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Experimental Study on the Performance of Geosynthetic-Reinforced and Tapered Pile-Supported Composite Foundation

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Abstract

Reinforced cushion and pile are two important components of the geosynthetic-reinforced and pile-supported (GRPS) composite foundation. Studies on the traditional GRPS composite foundation with uniform section piles have compared the performance of GRPS before and after the reinforcement of cushion yet neglects the effects of reinforcement type and pile shape on this composite foundation. To address this problem, the geosynthetic-reinforced and tapered pile-supported (GRTPS) composite foundation with section-variable piles was proposed in this study as a new form of the GRPS composite foundation. The settlement of the proposed composite foundation and the stress distribution on piles and soil under three cushion conditions (gravel cushion (GC), geogrid-reinforced cushion (GGRC), and geocell-reinforced cushion (GCRC)) were analyzed through a static test by using three models of specimens with nine piles. Test results demonstrate that under the test load, the pile-soil settlement differences under GGRC and GCRC are 43.4% to 49.8% and 34.7% to 39.8% of that under GC. Meanwhile, the pile-soil stress ratios under GGRC and GCRC are 1.47 to 1.88 and 1.77 to 2.08 times of that under GC. The reinforced cushion can effectively reduce the settlement of the composite foundation and the pile-soil settlement difference, increase the pile-soil stress ratio, and relieve stress concentration in some piles. GCRC can improve the performance of the GRTPS composite foundation more effectively than GGRC under the same conditions. No negative friction region is observed on the upper piles in the GRTPS composite foundation. The tapered piles are better than the uniform section ones as well as can increase the bearing capacity and decrease the settlement of the composite foundation. The findings of this work can provide references for the engineering design and application of the GRTPS composite foundation.

Keywords: Geosynthetic-reinforced and pile-supported, Reinforced cushion, Rammed cement soil, Tapered pile

1. Introduction

Given its low bearing capacity and large compressive deformation, soft foundation requires certain treatment to meet engineering foundation requirements. Geosynthetic-reinforced and pile-supported (GRPS) composite foundation, which integrates the advantages of horizontal and vertical reinforcement, can effectively increase the bearing capacity of the foundation, control its settlement, and accelerate its construction. Accordingly, GPRS has been widely used in soft foundation treatment projects [1-2]. To disclose the effects of cushion reinforcement type and pile shape on the performance of the GRPS composite foundation, a new form of GRPS composite foundation with section-variable piles is proposed in this study and is expected to have a vital role in soft foundation treatment.

GRPS composite foundation takes many forms. However, previous studies [3-5] have mainly focused on concrete pile, gravel pile, and mixing cement soil pile. Although these common GRPS foundations can improve the bearing capacity of the foundation and reduce the settlement to some extent, they are difficult to be fully developed due to the restraints of the pile and soil properties as well as the site construction conditions. For instance, the pile body bears most of the upper load in the geosynthetic-reinforced and concrete pile-supported composite foundation, but the bearing capacity of the soil around the pile cannot be easily used, which is disadvantageous to the formation of the composite foundation [6]. Although the geosynthetic-reinforced and gravel pile-supported composite foundation can effectively increase bearing capacity, the large compression deformation of the pile body limits the control of the foundation settlement to some extent [7]. Meanwhile, the pile body of the geosynthetic-reinforced and mixing cement soil pile-supported composite foundation has poor strength uniformity, thereby reducing the stability and reliability of the foundation [8]. Previous studies on GRPS composite foundation have also focused on uniform section piles under a specific reinforced cushion condition yet neglected the influences of cushion reinforcement type and pile shape on the performance of the GRPS composite foundation.

To address these research gaps, this study proposes the geosynthetic-reinforced and tapered pile-supported (GRTPS) composite foundation by considering the influences of cushion reinforcement type and pile shape on the performance of the GRPS composite foundation. The performance of GRTPS under different cushion conditions is also evaluated.

2. State of the Art

GRPS composite foundation takes many forms due to the tremendous amount of piles and reinforcement materials.

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Many model tests, theoretical analyses, and numerical calculations on the bearing capacity and settlement of GRPS composite foundations as well as on the pile-soil stress ratio have been conducted. Some test results and calculation methods applicable to engineering design have also been proposed. Xing H. et al. [9] analyzed the bearing behavior of concrete pile-supported composite foundations with and without geogrid by performing a large scale test and found that the geogrid could increase the upper load proportion assumed by piles. Moreover, the role of the geogrid increases along with the load. Emersleben A. et al. [10] analyzed the bearing capacity of a geocell-reinforced and rigid-pile-supported composite foundation by conducting a model test and proved that the geocell could improve the bearing capacity of the composite foundation. However, most upper loads are assumed by the pile body and developing the bearing capacity of the soil surrounding the piles is difficult. Dash S. K. et al. [11] tested the effects of geocell reinforcement on the bearing capacity of gravel-pile-supported composite foundation by performing a model test and found that using a reinforced cushion was more effective than lengthening the piles and reducing the spaces between piles in increasing the bearing capacity of the foundation. Deb K. et al. [12] examined the soil arch effect of the geosynthetic-reinforced cushion and gravel-pile-supported composite foundation via a theoretical analysis and proposed a formula for calculating the settlement of the composite foundation. Several influencing factors have also been discussed in the literature. Hasan M. and Gu M. et al. [13-14] found that geosynthetic-reinforced and gravel pile-supported composite foundation has a relatively large settlement and proposed solutions to such problem. Rowe R. K. et al. [15] calculated the settlement of soft foundation under no treatment, single vertical pile treatment, and GRPS treatment via a 3D finite element analysis. Their calculations showed that given the calculation load, the settlement under the single vertical pile treatment and GRPS treatment are 52% and 31% of that under no treatment, respectively. Therefore, compared with the single vertical reinforced composite foundation, the GRPS composite foundation can increase the bearing capacity and reduce the settlement of the foundation. However, the bearing capacity of the soil surrounding the piles will be underused in the geosynthetic-reinforced and rigid pile-supported composite foundation due to the high pile strength. Meanwhile, the geosynthetic-reinforced and gravel pile-supported composite foundation has a relatively high settlement due to the low pile strength.

To solve the aforementioned limitations of the GRPS composite foundation, researchers have examined the GRPS composite foundations of flexible piles with moderate strength. Guo Z. X. et al. [16] studied the stress and settlement behavior of geogrid reinforcement and rammed cement soil pile-supported composite foundation by conducting a model test and reported that geogrid could adjust the pile-soil stress and constrain the lateral displacement of the foundation. Zhang C. et al. [17] conducted a site test on reinforced cushion with cement fly ash gravel pile composition foundation in high-speed railroad subgrade and found that this composition foundation could effectively reduce the vertical settlement and horizontal displacement of the foundation. The bearing capacity of the pile and soil can also be greatly enhanced. Han J. et al. [18-19] calculated the total and difference settlements of the geogrid-reinforced and different strength piles-supported composite foundation by using the discrete element method and found that the settlement decreased along with increasing pile strength. The above results demonstrate that the GRPS composite foundation of flexible piles not only makes full use of the bearing capacity of the soil surrounding the piles and increase the bearing capacity of the foundation but can also realize the goal of settlement control. Given that the GRPS composite foundation performs well while meeting the bearing capacity of the foundation, the rammed cement soil pile was used as the test object in this study.

The above results concerning GRPS composite foundation all focus on uniform section piles under a specific reinforced cushion yet neglect the effects of cushion reinforcement type and pile shape on the GRPS composite foundation. The uniform section pile has a mature theory and rich construction experience, while the tapered pile has a high bearing capacity and economic advantage due to the special sloped sidewall. By conducting a model test on the tapered pile, Matsumiya H. et al. [20-21] showed that under the same conditions, the bearing capacity per unit volume of the tapered friction pile is 0.5 to 2.5 times higher than that of a common cylinder friction pile, but its engineering cost of foundation treatment is 40% to 60% lower than the latter. By combining the advantages of the rammed cement soil pile and the tapered pile, He J. et al. [22-24] discussed the bearing capacity advantages of cement soil tapered piles through a model test and proposed a reasonable wedge angle range. Further studies on GRTPS composite foundation are warranted.

To address the limitations of previous studies, the GRPS composite foundation was combined with the tapered pile and the new GRTPS composite foundation with section-variable piles was proposed in this study. Three models of GRTPS composite foundation with nine piles were also designed. The effects of cushion reinforcement type and pile shape on the performance of the GRTPS composite foundation were discussed by performing a static test under different cushion conditions. The test results can provide references for the design and application of the GRTPS composite foundation.

In this study, section 3 presents the static test of the composite foundation model. Section 4 analyzes the settlements and stress distribution of the piles and soil in the composite foundation under different cushion conditions, discusses the settlement of the composite foundation, pile-soil settlement difference, pile-soil stress ratio, and axial force transmission feature of the pile shaft during the loading process, and evaluates the performance of the GRTPS composite foundation under different cushion conditions. Section 5 concludes the study.

3. Methodology

3.1 Test program and experimental apparatus

To analyze the effects of cushion reinforcement type and pile shape on the performance of the proposed composite foundation, three models with nine piles were designed. Although they have the same piles and soil, these three models consider different cushion conditions, namely, gravel cushion (GC), geogrid-reinforced cushion (GGRC), and geocell-reinforced cushion (GCRC) (Table 1). A model test was conducted in an indoor pit (6.0 m (length)×3.0 m (width)×3.0 m (depth)). The plane distribution of the model test is shown in Fig. 1. The three models were distributed at an equal interval along the perpendicular bisector of the pit width. The distributions of the pressure gauges and settlement rods on the piles and soil surface are shown in Fig. 2(a), while the piles, soil, cushion, settlement observation systems, and static loading device used in the test are shown in Fig. 2(b). A load box was set to facilitate the installation and reading of the apparatus. The load was applied onto the cushion by using a jack and counter-force beam through a load plate. The vertical displacements on the pile and soil surface were transmitted to the dial indicators through the settlement rods.

The field situation at the pile formation of the nine-pile model is shown in Fig. 3. USB cables were used to measure the axial force at different depths of the pile body. The static test site is shown in Fig. 4.

Table 1. Cushion conditions of model test

Model	Cushion thickness (cm)	Cushion material	Reinforcement type	Paving location
GC	20	Gravel		
GGRC	20	Gravel	Geogrid	Middle of cushion
GCRC	20	Gravel	Geocell	Middle of cushion

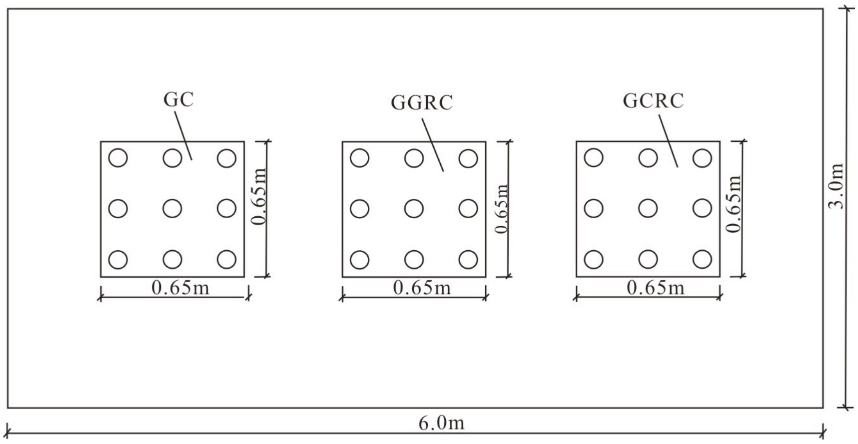
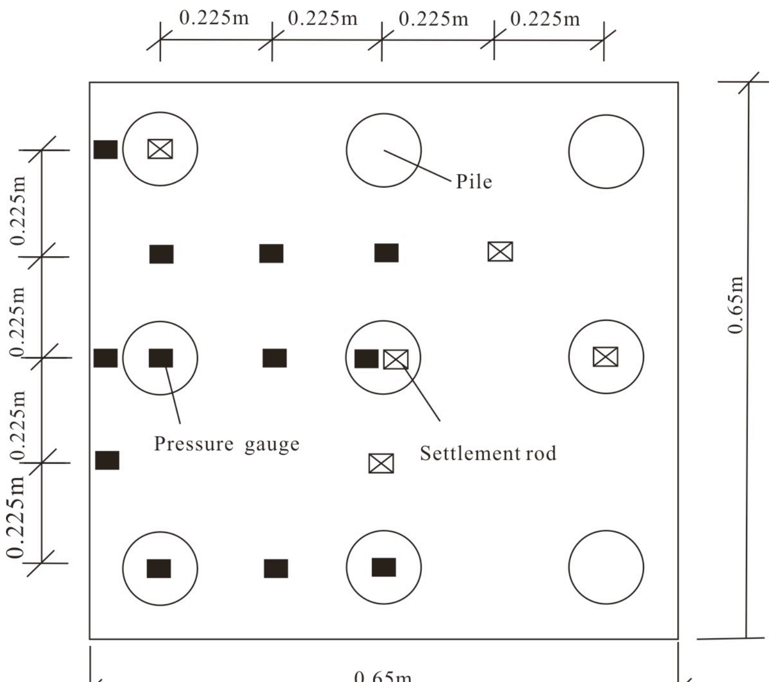


Fig. 1. Plane distribution of model test



(a)

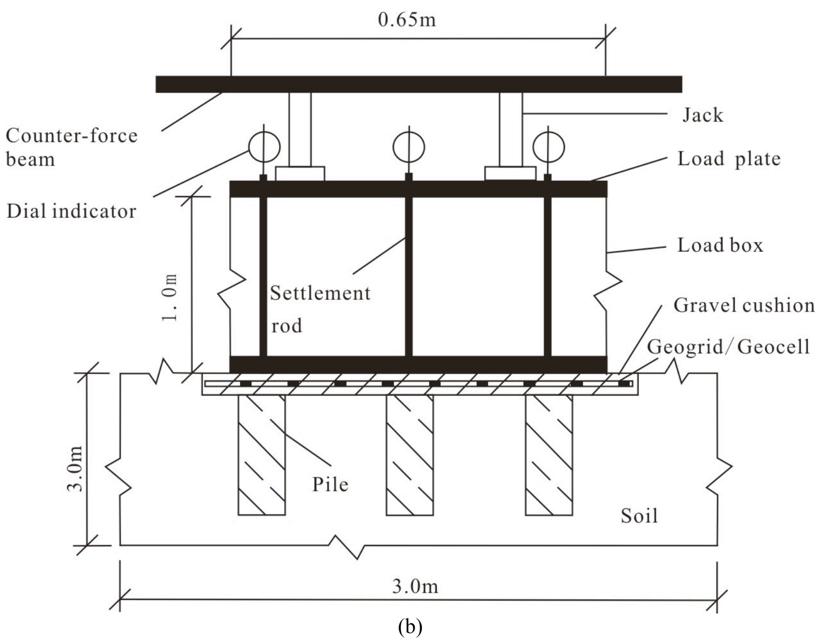


Fig. 2. Experimental apparatus diagram. (a) Plan view. (b) Cross section view

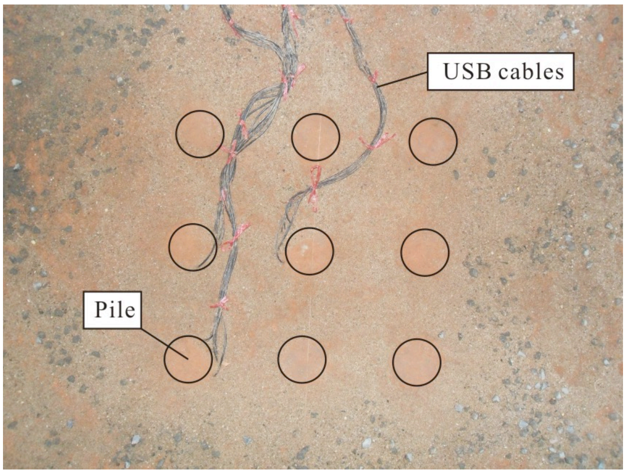


Fig. 3. Field situation at pile formation

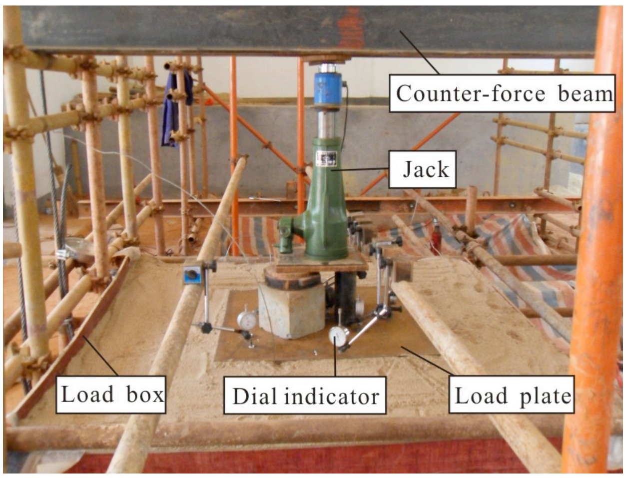


Fig. 4. Static test site

3.2 Pile formation and test process

After determining the test program, the pit was filled with 2.8 m thick soft soil with 25% water content. One week later, tapered wooden model piles (pile length L=1.2 m, diameter at pile top d1=10 cm, diameter at pile bottom d2=5 cm, average pile diameter d=7.5 cm, and pile interval 3d=22.5 cm) were pressed into the soil to form holes at designated positions. These holes were then filled with the cement soil mixture and were rammed layer by layer at a 90% compactness to form rammed cement soil tapered piles. The mixture contained 10% cement grade no. 325. Strain gauges were paved every 20 cm in the piles to measure the vertical stress of the piles. The formed pile profile is shown in Fig. 5.

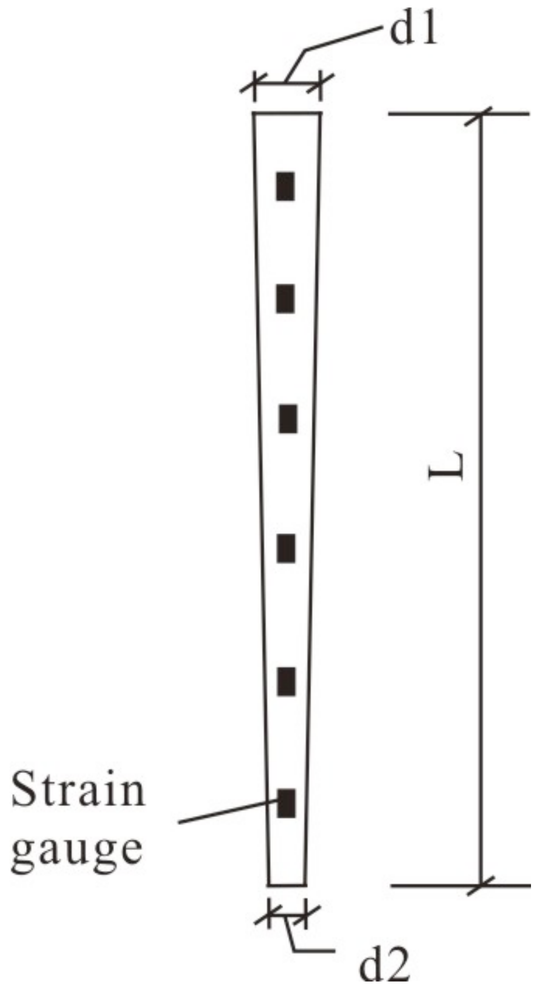


Fig. 5. Profile of test pile

In the next 28 d following the pile formation, an indoor conventional test was conducted on the main physical and mechanical parameters of the foundation soil. The test results are shown in Table 2.

The rammed cement soil test blocks were fabricated in the same way as the formation of the cement soil tapered pile. After 28 d, the unconfined compressive strength of the rammed cement soil was measured at 0.95 MPa. The deformation modulus of the rammed cement soil was measured at 81.3 MPa by using the test method proposed by Ye S. L. [20].

The cushions were paved 41 d after the pile formation. The gravel diameter in the cushion ranged between 10 mm and 20 mm. The compactness of gravel was 90% and the cushion thickness was 20 cm. Geogrid and geocell were paved in the middle of GGRC and GCRC, respectively. The model test used a two-way polypropylene geogrid. The related technical indexes are shown in Table 3, while the related technical indexes of the geocell are listed in Table 4.

After paving the cushions, a static test was performed according to the Chinese technical code for the ground treatment of buildings (2012). The load plate was square with a side length of B=0.65 m. The distance from the loading surface to the bottom of the pit was 3.0 m. To facilitate meter installation and reading, a load box was added on the cushion and used as the first level of load. The follow-up levels of load were applied by using a jack.

A dial indicator was used to observe the settlement, and a TXR-2030 strain type mini soil pressure gauge was used to measure the pressure at the pile top and the surface of the soil surrounding the piles.

Table 2. Physical and mechanical parameters of foundation soil

Unit weight ($kN \cdot m^{-3}$)	Water content (%)	Liquidity index	Plasticity index	Cohesive force (kPa)	Internal friction angle (°)	Characteristic bearing capacity (kPa)	Compression modulus (MPa)
18.04	30.5	0.40	21.7	9.4	8.3	56	3.4

Table 3. Technical indexes of geogrid

Mass per unit area ($g \cdot m^{-2}$)	Mesh size (mm)	Tensile strength ($kN \cdot m^{-1}$)		Elongation (%)	
		Longitudinal	Transverse	Longitudinal	Transverse
463	21×21	68.4	78.2	2.7	2.8

Table 4. Technical indexes of geocell

Weld spacing (mm)	Height (mm)	Tensile strength of geocell sheet(MPa)	Tensile strength of weld joint ($kN \cdot m^{-1}$)	Tensile strength of geocell group junction ($kN \cdot m^{-1}$)	
				Middle of junction	Edge of junction
200	50	≥23.0	≥100	≥200	≥120

4 Analysis of test results

4.1 Load-average settlement relation

The reading data of the pile and soil settlements obtained from the model test were used to illustrate the load-average settlement relation curves of the three models as shown in Fig. 6.

Fig. 6 shows that (1) the load-average settlement curves of all three models are slow deformation curves and the average settlement of different models is positively correlated with the load. (2) Under the same load, the average settlements of the three models are GC>GGRC>GCRC. (3) A slight difference is observed among the three models in terms of their average settlements during the early loading periods, and such difference increases along with the load. The gaps between GC and GGRC and that between GC and GCRC expand rapidly.

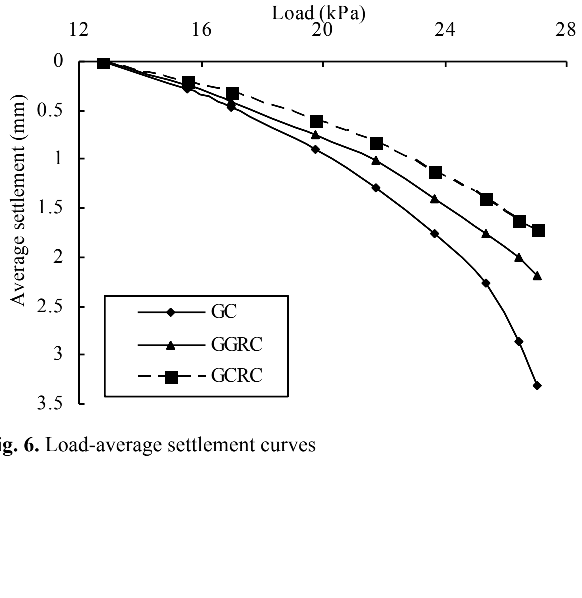


Fig. 6. Load-average settlement curves

According to the above analysis, the geosynthetic-reinforced gravel cushion can reduce the average settlement of the GRTPS composite foundation. GCRC is superior to GGRC in terms of settlement reduction.

4.2 Pile-soil average settlement difference

The reading data of the dial indicators were obtained from the model test to illustrate the pile-soil average settlement difference curves of the three models during the loading process as shown in Fig. 7.

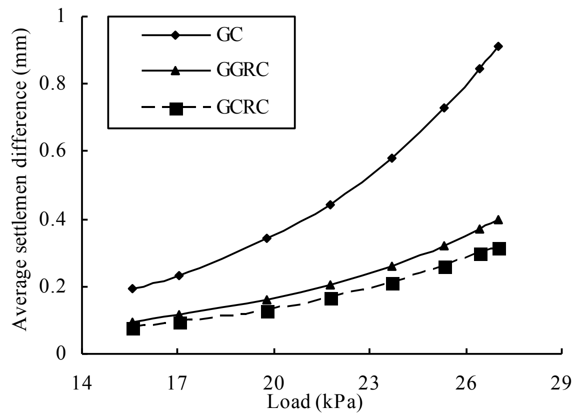


Fig. 7. Load-average settlement difference curves

Fig. 7 shows that (1) the pile-soil average settlement difference among the three models increases along with the load. The growth rates under differ cushion conditions are GC>GGRC>GCRC. (2) The pile–soil average settlement differences among these models intensify along with the increase in load. The growth rate under GC is higher than that under GGRC and GCRC. (3) Under different load tests, the pile–soil average settlement differences of GGRC and GCRC are 43.4% to 49.8% and 34.7% to 39.8% of that of GC, respectively.

In sum, the reinforced materials in the cushion can constrain the lateral displacement of gravel. Therefore, adding reinforced materials in the gravel cushion can increase the rigidity of the cushion and decrease the insertion quantity of the piles and the pile–soil settlement difference. The constraints of the geocell to gravel are stronger than those of the geogrid.

4.3 Average pile–soil stress ratio

The reading data of the micro soil pressure gauge at the pile top and the soil surface around piles were obtained during the model test to illustrate the average pile–soil stress ratio curves of the three models during the loading process (Fig. 8).

Fig. 8 shows that (1) the average pile–soil stress ratios of the three models gradually increase along with the load. However, the growth rate decreases along with increasing load, thereby suggesting that the load assumed by piles is positively related to the load yet the soil still assumes a certain proportion of the upper load. (2) Under the same load, the pile-soil stress ratios of the three models are GCRC>GGRC>GC. (3) Under the test load, the average pile–soil stress ratios of GGRC and GCRC are 1.47–1.88 and 1.77–2.08 times of that of GC.

In sum, the bearing performance of the pile is continuously enhanced along with increasing amount of upper loads assumed by the pile body. Compared with GC, both GGRC and GCRC, especially the latter, can increase the pile–soil stress ratio more effectively.

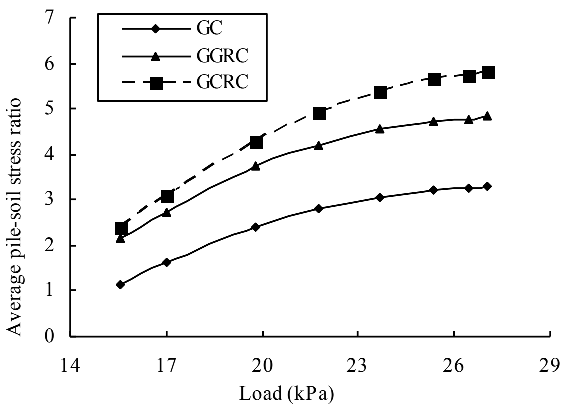


Fig. 8. Load-average pile-soil stress ratio curves

4.4 Pile top stress

The reading data of the mini soil pressure gauges of the corner pile, edge pile, and central pile tops were obtained from the model test to illustrate the pile top stress–load relation curves at different positions in the three models as shown in Figs. 9 to 11.

Figs. 9 to 11 indicate that (1) under the same load, the pile top stresses in the three models are GCRC>GGRC>GC. The difference in pile top stresses intensifies along with increasing load. (2) In the same model, the piles at different positions of the foundation assume different vertical loads. The corner pile has the highest pile top stress, followed by the edge pile and the central pile.

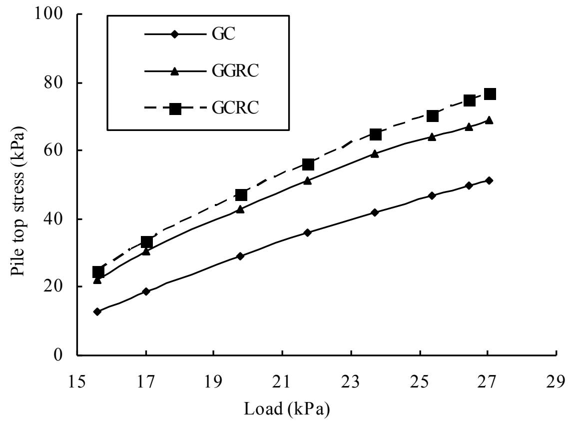


Fig. 9. Load-pile top stress curves of central pile

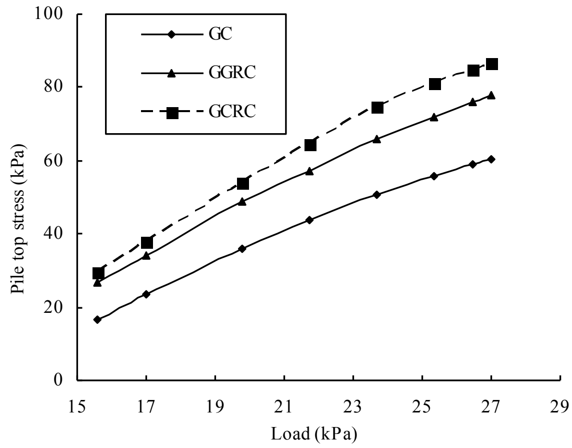


Fig. 10. Load-pile top stress curves of edge pile

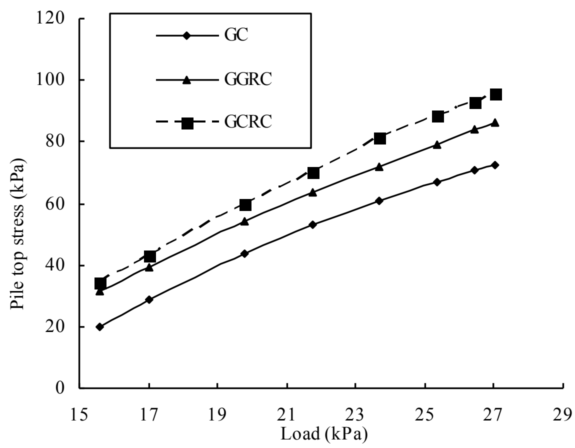


Fig. 11. Load-pile top stress curves of corner pile

The ratios between the central and average pile top stresses in the three models were calculated under different levels of the test load. The calculation ranges of the ratio under different levels of load are 0.776–0.823 for GC, 0.835–0.887 for GGRC, and 0.842–0.894 for GCRC. This ratio is positively related with the load.

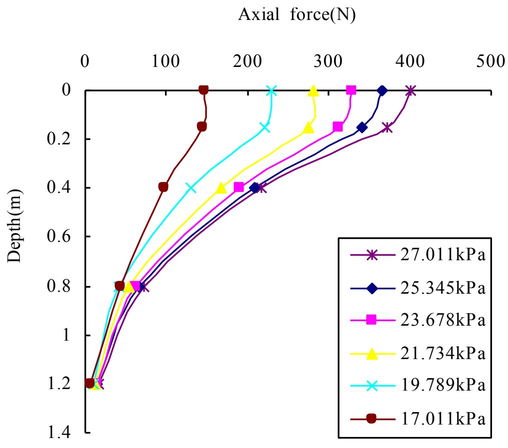
According to the above analysis, GCRC and GGRC are superior to GC in motivating the bearing capacities of piles in the GRTPS composite foundation, relieving the stress concentration of some piles, and improving the bearing performances of piles at different positions. Moreover, GCRC outperforms GGRC in adjusting pile stress.

4.5 Axial force transmission features of the pile body

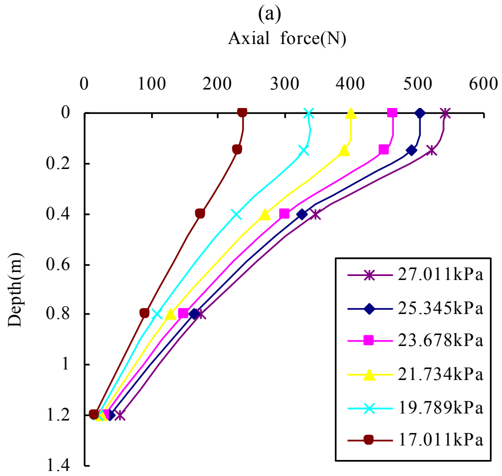
The variation curves of the axial force of the pile body with depth in the three models were drawn based on the reading data of mini soil pressure gauges at the pile top and body. Given that the pile stress at different positions changes along with load in the same model, only the central pile was analyzed in this study. The results are shown in Fig. 12.

Fig. 12 shows that (1) the axial force of the pile body attenuates continuously along the depth direction, while the attenuation rate increases continuously along with the total load. (2) Under the same load, the axial forces of the pile body in the three models are GCRC>GGRC>GC. (3) The ratio between the axial force at the pile end and that at the pile top is very small, and most pile stresses are transmitted to the soil around the piles via pile–soil interaction. (4) No negative friction force was observed in the different piles of the three models. However, a negative friction region is observed below the uniform section pile top.

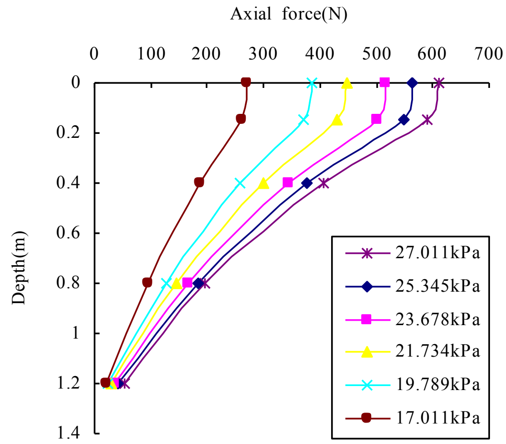
In sum, (1) the rammed cement soil tapered pile is a relatively typical friction pile. Under a certain load, the axial force at the pile top is transmitted to the soil around the piles via pile–soil interaction, which mainly occurs at the upper position of the pile. A small axial force is observed at the pile bottom. (2) The reinforced cushion can increase the load proportion of the pile body and motivate the pile–soil interaction at the middle and upper positions. GCRC outperforms GGRC in increasing the axial force of the pile body. (3) The axial force decreases continuously from the top to bottom of the tapered pile. Without the negative friction region, the tapered pile is better than the uniform section piles, increases the bearing capacity, and reduces the settlement of the composite foundation.



(a)



(b)



(c)

Fig. 12. Axial force along pile body. (a) Model GC. (b) Model GGRC. (c) Model GCRC

5. Conclusions

To discuss the effects of reinforcement type and pile shape on the performance of the GRPS composite foundation, GRTPS, is proposed in this study as a new form of the GRPS composite foundation. A static test of three GRTPS composite foundation models with nine piles is also performed. The settlement of the composite foundation, the pile–soil stress ratio, the pile top stress, and the axial force transmission features of the pile body under three cushion conditions are analyzed. The following conclusions are obtained:

(1) Compared with GC, GGRC and GCRC can effectively increase the rigidity of the cushion and reduce the insertion quantity of piles. Such advantage is attributed to the displacement and confinement of reinforced materials to gravel. These models can also reduce the average settlement of the proposed composite foundation and the pile–soil settlement difference.

(2) Pile–soil stress ratio is sensitive to upper load and cushion rigidity. The reinforced materials in cushion can strengthen the cushion adjustment of the pile and soil stresses as well as increase the pile–soil stress ratio, thereby effectively increasing the bearing capacity of the pile bodies. Moreover, the reinforced materials can homogenize the foundation base stress and make full use of the bearing capacities of the piles at different positions, thereby relieving the stress concentration at some piles.

(3) By contrasting the settlement and stress distribution features in the three models, GCRC shows the best performance, followed by GGRC and GC. Therefore, reinforced cushion can effectively improve the performance of the composite foundation, especially GCRC.

(4) The axial force on the tapered piles is analyzed, and the results indicate that the pile–soil interaction mainly occurs at the upper position of the piles and that the axial force at the pile bottom is very small. This pile shape is a typical friction pile. The axial force of the tapered pile decreases continuously from top to bottom and no negative friction region is observed. The tapered pile is better than the uniform section ones and is conducive in increasing the bearing capacity and reducing the settlement of the composite foundation.

The proposed GRTPS composite foundation integrates the advantages of the GRPS composite foundation and tapered pile. Therefore, GRTPS outperforms the traditional GRPS composite foundation with uniform section piles. The model test results can provide technical references for the design and application of the GRTPS composite foundation. However, given that the model test in this study uses a small vertical load, the performance of the proposed composite foundation under actual engineering load warrants further study

References

1. Liu, H. L., Ng, C. W. W., Fei, K. , "Performance of a geogrid-reinforced and pile-supported highway embankment over soft clay: case study". *Journal of Geotechnical & Geoenvironmental Engineering,* 133(12),2007,pp.1483-1493.
2. Jones, C. J. F. P., Lawson, C. R., Ayres, D. J., "Geotextile reinforced piled embankments". *Proc. 4th int. conf. on Getextiles*, Rotterdam: Balkema, 1990,pp.155-160.
3. Watts, D. J., Strogatz, S. H., "Collective dynamics of "small-world" networks". *Nature*, 393(6684), 1998, pp.440-442.
4. Phanikumar, B. R. , "Influence of Geogrid Reinforcement on Pullout Response of Granular Pile-Anchors (GPAs) in Expansive Soils". *Indian Geotechnical Journal*, 46(4), 2016,pp.437-444.
5. Choi, C. L., Lee, K. W., Kim, E. H., Jung, J. W. , " A Study on the Pile Material Suited for Pile Supported Embankment Reinforced by Geosynthetics". *Journal of the Korean Geosynthetic Society*, 15(1), 2016,pp.21-35.
6. Ariyarathne, P., Liyanapathirana, D. S., Leo, C. J. , "Comparison of different two-dimensional idealizations for a geosynthetic-reinforced pile-supported embankment". *International Journal of Geomechanics*, 13(6), 2013,pp.754-768.
7. Khabbazian, Majid, V. N. Kaliakin, and C. L. Meehan. , "Column Supported Embankments with Geosynthetic Encased Columns: Validity of the Unit Cell Concept". *Geotechnical & Geological Engineering* 33(3),2015,pp.425-442.
8. Cui, W., Yan, S. W. , " Centrifugal model test of an embankment on soft clay reinforced with geogrid and supported by soil-cement piles". *Rock & Soil Mechanics*, 29(5), 2008,pp.1315-1319.
9. Xing, H., Zhang, Z., Liu, H., Wei, H., " Large-scale tests of pile-supported earth platform with and without geogrid". *Geotextiles & Geomembranes*, 42(6),2014,pp. 586-598.
10. Emersleben, A., Meyer, N., " The Use of Vertical Columns in Combination with Geocell Stabilized Load Transfer Platforms for the Construction of Roadways over Soft Soils". *Geocongress*, 2014,pp.1302-1309.
11. Dash, S. K., Bora, M. C., "Improved performance of soft clay foundations using stone columns and geocell-sand mattress". *Geotextiles and Geomembranes*, 41,2013,pp. 26-35.
12. Deb, K., Mohapatra, S. R., "Analysis of stone column-supported geosynthetic-reinforced embankments". *Applied Mathematical Modelling*,37(5), 2013,pp.2943-2960.
13. Hasan, M., Samadhiya, N. K., "Performance of geosynthetic-reinforced granular piles in soft clays: Model tests and numerical analysis". *Computers and Geotechnics*, 87,2017,pp. 178-187.
14. Gu, M., Han, J., Zhao, M., "Three-dimensional DEM analysis of single geogrid-encased stone columns under unconfined compression: a parametric study". *Acta Geotechnica*,(2010), 2017,pp.1-14.
15. Rowe, R. K., Liu, K. W., "Three-dimensional finite element modelling of a full-scale geosynthetic-reinforced, pile-supported embankment". *Canadian Geotechnical Journal*, 52(12),2015,pp. 2041-2054.
16. Guo, Z. X., Liu, J., Qi, Y. S. , "Cushion impact on bearing capacity exerting degree of soil between piles for rammed cement-soil pile composite foundation". *Advanced Materials Research*, 2011,pp.250-253, 1498-1502.
17. Zhang, C., Jiang, G., Liu, X., Wang, Z., " Deformation performance of cement-fly ash-gravel pile-supported embankments over silty clay of medium compressibility: a case study". *Arabian Journal of Geosciences*, 8(7), 2015,pp.4495-4507.
18. Han, J., Bhandari, A., Wang, F., "Dem analysis of stresses and deformations of geogrid-reinforced embankments over piles". *International Journal of Geomechanics*, 12(4),2012,pp. 340-350.
19. Han, J., Gabr, M. A., "Numerical Analysis of Geosynthetic-Reinforced and Pile-Supported Earth Platforms over Soft Soil". *ASCE, J. of Geotechnical and Geoenvironmental Engineering*, 128(1),2002,pp.44-53.
20. Matsumiya, H., Ishihama, Y., Taenaka, S., "A study on the bearing capacity of steel pipe piles with tapered tips". *Japanese Geotechnical Society Special Publication*, 1(6), 2015,pp.47-52.
21. Fahmy, A., Ei, N., M, H., "Axial and lateral performance of spun-cast ductile iron helical tapered piles in clay". *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 2017, doi: 10.1680/jgeen.16.00116.
22. He, J., Liu, J., Zhang, K. N., Wu, Y. P., Cao, Z., " Experimental study of bearing behaviour of composite foundation with rammed soil-cement tapered piles". *Journal of Central South University*, 31(7),2012,pp. 1506-1512.
23. Liu J, He J, Min C. Q., "Study of the rational wedge angle range in a composite foundation with rammed soil-cement tapered piles". *China Civil Engineering Journal*, 43(6),2010,pp. 122-127.
24. Li, Y. C., Peng, Z. B., He, J., "Comparative experimental study on working behavior of rammed cement-soil pile-net composite foundation". *Journal of Central South University*, 45(10),2014,pp. 3531-3535.
25. Ye, S. L., "*Handbook on practice of foundation treatment*". Beijing: China Architecture and Building Press, China, 1988, pp.468-469.