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관입말뚝을 위한 새 국제적 시방서에의 방문

VISTING NEW INTERNATIONAL CODES OF PRACTICE FOR DRIVEN PILES

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개요(SYNOPSIS) : 한계상태설계법이 지반공학에 도입되었다. 하중과 지지력계수법 그리고 유로코드로 되어있는 본설계법에서 신뢰성이론을 토대로 한 전자는 북미지역에서, 반통계론적인 후자는 최근에 통합된 유럽연합에서 오래동안 연구 후 채택하였다.

본 논문은 이러한 설계법을 방법론적으로 검토접근하며 다른 선진국의 연구현황을 알아봤으며, 하중과 지지력계수설계법에서 관입말뚝에 대한 지지력계수를 결정하는 합리적인 방법론을 제시하는데 있다.

INTRODUCTION

Foundation design practices are traditionally based on the deterministic method, called allowable stress design (ASD) approach. This principles normally adopts a factor of safety (FOS) to reflect all uncertainties of material strength, design models and construction errors. Limit State Design (LSD) principles, however, have been adopted in foundation engineering community around the world. North America (USA and Canada) and European Community (EC) have recently released their own design codes based on LSD, which are called Load and Resistance Factor Design (LRFD) and Eurocode.

These new international codes are totally different with ASD because LSD were developed based on reliability theory (LRFD) and semi-probability concepts (Eurocode). Thus, LSD provides a more rational basis for dealing with uncertainties in geotechnical design. Even though LSD method has so far been very limited in foundation engineering community, structural engineering fields has adopted it for over twenty years ago (Ovesen and Oorr, 1991).

This paper describes the evolution of the principles of LSD, and in particular emphasizing with determination of resistance factors for driven pile design. In addition, the experiences of other developed countries with the new LSD are investigated. This paper should be prove useful to those involved with the new international code both as engineers, designer and subsequently as users. Thus, it might hopefully be expected that a rational code of practice could be developed by Korean geotechnical engineers.

CONCEPTS OF LIMIT STATE DESIGN

As stated above, there are two methods of approach in LSD method; LRFD method in North American and Eurocode method in European Community. In LRFD code, the resistance is calculated by design models and then multiply resistance factors into computed resistance in order to reflect the uncertainties of material and design model, while in Eurocode approach employs partial resistance factors which are applied directly to the individual variables in the resistance equation, which means partial factors are applied to the individual soil strength properties such as cohesion (c) and angle of internal friction. Thus, selection of reasonable resistance factors and partial safety factor for material parameters is the key element in both codes.

The basic design premise in LSD can be expressed in the following form (1).

$$\phi R_n = \sum r_i Q_i \qquad (1)$$

where

ϕ is the resistance factor,

R_n is the nominal resistance, r_i is the load factors and

Q_i is the applied loads.

Eq. 1 means that the factored resistance of structure always must be greater than the summation of the factored load.

The load factors, r_i, have been generated by structural engineers for the various loads in selected load combinations using probabilistic concepts. The resistance factors, ϕ are main concern to foundation engineering community. Some of comprehensive research on these factors for foundation design was performed by Barker et al (1991).

The design concepts of 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 which attempts to show the difference in concepts between ULS and SLS:

- Structure will not be reached a point of ultimate limit state (plasticity state) by introducing a safety margin which is normally incorporated by load and resistance factors and
- 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 approach.

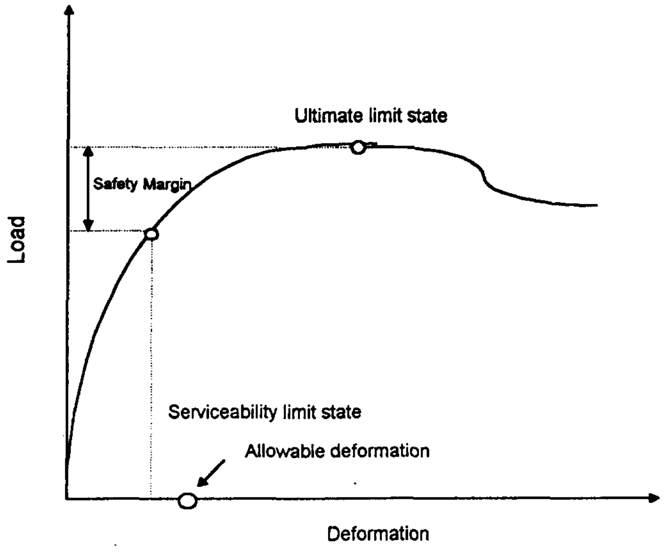

Fig. 1 The Concepts of Limit State Design

INVESTIGATION OF RESEARCH EXPERIENCES WITH LSD

Historically, many geotechnical researchers have investigated the code of practice for reliability of geotechnical structure 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 are basically adopted recently by European Community (11 countries). Eurocode based on partial safety factor design principles has been studied for a century from 1970 to 1990, which resulting in Eurocode 7, chaired by Niels Krebs Ovesen, Danish Geotechnical Institute, Denmark.

According to Canadian Foundation Engineering Manual (1992), research on LSD method in Canada was started early in 1970. The 1983 Bridge Foundation Gode published by the Ministry of Transportation Ontario (MTO) applied the Danish partial factor of safety approach with fixed reduction of cohesion and friction. However, the new code of 1991 abandoned this approach in favor of applying a resistance factor to the ultimate resistance of the foundation rather than to the soil strength and to differentiate between foundations types and design methods for resistance (Fellenius, 1994). In 1992, it was decided that the new code should be further developed into a national code on foundations, which work is now underway.

In America, an parallel development to 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). Also. American Petroleum Institute (API) released a first edition of LRFD code for offshore structure (API, 1993).

One of extensive researches on LRFD is from Cornell University geotechnical group, which focuses on transmission tower structures (Phoon et al, 1995). They used first order and second moment reliability theory and large soil shear strength data base acquired from various sites. In a very recent research on LRFD for driven piles is performed at the University of Houston National Geotechnical Experimentation Site (NGES-UH) in terms of full-scale pile loading test, reliability theory and rational site characterization study with extensive cone penetration test (CPT) data (Yoon, 1995).

In 1989, Japan Geotechncial Society made a committee (Working Group) to encounter a new international code, LSD. They organized several committee; (1) highway bridge foundation group, which comes from Japan highway association, (2) railroad substructure group for foundations and piles (RCL, 1994). Their primary researches on LSD code are to develop a manual for earthquake-resistance design in foundation engineering. Some of research activities were published in Japanese soil and Foundation Journal (RCL, 1994).

One of extensive researches on LSD from Australia is being performed by the University of New South Wale and Australian Defense Force Academy leaded by K.S. Li. and I.K. Lee. They have normally adopted a partial safety factor concepts, and a number of draft limit state design geotechnical codes were released recently in Australia, including AUSTROAD foundation code for bridges in 1990, the Draft Reinforced Soil Code (SAA, 1991) and the Draft Australian Piling Code (SAA, 1992).

In the last ten years, LSD method based on the probabilistic principles has been researched in China, which resulted in the first draft "The United Standard of Structure Design," This draft adopted the partial safety factor concepts. Also, significant research has been performed mainly at the Tongji University leaded by Gao and Li, (1994). Their researches are associated with the new development of partial factors design on pile foundation, which will be included in revised "Shanghai Foundation Design Code"

CODE CALIBRATION FOR RESISTANCE FACTOR

The development of a LSD foundation code involves the optimization of load and resistance factors. Code calibration is the process of assigning values to code parameters (i.e., load and resistance factors). Codes may be calibrated by judgment, fitting, optimization or a combination of these approaches. The load and resistance factors in LRFD are obtained based on reliability theory in which risk levels implied in existing working stress criteria are determined from statistical analysis of existing data, or when the data is not available, by matching the results of proven design methods. However, the resistance factors should basically be developed independently with working stress criteria because its values depends largely on bias factors and variance of the resistance and load effects (Yoon and O'Neill, 1996).

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 found to be 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.

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 a example of application to LRFD, estimation of resistance factors for driven piles is selected and investigated.

The ultimate capacity of a pile is the sum of the shaft resistance Rf and the base resistance RB and the applied load may consist of dead load QD and live load QL as shown in Fig. 2. Therefore, the Limit State function for reliability analysis can be formulated as

$$Z(x) = \sum_i R_{fi} + R_B - Q_D - D_L \quad (2)$$

$$= R - Q \quad (3)$$

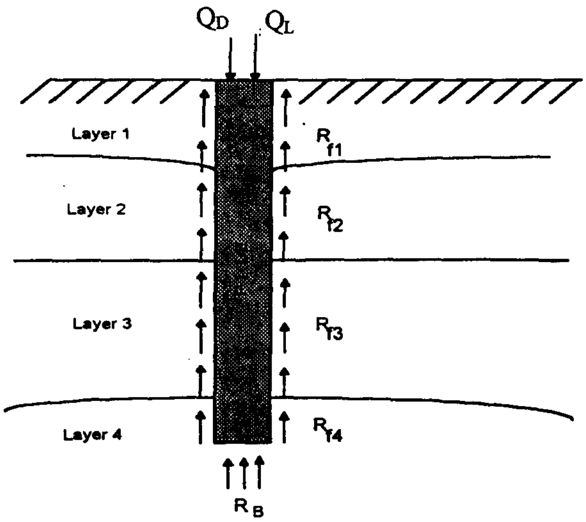

Fig. 2. Terms in the Pile Capacity Calculation

There are many design methods in computing resistance R such as laboratory based models; alpha method, beta method and lambda method, and in situ-based methods; CPT and SPT method.

If one assumes that the random variables R and Q are normally distributed and independent, then the probability functions of Z(x) can be plotted as shown in Fig. 3. The mean value and standard deviation of Z(x) for normal distributions can be described by

$$\mu_Z = \mu_R - \mu_Q \quad , \tag{4}$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_Q^2} \tag{5}$$

Reliability index method is pioneered by Cornell (1969) in order to simplify full distribution functions of random variables. This method requires just mean value and variance of random variables of interest:

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{6}$$

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.

By substituting Eqs, 4 and 5 into Eq, 6, one can obtain a reliability index β for normal distributions of R and Q as

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{7}$$

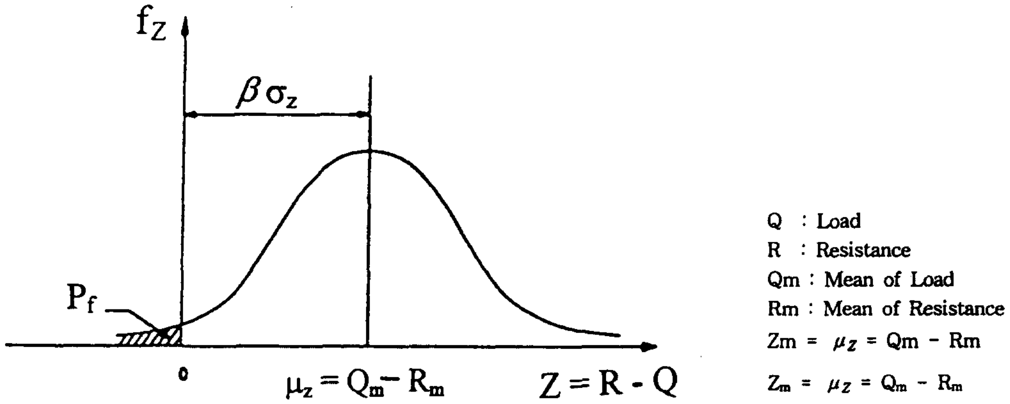

Fig. 3 The Concepts of Reliability Index

The probability of failure P_f in Fig. 3 can be expressed by

$$P_f = 1 - \Psi(\beta) \tag{8}$$

where

Ψ is a normalized cumulative distribution function.

In order to determine resistance factor ϕ from basic LRFD equation (1), one can arrange Eq. 1 as

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

If one defines nominal resistance Rn and nominal load Q_n as

$$R_n = \frac{\overline{R}}{\lambda_R}, \quad Q_n = \frac{\overline{Q}}{\lambda_Q}, \quad Q_{n_i} = \frac{\overline{Q_i}}{\lambda_Q} \tag{10}$$

where

$\overline{R}$ is mean value of resistance(= R_m),

λ_R is the bias factor for resistance,

$\overline{Q}$ is mean value of load(= Q_m),

$\overline{Q_i}$ is mean value of i-th state load(= Q_{mi}) and

λ_Q is the bias factor for load,

then, the reliability index in Eq. 7 can be modified for lognormal distribution as

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

where

V_Q is the coefficient of variation of load and

V_R is the coefficient of variation of resistance.

Equation 11 can be modified as Eq. 12 for mean resistance value as

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

Substituting Eqs. 9 and 10 with Eq. 12 gives

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

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

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

where

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

Eq. 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 factor.

The selection of the optimum reliability index and the optimum values of different resistance factors or partial safety factors 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, which would be fruitful future research area.

The inherent spatial variability of soil properties, which is one of basic input factors affecting variance and bias in the resistance, can be identified by a geostatistical principle. Yoon and O'Neill (1995) analyzed the spatial variability of cone penetration test data in overconsolidated clay. Also, variance and bias in the resistance due to design models can be computed through this site characterization study.

DISCUSSION

A new foundation code of practice for driven piles has been described with emphasized on determination of resistance factors. This code is expected to be international standard code for foundation engineering community in the future because of its rational approach and a combination with structural engineering code, which has adopted this code for a long time.

Relevant overview of limit state design concepts and analysis of determination of resistance factors in the LRFD indicate that, as derived from reliability theory and basic premise of LRFD, there exists many variables effecting the resistance factor. Among these variables, geotechnical engineers would take control of variance and bias in the resistance in terms of site-specific characterization study, which require a large data base. Thus, a prerequisite to computing reasonable resistance factor for a given site is the development of reliable large data base.

As stated before, many countries already stated to develop their own code, which depends largely on each countryÆs soil characteristics and design models. The author hope strongly that Korean expert groups consisting of practicing geotechncial engineers from industry, professors from academia and researchers from government institutions can make every possible effort to perform research in these area in order to adopt new geotechnical code of practice according to Korean circumstances.

CONCLUSIONS

The following conclusions are drawn from this study.

- Limit State Design represents more consistent, systematic and rational approach compared to Allowable 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 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.

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