow for a greater perceived significance of some of the risk factors. This weighting is somewhat subjective, and the values indicated in Table 2 may be open to some debate.

Having assessed the risk rating for each factor, an average risk rating, ARR, can be computed as follows:

$$ARR = \Sigma\, W_i .(IRR_i) \,/\, \Sigma\, W_i \qquad (4)$$

where IRR_i = individual risk rating (between 1 and 5) for each risk factor considered in Table 2, W_i = weighting factor for each risk factors considered. If not all the risk factors are relevant, the irrelevant factors are not included in calculating ARR (i.e. $W_i = 0$).

Relating ARR to Overall Factor of Safety

The next stage in the process is to try and relate the ARR to some measure of the uncertainty in the pile resistance. This can be done by assuming that the uncertainty can be expressed in terms of the coefficient of variation of the resistance. Clearly, the greater the coefficient of variation of the resistance, the greater is the uncertainty (and hence the risk) in assessing the pile capacity. Table 3 gives a suggested categorization of the average risk with the coefficient of variation of the resistance, COV_f and also with an overall risk category. While there is a considerable element of subjectivity in the values of COV_f in this table, it is considered that they represent a reasonable range of values of coefficient of variation of geotechnical parameters and resistances in practice (Kulhawy et al, 1991).

Having obtained the appropriate coefficient of variation of pile resistance to represent the ARR, it is now possible to use the relationships between overall factor of safety, coefficients of variation of load and resistance, and reliability index, to arrive at an appropriate overall factor of safety. In so doing, the following assumptions have been made:

i. The coefficient of variation of the applied loadings is 0.15;
ii. The target reliability index for foundations with a low level of redundancy is 3.0;
iii. The target reliability index for foundations with a high level of redundancy is 2.5.

The assumed coefficient of variation of load of 0.15 is the mean of values suggested by Paikowsky (2002) for dead load and live load (0.10 and 0.20 respectively). This approach may be slightly conservative for tall buildings, since in many such buildings, the dead load dominates, and hence the overall coefficient of variation of loads may be slightly less than the 0.15 value assumed.

Figure 1 shows the computed relationships between overall factor of safety FS and coefficient of variation for the above two target reliability indices. Clearly, the higher the coefficient of variation, the higher is the required overall factor of safety to maintain the target reliability index.

On the basis of Figure 1, it is possible to develop guidelines for the required factor of safety based on the ARR. Table 4 shows these guidelines for foundation systems with both low redundancy and high redundancy. A sub-division has been made between the risk categories previously defined in Table 3 so that the ranges of ARR are not too large. The values of factor of safety have also been rounded off in Table 4.

The following observations can be made from Table 4:

i. For low-redundancy pile foundation systems, the factors of safety range between 2.1 and 3.5, and this range is reasonably consistent with common practice;
ii. For high-redundancy pile foundation systems, the factors of safety are typically 0.3 to 0.5 below the values for low redundancy systems.

Relating ARR and Geotechnical Reduction Factor ϕ_g

The final step in developing a risk-based approach to selecting the geotechnical reduction factor ϕ_g is to assume an average value of load factor of 1.4 and then to convert the overall factors of safety in Table 4 to values of ϕ_g. The final result is shown in Table 5.

An advantage of adopting the approach suggested herein is that it is possible to assess the influence of taking measures to reduce one or more of the risk factors, for example, by carrying out additional load tests or basing the design on a lower bound or minimum values, rather than on a mean value.

Table 1. Summary of Individual Risk Level Ratings.

Risk Level	Individual Risk Rating
Very Low	1
Low	2
Moderate	3
High	4
Very High	5

Table 2. Summary of Factors to Be Considered for Risk Level Assessment.

Risk Factor	Weighting Factor W_i	Typical Circumstances For Very Low Risk	Typical Circumstances For Very High Risk
Geological complexity of site	2	Horizontal strata, well-defined soil and rock characteristics	Highly variable profile, and/or presence of karstic features, and/or steeply dipping rock levels, faults present on site
Extent of ground investigation	2	Extensive drilling investigation covering whole site, with geophysical data to "fill in" between boreholes	Very limited investigation, with few shallow boreholes
Amount and quality of geotechnical data	1	Detailed information on strength, compressibility, grading and permeability for all or main strata	Limited amount of data, restricted to SPT (or similar) data
Method of assessment of geotechnical parameters for design	2	Based on appropriate laboratory or in-situ tests, or load test data	Based on non-site-specific correlations with (for example) SPT data
Design method adopted	1	Well-established and soundly-based method(s)	Simple empirical methods, or sophisticated methods which are not well-established
Amount of in-situ testing	1	Comprehensive foundation testing program (on site)	No in-situ foundation testing
Method of utilizing results of in-situ test data	2	Design values based on minimum measured values, or piles loaded to failure	Design values based on maximum measured values, or test piles loaded up only to working load
Experience with similar foundations in similar geological conditions	1	Extensive	None
Level of construction control	2	Detailed, with professional geotechnical supervision, construction processes well-established and relatively straight-forward	Very limited or no involvement by designer, construction processes not well-established or complex
Level of performance monitoring during and after construction	1	Detailed measurements of movements and pile loads	No monitoring

Table 3. Assumed Values of Coefficient of Variation for Various Average Risk Rating Values.

Average Risk Rating (ARR)	Overall Risk Category	Assumed Coefficient Of Variation Of Pile Capacity*
≤1.5	Very Low	0.20
1.5 - 2.5	Low	0.25
2.51 - 3.5	Moderate	0.30
3.51 - 4.5	High	0.35
>4.5	Very High	0.40

* values adopted for assessment of factor of safety in Table 5.

Table 4. Overall Factor of Safety Versus Average Risk Rating.

Average Risk Rating (ARR)	Overall Risk Category	Factor Of Safety For Pile Systems With Low Redundancy	Factor Of Safety For Pile Systems With High Redundancy
≤1.5	Very Low	2.10	1.85
1.5 - 2.0	Very Low - Low	2.30	2.00
2.01 – 2.5	Low	2.50	2.20
2.51 - 3.0	Low - Moderate	2.70	2.35
3.01 – 3.5	Moderate	2.90	2.50
3.51 – 4.0	Moderate - High	3.10	2.65
4.01 – 4.5	High	3.30	2.80
>4.5	Very High	3.50	3.00

Table 5. Geotechnical Reduction Factor ϕ_g Versus Average Risk Rating.

Average Risk Rating (ARR)	Overall Risk Category	ϕ_g For Pile Systems With Low Redundancy	ϕ_g For Pile Systems With High Redundancy
≤1.5	Very Low	0.67	0.76
1.5 - 2.0	Very Low - Low	0.61	0.70
2.01 – 2.5	Low	0.56	0.64
2.51 - 3.0	Low - Moderate	0.52	0.60
3.01 – 3.5	Moderate	0.48	0.56
3.51 – 4.0	Moderate - High	0.45	0.53
4.01 – 4.5	High	0.42	0.50
>4.5	Very High	0.40	0.47

APPLICATION OF PROCEDURE TO A TYPICAL CASE

The above procedure for assessing the appropriate factor of safety has been applied to the case of a high-rise development in Hong Kong, involving the use of shaft grouted bored piles. The assessment of the average risk rating ARR is set out in Table 6. It is found that ARR is 2.87, which is within the range of an overall "low to moderate" risk rating. The proposed foundation system is highly redundant, since it involves a large number of barrettes, a perimeter diaphragm wall, and a thick pile cap connecting the elements. Thus, from Table 5, an appropriate geotechnical reduction factor for a highly redundant foundation system in the average risk category is 0.60.

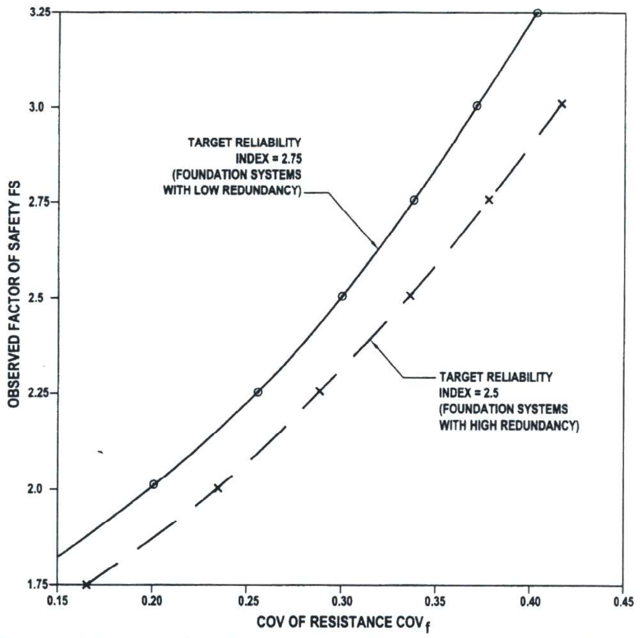

Figure 1. Relationship Between Factor of Safety and Coefficient of Variation for Target Reliability Indices

Table 6. Risk Rating Assessment for Shaft Grouted Bored Piles in Hong Kong.

Factor	Weighting Factor W_i	Risk Rating Irr_i	$Irr_i.W_i$	Comments
Geological complexity of site	2	5	10	Steeply dipping bedrock, variable SPT values, fault across site
Extent of ground investigation	2	2	4	Comprehensive ground investigation, including geophysical data
Amount and quality of geotechnical data	1	3	3	Moderate amount of geotechnical data, primarily SPT data
Method of assessment of geotechnical parameters for design	2	2	4	Based on results of in-situ test data on shaft grouted barrettes, taking account of other data
Design method adopted	1	2	2	Well-accepted approach, including consideration of block mode of failure. Skin friction based on SPT rather than effective stress
Amount of in-situ testing	1	2	2	5 tests carried out preconstruction, additional tests during construction
Method of utilizing results of in-situ test data	2	3	6	Based on maximum values from in-situ test data, but compensated by reference to test data from other sites and very conservative assumption of end bearing.
Experience with similar foundations in similar geological conditions	1	4	4	Limited previous experience with shaft grouted bored piles in Hong Kong
Level of construction control	2	3	6	Presumed high level of control with designer on-site and in control, but uncertainty regarding the shaft grouting process
Level of Performance Monitoring during and after construction	1	2	2	Measurements of settlement assumed to be taken; pile loads not to be measured
TOTALS	*15*	*28*	*43*	
AVERAGE RISK RATING (ARR)			**2.87**	**OVERALL RISK CATEGORY = LOW - MODERATE**

It should be noted that, in this case, an ARR value of 2.8 would be obtained if equal weighting factors were adopted in the risk rating assessment. This would lead to the same low-moderate risk classification, and the same recommended geotechnical reduction factor of 0.60.

CONCLUSIONS

A procedure for assessing an appropriate geotechnical reduction factor for pile design has been developed and described. This procedure employs simple probabilistic methods, in combination with engineering judgement, to arrive at an overall risk rating for a project. The steps involved are:

- Assessment of the individual risk ratings for a series of factors affecting the design and construction and performance of bored pile or barrette foundations;
- The assessment of an overall risk rating;
- The assignment of an appropriate factor of safety, and then the geotechnical reduction factor ϕ_g, depending on the level of redundancy of the foundation system and the overall risk rating.

This approach should provide a more logical process for assessing ϕ_g, while retaining a good measure of engineering judgement.

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