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A practical method of calculation of bearing capacity and settlement of large-diameter post-grouting piles

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Abstract: Based on the static load test data of 716 test piles collected from 139 projects, the practical calculation method of bearing capacity and settlement of large-diameter post-grouted piles was studied. The improvement coefficients of the side friction and base resistance of soil layer were given primarily based on statistics analysis, and the practical calculation approach for the bearing capacity of large-diameter post-grouted piles applicable to different grouting types was presented. The reliability of the proposed approach was verified by a large number of measured data. Moreover, the influence coefficient of post-grouting settlement was introduced based on the settlement calculation method of large-diameter pile foundation without grouting. Based on the statistical analysis, the recommended range of influence coefficient of post-grouting settlement was given, and an empirical estimation method for calculating settlement of large-diameter post-grouted piles suitable for different soil layers was proposed. Finally, the applicability of the proposed method was verified using engineering examples. The research results have been incorporated into the industry standard of the People's Republic of China *Code for design of ground base and foundation of highway bridges and culverts* (JTJ 3363－2019) and the industry standard of national project construction *Technical specification for post-grouting of cast-in-place pile of highway bridges* (T/CECS G: D67-01－2018), which can promote the wide application of post-grouting technique.

Keywords: large-diameter post-grouted pile; bearing capacity; improvement coefficient; statistical analysis; settlement calculation; influence coefficient of post-grouting settlement

1 Introduction

With the continuous emergence of super high-rise buildings and long-span bridges, the diameter and length of bored piles are increasing. Piles with large diameters and extended length are gradually gaining popularity in the industry [1]. In order to obtain higher bearing capacity in piles, post-grouting technology has been widely used. At present, post-grouting technology has been incorporated into the industry standard of the People's Republic of China "*Technical Code for Building Pile Foundations*" (JGJ 94-2008) [2] and "*Code for Design of Ground base and Foundations of Highway Bridges and Culverts*" (JTG D63-2007) [3]. Both codes of practice give design methods based on bearing capacity. The current "*Technical Code for Building Pile Foundations*" is given based on the research on the static load test data of post-grouting piles with small and medium diameters. The calculation of the bearing capacity of grouted piles with large-diameters is not applicable. The current " *Code for Design of Ground base and Foundations of Highway Bridges and Culverts* " is derived from the collected static load test data of 69 large-diameter pile ends with post-grouting piles. In the past 10 years since the promulgation of the two regulations, engineering projects related to postgrouting have been rapidly developed and the technology has been applied nationwide. Numerous on-site data of large-diameter post-grouting piles have been measured and collected. Post-grouting piles have also been continuously used in practical engineering projects[4–8]. Therefore, the existing literature[3] can no longer satisfy the design requirements of the current large-diameter post-grouting pile engineering projects, and the post-grouting technology is no longer limited to the post-grouting type of pile end. In addition, the applied stratum conditions are extended to more soil types. Therefore, improving the existing specifications is an issue that needs to be solved urgently.

With the increasingly strict requirements of foundation settlement for superstructures, post-grouting technology is not only used as a means to increase the bearing capacity, but also gradually becomes a means of settlement control, especially for critical buildings such as super high-rise buildings, long-span bridges and high-speed railways [9]. In the basic design of high-speed railways, in order to ensure the smooth operation of the railway under long-term dynamics, it is required that the post-construction settlement shall not exceed 15 mm, and the differential settlement between adjacent piers and abutments of the bridge foundation shall not exceed 5 mm. Therefore, effective control of the settlement of pile foundations has become a key concern in practical engineering projects. At present, there are few researches on the settlement calculation of post-grouting piles. Researchers found that the post-grouting pile settlement calculation involved in the code or manual has adopted the following two methods by referring to

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domestic and foreign documents. In the first method, relevant regulations are made for the settlement calculation of cast-in-place piles using post grouting technology[2]. The empirical coefficient of settlement of pile foundation should be reduced by 0.7 (for sand, gravel and cobbles) to 0.8 (for cohesive soil and silt) based on the type of bearing course at pile end. Then the settlement of post-grouting piles can be evaluated. However, the method for calculating the settlement of pile foundations in the code is mainly for the ordinary short and medium piles with small or medium diameters. It is not necessarily applicable to the settlement calculation of large-diameter post-grouting piles. Mullins et al.[10] proposed the second design method that considers the correlation between the grouting pressure and improvement coefficient of the tip resistance. The corresponding grouting pressure ratio and the tip resistance of the grouting pile can be obtained based on the settlement of different pile tops, thereby obtaining the approximate load–displacement relationship of the mortar pile. This design method has been incorporated into the "*Soils and Foundations Handbook*" by the Florida Department of Transportation [11]. However, this method does not consider the influence of grouting on the pile side friction resistance, which leads to certain limitations. Therefore, studying the design method for settlement calculation of large- diameter post-grouting piles has important practical significance for the popularization and application of post-grouting technology.

Based on the " *Code for design of ground base and foundation of highway bridges and culverts* " (Revised edition 2019) [12], this paper collects static load test data of 716 trial piles in 139 projects and presents results based on statistical analysis. For improvement coefficients of side friction and tip resistance of soil layers, a practical method for calculating the bearing capacity of large-diameter post-grouting piles with different grouting types is established using the side friction and tip resistance improvement coefficient method. In view of the problem that the settlement calculation of large-diameter post-grouting piles has not yet formed a unified standard, the post-grouting settlement influence coefficient is introduced based on the settlement calculation method of the large-diameter pile foundation without grouting. The suggested value range of the influence coefficient of grouting settlement after combination is proposed, and an empirical estimation method for settlement calculation of large-diameter grouting piles suitable for different soil layers is proposed.

2 Static load test data

In engineering practice, the design of post-grouting piles is affected by many factors, such as pile diameter, pile length, pile end bearing layer, soil layer around the pile, grouting type and grouting parameters. Based on post-grouted pile static load tests completed by this research group and combined with the collected test pile data from published literature, authors performed statistics analysis of the specific parameters of post-grouting piles and non-grouted piles. Figure 1 shows the distribution of the number of engineering projects and the number of test piles in different regions across the country.

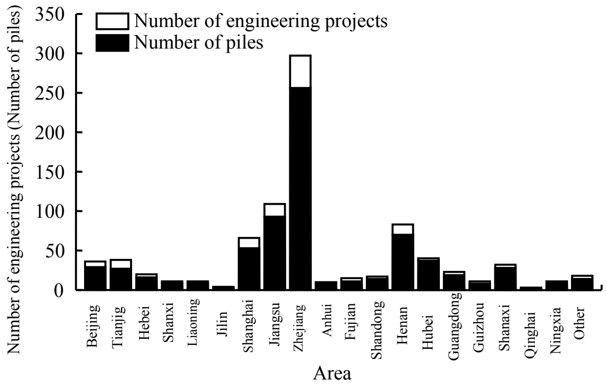

Fig. 1 Distribution of the number of engineering projects related to grouting piles and number of grouting piles in various areas

It can be seen from the statistical results that the number of projects and the number of test piles are 139 and 716, respectively, and their distribution basically covers most areas of China. In this paper, piles with a diameter greater than 800 mm are regarded as large-diameter piles, and the statistical distribution range of pile diameter is 800–2 800 mm, of which large-diameter piles with pile diameters of 1,000 to 1,500 mm account for the majority. Piles with diameter larger than 2,000 mm accounted for 12.43% of the total statistics. After statistically analysing different factors in the grouting process, including pile diameter, pile length, bearing soil layer, types of grouting and other less significant factors, it can be concluded that the post-grouting technology is gradually gaining its popularity in grouting piles with larger diameter and longer pile length. In addition, there is an increasing trend in adopting super-long piles with a length-to-diameter ration of over 50 in the industry. The post-grouting technology can be applied to clay soils, silt layer, sand layer, gravel soil layer and weathered rock layer. This technology is more suitable for sand layer and gravel soil layer in engineering practice, and it is also widely used in silty clay layer. In addition, the pile end post-grouting is currently most applied to large-diameter piles, and the pile side post-grouting and combined post-grouting are gradually being used in real projects. It should be pointed out that the non-grouted piles obtained from statistical analysis are used as comparative test data of the post-grouting piles.

3 Calculation of the bearing capacity

3.1 Resistance improvement coefficient and statistical analysis of post-grouting piles

The ultimate bearing capacity of post-grouting piles in the vertical direction is affected by many factors, and the property of the soil at pile end and pile side is one of the most critical factors. In other words, the ultimate side friction resistance and ultimate tip resistance of the soil determine the ultimate bearing capacity of the post-grouting pile. Therefore, it is more reasonable to consider the grout to reinforce the soil at the end or side of the pile to enhance the resistance of the pile foundation when the post-grouting pile is designed based on its bearing capacity. In order to further improve the calculation formula for the bearing capacity of large-diameter post-grouting piles, improvement coefficients of the post-grouting side friction and tip resistance are given based on the collected static load test data of 716 post-grouting piles and non-grouted piles. The data is categorized and summarized according to soil layers to make the calculation formula for the bearing capacity of the post-grouting pile more applicable. Among the data, the improvement coefficients of ultimate side friction resistance β_{si} and tip resistance β_{p} of the post-grouting pile are given as follows:

$$\beta_{si}=\frac{q'_{sik}}{q_{sik}},\ \beta_{\mathrm{p}}=\frac{q'_{\mathrm{pk}}}{q_{\mathrm{pk}}} \qquad (1)$$

where q_{sik} and q_{pk} are standard values of the ultimate side friction and ultimate tip resistances of the i-th layer of soil on the side of the non-grouted pile, respectively; q'_{sik} and q'_{pk} are standard values of the ultimate side friction resistance and ultimate tip resistance of the i-th layer of soil on the side of the post-grouting pile, respectively.

The data collection of improvement coefficients of ultimate side friction β_{si} and ultimate tip resistance β_{p} is based on the following principles: (1) For β_{si}, classified according to properties of the soil layer, the ratio of the side friction between the post-grouting pile and the non-grouted pile in each soil layer is calculated. The data of pile tip grouting piles in a certain range above the pile tip is summarized and collected[13]; for side grouting piles and combined grouting piles, the data in the whole length range of the piles should be collected. When only the post-grouting pile data can be collected but the corresponding non-grouted pile data cannot be collected, the standard value of the ultimate side friction provided by the geotechnical engineering survey report will replace the non-grouted pile data. (2) For β_{p}, it is obtained by classifying soil layers and then calculating the side friction ratio of the post-grouting pile and the non- grouted pile. When only the post-grouting pile data can be collected but the corresponding non-grouted pile data cannot be collected, the tip resistance of the non-grouted pile should be determined based on the size of the pile, geological data and construction technology using the method recommended in the codes [2–3].

The data obtained by the above collection methods often need to be filtered before they can be used. The data collected in four cases is not available. (1) If the resistance of pile foundation after grouting is smaller than that before grouting, in the context, the data does not exist in theory, but in real projects, such data may exist due to testing process, reading errors or other reasons. (2) Post-grouting piles and the corresponding non-grouted piles are tested, but the data is collected without reinforcement stress gauges. (3) The side friction resistance of piles is not fully exerted due to insignificant grouting effect or small relative displacement between pile and soil, which results in the side friction ratio of post-grouted piles and non-grouted piles being close to 1.0 or even less than 1.0. (4) The tip resistance of the post-grouting pile is not fully exerted because the loading equipment reaches its limit, or it is not fully brought into play to the limit and is less than that of the non-grouted pile.

Because the testing data collected is affected by factors such as construction process, human and environmental factors, the dataset has a certain degree of dispersion. Therefore, proper mathematical methods are used to filter the data, that is, to calculate the standard value X_{k} or mean X_{m} of the statistical data, and then check the individual points in the entire interval and discard data with large deviations. In the actual data analyzing process, the 3 times standard deviation method is used to make judgment. The standard value plus or minus 3 times the standard deviation, or the mean plus or minus 3 times the standard deviation is used. If the testing data is in the $X_{\mathrm{k}}-3\sigma\leqslant X_i\leqslant X_{\mathrm{k}}+3\sigma$ or $X_{\mathrm{m}}-3\sigma\leqslant X_i\leqslant X_{\mathrm{m}}+3\sigma$ range, it is the normal value, and the data outside this range is discarded as abnormal value. The mean, standard deviation, coefficient of variation, standard value and statistical correction coefficient are calculated for the post-processed testing data, until all the testing data are in the $X_{\mathrm{k}}-3\sigma\leqslant X_i\leqslant X_{\mathrm{k}}+3\sigma$ or $X_{\mathrm{m}}-3\sigma\leqslant X_i\leqslant X_{\mathrm{m}}+3\sigma$ range, then the mean, standard deviation and coefficient of variation are calculated again.

In data processing, coefficient of variation δ can be used to evaluate the discrete degree of the sample, and it can also be used to compare the discrete degree of testing samples with different indicators[14]. In order to obtain accurate calculation results, the confidence level $1-\alpha$ is introduced in the data processing. According to the principle of standard normal distribution, the calculation result can be obtained as $X_{\mathrm{m}}\pm z_{\alpha/2}\sigma/\sqrt{n}$, and the confidence interval is $(X_{\mathrm{m}}-z_{\alpha/2}\sigma/\sqrt{n},\ X_{\mathrm{m}}+z_{\alpha/2}\sigma/\sqrt{n})$, where n is the number of samples. Figure 2 shows a schematic diagram of the confidence interval of the normal distribution function.

By setting different confidence levels, different confidence intervals can be obtained using the standard normal distribution principle, and the higher the confidence level, the greater the corresponding critical value. Therefore, when other factors remain unchanged, a higher confidence level leads to a wider confidence interval. In addition, the confidence interval is not only related to the confidence level, but also affected by the sample size. Therefore, when calculating the resistance improvement coefficient of post-grouted piles with large diameters, the principles for setting confidence level are as follows: (i) the value should meet the accuracy requirements; (ii) the estimated interval should meet the requirements (that is, the size of the value range).

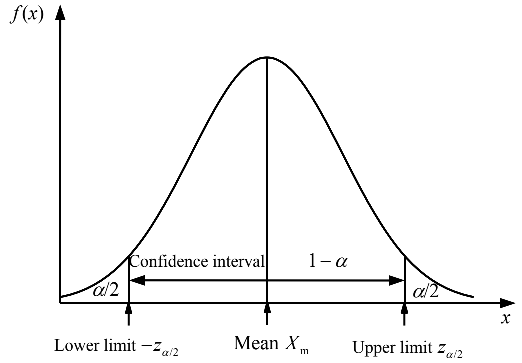

Fig. 2 Schematic diagram of confidence interval for normal distribution

3.2 Analysis of the value of the resistance improvement coefficient of the post-grouting pile

Using the above-mentioned data collection method and processing principle, the statistical distribution of resistance improvement coefficients of post-grouting pile side and pile end in different soil layers can be achieved as shown in Fig.3. The sample sizes of effective post-grouting side friction and tip resistance improvement coefficients are 1,160 and 220, respectively, and the pile side and end are related to the main soil layer. It is worth noting that among the data collected on the combined grouting piles, the distribution of the loess layer on the side of the pile is summarized. It can be seen from the distribution of soil layers that post- grouting technology can be used for gravel soil and sandy soil, as well as silt, cohesive soil and weathered rock.

The collected data for improvement coefficients of ultimate side friction and tip resistance are processed based on the principle mentioned in section 3.1. Improvement coefficient for side friction β_{si} and tip resistance β_p of post-grouting piles in different soil layers are presented in Tables 1 and 2. It can be seen from the tables that the resistance of post-grouting pile foundations in different soil layers increases to a certain degree compared to those of non-grouted piles, and the increase is more significant as the soil particles become larger. Among them, the soil layers where the pile side and tip resistances increase significantly are rubble, cobble layers and coarse sand, gravelly sand layer, while the pile side and pile tip resistance in clay, silty clay and weathered rock layer are smaller compared to other soils. This means that the increase of the resistance of the post-grouting pile foundation is related to the properties of the soil layer.

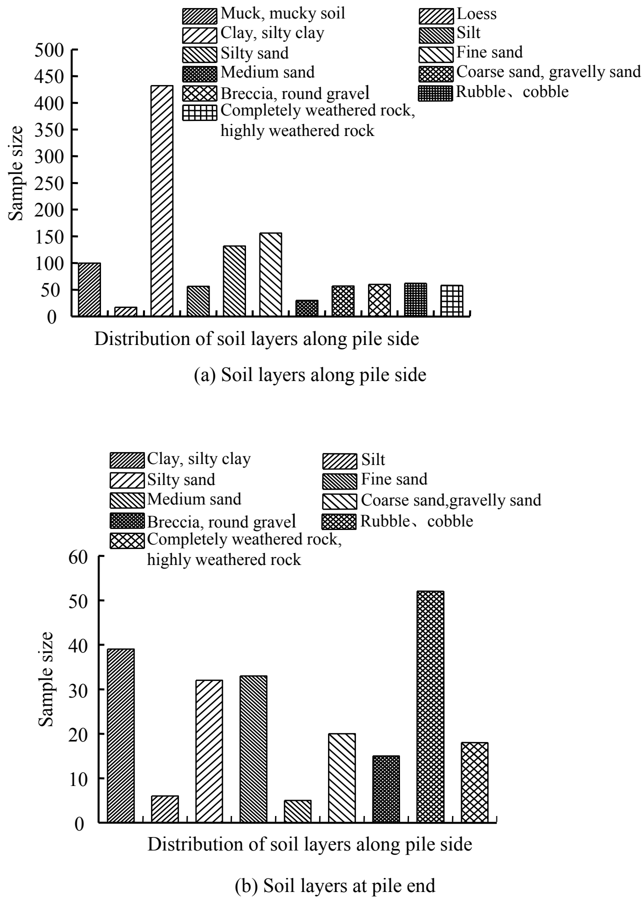

Fig. 3 Statistical distribution of sample numbers in different soil layers

Table 1 Improvement coefficients of side friction β_{si} for post-grouting in different soil layers

Soil layer	Mean	Standard deviation	Range of β_{si}	Coefficient of variation
Muck, mucky soil	1.29	0.15	1.23–1.34	0.12
lay, silty clay	1.38	0.22	1.34–1.41	0.16
Loess	1.53	0.23	1.44–1.62	0.15
Silt	1.47	0.30	1.41–1.52	0.21
Silty sand	1.58	0.32	1.54–1.63	0.21
Fine sand	1.62	0.19	1.57–1.67	0.12
Medium sand	1.77	0.28	1.66–1.88	0.16
Coarse sand, gravelly sand	1.89	0.44	1.81–1.97	0.23
Breccia, round gravel	1.66	0.26	1.56–1.75	0.16
Cobble	1.86	0.43	1.77–.96	0.23
Completely weathered rock, highly weathered rock	1.32	0.27	1.20–1.44	0.20

Table 2 Improvement coefficients of tip resistance β_p for post-grouting in different soil layers

Soil layer	Mean	Standard deviation	Range of β_p	Coefficient of variation
Clay, silty clay	1.73	0.430	1.63–1.83	0.25
Silt	2.00	0.130	1.83–2.11	0.06
Silty sand	2.06	0.490	1.92–2.21	0.24
Fine sand	2.15	0.710	1.97–2.33	0.33
Medium sand	2.15	0.195	2.03–2.28	0.09
Coarse sand, gravelly sand	2.27	0.210	2.17–2.37	0.09
Breccia, round gravel	2.37	0.290	2.24–2.50	0.12
Cobble	2.40	0.430	2.30–2.50	0.18
Completely weathered rock, highly weathered rock	1.47	0.180	1.34–1.60	0.12

3.3 Practical formula for calculating the bearing capacity of post-grouting piles

Table 3 gives the recommended value ranges for improvement coefficients of the side friction and tip resistance in different soil layers after grouting. Therefore, through the statistical analysis of the resistance ratio of the post-grouting pile and the nongrouted pile foundation, a practical calculation formula for the vertical ultimate bearing capacity of the post-grouting pile is obtained.

$$Q_{\mathrm{uk}} = u\sum \beta_{si} q_{sik} l_i + \beta_{\mathrm{p}} q_{\mathrm{pk}} A_{\mathrm{p}} \qquad (2)$$

where Q_{uk} is the standard value of the ultimate bearing capacity of the post-grouting pile; u is the circumference of the pile; l_i is the thickness of the i-th layer around the pile; and A_{p} is the cross-sectional area of the pile. In addition, the ultimate improvement coefficients of side friction β_{si} and tip resistance β_{p} can be taken according to Table 3. When the pile tip is grouted in a saturated soil layer, only the side friction of the pile in the range of 10.0–12.0 m above the pile tip is improved and corrected. When the pile tip is grouted in an unsaturated soil layer, only the side friction in the range of 5.0–6.0 m is strengthened and corrected. When the pile side is grouted in a saturated soil layer, the pile side friction in the range of 10.0– 12.0 m above the grouting section is strengthened and corrected. When the pile side is grouted in an unsaturated soil layer, the pile side friction within the range of 5.0 to 6.0 m on the upper and lower sections of the grouting section is enhanced and corrected. As for sections that are not included in the range mentioned above, $\beta_{si} = 1$.

Table 3 Improvement coefficients of side friction and tip resistance for post-grouting

Soil layer	β_{si}	β_{p}
Mucky soil	1.2–1.3	—
Clay, silty clay	1.3–1.4	1.6–1.8
Loess	1.4–1.6	—
Silt	1.4–1.5	1.8–2.1
Silty sand	1.5–1.6	1.9–2.2
Fine sand	1.6–1.7	2.0–2.3
Medium sand	1.7–1.9	2.0–2.3
Coarse sand, gravelly sand	1.8–2.0	2.2–2.4
Breccia, round gravel	1.6–1.8	2.2–2.5
Rubble、cobble	1.8–2.0	2.3–2.5
Completely weathered rock, highly weathered rock	1.2–1.4	1.3–1.6

Equation 2 is based on the actual measurements of real engineering projects. The data collected covers most areas in China, and they are all about large- diameter bored piles, which have great practical value. This formula has been applied to the compilation of the "*Code for Design of ground base and Foundation of Highway Bridges and Culverts*" (2019 revised edition), and has been incorporated into the "*Technical Specification for Post-grouting of Highway Bridges and Culverts*" (T/CECS G: D67-01-2018) [15], with strong pertinence. In addition, this statistic supplemented the test data on combined post-grouting piles, regarding pile tip and side, which was not mentioned in the original specification[3]. The calculation of the bearing capacity of combined post-grouting piles is based on the improvement coefficients of pile tip and side grouting. The scope of influence shall be revised, and the overlapping part shall be deducted.

3.4 Case analysis and verification

In order to verify the rationality and applicability of the Eq.(2) for the ultimate bearing capacity of post-grouting piles proposed in this paper, 190 post-grouting piles with complete test data are selected and the corresponding $Q_{\mathrm{uk\,c}}$ is calculated using Eq. (2). It is suggested to take the recommended values provided in the geotechnical engineering survey report for q_{sik} and q_{pk}, and take the upper limit listed in Table 3 for improvement coefficients for side friction β_{si} and tip resistance β_{p}. Results calculated of the ultimate bearing capacity of the post-grouting pile are shown in Figs. 4 and 5.

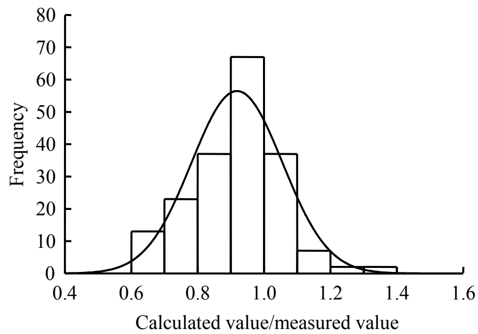

Fig. 4 Histogram of calculated and measured values of ultimate bearing capacity for post-grouted pile

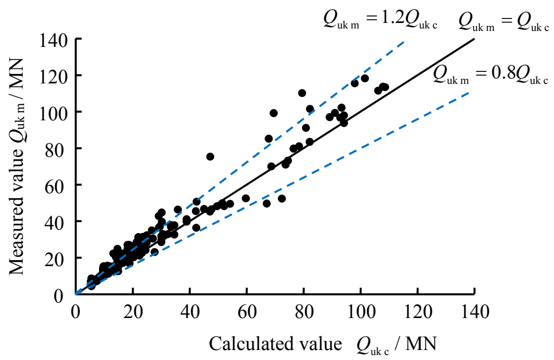

Fig. 5 Scatter diagram of calculated and measured values of ultimate bearing capacity for post-grouted piles

Figure 4 presents the ratio of the calculated results to the measured results follows a normal distribution, and the samples with the ratio close to 1.0 account for about 54% of all samples. Figure 5 shows the comparison between the calculated and measured values of the ultimate bearing capacity of 190 post-grouting piles. The figure shows that the data points are mainly concentrated on both sides of the contour between the calculated and measured values, and most of the data points are located within ±20% of the deviation curve on both sides of the contour. There are 35 samples outside the ±20% deviation curve, accounting for about 18.4% of the all samples. This shows that the guarantee rate of the calculation results of the bearing capacity reaches 81.6%. In addition, there are 140 samples with data points above the isoline, accounting for about 73.7% of all samples, that is, the majority of the calculated value is less than the measured value. This shows that the ultimate bearing capacity of the post- grouting pile is highly reliable when calculated using Eq. (2).

The verification and analysis process show that improvement coefficients obtained in this paper for side friction and tip resistance are reasonable and feasible. The proposed formula for the vertical ultimate bearing capacity of post-grouting piles using improvement coefficients method for the side friction and tip resistance has relatively high accuracy and reliability. The formula is based on the measured data and has high practicability. It can be used by engineering designers when designing large diameter post-grouting piles.

4 Empirical prediction method for calculating settlement of post-grouting piles

Literature [3] does not involve settlement calculation of post-grouting piles, so there is no uniform standard for settlement calculation of large diameter post-grouting piles. In this paper, the settlement calculation formula method in literature[2] is revised to perfect the design method for settlement calculation of the large diameter post-grouting pile.

4.1 The influence coefficient of post-grouting settlement

A simplified layered sum method for the settlement calculation of pier foundation is presented in literature [3]. Since the formula for calculating settlement of pile foundation is not clearly given, this method has certain limitations. Let's deduce the influence coefficient of post grouting settlement. The formula for calculating the settlement of pile foundation recommended by the "*Code for Design of Building Foundations*" (GB 50007-2011) [16] is as follows:

$$s = \psi_{\mathrm{s}} \sum_{i=1}^{n} \frac{\sigma_{zi}}{E_{si}} \Delta z_i \qquad (3)$$

$$\sigma_{zi} = \sum_{j=1}^{n} \frac{Q_j}{l_j^2} \left[\alpha_j I_{\mathrm{p},ij} + \left(1-\alpha_j\right) I_{\mathrm{s},ij} \right] \qquad (4)$$

where ψ_{s} is the empirical coefficient for settlement calculation; E_{si} is the compression modulus of the i-th layer of soil under the bottom of the foundation, which should be calculated from the self-weight compressive stress of the soil to the sum of the soil's self-weight compressive stress and the additional stress; σ_{zi} is the sum of the vertical additional stress generated at 1/2 thickness of the i-th layer of soil below the plane at the pile tip; z_i is the distance from the bottom of the foundation to the bottom of the i-th layer of soil; Q_j is the additional load on the top of the j-th pile under the quasi-permanent combination of load effects. l_j is the pile length of the j-th pile; α_j is the ratio of the pile tip resistance of the j-th pile to the pile top load; $I_{\mathrm{p},ij}$ and $I_{\mathrm{s},ij}$ are stress influence coefficients of the pile tip resistance and the pile side friction of the j-th pile on the calculation axis at 1/2 thickness of the i-th calculation soil layer, respectively, they can be derived by integrating the Mindlin stress formula.

In addition, the pile top settlement of large-diameter and super-long piles under high stress levels is mainly derived from compression of the pile, which is concluded in the literature [17]. Therefore, when the primary settlement of pile foundation is calculated using the unidirectional compression method as described in the Reissner-Mindlin equation, the compression of the pile body s_{e} should be included. From Eq. (3), we can get

$$s = \psi_{\mathrm{s}} \sum_{i=1}^{n} \frac{\sigma_{zi}}{E_{si}} \Delta z_i + s_{\mathrm{e}} \qquad (5)$$

The above is the calculation formula for the settlement of large-diameter pile foundation without post-grouting. In order to consider the settlement control of large-diameter pile foundation by post- grouting, this paper introduces the post-grouting settlement influence coefficient that refers to the ratio of the settlement at the pile top of the grouted pile to that of the non-grouted pile under the same load, and it can be expressed as

$$\zeta = \frac{s'}{s} \qquad (6)$$

where ζ is the influence coefficient of post-grouting settlement; s and s' are the pile top settlements of non-grouted piles and grouted piles under the same load, respectively.

From Eqs. (5) and (6), we can get

$$s' = \zeta \left(\psi_{\mathrm{s}} \sum_{i=1}^{n} \frac{\sigma_{zi}}{E_{si}} \Delta z_i + s_{\mathrm{e}} \right) \qquad (7)$$

Equation (7) is the calculation formula for the settlement of large diameter post-grouting piles.

In order to further illustrate the influence of pile top settlement on the influence coefficient of post-grouting settlement, the settlement values are given in Fig. 6 for the non-grouted and grouted piles under different load conditions from a large number of measured pile top load Q–pile top settlement curves.

From Fig. 6, it is found that the settlement at the pile top of the grouted pile under ultimate load is greater than that of the non-grouted pile. This is mainly due to the substantial increase in the bearing capacity of the pile foundation after grouting, leading to larger settlement at the pile top when it is loaded to the ultimate load. Therefore, the influence coefficient of post-grouting settlement should be determined according to the pile top settlement corresponding to the non- grouted pile and the grouted pile under the load condition of the grouted pile in the normal service limit state. In general, the service load Q'_{a} is 1/2 of the ultimate load, so the corresponding settlement ratio under the service load of the grouted pile can be defined as the post-grouting settlement influence coefficient, and its expression is

$$\zeta = \frac{s'_{\mathrm{a}}}{s_{\mathrm{a}}} \qquad (8)$$

where s_a and s'_a are the pile top settlement corresponding to the non-grouted pile and the grouted pile under the service load, respectively.

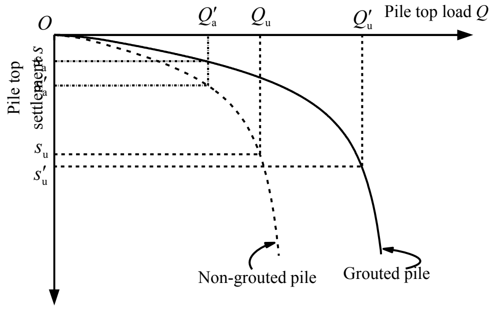

Fig. 6 Schematic diagram of settlement value of non-grouted and grouted piles under different loading conditions

4.2 Analysis of the influence coefficient of post-grouting settlement

The value of the post-grouting settlement influence coefficient can be determined based on the static load test data of 716 post-grouting and non-grouted piles. In order to provide reference for engineering designers in the preliminary design of large-diameter post-grouting piles, the obtained post-grouting settlement influence coefficient is used as a random variable, and the post-grouting settlement influence coefficient is statistically analyzed based on different soil types. This paper gives the value range of the influence coefficient of post-grouting settlement.

This statistical analysis involves the trial pile data of different grouting types, but the proportion of side grouting piles is small, and the sample size has a substantial impact on the accuracy of the post-grouting settlement influence coefficient. Therefore, in order to satisfy the accuracy requirement of the value range, this paper only compares the tip grouted pile and the combined grouted pile with the non-grouted pile to obtain the post-grouting settlement influence coefficient. In addition, the calculation of the post-grouting settlement influence coefficient follows principles described in section 3.1. Therefore, settlement influence coefficients of pile tip post-grouting and combined post-grouting in different types of soil layers can be obtained, as shown in Tables 4 and 5.

It can be seen from Tables 4 and 5 that, compared with non-grouted piles, the settlement of grouted piles in different bearing strata is reduced, and the decrease is more significant with the increase of particle size, which shows that post-grouting piles technology has a significant effect on controlling the settlement of pile foundation. By comparing the settlement influence coefficients of pile tip post-grouting and combined post-grouting, it can be seen that the effect of combined post-grouting on the settlement of pile foundation is better than that of pile tip post-grouting. It should be noted that the weathered rock layers in this study mainly involve moderately weathered, highly weathered and completely weathered rock layers. In addition, the sample size of combined grouting piles in the medium-coarse sand layer, gravelly sand layer, gravel layer, cobble layer and weathered rock layer is small, which affects the accuracy of the value of the influence coefficient of post-grouting settlement. In particular, it leads to smaller settlement influence coefficient of combined post-grouting piles in the middle-coarse sand layer and gravelly sand layer, but on the whole it can still reflect similar trend of influence coefficient as that of the post- grouting settlement of the pile tip.

According to the collected static load test data of post-grouting piles and non-grouted piles, a recommended value range of settlement influence coefficients of pile tip post-grouting and combined grouted piles in differ-rent soil layers is obtained, as shown in Table 6.

Table 4 Influence coefficients of settlement ζ for post-grouting at pile tip

Soil layer	Mean	Standard deviation	Range of ζ	Coefficient of variation
Clay and silt layer	0.72	0.12	0.68–0.79	0.16
Silt and fine sand layer	0.63	0.19	0.58–0.69	0.30
Medium coarse sand and gravelly layer	0.62	0.19	0.53–0.71	0.30
Gravel and cobble layer	0.66	0.20	0.57–0.71	0.30
Weathered rock	0.74	0.29	0.56–0.93	0.29

Table 5 Influence coefficients of settlement ζ for combined post-grouting at pile tip and side

Soil layer	Mean	Standard deviation	Range of ζ	Coefficient of variation
Clay and silt layer	0.71	0.16	0.62–0.78	0.23
Silt and fine sand layer	0.57	0.16	0.52–0.62	0.28
Medium coarse sand and gravelly layer	0.22	0.02	0.20–0.27	0.11
Gravel and cobble layer	0.54	0.34	0.36–0.72	0.63
Weathered rock	0.47	0.12	0.38–0.56	0.26

Table 6 Recommended range of influence coefficients of settlement ζ for post-grouting

Type of grouting	Clay and silt layers	Silty sand and fine sand layers	Medium-coarse sand and gravelly sand layers	Gravel and cobble layers	Weathered rock formation
Pile tip grouting	0.7–0.8	0.6–0.7	0.5–0.7	0.6–0.7	0.6–0.9
Combined grouting	0.6–0.8	0.5–0.6	0.2–0.3	0.4–0.7	0.4–0.6

By comparing the post-grouting settlement influence coefficient of the pile tip in Table 6 with the reduction factor of the empirical settlement calculation coefficient

ψ for post-grouting pile technology specified in the literature [2], it can be found that the two show the same trend with different bearing layers at the pile tip. The post-grouting settlement influence coefficient obtained in the statistical analysis of collected data is smaller than the reduction factor of the empirical settlement calculation coefficient in the existing "*Technical Specification for Building Pile Foundations*"[2]. This also indicates that the post-grouting settlement influence coefficient obtained from this statistical analysis of large-diameter piles is different from the small and medium-diameter piles collected in the specification, and further shows that the post-grouting pile settlement calculation method given in the literature [2] is conservative for large-diameter post-grouting piles. Therefore, the calculation result of large-diameter post-grouting pile settlement is more in line with engineering practice with the help of the settlement influence coefficient of post-grouting that is derived from the measured data of large-diameter piles and combining Eq. (7).

4.3 Calculation example

In order to verify the rationality of the empirical estimation method for the settlement calculation of large-diameter post-grouting piles using the post-grouting settlement influence coefficient, a project in Taizhou, China[18] is taken as an example for calculation and comparison. In this project, large-diameter super-long bored pile was used, and the post-grouting construction technology of pile tip was adopted. The trail pile SZ4 has a diameter of 1500 mm and a length of 82 m. Concrete used for the pile body has a strength grade of C30. The bearing layer at the pile end is clay. The soil types along the pile shaft are mainly silty clay and clay. The basic parameters of each soil layer of the trail pile SZ4 are shown in Table 7.

Table 7 Physico-mechanical parameters of soil layers for trial pile SZ4

Soil layer	l_i /m	ω /%	γ /(kN·m^{-3})	E_{s1-2} /MPa	f_{a0} /kPa	q_{sik} /kPa
①$_1$ Silty clay	1.8	24.20	19.42	6.54	100	30
②$_2$Mucky clay	24.0	49.50	16.48	1.92	55	12
③$_3$ Clay	8.0	44.80	17.36	3.40	80	20
④$_2^1$Silty clay	19.7	30.20	18.15	3.82	120	20
④$_2^1$Silty clay	4.2	31.20	18.44	4.87	140	30
⑤$_2^1$Silty clay	12.3	32.40	18.34	6.42	140	35
⑤$_5$Clay	14.8	34.80	18.44	5.35	160	35
⑥$_1$Silty clay	12.5	29.40	19.13	5.82	180	45
⑥$_2$Silty clay	28.6	27.50	18.74	5.65	140	40

Note: l_i is the thickness of each soil layer; ω is the water content of the soil; γ is the unit weight of the soil; E_{s1-2} is the soil compressive modulus; f_{a0} is the characteristic value of the foundation bearing capacity; q_{sik} is the standard value of the pile side friction resistance of each soil layer corresponding to l_i.

Before calculating the settlement of the post-grouting single pile, the vertical ultimate bearing capacity of the post-grouting single pile should be estimated using Eq. (2). The improvement coefficients of side friction β_{si} and the tip resistance β_p should take the upper limit listed in Table 3, and the improvement range of pile tip grouting to increase the pile side friction resistance is 12 m. The detailed calculation for the bearing capacity of the trial pile SZ4 after grouting is shown in Table 8.

Table 8 Calculation of bearing capacity of trial pile SZ4 after grouting

Soil layer	l_i /m	q_{sik} /kPa	$\beta_{si}q_{sik}l_i$ /kPa	Calculation of bearing capacity of post-grouting single pile	
①$_1$Silty clay	1.8	30	1.0×54	Allowable value of pile end bearing capacity /kPa $q_r = m_0\lambda[f_{a0} + k_2\gamma_2(h-3)]$	1 416
②$_2$Mucky clay	24.0	12	1.0×288		
③$_3$Clay	8.0	20	1.0×160	Pile tip ultimate value after grouting /kN $Q'_p = 2\beta_p q_r$	9 009
④$_2^1$Silty clay	19.7	20	1.0×394		
④$_2^1$Silty clay	4.2	30	1.0×126	Total side friction resistance after grouting /kN $Q'_s = u\sum\beta_{si}q_{sik}l_i$	9 616
⑤$_2^1$Silty clay	12.3	35	1.0×431		
⑤$_5$Clay	12.0	35	1.4×420	Single pile ultimate value after grouting/kN $Q'_u = Q'_p + Q'_s$	18 625

According to the calculated ultimate bearing capacity of single pile after grouting Q'_u, it can be assumed that the service load of the trial pile SZ4 after grouting Q'_a is close to 9313 kN, which is the additional load on the pile top. The tip resistance ratio of the trail pile SZ4 when it is loaded after grouting to the tip resistance without grouting $\alpha = 0.08$. The self-weight stress at the tip of the pile is 647 kPa, and the settlement calculation depth z_n is calculated using the equation $\sigma_z = 0.2\sigma_c$. $z_n = 1.2$ m. From Eq. (5), the settlement caused by the foundation pile $s_p = 14.09$ mm, and the pile compression is $s_e = 7.2$ mm, thus, the non-grouted pile settlement under the service load after grouting is 21.29 mm. It should be noted that the compressive modulus given in Table 7 is taken from the range of 100 to 200 kPa, which has little effect on the result of direct settlement calculation for shallow foundations. However, in the case of greater depth, the self-weight stress will exceed 200 kPa. If the compression modulus given in the geological survey report is directly used to calculate the settlement of the pile foundation, it does not meet the requirements of the code. Therefore, this article used 2.5 times the compression modulus given in Table 7 to calculate the settlement of pile foundation referring to the modified the formula of soil modulus $E_s = (2.5\text{–}3.5)\,E_{s1-2}$ from literature [19]. The settlement of the trial pile SZ4 after grouting can be calculated using Eq.(7). Here, the settlement influence coefficient ζ of the cohesive soil layer after grouting can be taken as 0.8, such that $s' = \zeta_s = 17.03$ mm according to Table 6.

Figure 7 illustrates the measured pile top load– settle-

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ment curves of the trial pile SZ4 before and after grouting. Table 9 shows the comparison of load and settlement of trial pile SZ4 at the pile top between measurements and estimates before and after grouting. It shows that the post-grouting settlement influence coefficient obtained in this paper has good applicability and can meet the accuracy requirements for the settlement calculation of large-diameter post-grouting piles. The comparison analysis indicates that the two values are close, which further means that the side friction resistance and tip resistance enhancement coefficients given in this paper are reasonable and feasible, and the estimated results are reliable.

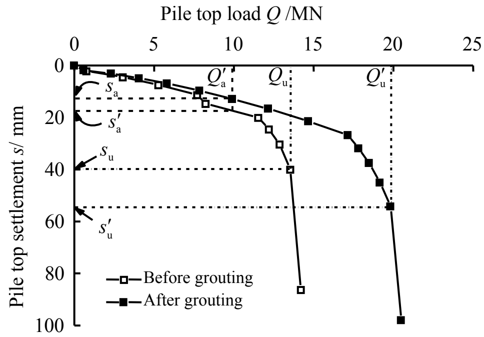

Fig. 7 Measured Q–s curve of trial pile SZ4 before and after grouting

Table 9 Comparison of measured and calculated values of load–settlement of trial pile SZ4

Type of grouting	Measured value of service load		Calculated value of service load		Measured ultimate load		Calculated ultimate load	
	Pile top load /kN	Pile top settlement/mm	Pile top load /kN	Pile top settlement/mm	Pile top load /kN	Pile top settlement/mm	Pile top load /kN	Pile top settlement/mm
Before grouting	9 917	17.38	9 313	21.29	13 531	39.94	13 829	N/A
After grouting	9 917	12.61	9 313	17.03	19 833	54.27	18 625	N/A

In order to further illustrate the applicability of the empirical prediction method for the settlement calculation of large-diameter post-grouting piles given by the post-grouting settlement influence coefficient, another analysis comparison is carried out with a trial pile of a cross-sea bridge project as an example. The foundation of the project adopts large-diameter bored piles and the post-grouting construction technology at pile tips. The diameter of the trial pile is 1600 mm. The pile length is 57.6 m. The concrete strength grade of the pile body is C30. The post grouting slurry at the pile tip is made of PO42.5 ordinary Portland cement with a water-cement ratio of 0.5. The grouting cement consumption of a single pile is 6.9 t. The end pressure of grouting is 2.3 MPa. The main soil layers at the static load test site are silty clay, clay and fine sand within an exploration depth of 60 m. The pile end bearing layer of the trial pile is a clay layer, and the soil type and basic parameters along the pile are shown in Table 10. The groundwater level is 1.5 m below the surface.

Using formula (2), the vertical ultimate bearing capacity of the post-grouting single pile is estimated. The side friction improvement coefficient β_{si} and the tip resistance improvement coefficient β_p take the upper limit listed in Table 3. The range of pile tip grouting increasing the pile side friction resistance is taken as 12 m. Therefore, using the practical calculation formula of the vertical ultimate bearing capacity of post-grouting piles, the ultimate load of the trial pile after grouting Q'_u = 19325 kN. The service load of the trial pile after grouting $Q'_a = 9\ 662$ kN. The tip resistance ratio of the trial pile when it is loaded after grouting to the tip resistance without grouting $\alpha =$ 0.13. The self-weight stress at the pile tip $\sigma_c = 451$ kPa. The settlement calculation depth $z_n = 1.8$ m. Using formula (5), the settlement of the non-grouted pile under the service load after grouting is $s = 13.84$ mm, of which the pile shaft compression $s_e = 5.69$ mm. Therefore, using formula (7), the settlement of the trial pile after grouting can be obtained as $s' = 11.07$ mm, and the influence coefficient ζ of the settlement of the cohesive soil layer after grouting is taken as 0.8. The measured ultimate load of the test pile after grouting is 20209 kN. The measured settlements of the non-grouted pile and the grouted pile under the service load after grouting are 12.09 and 9.69 mm, respectively. By comparing the settlement of pile foundation after grouting, the calculated results are slightly different from the actually measured results, but they can basically reflect the actual situation, which further shows that the empirical estimation method for settlement calculation of large-diameter grouted piles given in this paper is reasonable and feasible.

Table 10 Physico-mechanical parameters of soil layers for trial pile

Soil layer	l_i / m	ω / %	γ / (kN·m^{-3})	$E_{s1\text{-}2}$ / MPa	f_{a0} / kPa	q_{sik} / kPa
②$_1$Muck	4.09	63.10	16.09	1.72	50	10.0
②$_3$Mucky clay	6.00	52.30	16.19	1.41	60	13.5
③$_1$ Clay	3.00	32.10	18.54	5.43	180	45.0
③$_3$Clay	6.00	43.10	17.66	3.11	100	30.0
④$_1$Clay	7.00	33.80	18.54	4.60	180	45.0
④$_4$Clay	10.00	34.00	18.05	4.73	140	35.0
④$_4$Silty clay	8.00	32.80	18.25	7.47	140	35.0
④$_3^2$Fine sand	3.51	—	—	—	180	45.0
⑤$_3$Clay	2.69	34.20	18.34	3.56	160	40.0
⑤$_3$Silty clay	1.80	29.40	19.13	9.50	180	70.0
⑥$_1$Clay	4.00	34.60	18.44	3.76	200	50.0
⑨$_2^1$Clay	4.00	33.40	18.74	13.62	220	55.0

5 Conclusion

(1) Through the statistical analysis of the collected static load data of trial piles, improvement coefficients of side friction and tip resistance classified by soil layer are given. The side friction and tip resistance improvement coefficient method is used to establish practical calculation formulas for the bearing capacity of large-diameter post-grouting piles of different grouting types.

The method is verified by data measured from real tests, which shows that the formula has high reliability and can be used by engineering designers on large-diameter post-grouting piles.

(2) Since there is no unified standard for calculating the settlement of post-grouting piles at the moment, the influence coefficient for post-grouting settlement is introduced on the basis of the settlement calculation of large-diameter pile foundations without grouting, and the post-grouting settlement is given based on statistical analysis. The suggested value range of the influence coefficients of pile tip post-grouting and combined post-grouting is proposed. An empirical estimation method for settlement calculation of large-diameter grouting piles suitable for different soil layers is proposed.

(3) The applicability of the post-grouting pile settlement calculation method given in this paper is verified through engineering examples, and it can meet the accuracy requirements for the settlement calculation of large-diameter post-grouting piles, which can be used for reference by engineering designers in the design of large diameter post grouting pile

(4) The research results have been incorporated into the industry standard of the People's Republic of China "*Code for Design of ground base and Highway Bridges and Culvert Foundations* " (Revised Edition 2019) and the engineering construction industry standard "T*echnical Specifications for Post-grouting of Highway Bridge Cast-in-place Piles*" (T/CECS G: D67-01-2018), which provides a reliable basis for the design of post-grouting piles for highway bridges, and can further promote the wide application of post-grouting technology in highway bridge engineering.

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