Overview and Analysis of New International Code of Practice for Pile Foundation

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요 지

하중과 저항계수 설계론을 채택하는 극한상태설계법이 지반공학분야에도 세계적인 추세로 적용되고 있다. 현재의 허용응력설계법은 논란을 거듭하면서 극한상태설계법으로 교체되리라 전망된다. 최근에 북미와 유럽에서 시방서로 발간되면서 본격적으로 지반공학설계분야에 관심이 되고 있다. 이러한 세계적인 설계이론을 적절히 비교분석함은 장차 한국의 건설여건에 맞도록 적용하는데 기본요건이라 하겠다. 본 논문에서는 극한상태설계법을 검토하고 말뚝설계에 하중과 저항계수 설계론을 적용하여 분석하고자 한다.

Abstract

Limit state design(LSD) principles employing load and resistance factor design(LRFD) are coming into use in geotechnical engineering community around the world. Current working(allowable) stress design principles are expected to be replaced by LRFD method in the near future. North America has recently adopted LRFD principles, and European community has also developed its own code called "Eurocode" based on partial safety factor design, which is essentially the same as LRFD.

Relevant review and analysis of new global design codes are prerequisites to adopting these codes in the Korean construction industry and in the Korean foundation design practice. This paper reviews geotechnical aspects of LRFD and Eurocode, and analyzes the geomaterial resistance factors in LRFD for the design of axially-loaded driven piles.

Keywords : Pile, Pile Foundation, Design, LRFD

1. Introduction

With the advent of the global economic circumstances around the world, the South Korean government has decided to open its construction market to the world including the

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engineering design and consulting fields in 1996. To properly encounter the expected high competition in construction industry and the challenge of high-level design technology from the advanced countries, it is desirable that Korean geotechnical engineers be aware of the new trends in the foundation design code. Thus, one of the primary objectives of this paper is to inform South Korean geotechnical engineers of new design code of practice, LSD, which is coming into common use in geotechnical design practices around the world.

It is well konwn that foundation design practices are traditionally based on the deterministic approach called the allowable stress design(ASD) approach. This method normally adopts a factor of safety(FOS) to reflect all uncertainties of material strength, design models and construction errors. North America(USA and Canada) and European Community have recently released their own design codes based on LSD. The LSD method has been adopted for over twenty years in structural engineering(Ovesen and Oorr, 1991) even though its acceptance has so far been very limited in geotechnical engineering.

In America, an approach to load and resistance factor design(LRFD) applications to foundation design was recently presented by Barker et al.(1991) who proposed the necessary resistance factors for a number of geotechnical applications, including pile design. This approach has been incorporated into the most recent AASHTO design code (AASHTO, 1994). LRFD principle requires that

$$\phi R_n \geq \Sigma \gamma_i Q_i \tag{1}$$

where ϕ is the resistance factor, R_n is the nominal resistance, γ_i is the load factors and Q_i is the applied loads. Equation 1 states that the factored resistance of structure must always be greater than the summation of the factored loads.

Historically, many geotechnical researchers have investigated the code of practice for reliability of geotechnical structures and suggested some solutions. In 1953, Brinch Hansen, in order to introduce safety margins into geotechnical design, proposed the principle of partial factors of safety concepts, which has been basically adopted recently by European countries. Eurocode based on partial safety factor design principles has been studied for two decades from 1970 to 1990, resulting in Eurocode 7 [Geotechnical design](1993). Partial factors in the ultimate limit state design are linked to the variability of the loads and soil parameters, the design approximations, and construction tolerances(Meyerhof, 1994).

There is an increasing pressure on the geotechnical professionals now come up with appropriate resistance factors for the design of foundation components and systems based on the prescribed load factors from superstructure. Also, a comprehensive review on practicality of LRFD (Fellenius, 1994) shows that geotechnical engineers are very interested in the estimation of reasonable resistance factors rather than load factors. The main purpose of this paper is to review the procedures in ASD and LSD methods and analyses and determine reasonable geomaterial resistance factors for design of driven pile.

2. Limit State Design Method

There are two methods of approach in LSD : LRFD method used in North America and Eurocode method used in European Community. In LRFD code, the resistance is calculated by design models, and then the computed resistance is multiplied by resistance factors in order to reflect the uncertainties of material and design model. Eurocode approach, however, employs partial resistance factors which are applied directly to the individual variables in the resistance equation, which means that partial factors are applied to the individual soil strength properties such as cohesion(c) and angle of internal friction(ϕ). Thus, selection of reasonable resistance factors and partial safety factors for matrial parameters is the key element in both codes.

LSD method has been in common use for over a century in structural egnineering since the quantification of uncertainty about material strength and external loads became possible with probability and reliability theories. The design concepts in the LSD approach are commonly divided into ultimate limit state(ULS) and serviceability limit state(SLS). The ULS is associated with failure or instability of structures, and the SLS relates to the performance of structures under service conditions such as settlement of foundations and deformations of structures. The basic concept of limit state design is illustrated in Fig. 1 where the difference between concepts in ULS and SLS is shown.

Design Principles in ULS :

Structure will not reach ultimate limit state(plasticity state) by introducing a safety margin which is normally incorporated by load and resistance factors.

Design Principles in SLS :

Structure will be prevented from exceeding a state of allowable deformation by introducing a constraint on the movement of structure.

The safety margin as shown in Fig. 1 in foundation engineering depends mainly on the uncertainties and variability of the soil properties, the approximations in the stability analyses such as design models, and the applied external load conditions. Therefore, if one can quantify these uncertainties by simple probability and reliability theories, the foundation design can become more rational, consistent and systematic.

LRFD code formally uses reliability theory because this theory provides a way of evaluating the safety of structures and foundations in a logical and consistent manner. Load and resistance in LRFD are considered as random variables and are represented by their mean values and standard deviations. The corresponding load and resistance facotrs depend on the value of the safety level(reliability index), which is directly related to the probability of failure.

Meyerhof(1994) reviewed both European and North Americal codes and found that there

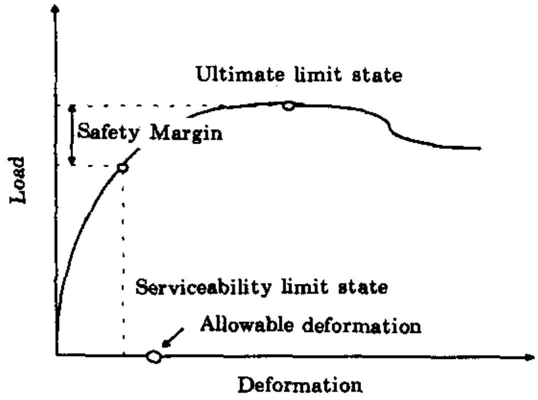

Fig. 1 The Concepts of Limit State Design

is no difference between their concepts because they were derived by calibration with conventional total safety factor and semi-probabilistic studies of the resistance. He also suggested that the choice between the two methods of geotechnical design depends on familiarity and convenience, and stressed that the determination of *in-situ* soil strength is the most important problem, which is the main topic of this paper.

3. Code Calibration

Code calibration is the process of assigning values to code parameters(e.g., load and resistance factors). Codes may be calibrated by judgement, fitting, optimization or a combination of these approaches. The load and resistance factors are based on reliability theory in which risk levels implied in existing working stress criteria are determined from statistical analysis of existing data, when the data is not available, by matching the results of proven design methods.

This reliability index associated with ASD needs to be predetermined to calibrate the LRFD. However, the general information on reliability index for geotechnical structures is not easily available. Reliability index method is pioneered by Cornell(1969) in order to simplify full distribution functions of random variables. This method requires mean value and variance of random variables of interest :

$$\beta = \frac{\mu_z}{\sigma_z} \qquad (2)$$

where β is the reliability index,

μ_z is the mean value of random variable Z, and

σ_z is the standard deviation of random variable Z.

The procedure shown in Fig. 2 consists of performing a reliability analysis to determine reliability indices for exsting designs, selecting target reliability indices based on the results of the reliability analysis, and then determining resistance factors that are consistent with the selected target reliability indices.

The development of a foundation design code involves the optimization of load and resistance factors. The designer is interested in a simple format, and the simplicity depends on the number of different sets of load and resistance factors. The selection of the optimum reliability index and the optimum values of different resistance factors partial safety facors is the key for this purpose because the calculated safety factors from reliability analysis can be used to select the optimum resistance factors for a given target reliability index. The best way to find a reliability index in geotechnical problems is to conduct a large number of test calculations with parameter variation for different standard problems. The resistance factor determined by calibration model accounts for uncertainties in resistance and its value depends on the variability in strength and the statistical difference between design models and experimental data.

Partial safety factors have been refined subsequently by semi-probabilistic methods on the basis of the variability of the loads, soil strength parameters and other design data in practice(Meyerhof, 1994). It was necessary to perform separate studies and to develop different resistance factors for each combination of foundation type, soil type, soil testing procedure, and design models. Thus, for example, driven piles deriving support from sand with capacity estimated by using CPT(cone penetration test) results will have a different value of resistance factor from the ones with capacity estimated by using SPT(standard penetration test) results. Similarly, piles in clay will have different resistance factors from those in sand, and drilled shafts will have different resistance factors from driven piles (Barker, 1991).

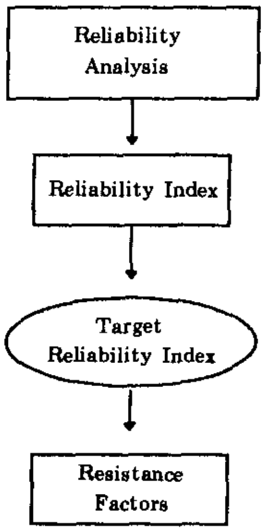

Fig. 2 Calibration Procedure

Fellenius(1994) reviewed that foundation engineers espousing LRFD have generally accepted the load factors prescribed for the superstructure and have focused on determining reasonable resistance factors. In this paper, as an example of application to LRFD, the estimation of resistance factors for driven piles is selected and investigated.

4. Applications of LRFD to Pile Foundation

Design methods for pile foundations are also shifting from ASD to LSD(Meyerhof, 1994). In order to introduce the LSD, a reliability design is indispensable for the determination of resistance factors. It is well-known that the magnitudes of total and partial factors of safety in ultimate limit state design normally depend on the reliability of information such as various loads condition, soil strength parameters, analysis method, and construction techniques. The partial safety factors have been obtained mainly by calibrating the conventional geotechnical design and analysis using total safety factors to ensure the same margin of safety as that provided by present good practice and experience(Meyerhof, 1994).

The ultimate capacity of a pile is the sum of the shaft resistance, R_f and the base resistance, R_B, and the applied load may consist of dead load, S_D, and live load, S_L, as shown in Fig. 3. Therefore, the Limit State function for reliability analysis can be formulated as

$$Z(x) = \sum_i R_{fi} + R_B - S_D - S_L \qquad (3)$$

$$Z(x) = R - S \qquad (4)$$

There are many design methods in computing resistance R such as laboratory based models α-method, β-method and λ-method, and *in-situ* based models ; CPT method and SPT

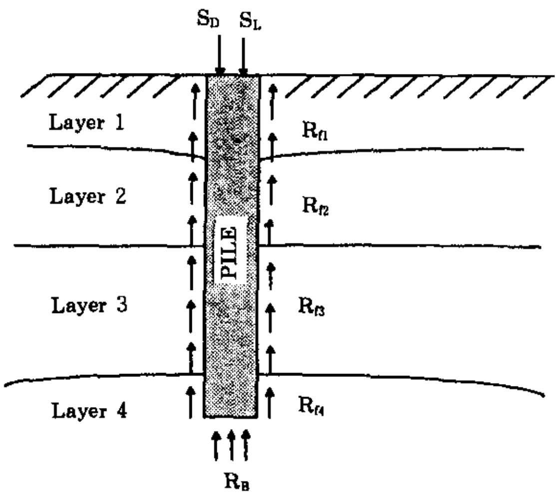

Fig. 3 The Pile Capacity Calculation

method. Note that these models have different results, which result in variance and bias in computing the resistance of piles. Thus, it is necessary to determine these differences in design models in order to determine reasonable resistance factors.

If one assumes that the random variables R and S are normally distributed and independent, then the probability functions of Z(x) can be plotted as shown in Fig. 4. The mean value and standard deviation of Z(x) for normal distributions can be described as

$$\mu_Z = \mu_R - \mu_S \tag{5}$$

$$\sigma_Z = \sqrt{\sigma_R^2+\sigma_S^2} \tag{6}$$

The reliability index β which is related to the probability of failure $P(f)$ in Fig.4 can be expressed as

$$P(f) = 1-\phi(\beta) \tag{7}$$

where, $$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}} \tag{8}$$

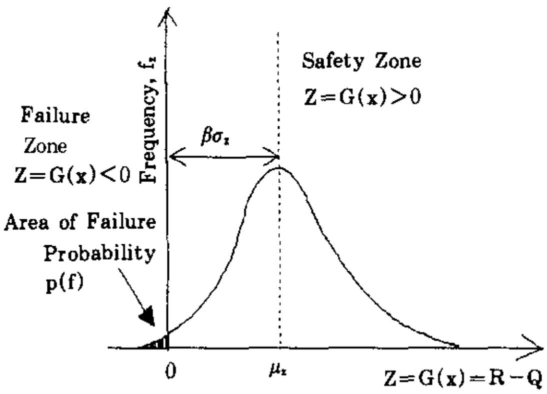

Fig. 4 The Concept of Reliability Index

5. Determination of Resistance Factor ϕ

By rearranging Eq.1 we have

$$\phi \geq \frac{\sum_{i=1}^{N} r_i Q_i}{R_n} \tag{9}$$

If one defines nominal resistance R_n and nominal load Q_n as

$$R_n = \frac{R}{\lambda_R},\ Q_n = \frac{Q}{\lambda_Q},\ Q_{ni} = \frac{Q}{\lambda_Q} \tag{10}$$

where Q_i is the mean value of i-th state load and

λ_Q is the bias factor for load,

R is the mean value of resistance,

λ_R is the bias factor for resistance,

Q is the mean value of load,

then, the reliability index in Eq. 8 can be modified for lognormal distribution by

$$\beta = \frac{ln\frac{R}{Q}\sqrt{\frac{1+V_R^2}{1+V_Q^2}}}{\sqrt{ln[(1+V_R^2)(1+V_Q^2)]}} \tag{11}$$

where V_Q is the coefficient of variation of load and

V_R is the coefficient of variation of resistance.

Equation 11 can be described for mean resistance value as

$$R = Q\sqrt{\frac{1+V_R^2}{1+V_Q^2}}\ e^{\beta\sqrt{ln(1+V_R^2)(1+V_Q^2)}} \tag{12}$$

Substituting Eqs. 9 and 10 with Eq. 12 gives

$$\phi = \frac{\lambda_R \sum_{i=1}^{N} r_i Q_i}{Q\sqrt{\frac{1+V_R^2}{1+V_Q^2}}\ e^{\beta\sqrt{ln(1+V_R^2)(1+V_Q^2)}}} \tag{13}$$

If one assumes just two types of load(dead and live loads), then Eq. 13 will be changed to

$$\phi = \frac{\lambda_R[r_D\frac{Q_{nD}}{Q_{nL}} + r_L]}{[\lambda_D\frac{Q_{nD}}{Q_{nR}} + \lambda_L]\ \sqrt{\frac{1+V_R^2}{1+V^2q}}\ e^{\beta_t\sqrt{ln(1+V_R^2)(1+V_Q^2)}}} \tag{14}$$

where $V_Q^2 = V_L^2 + V_D^2$

Equation 14 shows that the resistance factors in LRFD depend largely on variance and bias in the resistance, variance and bias in the applied load, and desired safety level(reliability index). Therefore, the determination of these variables is the prerequisite to computing reasonable resistance factors. O'Neill (1994) suggested a rational method for determining reasonable resistance factor through a direct experimentation including site characterization study. The inherent spatial variability of soil properties, which is one of the basic input factors affecting variance and bias in the resistance, can be identified by a geostatistical principle. Yoon (1995) analyzed the spatial variability of cone penetration test data in overconsolidated clay. Also, variance and bias in the resistance caused by design models can be computed through this site caharacterization study. For driven piles, AASHTO (1994) recommends three rational methods ; α-method, β-method and λ-method, and two *in-situ* methods ; SPT method and CPT method.

6. Discussion and Conclusions

Overview of limit state design concepts and analysis of determination of resistance factors in the LRFD indicate that correct resistance factors are largely based on calibration against traditional factors of safety and do not significantly reflect the variance and bias in design methods and soil strength calculations. As derived from reliability theory and basic premise of LRFD, there exists many variables affecting the resistance factor. Among these variables, geotechnical engineers should control the variance and bias in the resistance in terms of site-specific characterization study, which requires a large data base. Thus, a prerequisite to computing reasonable resistance factor for a given site is the development of reliable and large data base.

In conclusion, this paper overviewed the backgrounds of limit state design and reviewed procedures to determine rational resistance factors, which are essential for design of foundations such as piles. Detailed determination of resistance factors can be obtained whenever the variance and bias in resistance are available. Korean expert groups consisting of practicing geotechnical engineers from industry, professors from academia and researchers from government institutions should make every possible effort to perform research in these area to adopt new foundation code of practice according to Korean circumstances.

From the basic review and analysis of the LSD method, the following conclusions are drawn :

- Limit state design represents more consistent, systematic and rational approach compared to allowble stress design. This LSD code is expected to govern foundation design code of practice around the world in the future.
- The next phase in the evolution of resistance factors should be site-specific and based on global assessment of the variance and bias in geomaterial properties and design methods.
- Development of reliable data base is a prerequisite to site characterization study, which makes it possible to compute reasonable resistance factors to reflect the uncertainty of geomaterial properties and design models.

−Spatial correlation study such as geostatistics is required to identify the inherent spatial variability of soil properties.

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