Foundation Reinforcement and Tilt Correction of High-Rise Buildings on Weathered Rock

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Keywords: Down-the-hole (DTH) hammer, Cast-in-place (CIP) pile, Composite pile foundation, Weathered rock, Foundation reinforcement.

Abstract. This paper explores the foundation reinforcement and tilt correction of a high-rise residential building in northern China. Based on third-party monitoring data, the author looked for the causes of the settlement and tilt of the target building, which is built on weathered rock, and decided to underpin the foundation with cast-in-place (CIP) piles. The underpinning was implemented with down-the-hole (DTH) hammer and post-grouting. The reinforcement effect of our method was evaluated against the monitoring data. The results show that our method can effectively control the late settlement and tilt of the building through a simple and cost-effective procedure. The research findings provide reference for foundation reinforcement and tilt correction of high-rise building in similar geological conditions.

Introduction

In recent years, largescale projects have sprung up across China. However, many of them witnessed quality accidents in foundations. Most of these accidents occur in soft-soil regions, and few takes place in regions with good geological conditions. Featuring excessive settlement, over-tilting and tensile cracking, quality accidents often create defects that are difficult to repair and costly to reinforce. The frequent occurrence of such accidents is attributable to the particularity of geotechnical engineering. As a professional discipline, geotechnical engineering has strong regionality. The geology, rock formation and groundwater conditions all differ from region to region, so do the construction conditions of each project. Quality accidents are extremely likely to occur if the construction stick rigidly to the construction drawings. The engineering example in our research is a quality accident induced by changes in geological and construction conditions. In general, the quality defects remain unobvious until the upper load increases to a certain level during the construction of the main structure. Oftentimes, the foundation settlement is found to be uneven when the structure has been topped out. In the long run, the building will over-tilt to one side, failing to meet the requirements on safe use.

Underpinning is the most popular way to reinforce the foundation of the existing building[6,7]. The foundation is often underpinned by piles. Depending on the conditions of the existing building, the piles adopted for underpinning include cast-in-place (CIP) pile, static pressure anchor pile and micro root pile. In this paper, the foundation of the engineering example is subjected to CIP pile reinforcement and tilt correction by soil extraction. The original geological data, construction conditions and test data were analyzed, highlighting the importance of the selection of foundation form in regions of weathered rock. Next, the data monitored before and after the foundation treatment were discussed, and recommendations were put forward for foundation reinforcement and tilt correction on weathered rock.

Engineering Example

Project Overview

The engineering example is a high-rise residential building in a city of northern China. The 96.6m-tall building has 33 floors above ground and 2 underground. It is supported by a shear wall structure and a 1.2m-thick raft foundation. On the south of the building lies a garage, whose base is
3m deeper than the raft bottom. The high-rise residential building is connected to the underground garage through a corridor. The base soil of the main building can withstand a load up to 500kPa, and the foundation is a natural foundation.

In May 2018, the main structure passed the acceptance check. This is followed by plastering of the interior and exterior walls and the external decoration. Before the foundation reinforcement in November 2018, the monitoring data show a significant differential settlement (42mm) was observed between the north and south sides of the building. The top of the building tilted southward by 200mm at the maximum. The tilt rate (2‰) is close to the allowable value (2.5‰) in the specification [7]. During the installation of elevators, it was found that the stairs had tilted beyond the range for the adjustable error of elevators. Although the foundation and superstructure of the building had not cracked, there were fissures on the roof and wall of the corridor between the building and the garage, due to the significant differential settlement. To curb the development of absolute and differential settlements and prevent further damage to the main structure, it is imperative to reduce the settlement and correct the tilt of the foundation.

Analysis of Settlement Causes

According to field drilling, the upper part of the local stratum is Quaternary loose deposit, including artificial fill, silty clay and residual sandy clayey soil, while the lower part is a layer of weathered Archean migmatite and granite. The stratum within the drilling depth can be divided into five layers according to the differences in lithology, genesis, weathering degree and physical-mechanical properties.

The typical geological profile in Figure 1 shows that the building base mostly belongs to the fifth layer (highly weathered migmatite and granite) and partly fall in the fourth layer (fully weathered migmatite and granite) in the east and south. As shown in Table 1, the eigenvalue of foundation bearing capacity fak is 300kPa in the fourth layer and 500kPa in the fifth layer. Three points were randomly selected in the range of the base for static load test on the natural foundation. The test results reveal that the bearing capacities at the three points all reached 500kPa. In addition, fully weathered soil layer was not found in large areas through the trench inspection of foundation subsoil.

The author learned from the construction drawings and records that the building and the garage were constructed at the same time. The two structures had a height difference of about 3m (Figure 2). During the construction, the earthwork adjacent to the garage was under unprotected open-cut excavation at the scale of 1:1. After the excavation, there was still a 2m-wide earthwork on the south of the building, but the building was no longer constrained on that side. As a result, the eigenvalue of foundation bearing capacity dropped on the south, leading to a decline in overall bearing capacity and large deformation.

What is worse, the trenching of the foundation pit took place in the rainy season. The garage was soaked in water due to its low floor. Thus, the base soil on the south of the building was also immersed in water. Since the highly weathered granite in the fifth layer may soften and collapse in water, the ponding of the foundation trench is another reason for the difference in uneven distribution of foundation bearing capacity in the south-north direction.
Table 1. Parameters of the soil stratum.

<table>
<thead>
<tr>
<th>No. of soil layer</th>
<th>Name of soil layer</th>
<th>Mean thickness (m)</th>
<th>Dry density $\rho_d$ (g/cm$^3$)</th>
<th>Cohesion $C$ (kPa)</th>
<th>Internal friction angle $\varphi$ (°)</th>
<th>Standard value of ultimate pile-side resistance $q_{pk}$ (kPa)</th>
<th>Standard value of ultimate pile-end resistance $q_{pk}$ (kPa)</th>
<th>Modulus of compression $E_{(1-2)}$ (MPa)</th>
<th>Eigenvalue of foundation bearing capacity $f_{ak}$ (kPa)</th>
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<tbody>
<tr>
<td>②</td>
<td>Silty clay</td>
<td>1.44</td>
<td>1.81</td>
<td>53.0</td>
<td>12.1</td>
<td>70</td>
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<td>5.6</td>
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<td></td>
<td>Sandy clay</td>
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<td>③</td>
<td>Fully weathered</td>
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<td>1.85</td>
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<td>35</td>
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**Foundation Reinforcement and Tilt Correction Plan**

Considering the field conditions and comparing multiple plans, the author decided to underpin the foundation with CIP piles, which will partly bear the superstructure load, forming a composite pile foundation with reduced settlement. In this way, the building settlement will be effectively controlled. To bear 50% of the total superstructure load, sixty CIP piles were arranged around the raft, each of which has a length of 15m, concrete strength of C45, and eigenvalue of bearing capacity of no less than 1,500kN. The design parameters of the CIP piles are listed in Table 2 below. Before the construction, three piles were tested in a nondestructive manner. The test report indicates that the bearing capacity of each pile satisfied the design requirements. Then, the piles were deployed outside the raft of the building according to the parameters in Table 2. The layout of the piles is illustrated in Figure 3. The top of each pile was connected to the original foundation by a casted cap embedded with steel bars. The overhanging caps were made of C45 micro-expansion high early-strength waterproof concrete.

The house owners in the building demand tilt correction, because the severe tilt rate of the building (close to the allowable value) impedes the installation of elevators. For safe operation in the nearly 100m-tall building, the tilt was corrected by forced settlement through soil extraction. There are very few cases of soil extraction in highly weathered rock. The difficulty mainly comes from the high strength of the highly weathered soil layer: the tilt cannot be corrected effectively if
the extraction holes are too small or the extracted volume is too limited. In light of the above, the preliminary soil extraction plan was prepared as follows: the hole diameter=50mm; hole depth: 10m; the depth into the raft: 2/3 of the raft width; the initial hole interval: 2m (which was gradually reduced according to the monitoring data). The layout of the soil extraction holes is presented in Figure 4 below.

Table 2. The parameters of the CIP piles.

<table>
<thead>
<tr>
<th>Number of piles</th>
<th>Pile length (m)</th>
<th>Pile diameter (m)</th>
<th>Mean pile interval (m)</th>
<th>Post grouting</th>
<th>Concrete strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>15</td>
<td>0.5</td>
<td>2</td>
<td>Pile side/pile end</td>
<td>C45</td>
</tr>
</tbody>
</table>

Figure 3. The layout of the piles.

Figure 4. The layout of the soil extraction holes.

Process Control

Our project contains two tasks, namely, foundation reinforcement and tilt correction. The former includes pile foundation construction and raft casting, while the latter involves soil extraction and hole grouting. The sequence of operations must be well coordinated to prevent foundation from being disturbed by cross-construction and minimize the construction duration.

In view of the soil hardness, the CIP piles were bored by down-the-hole (DTH) hammer in the layer of highly weathered migmatite and granite, and received post-grouting. The DTH drilling causes large vibrations. Thus, the operation sequence and speed both affect the building settlement.

Considering the above, the operation sequence was adjusted as follows: (1) Bore the CIP piles...
the side with smaller settlement to increase the disturbance and promote the settlement on the north; Do not cast the raft on the north for the moment. (2) Bore the CIP piles on the east. (3) Bore the CIP piles on the south, where the settlement was greater, and avoid concentrated construction to reduce the disturbance-induced settlement. (4) Embed and fix the steel bars, expand the raft on the south, and connect it with the pile foundation in that direction. (5) Extract soil on the north with four extractors at the same time, two in the middle and one on each side.

The soil extraction holes were constructed in the following steps: extract holes at an interval of 2m; suspend the operation for 1d, and monitor the building settlement; if there is no big change to settlement, reduce the interval to 1m; suspend the operation for 1d, and monitor the building settlement; if there is no big change to settlement, further reduce the interval. These steps were repeated until the extracted volume reached the required volume. The soil extraction must be stopped after acquiring the required volume. Then, the base soil was further disturbed by vibrating hole walls, introducing high pressure gas through the extractors or injecting water, so that the settlement can be enhanced.

Analysis of Monitoring Data

Building Settlement-time curves (S-t curves)

It can be seen from the S-t curves in Figure 5 that, the settlements at the monitoring points of the buildings changed in sync with the operation sequence of foundation reinforcement and tilt correction, from the start of settlement monitoring in December 7, 2018 to the stabilization of the settlement (i.e. the foundation reinforcement and tilt correction is completed, and the building is ready for acceptance check) in April 12, 2019. The S-t curve could be divided into five segments:

(1) From December 7 to 17, 2018, the CIP piles were bored on the south and the north. Under the construction disturbance, the monitoring points on the south and north settled unevenly.

(2) From December 18, 2018 to January 4, 2019, the foundation trench was excavated on the south, the south expansion raft was embedded with steel bars and casted, and the trench on that side was backfilled. During this period, the monitoring points on the south continued to settle, but at a slow rate, while those on the north firstly rose slightly and then settled again. This trend is related to the strong overall rigidity of the building and the seesaw effect of the building settlement.

(3) From January 5 to February 30, 2019, the soil was extracted to correct the tilt. In this period, the settlement on the south gradually slowed down, as the CIP piles were connected to the raft in that direction. From February 18, 2019, the south side began to rise at a slow rate. Meanwhile, the settlement on the north was increased slightly, because the soil was being extracted evenly from that direction. The monitoring points on the north were always settling before the end of soil extraction on February 30, 2019.

(4) On March 1, 2019, the soil extraction came to an end, the soil extraction holes were grouted, and the raft on the north was casted. The operations on the north were completed on March 9, 2019. During this period, the north side continued to settle while the south side slowly rebound, exhibiting an obvious seesaw effect.
Since the project completion on March 9, 2019, the stable settlement was observed at the monitoring points on both north and south sides. The S-t curve was levelled out. In less than 100 days after the completion, the settlement rate was lower than 1mm/100d, which satisfies the requirements on stabilization.

After the foundation treatment, the monitoring points on the north all exceeded those on the south in terms of settlement, indicating the success of foundation reinforcement and tilt correction.

**Tilts Curves of the Building**

Figure 6 presents the tilt curves of the main building. It can be seen that the tilt rate of the building continued to increase from November 27, 2018 to January 4, 2019. The tilt rate slowed down and started to decrease since the start of the soil extraction on January 5, 2019. Through the foundation treatment, the tilt rate dropped from 1.96‰ to 1.58‰ on the east and from 1.68‰ to 1.0‰ on the west. Overall, the tilt rate of the building declined step by step and remained at around 1.0‰ till now. The current tilt rate satisfies the requirements in relevant specification.

![Tilt Curves of the Building](image)

**Conclusions**

The following conclusions were drawn from the foundation treatment:

1. If hard soils like weathered rock exists under the base of high-rise buildings, the base soil of the natural foundation must be strictly uniform. The soft soil layer in local places should be replaced with artificial filling. If the base soil is highly uniform, it is advised to adopt rigid pile composite foundation or pile foundation.

2. The CIP piles, coupled with the expansion raft, can effectively reduce the settlement and reinforce the foundation of high-rise buildings. In our plan, the pile foundation bears 50% of the load from the superstructure. Compared with the pure pile foundation, the proposed composite pile foundation can achieve high cost efficiency, effectively reduce the subsequent settlement of the target building, and satisfy the requirements on the control of foundation deformation and overall tilt of the building.

3. The DTH hammer boring and post-grouting can apply to the foundation reinforcement on weathered rock. However, the operation sequence and speed must be controlled rationally to prevent excessive disturbance of foundation. If the project has special requirements on tilt correction, the pile-cap connections should be arranged in a proper sequence.

4. During forced settlement and tilt correction of high-rise buildings, there are significant differences in extractors, hole diameter, hole interval and total extraction volume between weathered rock foundation and general soil foundation (silty soil, clayey soil, etc.). First, the extractors must have vibration and wind pressure effects, such as the DTH hammer; Second, the extraction holes should not be too small, and the diameter should reach 5cm at least; Third, the holes should be bored at a small interval. In our project, the tilt of the building was successfully corrected at the hole interval of 15cm, and the final extraction volume was much greater than the calculated volume.

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216
References


