AMSE JOURNALS-AMSE IIETA publication-2017-Series: Modelling C; Vol. 78; N°2; pp 225-241
Submitted Mar. 31, 2017; Revised May 25, 2017; Accepted Jun. 12, 2017

Experimental Study on Load Transfer Law of Rigid Pile-raft Composite Foundations

Hongwei Chen*, Yongsuo Li

Geotechnical Engineering Department, Faculty of Civil Engineering, Hunan City University, Yiyang 413000, China (cai7698@126.com)

Abstract

The rigid pile-raft composite foundations are adopted for the test section of the subgrade of Changzhutan Intercity Railway according to the design concept of settlement control. The author performs long-time observation towards the bearing characteristics of rigid piles, stress distribution of soil-between-piles, stress of rafts, deformation, etc. during construction, so as to explore its settlement control mechanism and bearing characteristics; and obtains some objective data as well. The author also analyzes the bearing characteristics of composite foundations, lateral distribution of the stress of soil-between-piles along subgrade, deformation characteristics under the stress of rafts and the change rule of stress of soil-between-piles over time under the effect of embankment load, and discusses the load transfer law of rigid pile-raft composite foundations, providing the test basis for further theoretical study and design optimization for rigid pile-raft composite foundations.

Key words

Intercity high-speed railways, Rigid pile-raft composite foundations, Land transfer and field test.

1. Introduction

The rigid pile-raft composite foundations, which take the rigid piles as vertical reinforcement, and form the bearing system together with soil-between-piles, cushions and reinforced concrete rafts, are effective reinforcement methods for soft soil foundations. This type of foundations can enhance the bearing capacity of the soil mass, have a short construction period, and can effectively reduce the differential settlement and post-construction settlement. This type of foundations has been gradually promoted and applied in soft foundation reinforcement of high-speed railways, foundation treatment of transition sections between roads and bridges and other projects in recent years [1-3].

Since the proposal of the concept of pile-raft foundation by Davis and Poulos [4] (1972), scholars both at home and abroad have been performing increasingly more studies over the pile-raft foundations, which are extensively used in foundation treatment of high-rise buildings [5-7]. However, the application to the subgrade of intercity railways has been just initiated in recent years. There are very different requirements for the rigid pile-raft composite foundations between the application in railway embankments under stress and in house-building projects. In particular, the ballastless track subgrades of intercity railways should not only satisfy the strength requirement but also the deformation requirement (especially the post-construction settlement), their requirement on post-construction settlement is extremely stringent too (≤15mm) and the construction period is relatively short; while the house-building projects only stress on the total settlement control (≤120mm) and their requirement on construction period is less urgent than that of intercity railways [8]. At present, the study on the rigid pile-raft composite foundations mainly focuses on theoretical analysis [9-10] and numerical modeling [11-12] instead of field test [13-14], Thus, it is still difficult to figure out the settlement control mechanism, bearing capacity, etc. of the rigid pile–raft composite foundations of intercity railways.

The post-construction settlement control has become one of the urgent problems pending for solution for the construction of high-speed railways in soft soil areas. It is quite necessary to perform in-depth test, study and exploration of the rigid pile–raft composite foundations, because the study over the action mechanisms, calculation theories of the rigid pile-raft composite foundations under railway embankment load is not mature, and there is no relevant experience for reference either. This paper selects the test section of the rigid pile-raft composite foundation of Changzhutan Intercity Railway to perform long-term observation towards the bearing characteristics of rigid piles, distribution of the stress of soil-between-piles, stress of rafts, deformation, etc.; discusses the bearing characteristics of composite foundations under the effect of embankment load, lateral distribution of the stress of soil-between-piles along subgrade, deformation characteristics under stress of the rafts and the change rule of the stress of soil-between-piles over time; and studies and analyzes the load transfer law of rigid pile-raft composite foundations, providing measured data support to the design, settlement control and in-depth study of the rigid pile-raft composite foundations for high-speed railways.

2. Bearing Characteristics of Single Rigid Piles

The core issue for the calculation of the bearing capacity of single rigid piles based on load transfer method is to properly define the load transfer model of foundations piles. Seed and Reese [15] (1957) proposed the single pile load transfer method firstly, then Kezd (1957), Misaki Sato (1965), Holloway (1975) and Zhao et al. (2007) developed the load transfer function method consecutively thereafter; and the load transfer model is shown in Figure1.

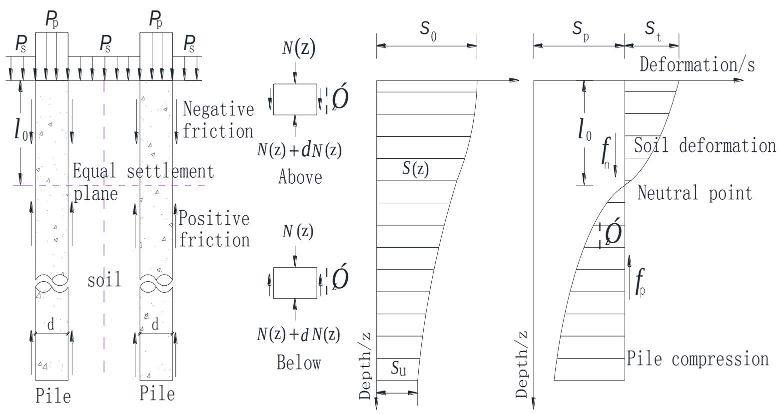

Fig.1. Diagram on the Calculation of Load Transfer Method of the Rigid Piles

It is supposed in the load transfer method that the stress and displacement of any point in the pile body are only related to the side friction of that point, the piles are systems that consist of many elastic units, and each unit has a nonlinear spring connection with the soil mass (including the pile tops). These nonlinear springs can indicate the relation between side friction of the piles (or pile top resistance) and shear displacement (or pile top displacement), which is usually called the load transfer function or (τ-z Curve), simplifies and assumes the transfer function as a certain type of curvilinear equation, and then calculates the differential equations of equilibrium directly.

Take a micro-pile section *dz* at the depth of *z*, and obtain the following equations based on equilibrium conditions of the force:

$$N(z) = P_p - \pi d \int_0^0 \tau(z) dz \quad (1)$$

$$\tau(z) = -\frac{1}{\pi d}\frac{dN(z)}{dz} \tag{2}$$

where, P_p is the pile top load; $\tau(z)$ is the side friction of pile body; $N(z)$ is the load of the cross section at any depth of the pile body, and d is the diameter of the piles.

Suppose the relative settling volume at pile top is S_0, the elasticity modulus of pile body is E_p and the sectional area of pile body is A_p, the vertical displacement $s(z)$ of at the depth z of the rigid piles can be expressed as follows:

$$s(z) = S_0 - \frac{1}{E_p A_p}\int_0^z N(z)dz \tag{3}$$

The compression amount of micro-pile section dz can be expressed as follows:

$$ds(z) = -\frac{N(z)}{A_p E_p}dz \tag{4}$$

Thus, we have:

$$N(z) = -A_p E_p \frac{ds(z)}{dz} \tag{5}$$

Substitute Equation (3) and Equation (4) into Equation (2), and we have:

$$\tau(z) = -\frac{1}{\pi d}\frac{dN(z)}{dz} \tag{6}$$

In engineering practice, static load test is usually conducted to define the vertical ultimate bearing capacity of the single piles; however, the ultimate bearing capacity of piles cannot be obtained due to various restrictions in static load test. This paper adopts the Vanderveen fitting curve function to infer the ultimate bearing capacity of the test piles based on limited test data; and employs the principle of the least square method based on statistics to perform regression treatment of load-settlement curve. The calculated results are close to measured values based on the acceptable conditions that the coefficient of determination γ^2 is the largest through hypothesis test, and the functional forms are as follows:

$$N(z) = N(z)_u (1 - Ae^{-BS}) \tag{7}$$

$$S = -\frac{1}{B}\ln(1 - \frac{N(z)}{N(z)_u}) + \frac{1}{B}\ln A \tag{8}$$

Suppose $\alpha=-1/B$ and $b=ln(A)/B$, and we have:

$$S = a\ln(1 - \frac{N(z)}{N(z)_u}) + b \tag{9}$$

where, $N(z)$ is the load (kN), S is the stable settling volume (mm) corresponding to $N(z)$, $N(z)_u$ is the ultimate bearing capacity in theory when $S \to \infty$; and A and B are undetermined coefficients.

The PHC and CFG pile-raft composite foundation *Q-S* curves can be seen in Figure 2 and Figure 3 respectively. Carry out fitting calculation with the foregoing load transfer function method, and relevant results are provided in Figure 4, Figure 5 and Table 1 respectively.

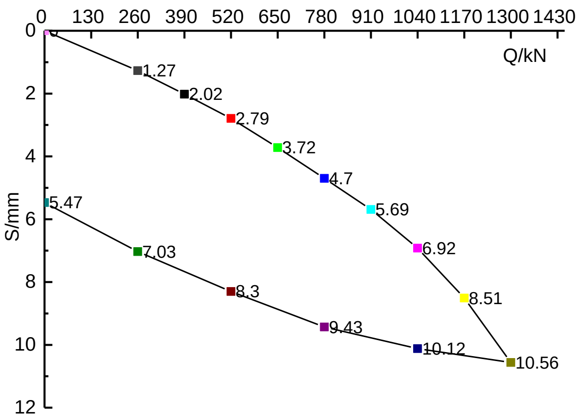

Fig.2. Single Pile Q-S Curve of PHC Pile- Raft Composite Foundations

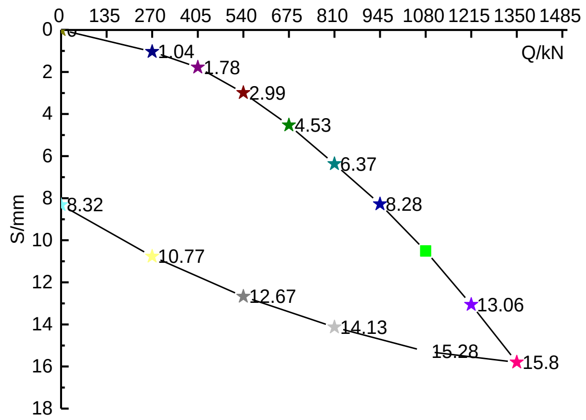

Fig.3. Single Pile Q-S Curve of CFG Pile- Raft Composite Foundations

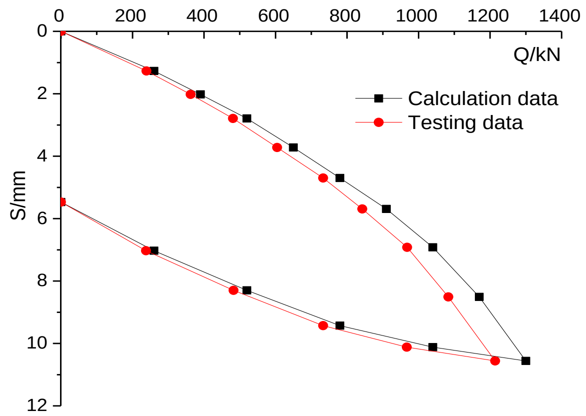

Fig.4. Comparison of Measures Values and Calculated Values (PHC pile)

Suppose the points on the curves are the stable settlement points corresponding to the load, the load on rigid piles is the ultimate bearing capacity, when the load is increased to higher than 2 times' of the design load which is corresponding to the maximum pile top settling volume. Further suppose the design value of the bearing capacity of single piles for the test section of CFG pipe-raft composite foundations is 618kN, the design value of the bearing capacity of single piles for the test section of PHC pipe-raft composite foundations is 652kN, impose the field test load by 9 levels, impose the load of the next level after the load of the previous level becomes stable, discharge the load by 4 equivalent levels, and record the rebound quantity.

When $N(z)_u$=618kN, and γ=-0.99, the significance test of the test section of CFG pile – raft composite foundations: if H_0: $\beta=0$, the relation of $S=\alpha ln(1-N(z)/N(z)_u)+b$ does not exist between $N(z)$-S; and if H_1: $\beta\neq0$, there is a linear relation of $S=\alpha ln(1-N(z)/N(z)_u)+b$ between Q-S.

The test statistics are as follows:

$$t=\gamma(\text{n}-2)^{\frac{1}{2}}/(1-\gamma^2)^{\frac{1}{2}}=-25.5 \tag{10}$$

Look up the t distribution table based on the significance level of α=0.01 and the degree of freedom of n-2=13, the test critical value is identified to be t_{α}=3.01 and |t|> t_{α}; therefore, there really exits the linear relation between ln$(1-N(z)/N(z)_u)$ and S, which means that the relation of load and settlement is $N(z)=N(z)_u(1-Ae^{-BS})$. From the abovementioned analysis, it can be seen that the theoretical calculation results and measured results are close to each other, with a high accuracy. When S=10.56mm, the corresponding ultimate load is 1214.2kN; when S=10.56mm, the measured ultimate load is 1300kN; and the difference between both values is small, with the relative error being 6.6%.

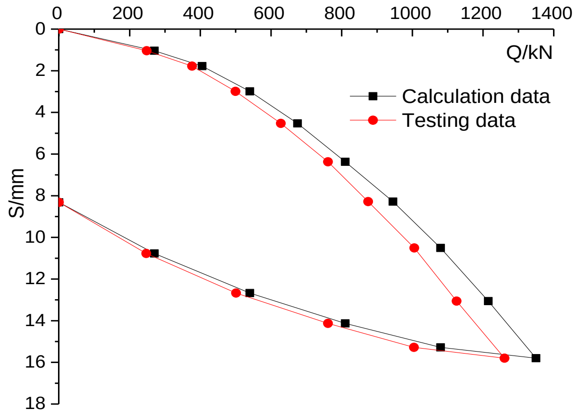

Fig.5. Comparison of Measured Value and Calculated Value (CFG Pile)

For the test section of PHC pile-raft composite foundations, $N(z)_u$=652kN and γ=-0.991 through statistical calculation.

The test statistics are as follows:

$$t=\gamma(\mathrm{n}-2)^{\frac{1}{2}}/(1-\gamma^{2})^{\frac{1}{2}}=-24.08 \tag{11}$$

Look up the t distribution table based on the significance level of $a=0.01$ and the degree of freedom of n-2=10, the test critical value is identified to be t_{α}=3.17 and |t|> t_{α}; therefore, there really exits the linear relation between ln$(1-N(z)/N(z)_u)$ and S. When S=15.28mm, the corresponding ultimate load is 1004.4kN. The pile test results show that when S=15.28mm, ultimate bearing load is 1080kN, and the two values are close to each other, with the relative error being only 7%.

Tab.1. Calculation Results of Fitting Parameters

Pile	*a*	*b*	Q_u/kN	Q_s/kN	γ	*A*	*B*
CFG	-15.35	-0.83	618.00	605.64	-0.99	0.95	0.07
PHC	-19.40	-2.99	652.00	638.96	-0.99	0.86	0.05

3. Stress-strain Distribution Law

3.1 Lateral Distribution of Stress of Soil-between-piles

Lateral distribution law of the stress of soil-between-piles along subgrade of PHC pile-raft composite foundations and CFG pile-raft composite foundations are shown in Figure 6 and Figure 7.

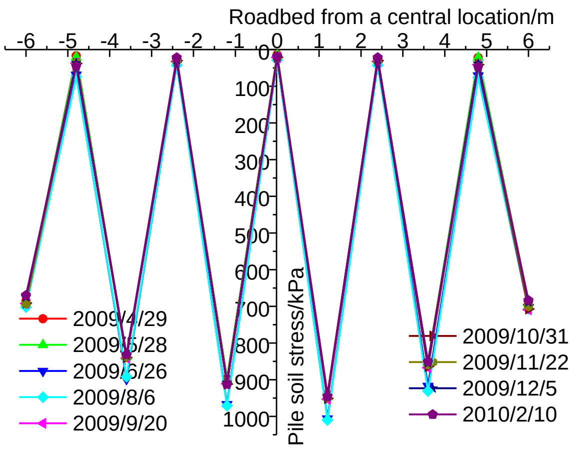

Fig.6. Lateral Distribution of Stress of Soil-Between-Piles of PHC Pile-Raft Composite Foundations

It can be seen from Figure 6 and Figure 7 that the pile top stress and soil-between- piles stress of PHC pile-raft composite foundations and CFG pile-raft composite foundations under the raft is in lateral distribution of zigzag shape along subgrade, with the peak of wave being pile top stress and the trough of wave being the soil-between-piles stress, which indicates that stress is obviously concentrated at pile top.

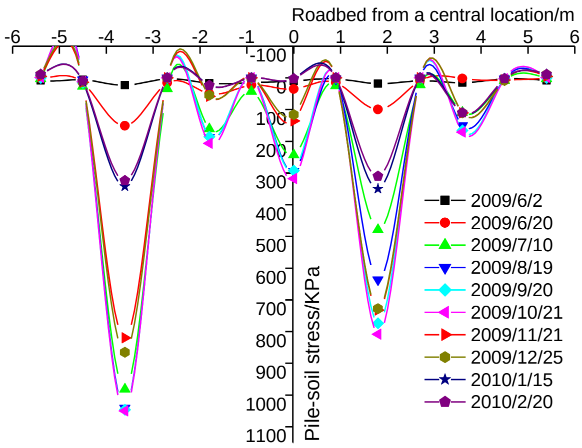

Fig.7. Lateral Distribution of Stress of Soil-between-piles of CFG Pile-Raft Composite Foundations

Under the effect of embankment load, differential settlement forms between soil-between-piles since the elasticity modulus of pile body far outweighs that of the soil around the piles. Moreover, the rigidity of reinforced concrete rafts is relative high, settlement of piles and soil-between- piles is the same under stress, most load is borne by the pile body, pile top stress is much higher than that among soil-between-piles and stress is significantly concentrated at pile top with most of the load being borne by the pile body and a small proportion of load being borne by the soil-between-piles. The pile top stress and stress of soil-between-piles increases quickly with the construction of embankment and application of pre-pressing load, with the former increasing faster than the latter. Under the effect of maximum load, the maximum pile top pressure of the PHC pile-raft composite foundations under the rafts is 1020kPa (occurs in the central pile), the maximum stress of soil-between- piles is 87kPa, which appears in the location that is 2.4m away from the center of subgrade; the maximum stress at CFG pile top on the external side of the rafts is 680kPa, and the concentration of stress at pile top is not that obvious as that under the rafts. The maximum stress at the pile top of the CFG pile-raft composite foundations under the rafts is 1,050kPa, which does not occur in the central pile (but the CFG pile top that is 4.5m away from the center of the subgrade); the maximum stress of soil-between- piles is 348kPa, which occurs at the location that is 1.8m away from the center of the subgrade; and the maximum stress at the CFG pile top on the external side of the rafts is 32kPa, which is obviously small than that under the rafts.

From the late stage of prepressing to discharge of overload, the pile top stress and stress of soil-between-piles increases gradually, with the former increasing more slowly than the latter; which indicate that the piles are given a better paly in term of bearing performance under the effect of rafts, and the cushions make sure that the piles and soil-between-piles can jointly bear the load.

3.2 Deformation Characteristics of Rafts under Lateral Stress

The lateral reinforcement stress test results along subgrade of the rafts of test section of PHC pile-raft composite foundations and CFG pile-raft composite foundations are provided in Figure 8 and Figure 9 respectively; and the concrete strain test results are shown in Figure 10 and Figure 11 respectively.

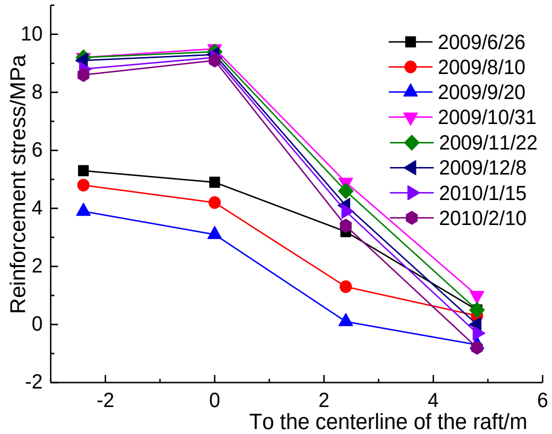

Fig.8. Lateral Reinforcement Stress of Raft of PHC Pile-Raft Composite Foundations

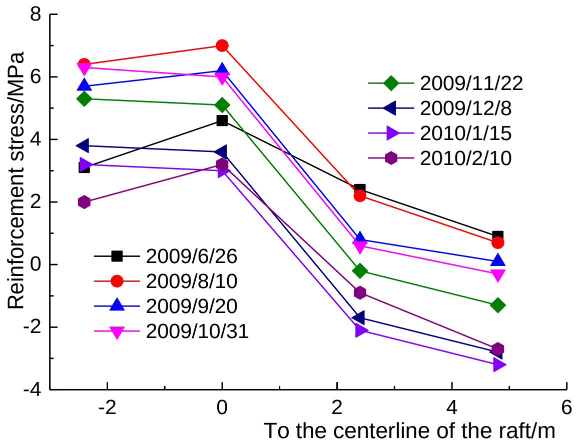

Fig.9. Lateral Reinforcement Stress of Raft of CFG Pile-Raft Composite Foundations

It can be seen from the reinforcement stress and concrete stress test results that the overall performance of reinforcement stress of the rafts under the effect of subgrade is as follows: the bottom of the rafts is in tension, the top is under stress and the reinforcement stress decreases slightly from the center of the rafts. It indicates that the rafts bend a little, which is consistent with the settlement test results. Generally speaking, the concrete at test position is under stress, with only some parts being in tension (15$\mu\varepsilon$). During the test, the maximum lateral tension stress of the rafts of PHC pile-raft composite foundations and CFG pile-raft composite foundations is 17.3MPa and 14.2MPa respectively; and the maximum concrete compressive strain of PHC pile-raft composite foundations and CFG pile-raft composite foundations is 108.6$\mu\varepsilon$ and 82.3$\mu\varepsilon$ respectively.

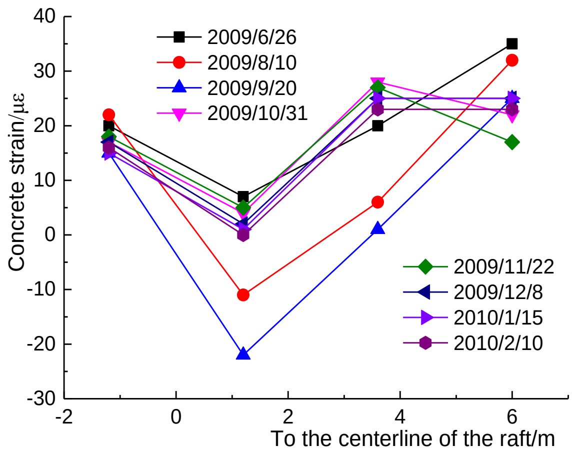

Fig.10. Lateral Concrete Strain Distribution of the Rafts of PHC Pile-Raft Composite Foundations

It is shown in Figure 9 and Figure 10 that the overall performance of lateral reinforcement stress of the rafts under the effect of subgrade is as follows: the bottom of the rafts is in tension, the top is under stress and the reinforcement stress decreases slightly from the center of the rafts. It indicates that the rafts bend a little, which is consistent with the settlement test results. Generally speaking, the concrete at test position is under stress, with only some parts being in tension (15$\mu\varepsilon$). During the test, the maximum lateral tension stress of the rafts of PHC pile-raft composite foundations and CFG pile-raft composite foundations is 17.3MPa and 14.2MPa respectively; and the maximum concrete compressive strain of PHC pile-raft composite foundations and CFG pile-raft composite foundations is 108.6$\mu\varepsilon$ and 82.3$\mu\varepsilon$ respectively.

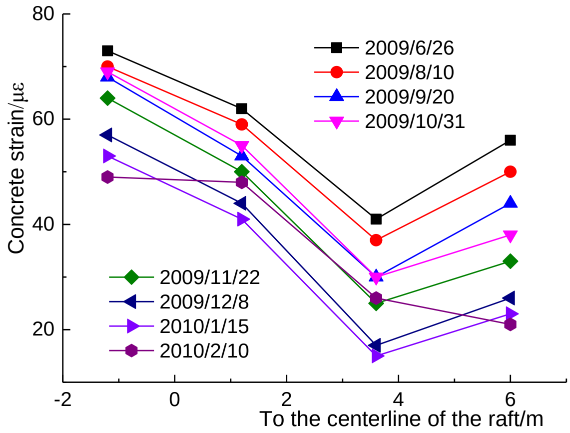

Fig.11. Lateral Concrete Strain Distribution of the Rafts of CFG Pile-Raft Composite Foundations

3.3 Deformation Characteristics of Rafts under Vertical Stress

The vertical reinforcement stress test results along subgrade of the rafts of test section of PHC pile-raft composite foundations and CFG pile-raft composite foundations are shown in Figure 12 and Figure 13 respectively; and the concrete strain test results are shown in Figure 14 and Figure 15 respectively.

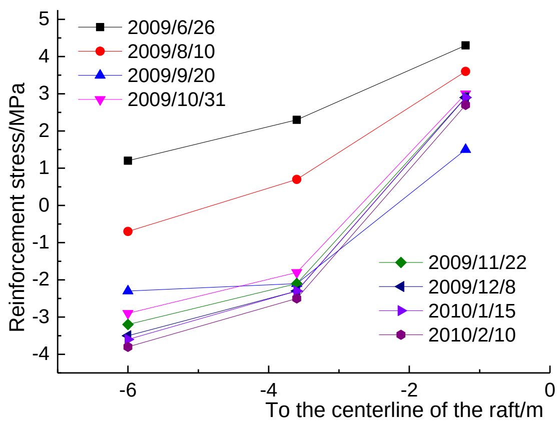

Fig.12. Vertical Reinforcement Distribution of the Rafts of PHC Pile-raft Composite Foundations

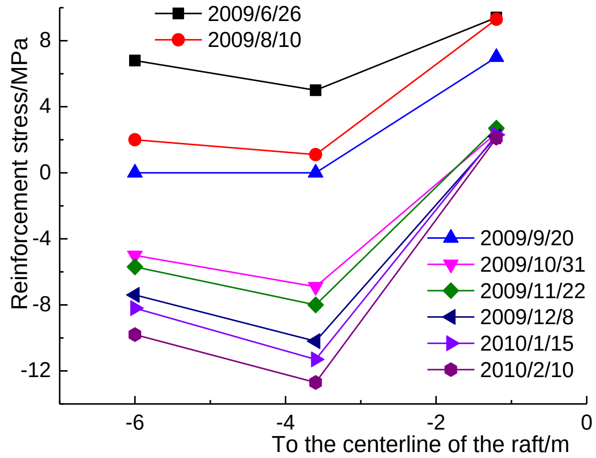

Fig.13. Vertical Reinforcement Distribution of the Rafts of CFG Pile-raft Composite Foundations

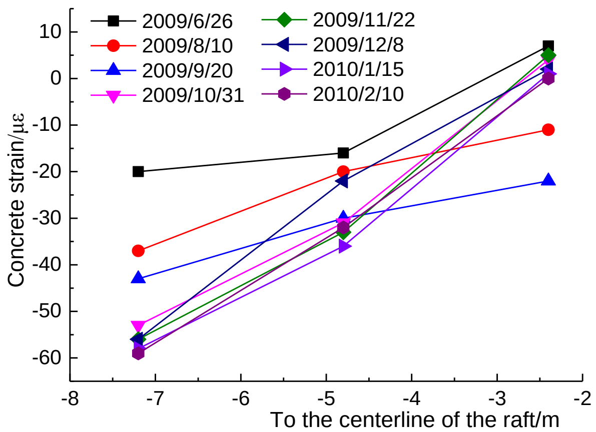

Fig.14. Concrete Strain Distribution of the Rafts of PHC Pile-raft Composite Foundations

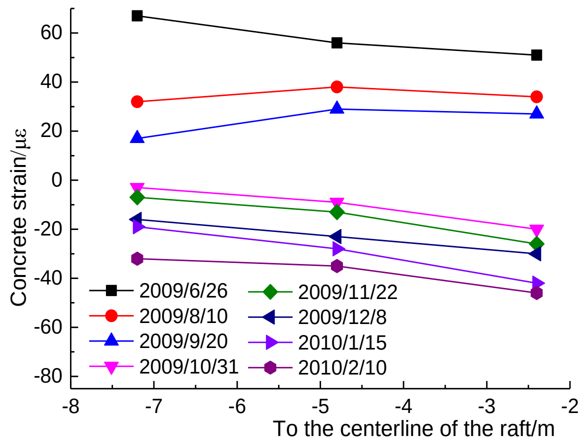

Fig.15. Concrete Strain Distribution of the Rafts of CFG Pile-raft Composite Foundations

As shown in Figure 12 and Figure 15 that the rebar and concrete in vertical rafts are under stress along the subgrade in general. The reinforcement stresses test results show that the stress of the rafts changes a little in vertical direction along the subgrade, which can be simplified into a plane strain problem calculation and analysis. The maximum compressive stress of vertical rebar in the rafts of the PHC pile-raft composite foundations and PHC pile-raft composite foundations is 14.6MPa and 15.8MPa respectively; and the maximum compressive stress of concrete in PHC pile-raft composite foundations and CFG pile-raft composite foundations is 137.8$\mu\varepsilon$ and 83.5$\mu\varepsilon$.

4. Change of Load-time-stress of Soil-between- piles

The curves on the change of the stress of soil-between-piles in PHC pile-raft composite foundations and CFG pile-raft composite foundations are shown in Figure 16 and Figure 17.

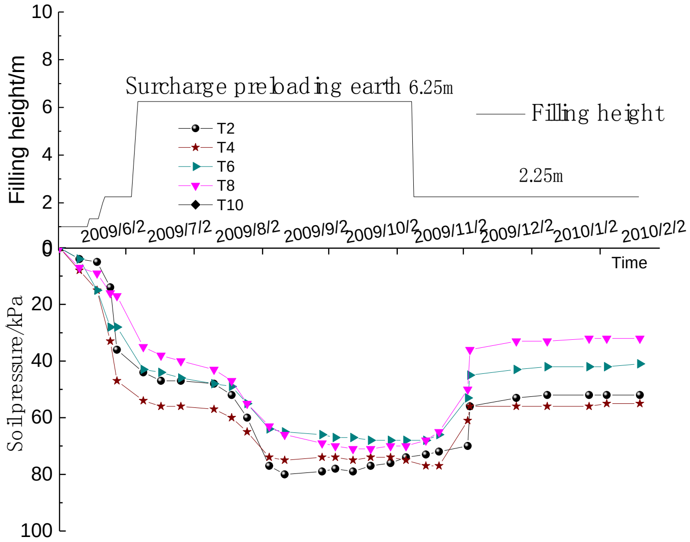

Fig.16. Curve on the Change of Stress of Soil-between-piles in PHC Pile-raft Composite Foundations

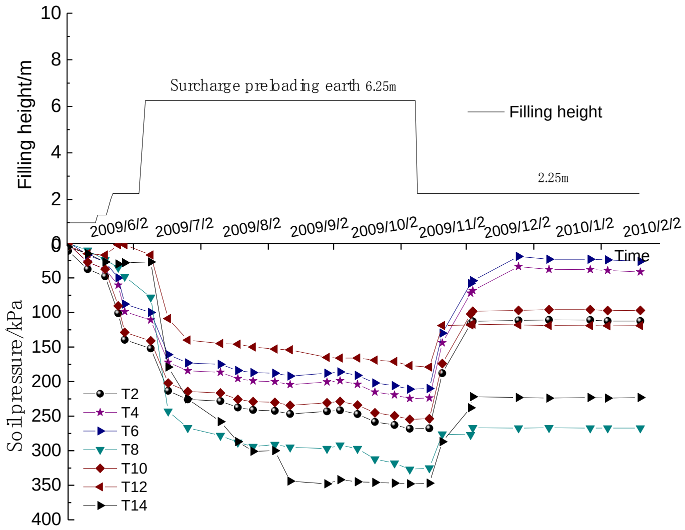

Fig.17. Curve on the Change of Stress of Soil-between-piles in CFG Pile-raft Composite Foundations

According to the test results, the stress of soil-between-piles changes accordingly with the change of fill load, which is obvious after pouring of rafts and at early stage of earthwork filling and overload prepressing; the stress remains stable during prepressing of overload basically; and the stress falls significantly after depressurization, and becomes stably gradually afterwards.

The stress of soil-between-piles in the center of the subgrade is relatively higher, the range value of the stress of soil-between- piles of PHC pile-raft composite foundations during overload prepressing is between 38kPa and 82kPa, with the average value being about 67kPa; the range value for CFG pile-raft composite foundations is between 149kPa and 348kPa, with the average value being about 243kPa. The stress of soil-between- piles increases with the increase of filing load, but they are not in a linear relation, and the increase of the stress of soil is much slower than that of the fill load. When the upper load is increased from 2.25m at the early stage of filling to 6.25m at the initiation of overload prepressing, the stress increases at average, but the stress remains relatively stable during overload prepressing, which indicates that the proportion of load shared by the pile body grows with the increase of upper load and the extension of prepressing time, a part of the embankment load directly transfers to the piles through the rafts and cushions, the other part of the load transfers to the soil-between-piles through the cushions, and then transfers to the piles through frictional effect of soil-between-piles. It can be seen, combining the lateral distribution law of the stress of soil-between-piles along the subgrade, that the cushions play a better role in stress transfer and transmission through compatibility of deformation, and effectively reduce the subsidiary stress from upper load to the foundations.

Conclusions

(1) This paper reveals the load transfer law of rigid pile –raft composite foundations by adopting the monitoring technology of the bearing characteristics, distribution of the stress of soil-between-piles, raft stress and deformation of rigid piles, so as to work out the issue of settlement control in a short time for the test section of the rigid pile- raft subgrade of the intercity railway.

(2) The negative frictional resistance of soil-between-piles increases the bearing capacity of soil-between-piles, and makes the load transfer to deeper layers, which is helpful to mitigate the post-construction settlement.

(3) The pile top stress and stress of soil-between- piles is in lateral distribution of zigzag shape, which is obviously concentrated, and the rigid piles are given a better play in term of bearing performance under the effect of the rafts.

(4) The cushions play a better role in stress transfer and transmission through compatibility of deformation, effectively reduce the subsidiary stress from upper load to the foundations, and make sure that the piles and soil-between- piles can jointly bear the load. Finally, the stress of soil-between-piles ratio and load-bearing ratio is stable at 31.8% and 67.8% respectively.

Acknowledgements

This study was supported by the Natural Science Foundation of China (Project no. 51678226 and 51608183), Key project of scientific research of Hunan Provincial Education Department (no. 15A035), and Hunan science and technology project (no. 2014SK3180).

The authors woule like to thank all colleagues and students who contribute to this study. We are grateful to Dr. Cao Guohui and Zeng Ge who as the reviewers provide some constructive comments.

We thank the editor and series editor for constructive criticisms of an earlier version of this chapter. The errors, idiocies and inconsistencies remain our own.

References

1. J.W. Zhang, J.C. Zeng, T.U Yong-Ming, X.D. Tong, Experimental study on CFG pile-raft composite foundation of Beijing-Shanghai high-speed railway, 2011, Journal of the China Railway Society, vol. 33, no. 1, pp.83-88.
2. H.W. Chen, L.R. Xu, Field experiment of pile-soil stress ratio of pile-raft (net) composite foundation, 2014, Hydrogeology and Engineering Geology, vol. 41, no. 6, pp.64-69.
3. Y.P. Shen, J.J. Du, S.C. Wang, Test for static or dynamic response of subgrade-culvert transition section for high-peed railways in soft soil ground, 2012, China Civil Engineering Journal, vol. 45, no. 8, pp.158-165.
4. E.H. Davis, H.G. Poulos, The analysis of pile raft systems, 1972, Australian Geomechanics Journal, vol. G2, no. 1, pp.21-27.
5. J.M. Zai, G. Jiang, X.D.Wang, Model test on pile-raft foundation interaction under ultimate load ,2007, Chinese Journal of Geotechnical Engineering, vol. 29, no.11, pp. 1597-1603.
6. M.A. Chaudhary, FEM modelling of a large piled raft for settlement control in weak rock, 2007, Engineering Structures, vol. 28, no.11, pp. 2901-2907.

7. B. El-Garhy, A.A. Galil, A.F. Youssef, Behavior of raft on settlement reducing piles: Experimental model study, 2013, Journal of Rock Mechanics and Geotechnical Engineering, vol. 5, no.5, pp. 389-399.
8. J.C. Zeng, J.W. Zhang, X.D. Tong, In-situ test on settlement of CFG pile-raft composite foundation in high-speed railway, 2010, Journal of Southeast University (Natural Science Edition), vol. 40, no. 3, pp. 570-575.
9. D.C.N. Dang, D.S. Kim, S.B. Jo, Parametric study for optimal design of large piled raft foundations on sand, 2014, Computers and Geotechnics, vol. 55, no. 1, pp. 14-26.
10. W. Su, H.Z. Yang, J.L. Ma, Experimental study on settlement performance of CFG pile-RC mat and CFG pile-geosynthetic net composite foundations for improving deep-thick-soft soil layer of high speed railway, 2009, Railway Engineering, vol. 7, no. 3, pp. 66-69.
11. J.Z. Jun, S.W. Abusharar, Z.W. Xian, Three-dimensional nonlinear finite element modeling of composite foundation formed by CFG–lime piles, 2008, Computers and Geotechnics, vol. 35, no. 4, pp. 637-643.
12. A.J. Zhou, B. Li, Experimental study and finite element analysis of cushion in CFG pile composite foundation, 2008, Rock and Soil Mechanics, vol. 29, no. 5, pp. 1275-1279.
13. L.R. Xu, H.G. Wang, S. Zuo, Test study of performance of composite pile foundation of high-speed railway controlling settlement, 2012, Rock and Soil Mechanics, vol. 33, no. 9, pp. 2605-2612.
14. E. Bourgeois, P.D. Buhan, G. Hassen, Settlement analysis of piled-raft foundations by means of a multiphase model accounting for soil-pile interactions, 2012, Computers and Geotechnics, vol. 46, no. 11, pp. 26-38.
15. H.B. Seed, L.C. Reese, The action of soft clay along friction piles, 1957, Trans. ASCE, vol. 122, no. 11, pp. 101-105.