Calculation and analysis of bearing capacity reliability index of post-grouting pile

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ABSTRACT

The bearing capacity of bored piles is significantly improved and the dispersion of bearing capacity is reduced obviously by employing the method of grouting. However, there is still a lack of systematic research on the calculation and analysis of the reliability index of post-grouting pile. In this paper, the static load test data of 152 non-grouted bored piles and 113 post-grouted bored piles are collected. The influence of factors such as safety factor K , types of load effect combination, and the pile diameter are taken into account. Then, the approximate probability method based on the first-order second-moment method (JC method) and Monte Carlo method is employed to analyze the reliability indexes of post-grouted bored piles and non-grouted ones.

Keywords: post-grouted piles, reliability, load effect combination, JC method, Monte Carlo method

1 INTRODUCTION

In 1958, Venezuela Maracaibo bridge foundation engineering used the grouting pipe to grout the pile foundation. At present, it has been widely used in foundation projects such as super high-rise buildings, long-span bridges and high-speed railways because of its simple process, low cost and reliable reinforcement effect. Bruce (1986) summarized the technology and test of the grouting method for bored pile and analyzed the influence of the grouting at the end of the pile on the bearing capacity and settlement of bored pile. Hai, et al. (2015) carried out static load tests on one pile with 1.5 m diameter and three piles with 2.0 m diameter in Vietnam, and the results showed that the lateral friction resistance of the pile with 1.5 m diameter and three piles with 2.0 m diameter increased by 2-3 times compared with that of the ungrouted pile. Zhang, Z. M. et al. (2000) analyzed the grouting principle of pile toe by using the expansion theory of column (ball) hole, and found that the post-grouting pile increases the friction resistance by increasing the slurry diffusion and residual stress. Therefore, a large number of research results show that the bearing characteristics of bored pile after grouting are significantly improved and the dispersion degree is significantly reduced.

Reliability methods have become increasingly important as decision support tools in civil engineering and in geotechnical applications, especially over the

past two decades. At present, analysis on reliability of foundation pile is one of the important research topics in the field of geotechnical engineering. In order to make in-depth research to this topic, experts and scholars have done a lot of work. Most of these researches are conducted based on bearing capacity of foundation pile. Kumar and Samui (2019) examined the applicability of the machine learning algorithms (ELM and MARS) for the prediction of bearing capacity of the piles embedded in sandy soil, and concludes that the developed MARS model is more reliable than the developed ELM model. Zhang (2010) used static load test to correct the reliability index and safety factor of foundation pile bearing capacity. However, the reliability of post-grouting pile has not been studied systematically. The static load test data of 152 ungrouted piles and 113 grouted piles were collected in this paper. Then, JC method and Monte Carlo method were used to compare and analyze the reliability index of the grouted pile and ungrouted pile.

2 DERIVATION OF THE LIMIT STATE EQUATION

Generally, the basic equation of the limit state is defined as written in Eq.(1):

$$g(R, S_G, S_Q) = R - S_G - S_Q = 0 \quad (1)$$

where R is the ultimate bearing capacity of piles, S_G

denotes the constant load effect, S_Q denotes the variable load effect.

Factors such as the uncertainty of soil thickness, measurement error of physical and mechanical indexes of soil layers, and the influence of pile formation process on soil layers cannot be analyzed quantitatively. Therefore, the variability of factors affecting the ultimate bearing capacity of single pile can only be comprehensively reflected through the variability of the ultimate bearing capacity of single pile R . In each structural design code, the limit state formula for strength calculation can generally be summarized as Eq.(2):

$$R_{UK} = K(S_{GK} + S_{QK}) = K(1 + \rho)S_{GK} \quad (2)$$

Where R_{UK} , S_{GK} and S_{QK} are the standard values of structural resistance, constant load effect and variable load effect respectively, K is the safety factor, and the value is 2, $\rho = S_{QK}/S_{GK}$, called load effect ratio. And Eq. (3) is obtained by dividing Eq.(1) and Eq.(2):

$$\frac{R}{R_{UK}} - \frac{1}{K(1+\rho)} \frac{S_G}{S_{GK}} - \frac{\rho}{K(1+\rho)} \frac{S_Q}{S_{QK}} = 0 \quad (3)$$

R_{UK} can be determined by the Eq.(4):

$$R_{UK} = Q_{SK} + Q_{PK} = u \sum_{i=1}^n q_{sik} l_i + q_{pk} A_p \quad (4)$$

Where Q_{SK} is the standard value of the limit side resistance of the pile, Q_{PK} is the standard value of the limit toe resistance of the pile, u is the perimeter of the pile, l_i is the thickness of the soil layer i along the pile, q_{ik} is the standard value of the limit side resistance of the soil per unit area, q_{PK} is the standard value of the limit toe resistance; A_p is the section area of the pile toe; n is the total number of soil layers.

If $\lambda_R = R/R_{UK}$, $\lambda_G = S_G/S_{GK}$, $\lambda_Q = S_Q/S_{QK}$, then Eq.(4) can be converted into Eq.(5):

$$\lambda_R - \frac{1}{K(1+\rho)} \lambda_G - \frac{\rho}{K(1+\rho)} \lambda_Q = 0 \quad (5)$$

where λ_R is the ratio of test data to design data, λ_G is the constant load effect coefficient, λ_Q is the variable load effect coefficient.

3 STATISTICS AND ANALYSIS OF THE RANDOM VARIABLES

3.1 Statistical characteristics of the bearing capacity dimensionless ratio

In this paper, The static load test data of 265 bored piles were collected. With the bearing layers of cohesive soil, the post-grouting bored piles and non-grouting bored piles were 30 and 60, respectively.

In addition, 83 post-grouting bored piles and 92 non-grouting bored piles with the bearing layer which is non-cohesive soil. According to the statistics, the mean value μ_1^c of λ_1^c is 1.074, and the coefficient of variation COV_1^c is 0.225. The mean value μ_1^n is 1.214, and the COV_1^n is 0.132. The μ_2^c is 1.188, and the COV_2^c is 0.114. And the μ_2^n is 1.434, and the COV_2^n is 0.155.

In this paper, the superscript "c" means that the bearing layer is cohesive soil, "n" means cohesionless soil, and the subscript "1" means non-grouting bored piles, and "2" means post-grouting bored piles.

3.2 Distribution test of bearing capacity dimensionless ratio

Load and resistance are two basic statistical parameters for reliability analysis of vertical bearing performance of pile foundation. The significance level was set at 0.05. Kolmogorov-Smirnov test method was used to conduct fitting test on the bearing capacity ratio, to determine the optimal overall distribution type. The K-S test results displays that λ_1^c and λ_1^n are better to follow normal distribution, then λ_2^c and λ_2^n are better to follow lognormal distributed. Fig.1 shows the comparison between histogram and probability density function. It can be seen that the trend of normal distribution function curve is closer to the change rule of histogram in Fig.1(a) and (b). However, in Fig.1(c) and (d), the variation trend of the logarithmic normal distribution function curve is closer to the histogram variation rule.

(a) $f(\lambda_1^c) - \lambda_1^c$

(b) $f(\lambda_1^n)-\lambda_1^n$ (c) $f(\lambda_2^c)-\lambda_2^c$ (d) $f(\lambda_2^n)-\lambda_2^n$

Fig. 1. Comparison of probability density function curves.

In conclusion, both the K -S test results and the comparison of distribution function curves indicate that the probability distribution types of normal distribution and lognormal distribution have a better fitting degree. Therefore, when the reliability analysis is carried out in this paper, λ_1^c and λ_1^n are considered as normal distribution, while λ_2^c and λ_2^n are considered as lognormal distribution.

3.3 Statistical characteristics of load effects

According to the “unified standard for reliability

design of building structures”, the constant load effect (G) follows normal distribution, and gumbel max distributed is better for variable load effect (Q). Then the variable load including office load(Q_O), residential load(Q_R) and wind load(Q_W). The bearing capacity test ratio and the statistical parameters of the loads are displayed in Table 1. Generally, the simple combination of constant load and one kind of variable load is encountered in structural design. In the calculation of reliable indicators, this paper only considers the combination of $G+Q_O$, $G+Q_R$ and $G+Q_W$.

Table 1. Statistical parameters of stochastic variables.

Random variable	μ	COV	Distribution type
λ_1^c	1.0744	0.2246	Normal
λ_1^n	1.2141	0.1315	Normal
λ_2^c	1.1880	0.1143	Lognormal
λ_2^n	1.4278	0.1558	Lognormal
λ_G	1.0600	0.0700	Normal
λ_{QO}	0.7000	0.2900	Gumbel Max
λ_{QR}	0.8600	0.2300	Gumbel Max
λ_{QW}	0.9990	0.1930	Gumbel Max

4 CALCULATION AND ANALYSIS OF RELIABILITY INDEX

4.1 The calculation of the reliability index of piles

In this paper, JC method and Monte Carlo(MC) method are used for calculation for comparison. The corresponding calculation program is compiled.

According to the statistical indexes of each dimensionless random variable in table 1, the reliability indexes are calculated when the total safety factor K is 2.0 and ρ is 0.25~2.50. The calculation results of reliability indexes under different load combinations are shown in table 2~5. As can be seen from the table, JC method and MC method are used to calculate the reliability index. There is little difference between them, and the reliability index of bearing capacity with post-grouting bored pile is higher, which can fully meet the engineering requirements.

Table 2. Calculated value of reliability indexes β^c of non-grouted piles

Load effects	Method	ρ							The average
		0.25	0.5	0.75	1.0	1.5	2.0	2.5	
$G+Q_O$	JC	2.3937	2.4925	2.5563	2.997	2.6532	2.6833	2.702	2.5830
	MC	2.3756	2.4642	2.5230	2.5595	2.6036	2.6229	2.6393	2.5412
$G+Q_R$	JC	2.3281	2.3842	2.4185	2.4407	2.4660	2.4788	2.4859	2.4289
	MC	2.3130	2.3610	2.3867	2.4015	2.4159	2.4198	2.4294	2.3896
$G+Q_W$	JC	2.2711	2.2900	2.2985	2.3020	2.3024	2.2996	2.2961	2.2942
	MC	2.2586	2.2655	2.2679	2.2602	2.2234	2.2476	2.2438	2.2524

Table 3. Calculated value of reliability indexes β^n of non-grouted piles

Load effects	Method	ρ							The average
		0.25	0.5	0.75	1.0	1.5	2.0	2.5	
$G+Q_O$	JC	4.4198	4.5171	4.5191	4.4703	4.3522	4.2597	4.192	4.3900
	MC	4.3934	4.4663	4.453	4.4074	4.2853	4.2127	4.1296	4.3354
$G+Q$	JC	4.3235	4.3654	4.3431	4.2875	4.1656	4.0702	3.9999	4.2222

	MC	4.2987	4.3187	4.2806	4.2246	4.0863	4.0237	3.9435	4.1680
$G + Q_w$	JC	4.2399	4.2328	4.186	4.1211	3.9932	3.8945	3.8216	4.0699
	MC	4.215	4.1843	4.1145	4.058	3.9332	3.7935	3.7624	4.0087

Table 4. Calculated value of reliability indexes β^c of post-grouted piles

Load effects	Method	ρ							The average
		0.25	0.5	0.75	1.0	1.5	2.0	2.5	
$G + Q_o$	JC	5.5388	5.1869	4.8897	4.6881	4.4406	4.2958	4.2011	4.7487
	MC	5.5027	5.1333	4.8847	4.6371	4.4442	4.3017	4.2056	4.7299
$G + Q_R$	JC	5.3929	5.038	4.7337	4.5252	4.2671	4.1153	4.0156	4.5840
	MC	5.3543	5.0254	4.7269	4.5191	4.2608	4.1192	4.0143	4.5743
$G + Q_w$	JC	5.2626	4.902	4.5909	4.3757	4.1073	3.9484	3.8437	4.4329
	MC	5.223	4.8691	4.5738	4.3567	4.0993	3.9368	3.8402	4.4141

Table 5. Calculated value of reliability indexes β^n of post-grouted piles

Load effects	Method	ρ							The average
		0.25	0.5	0.75	1.0	1.5	2.0	2.5	
$G + Q_o$	JC	6.1488	5.7819	5.4682	5.2533	4.9867	4.8295	4.7261	5.3135
	MC	6.1075	5.7733	5.471	5.2569	4.9885	4.8327	4.737	5.3096
$G + Q_R$	JC	6.0174	5.6519	5.3335	5.1132	4.8382	4.6751	4.5675	5.1710
	MC	5.987	5.5081	5.3328	5.1172	4.8248	4.6793	4.57	5.1456
$G + Q_w$	JC	5.9004	5.5338	5.2114	4.9862	4.7031	4.5343	4.4226	5.0417
	MC	5.8455	5.5052	5.2041	4.9615	4.7069	4.5327	4.4192	5.0250

4.2 Comparative analysis of the reliability index of bored pile with grouting and non-grouting

The calculation results of JC method were used to reflect the influence of post-grouting technology on the reliability index of bearing capacity of bored pile, and the reliability index of bearing capacity of ungrouted piles and grouted piles was compared with in the bearing layer is that of cohesive soil and non-cohesive soil respectively. The following conclusions could be drawn from table 6:

(1) In the above two holding layers, the reliability index of the post-grouting pile was greatly improved by 88.41% and 22.43% respectively, and the reliability index of the holding layer in the cohesionless soil was higher than that in the cohesive soil whether the grouting was done or not.

(2) For ungrouted piles, when the bearing layer at the pile end is cohesive soil, the average reliability index of the pile is 2.4354, which is significantly lower than the average reliability index of 4.2274 when the bearing layer at the pile end is cohesionless soil, and the ratio of the two is 1.74.

(3) For post-grouted piles, when the bearing layer at the pile toe is cohesive soil, the average reliability index is 4.5885; while the bearing layer at the pile toe is cohesionless soil, the average value of the reliability index is 5.1754, and the difference between the above indexes is significantly reduced, with the ratio of 1.13. The results show that the

post-grouting technology can eliminate the adverse influence of the factors of pile foundation construction, improve the reliability index of pile greatly, and reduce the influence of bearing layer on the reliability.

Table 6. Comparison of reliability indexes of post-grouted piles and non-grouted piles.

Load effects	Bearing layer	β		Increased values(%)
		ungrouted	grouted	
$G + Q_o$	Cohesive	2.5830	4.7487	83.84
	Cohesionless	4.3900	5.3135	21.04
$G + Q_R$	Cohesive	2.4289	4.5840	88.73
	Cohesionless	4.2222	5.1710	22.47
$G + Q_w$	Cohesive	2.2942	4.4329	93.22
	Cohesionless	4.0699	5.0417	23.88
average	Cohesive	2.4354	4.5885	88.41
average	Cohesionless	4.2274	5.1754	22.43

5 ANALYSIS OF INFLUENCING FACTORS OF RELIABILITY INDEX

5.1 The influence of K on the reliability index β

Table 2~5 lists the reliability indexes under the ratios of 7 different kinds of load effects. Figure 2 shows the relationship between the safety factor K and the reliability index β of two types of pile foundation. As shown in Fig.2, when ρ is constant, the reliability index β increases with the increase of K , which is also consistent with people's experience.

Fig.2. Relationships between β and K

5.2 Effect of pile diameter on reliability index β

According to the bearing capacity dimensionless ratio under different pile diameters, the relationship curves between the diameters D of piles and the reliability index β were drawn, as shown in Fig.3. It can be seen from Fig.3, the reliability index of both post-grouting piles and ungrouted piles increases with the increase of pile diameter, and the variation rule of the reliability index with pile diameter is basically consistent under different load effect ratios. When the pile diameter is the smaller values, reliability index along with the increase of pile diameter, the increase of amplitude is higher, when the pile diameter increased to a certain value (0.8m), its increasing range will reduce gradually, but still is a trend of increase, this phenomenon shows that as the pile diameter increased, pile bearing capacity of the discreteness of gradually reduce, reliability index increased gradually, while the pile diameter increases to a certain value, by increasing the pile diameter way to improve the bearing capacity of pile showed the effect

of diminishing. Compared with non-grouting piles, the reliability index of post-grouting piles is higher under the condition of the same pile diameter. With the increase of the same pile diameter values, the reliability index of post-grouting piles increases more slowly and the change trend is more stable. In other words, the bearing capacity stability of post-grouting piles foundation is relatively higher.

Fig.3. Relationships between β and D

6 CONCLUSIONS

(1) In this paper, the reliability indexes under the ratios of 7 different kinds of load effects are calculated, the results indicate that the reliability index β increases with the increase of the safety factor K when the ratio of load effects is a certain value.

(2) Based on JC method and MC method, the reliability index of bored pile before and after grouting was calculated and analyzed. This indicates that grouting can weaken the adverse influence of construction technology factors of bored pile, enhance the strength and stiffness of soil around the pile, and reduce the

influence of soil properties of bearing layer on the reliability.

(3) The reliability of post-grouting pile tends to increase with the increase of pile diameter, and the reliability tends to be consistent with the change of pile diameter under different load effect ratios. When pile diameter D is a relatively small value, β increases rapidly as pile diameter increases. However, when D increases to a certain value, β tends to increase slowly with the increase of pile diameter, and finally tends to be stable. This indicates that there is a certain upper limit value in the way of increasing pile diameter to improve the bearing capacity of pile foundation. When the value of pile diameter reaches this value, it is unreasonable to increase pile diameter to enhance the bearing capacity of pile foundation.

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