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Research Article

Stress Analysis of CFG Pile Composite Foundation in Consolidating Saturated Mine Tailings Dam

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Cement fly-ash gravel (CFG) pile is a widely used ground reinforcement technique. This paper aims to address the mechanical characteristics of CFG composite foundation in consolidating saturated mine tailings (MTs) dam. The field static load tests were employed to explore the bearing capacity of the CFG composite foundation, and finite element (FE) models in three dimensions validated through comparison with experimental results were used to discuss the pile-soil stress distribution and pile-soil stress ratio of the CFG composite foundation. The results indicate that the distribution of earth pressure and pile stress is relatively homogeneous and stable over depth and load, while the development of CFG composite foundation bearing capacity is insufficient, in which the developed bearing capacity of CFG piles is less than 50% of its characteristic value. Additionally, compared with the laboratory model test results, the pile-soil stress ratio decreases with the increasing of the load in FEM results proved to better conform to the actual engineering conditions. Furthermore, the deformation modulus and thickness of cushion exert significant influence on pile-soil stress ratio and integral bearing capacity of CFG composite foundation.

1. Introduction

Recently, as a common foundation type, composite foundation reinforcement technology has been implemented in varied engineering fields in China, such as building foundation engineering and subgrade engineering [1–5]. Simultaneously, CFG pile composite foundation has been applied in various foundation treatments engineering due to its virtue of wide application scope, quick construction, and low engineering cost [6–8]. In highway engineering, CFG pile composite foundation is commonly used in flexible foundation reinforcement; however, CFG pile composite foundation under flexible foundation will bear incomplete development of pile bearing capacity and insufficient bearing capacity of the composite foundation [9–12]. Thus, it is important to study the mechanical behaviors of composite foundation, such as load-transferring mechanism, pile-soil load sharing ratio, and pile-soil stress ratio, which can improve the bearing capacity of composite foundation.

Over the recent years, a substantial amount of studies including analytical, experimental, and numerical approaches have been conducted on CFG pile composite foundation under flexible foundation to address its mechanical behaviors. In terms of theoretical analysis, for instance, Wang et al. [13] studied the determination approach of bearing capacity of CFG pile composite foundation under railway flexible foundation. Dan et al. [14] used simple and convergent approach to deduce the computational formula for pile-soil stress ratio of CFG pile composite foundation. There are many experimental studies: for example, Han and Ren et al. [15, 16] explored the pile-soil stress ratio and pile-soil load sharing ratio through *in situ* test. Zeng et al. [17] discussed the stress distribution and friction distribution at the round of pile of CFG composite foundation in high speed railway. Ding et al. [18] researched the bearing capacity characteristics of large-size oil tank group through *in situ* test. Xue et al. [19] investigated the effects of different influence factors on the pile-soil stress ratio based on the laboratory model test.

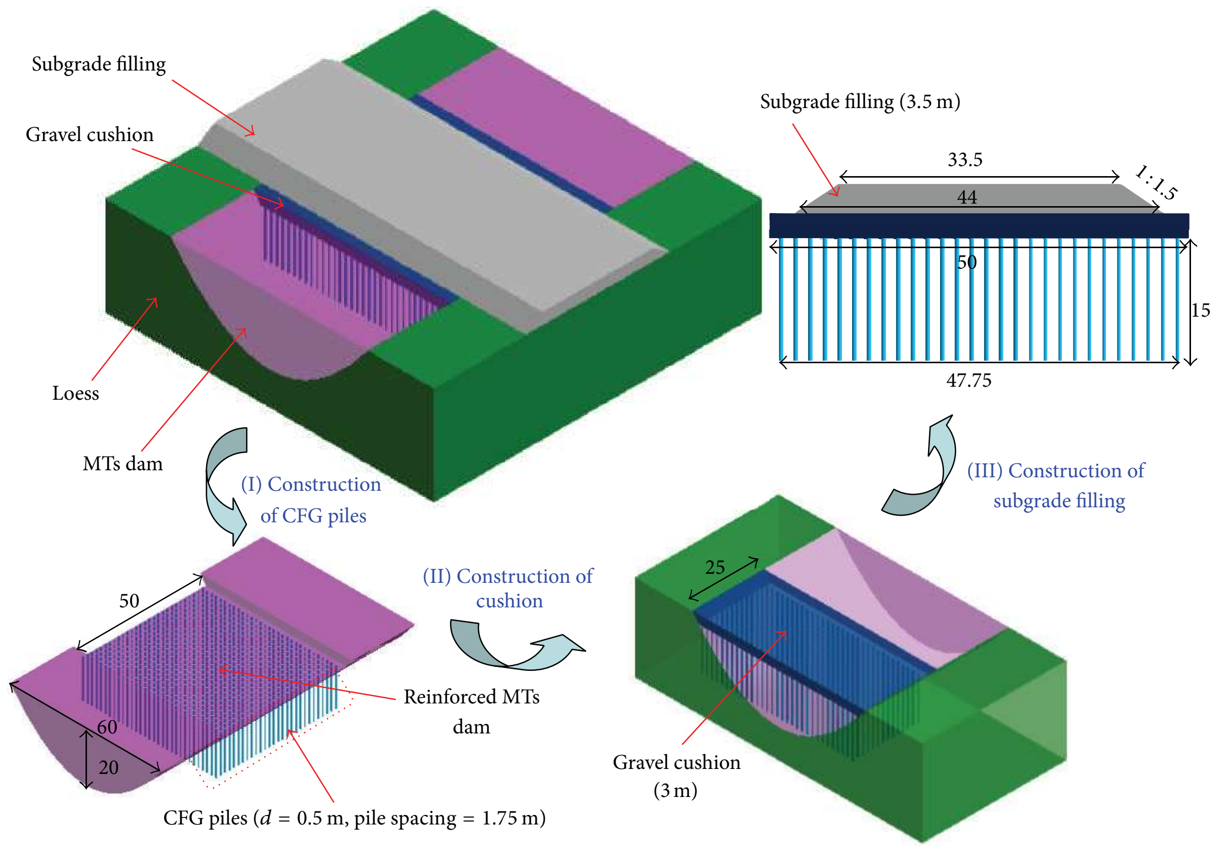


Figure 1: Diagram of CFG pile composite foundation (unit: m).

Numerical investigation has also been launched to study the CFG composite foundation: for instance, Wang et al. [20] conducted numerical analysis on the joint function mechanism of pile and soil and analyzed the stress distribution. Huang and Zhou [21, 22] studied the influence of different cushion parameters on pile-soil stress ratio based on FEM. The aforementioned research greatly promoted the development of CFG pile composite foundation. However, the theoretical studies and field tests on the reinforcement of saturated MTs dam are considered as a deficiency with the use of CFG pile composite foundation [23, 24]. Hence, this paper conducts a detailed analysis on the mechanical behaviors of CFG pile composite foundation in the consolidation of saturated MTs dam under embankment flexible load of an expressway.

2. Field Test of CFG Pile Composite Foundation

2.1. Engineering Overview. Shanxi Wangcheng expressway links Wangzhuangbao and Fanshi. The route design standard is bidirectional with six lanes; the design speed is 100 km/h; the subgrade width is 33.5 m, and the separate subgrade width is 16.75 m. The high demand construction quality is proposed to avoid the uncontrolled deformation.

The whole route has nine sections drilling through or passing near saturated MTs dam area, in which Yuehong magnetic plant saturated MTs dam (a "V"-shaped MTs dam, see Figure 1) from K55 + 650 to K55 + 770 was reinforced by CFG pile composite foundation. The CFG pile length is 15 m and the pile diameter is 0.5 m with the pile spacing of 1.75 m, and the piles are distributed in square shape. Besides, the bearing capacity characteristic values were provided by the design department in the document of construction drawing according to the geological survey report and relevant criterion [26–28], in which bearing capacity characteristic value of composite foundation should not be less than 280 kPa and that of single pile should not be less than 400 kN, and the limit value of bearing capacity of soil among piles should not be less than 200 kPa. However, due to the high quality requirements of the project, the composite foundation field static load tests, including bearing capacity test of single pile composite foundation, bearing capacity test of single pile, and bearing capacity test of soil among piles, were imperative and were thus performed to explore the bearing capacity characteristics of CFG pile composite foundation. The diagram of CFG pile composite foundation is presented in Figure 1. Figure 2 shows the *in situ* conditions in various stages of construction.

2.2. Results of Field Test

2.2.1. Bearing Capacity of Composite Foundation. Static load test is presented in Figure 3. In this test, fourteen groups of CFG piles were selected to investigate the bearing capacity of

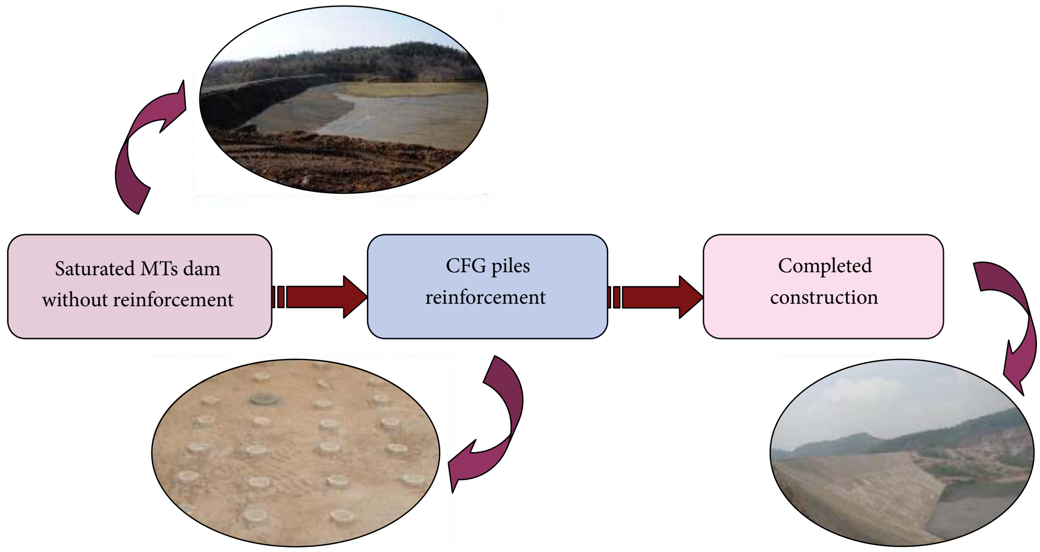


Figure 2: *In situ* diagrams in various construction stages.

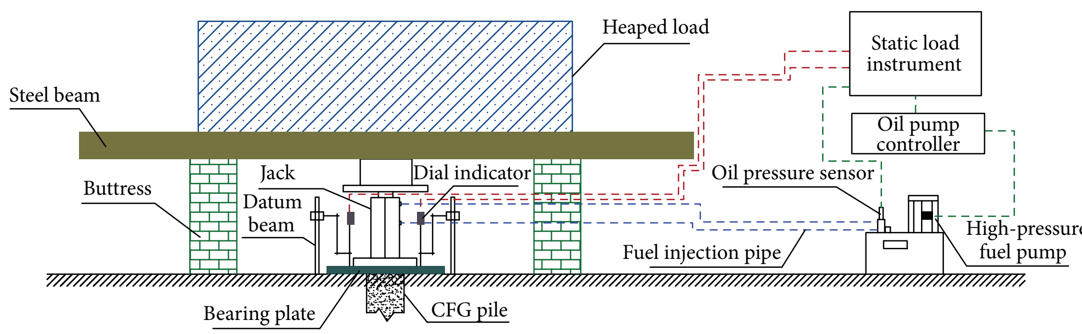


Figure 3: Diagram of static load test of composite foundation.

the composite foundation, and two of fourteen groups were chosen for the analysis in this study [29]. The bearing plate for the test was a square steel plate at a size of 1.75 × 1.75 m; loading devices were hydraulic jack, and four dial indicators were used to measure settlement. Loading increased step by step, and the loading of each step was 1/10 of total loading (2 times of designed bearing capacity); additionally, loading of the first step was two times of step loading. When the loading increased to the maximum value of 560 kPa, there was no obvious settlement; hence, loading was stopped and unloading subsequently. The *P*-*S* curve (Figure 4) illustrates that the settlement curve of CFG piles composite foundation is stable and changes slowly. According to the "JGJ79-2012, Technical Code for Treatment of Buildings" [30], the bearing capacity characteristic value of composite foundation can be determined by relative settlement approach. When the CFG piles are located at foundation of thick medium sand, the parameter $S/b = 0.008$ (where "S" is settlement and "b" represents the width of bearing plate) can be obtained. The width of bearing plate in this test is $b = 1.75$ m, and the corresponding settlement is $S = 14$ mm in Figure 4; hence, the bearing capacity characteristic value ($f_{spk} = 526$ kPa) of CFG composite foundation can be determined based on the loading towards $S = 14$ mm. Obviously, the characteristic value of bearing capacity is much more than the designed value (280 kPa). Obviously, the design is too conservative, which will result in the increased technical inputs, higher cost of construction, and other negative results [31].

2.2.2. Bearing Capacity of Single Pile. Three groups of CFG piles were selected to carry out the single pile vertical static load test. Hydraulic jack was employed to loading step by step, and steel beam was used as antiforce device. The loading of each step was 1/10 of the predicted maximum load (1500 kN). The settlement of the first nine steps was stable, while sharp settlement, sharp oil pressure fall, and pile damage occurred when loading tenth. This indicates that CFG pile is at ultimate limit state when the load reaches 1500 kN. According to the "JGJ94-2008, Technical Code for Building Pile Foundations" [28] ($R_a = Q_{uk}/K$, where Q_{uk} is single pile ultimate bearing capacity of 1350 kPa in this test and K is safety factor of 2), the bearing capacity characteristic value of single pile is

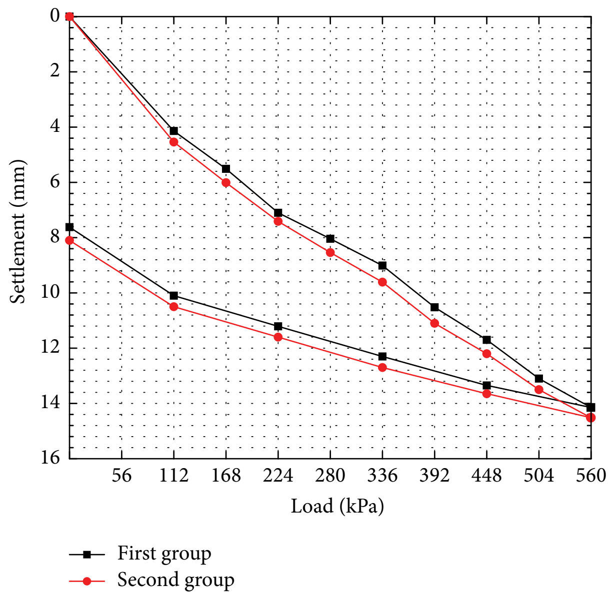


Figure 4: *P-S* curve of single pile CFG composite foundation.

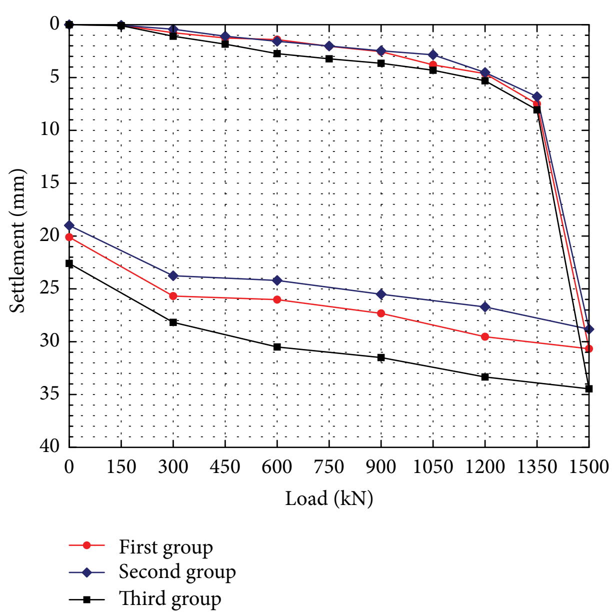


Figure 5: The *Q-S* curve of single CFG pile.

R_a = 675 kN (>400 kN). The design requirements are satisfied. The *Q-S* curve of single CFG pile is plotted in Figure 5.

2.2.3. Bearing Capacity of Soil among Piles. Shallow plate load test was conducted to the three groups of the soil among piles. The bearing plate used in this test was a square steel plate at a size of 0.8 × 0.8 m. No more than 20 mm thick coarse sand was laid under the bearing plate. Load was applied through slow loading method, and the loading of each step was 20 kPa which was 1/10 of total loading (2 times of designed bearing capacity). The first loading was two times of step loading, the maximum load was 220 kPa, and load was applied by 50 t oil jack. Four dial indicators were used to measure the settlement, and the field test diagram is shown in Figure 6. When the load reached 220 kPa, settlement rate of soil among piles was stable, and no sharp drop occurred. Since this load had exceeded the limit value in design (200 kPa), loading was stopped and unloading subsequently. The *P-S* curve of soil among piles (Figure 7) depicts that the settlement is stable and the ultimate load of soil among piles satisfies the design. However, due to the different bearing capacity of soil between piles at the test sites, a relatively large settlement happens in the second group compared with that in the first and third groups. Furthermore, since settlement sharp drop does not occur and settlement change is stable, the ultimate value of bearing capacity of soil among piles is above the maximum loading force of 220 kPa. According to "GB50007-2002, Code for Design of Building Foundation" [32], the bearing capacity characteristic value of soil among piles is f_{sk} = 110 kPa after reinforcement.

Figure 6: Field diagram of shallow flat plate static load test.

3. Numerical Analysis of CFG Pile Composite Foundation

3.1. Numerical Modeling. In this paper, MIDAS-GTS (Geotechnical and Tunnel Analysis System) software [33], which was generally employed for geotechnical analysis, was used to develop the FE analysis. MIDAS-GTS software is FEM analysis software which is developed by the MIDAS Information Technology Co., Ltd., based on the visual C++ and Windows. MIDAS-GTS software can provide the users with various analysis types, which includes nonlinear elastic plastic and construction stage analysis, unsteady seepage and stress-seepage coupling analysis, consolidation analysis, and earthquake and dynamic analysis. In this software, the graphic user interface (GUI) environment is supported during the modeling process, and the complex geometric model can be constructed in a visual environment.

To investigate the pile-soil stress and stress ratio of CFG pile composite foundation under vertical load, a three-dimensional FE modeling at a size of 14 × 10 × 31.5 m is constructed, in which displacements are restricted at the model boundaries in the normal direction to their respective planes. In the FE modeling (Figure 8(a)), the saturated MTs and loess layers are at a depth of 25 m in total; gravel cushion is 3 m and subgrade filling is 3.5 m. Figure 8(b)

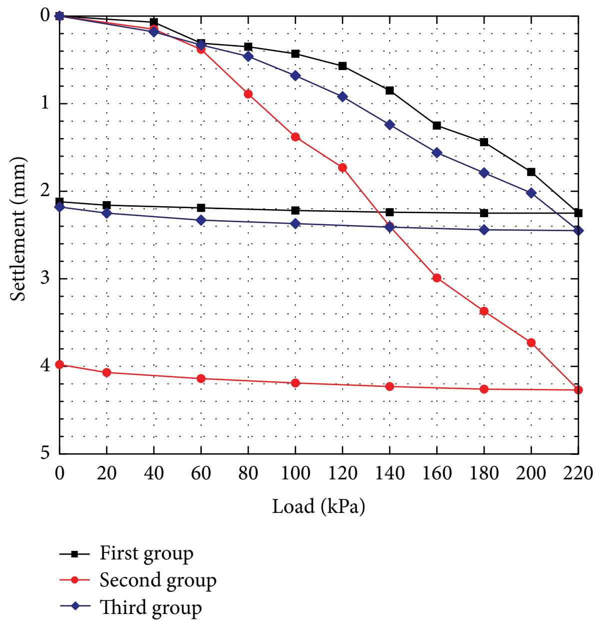
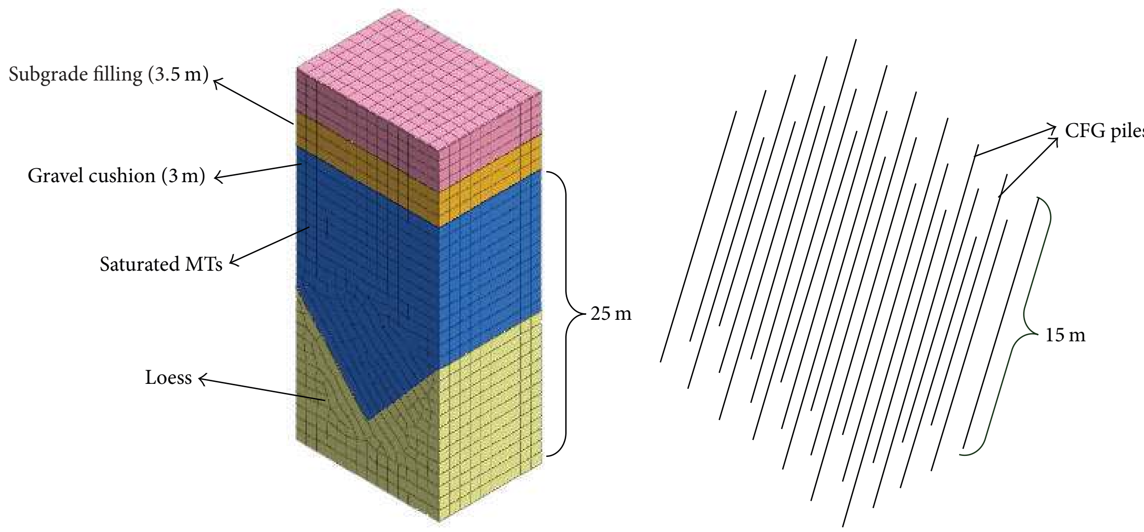


Figure 7: The *P*-*S* curve of soil among piles.

shows the total simulated 35 CFG piles, in which the length of CFG pile is 15 m, pile diameter is 0.5 m, and pile spacing is 1.75 m. On the other hand, the interface of all soil layers was simplified to be plane, and the soil strata in this modeling were modeled as elastoplastic materials following a Mohr-Coulomb criterion [34, 35], while the piles were assumed to be linearly elastic material. Besides, contact element was constructed between pile and soil. Analyses were performed for loading intensities of 50, 100, and 150 kPa. Furthermore, in order to study the influence of cushion parameters on pile-soil stress, different cushion thickness and deformation modulus were set to analyze pile-soil stress ratio. Soil strata parameters in this study were derived from field tests [25], and the CFG piles input parameters were typical values [21]. Modulus of deformation was employed for soil, and modulus of elasticity was used for the CFG piles. Consolidation behavior was not considered. The material properties of the various components are summarized in Table 1. Figure 8 shows integral modeling of CFG composite foundation.

3.2. Pile Stress Analysis. The FEM results of CFG piles stress and axial force distribution under the loading of 150 kPa are shown in Figure 9, in which stress of central pile, intermediate pile, side pile, and corner pile (cf. Figure 10) were selected for analysis. The variations of the CFG piles with depth and pile position are presented in Figures 11 and 12, respectively. Accordingly, the stress of single CFG pile increases and then decreases with depth increasing and the stress on pile top and pile bottom is relatively small (Figure 11). Specifically, the stress tends to increase rapidly near the top of the piles and decrease rapidly at the bottom but presents a relatively small increment at the middle of the piles. In addition, the maximum value is near pile bottom, and the position of maximum pile stress gradually moves up when the distance to the central pile increases (Figure 9). Additionally, compared with other piles, the stress of central pile is comparatively small under the same conditions, while corner pile stress changes greatly and has the maximum stress of about 1102 kPa (Figure 11). On the other hand, as can be seen in Figure 12, the analogous stress of CFG piles is displayed at the same depth. Generally, the stress of CFG piles is uniform and stable among depth and position. However, compared to the bearing capacity characteristic value of single pile obtained from field test, it is evident that the bearing capacity utilization of CFG piles rate is less than 50%. As reported in [21], the utilization rate of bearing capacity of CFG piles only accounts for 35.3% of the ultimate bearing capacity under flexible foundation. The foregoing analysis indicates that it is difficult to make full use of the bearing capacity of CFG piles in composite foundation under flexible foundation.

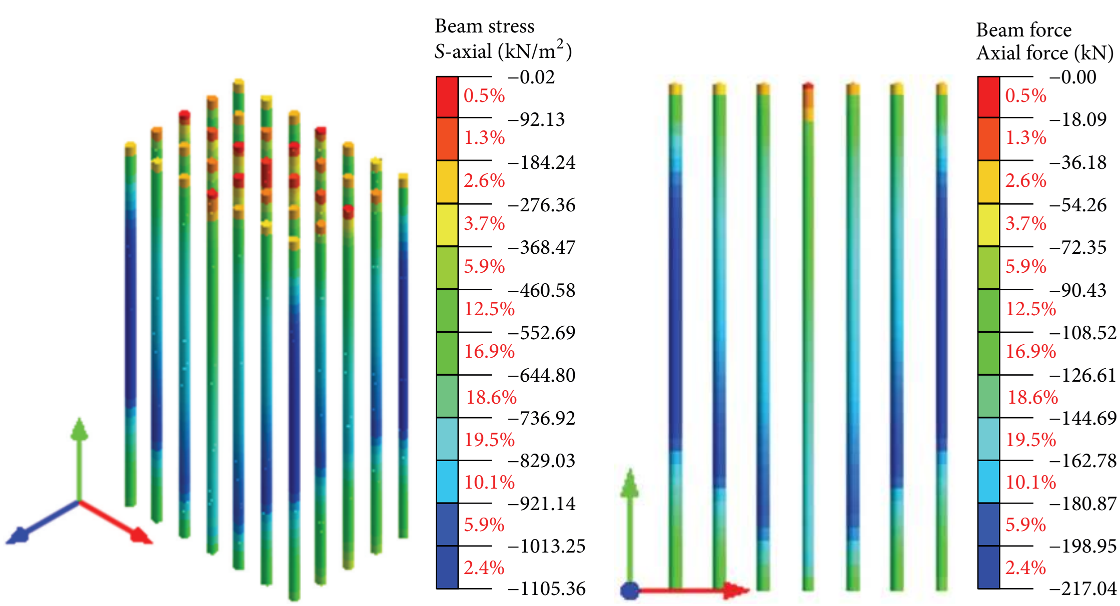
3.3. Earth Pressure Analysis. The FEM results of various soil layers pressure of 150 kPa load are shown in Figure 13. The isoclines distribution in FEM results evince that the earth pressure of various soil layers is consistent and stable. Therefore, the earth pressure of the different soil layers near the central pile was selected to analyze the variation of earth pressure. The earth pressure distribution is illustrated in Figure 14. The results demonstrate that, under the different loads, the earth pressure in saturated MTs area reinforced by CFG piles shows an approximate straight-line increase with the increase of depth, and the increasing range tends to reduce with the increase of depth. Furthermore, the earth pressure in reinforced saturated MTs area causes a relatively small change during the three times loading (i.e., 50, 100, and 150 kPa), and the average value of that is 128, 139, and 165 kPa, respectively, which is smallest among the various soil layers. Hence, it is apparent that the CFG piles in saturated MTs layer have shared a certain load and obtained a good reinforcement effect. At the gravel cushion and subgrade filling layers, the soil pressure builds up with the depth at a relatively stable increasing range about 10 kPa. However, the earth pressure decreases with depth at the depth of 0.5 m to the pile top, which is because of the penetration of piles to the cushion, that is, a part of the load has been transferred to the CFG piles. Besides, at the MTs and loess layers which locate below the bottom of pile, earth pressure builds up greatly with the increase of depth compared with the reinforced MTs layer, and the increase range reaches up to around 50 kPa with the load increasing. Overall, the earth pressure of the different soil layers is stable and consistent with the change of depth and load. On the other hand, the average increasing range of earth pressure, which occurs at soil between piles during the loading for three times, is stable at 6 kPa, 11 kPa, and 26 kPa, respectively. This means that the soil between piles carries much more loads at the later period of loading, which is consistent with the results reported in [36–39]. According to the FEM results in this paper, the load sharing ratio of pile and soil is only 23%: that is, the soil among piles bears most of the loads, and the piles fail to develop their bearing capacity sufficiently. In the previous research, it is discovered that the effect of changing CFG pile parameters to improve the



(a) Integral modeling

(b) CFG piles element

Figure 8: FE modeling of composite foundation and pile element.



(a) CFG piles stress

(b) CFG piles axial force

Figure 9: FEM results of CFG piles stress and axial force under the loading of 150 kPa.

Table 1: Geotechnical properties of CFG pile and soil layers [25].

Number	Material types	Modulus/MPa	Poisson's ratio	Soil unit weight/(kN/m^3)	Cohesion/kPa	Angle of internal friction/(°)
1	CFG pile	1600	0.25	21.5	900	35
2	Saturated MTs	2	0.32	18.7	7	40
3	Loess	40	0.25	20	35	45
4	Gravel cushion	140	0.16	20	0	36
5	Subgrade filling	100	0.2	19	15	20

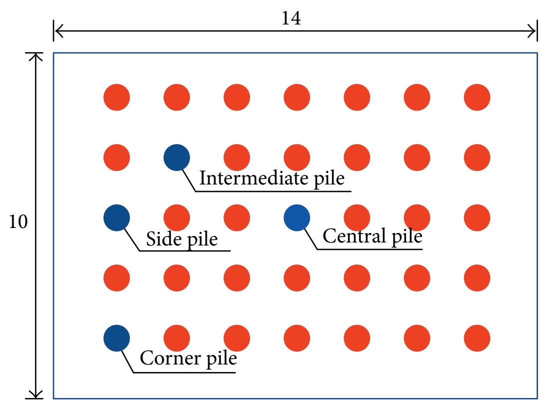


Figure 10: Distribution of CFG piles (unit: m).

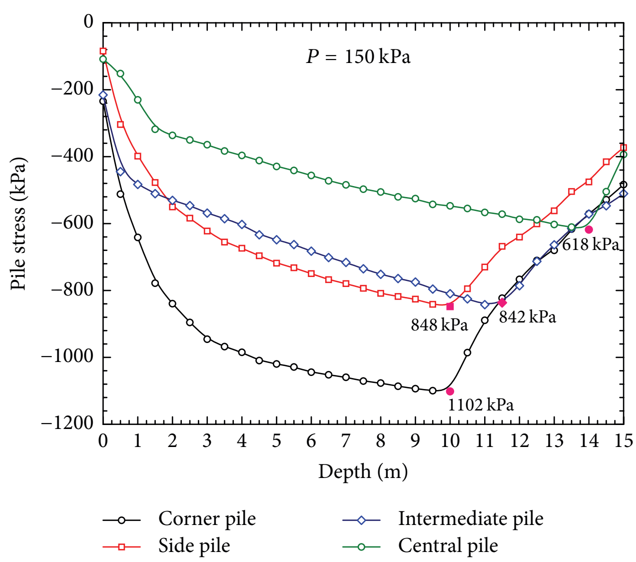


Figure 11: Distribution of the CFG piles stress with depth.

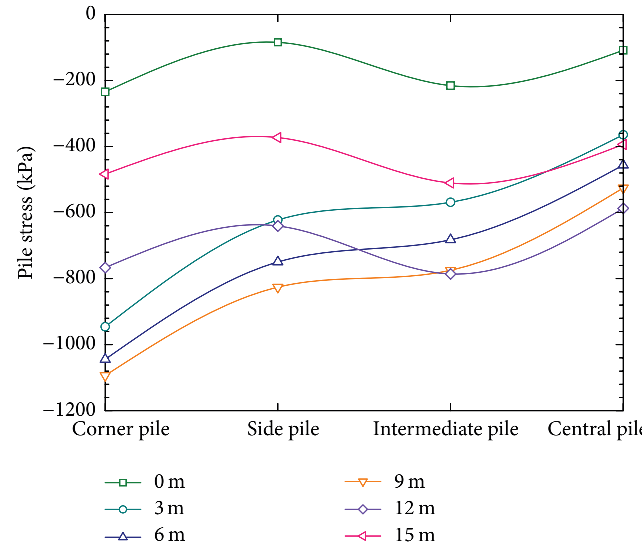


Figure 12: Distribution of the CFG piles stress with pile positions.

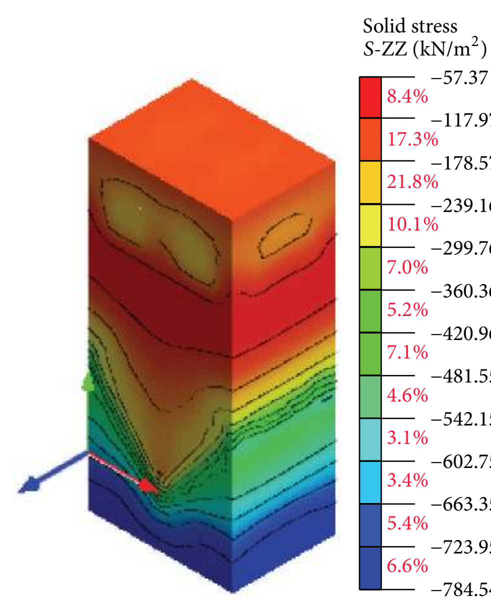


Figure 13: FEM results of earth pressure under the loading of 150 kPa.

bearing capacity of composite foundation is not significant under flexible foundation [40–42]. However, improving the parameters of soft soil foundation and enhancing the material properties of soft soil foundation can improve the bearing capacity of composite foundation effectively. In addition, altering the connecting type of pile-cushion system will also enhance bearing capacity of composite foundation [43].

4. Comparison of the Results in Laboratory Model Test and FEM on Pile-Soil Stress Ratio

Based on the saturated MTs dam at K55 + 650–K55 + 770 sections of Wangzhuangbu-Fanshi Expressway in Shanxi, China, Xing [25] had launched laboratory model test (the model trough is at a size of 2 × 2 × 2 m) on the CFG pile composite foundation with a geometric similarity ratio α_l of 10. In the laboratory model test, five different test areas were selected to study the pile-soil stress ratio of composite foundation (cf. Figure 15). The accumulation load method was used for loading of three times, and the loads were converted based on *in situ* loads according to the similarity ratio in the model test. Figure 16 shows some of the diagrams in the model test construction. The results of pile-soil stress ratio in laboratory test are compared with that in FEM, which is shown in Figure 17.

In the laboratory model test (Figure 17), the pile-soil stress ratio increases with the increase of load and the average value of stress ratio in different test areas for three times loading is 2.0, 2.1, and 3.7, respectively. It is apparent that the increasing range of pile-soil stress ratio in later period of loading is larger than that in earlier period, which indicates that the load shared by the pile increases gradually with the increase of loading, and the bearing capacity of pile

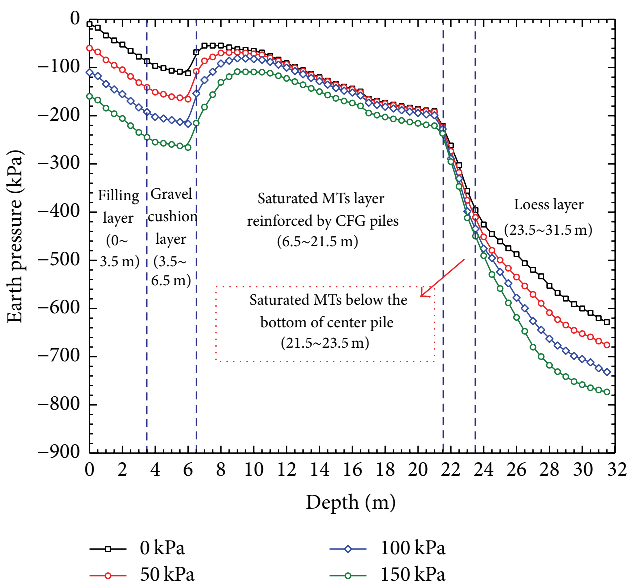


Figure 14: Distribution of the earth pressure with depth.

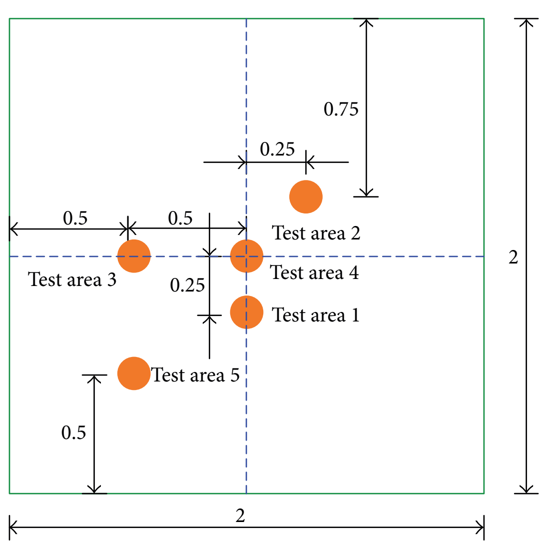


Figure 15: Diagram of CFG pile model test area (unit: m).

is gradually developed. While in the FEM results, pile-soil stress ratio gradually reduces with the increase of load, and the average value of stress ratio in the various test areas for three times loading is 3.6, 3.1, and 2.3, respectively. The pile-soil stress ratio is much larger at the earlier period of loading, while it tends to decrease with the increase of loading, which has a good agreement with the results reported in [36, 37]. Furthermore, field measurement result of the pile-soil stress ratio is 1.1~1.7, 1.1~1.6, and 1.18~2.26, respectively [44–46], and the recommended value in "JTJ 017-96, technical specifications for design construction of highway embankment on soft ground" is 3~6 [47]. Thus, the pile-soil stress ratio in laboratory model test and FEM are close to the actual conditions. On the other hand, the pile-soil stress ratio is variable among different test areas with a small change in the laboratory model test, in which the maximum value of pile-soil stress ratio occurs in test area 3, while the minimum value happens in test areas 1 and 2. Simultaneously, the pile-soil stress ratio in FEM increases gradually with the increase of the distance to the central pile, and the pile-soil stress ratio of central pile (test area 3) is the smallest. According to the results in the laboratory model test and FEM, the settlement increases with the distance to central pile decrease [25, 48]. The greater settlement will result in a wider scope of negative friction area, and more loads will be carried by soil among piles [36, 37]. Hence, the pile-soil stress ratio increases with the increase of distance to the central pile in FEM which conforms to practical engineering situation.

Overall, there is a great difference of the variation of pile-soil stress ratio between the laboratory model test and FEM, in which the opposite variation trend with load is observed. The thickness of gravel cushion in actual engineering is 3 m, while that in actual engineering in laboratory model test is 0.05 m. However, based on geometric similarity ratio (α_l = 10), the thickness of cushion in model test should be 0.3 m, with the addition of the indeterminacy of model test. Hence, it is concluded that the FEM results are closer to the actual situations by referring to the previous research results. Furthermore, based on the results in laboratory model test and FEM, the pile-soil stress of composite foundation is smaller than the recommended value 3~6 [47]. Hence, the development of bearing capacity of CFG pile in composite foundation of saturated MTs dam after CFG pile treatment can be further improved.

5. Influence of Cushion Parameters on the Properties of Bearing Capacity of CFG Pile Composite Foundation

It is effective to improve the development of CFG piles bearing capacity in composite foundation by changing the parameters of cushion [49–52]. Therefore, in order to investigate the influence of cushion parameters on pile-soil stress ratio, variations of pile-soil stress ratio in test areas 4 (smallest stress ratio, cf. Figure 15) and 5 (largest stress ratio) are discussed.

5.1. The Influence of the Cushion Thickness on Bearing Capacity of CFG Composite Foundation. Pile-soil stress ratio decreases with the increase of cushion thickness (cf. Figure 18, the cushion deformation modulus is E_0 = 140 MPa). And when the thickness reaches about 1 m, the whole curve has an obvious inflection point, which demonstrates that when the range of cushion thickness is between 0.1 and 1 m, pile-soil stress ratio decreases greatly with the increase of thickness, and the amplitude decreases with the increase of thickness. However, when the cushion thickness is 1–3 m, the changes of pile-soil stress ratio are sufficiently small with increase of thickness, which illustrates that the bearing capacity of pile obtains a better exertion with a thinner thickness. Hence, the 3 m thickness of cushion in design plan should be decreased to about 1 m, which can not only satisfy the waterproof requirement of highway subgrade, but also improve the

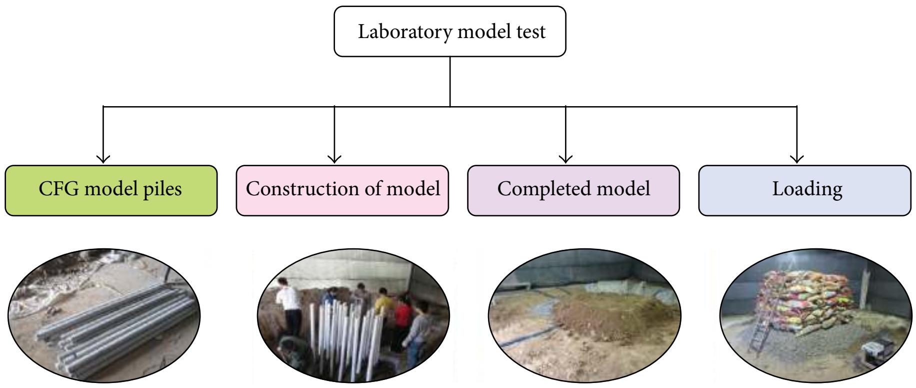


FIGURE 16: Construction of laboratory model test [25].

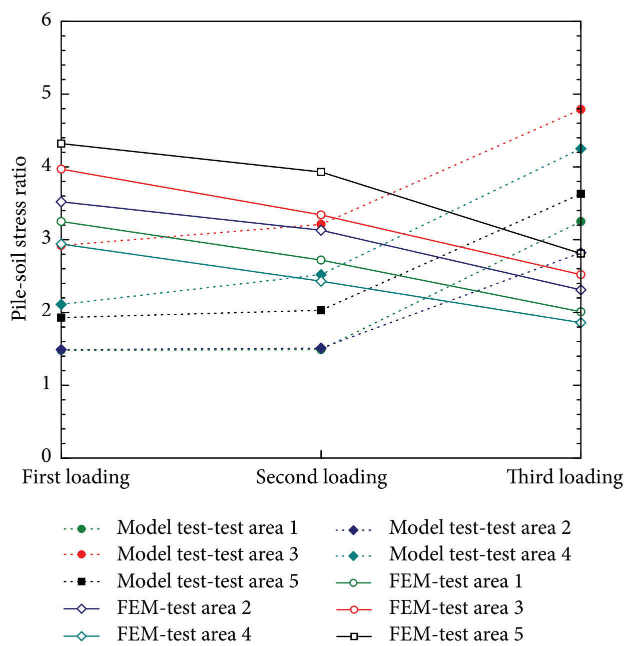


FIGURE 17: The results of pile-soil stress ratio in model test and FEM.

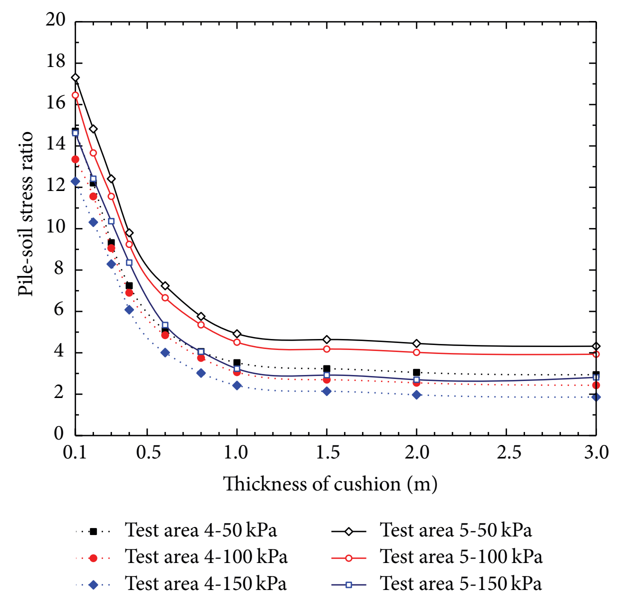


FIGURE 18: Effect of cushion thickness on pile-soil stress ratio curve.

bearing capacity of composite foundation greatly. On the other hand, the influence of cushion thickness on the pile-soil stress ratio in later loading period is greater than that in earlier loading period, and the influence of cushion thickness on the pile-soil stress ratio in test area 5 is smaller than that in test area 4. This is because of the negative friction of pile which has more effect in test area 4. Therefore, it is recommended that the bearing capacity of composite foundation can be improved by enhancing the compactness in test area 4 (the central area of subgrade, cf. Figure 15).

5.2. The Influence of Cushion Deformation Modulus on the Bearing Capacity of CFG Composite Foundation. Curve of pile-soil stress ratio over cushion deformation modulus (Figure 19, cushion thickness is 1 m) demonstrates that pile-soil stress ratio increases with the increase of cushion deformation modulus, which is small relatively when deformation modulus is below 120 MPa and then increases rapidly when the deformation modulus range is between 120 and 160 MPa. When the deformation modulus is larger than 160 MPa, the increasing range is relatively small and the pile-soil stress ratio tends to be stable. As the cushion deformation modulus gradually increases, the effect of pile negative friction gradually decreases, and the loads gradually transform to pile; hence, the pile-soil ratio gradually increases. Furthermore, when the cushion deformation modulus is small relatively, the effect of negative friction is much great and the influence of deformation modulus on the pile-soil ratio is unobvious. However, when the deformation modulus increases to about 120 MPa, the effect of negative friction becomes small gradually, and the increasing range of pile-soil stress ratio became larger. When the deformation modulus reaches about 180 MPa, the effect of negative friction is sufficiently small; thus, the pile-soil stress ratio tends to be stable with the further increase of cushion deformation modulus. These results demonstrate that bearing capacity of CFG pile can

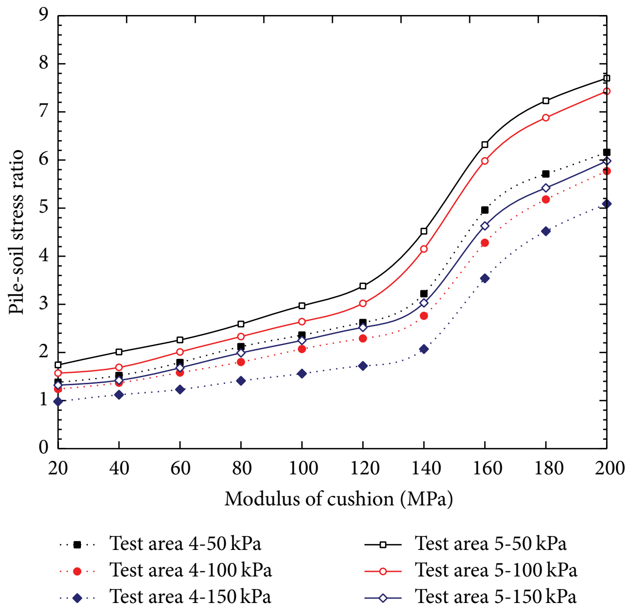


Figure 19: Effect of cushion thickness on pile-soil stress ratio.

be enhanced by improving cushion deformation modulus. However, the influence of cushion deformation modulus on the bearing capacity is not obvious when the cushion deformation modulus increases to a certain extent. It is reasonable to increase the cushion deformation modulus to about 200 MPa. Thus, the deformation modulus of gravel cushion adopted in construction is relatively small, which is unfavorable for the development of bearing capacity of CFG pile.

6. Conclusions

This paper studied the mechanical characteristics of CFG composite foundation in the application of saturated MTs dam. The field static load tests were carried out to investigate the bearing capacity of the CFG composite foundation, and FE modeling in three dimensions validated through comparison with experimental results were used to discuss the pile-soil stress distribution and pile-soil stress ratio of the CFG composite foundation. Furthermore, the effects of cushion on the CFG composite foundation pile-soil ratio were studied. Based on the foregoing mechanical characteristics studies, some of the main findings are summarized as follows.

(1) In the field tests, the bearing capacity characteristic value of CFG composite foundation is $f_{spk} = 526$ kPa and that of single pile is $R_a = 675$ kN, which are proved to be much more than the designed value. The results uncover the fact that the development the bearing capacity of CFG composite foundation is insufficient because of the relatively conservative designed value.

(2) According to the FEM results, it is confirmed that the distribution of CFG piles stress is uniform and stable over depth and position, stress on pile top and pile bottom is small, and the maximum value is near pile bottom. Furthermore, the exertion degree of bearing capacity of pile is lower than 50%. On the other hand, the earth pressure is homogeneous with depth and load in each soil layer. Especially in the reinforced MTs area, due to the good reinforcement effect of CFG piles, the reinforced MTs layer has a more small earth pressure and increase range. Furthermore, load sharing ratio of soil between piles at the later period of loading is much larger than that at the earlier period of loading.

(3) Comparing the results in FEM and laboratory model test, the magnitude of pile-soil stresses is similar, while their changes trends with load are opposite and the pile-soil stress ratio decreases with the increase of load in FEM which is much close to the actual engineering.

(4) According to the FEM results, when the thickness of cushion is less than 1 m, it exhibits significant influence on the pile-soil stress ratio, and the stress decreases approximately linearly with the increase of thickness. However, when the thickness is more than 1 m, pile-soil stress ratio has slight changes with thickness. Therefore, the bearing capacity of CFG composite foundation can be improved when the cushion thickness reduces to about 1 m.

(5) Cushion deformation modulus has significant influence on the pile-soil stress ratio, which increases with the increasing of cushion deformation modulus. Furthermore, the influence of cushion deformation modulus on pile-soil stress ratio is different due to the different effect degree of negative friction. Large cushion deformation modulus around 200 MPa should be set to improve the pile-soil stress ratio in the CFG composite foundation, simultaneously, to enhance the bearing capacity of composite foundation.

Although the utilization of CFG composite foundation in saturated MTs dam has obtained a good consolidation effect, the bearing capacity of CFG composite foundation can be further improved in pursuit of a more effective consolidation according to the results in this study. Additionally, increasing of strength and rigidity of CFG pile has little effect on improving the bearing capacity of composite foundation, while improving the material parameters of soft foundation and changing the connecting type among cushion; pile and soil are effective in the improvement of bearing capacity of composite foundation. Hence, further research should focus on the aforementioned two aspects.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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