Analysis of settlement of existing buildings caused by unreasonable design of foundation

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Abstract. As for the settlement accidents of existing buildings, people pay more attention to the construction quality than the rationality of foundation design. This paper analyzes and discusses the problem of excessive settlement of existing buildings caused by unreasonable design based on three typical engineering cases. The conclusion is that as for the upper filled soil and lower soft soil foundation, the heavy tamping method is not suitable without auxiliary measures if the foundation settlement is strictly controlled; cement-soil mixing pile method is not suitable for high-rise buildings based on soft soil foundation; the foundation design should be based on deformation control when high compressibility soil layer exists, the pile body should penetrate the main compression deformation layer, and the pile end should fall on the good bearing stratum when using pile foundation or rigid pile composite foundation.

1. Introduction

Excessive settlement of foundation is a common engineering quality accident for existing buildings in recent years. It causes structural cracks, or even results in destruction of the structure. The reasons that cause excessive settlement of existing buildings foundation include: (1) the geotechnical investigation doesn’t reflect the actual geological conditions; (2) unreasonable design of foundation; (3) construction quality defects; (4) improper use or rebuilding after construction; (5) influences of deep foundation pit excavation or groundwater extraction of nearby buildings; (6) other factors, such as natural disasters and so on. Among them, the unreasonable design factor that causes the excessive settlement of existing building is often ignored. Based on three typical engineering cases, this paper analyzes and discusses the problems of unreasonable foundation design which causes the excessive total or differential settlement of the existing buildings.

2. Unreasonable design of foundation

2.1. Engineering case 1: Heavy tamping is used to treat the upper filled soil and the lower mucky soil foundation

A townhouse project was located in Qingdao. It has two floors above ground and one underground floor with frame structure and beam-slab raft foundation. The bearing stratum lies in filled soil layer and the foundation treatment is needed.

Within the investigation depth, the soil layers are described in details as follows: miscellaneous fill layer ①, plain fill layer ①₁ and layer ①₂ with a thickness ranging from 1.8-2.5m. Layer ① mainly consists of coarse gravel sand, broken stone and broken brick blocks and other construction waste, mixed with clay, loose, disorderly; layer ①₁ mainly consists of clay filled soil mixed gravel sand with a few broken bricks; layer ①₂ mainly consist coarse gravel sand, mixed with a few crushed stone,
pebbles and clay, locally mixed silty soil. The self-weight consolidation has not been completed because the backfill time of this layer is short; the soil composition is complex and the density is not uniform. Mucky soil layer ⑥ with a thickness of 3m, flow-soft plasticity, the surface layer is disturbed by filled soil, the characteristic value of foundation bearing capacity is 70kPa, the modulus of compressibility \(E_{S1-2}=2.7\)MPa. Silty clay layer ⑦, silty clay with lens body coarse gravel sand layer ⑦1 with a thickness of 2.75m, plasticity, the characteristic value of foundation bearing capacity is 220kPa, the modulus of compressibility \(E_{S1-2}=6.3\)MPa. Coarse gravel sand layer ⑨, not drilled through, middle compressibility-dense, the characteristic value of foundation bearing capacity is 350kPa, the modulus of deformation \(E_0=25\)MPa. The underground water is about 1m. The typical geological section is shown in figure 1.

![Figure 1. Typical geological section of Case 1](image)

The foundation bearing stratum of the building is the filled soil layer, which was treated by heavy tamping. The characteristic value of foundation bearing capacity after treatment is required to be 100kPa. The tamping scheme is spot tamping and surface tamping, the first step is spot tamping with square arrangement, the energy and the spacing are 1000KN-m and 5m respectively. Every point is hit 7-10 times. The second step is surface tamping, the energy is 600KN-m, the rammers overlap each other for 1/3 area, 3-4 tamping strokes per point.

After heavy tamping, the ground testing was carried out by means of static load test, heavy dynamic penetration test and drilling. The results showed that the compactness and strength of hard shell are improved greatly and bearing capacity characteristic value meets the requirement with dynamic detection larger than 5 strokes. But the thickness of the hard shell distributes unevenly, ranging from 2.8m to 4.8m. The average dynamic hits of layer ⑥ are 2-3. Compared with the untreated soil, the physical and mechanical properties of mucky soil change little. The results can refer to table 1 and figure 2.

| Project introduction | Thickness (m) | N63.5 (hits) | Water content (w) (%) | Porosity (e) | \(I_s\) | \(I_r\) | \(E_{S1-2}\) (MPa) | \(f_s\) (kPa) |
|----------------------|--------------|--------------|----------------------|--------------|-------|-------|----------------|-------------|
| before               | 1.8-2.5      | 2.2          | 41.2                 | 1.261        | 1.30  | 14.20 | 2.696          | 70          |
| after                | 2.8-4.8      | 2-3          | 33.8                 | 1.077        | 1.27  | 15.8  | 3.270          | 75          |
After the project was completed, it was found that most of the buildings had relatively large total and differential settlement, and some of the settlement and inclination exceeded the standard. But the integrity of the superstructure was good.

According to the analysis, for its complex component, the backfill soil is not uniform, and the bearing capacity and compression modulus of mucky soil, which is in the form of soft-fluid plastics state are low. In the process of filling construction and heavy tamping, rolled by the construction equipment, the lower mucky soil was squeezed out and the upper filled soil was squeezed in, which further aggravates the inhomogeneity of foundation soil. Only a thin, uneven and complicated hard-shell layer was form by heavy tamping, which means that there is no reinforcement effect to the mucky soil. Because the deformation of foundation has not reached the stability under the load of building and the load of filling soil, the large uneven deformation of foundation happened, and thus the building was inclined.

Root pile was adopted to reinforce foundation. The piles supported nearly 40% of the total structure load. The pile spacing, diameter and length are 2.7m, 180mm and 9-12.5m respectively. The pile end was put into coarse gravel layer ⑨ no less than 0.5m. Geological drill dry pore-forming and pile formation by casing wall protection were adopted in the construction. For the buildings with excessive inclination, the method of horizontal soil digging was adopted below the basement.

2.2. Engineering case 2: The foundation treatment scheme is not suitable for the geotechnical engineering conditions

A residential quarter in Haikou consists of 6 buildings with 11-18 floors, underground garage and podium. All the main buildings are shear wall structure and raft foundation. One and a half floors of basement are set, and the buried depth of foundation is about 2.5-3.5m. The characteristic bearing capacity of the basement soil is 120kPa; the bearing capacity and deformation of the natural foundation cannot meet the requirements of the superstructure, so the foundation treatment is needed.

Within the investigation depth, the soil layers are described in details as follows: plain fill layer ①, the packing is silty soil and silt, slightly wet and loose, the filling time is about 5 years and the thickness is about 3m; medium sand layer ②, clip fine sand layer ②1, saturated, loose, the thickness is about 4m, this slyer is the building base bearing stratum; mucky silty clay layer ③, upper flow plastic, lower soft plastic, high compressibility, thickness is about 9-15m; gravel sand layer ④, the diameter is about 1-3cm, saturated, medium dense, thickness is about 4m thick, which is the good pile end bearing stratum; silt clay layer ⑤, plastic - hard plastic, with a thin layer of silt particles, partially half consolidated diagenesis. The measured depth of stable water level is about 3m. The typical geological section is shown in figure 3.
The original foundation treatment method applies cement-soil mixing pile composite foundation. The pile diameter, length and spacing are 500mm, 18m and 1m respectively. The end of the pile falls on the gravel sand layer ④. The strength grade of cement-soil body of the pile is not less than 5.1Mpa, and the thickness of the cushion is 250mm.

After the structure was capped, the settlements of 6 main buildings were larger than 20cm, among which the maximum settlement reached 30cm and the maximum inclination reached 4.76‰. The total and differential settlement didn’t show the trend of convergence.

The core drilling and test analysis were used to find out the causes of excessive settlement and inclination. The results showed that only part of the pile has formed a stable consolidation body in the middle sand layer ②, and the treatment effect of layer ③ was poor. Only part of pile formed cemented bodies with a certain strength. But it was distributed uneven and became more easily broken. No obvious cemented body was found and there were serious defects in pile quality. The core sample of pile drilling is shown in figure 4.

Because the average compression modulus of layer ③ is only 2.30Mpa, its compressibility is high. The thickness varies greatly (from 9 to 15m). Because cement-soil mixing pile does not form cemented body in this layer, under the additional pressure of the base, the mucky silty clay in layer ③ produces large uneven compression deformation, resulting in uneven settlement of the foundation and the overall inclination of the main structure.

Composite pile foundation was adopted for foundation reinforcement. 40-50% of the structure load was transferred to the settlement reducing piles. Steel pipe pile was adopted, with diameter of 245mm and 299mm, wall thickness of 8mm and pile length of 18m. the pile penetrated mucky silty clay layer ③, and the end of the pile fell on gravel sand layer ④. Anchor jacked pile technology was adopted in construction. For buildings with excessive inclination, schemes combined with precipitation, heap loaded and inclined soil digging.
2.3. Engineering case 3: The designed pile length is short; the soil layer with high compressibility exists below the pile end

A 5-floors residential building in Dongying, with a height of about 28m (actually equivalent to a 9-floors building) and a frame structure, is 116.4m long from east to west and 14.2m wide. The foundation adopted pile foundation and strip beam with a buried depth of 1.9m; static pressure prestressed pipe pile was adopted for pile foundation, and uniform pile layout design was carried out under strip beam. The pile diameter and length are 400mm and 12m, and the bearing stratum layer of pile end is silt layer ⑦.

The settlement of the building developed rapidly when the main structure was capped. Before the foundation reinforcement construction, the settlement in the middle of the building was the largest, reaching 110mm, while the settlement in the east and west ends of the building was relatively small, about 70mm and 40mm respectively, showing a significant disc-shaped settlement; There was no convergence trend and the settlement continued to increase.

The typical geological section is shown in figure 5. The stratum of the site is newly deposited soil, mainly composed of silt clay and silt soil, with high water content and large void ratio, and locally distributed soft soil layer, with high sensitivity of silt soil and poor foundation conditions. The length of the original foundation pile is 12m, and the pile end falls on the silt soil layer ⑦, the soil layer is in a compact state with a thickness of about 3m, which can be used as the bearing stratum layer of the pile end. However, within the depth of 18m below the basement, the silt clay is in the soft plastic state. Under the pile end, two high-compressibility layers, layer ⑦ and layer ⑧, are the main foundation compression deformation layers. To sum up, the design of the original pile foundation scheme shows that the pile length is unreasonably short, and the thick soil layer with high compressibility below the pile end causes a large compression deformation, resulting in excessive settlement of the building.

Settlement reducing pile was used to reinforce foundation. The pile diameter and length are 500mm and 21.55m. It penetrated the silt clay layer ⑦ and silt clay layer ⑧, and the pile end was put into silt layer ⑨ to reduce the total settlement of the building. In order to control the differential settlement, the number of piles in the middle and the edge of the building was increased and decreased, respectively. Also, the strip cap beam was thickened and widened to increase the stiffness of the foundation. The piles were constructed by cast-in-place techniques, and post-grouting technology was adopted in pile end and side as well.
3. Conclusion

(1) As for the existing building’s settlement accidents, people pay more attention to the quality of foundation construction than the rationality of foundation design.

(2) When heavy tamping method is used to treat the upper filled soil and the lower soft soil foundation, the general treatment effect is not satisfactory, it can only form a hard shell of filled soil and cannot strengthen the soft soil, and the foundation could be more uneven due to construction disturbance. Therefore, when there are strict requirements for foundation settlement, it is not suitable to simply adopt heavy tamping method without other auxiliary measures.

(3) Using the cement-soil mixing pile to treat the foundation with sludge and mucky soil, the cement soil formed by mixing cement with sludge and mucky soil has poor cementation degree and low strength, and is easy to form "interlayer" pile; for high-rise buildings, cement-soil mixing pile method is not suitable for foundation treatment.

(4) When the foundation of a building has a high compressible soil layer, the foundation design should be carried out according to the deformation control, and the main compression deformation layer should be reinforced; when adopting pile foundation or rigid pile composite foundation, the pile body should pass through the main compression deformation layer, and the pile end should fall on the better bearing stratum layer.

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