SETTLEMENT OF COMPOSITE FOUNDATION - A CASE HISTORY WITH REINFORCEMENT OF STEEL PIPE MICRO-PILE

Jianping Sun¹, Junhua Xiao^{1,*}, Qingpeng Wang²

¹School of Civil Engineering, Shandong Jianzhu University, Jinan, China

²Institute of Project Appraisal and Reinforcement of Shandong Jianzhu University, Jinan, China

*13606412056@163.com

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ABSTRACT

This paper presents a case history of high-rise building that is located in deep alluvium deposits with composite foundation. When the building construction approached completion, the monitoring data showed that the foundation settlement and the latest settlement rate was approaching or far more exceeding the control values. Foundation re-analysis demonstrated that even though the foundation capacities could satisfy the design requirement, the total final settlement would be more than 200mm due to the thick compressible soils, which couldn't meet the designed settlement requirement. To guarantee the building security, steel pipe micro-pile as settlement reducer was utilized for its clean construction environment to control post-settlement. The total 624 micro-pile of 18 meter long and 30mm in diameter had been pressed tipping into fine sand layer within 50 days. During and after micro-pile construction, settlement monitoring was carried out by the settlement remarks installed at the columns. The monitoring data demonstrated that during the reinforcement construction the building steadily settled down due to construction disturbance and the differential settlement almost could be negligible. Six months later the settlement tended to convergence and the settlement rate had satisfied the relevant code standard. The method of foundation reinforcement is feasible and successful.

1. INTRODUCTION

For high-rise buildings located at the site with deep alluvium deposits, settlement-reducing piles or composite foundation is often adopted. In the view of economy and construction convenience, composite foundation is preferred [1]. For the composite foundation of cement-fly ash-gravel (CFG) pile, two aspects should be considered intensively at design stage. One is capacity of the composite foundation provided by CFG pile and intermediate soil, and the other is the settlement developed by the compression of composite foundation and under-lying soils. However, usually in composite foundation design, when the capacity is enough to an adequate factor-of-safety, settlement issues are taken care of automatically. This is not necessarily so, as shown in the following case history of a settling foundation.

A 15-storey building with one level basement is founded on 1.1 meter thick raft supported by CFG composite foundation. The CFG pile is 0.5m in diameter, 10.5m in length and lay out in the space of 1.6m×1.6m. Upon the CFG pile is 0.4m gravel cushion to adjust the stress ratio between the CFG pile and the soil. After the completion of the structure foundation settlement developed continuously and showed no trend of convergence. For the safety of the building the foundation was improved by steel pipe micro-piles to control the post-construction settlement, and monitoring work was carried out during and after the reinforcement construction.

2. Geological Conditions

The site is located in the plain area, and at the range of exploring depth of 37m the soil is composed of alluvial deposits. The groundwater was buried at the depth of about 16.3m at the exploring time in February, 2013, and water level changes periodically with seasons in the range of 7.0m. The typical soil profile and soil mechanical property is shown in Fig.1.

3. Foundation Settlement

Settlement monitoring was started at the construction progressing to the

4th floor above the ground level on April 21, 2014. The settlement marks together with the lately installed marks for foundation strengthening are shown in Fig.2. During the building construction, most settlement marks were destroyed. Fortunately, three marks labelled as S1, S2 and S13 had offered intact settlement data till to the time when the indoor equipment was installed. The curves of settlement development are shown in Fig.3. It can be seen from the curves that during the period of structure construction and the post-construction, the settlement developed continuously without signal of converge. On the June 17, 2015, the maximum settlement of the three monitoring points was 178mm. During the period from May 1, 2015 to June 17, 2015, the average settlement rate was 0.38mm/d.

Based on the "Code for Design of Building Foundation (GB50007-2011)", building settlement value is generally controlled within 200mm. The monitoring started at the time when the construction progressed to the 4th floor above the ground level. The effective settlement marks were at the west

Fig. 1. Soil profile and soil mechanical properties

Fig. 2. Layout of settlement marks

Fig. 3. Curves of settlement development

side of the building. The corresponding load was about 90% of the total designed load and no sign indicated the settlement converges. Taking all above information into account, the final total settlement at the building foundation centre must be more than 200mm, higher than the control value.

Based on the "Code for deformation measurement of building and structure (JGJ8-2007)", when the settlement rate reaches to 0.01-0.04mm/d in the latest 100 days, the building can be judged stable. Apparently the building settlement rate was far higher than the stability standard.

In May, 2015, the building tilt was measured and the result indicated that the building was inclined to the North, and the maximum tilt value was 1.82‰. Based on the "Code for Design of Building Foundation (GB50007-2011)", when the building height is at the range of 60-100m, the allowable value is 2.50‰. The measured tilt was still under the control. However, the total settlement and the latest settlement rate couldn't meet the code requirements. In order to secure the safety of the building, foundation reinforcement was proposed to limit the post-construction settlement.

4. Re-analysis on Foundation Capacity and Settlement

For foundation design of buildings, two aspects should be considered intensively. One is the foundation capacity including capacities of bearing layer and of soft underlying layer. Another is the foundation settlement caused by compression of the CFG pile-reinforced layer and following soil layers.

4.1 Check for Foundation Capacity

Based upon the structure load of 1,133,000 kN, the raft self-weight of 130,000 kN and the raft area of 3965 square meters, the average pressure at the raft bottom is 318.5kPa. For the composite foundation of CFG pile, the most reliable method of determining bearing capacity is static load test. The result of load test for the single CFG pile with its surrounded soil indicates the characteristic value of bearing capacity is 330kPa. The reinforced strata is buried at the depth of 5.7m under the ground level, thus the characteristic value can be furthered rectified by following formula:

$$f_{spa} = f_{spk} + \eta_d \gamma_m (d - 0.5) \quad (1)$$

In which, f_{spa} =rectified value of bearing capacity; f_{spk} = characteristic value of bearing capacity, 330kPa; η_d =correction factor by depth, here the value is 1.0; γ_m =bulk density of the soil above the composite foundation level, here the value is 17kN/m³; d =the depth of the composite foundation, here the value is 5.3m.

Submitting all specified value to the formula (1), the rectified value is 412kPa, much higher than the average pressure of 318.5kPa caused by structure load. This indicates no capacity problem would be happen at the raft bottom.

At the CFG pile bottom, the $\varnothing$ layer of clay as soft underlying layer is needed to satisfy the following formula:

$$p_z + p_{cz} \leq 1.05 f_{az} \quad (2)$$

In which, p_z =additional stress at the top of the soft underlying layer; p_{cz} =soil self-weight at the same level; f_{az} =rectified bearing capacity by depth of the soft underlying layer.

At the raft bottom, by the average pressure of 318.5kPa minus the self-weight of 5.3m above soil, the additional stress of 220kPa is obtained. Assuming the stress disperse to the CFG pile bottom at the spreading angle of 24 degree, the additional pressure is calculated as follows:

$$P_z = (220 \times 148 \times 26.8) / [(148 + 2 \times 10.9 \times \tan 24^\circ) \times (26.8 + 2 \times 10.9 \times \tan 24^\circ)] = 151.6 \text{ kPa}$$

The soil self-weight at the top of the soft underlying layer is:

$$p_{cz} = 16.2 \times 18.8 = 304.6 \text{ kPa}$$

As for the rectified bearing capacity of the soft underlying layer, it can be calculated by the following formula:

$$f_{az} = f_{ak} + \eta_d \gamma_m (d - 0.5) \quad (3)$$

In which, f_{ak} = characteristic value of bearing capacity, here is 150kPa based on the geotechnical investigation report; $\eta_d = 1.0$; γ_m =bulk density of the soil above the soft underlying strata, 18.8kN/m³.

Submitting all specified value to the formula (3), the rectified bearing capacity of 445.2kPa is obtained. Apparently, the sum of P_z and p_{cz} is 456.2kPa, no more than 1.05 f_{az} (i.e. 467.5kPa), indicating no capacity problem would be happen at that depth.

4.2 Settlement Analysis

Settlement is a key consideration in foundation design especially for high-rise building. Differential settlement directly causes the building tilt. However, settlement prediction is very difficult in the view of geotechnical complexity [2-4], and differential settlement control is often fulfilled by limiting the total settlement.

In order to give a rough evaluation, a layer-wise summation method based on "Code for Design of Building Foundation (GB50007-2011)" is adopted, and the lower limit of compression is down to the 11 layer bottom of about 37m, which is also the maximum exploration depth. The calculating sketch model is shown in Fig.4.

The total settlement is calculated by the following formula:

$$s = \Psi_s s' = \Psi_s \sum_{i=1}^n \frac{p_0}{E_{si}} (z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1}) \quad (4)$$

In which, Ψ_s = empirical coefficient, also depending on the compression modulus of the being compressed strata; n =number of soil layers; p_0 =additional stress at raft bottom, 210kPa; E_{si} =compression modulus of i soil layer, here the value is based on the explosion reports; z_i, z_{i-1} =the distance from the raft bottom to the bottoms of $i, i-1$ layer respectively; $\bar{\alpha}_i, \bar{\alpha}_{i-1}$ =the average value of additional stress coefficient in the depth of z_i, z_{i-1} respectively.

When calculating the foundation settlement, the raft is equivalent to a rectangular of 148m×26.8m according to area equivalent principle and the calculation point is at the raft center. The quick calculating process is summarized as Tab.1:

Fig.4 The calculating sketch model for foundation settlement

The total settlement is:

$$s' = 425\text{mm}$$

Utilizing s' to calculate the equivalent compression modulus in the scope of compression soils, it can be obtained:

$$\bar{E}_s = p_0 z_n \bar{\alpha}_n / s' = 210 \times 29.1 / 425 = 14.4\text{MPa}$$

Based on the equivalent compression modulus, the empirical coefficient Ψ_s is taken as 0.4, the final total settlement is:

$$s = \Psi_s s' = 0.4 \times 425 = 170\text{mm}$$

Neglecting the compression of cushion and following soils below 11 layer, the calculated total settlement is still 170mm. Base on the transfer law of additional stress in foundation, at the bottom of the 11 layer, the additional stress from raft bottom decrease to 76% of the original value, indicating still considerable settlement would be developed in underlying stratum of 11 layer. A few of signs in the field also indicated that the total settlement would have exceeded 200mm.

5. Foundation Reinforcement

To control the post-construction settlement, the foundation improvement is needed. Being limited by the construction space, micro-pile is often preferred for its construction convenience [5-7]. Two measures were proposed. One is bored micro-pile with steel tube as reinforced core and cement mortar as casting material. For this micro-pile type, secondary grouting before the initial setting of cement mortar is often

Table 1 the summary of quick calculating process for foundation settlement

z	l/b	z/b	α_i	$z \alpha_i$	$z \alpha_i$	$z \alpha_i$	$E_s(\text{MPa})$	$\Delta s'_i(\text{mm})$	$\sigma \Delta s'_i(\text{mm})$
0	5.5	0	1.0	0	0	0	15.0	151.2	
10.9	5.5	0.41	0.9940	10.8	10.8	10.8	15.0	151.2	
17.7	5.5	0.66	0.9773	17.3	6.5	6.5	8.0	170.6	
31.7	5.5	1.18	0.9178	29.1	11.8	11.8	24.0	103.2	425

adopted to enhance pile bearing capacity. Another is driven steel pipe pile, with cement mortar pouring into the pipe.

For the present building, when the reinforcement decision was made, all equipment had been installed and the indoor ground had been paved. For the owner of the building, it was difficult to accept the environmental pollution caused by mud discharge. Even though the bored micro-pile would be perform some bit better than the driven steel pipe pile in settlement control, the latter was still adopted for its clean construction environment.

The theory of foundation reinforcement is taking micro-pile as settlement reducer. The layout of piles was based on several factors: (1) settlement in the north part was bigger than in the south; (2) micro-pile position should avoid the original CFG pile; (3) above the pile position there should be the operating space for pressing pile. The layout of 624 micro-piles is shown in Fig.5

The micro-pile is 300mm in diameter, 8mm in wall thick, and about 18m in length dipping into the 11 layer of fine sand no less than 1.0m. In order to decrease the squeezing effect and reduce the disturbance to the soil, pile was pressed at interval method and by symmetrical construction way at the whole raft. The ultimate bearing capacity of the pile is 1500kN, and the final pressing force is 1800kN, equal to 1.2 times of the ultimate bearing capacity [8-10]. The construction duration is 50 days from September 4, to October 24, 2015.

Assuming 80% of the ultimate bearing capacity of the micro-pile is mobilized [11-12], the finally shared load of 624 piles is about 748,800kN, accounting for 60% of the total structure load of 1263,000kN. The monitoring results during and after pile construction are shown in Fig.6 and Fig.7.

Fig.5 Layout of the steel pipe micro-pile

Fig. 6. Foundation settlement during and after micro-pile construction

It can be seen from Fig.6 that the settlement developed quickly during the micro-pile construction stage, mainly due to the construction disturbance. Once the piles had been pressed in the position and locked in the raft, the settlement rate slowed down and showed the trend of convergence. The settlement rate calculated from the latest two times of measurement was 0.02-0.04/d, satisfied the standard in "Code for deformation measurement of building and structure (JGJ8-2007)", 0.01-0.04mm/d. Fig.7 shows the south and north settlement development sections of the building. The settlement progressed uniformly during and after the reinforcement construction. The differential settlement between south and north sections was no more than 5mm, indicating the foundation settled down in a very uniform way.

6. Conclusions

Through this case study some conclusions can be given as follows:

- (1) For high-rise building the foundation settlement and settlement rate are key factors affecting the building safety.
- (2) Re-analysis on composite foundation of a case history indicates even though the capacities of the composite foundation and soft following strata can satisfy the design requirement and code specifications, the final settlement and settlement rate exceeding standard or code specifications are still the potential safety risk, which means foundation reinforcement is essential.
- (3) The measures taken for foundation reinforcement sometimes is strictly limited to environment restrictions; Of the two optional micro-piles, bored pile with secondary grouting and driven steel pipe pile, the former was abandoned for its slurry discharge pollution while the latter was adopted for its no environmental pollution.
- (4) The monitoring data during and after foundation reinforcement demonstrated the building steadily and slowly settled down with the convergence trend, and 6 months after the foundation reinforcement the two latest measurement showed that the settlement rate

decreased down to 0.02-0.04mm/d; The improvement measure is feasible and successful.

Fig. 7. Settlement sections in the north and south of the building

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