Difference analysis on the performance of the pile-net composite foundations (different pile types) of high speed railway

Yan-qun Xu, Lin-rong Xu, Yu-hua Huang & Jun-jie Zhou
School of Civil Engineering of Central South University, China

ABSTRACT: With Shanghai-Nanjing intercity railway CFG pile-net composite foundation and Beijing-Shanghai high speed railway sand pile-net composite foundation of Kunshan test section, in order to get variation law of properties of composite foundations ,monitoring components, such as the soil pressure boxes, the settlement gauges and the pore water pressure gauges, etc, were put into the field test sections, to monitor and obtain the magnitude of ground settlements(post construction), pile tops soil pressure and soil pressures between piles , pore water pressures and other field test data. The settlement control effect of two different pile types (CFG pile-net and sand pile-net) was comparatively analyzed with field test during construction period and post construction settlement. The results show that both ground improvement method,i.e. CFG pile-net and sand pile-net preloading, can meet the settlement control requirement of ballastless track of High-speed Railway Post-construction Settlement (less than 15mm) with different preloading periods according to the field tests. The total settlements and settlement velocity of CFG pile-net foundation are smaller than that of sand pile-net foundation. The convergence speed of CFG pile-net foundation is faster, which means it requires a less period of time for preloading. But there is a big difference affected by the pile stiffness on the law of stress of pile and soil. The stress ratio of pile and soil in CFG pile-net foundation is increases with the increasing of the filling of the embankment and eventually stabilized, while that of sand pile-net foundation decreases with the increasing of load first, presenting the wave shape change. And the dissipation rate of excess pore water pressure in CFG pile-net foundation is far less than the latter. In the case of short construction period, compared with the sand pile-net composite foundation, the settlement control effect of CFG pile-net composite foundation is more efficiently.

Keywords: CFG pile-net composite foundation; sand pile-net composite foundation; pile-soil stress ratio; post construction settlement control

1 INTRODUCTION

Pile-net composite foundation works as a combined foundation in two aspects, the geogrid in horizontal and the pile in vertical. At present, pile-net composite foundation has been widely used not only in transition section between road and bridge in order to decrease differential settlement but also in Expressway and high-speed railway so as to treat soft subgrade. Pile-net composite foundation has played an important role in the mobilization of potential of pile, net and soil as well as making them work together in order to make pile and soil bear load(Lian Feng et al. 2008).

At present, there are a variety of studies on pile-net composite foundation which are mainly concentrated in separate mechanical bearing characteristics(Ma Jian-lin et al. 2009;Zhang Liang et al. 2010;A Jiang & Wang Mei-xia 2011)and load distributions of pile and net(Zhang Ji-wen et al. 2009;-Wang Chang-dan et al. 2011), mechanism of reinforcement of pile net composite foundation(Jiang Dan-ping & Wang Bing-long 2012;Zuo Shen et al. 2014)and effect of geosynthetics(Wang Hong-gui et al. 2008;Yu Jin-jiang et al. 2012)etc. However, literatures aboutthe performance of different types of pile-net composite foundation under similar engineering environment and the comparison about working behaviors during post construction period are limited. So in this paper, based on the field test of the Shanghai Nanjing Intercity Railway CFG pile-net composite foundation and the Beijing Shanghai high speed railway sand pile-net composite foundation (Kunshan test section), presents the changing laws of subgrade settlement, pile-soil stress variation ratio, pore water pressure, then analyze working behaviors and different treatment effects of CFG pile net and sand pile net composite foundation which provide guidelines for the ground improvement schemes in similar engineering.

2 TEST SURVEY

2.1 *Zhenjiang test section of Shanghai-Nanjing intercity railway*

Test site is located in Shanghai-Nanjing Intercity High Speed Railway Zhenjiang test section where existing hillock，valley and a slightly undulating terrain. Part lines of the test section have the overlap with the existing Beijing-Shanghai Railway and are along the paddy fields and fishponds. The subgrade surface of selected test section is rich in silty clay, gray brown, soft plastic~hard plastic, the thickness is ranging from 0 to 9.8m. The silt clay and silty clay are distributed under the subgrade surface. The properties of soil are listed in table 1. The CFG pile-net composite foundation is used in ground improvement. The CFG pile were 8m long, with diameter of 0.5m and spacing of 1.8m. The geosynthetics was placed in gravel layer with thickness of 0.5m.

Table 1 shows that the subgrade soil is a compressible soil.

2.2 *Kunshan test section of Beijing-Shanghai high speed railway*

Test site is located in the Beijing-Shanghai high speed railway Kunshan test section. The subgrade surface is mainly clay that appears gray yellow, soft ~ hard plastic. the thickness is ranging from 0.76to 3.60m. There is silty clay under the subgrade surface which exists a small amount of silt, taking on a dark gray and thickness of ranging from 3.2m to16.5m. The under lying layer is composed of clay, silt and silty clay.The properties of soil are listed in table 3. As shown in Figure 1, It can be inferred that the soil are highly compressible soil from the properties of moisture content, void and quick shear strength. The test sections were carried out preloading by two times. After the first preloading, the settlements had reached the criterion of ballast track subgrade engineering. Consolidation settlement lasted for 4 years, and thenthe second surcharge preloading were carried in order to reach the settlement control standard for subgrade of ballastless track during post construction period. For the first preloading, the soil consolidation in test sections is basically completed, so the soil are considered to be a lowly compressible soil when suffered the second preloading.

Sand pile-net composite foundation was used for reinforcement in Kunshan test section. The sand piles were 15m long, with diameter of 0.4m and spacing of 2m. The Geogrid was placed in sand cushion with the thickness of 0.6m. The properties of geogrid are listed in table 2.

Table 1. The properties of Huning subgrade test section soil.

Depth /m	Moisture content/%	Density /g·cm-3	Void	Liquidity index	Plasticity index	modulus of compressibility /MPa	Quick Shear strength	
							c/KPa	Φ/°
1.2	23.7	1.63	0.63	0.26	16.30	7.34	——	——
6.5	33.9	1.49	0.87	0.70	19.40	5.63	14.21	11.33
13.5	25.3	1.60	0.68	0.44	15.60	7.85	21.70	9.67
19	23.6	1.62	0.66	0.39	14.60	7.76	42.55	8.00
31	22.9	1.63	0.63	0.04	23.00	6.80	31.54	11.50

Table 2. The properties of geogrid.

Program	The horizontal grid size / mm	Vertical grid size / mm	Weight of a unit/ ($g \cdot m^{-2}$)	Extension rate /%	maximal tensile strength / ($kN \cdot m^{-1}$)	The tensile strength at 2% elongation /($kN \cdot m^{-1}$)	The tensile strength at 5% elongation /($kN \cdot m^{-1}$)
Data	25	25	400	9.11	24.4	7	16.85

Table 3. The properties of test section soil of the Beijing-Shanghai Kunshan test section.

Depth/ m	Moisture content /%	Weight /KN·m -3	void	Liquid limit	Plastic limit	Plasticity index	coefficient of compressibility	Quick Shear strength	
								c/KPa	Φ/°
2.86	31.9	19.2	0.89	40.9	19.7	21.1	0.25	24.5	8.7
3.24	44.4	17.8	1.23	35.8	19.9	16	0.30	8.4	6.3
4.51	35	18.8	0.97	33.2	19.8	15.5	0.14	29.0	10.6
2.63	26	19.9	0.70	35.2	16.4	17.0	0.25	30.5	7.9
5.63	24.5	20.3	0.69	36.2	17.1	19.1	0.14	57.3	16.7
4.37	35.5	18.7	0.98	33.9	21.9	12.7	0.20	15.6	15.0
6.68	36.4	18.7	0.99	34.8	20.4	14.4	0.33	14.7	15.3

3 FIELD TEST SCHEME

3.1 *Shanghai-Nanjing CFG pile-net composite foundation*

Single point settlement gauges were used to measure settlements of Shanghai-Nanjing test section, in order to obtain surface settlements, settlements of reinforced area and substratum, and the law of settlements varying with time and load. Earth pressure cells were embedded at the different positions of test sections, such as the top of pile, the centroid of two piles or four piles and so on. Then the changing laws of pile-soil stress ratio and the load-sharing ratio of CFG pile-net composite foundation were acquired from the field measurement results. The test elements specific buried positions are shown in figure 1.

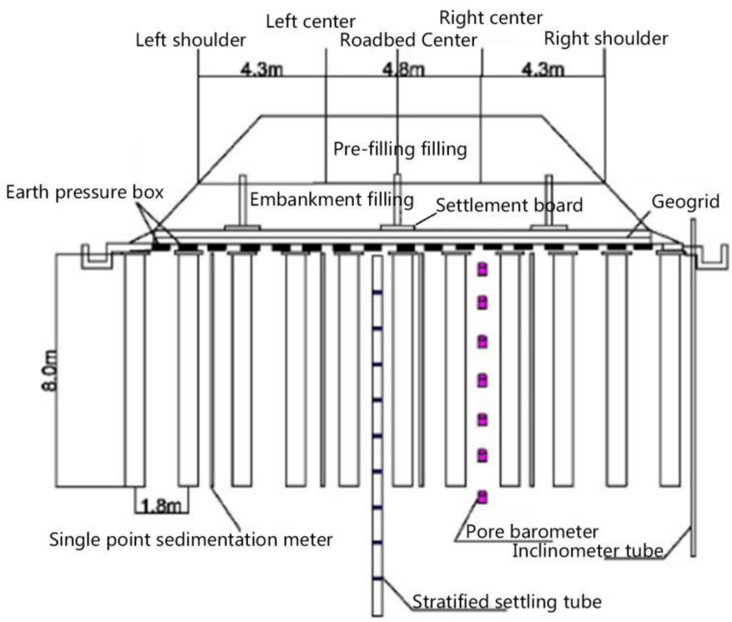


Figure 1. Observation element buried diagram of Huning test.

3.2 *Beijing-Shanghai sand pile net-composite foundation*

The settlement plates were respectively embedded in the line center, the left side of the line, and the right side of the subgrade to observe total settlements of sand pile-net composite foundation. The soil pressure gauges were respectively embedded in the top of sand pile, the center of two piles and the centroid of three piles for analyzing and summary the measured soil pressure to obtain the variation law of pile-soil stress ratio and load sharing ratio. The test elements locations are as shown in figure 2.

Most of the test elements should be buried after the completion of the subgrade filling construction and before the foundation reinforcement start working, however, the subgrade surface observation piles′ embedment shall be buried after completion of subgrade filling construction. This test section was carried out two times foundation treatments totally. For the first time, the sand pile joint preloading (6.29m) measures were taken to reach the ballast track subgrade engineering settlement standard (less than or equal to 10 cm). For the second, preloading measures (2-3m) was carried out on the original sand pile foundation to reach the ballastless track subgrade settlement standard (less than or equal to 15 mm). The pile-soil stress ratio and pore pressure analysis use data obtained from the first preloading pressure, while the settlement changing law uses second times preloading results.

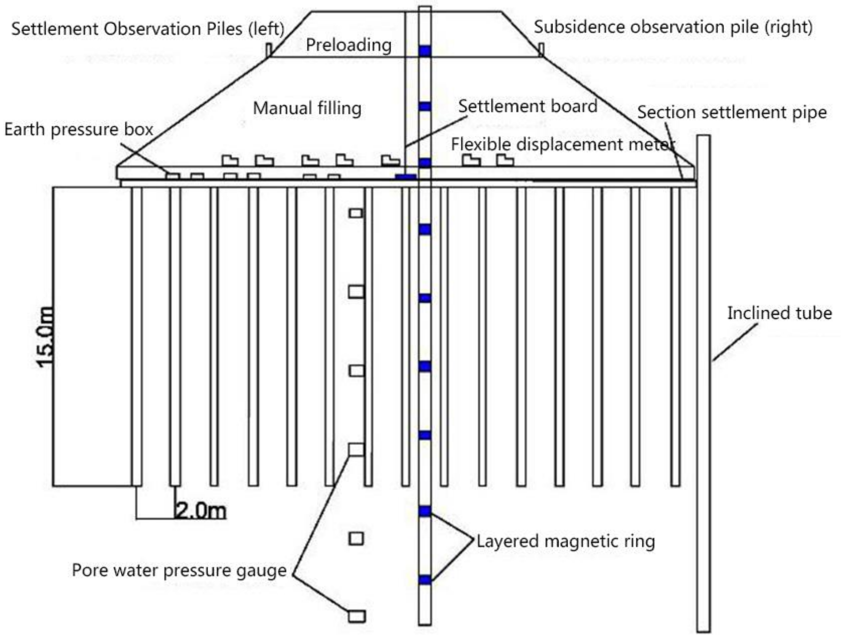


Figure 2. Observation elements buried diagram of Beijing-Shanghai Kunshan test section.

4 ANALYSIS AND COMPARISON OF THE TEST RESULTS

4.1 *Analysis of settlement deformation law*

The long-term settlement monitoring after construction has gained Figure 3-1 that shows the CFG pile-net composite foundation settlement-time-load diagram of Shanghai-Nanjing Intercity Railway. It can be seen that the settlement increases with the increase of load and time respectively. Moreover, the settlement rate and the settlement rises rapidly during the loading period, while the settlement rate decreases and the settlement amount tends to be stable during the constant loading period. There is no obvious settlement springback when unloading. With the same buried depth, settlement of shoulder at the bottom of pile is far greater than that of middle of Subgrade. The settlement buried in the shallow parts fluctuated largely due to the larger outside interference.

Kunshan test foundation exists some highly compressible soil, which was coped with two times heap preloading. It can be considered that the consolidation of highly compressible soil has completed when the second time preloading after four years′ consolidation. Therefore, the foundation soil is deemed low compressible soil during the second time preloading. Figure 3-2 is the foundation settlement-time-load diagram during second times preloading. Figure 3-2 shows that the minimum settlement value occurs at the top of pile on the left side, then becomes larger at center, and finally reaches the maximum on the right.

The three settlements were rapidly increased with the increasing of load during filling period, and rising slowly with time during constant load period. The three-settlement amount is generally consistent.

It can be found that, in the low compressible foundation soil, the two types of pile show some similarities and differences in foundation settlement process by a comparative analysis of two types of pile-net composite foundation settlement deformation law: Firstly, in the loading process, CFG pile settlement gradually raises with the loading and sedimentation rate obviously is slower than that of sand pile. Secondly, sand pile settlement increases rapidly and sedimentation rate is much faster. Thirdly, both settlement curves are relatively stable in the constant load period and are tending towards stability and settlement law at different foundation positions showed identical.

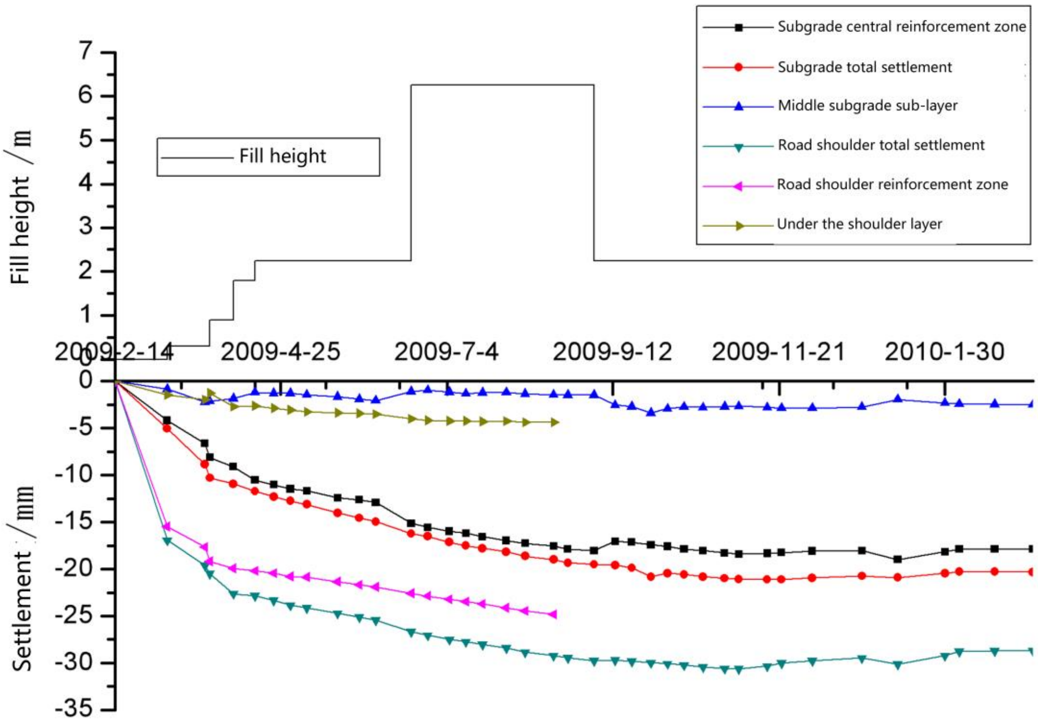


Figure 3. CFG pile-net composite foundation settlement - time - load curve.

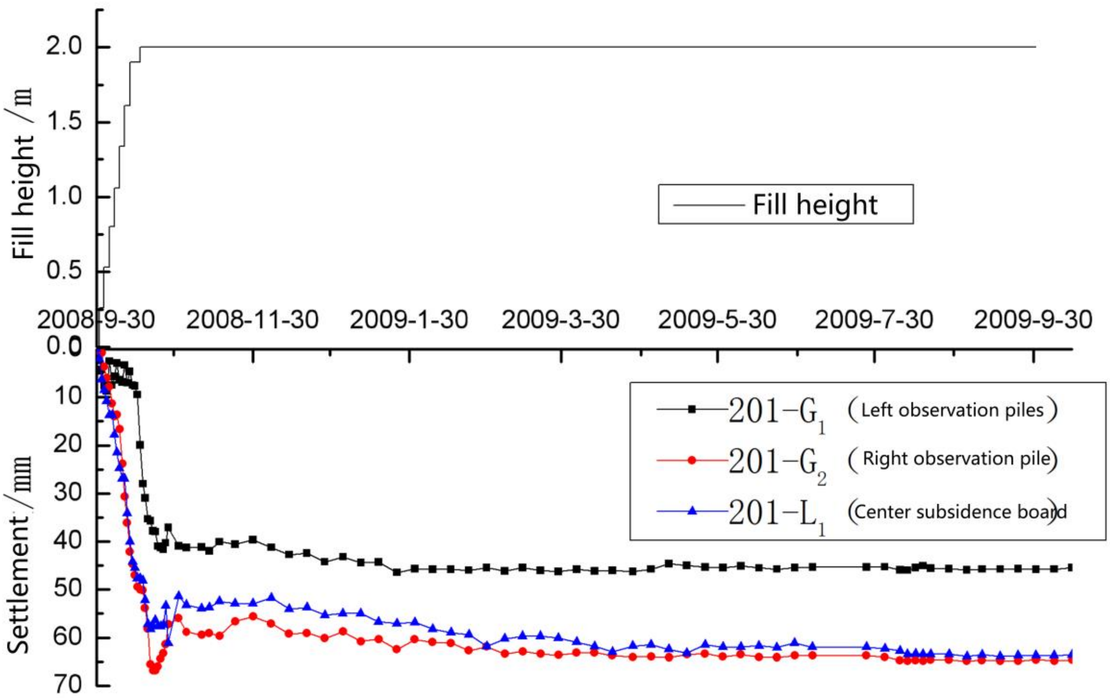


Figure 4. Sand pile-net foundation settlement - time - load curve.

According to the settlement data of actual measurement during the construction period, table 4 and table 5 show the composite foundation settlement prediction value after construction with a variety of forecasting methods.

It can be seen from table 4 and table 5 that the forecasting settlement values of the CFG pile and sand pile after surcharge preloading both can meet the control requests of high-speed railway ballastless track, including prediction of the maximum working settlement values which are 6.03mm and 5.07mm respectively (where the sand pile-net composite foundation takes the second pre pressure settlement prediction values). Post-construction settlement of CFG pile-net foundation predicted according to the measured data is slightly larger than that of sand pile-net foundation. However, the total amount of settlement and settlement rate of CFG pile-net foundation were less than that of the sand pile foundation. The former total settlement value is 34.71mm, and the latter is 68.60mm, thus is mainly because the latter contains part of highly compressible soil.

Table 4. Settlement prediction of Huning CFG pile-net composite foundation.

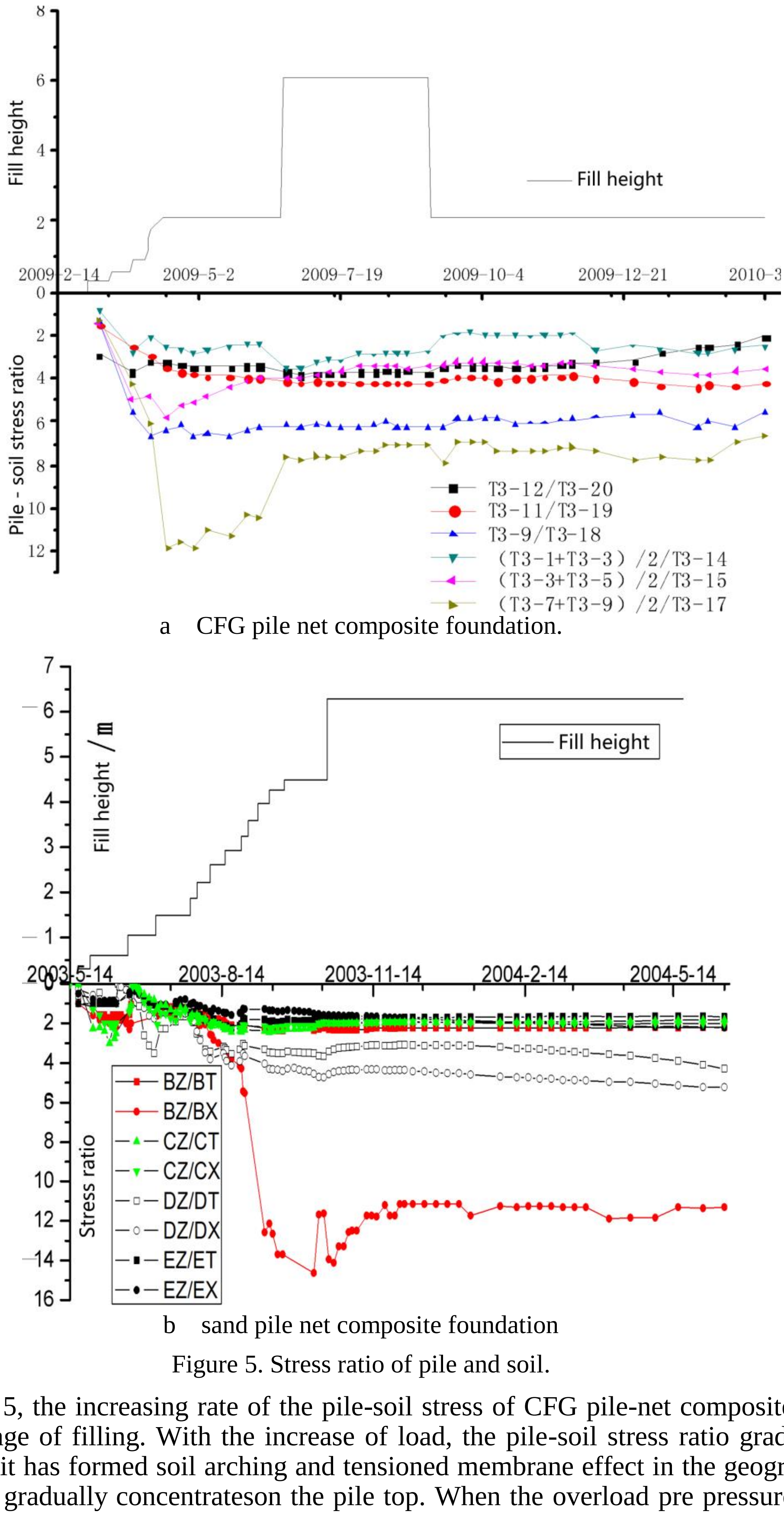
Project name	Three point method	Hyperbolic method	Hoshino Nori	Parabola method	Asaoka method	GM(1,1) method	Verhulst method
2010-03-08	28.68	28.68	28.68	28.68	28.68	28.68	28.68
The final settlement	32.54	33.99	34.71	31.21	31.84	31.50	31.66
post construction settlement	3.86	5.31	6.03	2.53	3.16	2.82	2.98

Table 5. Settlement Prediction of sand pile-net composite foundation after second time's preloading.

Position	Settlements	Hyperbolic method	Three point method	Hushino method	Asaoka method
The center of Subgrade	Total settlement	65.62	64.18	68.60	63.00
	Post-construction settlement	0.09	0.65	5.07	0
Left observation pile	Total settlement	46.01	45.72	45.45	45.95
	Post-construction settlement	0.58	0.29	0.02	0.52
Right observation pile	Total settlement	65.6	65.19	66.78	64.42
	Post-construction settlement	0	0.55	2.14	0

4.2 *Analysis of pile-soil stress ratio*

In order to know the stress state of composite foundation and the stress characteristics of pile and soil, the changing law of pile-soil stress ratio value of composite foundation and load sharing ratio value changing with time and load are analyzed. The laws of pile-soil stress ratio of two types of pile-net composite foundation changing with load are shown in figure 5.



a CFG pile net composite foundation.

b sand pile net composite foundation

Figure 5. Stress ratio of pile and soil.

As shown in Figure 5, the increasing rate of the pile-soil stress of CFG pile-net composite foundation is slow in the early stage of filling. With the increase of load, the pile-soil stress ratio gradually increase. This is because that it has formed soil arching and tensioned membrane effect in the geogrid and cushion layer, and then load gradually concentrateson the pile top. When the overload pre pressure filling height came to 6.25m, pile-soil stress ratio is stabled at 2~8. It means that geogrid plays a vital role in the adjustment of pile-soil relative displacement and transferring soil bearing capacity, making pile-soil stress ratio in the small difference. Unloading to the design elevation of 2.1m, the pile-soil stress ratio decreased and finally stabilized at around 4.2, which is due to stress resilience of pile top after unloading is larger than that of soil.

The pile-soil stress ratio of sand pile-net composite foundation on the whole shows a trend of increasing at the beginning and stable at last. Figure 5 (b) shows the pile-soil stress ratio tend to be stable after 4 months of filling. However, only a set of pile-soil stress ratio is not constant until the end of the filling and the height of which is 4.5m after four months′ subgrade filling. This shows that pile-soil stress ratio of the lowly compressible foundation soil can be stable in a relatively short period of time after dealing with sand pile.

The bearing capacity of sand pile as granular pile, is far less than that of CFG piles which belongs to semi-rigid pile. Pile-soil stress ratio of sand pile is stable at about 3.5, and its load sharing ratio is 17.9%. While the pile-soil stress ratio of CFG pile-net composite foundation is stabilized at around 4.2, the load sharing ratio reached 50%. The law of the two varies with time and load shows some differences: The pile-soil stress ratio of CFG appears nonlinear growth in progress of loading and finally tends to a stable value. The pile-soil stress ratio of sand pile-net composite foundation appears to fluctuate at the early stage of loading, decreasing with the load increases and then raising gradually. This is mainly because foundation stress concentrated on pile rapidly when load just begins to effect. With the load increasing, sand pile gradually plays a role as composite foundation, and the bearing capacity of soil starts to work. During the late period of loading, due to the limitation of soil bearing capacity, most of the load is distributed to sand pile. But the growth rate of top pile stress grows slowly, synchronizing with that of soil stress. The pile-soil stress ratio tends to be stable. It is explained that the stress growth of pile body and the soil began to develop coordinately when the sand pile-net composite foundation began to play a role. Compared with the CFG pile, the pile-soil stress ratio and load sharing ratio of low-compression soil treated with sand pile can tend to be stable in a relatively short time.

4.3 *The distribution law of pore water pressure*

As shown in Figure 5, the pore water pressure of the CFG piles net composite foundation at different depths changes with the load and time. In general, depth of burying has little effect on change of pore water pressure, and upper load has some impact on the change of the pore water pressure. The pore water pressure increases slightly with the increase of load, and dissipates gradually at constant load period. The pore water pressure at deep point appears rebound during constant load period, which indicates that the pore water seeps from top to bottom, and soil gradually consolidated. The pore pressure keeps on reducing after unloading to the design elevation. The maximum pore pressure appears at the depth of 16m, and that of subjacent bed is smaller, while pore pressure of soil is relatively smallest.

The pore pressure-load - time process diagram of sand pile net composite foundation is shown in Figure11. In general, the variation of pore pressure at different depth shows identically, which shows a trend of regular increase and eliminate like steps. The deeper depth being buried, the more slightly effects on pore water pressure caused by load variation. This is because the effect of load on pore pressure is generated by the additional stress, while additional stress of foundation decreased gradually with the increase of depth. At the beginning of loading, load is small and the loading rate is also slow. The pore water pressure increases slowly with the increasing of load and begins to dissipate in intermittent period. In the late loading period, loading rate increased to 1.3KPa/d, and the pore pressure changed rapidly with the increase of loading rate, which leads to the curves′ steps are intensive. In the dead load period, pore water pressure gradually dissipates with time.

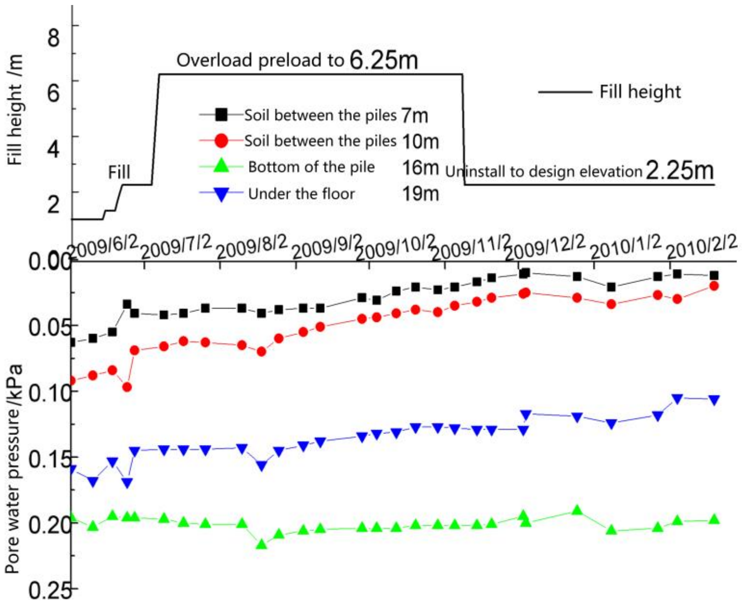


Figure 6. The change curve of hole pressure in CFG pile-net composite foundation.

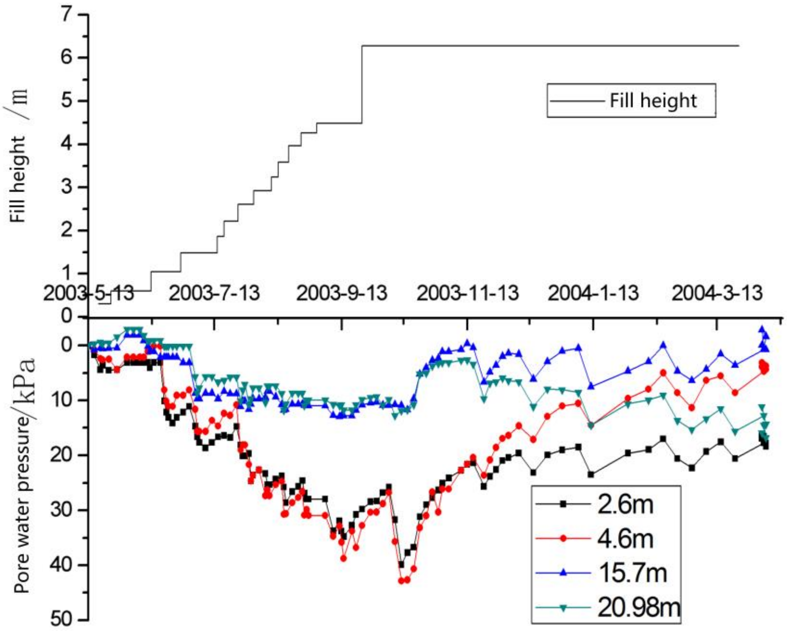


Figure 7. The change curve of hoe pressure in the sand pile-net composite foundation.

Although pore water pressures of sand pile and CFG pile are affected by the depth, the value of the pore pressure is far different at the same depth (not in the same order of magnitude). The excess pore water pressure of sand pile is far larger than that of CFG pile. The excess pore pressure of CFG pile is insensitive to the variation of upper load, while that of sand pile impacted by the upper load is more obviously. This is because the CFG pile as semi-rigid pile is considered with complete impervious to water, and sand pile belongs to loose material pile, its permeability is very evident. So the excess pore pressure dissipation rate of CFG pile-net foundation (0.0002kPa/d) is far less than that of sand pile-net foundation. Through the analysis of pore pressure variation, it also can be known that sand pile is mainly to drainage consolidation at the beginning of loading. In the process of it, the soil fine particles are being into the sand pile, and the strength and compactness of the sand pile itself gradually increase. Finally, the consolidation process gradually complete with the increase of time and load.

5 CONCLUSION

(1) The settlement laws of CFG pile-net composite foundation and are similar with the sand pile-net composite foundation in general. Both of settlement during the post construction period after preloading can meet the control requirements of high-speed railway ballastless track, but the total settlement and settlement rate of CFG pile-net composite foundation was less than that of sand pile-net foundation. The convergence speed of CFG pile-net composite foundation is faster than sand pile-net foundation.

(2) The bearing capacity of CFG pile as semi-rigid pile is much larger than sand pile with loose material. But compared with CFG pile-net, the pile-soil stress ratio in sand pile-net composite foundation tends to stable in a shorter time.

(3) There is a big difference in the law of the varied pile-soil stress ratio due to different pile stiffness. The pile-soil stress ratio of CFG pile-net increases with the embankment loading and finally tends to be stable. The pile-soil stress ratio of sand pile-net decreases with loading firstly and then increases, showing wavy changes.

(4) The pore water pressure in two different types of pile-net foundation is influenced by the buried depth. Changing load has slight effect on the pore water pressure of CFG pile, while pore water pressure of sand pile is more sensitive to load variations. Compared with CFG pile, the pore water pressure in sand pile dissipates faster greatly.

(5) Lowly compressible soil should be improved in a short construction period. The control effect of settlement in post construction period improved by CFG pile-net composite foundation is better than sand pile-net composite foundation.

REFERENCES

Wang Chang-dan ,Su Hui and Zou Chun-hua 2011. Comparative Analysis on Neutral Point Distribution in Rigid Pile Composite Foundation on Collapsible Loess in High Speed Railway. Applied Mechanics and Materials,v 90-93, p 471-6.

A Jiang & Wang Mei-xia 2011. Composite Foundation on bearing Characteristics and Simulation Analysis CFG Pile for the High Speed Railway. Applied Mechanics and Materials, v 71-78, pt.6, 3827-31.

Jiang Dan-ping & Wang Bing-long 2012. An Analysis on Failure Pattern of CFG Pile-net Composite Foundation of High-speed Railway. Advanced Materials Research, v 594-597, pt.2, 1357-62, 2012.

Yu Jin-jiang, Cheng Qian-gong, Li Cheng-hui, Wu Jiu-jiang and Wen Hua 2012. Model Test Research on Bearing Behavior of Pile-Net Composite Foundation in Super Large Area and Deep Soft Soil. Advanced Materials Research, v 378-379, p 470-6.

Lian Feng, Gong Xiao-nan and Zhao You-ming etc 2008. Field test study on strengthening mechanism of pile net composite foundation [J].CHINA RAILWAY SCIENCE, 29(3): 7-12.

Ma Jian-lin; Liu Jun-fei; Zhu Ming etc 2009(7). Experimental study on bearing capacity of composite foundation of CFG pile Engineering, 56-58.

Wang Hong-gui, Xu Linrong and He Xiaoguang etc 2008. Analysis on the Stability of High Embankment Influnced by Vertical Reinforcement Interval, The second national environmental geotechnical and geotechnical composite technology symposium,: Changsha, Hunan, China.

Zhang Ji-wen, Li Dian-long, Zeng Jun-jie etc,2009. Experimental study on stress load ratio of CFG pile composite foundation [J].Railway Engineering, 07:59-61.

Zhang Liang, Luo Qiang, Liu Xiao-xiao etc, 2010. CushionEffectAnalysisofPile-NetComposite Foundation Based on Field Tests[J].JOURNALOFSOUTHWESTJIAOTONGUNIVERSITY, (05): 787-793.

ZUO Shen, Wang min and Xu Lin-rong etc,2014. Research on reinforce effect of high-speed railway low and medium compressible soil pile-raft (net) foundation. Journal of Central South University (Science and Technology) ,.1590-1597.