Field grouting experiment on reinforcing the pile-raft composite foundation of high-speed railway

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Abstract: With the rapid development of China’s high-speed railway construction in recent years, there are more and more railway lines constructed on the soft ground, especially in the southeast coastal areas. After a long period of train operation, there are some local settlement, non-uniform deformation and other diseases occurred in the subgrade. In order to explore the rational and effective reinforcement measures for the subsidence disease of soft soil subgrade, it is combined with an actual engineering practice that the field experiments are carried out on whole layers continuous grouting and part layers discontinuous grouting. Based on the results analysis on the monitored data, such as ground surface deformation, subsoil lateral deformation and pore water pressure etc., the stratum disturbance mechanism and its influence range caused by grouting is concluded, and finally a new reinforcement scheme is proposed. These results can not only provide effective recommendations for the design and construction of later formal reinforcement activities but also serve as reference for future similar projects.

Key words: High-speed railway; Long-term settlement; Pile-raft composite foundation; Field grouting experiment
INTRODUCTION

In recent years, there are increasing investments have been put into transporataion infrastrue areas in China, especially for high-speed railway industry. Presently, more than ten high-speed railway lines had been built and put into service, mostly lied in the eastern coastal areas, such as Shanghai-Hangzhou line, Shanghai-Nanjing line and Beijing-Shanghai line etc., and a considerable part of these lines are built on soft ground.

Since strict control standard of track surface deformation is required by the high speed train, the unballasted track structure with pile-raft or pile-net composite foundation is often used in soft ground. However, due to poor construction quality sometimes or other factors, there are different subgrade diseases occurred after a long period of service, such as local settlement and track surface tilt, etc., which largely affects the safe operation of high speed train. Presently, the problems on the soft soil subgrade of high-speed railway have attracted the interest of many scholars [1-6], and a lot of succeed experiences have also been accumulated in subgrade disease diagnose and treatment [7-9]. So far, there are few succeed cases reported on the settlement control and disease treatment of soft subgrade for high-speed railway. In this paper, a specific field grouting experiment is introduced on reinforcing the subsided pile-raft composite foundation of high speed railway. Based on the analysis of test results, some useful conclusions are drawn and a preferable scheme is proposed, which can not only guide the reinforcement activities but also serve as reference for future similar engineering.

Project overview

A high speed railway line, located in the east costal plain of China, was put put into operation on October 26, 2010. Its track structure is the unballasted one supported by prestressed pipe pile-raft composite foundation. After half year service, local subsidence occurred on the both sides of a roadway bridge culvert passing beneath the subgrad. Figure 1 shows the settlement distribution curve of the two most prominent subgrade sections, i.e., with mileage from K1+130 to K1+180 and from K0+930 to K1+000. The corresponding plane and cross-sectional schematic view of these two sections can be found in figure 2. It can be seen that the maximum settlement value is close to 50mm at the section of K0+970 and K1+150.

![Fig.1 Settlement distribution curve of subgrade surface after half year service](image-url)
The subgrade cross section is shown in figure 3. The left part with short piles, are arranged with space of 2.4×2.4m, corresponding to the old ballasted track subgrade. In the right part, it is the new constructed unballasted track subgrade supported by pile-raft structure. The pile is 38m long with diamater of 0.5m, arranged with the space of 2.4×2.4m, and the raft is 12m wide with thickness of 0.5m.

Fig.3 Sectional drawing of the railway subgrade (unit: m)

Engineering geology

Along the railway line, the terrain is flat, broad and little fluctuation, and the ground elevation is generally +3.0 to +5.0 m. The groundwater belongs to phreatic type. It is abundant, and the buried depth of water table is commonly 1.0 to 1.5m. According to the engineering geological investigation report, the strata types, some basic characteristics and foundation bearing
capacity from top to bottom are depicted in Table 1.

TABLE 1 Strata characteristics and its bearing capacity

<table>
<thead>
<tr>
<th>Stratum number</th>
<th>Layer description</th>
<th>Basic characteristics</th>
<th>Bearing capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>①₁</td>
<td>fill</td>
<td>mottled, loose</td>
<td></td>
</tr>
<tr>
<td>①₂</td>
<td>clay</td>
<td>brown yellow, hard plastic to plastic</td>
<td>150kPa</td>
</tr>
<tr>
<td>①₃</td>
<td>silt, silt sand</td>
<td>loose to slightly dense, saturated</td>
<td>100kPa</td>
</tr>
<tr>
<td>①₄</td>
<td>muddy clay</td>
<td>gray, flow plastic</td>
<td>60kPa</td>
</tr>
<tr>
<td>①₅</td>
<td>silt</td>
<td>gray, slightly dense, saturated</td>
<td>100kPa</td>
</tr>
<tr>
<td>①₆</td>
<td>muddy clay</td>
<td>gray, soft plastic</td>
<td>80kPa</td>
</tr>
<tr>
<td>①₇</td>
<td>silt</td>
<td>slightly dense to middle dense, saturated</td>
<td>120kPa</td>
</tr>
<tr>
<td>①₈</td>
<td>silty clay</td>
<td>gray, hard plastic to plastic</td>
<td>120kPa</td>
</tr>
<tr>
<td>①₉</td>
<td>silty clay</td>
<td>Dark green to yellow grass, hard plastic</td>
<td>180kPa</td>
</tr>
<tr>
<td>①₁₀</td>
<td>silt</td>
<td>slightly dense to middle dense, saturated</td>
<td>150kPa</td>
</tr>
<tr>
<td>①₁₁</td>
<td>silty sand</td>
<td>grey, dense, saturated</td>
<td>160kPa</td>
</tr>
</tbody>
</table>

Problems and Solutions

According to construction recordings, the original designed six-month preloading was cancelled during the subgrade construction. On the other hand, the pipe piles located on both sides of the bridge culvert were constructed early, while the culvert pit was excavated later. In addition, it was dewatered in the pit during the excavation process. These activities may have important impact on the subgrade subsidence.

As for the embankment in service, grouting may be an effective way in treating the subgrade subsidence. However, grouting itself will inevitably disturb soft ground; on the other hand, it is required that the high-speed trains should not be interrupted during the grouting process. Therefore, it is necessary to carry out some field experiments for exploring the grouting disturbing law and reasonable grouting technology.

Field grouting design

Selecting suitable grouting mode

In order to reduce the disturbance to the stratum, static pressure grouting is recommended in the treatment of soft soil subgrade subsidence. Static pressure grouting can be divided into four types, i.e., filling grouting, permeation grouting, compaction grouting and split grouting. Since there is no large holes or cracks in the soil mass, it is inappropriate to use filling grouting method, and the suitable grouting technology for this project is that permeation grouting in the sandy layer, compaction grouting and split grouting in the clay layer. For this purpose, the flower tube grouting method is chosen for this project.

Design of Grouting Scheme

It is considered that the piles below the raft is frictional type, therefore, the initial idea mainly concentrates on how to reinforce the soil mass outside the pile, namely, for the purpose of improving the pile lateral friction.
As shown in figure 4, the grouting holes, located outside the subgrade symmetrically, are arranged with space of 2.4m of pile along the railway line. The cross-sectional view of flower tube grouting arrangement can be found in figure 3. The L₁ and R₁ tubes situated in the inner side are used to grout continuously form the bottom of layer ⑤ to the top of layer ②, which is the so called whole layers continuous grouting mode. The outside L₂ and R₂ tubes are used to grout layer ⑤ firstly, and then enter upwards into layer ④ twelve hours later, namely, that is the part layers discontinuous grouting mode.

Grouting material and grouting parameters

The slurry is injected through steel flower tube with diameter 50mm, and the cement slurry is selected as main grouting material. The water cement ratio of the slurry is 0.75:1, which is incorporated with 1% carboxylate superplasticizer and 1% sodium silicate.

It is required that the grouting volume per meter should not exceed 0.7m³ in the silt and silt sand, while not beyond 1.0m³ in the clay. As for the grouting pressure, it is controlled under 0.5MPa for those layers 10m below ground surface, while that does not exceed 0.2MPa for the layers from ground surface down to the 10m depth.

Design of Monitoring Scheme

The deformation of rail support plate is monitored at the track centers of uplink and downlink shown in figure 3. As shown in figure 5, inclinometer tubes with length of 30m were embedded on both sides of the subgrade. Six pore water pressure gauges are also embedded besides the inclinometer tube with depth of -5m, -15m, -15m, -20m, -25m and -28m respectively.

Test results analysis

The grouting tests can be divided into two stages. The first stage, i.e., whole layers continuous grouting, was carried out from May 28, 2011 to June 14, 2011. The second stage, part layers discontinuous grouting started from July 12, 2011 to September 22, 2011. In the following parts, the results from section K0+930 to K1+000 are chosen to analyze.

Deformation of rail support plate

Figure 5 shows the rail support plate deformation development curve of sections K0+930 to K1+000. The plate surface longitudinal deformation distribution curve at different time can be
found in figure 6. As can be seen, the plate will uplift if slurry is injected, and it then declines when grouting is stopped, which confirms grouting indeed has disturbance to soil mass. Secondly, whether the absolute or the relative value of rail plate deformation caused in the first stage grouting is higher than that in the second stage. In addition, as seen from figure 7, when grouting is stopped, the plate surface sinks faster in the first stage than that in the second stage. These indicate that whole layers continuous grouting has larger disturbance to stratum. Therefore, part layers discontinuous grouting is recommended in the reinforcement activities. Thirdly, In the second stage grouting, the plate deforms gently when layer ⑤ is grouted. Once the flower tube enters upwards to grout in layer ④, the plate deforms rapidly and an leap appears obviously. It indicates that the saturated muddy clay is sensitive to disturbance, so this layer should avoid to be disturbed as much as possible.

![Fig.5 Deformation development curve of sections K0+930 to K1+000](image1)

![Fig.6 Longitudinal deformation distribution curve of section K0+930 to K1+200 at different time](image2)
During the entire test period, section K0+960 uplifts and sinks most dramatically, and it happens to be the place where the subgrade subsides most obviously before grouting. It indicates that the deformation of pile-raft structure changes passively with the soil deformation, thus the underlying soil deformation may be the main source of subgrade settlement. On the other hand, there is no obvious effect to reduce subsidence by grouting the lateral soil around piles, and the pile lateral friction may not be the major factor affecting subgrad settlement.

**Differential deformation of rail support plate**

Figure 8 shows the differential deformation between the uplink and downlink of rail support plate. The differential deformation will increase when grouting, and it decreases if grouting is stopped. Secondly, the differential deformation at section K0+960 also varies dramatically. Thirdly, this deformation in the first stage is larger than that in the second stage, which also means that the whole layers continuous grouting can do larger disturbance. Fourthly, the deformation has a rapid leap when flower tube enters from layer ⑤ to layer ④, which indicates again that the muddy clay should not be disturbed.

The differential deformation is mainly caused by the unsynchronous soil deformation at the left and right side of rail support plate. Therefore, it is proposed that grouting should be conducted symmetrical on the left and right sides of subgrade.
Deformation rate of rail support plate

Figure 9 shows the average daily deformation rate of rail support plate at section K0+960. The deformation rate varies dramatically during grouting process, especially in the first stage, which indicates that the whole layers continuous grouting has relatively adverse effect.

Lateral deformation of soil mass

Figure 10 and 11 give the lateral deformation variation curve of soil mass at different depth located at the east and west side of the subgrade respectively. In the figure, a positive value represents soil expanded outwards, while a negative value means that the soil contracted inwards. Figure 12 shows the lateral deformation distribution curve of soil mass detected by inclinometer at different time. As can be seen, when the slurry is injected, the soil mass at both sides of subgrade expands outwards, which corresponding to ground surface uplift. Once the slurry injection is completed, the soil begins to contract after a long period time, but the contraction is limited, and this stage corresponds to ground surface settlement. In addition, the lateral deformation varies dramatically when layer ④ is grouted, which means that this layer is sensitive to disturbance.
As seen from figure 13, when slurry is injected, an obvious fluctuation in pore water pressure can be found, which corresponding to the uplift of ground surface and the soil lateral expansion; if grouting is stopped, the pore water pressure presents the trend of decrease gently, indicating the soil resolidation, which results in the settlement of ground surface and lateral contraction of soil mass. Secondly, the variation magnitude of pore water pressure in the deep ground is higher than that in the shallow part, which indicates that the soil disturbance in the deep stratum is relatively large. As shown in figure 13 and 14, whether the variation amplitude or the variation rate of pore water pressure before and after grouting in the first stage is higher than that in the second stage, which indicates again that the whole layers continuous grouting has larger perturbation to stratum.
Fig. 13 Pore water pressure duration curve at section K1+000 after different modes of grouting

As mentioned before, pore water pressure has close correlation with the ground surface deformation and the soil lateral deformation, especially in the muddy clay layer, which is confirmed in figure 14 and 15. It indicates again that this layer has important influence on ground subsidence, and should not be disturbed during grouting process. On the other hand, it shows again that the ground surface settlement mainly comes from the soil deformation at the pile bottom, so the new scheme should consider how to strengthen the soil at pile bottom.

Fig. 14 Ground surface settlement value with pore water pressure of section K1+000 at the depth of 25m

Fig. 17 Soil lateral deformation with pore water pressure of section K1+000 at the depth of 25m

Conclusions and proposed measures

In order to explore the rational and effective reinforcement measures for the settlement of soft

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soil subgrade, a series of field experiments on whole layers continuous grouting and part layers discontinuous grouting were carried out. According to the results analysis on, some useful conclusions can be drawn and proper reinforcement scheme is proposed as blow.

(1) As revealed by field experiment, grouting will inevitably disturb stratum especially for whole layers continuous grouting, so the part layers discontinuous grouting may be more preferable for this project.

(2) The muddy clay, i.e., layer ④, is high sensitive to soil disturbance, so this layer should avoid to be disturbed during the grouting process.

(3) The soil disturbance deformation has close relation to pore water pressure, therefore, the reasonable grouting reinforcement scheme should consider the drainage of excessive pore water during grouting process.

(4) The subsidence of rail support plate has great relevance to stratum deformation in deep soft layers, so the preferable reinforcement scheme should grout the subsoil at pile bottom.

(5) The new proposed reinforcement scheme is shown in figure 17. Firstly, drilling hole from ground surface to layer ⑦, and then grout the pile bottom soil following the order from the inside to the outside, and permeation grouting is suggested in this layer. Secondly, in order to avoid excessive pore water pressure caused by grouting, it is necessary to drill sand drain from ground surface down to layer ⑦ to form drainage channel about 15m away from the grouting hole. Thirdly, for the purpose of reducing the differential deformation, the grouting machines should be arranged symmetrically on both sides of subgrade, and the interval between the two adjacent grouting machines is at least 10m away to avoid grouting additive effect on ground deformation.

![Fig.17 Proposed scheme of soil reinforcement below pile end](image)

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REFERENCES


