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Research Article

Experimental Study and Numerical Simulation of the Effect of Rigid Pile Composite Foundations on Slab Culverts

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For culverts installed in soft soil, the rigid composite pile foundation is used for soil treatment, and the stresses around the culverts are complicated. Centrifuge experiments and numerical simulations are conducted to investigate the vertical earth pressures and soil settlement over a slab culvert under high backfill in soft soil, and the foundations are treated with rigid composite piles. The influences of lateral pile length and pile spacing on the earth pressures at the top of the culvert are analysed, and they have significant effects on the vertical earth pressure coefficients. It also indicates a strong correlation between the backfill height and the vertical earth pressure coefficients. For a high-backfill culvert, there is a uniform settlement surface where the settlement of the interior and exterior soil prisms is at the same level. According to the experiments, the height of the uniform settlement surface and the vertical earth pressures decrease with increasing the lateral pile length and pile spacing. Numerical simulations were conducted using finite element software Midas GTS to evaluate the performance of the experiments. Further, recommendations for selecting an appropriate pile composite foundation for slab culvert in soft soil are provided.

1. Introduction

Trench installation culverts are commonly used in high-backfill construction. Marston has analysed the interaction between underground conduits and the surrounding soils. It was found that the soil arching effect appears because the stiffness difference between rigid structure and soil. Differential settlement of interior and exterior soil prisms can cause stress concentration at the top of the conduits [1–4]. Based on Marston's research, Spangler [5] carried out a series of field tests to measure the settlement ratio of pipe, box, and arch culverts, and the settlements of soil adjacent to the culverts were studied. Many researchers have studied the soil pressure of culverts under embankments [6–11]. Characteristics of foundation is a factor that will affect the soil–structure interaction, including the height of the backfill, shape of the trench, and soil type etc. [12, 13]. The vertical earth pressure coefficient also known as the soil–structure interaction factor, which is an important factor to evaluate the vertical pressure on the culvert [14, 15]. In the AASHTO [16] specification, limitations of vertical earth pressure coefficient are provided, and the calculation of the coefficient for embankment installation culvert is different from the trench installation. Spangler [17] suggested the vertical earth pressure coefficient is a constant for very high embankment, and Yang [18] found that the coefficient was larger than 1 even thick layer of soil was uncompacted to reduce the vertical earth pressure on the culvert. When the culvert is constructed with backfill on top, it was found that the foundations influence the vertical pressure more than the differential settlement of interior and exterior soil prisms. Therefore, treatment of the foundations is required [19, 20].

In soft soil area, the settlement of soil above culverts is more serious [21]. Pile composite foundation is a soil treatment method that can improve the bearing capacity of foundation, and the soft soil settlement can be reduced [22–25]. A pile composite foundation refers to a foundation system where the natural soil is partially strengthened or displaced during the foundation treatment process, or a series of vertical piles are installed into the soil. The reinforced zone consists of two parts: the natural soil or the treated soil and the reinforcement piles. In this article, the term pile composite foundation refers to the arrangement of rigid piles in a vertical direction within the foundation soil. It is suitable for areas where the bearing capacity of soil is insufficient for construction requirements, such as soft soil [26–28]. However, the settlement of pile composite foundation is different from the pile foundation, and it is worthy to study the influence of composite foundation on the soil pressure and settlement. A lot of experiments have been done to study the pile composite foundation [29, 30]. Oh and Shin [31] accomplished field tests and highlighted that the pile spacing was an important factor for soil treatment. Many researchers have conducted numerical analyses to study the pile composite foundation in various conditions [32–36]. They are good references regarding the effect of pile composite foundation in high backfill. In general, larger diameter of piles can enhance the bearing capacity of the foundation, and longer pile length can reduce the foundation settlements. Nevertheless, there is few researches about the culvert constructed in soft soil area, meanwhile, the foundation is stabilised with pile.

This paper is based on the actual project located in south of China, where the project site is located in soft soil area. The culvert was constructed with backfill of the 18 m, while the pile composite foundation was used. The effect of physical characteristics of pile on the vertical pressure on top of the culvert were studied, including the lateral pile length and spacing of piles. Centrifuge tests and numerical modelling were carried out to study the problem.

2. Centrifuge Modelling

A series of centrifuge tests were conducted at the Chang'an University Geo-centrifuge laboratory located in Xi'an, China. To investigate the effect of pile foundation on the response of slab culvert. The performance index of the equipment is as follows: the maximum weight is 60 g·t, the maximum load (model box and the model): when the gravitational acceleration is 100 g, the applied load is 600 kg, and when the gravitational acceleration is 200 g, the applied load is 300 kg.

Polymethyl methacrylate (PMMA) was used to make the slab culvert model, the elastic modulus was similar to concrete, and both concrete and PMMA have similar stress–strain characteristics during the elastic phase. The size of the model box was $700 \times 360 \times 500$ mm. The culvert model was made according to the culvert onsite with the scale of 1:50. The length of the model culvert was 300 mm. Strain gauges and earth pressure cells were used. The testing points layout and the dimensions of the culvert model are shown in Figures 1 and 2. The elastic modulus of the piles and bamboo sticks were 35 and 30 GPa, respectively. The Poisson's ratio of the bamboo sticks used in the experiment was 0.18, which was close to the Poisson's ratio of 0.17 for the on-site piles. From the perspective of material characteristics, it was reasonable and feasible to use the bamboo sticks as model piles in the centrifuge tests. The water content of the soft soil was 41% and the void ratio was 1.2. Parameters of the backfill and soft soil are shown in Table 1.

Nine set of tests were performed involving different lengths of the culvert lateral piles, pile diameters, and distances between piles, respectively. The tests focused on studying the response of high-backfill slab culverts to the precast concrete pile foundations. The centrifuge tests were performed by varying the length, the diameter, and spacing of piles. The data collected from all the sensors during the tests were interpreted to estimate the reasonable composite pile foundation design for slab culvert located in the soft soil area. The width of section 2 (S2) in Figure 1(a) was same as the width of the slab culvert, and the foundations on both sides of S2 were section 1 (S1) and section 3 (S3). A PMMA slab was placed at one side of the model box, with grid drawn on the outer side of the slab and settlement markers placed on the inner side. A fixed digital camera was used to capture fixed-point shooting images of the culvert and the backfill soil in the model box. Through digital image processing, the soil settlements of the backfill were obtained. The settlement markers were arranged in both vertical and horizontal directions, with five vertical positions were selected on each soil layer, including the culvert central axis, 3 and 10 m away from the central axis on both sides of the culvert. For backfill height of 20 m, three horizontal layers were set at the heights of 3, 7, and 11 m above the culvert top, respectively, which corresponded to 15%, 35%, and 55% of the backfill height. The arrangement of the settlement markers is depicted in Figure 1(b). The lengths of modelled piles in each section were $h1$, $h2$, and $h3$, respectively. The diameter of the pile was d, and the pile spacing was s. Height of the backfill was 5–50 m, and the tests were performed in nine test conditions (Table 2).

3. Experiment Results

3.1. *Influence of Lateral Pile Length on Earth Pressure and Soil Settlement*

3.1.1. Influence of Lateral Pile Length on Earth Pressure around Slab Culvert. The effects of the lateral pile length on the earth pressure around the slab culvert of backfill height 20 m are presented in Figure 3. For the same backfill height, the earth pressures around the culvert with pile composite foundation were larger than the foundation without piles. The earth pressures at the top of the culvert decreased as the length of pile increased. With the increase of pile length, the foundation at side of the culvert was strengthened, and the settlement of the foundation on the side of the culvert was smaller than that of the bottom. Meanwhile, settlement of the exterior soil prism decreased, and the absolute values of the settlement difference between the interior and exterior soil of the culvert decreased; the earth pressure transferred from the exterior to the interior soil prism decreased. Therefore, the earth pressure at culvert top reduced. It was shown in Figure 4, when the lateral pile was longer than 15 m, the increasement of strength of the foundation on the side of the culvert decreased, and the earth pressure transferred from the interior soil prism to the exterior soil prism stayed the same. Therefore, the earth pressure variation of the culvert top was stable. With the increase of backfill height, the change of relative settlement difference between inner and exterior soil prism due to variation of lateral pile length was more significant, so the vertical earth pressure at the top of the culvert dropped more prominently. At a backfill height of 20 m, it was observed that, as compared to soil without piles, the increase in vertical earth pressure at the culvert top was

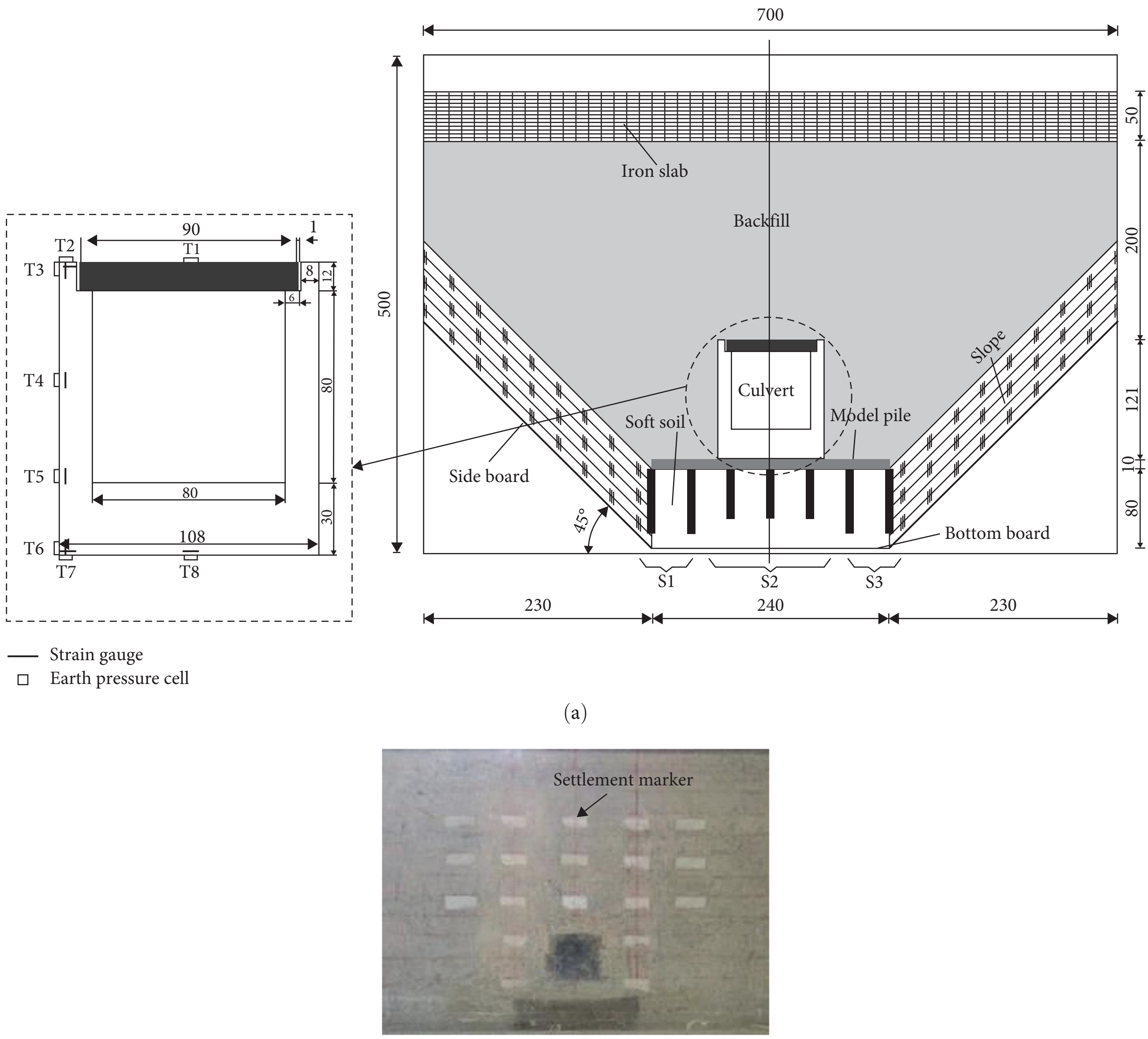

Figure 1: Experiment setup: (a) cross-section of the model box (unit: mm) and (b) arrangement of settlement markers.

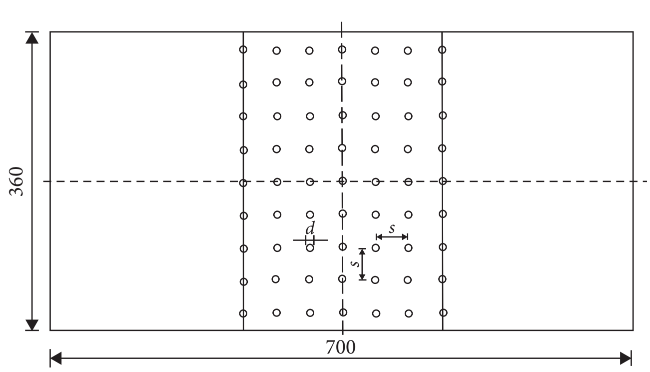

Figure 2: Arrangement of the model piles (unit: mm).

found to be 20.9%, 15.2%, and 13.4% for lateral pile lengths of 10, 15, and 20 m, respectively. Backfill height of 40 m, compared with soil without piles, the increase in vertical earth pressure at the culvert top was found to be 24.6%, 18.9%, and 14.4%, and the increasement for backfill height of 40 m was larger than the value of backfill of 20 m.

As can be seen in Figure 4, the earth pressures acquired from the centrifuge test were scattered. This was due to the fact that the process of soil backfilling was simulated by increasing the acceleration in the test, which was not exactly the same as backfilling construction.

In order to demonstrate the effects of lateral pile length on earth pressure under high backfill, the vertical earth

Table 1: Material properties of centrifuge experiments.

Materials	Elastic modulus (MPa)	Poisson's ratio	Γ (kN/m^3)	Cohesion (kPa)	Friction angle (°)
Backfill	20	0.3	19	30	30
Soft soil	5	0.27	19	18	20

Table 2: Test conditions.

Test conditions	Length, L (m)	Diameter, d (cm)	Spacing, s (m)
Pile length	$h1 = h2 = h3 = 10$ $h1 = h3 = 15$, $h2 = 10$ $h1 = h3 = 20$, $h2 = 10$	40	2
Pile spacing	$h1 = h3 = 15$, $h2 = 10$	40	1.5 2 2.5

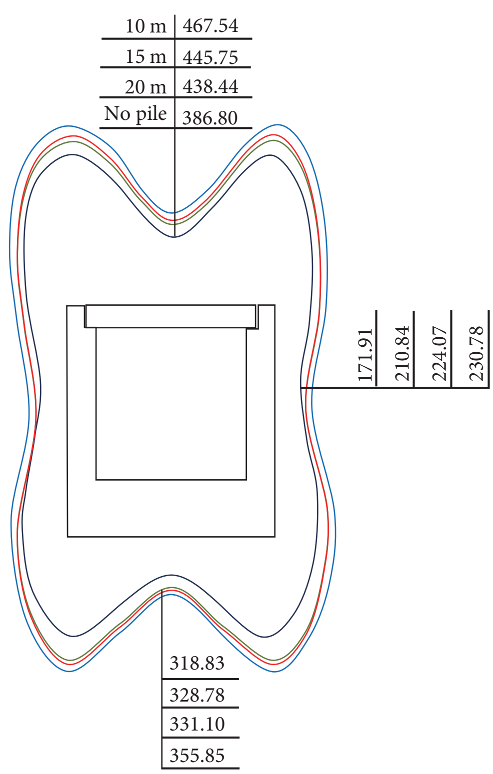

Figure 3: Effects of lateral pile length on earth pressure around the slab culvert (backfill height: 20 m) (unit: kPa).

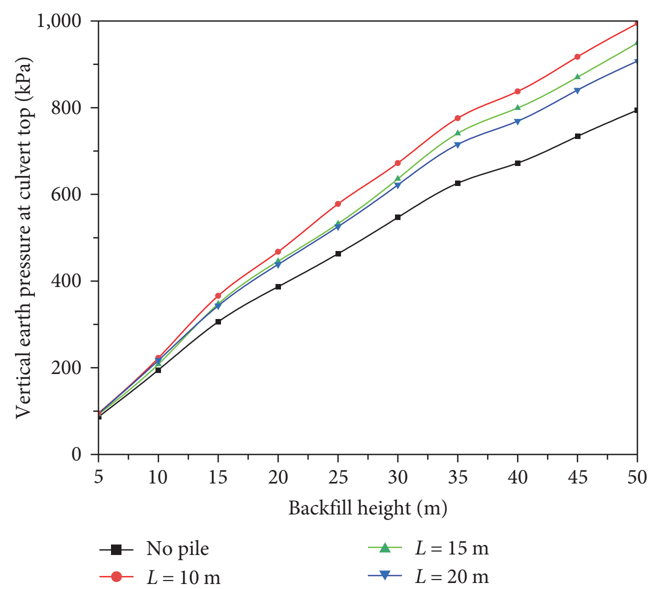

Figure 4: Earth pressure of centre of culvert top versus lateral pile length for backfill height 5–50 m.

pressure coefficient K_s of culvert top for backfill height ranging 5–50 m were calculated using the following equation:

$$K_s = \sigma_v / \gamma h, \quad (1)$$

where σ_v is the vertical earth pressure at the centre of the culvert top with the unit kPa, γH is the self-weight of the backfill soil above the culvert with the unit kPa.

The vertical earth pressure coefficient K_s can be used to characterise the degree of concentration of vertical earth pressure at the top of the culvert. When K_s larger than 1, the actual load at the centre of the culvert top is greater than the self-weight of the backfill soil over the culvert, thereby inducing stress concentration at the culvert top. Moreover, the degree of stress concentration at the culvert top becomes more obvious as K_s increases. Conversely, when K_s smaller than 1, the actual vertical pressure at the centre of the culvert top is smaller than the self-weight of the backfill soil over the culvert, leading to stress diffusion at the culvert top. A smaller value of K_s is more beneficial for the load bearing capacity of the culvert.

The results are shown in Figure 5. For the same backfill height, the K_s for foundation with piles were larger than the foundation without piles, as the stress concentration at the top of the culvert increased when the soft soil foundation is treated with piles.

With the change of lateral pile length from 10 to 20 m, the K_s at the top of the culvert is gradually decreasing. As the

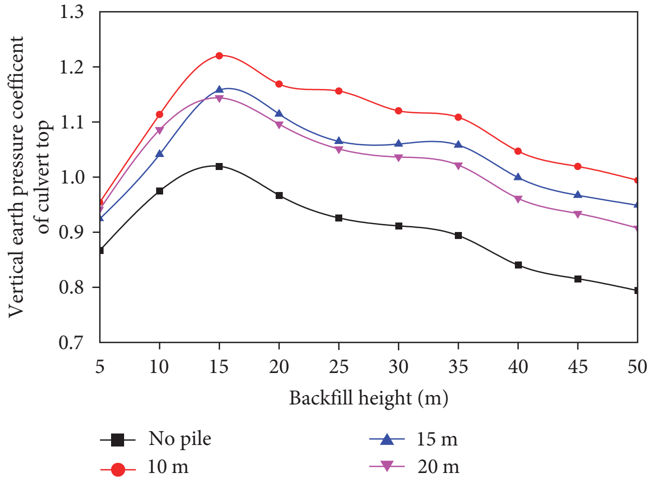

Figure 5: Influence of lateral pile length on the vertical earth pressure coefficient of culvert top.

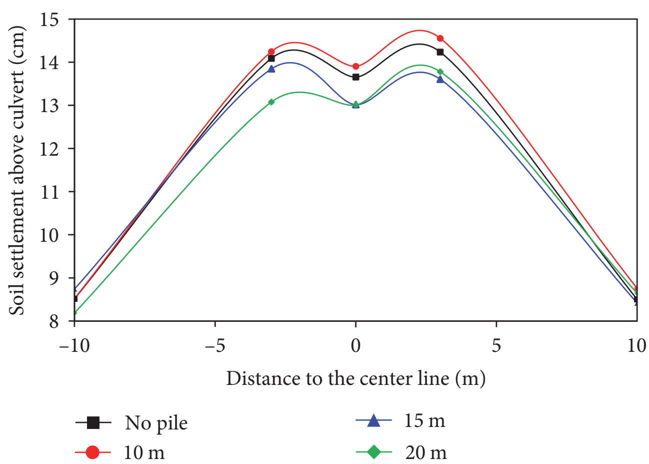

Figure 6: Soil settlement above the culvert of different pile lengths (backfill height 20 m).

backfill height increased, the K_s of different lateral pile lengths all increased at the early stage and then decreased steadily. The maximum values of K_s appeared when the backfill height was 15 m, which were 1.22, 1.16, and 1.14 for pile length of 10, 15, and 20 m, respectively. Therefore, when using piles to reinforce the soft soil foundation in culvert construction, it is suggested that the length of lateral piles should be longer than the culvert bottom piles, and longer lateral piles are beneficial for the culvert structure under stress.

3.1.2. Influence of Lateral Pile Length on Soil Settlement. To take the tests of backfill height 20 m as an example, Figure 6 shows the soil settlement at culvert top for various pile lengths. It was found that the total settlement decreased with an increase in the pile length. When the lateral pile length changed from 10 to 20 m, the settlement approximately decreased by 7%; and the minimum soil settlement on top of the culvert centre was 13.09 cm for pile length of 20 m.

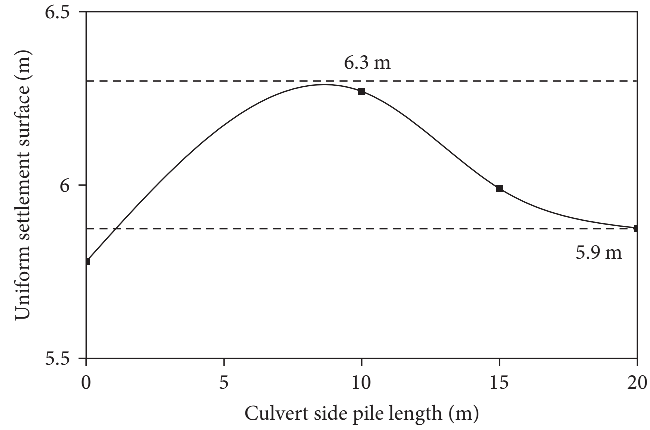

Figure 7: Height of the uniform settlement surface of different pile lengths (backfill height 20 m).

The settlement would be larger for higher backfill. The settlement at the centre of the culvert top was smaller than the settlement adjacent to the edge of the culvert because of the shear stress between the interior and exterior prism, resulting in additional downward earth pressure on the interior prism from the exterior prism above the culvert, which is the reason for the stress concentration at the top of the culvert. It can be noticed from Figure 5, with the gradual increase in backfill height, the variation trend of K_s reveals that the settlement difference between the interior and exterior soil prims above the culvert experienced an initial increase followed by gradually decreasing. This can be primarily attributed to the compaction of the backfill soil within the exterior prism due to the increasing backfill height. Once the backfill reached a certain height, the change in settlement difference between the interior and exterior soil prisms above the culvert became more gradual. With the same length of the lateral piles, the cumulative settlement of soil increased with increasing the backfill height.

When the length of lateral pile was 10–20 m, the uniform settlement surface was 5.9–6.3 m (Figure 7). The absolute value of settlement difference of interior and exterior soil prism reduced with increasing the lateral pile length, and the height of the uniform settlement surface reduced. When the pile length was larger than 15 m, changes in the height of the uniform settlement surface became relatively small.

3.2. Influence of Pile Spacing on Earth Pressure and Settlement of Slab Culvert

3.2.1. Influence of Pile Spacing on Earth Pressure of Slab Culvert. Earth pressures at culvert top are small at the middle of the slab and large at both ends. The earth pressures against pile spacing are shown in Figure 8, and it illustrates that the earth pressure at culvert top decreased with increasing the distance for the same backfill height (20 m). The earth pressures against backfill height are shown in Figure 9. The earth pressures on the culvert decreased with increasing the pile spacing. Before backfill height of 15 m, the earth pressure differences between different pile spacing were relatively

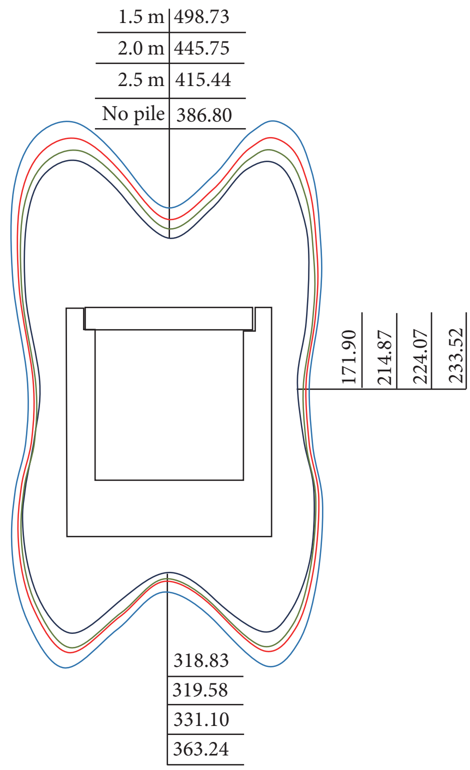

Figure 8: Effect of pile spacing on earth pressure around slab culvert (backfill height 20 m) (unit: kPa).

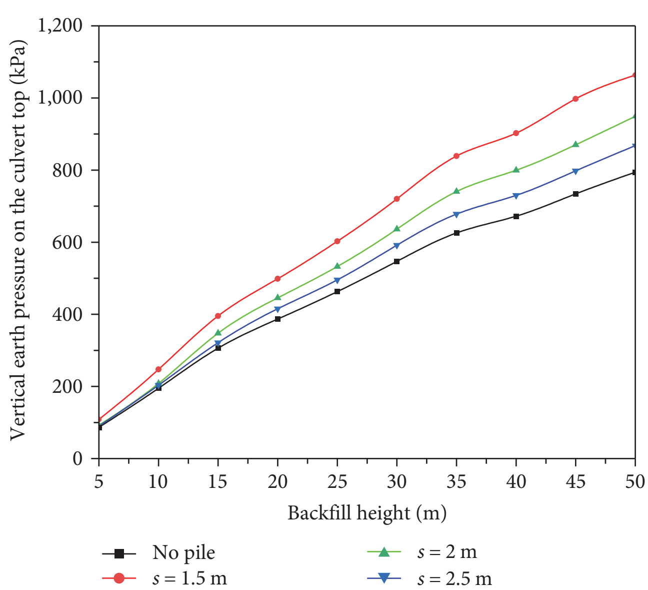

Figure 9: Earth pressure of centre of culvert top versus pile spacing for backfill height 5–50 m.

small, and they keep increasing as the backfill height increased. When the backfill height was 50 m, the vertical earth pressure at the culvert top for pile spacing 1.5 and 2.5 m were 1,063 and 868 kPa, respectively.

The earth pressure of lateral has similar trend as culvert top. The subgrade reaction of the culvert bottom was small in the centre and large at both ends. Figure 8 shows that for the same backfill height, the subgrade reaction of the culvert bottom decreased with increasing the pile spacing. The subgrade reaction of slab culvert for pile composite foundation were larger than the subgrade reaction for foundation without piles.

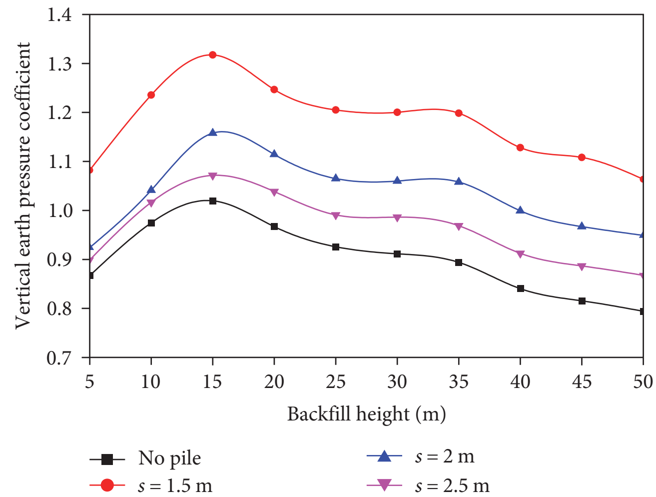

Figure 10: Influence of pile spacing on the vertical earth pressure coefficient of culvert top.

Figure 10 shows that for the same backfill height, the vertical earth pressure coefficient K_s at culvert top of pile composite foundation was larger than the K_s of foundation without piles. The K_s decreased with increasing the pile spacing, but the decrease tended to slow down when the spacing was larger than 2 m. With increasing the backfill height, the K_s of different pile spacing all increased and then decreased, and the maximum values of K_s appeared when the backfill height was 15 m, which were 1.3, 1.15, and 1.07 for pile spacing of 1.5, 2, and 2.5 m, respectively.

Dense arrangement of piles will increase the modulus of the foundation soil, which will intensify the stress concentration at the top of the culvert. Therefore, in order to reduce the adverse effects caused by the pile foundation, the pile spacing should be widened appropriately.

3.2.2. Influence of Pile Spacing on Soil Settlement. Settlement of backfill soil has effect on the earth pressure acting on the culvert. According to the Marston–Spangler theory of earth pressure, it is assumed the soil–culvert interaction is between the soil above the culvert (referred to as the interior soil prism) and the soil beside the culvert (referred to as the exterior soil prism). When the settlement of the exterior soil prism is greater than that of the interior soil prism, the load is transferred from the exterior soil prism to the interior soil prism through frictional resistance between soil prisms, resulting in an increase in loading on the culvert. Similarly, when the settlement of the interior soil prism is greater than that of the exterior soil prism, the loading on the culvert decreases. Figure 11 shows the soil settlement of the culvert top of backfill height of 20 m. It shows clearly that the soil settlement at centre of the culvert top was smaller than the

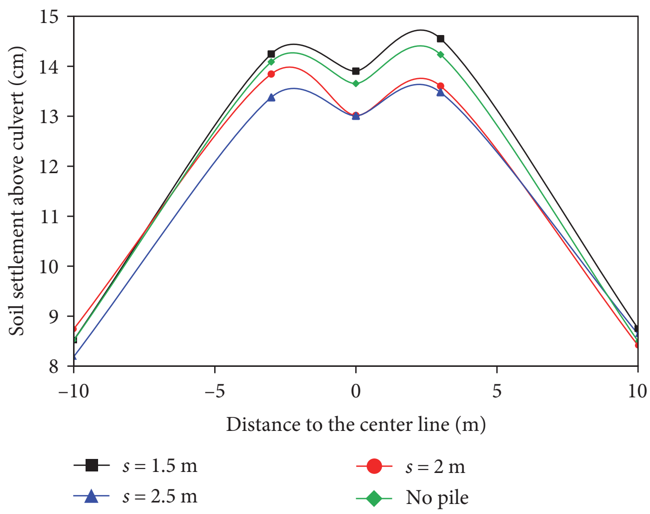

FIGURE 11: Soil settlement above the culvert of different pile spacings of backfill height 20 m.

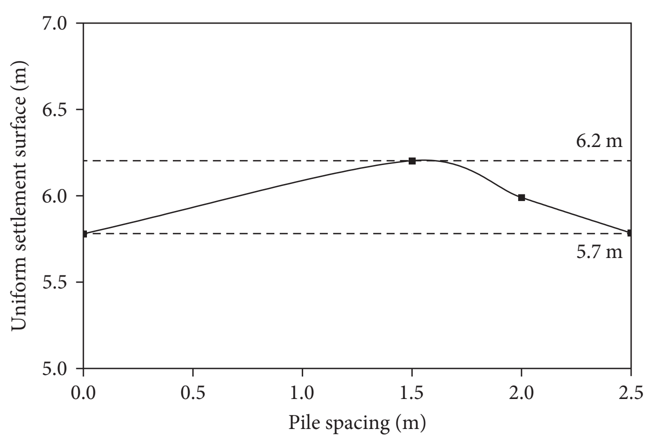

FIGURE 12: Height of the uniform settlement surface of different pile spacings of backfill height 20 m.

settlement close to the edge of the culvert. The reason was that the soil above the culvert was restricted by the slopes on both sides, thus causing smaller soil settlement near the slope, while the obstructive effect caused by the culvert led to the soil above edge of the culvert to settle more than the centre top. For the same pile spacing, the cumulative settlement of soil layers increasing with increasing the backfill height, and the absolute value of settlement difference between the exterior and the interior soil prism decreased. With increasing the pile spacing, the absolute value of settlement difference between the exterior and the interior soil prism increased. Figure 12 shows that the uniform settlement surface was 5.7–6.2 m when the pile spacing was 1.5–2.5 m, and the height of uniform settlement surface reduced with increasing the pile spacing.

4. Numerical Simulation

4.1. Numerical Model. The experimental structure behaviour was reproduced by evaluating the performance of the numerical model. The numerical simulation was performed using the finite element analysis software Midas GTS. The model is shown in Figure 13. In order to minimise the boundary effect, width of the numerical simulation model should be more than 10 times the span of the culvert. The width of one side in this model was taken as 12 times the span of the slab culvert, and the model length is taken as the length of the culvert, that is, the model size was 60×100 m, and the thickness of the foundation soil was 30 m. The culvert size was 4×4 m. In order to improve the accuracy of the results, the grids of the culvert and the soil around the culvert were densified. The finite element model involves two kinds of materials, concrete and soil. The ideal elastic constitutive model was selected for concrete and piles, and soil was modelled as the elastoplastic constitutive model. Boundaries and bottom of the model were fixed constrains. The backfill height ranged from 5 to 50 m were calculated, therefore, a clearer analysis of the effect of backfill height on the culvert performance can be conducted. The material properties obtained from field and laboratory tests were presented in Table 3. The earth pressure distribution acting on the slab culvert with pile composite foundation were calculated according to the simulation conditions in Table 4. Different lateral pile lengths and pile spacings were analysed.

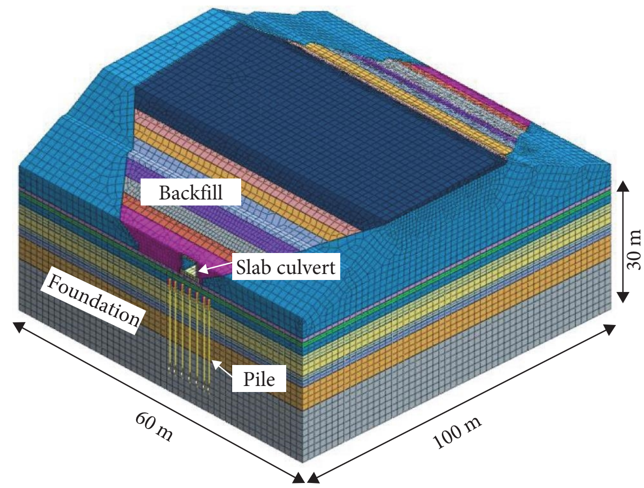

FIGURE 13: Quarter of the numerical model.

4.2. Analysis of Numerical Results. The comparisons of the numerical results with the test results are shown in Figure 14. The numerical results were found to be in reasonable agreement with the experiments.

Similar to the centrifuge tests, the K_s decrease with increasing lateral pile length and pile spacing (Figure 15). With backfill heights increase from 5 to 50 m, the K_s value increases rapidly, when the backfill height is less than 15 m then decreases relatively stable, which validates the experiment results. According to the calculation, changing in the pile arrangement had different effects on K_s, and pile length had greater impact on K_s.

The values of calculated K_s are ranging 1.50–1.37 for pile length of 10–20 m, while the experiment value is 1.17–1.10.

Table 3: Material properties of numerical simulation.

Materials	Elastic modulus (MPa)	Poisson's ratio	Γ (kN/m^3)	Cohesion (kPa)	Friction angle (°)
Backfill	20	0.3	19	30	30
Culvert	30,000	0.15	26	—	—
Soft soil	5	0.41	19	18	20
Pile foundation	35,000	0.17	25	—	—
Cushion	50	0.25	21.5	0	40
Slope	3,000	0.2	23	150	35

Table 4: Numerical simulation conditions.

Test conditions	Length, L (m)	Diameter, d (cm)	Spacing, s (m)
Pile length	$h1 = h2 = h3 = 10$ $h1 = h3 = 15$, $h2 = 10$ $h1 = h3 = 20$, h2 = 10 $h1 = h3 = 25$, h2 = 10	40	2
Pile spacing	$h1 = h3 = 15$, $h2 = 10$	40	1, 1.5, 2, 2.5

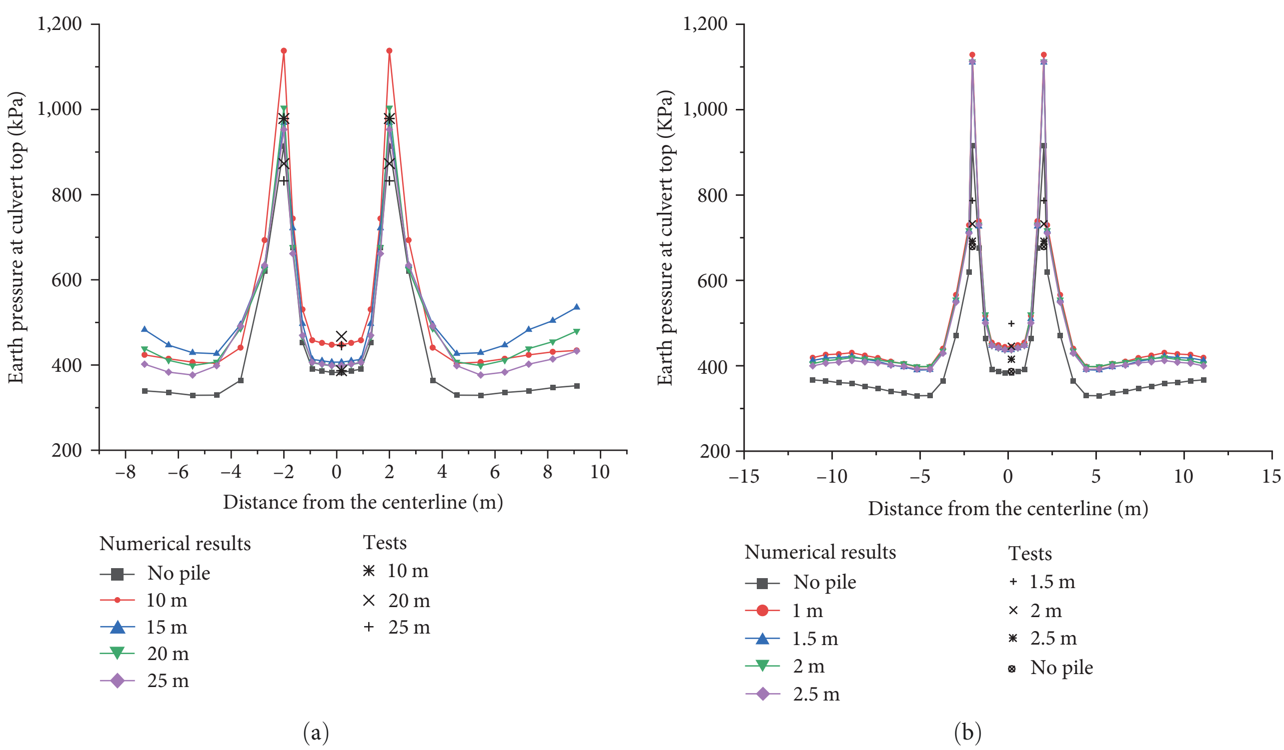

Figure 14: Experiment and numerical results of earth pressure at culvert top: (a) lateral pile length and (b) pile spacing (backfill height: 20 m).

Variation of K_s was relatively small for the different pile spacings, with increasing spacing from 1.5 to 2.5 m, the calculated and experiment values of K_s drop from 1.50 to 1.48 and 1.25 to 1.04, respectively. The K_s of numerical simulation is larger than experimental values, because the backfilling process in the centrifuge experiment was simulated by increasing the acceleration, which is not exactly the same as the actual construction conditions. Spangler [17] suggested that K_s was recommended as a constant value for high backfills. However, according to the experiment and numerical analysis in this paper, the K_s should be considered as variables when the soft soil foundation of the culvert was treated with piles. As the maximum K_s appeared at backfill of 15 m, therefore, it is recommended that the K_s should range from 1.04 to 1.50 for a slab culvert with a span of 4 m over soft foundation treated with piles.

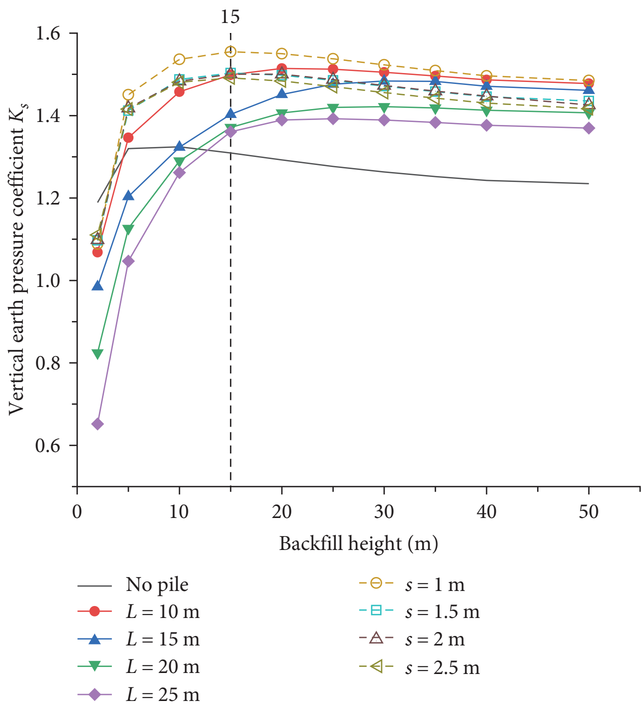

Figure 15: Coefficients of vertical earth pressure for various backfill heights.

5. Conclusions

Pile composite foundations are commonly used to treat soft soil for culvert construction, and the foundation can be reinforced. However, soil arching effect will occur when the foundation underneath the culvert has large strength, which resulting in an increase in the vertical earth pressure at the top of the culvert. It is essential that the piles are appropriately sited. The centrifuge tests and numerical simulation provided valuable data to facilitate the engineering applications of culverts under high backfill.

Experiments were conducted for trapezoidal trench installation culverts, which have different stress state from the trench installation or embankment installation culverts. It was found that compare to the trench installation, trapezoidal trench installation culverts have relatively low-earth pressure around the culvert, K_s and the settlement of the soil at the top of the culvert. It is noticeable that as the backfill height increased, vertical earth pressure coefficients increased first and then decreased relatively stable; and the maximum values of K_s were found at the backfill height of 15 m. The degree of stress concentration above the culvert is closely related to the settlement difference between the interior and exterior prisms above the culvert. The soil settles more at the edge than in the centre of the culvert, and the depth of the uniform settlement surface is inversely proportional to the lateral pile length and pile spacing.

Longer lateral pile lengths result in less soil concentration of the earth pressure at the culvert top, that is smaller value of K_s. Meanwhile, the lateral pile should be longer than the pile underneath the culvert, under the condition that the bearing capacity of foundation is satisfied.

Dense arrangement of piles will increase the modulus of the foundation soil, which will intensify the stress concentration at the top of the culvert. Therefore, under the condition of satisfying the bearing capacity of the foundation, the pile spacing should be widened appropriately. With pile spacing increasing from 1.5 to 2.5 m, the vertical earth pressure coefficient varies between 1.04 and 1.50, and the depth of uniform settlement surface is between 5.7 and 6.2 m.

Slab culvert were analysed in this research, and it is necessary to study the vertical earth pressure coefficient for different types of culverts, as the earth pressure concentration effect will vary because of the physical properties of the culvert.

Data Availability

All data and models generated or used during the study are included within the article.

Conflicts of Interest

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

Acknowledgments

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References

[1] A. Marston and A. O. Anderson, "The theory of loads on pipes in ditches, and tests of cement and clay drain tile and sewer pipe," in *Bulletin No. 31, Engineering Experiment Station*, Iowa State College of Agriculture and Mechanic Arts, Ames Iowa, 1913.

[2] M. G. Marston, "The theory of external loads on closed conduits in the light of the latest experiments," in *Highway Research Board Proceedings*, vol. 9 of *Bulletin 96, Iowa Engineering Experiment Station*, pp. 138–170, Iowa State College, Ames, 1930.

[3] J. Kang, F. Parker, and C. H. Yoo, "Soil–structure interaction for deeply buried corrugated steel pipes Part I: embankment installation," *Engineering Structures*, vol. 30, no. 2, pp. 384–392, 2008.

[4] American Concrete Pipe Association, *Concrete Pipe Design Manual*, ACI Journal Proceedings, 19th edition, 2011.

[5] M. G. Spangler, *Field Measurements of the Settlement Ratios of Various Highway Culverts*, vol. 170 of Bulletin 170, Iowa Engineering Experiment Station, Iowa, Ames, Iowa, 1950.

[6] X. Qin, P. Ni, and M. Zhou, "Improved analytical solution of vertical pressure on top of induced trench rigid culverts," *Geosynthetics International*, vol. 24, no. 6, pp. 615–624, 2017.

[7] R. M. Bennett, S. M. Wood, E. C. Drumm, and N. R. Rainwater, "Vertical loads on concrete box culverts under high embankments," *Journal of Bridge Engineering*, vol. 10, no. 6, pp. 643–649, 2005.

[8] A. Dasgupta and B. Sengupta, "Large-scale model test on square box culvert backfilled with sand," *Journal of Geotechnical Engineering*, vol. 117, no. 1, pp. 156–161, 1991.

[9] R. W. James, D. E. Brown, R. E. Bartoskewitz, and H. M. Coyle, *Earth Pressures on Reinforced Concrete Box Culverts*, The Texas A&M University System, Texas, 1986.

[10] O. Abuhajar, H. El Naggar, and T. Newson, "Numerical modeling of soil and surface foundation pressure effects on buried box culvert behavior," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 142, no. 12, pp. 1–13, 2016.

[11] M. Pimente, P. Costa, C. Félix, and J. Figueiras, "Behavior of reinforced concrete box culverts under high embankments," *Journal of Structural Engineering*, vol. 135, no. 4, pp. 753–761, 2009.

[12] B. Chen and L. Sun, "Performance of a reinforced concrete box culvert installed in trapezoidal trenches," *Journal of Bridge Engineering*, vol. 19, no. 1, pp. 120–130, 2014.

[13] K. Kyungsik and H. Y. Chai, "Design loading on deeply buried box culverts," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 131, no. 1, pp. 20–27, 2005.

[14] Z. Feng, S. Li, Y. Dong, Y. Hao, and H. Hu, "Vertical earth pressure distribution characteristics and calculation theory of high fill culvert," *Journal of Highway and Transportation Research and Development*, vol. 36, no. 12, pp. 69–78, 2019.

[15] I. Chu, S.-K. Woo, S. I. Woo, J. Kim, and K. Lee, "Analysis of vertical earth pressure acting on box culverts through centrifuge model test," *Applied Sciences*, vol. 12, no. 1, p. 81, 2022.

[16] AASHTO, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, Washington, DC, 17th edition, 2002.

[17] M. G. Spangler, "Underground conduits—an appraisal of modern research," *Transactions of the American Society of Civil Engineers*, vol. 113, no. 1, pp. 316–345, 1948.

[18] M. Z. Yang, "*Evaluation of factors affecting earth pressures on buried box culverts*," PhD dissertation, University of Tennessee, Knoxville, Tenn, 2000.

[19] J.-H. Zhang, Y.-S. Yao, J.-L. Zheng, and T. Zhang, "Centrifugal model test and numerical simulation of vertical earth pressure on soft foundation box culvert," *Journal of Central South University*, vol. 22, no. 9, pp. 3556–3563, 2015.

[20] O. F. S. Al-Damluji, M. Y. Fattah, and R. A. J. Al-Adthami, "Analysis of soil media containing cavities or tunnels by the boundary element method," *Alhosn University Journal of Engineering & Applied Sciences*, vol. 3, no. 2, pp. 27–49, ALHOSN University - Abu Dhabi - UAE, 2011.

[21] M. Y. Fattah, K. T. Shlash, and N. M. Salim, "Prediction of settlement trough induced by tunneling in cohesive ground," *Acta Geotechnica*, vol. 8, no. 2, pp. 167–179, 2013.

[22] I. Buddhima, C. Jian, and R. Cholachat, *Ground Improvement Case Histories, Embankments with Special Reference to Consolidation and Other Physical Methods*, pp. 623–659, Elsevier, Oxford, https://linkinghub.elsevier.com/retrieve/pii/C20140023702, 1st edition, 2015.

[23] R. P. Chen, Z. Z. Xu, Y. M. Chen, D. S. Ling, and B. Zhu, "Field tests on pile-supported embankments over soft ground," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 136, no. 6, pp. 777–785, 2010.

[24] M. Y. Fattah, K. H. I. Al Helo, and H. H. Abed, "Load distribution in pile group embedded in sandy soil containing cavity," *KSCE Journal of Civil Engineering*, vol. 22, pp. 509–519, Korean Society of Civil Engineers, 2018.

[25] F. A. Abdullah, M. Y. Fattah, and A. A. Al-Keifae, "Cavity effects on axially loaded single pipe piles embedded in a sand deposit," in *4th International Iraqi Conference on Engineering Technology and Their Applications (IICETA)*, pp. 290–295, 2021.

[26] Y. Lv, H. Liu, X. Ding, and G. Kong, "Field tests on bearing characteristics of X-section pile composite foundation," *Journal of Performance of Constructed Facilities*, vol. 26, no. 2, pp. 180–189, 2012.

[27] M. J. Tomlinson and J. D. Woodward, *Pile Design and Construction Practice*, CRC Press, 6th edition, 2014.

[28] M. Y. Fattah, K. T. Shlash, and N. M. Salim, "Settlement trough due to tunneling in cohesive ground," *Indian Geotechnical Journal*, vol. 41, no. 2, pp. 64–75, 2011.

[29] M. S. S. Almeida, M. Ehrlich, A. P. Spotti, and M. E. S. Marques, "Embankment supported on piles with biaxial geogrids," *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, vol. 160, no. 4, pp. 185–192, 2007.

[30] L. Briançon and B. Simon, "Performance of pile-supported embankment over soft soil: full-scale experiment," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 138, no. 4, pp. 551–561, 2012.

[31] Y. I. Oh and E. C. Shin, "Reinforcement and arching effect of geogrid-reinforced and pile-supported embankment on marine soft ground," *Marine Georesources & Geotechnology*, vol. 25, no. 2, pp. 97–118, 2007.

[32] M. Alamgir, N. Miura, H. B. Poorooshasb, and M. R. Madhav, "Deformation analysis of soft ground reinforced by columnar inclusions," *Computers and Geotechnics*, vol. 18, no. 4, pp. 267–290, 1996.

[33] J. Han and M. A. Gabr, "Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 128, no. 1, pp. 44–53, 2002.

[34] X. Lu, S. Mengen, and P. Wang, "Numerical simulation of the composite foundation of cement soil mixing piles using FLAC3D," *Cluster Computing*, vol. 22, no. S4, pp. 7965–7974, 2019.

[35] R. Lang, S. Yan, L. Sun, Y. Ji, and J. Chen, "Analysis of stress diffusion angle method for PTC pile composite foundation," *European Journal of Environmental and Civil Engineering*, vol. 22, no. sup1, pp. s434–s448, 2018.

[36] K. Y. Wang, Y. Zhuang, H. Liu, and Y. Miao, "Soil arching in highway piled embankments subjected to moving shakedown limit loads," *European Journal of Environmental and Civil Engineering*, vol. 24, no. 8, pp. 1120–1134, 2020.