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Research Article

Reliability Analysis of Bearing Capacity of Large-Diameter Piles under Osterberg Test

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Abstract: This study gives the reliability analysis of bearing capacity of large-diameter piles under osterberg test. The limit state equation of dimensionless random variables is utilized in the reliability analysis of vertical bearing capacity of large-diameter piles based on Osterberg loading tests. And the reliability index and the resistance partial coefficient under the current specifications are calculated using calibration method. The results show: the reliable index of large-diameter piles is correlated with the load effect ratio and is smaller than the ordinary piles; resistance partial coefficient of 1.53 is proper in design of large-diameter piles.

Keywords: Bearing capacity, large-diameter pile, partial coefficient, reliability, reliability index

INTRODUCTION

Scholars in China since late 1970s paid attention to the reliability study of pile foundations. They carried out researches of evaluation method of piles' safety and compiled the relevant standards. But the engineers and technicians tend to utilize deterministic design method in pile projects due to the variance of engineering requirements and the limitation of the standards in complex geological conditions. Christian *et al*. (1994) study the reliability applied to slope stability analysis. Deng *et al*. (2005) have a reliability research on bearing capacity of single bored pile. Dennis (1996) study the eighteenth canadian geotechnical colloquium: limit states design for foundations. Huang (2010) study the reliability analysis of vertical bearing capacity of driven-cast-in-place piles. Guo (2007) have a study on the Probability limiting state design method of bored piles in loess of Xi'an area. Li (2009) study the research and application of Osterberg testing method.

The large-scale projects will inevitably increase with the improvement of engineering technology. As for large-diameter piles, due to their large bearing capacities, traditional testing method is impropriate. Osterberg test is one of proper methods to test the bearing capacity especially for large piles: by mounting the load cell in the bottom of pile, the upper pile can be loaded with extreme large force upward, making the test of bearing capacity reality.

Based on the Osterberg tests in Longhua and Lanqi Super Large Bridges and combined with the corresponding data of other similar projects with the same test method, the study studies the large-diameter piles' reliability level under the direction of recent specifications in China. By using calibration method, the reliability index and resistance partial coefficient have been calculated, which may provide reference for the future design of large pile foundations.

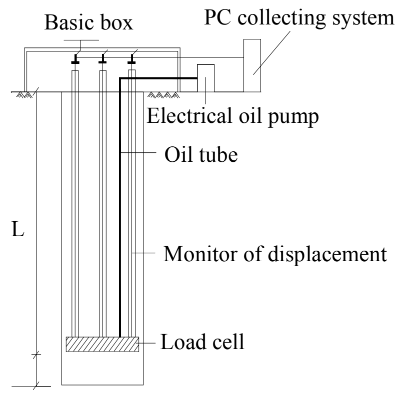

Fig. 1: Schematic diagram of Ostberg test

BASIC PRINCIPLES OF OSTERBERG TEST

This method is provided by Osterberg in the 1980s, by the application of load cell in the pile, most of the side friction is counteracted by tip resistance. So the heavy load can be applied on the pile.

Before the test, the exacting location of load cell should be calculated based on the geological condition and then the cell is welded with steel mesh reinforcement. During the test, high-pressure fuel pump in the ground infiltrate hydraulic fluid into the load cell, generating upward thrust force in the upper pile and downward in the lower part until the final failure. Then the ultimate bearing capacity of pile can be deduced by adding up the side friction and tip resistance (Fig. 1).

Longhua and Lanqi bridges of Songhua River locate in Jilin Province, China. During the construction

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of the two bridges, six piles of Longhua and three of Lanqi have been tested by Osterberg method to evaluate the bearing capacity. All of the nine testing piles have a diameter of 2.0 m and the length of piles range from 50.0 m to 65.0 m.

RELIABILITY THEORY AND ITS CALCULATION METHOD

The reliability design of pile foundation is a kind of limit state design method based on the probability theory, which introduces reliability index as the evaluation index for safety and uses partial coefficient to express the expression of design in limited state (Fig. 2 and 3).

The performance function of pile foundation, in form of resistance force R and load effect S, can be represented as follows:

$$Z = g(x_1, x_2, \cdots, x_n) = R - S$$

- $Z = R - S > 0$ means pile in the state of reliable
- $Z = R - S = 0$ means pile in the state of limit
- $Z = R - S < 0$ means pile in the state of failure

J-C method is one of the most common methods in the calculation of reliability index. And this method is recommended by Joint Committee on Structural Safety (JCSS), which is widely accepted by the majority of nations. In J-C method, normal distribution equivalent is used to transform non-normal distribution variables into normal distribution variables and then reliability index can be deduced with iterative method, which is usually realized in computer program.

Assume that the non-normal distribution variable X has a probability distribution function of $F_{X_i}(X)$ and a probability density function of $f_{X_i}(X)$. The mean and mean-square deviation of X is μ_{X_i} and μ_{X_i} respectively. After the transformation, the equivalent variable X' has a distribution and density function $F_{x_i'}(X)$ of $f_{x_i'}(X)$ and, while $\mu_{x_i'}$, $\sigma_{x_i'}$ is X' s mean and mean-square deviation. If P^* is the equivalent point, then X_i can be noted as X_i^*. The calculation is based on the two presumptions:

- In the design checking point, the values of distribution function between the non-normal distribution variable and the transformed normal distribution variable are equal
- In the design checking point p, the value of probability density function between the two variables is equal. These can be expressed as the following two equations:

$$\mathrm{F}_{\mathrm{X}_i}\left(\mathrm{X}_i^*\right) = F_{X_i'}(\mathrm{X}_i^*) = \Phi\left|\frac{X_i^* - \mu'_{X_i}}{\sigma'_{X_i}}\right|$$

Fig. 2: Load cell of Longhua Bridge

Fig. 3: Welding of load cell in Lanqi bridge

$$f_{X_i}(X_i^*) = f_{X_i'}(X_i^*) = \frac{1}{\sqrt{2\pi}\sigma'_{X_i}} e^{\frac{(X_i'-\mu'_{X_i})^2}{2(\sigma'_{X_i})^2}} = -\varphi\left|\frac{X_i^* - \mu'_{X_i}}{\sigma'_{X_i}} \bullet \frac{1}{\sigma'_{X_i}}\right|$$

The following equation can be deduced:

$$f_{X_i}(X_i^*) = \frac{1}{\sigma_{X_i'}} \varphi\left\{\Phi^{(-1)}\left[\mathrm{F}_{\mathrm{X}_i}\left(\mathrm{X}_i^*\right)\right]\right\}$$

Then the mean-square deviation of equivalent variable with normal distribution is:

$$\sigma_{X_i'} = \frac{\varphi\left\{\Phi^{(-1)}\left[\mathrm{F}_{\mathrm{X}_i}\left(\mathrm{X}_i^*\right)\right]\right\}}{f_{X_i}(X_i^*)}$$

Among which, $\Phi(\cdot)$ means standard normal distribution function; $\varphi(\cdot)$ means the standard normal distribution density function; and $\Phi^{-1}(\cdot)$ is the inverse function of standard normal distribution function.

After the equivalent normalization of non-normal distribution variables, the reliability index can be solved through the verification point method (Fig. 4). As for the μ'_{X_i} and $\sigma_{X_i'}$ are all unknown variables, iterative method is used in fixing the reliability index β .

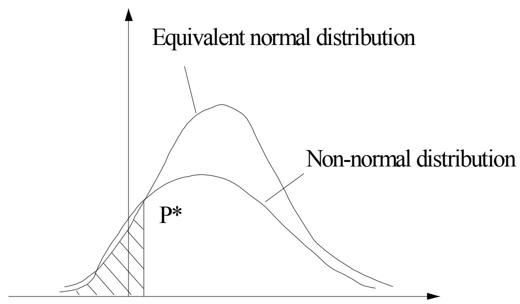

Fig. 4: Equivalent normalization of variables

In the reliability researches of piles, the bearing capacity should be considered primarily and it is determined by the interaction of the concrete pile itself and the surrounding rock and soil. But in practice, the properties of rock and soil, the geometric parameters of pile and the evaluation of bearing capacity are all various. These uncertainties almost make it impossible to deduce the piles' reliability mathematically.

So the ratio of test value to design value (TDR, λ_R) has been introduced, which can be expressed as: $\lambda_R = R/R_k$, where R is the value of bearing capacity in Osterberg test and R_k is the design value of the tested pile.

The limit state equation for vertical bearing capacity of pile can be expressed as follow:

$$Z = R - G - Q = 0$$

where R is the ultimate bearing capacity, G is the dead load and Q is the live load.
Then the standard value of bearing capacity is:

$$R_k = K(G_k + Q_k) = K(1+\rho)G_k$$

G_k, Q_k = The standard value of dead load and live load respectively
K = The safety factor, usually K = 2.0; and load effect ratio
ρ = The ratio of live load to dead load:

$$\lambda_R - \frac{\lambda_G}{K(1+\rho)} - \frac{\rho\lambda_Q}{K(1+\rho)} = 0$$

where,

$$\lambda_R = R / R_k, \lambda_G = G / G_k, \lambda_Q = Q / Q_k$$

Finally, reliability index β can be calculated with J-C method. Considering the partial coefficient, the design of resistance can be expressed as:

$$\gamma_G G_k + \gamma_Q Q_k = R_k / \gamma_R$$

Table 1: Statistical results of random variable λ_R

Number	R(kN)	R_k(kN)	λ_R
1	33444	22000	1.520
2	33444	22000	1.520
3	45684	56000	0.816
4	67779	56000	1.210
5	52036	56000	0.929
6	46617	46000	1.013
7	65131	62000	1.051
8	61292	62000	0.989
9	69714	62000	1.124
10	8444	7780	1.085
11	6706	6120	1.096
12	32494	35000	0.928
13	28420	15900	1.787
14	41500	49472	0.839
15	42730	49472	0.864
16	129078	80000	1.613
17	30811	42248	0.729
18	35265	42248	0.835
19	31921	43318	0.737
20	21211	20000	1.061
21	20190	20000	1.010
22	24497	20000	1.225
23	24259	20000	1.213
24	19605	20000	0.980
25	12790	11248	1.137
26	15050	19980	0.753
27	40418	40000	1.010
28	39097	38144	1.025
29	22305	19020	1.173
30	6935	6780	1.023
31	15110	14000	1.079
32	6216	6000	1.036
33	12393	11248	1.102

And the resistance partial coefficient can be deduced either by the fixed value method or the limit state equation method.

RELIABILITY ANALYSIS OF LARGE PILE'S BEARING CAPACITY

Based on the data of Osterberg tests in Longhua Bridge and Lanqi Bridge mentioned above and adding up with some similar projects' data with the same test method, the study has collected totally thirsty-three groups of test piles in China. The statistical results of test design ratios λ_R are shown in Table 1.

In Table 1, data from number 1 to 6 are the test results of Longhua Super Large Bridge and data from number 7 to 9 are the test results of Lanqi Super Large Bridge. Both of the two bridges are constructed in Jilin Province, China. And the rest of groups are collected from the other scholars' research including (Xu, 2010; Li, 2009).

All of the thirsty-three groups of test piles are conducted with Osterberg method and the average diameter of these piles is 1.73 m, much larger than the ordinary piles. The test design ratios λ_R are ranging from 0.729 to 1.787. Then Statistical histogram of random variable λ_R is drawn as Fig. 5.

Then the probability model distribution of λ_R has been tested with Chi-square Test Method. Normal

Table 2: Statistical parameters of λ_R

λ_R			Distribution type		
Mean	S.D.	Variation coefficient	Normal	Lognormal	Extreme value type I
1.076	0.243	0.226	Accept	Accept	Refuse

Table 3: Statistical parameters of random variables

Random variables X	Mean μ	S. D. σ	V.D. δ	Distribution type
$\lambda_R = R/R_K$	1.076	0.243	0.226	Lognormal
$\lambda_G = G/G_K$	1.060	0.074	0.070	Normal
$\lambda_Q = W/W_K$	0.999	0.193	0.193	Extreme value type I

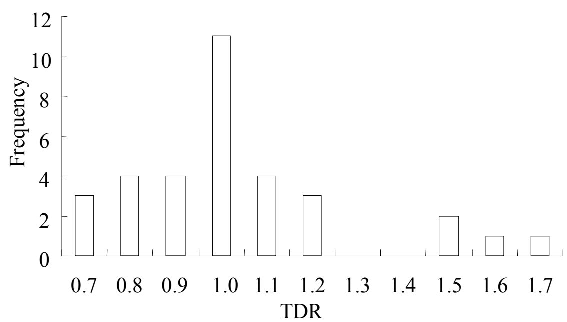

Fig. 5: Statistical histogram of random variable λ_R

distribution, lognormal distribution and extreme value type-I distribution are considered in the fitting process and the extreme value type I distribution is impropriate in the representation of λ_R while the lognormal and normal distribution are feasible, as is shown in Table 2.

From the statistical test result in Table 2 and the asymmetry of statistical histogram in Fig. 5, conclusion is made that the lognormal distribution is proper in expressing the distribution of λ_R.

In the calculating process of reliability index, the live load is considered primarily made up of wind load. According to "Unified Standard for Reliability Design of Building", the statistical parameters of dead load and live load are given in Table 3. And the equation of limit state is expressed as follow:

$$\lambda_R - \frac{\lambda_G}{K(1+\rho)} - \frac{\rho\lambda_Q}{K(1+\rho)} = 0$$

The equation of limit state above indicates that the reliability index of the pile is determined by the following factors:

- The distribution types of the three variables
- Statistical parameters of the three variables
- The value of safety factor K
- The choice of load effect ratio

In design of pile foundations, safety factor K is always taking as 2.0 according to the experience. When the distribution type and the statistical parameters of variables are fixed, then the reliability index is determined only by the load effect ratio ρ.

The J-C method is used in the calculation of reliability index. λ_R The is regarded as a lognormal distribution variable λ_G, is defined as a normal distribution variable according to the Chinese Unified Standard for Reliability Design of Building and λ_Q has a extreme value type I distribution.

In order to reduce the large amount of calculation, computer program is used as an efficient way in the calculating process. In this study, MATLAB has been utilized to compute the value of reliability index. The corresponding program is compiled within the MATLAB software according to the theory of J-C Method. And the load effect ratio is chosen from 0.25 to 2.50 depending on the practical survey.

The calculating results are shown in group *a* of Table 4 and the mean value of reliability index is 2.89. Based on the assumption that the reliability index with 2.89 is proper in large-diameter piles in recent design and construction, the resistance partial coefficient has also been calculated with the fixed value method. The resistance partial coefficient plays an important role in the design of pile foundations and the result will give a recommendation to the engineers in the similar projects.

COMPARATIVE ANALYSIS OF THE RELIABILITY PARAMETERS

The reliability of pile's vertical bearing capacity has been discussed by many researchers in the recent years, which provides a good resource for the comparisons among different types of piles. The study has provided some research results for the comparison of reliability between the large-diameter piles tested by Osterberg method and some other piles.

The reliability indexes of large-diameter piles under different load effect ratios ρ are given in *group a* of Table 4 and some China scholars' similar researches are also contained in the table, including: Wang Xiaowei's reliability study of Prestress High-strength Concrete piles (PHC piles), Huang Xiaojuan's statistical research of driven cast-in-place piles, Guo Wentao's study of bored piles in loess areas and Luo (2004) reliability parameters of bore piles depending on Cone Penetration Test (CPT), as is shown from group *b* to group *e*. And the live loads are all considered consisted of wind loads. The variation curve of reliability index from group *a* to group *e* are drawn in Fig. 6.

Table 4: Reliability indexes β in different researches

Group/ρ	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	Mean value
a	3.02	3.02	2.98	2.94	2.90	2.87	2.84	2.81	2.79	2.77	2.89
B	4.45	4.20	3.95	3.77	3.64	3.54	3.47	3.41	3.36	3.32	3.71
C	4.94	4.67	4.40	4.21	4.07	3.97	3.88	3.82	3.76	3.72	4.15
d	3.46	3.37	3.27	3.26	3.19	3.18	—	3.13	—	3.04	3.24
e	2.60	2.68	2.73	2.77	2.80	2.82	—	2.86	—	2.88	2.77

a. Large-diameter bore piles with Osterberg test *b.* PHC piles with static load test, by Wang Xiaowei; *c.* Bore piles with static load test, by Huang Xiaojun *d.* Bore piles in loess areas with static load test, by Guo Wentao *e.* Bore piles under CPT, by Luo Shuxue

Table 5: The calculating results of resistance partial coefficient

ρ	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	Mean value
γ_R	1.613	1.579	1.556	1.538	1.525	1.515	1.507	1.500	1.494	1.489	1.532

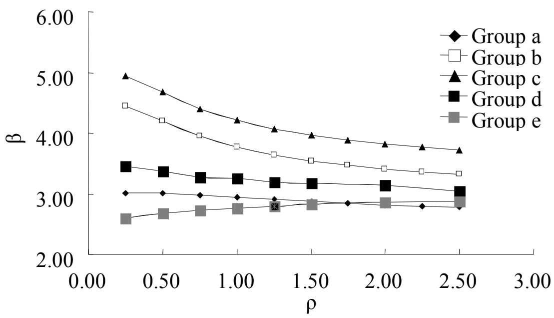

Fig. 6: Variation curve of reliability index

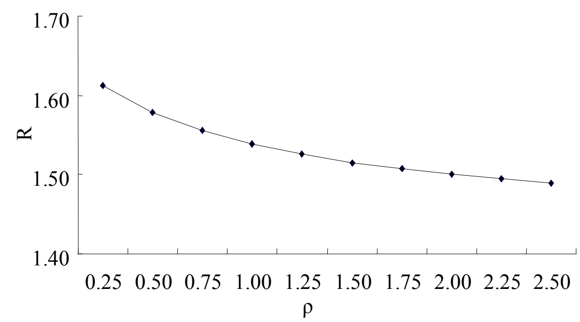

Fig. 7: Variation curve of resistance partial coefficient

It is noteworthy that the Osterberg method is utilized mainly in large-diameter piles: among the thirsty-three testing data, the smallest pile in diameter is 1.2 m and the average diameter of these piles is exceed 1.5 m; in the Osterberg test of Longhua and Lanqi Super Large Bridges, the diameter of testing piles are all 2.0 m; while the former scholars mainly collected data from the relatively small piles for the buildings.

From the Fig. 6, it can be seen that the reliability index among different piles decreases with the increase of load effect ratio. This kind of negative correlation is obvious in group *b* and group *c*. As for the large-diameter piles tested with Osterberg method, the variance of reliability index is relatively small, indicating that the composition proportion of live load and dead load has a relatively small influence in the pile foundation's safety.

The reliability index of bored piles with traditional static load test is above 3.20, only in CPT method the parameter is relatively small, about 2.77, which may due to the limitation of cone penetration test in the evaluating of bearing capacity.

Generally, the reliability index for large-scale engineering projects should reach 3.6. But this study shows: under the recent design code, the reliability index of large-diameter piles is 2.89, lower than the recommendation value. There are two major reasons:

- In large-scale projects, the geological condition is relatively clear, so the design of piles' geometric parameters is reasonable and economical.
- In China, the test results of Osterberg method should be transformed into the traditional P-S curve, among which the bearing capacity of pile has been reduced for the consideration of safety. Admittedly, the total volume of statistical samples is to some extent insufficient, more testing data of Osterberg method should be included in the future work.

The resistance partial coefficient is deduced with fixed value method: according to the existing designing experience, the partial coefficient of dead load and live load are selected as:

$$\gamma_G = 1.2, \gamma_Q = 1.4 \text{ and } K = 2.0$$

The calculating results of resistance partial coefficients are shown in Table 5. And the variation curve of resistance partial coefficient is drawn in Fig. 7, with the load effect ratio ranging from 0.25 to 2.50.

The curve above indicates that the resistance partial coefficient has a negative correlation with load effect ratio ρ. The variation ranges from 1.61 to 1.49 and is relatively small. The mean value of resistance partial coefficient is 1.532. When dead load takes up a great proportion of the total load, meaning a low value of ρ, the resistance partial coefficient is becoming larger.

CONCLUSION

In this study, the test data of large-diameter piles with Osterberg method is collected, including the Longhua Bridge and Lanqi Bridge. Based on the limit state equation of dimensionless random variables, the vertical bearing capacity has been analyzed with reliability theory and the reliability index and resistance partial coefficient are calculated with J-C method. Then the research results are compared with the similar study of other scholars.

The conclusions are as follows:

- When safety factor K = 2.0, the mean value of reliability index in large-diameter pile under recent design specifications is 2.89, lower than the recommendation value
- The average resistance partial coefficient of large pile is 1.532 and it may provide reference in the design of large-diameter piles
- The reliability index is smaller in large-diameter pile compared with the ordinary pile in other researches, which is above 3.20 generally
- The load effect ratio has ρ a negative correlation with the reliability index β and resistance partial coefficient γ_R, but the variation of both β and γ_R are relatively small

Admittedly, the collected samples are to some extent insufficient and more test data of Osterberg method should be collected in the future research.

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