Super-long bored pile foundation for super high-rise buildings in China

Fondation profonde sur pieux de très grandes longueurs pour les immeubles de grandes hauteurs en Chine

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ABSTRACT: In China, super-long bored piles are commonly used as deep foundations to support very heavily loaded super high-rise buildings. This paper presents some aspects of design and construction of super-long bored pile foundation together with a brief description of bearing behaviors of super-long bored piles. The issues of selection of pile type and pile tip bearing stratum, load test pile design, single pile design, pile foundation design, key construction technique and pile quality inspection are discussed with some engineering practices of super-long pile foundation. These will provide reference and help for futural engineering practice of super-long pile foundation for super high-rise building.

RÉSUMÉ : Les pieux de très grandes longueurs sont généralement utilisés en Chine pour les fondations profondes afin de supporter les immeubles de grandes hauteurs. Cet article présente certains aspects du désign et de la construction de ce type de pieux au travers notamment de leurs caractéristiques de chargement. La méthode de sélection de ces pieux, les tests de chargement, le désign du pieu lui-même, les aspects clé de la technique et enfin la méthode d'inspection sont discutés sur la base de certains cas pratiques. Cette discussion pourra apporter une référence et une aide pour les prochaines utilisations des pieux de très grandes longueurs.

KEYWORDS: super-long bored pile ; super high-rise building ; field load test ; double steel sleevs ; post grouting technique

1 INTRODUCTION

With the rapid economic growth in the past two decades, numerous super high-rise buildings have been built in Chinese riverside and coastal cities and there are more and more super high-rise buildings under construction or planned to be constructed. According to statistics, the number of tall buildings with height of more than 152m will be larger than 1000 in China during the next 10 years. Moreover, many of them will be more than 600m in height. Super high-rise buildings, especially those constructed in soft soil areas, have brought new challenges to geotechnical engineers. In order to obtain sufficient bearing capacities, super-long pile foundations are often adopted for super high-rise buildings. As shown in Table 1, super-long pile foundations were designed for some high-rise buildings in China by East China Architectural Design and Research Institute Co., Ltd. (ECADI) (Wang et al, 2011).

Table 1 A survey of pile foundations of some high-rise buildings in China

Building name	Height (m)	Floors	Pile type	Pile diameter (mm)	Pile length (m)	Pile tip bearing stratum
New CCTV Tower	234.0	51	Bored pile	1200	51.7	Sand and gravel
Tianjin Tower	336.9	75	Bored pile	1000	85.0	Silty sand
Tianjin 117 Tower	597.0	117	Bored pile	1000	98.0	Silty sand
Shanghai White Magnolia Plaza	320.0	66	Bored pile	1000	85.0	Medium sand with gravel
Wuhan Tower	438.0	88	Bored pile	1000	65.0	Moderately weathered mud rock and sand rock
Suzhou International Financial Center	450.0	92	Bored pile	1000	90.0	Fine sand
Wuhan Green Land Tower	636.0	125	Bored pile	1200	60.0	Slightly weathered mud rock

Until now the experience of design and construction of super-long pile foundation is very limited. Many of the traditional methods cannot be applied with any confidence since they require extrapolation well beyond the realms of prior experience. Therefore, geotechnical engineers are being forced to summary engineering experience and utilize more sophisticated methods for design and construction of super-long pile foundations (Poulos, 2009).

Base on some engineering practices of super-long pile foundations of super high-rise buildings in China, this paper presents some aspects of design and construction of super-long bored pile foundation. Some bearing behaviors of super-long piles will be reviewed firstly. Then selection of pile type and pile tip bearing stratum, design of field load test pile and pile foundation will be discussed. Moreover, some key construction techniques and pile quality control inspection standards are also presented. The methods and technical measures of super-long pile foundation, which are summarized and analyzed in this paper, can provide some valuable experience, reference and help for future super high-rise building foundation projects.

2 BEARING BEHAVIORS OF SUPER-LONG BORED PILE

Super-long bored piles mainly refer to piles with length larger than 50m and slenderness ratio larger than 50. Both theoretical research and engineering practice show that the bearing behaviors of super-long bored piles are different from those of short and middle long piles. The vertical loads supported by super-long bored piles are substantial. There are many soil layers around the pile shaft. The soils characteristics are usually complex. Construction of super long bored piles is complicated. It is difficult to control the construction quality. Furthermore, because of the large length and slenderness ratio of the super-long bored pile, the stiffness of pile-soil system is relative small. This directly influences the bearing characteristics of the super-long bored pile. According to the analysis of filed load tests results (Zhang and Liu, 2009), the basic bearing behaviors of super-long bored piles can be summarized as follows:

1. The pile load versus settlement curve (*Q~s* curve) has no significant change in slope if sediment under the pile tip is cleaned up or the pile tip is post grouted.
2. Under the ultimate bearing load, the pile top settlement is mainly caused by pile shaft compression, especially the compression of the upper half pile shaft. Moreover, the pile shaft presents large plastic compression deformation under very high load.
3. The mobilization of the pile shaft friction is asynchronous. In other words, the pile shaft friction in the shallow soil layers is mobilized before that in the deep layers. In the shallow soil layers, due to the large relative displacement between the pile shaft and the around soils, the pile shaft friction usually reaches ultimate value, and is prone to softening. The mobilization of the pile shaft friction in the deep soil layers and the pile tip resistance is hysteretic due to the small relative displacement between the pile shaft and the around soils. The pile tip resistance is difficult to be mobilized adequately due to the small pile tip deformation. The pile shaft friction resistance occupied a fairly large proportion of the pile ultimate bearing capacity. Therefore, super-long bored pile can usually be identified as friction pile.
4. The mobilization of the pile shaft friction is correlated with support condition at the pile tip. Not only the pile tip bearing capacity is low but also the pile shaft friction resistance can be cut down severely, when the bearing stratum is soft or the sediment is thick under the pile tip. However, both the pile tip resistance and pile shaft friction can be increased significantly after the support condition is improved by post grouting at pile tip.

3 SELECTION OF PILE TYPE AND PILE TIP BEARING STRATUM

Considering post grouting or not, super-long bored pile can be divided into normal pile, tip post grouted pile and tip and shaft post grouted pile. It is difficult to guarantee the bearing performance of the normal bored pile usually due to the problems of pile shaft mud cake and pile tip sediment. The sediment problem can be effectively solved by pile tip grouting technique, which can help to improve the bearing behaviors of the pile tip and pile shaft, and accordingly, the bearing capacity of the pile can be greatly increased. Therefore, the pile tip grouting technique is recommended for super-long bored pile. When the pile tip is embedded very deeply, or soils around the pile shaft are soft or settlement control of the pile is very strict, pile shaft grouting can be implemented, which can further improve bearing behaviors of the pile shaft and increase the pile shaft friction. Post grouting technique was adopted for all the projects listed in Table 1.

Although super-long bored pile is usually identified as friction pile, the pile tip bearing condition has a great influence on the mobilization of the pile shaft friction and the bearing capacity and deformation characteristics of the pile. Therefore, the deep and solid soil layers, such as rock, gravel layer and sand layer, are often selected as bearing stratums for super-long bored pile tip bearing stratums. As bearing behaviors of the soil at the pile tip and the pile bearing capacity are improved by post grouting, the shallower solid soil layer can be possibly selected as bearing stratum. The depth of pile tip extended into the bearing layer can also be decreased for this reason. Thus post grouting technique has expanded the range of selection of pile tip bearing stratum. This technique is benefit to shorten the length of the pile, save engineering quantity, and achieve optimization design of pile foundations.

4 FIELD LOAD TEST PILE DESIGN

Static filed load test is a basic and reliable method to obtain the bearing behaviors of the super-long bored pile. It is also a necessary link of inspection and optimization design of the pile foundation. As a design principle of the test pile, test data and technical parameters should be got as many as possible for design and construction of pile foundation. Besides the general contents, double steel sleeves, pile head, construction and measurement requirements should be especially concerned during the test pile design process.

4.1 DOUBLE STEEL SLEEVES DESIGN

The base rafts of the super high-rise buildings are often deeply buried. Therefore, it is necessary to concern how to reasonably deduct the pile shaft friction in the excavation segment when the load test is carried out at the ground surface. The pile test with double steel sleeves isolating pile-soil contact in the pit excavation segment can reasonably reflect the bearing behaviors of pile (Wang et al, 2011). Double steel sleeves have been applied in the pile load tests of several super high-rise building projects, such as the Shanghai Center Tower, The Tianjin 117 Tower, The Wuhan Green land Tower, et al. The design diagrams of double steel sleeves for the test piles of the Shanghai Center Tower project are shown in Figure 1.

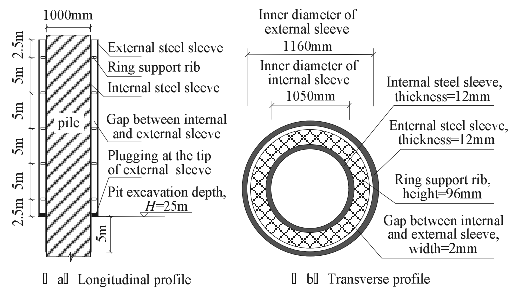

Figure 1 Design diagrams of double steel sleeves for the test piles of the Shanghai Center Tower project

4.2 PILE HEAD DESIGN

Super-long bored test piles often bear very large loads. For example, the load applied to the field test pile of Wuhan Green Land Tower reached 45000kN. Therefore, the test pile head need to be special designed. According to loading condition and test requirements, the pile head should be formed to provide a plane surface which is normal to the axis of the test pile and large enough to accommodate the loading and measuring equipments. The pile head should be adequately reinforced or protected to prevent damage caused by the concentrated loads applied from the loading equipment. The pile head should be concentric with the pile. The strength of the joint between the pile head and the pile should be equivalent to that of the pile. If the double steel sleeves are adopted for the test pile, measures should be made to ensure that the head and the external sleeve would not connect together during the construction process. Figure 2 shows the design schematic diagrams of the test pile head for the Shanghai Center Tower project. The anchor pile-cross beam reaction devices were used in this field test. The maximum load was 30000kN, which was applied using 8 hydraulic jacks. The capacity of each jack was 5000kN.

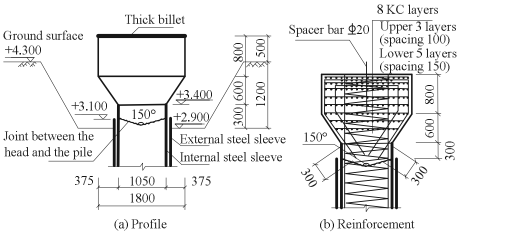

Figure 2 Design schematic diagrams of the test pile head for the Shanghai Center Tower project

4.3 CONSTRUCTION AND MEASUREMENT REQUIREMENTS

Practical construction conditions should be simulated in the construction process of the test piles. Artificial drilling fluid and desanding device should be used when the borehole is drilled through the deep sand layers. Vertical deviation of the borehole should be not more than 1/250. Thickness of the sediment at the borehole tip should be less than 50mm after the secondary tip cleaning. If post grouting technique is adopted for the test pile, the grouting construction parameters should be determined. The construction machineries, techniques and parameters are also need to be determined to form a guideline for pile construction.

Measurement items of super-long bored pile load test are illustrated as follows: (1) Drilling fluid density, viscosity, sand content and other technical indexes in different depth of the borehole. These parameters should be continuously monitored for not less than 36 hours in the construction process. (2) Concrete quality of the test pile, including pile shaft integrity and concrete strength. (3) Sediment and grouting effect under the test pile tip. (4) Ultimate bearing capacity of the test pile. (5) Pile shaft axial force and pile shaft friction. (6) Pile shaft deformations, including deformations of pile top, pile tip, section at the rock surface, and other pile shaft sections under each load level.

5 SINGLE PILE DESIGN

5.1 PILE ULTIMATE BEARING CAPACITY

The ultimate bearing capacity of super-long bored pile is determined by filed load test. If the load versus settlement curve of the test pile shows a slowly change in slope, the load corresponding to the pile head settlement of 40mm~60mm or 5% of the pile diameter can be used as the ultimate bearing capacity of the pile. For pile foundation under a condition of deep excavation, some factors, such as the soils gravity and pile shaft friction in pit excavation segment and unloading rebound of the soil at the bottom of the pit, should be concerned to determine the ultimate bearing capacity of engineering pile (Wang et al, 2012).

Due to the problems of pile shaft mud and pile tip sediment, measured values of the ultimate bearing capacities of the normal super-long bored piles are often lower than the values estimated by empirical methods. Test results of 10 field test piles from 5 different sites in Shanghai district were collected by the authors. It illustrates that the ratios of the measured values of the ultimate bearing capacities of the piles to the values estimated by empirical method range from 0.5 to 0.97. The average ratio is 0.69. The pile bearing capacity can be greatly improved by post grouting technique. Measured data of 28 post grouted piles from 9 Shanghai project sites indicate that the average ratio of the measured values of the piles ultimate bearing capacities to the values estimated by empirical method is 1.32. Therefore, the post grouting technique should be adopted for super-long bored piles in deep soft soils.

5.2 PILE SHAFT STRENGTH AND COMPRESSION

Due to the application of the post grouting technique, the bearing capacities of the foundation soils around the super-long pile are improved greatly. Therefore, the strength of pile shaft should match well with the bearing capacities of the foundation soils in the design of a single pile. The application of high-strength concrete is helpful to achieve this object. As shown in Table 2, in order to make the piles shaft strength meet the piles bearing capacities requirements, Grade C45 and even Grade C50 concrete were adopted for the foundation piles of several super high-rise buildings in China. Meanwhile, concrete strength can be enhanced by the effect of stirrup constraint. Thus, the spacing of spiral stirrups at the pile top within a scope of about 3*D*~5*D* (*D* is the pile diameter) should be appropriate reduced to increase the bearing capacity of pile shaft.

Table 2 Pile shaft strength of several projects in China

Project name	Concrete strength grade	*UCS* (MPa)
Shanghai Center Tower	C50	40.0
Shanghai magnolia square	C45	44.3
Tianjin 117 Tower	C50	59.3
Wuhan Center Tower	C50	54.6

Note: *UCS* is the average unconfined compressive strength of the concrete drilled from the shaft.

Pile shaft compression is a part of the pile top settlement deformation. It is often estimated by the following empirical formula:

$$S = \frac{1}{AE_{\mathrm{p}}}\int_0^L \left[Q_0 - \pi d \int_0^z q_{\mathrm{s}}(z)\,dz \right] dz = \xi_{\mathrm{e}} \frac{Q_0 L}{AE_{\mathrm{p}}} \quad (1)$$

Where Q_0 is the load applied at pile top; L is the pile length; A is the pile section area; E_p is the elastic modulus of the pile shaft; ξ_e is the pile shaft compression coefficient. For friction pile, ξ_e =1/2~2/3.

According to measured data of nearly 40 super-long bored test piles from 15 sites, diagram of the relationship between the measured values of the pile shaft compression and the calculated value of Q_0L/AE_p was drawn, as shown in Figure 3. As can be seen from the graph, under the working loads, the pile shaft compression coefficients are less than 1/2. Therefore, the value of ξ_e for calculating super-long bored pile shaft compression by formula (1) should be not larger than 1/2.

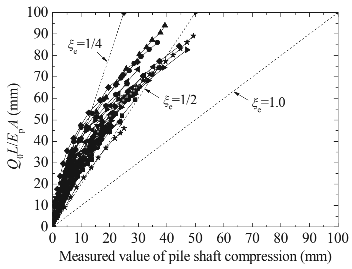

Figure 3 Diagram of the relationship between the measured values of the pile shaft compression and calculated values of Q_0L/AE_p

6 PILE FOUNDATION DESIGN

The synergism of the superstructure, foundation soils and pile foundations should be considered in the design calculation of pile foundations for super high-rise buildings. According to this, a practical method for analysis and calculation of the pile foundation is given in this paper. The theoretical framework and procedures of this method are illustrated in Figure 4. The general calculation process is shown in Figure 5.

Design calculation of the pile foundation consists of four parts, including foundation settlement calculation, bearing capacity calculation of the grouped piles, bending stress calculation of the raft, punching and shearing capacities calculation of the raft. The wind and earthquake actions need to be considered in the process of design calculation of the pile foundation for high rise building. The following load cases should be considered in the design. (1) Gravity load (dead load and live load); (2) Combination of gravity load and wind load; (3) Combination of gravity load and frequently earthquake load; (4) Combination of gravity load, wind load and frequently earthquake load; (5) Combination of gravity load and fortification intensity earthquake load.

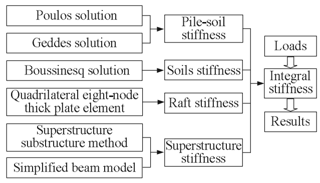

Figure 4 Theoretical framework and procedures of a practical method for analysis and calculation of pile foundation

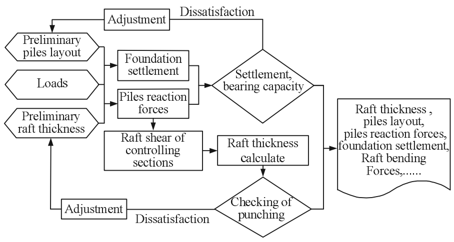

Figure 5 A general design calculation process of pile foundation

The lateral forces imposed by wind load and earthquake action may be very high for super high-rise buildings. When the eccentric vertical forces caused by wind load and earthquake action were accounted for in the design calculation process of the pile foundation, the characteristic value of the vertical bearing capacities of the piles can be increased about 20% and 50%, respectively. Moreover, if tension and compression zones generate in the foundation caused by the action of earthquake, for example as shown in Figure 6, the tension and compression bearing capacities of the piles in those zones should be checked.

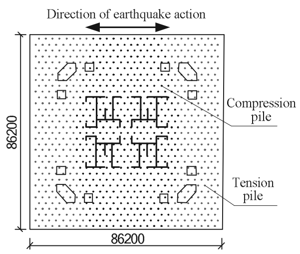

Figure 6 Distribution of tension and compression zones in the pile foundation of the Tianjin 117 Tower under the earthquake action

7 KEY CONSTRUCTION TECHNIQUES AND PILE QUALITY INSPECTION

Suitable drilling machine, techniques and some other auxiliary measures are key factors for successful construction of super long bored piles. Slewing drilling machine can be used in soft soils. But in the hard soils or soft rock layers, the construction efficiency of rotary drilling rig is higher than that of Slewing drilling machine. For example, in the Wuhan Tower project, which site soil stratigraphy consists of some dense slit, sand and moderately to slightly weathered mud rock within the drilling depth, about 79 hours were saved to construct a single pile when the rotary drilling rig was used instead of slewing drilling machine. Different types of rotary drilling rig bit can be selected for different soils in the borehole depth range. Different drilling machines can be combined to drill the boreholes in the complicated project site. For example, in the Wuhan Green Land Tower project, the rotary drilling rig was adopted for clay, sand and intense weathered mud rock layers, while the slightly weathered mud rock and sand rock were drilled by percussion drilling machine. In the process of the borehole drilling, sand content in the drilling fluid should be strictly controlled. Moreover, the density of the drilling fluid should be increased appropriately to ensure the stability of the super deep borehole wall. For example, in the Shanghai Center Tower project, the boreholes need to be drilled through about 60m thick sand layers. The indexes of the drilling fluid used in this project are shown in Table 3. If the borehole is very deep or located in coarse grained soil layers, the technique of pump suction or air-lift reverse circulation need to be utilized in the drilling construction process.

Table 3 Drilling fluid indexes of the Shanghai Center Tower project

index	Value
Density (g/cm^3)	1.1~1.2
Viscosity (s)	16~20
Sand content (%)	<4

Inspection and controlling standards of super-long bored piles are stricter than those of ordinary piles. Quality of the piles should be controlled in the process of construction. The borehole quality, including depth, diameter, verticality and sediment, need to be comprehensively inspected. The number of boreholes to be inspected should be not less than 30% of the total number of boreholes. The pile shaft quality should be evaluated mainly by sonic logging and core drilling methods. The number of piles to be inspected should be larger than 10% of the total number of engineering piles.

8 CONCLUSIONS

According to a great number of engineering practices of super-long bored pile foundations for super high-rise buildings in China, the paper systematically describes some key technical measures of design and construction of the super-long bored pile foundation together with a briefly summary of the bearing behaviors of the super-long bored pile. Post grouting technique is recommended for the super-long bored pile. Deep buried solid soils are usually selected for the pile tip bearing stratum. Application of the double steel sleeves, design of the pile top, construction and measurement requirements are essential issues that should be considered in the design of the field load test pile. Design calculation of the pile foundation should consider the synergism of the superstructure, soils and pile foundation. Inspection and controlling standards of super-long bored piles are stricter than those of ordinary piles. Quality of the piles should be controlled in the process of construction.

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