Soft soil foundation treatment and post-construction settlement investigation on metro depot

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ABSTRACT

Metro depot provides parking, inspection and maintenance services for trains of the whole metro line and its functional divisions have strict requirements on post-construction settlement. To study the suitability of soft foundation treatment methods and the controlling of post-construction settlement, the soft foundation treatment project of Dazhou metro depot in Guangzhou metro line 7 is taken as an example. The design schemes of soft soil reinforcement in different functional divisions of the metro depot is systematically explained. Settlement plates are arranged to establish a long-term monitor in throat area and testing line. Meanwhile, a numerical analysis model of vehicle-orbit-soil coupling is furtherly employed to analyze post-settlement regularity in metro depot under dynamic load. The results show that, in functional divisions, the post-construction settlement meets the requirements of current specifications after treated by corresponding methods. For the project satisfied surcharge preloading requirements, the plastic drainage consolidation method has good reinforcement effect and economic benefits. The accumulative deformation of throat area and testing line are moderately increased under repeated load. Moreover, the increasing of settlement rate is particularly pronounced at the early stage of operation period, so highly attention should be laid on the subgrade maintenance work.

Keywords: metro depot; soft clay; foundation treatment methods; post-construction settlement; numerical simulation

1 INTRODUCTION

As management center of subways, metro depots are the core component of subway transportation systems. To ensure normal operation of functional division in metro depots, requirements of foundation stability as well as post-settlement controlling are relatively higher for relevant structures, and appropriate methods should be adopted to treat underlying soft soil. Some scholars have made certain efforts on this felid (Xia, 2016; Zhang, 2012; Zhang, 2009). However, there are still few systematic researches on soft soil foundation associated with metro depots, and the majority of those are merely concentrated on short-term effect of one specific treatment method.

For this paper, in allusion to soft soil characteristics and foundation reinforcement methods in Dazhou metro depot, the long-term observation of post-construction settlement in different divisions is used for evaluating the adaptability of foundation treatment methods. A vehicle-orbit-soil coupling numerical simulation model is established to figure out settlement regularity of soft soil in the metro depot under dynamic load, which means to offer a reference for settlement controlling technology related to metro depots.

Table 1. Soft soil parameters in Dazhou metro depot

Types of soil	Density (g/cm^3)	Moisture content (%)	Void ratio (-)	Cohesion (kPa)	Friction angle (°)	Compressibility (MPa^{-1})	Permeability coefficient (m/d)
Mud	1.62	58.7	1.54	11.2	6.7	1.570	0.006
Muddy soil	1.72	47.9	1.28	12.4	6.4	1.389	0.006

2 SOFT FOUNDATION TREATMENT

2.1 Engineering situation

The west side of the depot is adjacent to Chencun water channel, and the east side is CRRC (China Railway Stock Corporation) base. Total area of the depot is around 254,000m^2. The field belongs to alluvial plain and its ground water system is relatively developed. From geological investigation report, soft soil is well-distributed in the sedimentary with the form of silt and silt soil, and its thickness ranges from 0.5m to 25.7m. The soft soil owns many unfavorable properties (Oliveira, 2017) and specific parameters are shown in Table 1. Foundation treatment should thus be induced to curb ground settlement which would seriously affect daily operation of the depot.

2.2 Design schemes

Dazhou metro depot is divided into 7 parts according to their functions as shown in Fig. 1, which are division-Ⅰ-parking shed, division-Ⅱ-maintenance shed, division-Ⅲ-Throat area, division-Ⅳ-testing line, division-Ⅴ-entrance, division-Ⅵ-building and road, division-Ⅶ-green area. Comprehensively considered the importance of upper structures and distribution of soft foundation along with construction period and cost, several treatment methods are employed to dealt with soft deposit. The soft soil reinforcement design schemes for each division are shown in Table. 2.

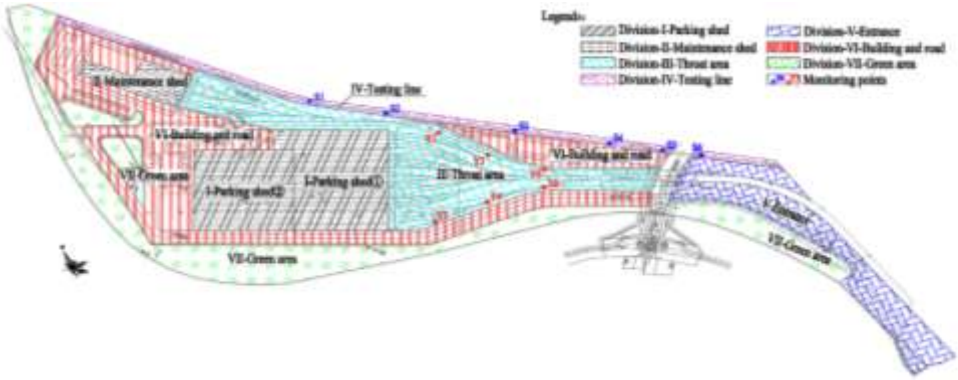

Fig. 1. Functional divisions of Dazhou metro depot

Parking shed 1 is closed to Parking shed 2, however, due to different types of track bed, two sheds are treated by distinct methods. Once differential settlement occurs, the maintenance difficulty of monolithic track is much greater than ballast track (Li et al, 2011). Therefore, monolithic track beds have a stricter requirement for post-construction settlement. Testing line undertakes dynamic testing for vehicles and its standard should normally be higher than main line (GB50157-2013). Based on the thickness of underlying soft soil, deep mixing piles and high-pressure jet grouting piles are devoted together to treating soft foundation in testing line. Although there is neither subway load nor important structures above, deep mixing piles are applied to decrease post-construction settlement in division □. Besides the green area is basically along the channel, and the driven piles can form a huge waterproof curtain to protect the depot from underground seepage.

Table 2. Treatment schemes and parameters of each division in Dazhou metro depot

	□ Parking shed 1	Parking shed 2	□ Maintenance shed	III Throat area	□ Testing line	V Entrance	□ Building and road	□ Green area
Track bed form	Monolithic track bed	Ballast track bed	Monolithic track bed	Ballast track bed	Ballast track bed	Ballast track bed	[-]	[-]
Depth of soft clay	1.2~13.9 m	0.8~12.7 m	0.50~15.8 m	1.2~12.9 m	1.0~20.5 m	1.6~25.7 m	2.3~17.8 m	5.4~16.4 m
Treatment methods	DMP	DCM	DMP	DCM	JGP/DMP	JGP/DMP	DCM	DMP
Main parameters	DMP[a] (depth of soft clay<18m): Water cement ratio: 0.45~0.55; ϕ500mm; Interval=1.0m; regular triangle layout. JGP[c] (depth of soft clay≥18m): Water cement ratio: 0.9~1.1; ϕ600mm; Interval=1.5m; regular triangle layout. DCM[b](Plastic drainage plate): Height of surcharge preloading=4.9m; Interval=1.1m; regular triangle layout.							

Note: [a]DMP means deep mixing piles; [b]DCM represents drainage consolidation method; [c]JGP implies jet grouting piles;
The underline means the specific methods depend on the underlying soft soil condition.

3 SETTLEMENT SURVEY AND ANANLYSIS

3.1 Measuring arrangement

Six settlement plates are arranged in throat area and testing line as shown in Fig. 1. The survey period of post-construction settlement totals 512 days. Based on different thickness of soft soil layers, the treatment methods for each measuring points are not same. For testing line, measuring points S1, S2, S4 are in DMP zones and S3, S5, S6 are treated by JGP.

3.2 Post-construction settlement analyses

Fig. 2 and Fig. 3 plot settlement-time variation curves for throat area and testing line respectively. Referring to the requirements of the specifications (GB50157-2013): the post-construction settlement of ballast track in testing line should not exceed 200mm and its settlement rate should not be greater than 50mm per year; for the ballast track of normal metro line, the settlement value should less than 300mm. Combining with the following two figures, the maximum post-construction settlement of the throat area and testing line are 23.9mm and 16.4mm, which both satisfy the requirements.

The plastic drainage plates combined with surcharge preloading are adopted to treat soft foundation at throat area. Fig. 2 indicates that the overall trend of measuring points (Y2~Y5) is consistent and stable; in contrast, the maximum settlement of point Y1 reaches up to 23.9mm and its tendency is relatively abnormal compared with the aforementioned points. This is likely because point 1 is located at the boundary of two treatment methods fields and plays a role as traffic node during the construction period.

Deep mixing piles (solid line) and jet grouting piles (dashed line) are chosen to treat soft foundation in light of the thickness of underlying soft soil, its settlement-time variation curve is shown in Fig. 3. The result shows that, compared with the DMP, the post-construction settlement of soft foundation treated by JGP is relatively large, and the maximum settlement value exceeds 11mm. At the end of the monitoring period, point S5 and S6 display an increased trend as well. Drawing on the historical experience of soft foundation treatment of Guangzhou metro depots (Wang. 2007; Zheng. 2008), with an ample construction time and appropriate thickness of soft soil, it is recommended to utilize plastic drainage plates combined with surcharge preloading to treat soft soil foundation of depots.

Dazhou metro depot was officially put into use on December 28, 2016. Based on Fig. 2 and Fig. 3, settlement rate of the most settlement plates are accelerated during the operation time (after 184 days). Considering that both two settlement curves become flat at earlier time, the main reason for this phenomenon is probably caused by the dynamic load generated by subway, which leads to a certain amount of settlement around the tracks. Hence, the next chapter will focus on the performance of dynamic load on post-construction settlement of soft foundation through a numerical analysis model.

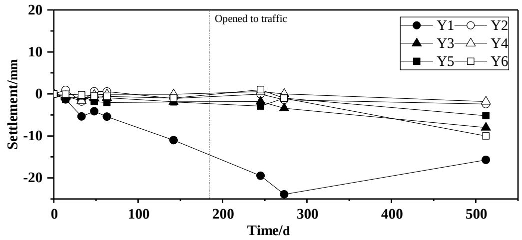

Fig. 2. Settlement-time variation curve for throat area

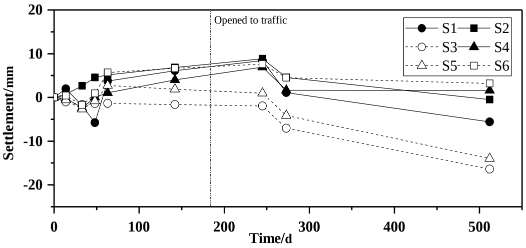

Fig.3. Settlement-time variation curve for testing line

4 NUMERICAL SIMULATION

4.1 Numerical model

A train-track dynamic coupling model is performed by considering the interaction between the vehicles, tracks, cushions, and fasteners, sleepers, ballast and foundation, which includes vehicles submodel and orbits submodel, as shown in Fig. 4. Through inputting the random irregularity of track at the contact between wheel and orbit, the wheel-track interaction force is obtained which leads to vibration of the system, and then coupling trains and tracks by taking advantage of the force equilibrium coordination of wheels and tracks.

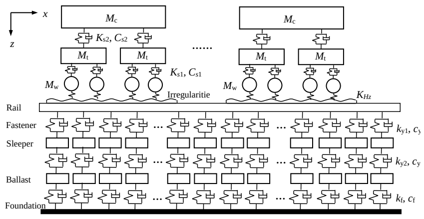

Fig. 4. Trains-wheel dynamic coupling model

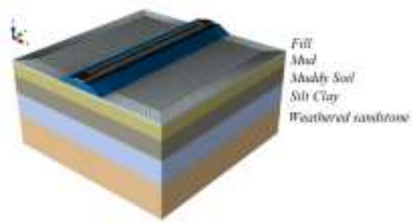

Fig. 5. 3D numerical analysis model of throat area

General finite element software ABAQUS was adopted for the analysis. Based on the dynamic model, the 3D numerical analysis model of orbit-bed-foundation system is set up associated with the throat area in Dazhou metro depot. The behavior of soft soil was modeled by a modified Cam-clay model and others were simulated by Drucker-Prager model. The parameters of each layers are displayed on Table 3. The size of foundation model is 60m×60m×25m shown in Fig. 5. Finite element model couples with infinite element model for numerical analysis to avoid distortion of numerical simulation resulted from setting artificially truncating boundary.

The rail and track bed model contain rails, sleepers, track bed (surface layer, ballast), and subway trains selecting B-type vehicles with corresponding geometric and dynamics parameters (Zou, 2017). The train-track dynamic coupling model is developed to analyze wheel-rail contact force changed with time history by using Newmark implicit integration algorithm and those data would load on the tracks through the subprogram VDLOAD.

4.2 Results and analyses

The consolidation settlement curve (incurred by static load), accumulative settlement curve (incurred by dynamic load) along with total settlement curve for throat area are shown in Figure 6. For the soft foundation treated by DCM, the changes in the settlement of the three are similar whose settlement rates are from fast to slow. And under the dynamic load of trains, a large plastic accumulative deformation is generated at the same time as the consolidation settlement occurs. In terms of the problems of post-construction settlement in depots, it's far from enough to merely consider the effect of consolidation, the plastic accumulative deformation of soft foundation incurred by dynamic load cannot thus be ignored.

Figure 7 shows variation curve of the accumulative deformation of foundation with times of the repeated load. It can be obtained by outputting the plastic strain of underlying soil and integrating it along the depth. From this figure, the dynamic load of the trains will promote post-construction settlement and the accumulative deformation of soft foundation will increase with the times of load. The rate of accumulated deformation is the largest at the early stage of loading, and as action times *N* increases, its growth rate would gradually slow down. The accumulated deformation curve finally becomes flat when *N* equals to 2,000,000. Therefore, highly attention should be poured into routine inspection and maintenance for subgrade at the start of depots operation.

Table 3. Basic soil parameters

No.	Soil layers	Depth (m)	γ (kN/m^3)	c' (kPa)	φ' (°)	M	λ	κ	v_s (m/s)	v_p (m/s)	ξ	v
1	Fill	1	18.0	16	11.5	[-]	[-]	[-]	198.7	378.7	0.02	0.35
2	Mud	4	16.2	11.2	6.7	0.78	0.15	0.022	170.3	354.5	0.02	0.38
3	Muddy soil	5	17.2	12.4	6.4	0.80	0.14	0.025	178.4	360.6	0.02	0.38
4	Silt Clay	6.5	18.9	13.8	10.5	1.0	0.052	0.0096	280.2	476.0	0.02	0.32
5	Weathered sandstone	8.5	20.2	36.2	18.4	[-]	[-]	[-]	330.5	564.8	0.02	0.21

Note: v_s =Shear wave velocity; v_p =Compression wave velocity; ξ =Damping ratio; v =Possion ratio.

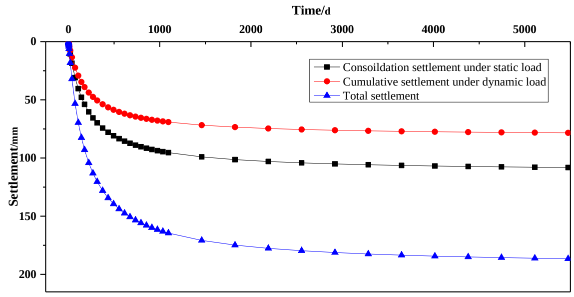

Fig. 6. Comparison between 3 types of settlement curves

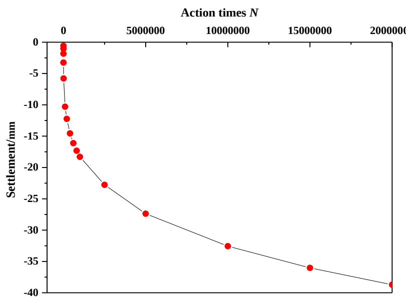

Fig. 7. Accumulative settlement curve associated with action times

4 CONCLUSIONS

(1) Plastic drainage plates, deep mixing piles and jet grouting piles are adopted for corresponding divisions at the depot, the post-construction settlement and its settlement rate are generally meet the requirements of current specifications during the long-term monitoring.
(2) For the project satisfied surcharge preloading requirements, the plastic drainage consolidation method has good reinforcement effect and economic benefits.
(3) The accumulative plastic strain induced by trains load make a significant contribution to total settlement. And the settlement rate is relatively faster at the early stage of operation period, so highly attention should be laid on the subgrade maintenance work in the prophase.

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