

Article

Research on the Load Transfer Law of Cross-Sections of Pile-Supported Reinforced Embankments Based on the Finite Element Method

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Abstract: Combining field test research with finite element numerical analysis, this paper studies the mechanical behavior of pile-supported reinforced embankments in soft soil areas. We analyze and compare the variation law of load transfer efficacy at the subgrade center, the right side of the centerline, and the road shoulder; the variations of the load sharing ratios of the soil arching effect and the load sharing ratios of the membrane effect; and the load variation law of wide subgrade cross-sections. Then, the model calculation results are compared with the calculation results of the five theoretical methods and the applicability of the various methods is evaluated. The results show that: increasing the pile length, pile cap width, and embankment height and reducing the pile spacing will increase the pile load transfer efficacy; pile cap width has the greatest influence on the load transfer efficacy; regarding the variation law of the load sharing ratios of subgrade cross-sections, the load-sharing ratio of the soil arch effect at the shoulder is smaller than that at the center of the subgrade, indicating that the deformation of the geogrid at the shoulder is large and the membrane effect is significant; and, regarding the load variation law of subgrade cross-sections, from the subgrade center to the shoulder direction, the pile load transfer efficacy decreases gradually and the load transfer efficacy at the shoulder decreases significantly.

Keywords: pile-supported reinforced embankment; soil arching effect; membrane effect



Citation: Wang, X.; Wang, X.; Yang, G.; Yang, X.; Zhang, D. Research on the Load Transfer Law of Cross-Sections of Pile-Supported Reinforced Embankments Based on the Finite Element Method. *Sustainability* **2022**, *14*, 7831. <https://doi.org/10.3390/su14137831>

Academic Editor: Andreas Ihle

Received: 26 May 2022

Accepted: 23 June 2022

Published: 27 June 2022

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1. Introduction

The core content of the load transfer mechanism of the pile-supported reinforced embankment is the “soil arching effect” of embankment fill and the “membrane effect” of horizontal reinforced materials. In recent years, many scholars have studied the load transfer law of pile-supported reinforced embankments. Han-Jiang Lai [1], Jun Zhang [2], Chen Yun-min [3], and Xin Wang [4] studied the load transfer mechanism of pile-supported reinforced embankments under various influencing factors through tests and numerical simulation. Chew [5], Van Eekelen [6], and Shunlei Hu [7] improved the calculation method of the load transfer of pile-supported reinforced embankments. Chen [8] and Yang [9] compared the test results with the standard calculation values of various countries and analyzed the applicability of each theory. Most of the above research results are based on model tests and numerical simulations to study the influence of different factors on load transfer. However, the interaction and mechanism between membrane effect and soil arching effect still lack in-depth research. The simplified load transfer analysis method of pile-supported reinforced embankments is to first calculate the load acting on the horizontal

reinforcement by using the relevant theory of soil arch effect, and second, to analyze the stress and deformation of the reinforcement [10,11]. However, the soil arching effect and membrane effect are interactive. The simplified analysis method is inconsistent with real situations. Therefore, it is of great significance to understand the mechanical behavior and load transfer mechanism of pile-supported embankments by clarifying the contribution of the soil arching effect and membrane effect on the load transfer.

Briancon [12] monitored the deformation of geogrid reinforcement and subgrade settlement through field tests, indicating that the membrane effect of geosynthetics plays an important role in the load transfer of pile-supported reinforced embankments. Liu [13], and Wachman [14] monitored the base soil pressure, geogrid deformation, pore water pressure, settlement of piles and soil between piles, and foundation lateral displacement of pile-supported reinforced embankments through field tests and analyzed the load transfer mechanism of pile-supported reinforced embankments in soft soil areas. Although many scholars have studied the load transfer law of pile-supported embankments, most of the research results summarize the load transfer law of a single measuring point, and there is no systematic study on the load change on the cross-sections of pile-supported embankments. Due to the large width of a subgrade cross-section and discontinuous geological conditions, the distribution characteristics of load on subgrade cross-sections are different. The research results of different scholars are also different. Zheng [15,16] studied the soil pressure change and geogrid deformation of subgrade cross-sections through a field test. The results show that the soil arching effect at the center of the subgrade is significant, and the grid at the shoulder is more efficient. Gao [17] studied the lateral distribution characteristics of pile-soil stress in the process of widening embankment filling. It shows that the stress concentration effect of the pile near the slope toe is small. Hu [18] observed the geogrid deformation in a subgrade cross-section, which shows that the geogrid tension at the center of the subgrade was the largest and gradually decreased to both sides of the shoulder.

Therefore, combining field test research and finite element numerical analysis, this paper studies the mechanical behavior of pile-supported reinforced embankments in soft soil areas. The load transfer law of pile-supported reinforced embankments under the influence of pile length, pile spacing, pile cap edge length, and embankment height; the load variation law of wide subgrade cross-section; and the variation law of load sharing ratio of soil arching effect and membrane effect are analyzed. Finally, the model calculation results are compared with the results of five theoretical methods to evaluate the applicability of the various methods.

2. Field Test

2.1. Introduction of Field Test

As shown in Figure 1, the Rongwu Expressway in Xiong'an New Area is located in the northern part of Hebei Province, China. Here, the soft soil foundation is treated with a prestressed pipe pile composite foundation, and the strength of the prestressed pipe pile concrete is C60, the pile length is 14 m, and the pile spacing is 2 m and 2.5 m, respectively, from the bridge abutment to the embankment. The top of the pile is set with a C30 square reinforced concrete pile cap of 1.0 m × 1.0 m × 0.3 m. The cushion thickness of the test section is 0.3 m, which consists of a gravel cushion and geogrid reinforced gravel cushion. The main technical parameters of the test section are shown in Table 1.

Earth pressure boxes were used to monitor the pile top pressure and the soil stress between piles. As shown in Figure 2, the earth pressure boxes were respectively buried in the top of the pile cap and in the soil between piles at the center line of the subgrade, 10 m on the right side of the center line and the road shoulder. Six earth pressure boxes are arranged in each section.

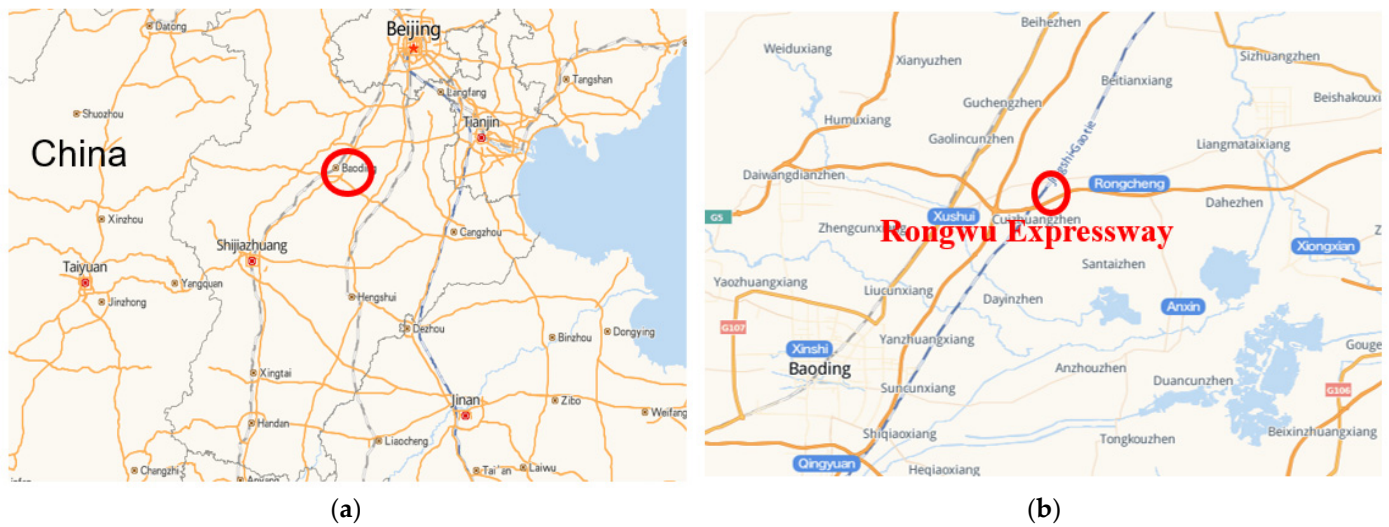


Figure 1. The geographical location of the test site. (a) Location of test section. (b) Local magnification of the test section location.

Table 1. Technical index of the cross-sections of test subgrades.

Section Number	Foundation Treatment Method	Cushion Thickness (m)	Embankment Height (m)	Pile Length (m)	Pile Diameter (m)	Pile Spacing (m)
Section I	prestressed pipe pile and gravel cushion	0.3	7.2	14	0.4	2.0
Section II	prestressed pipe pile and gravel cushion	0.3	7.2	14	0.4	2.5
Section III	prestressed pipe pile, geogrid, and gravel cushion	0.3	5.3	14	0.4	2.0
Section IV	prestressed pipe pile and gravel cushion	0.3	5.0	14	0.4	2.5

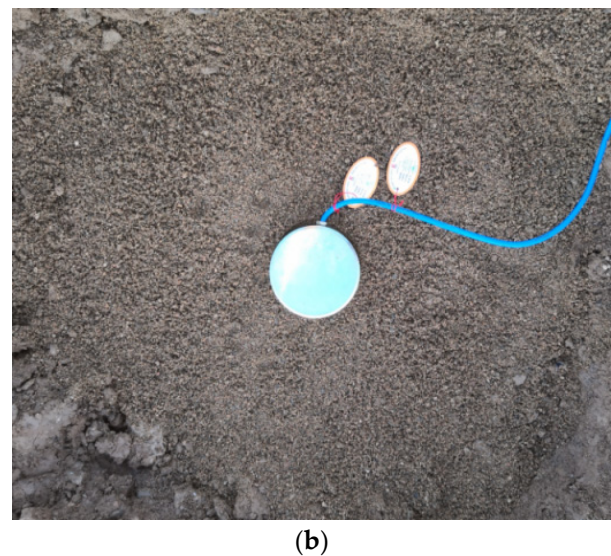
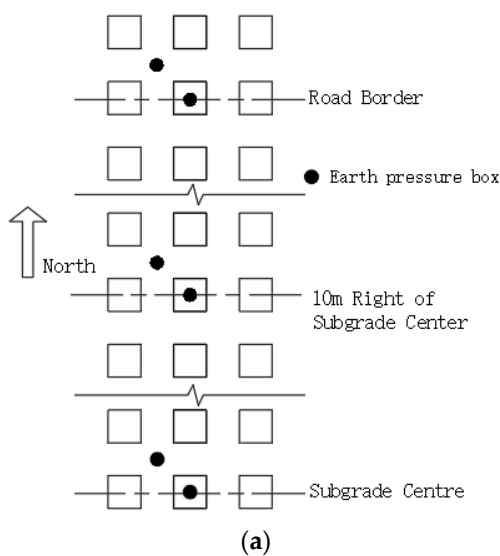


Figure 2. Schematic diagram of the monitoring element. (a) The layout of an earth pressure box in the test section. (b) An earth pressure box in the field test.

2.2. Test Results and Discussion

The field test observations started at the embankment filling and ended 5 months after completion of the filling. The construction period of Sections I and II was 0–60 days, and that of Sections III and IV was 0–30 days.

2.2.1. Variation Law of the Pile–Soil Stress Ratio

As shown in Figure 3, in the construction stage, the growth rate of the pile–soil stress ratio at each measuring point was the largest. With the embankment filled to the design elevation, the growth rate of the pile–soil stress ratio decreased gradually and tended to be stable. At the end of construction, the pile–soil stress ratio of each test section reached its peak value. The observation after 5 months shows that the pile–soil stress ratio decreased slightly and tended to be stable.

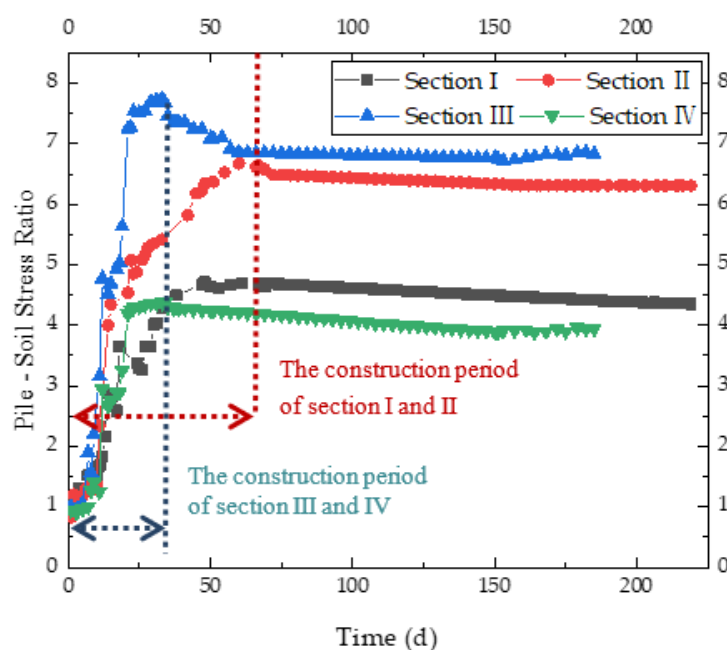


Figure 3. Pile–soil stress ratio curve of each test section.

The main reason is that with the increase in embankment filling height, the pile–soil differential settlement increased. The soil arch began to form under a small differential settlement and could remain stable under a certain differential settlement. Therefore, the pile–soil stress ratio of each section increased rapidly during construction. After the embankment was filled, with the continuous development of the consolidation settlement, the differential settlement between the piles and soil continued to increase and the new sliding surface soil arch structure inside the embankment was destroyed, and the pile–soil stress ratio curve began to decay. With the completion of the consolidation, a new soil arch structure was gradually formed inside the embankment, and the pile–soil stress ratio curve finally tended to be stable.

It can be seen that the pile–soil stress ratio decreased slightly after the completion of the embankment construction. The main reason is that the soil arching effect made the pile bear more load, which reduced the differential settlement, to a certain extent. Therefore, the pile–soil stress ratio decreased slightly during the post-construction observation period. As shown in Table 2, the pile–soil stress ratio of section III changed the most from the peak to the stable stage. It shows that when the embankment was completed, the pile–soil differential settlement was significantly reduced in the test section with reinforced materials compared with the unreinforced section. That is, reinforced materials had a certain effect on homogenization of the subgrade settlement.

Table 2. Pile–soil stress ratio of each test section.

No.	End of Construction Period	End of Observation Period	Decreasing Rate (%)
Section I	4.7	4.3	8.5
Section II	6.7	6.3	6
Section III	7.7	6.9	10.5
Section IV	4.3	4	6.9

To analyze the sensitivity of the pile spacing and embankment height to the change of the pile–soil stress ratios, the variation range of the influencing factors and pile–soil stress ratios of Sections I and IV were calculated by taking Section II as a reference. The pile–soil stress ratio of Section II was 6.3 at the end of the observation period. Compared with Sections I and II, the change rate of pile spacing was 20%, and the change rate of the pile–soil stress ratio was 31.7%. Compared with Sections II and IV, the change rate of the embankment height was 30.6% and the change rate of the pile–soil stress ratio was 36.5%. It can be seen that increasing the embankment height and pile spacing can improve the pile–soil stress ratios and promote the soil arching effect, but pile spacing has a greater impact on the pile–soil stress ratio.

2.2.2. Load Variation Law of Subgrade Cross-Sections

During the process of embankment filling, the magnitude and scope of the embankment load are constantly changing. Therefore, corresponding to different embankment filling heights, the pile–soil stress ratio and transverse load distribution characteristics will be different. Figure 4 shows the distribution of the pile and soil stress of Sections I and III in the subgrade cross-section. When the embankment filling height is smaller than 1 m, the soil pressure at the pile top and the soil stress between piles are the same. At this time, there is no obvious deflection of the stress, and the stress concentration effect of the pile is not obvious. With the increase in embankment filling height, the earth pressure on the pile top increases rapidly and the pile bears more embankment load. By analyzing the variation law of soil pressure at the pile top and the soil stress between piles in the subgrade cross-section of each test section, it can be seen that in the subgrade center to the shoulder direction of the pile top, the soil pressure gradually reduced, and the soil stress between piles increased gradually.

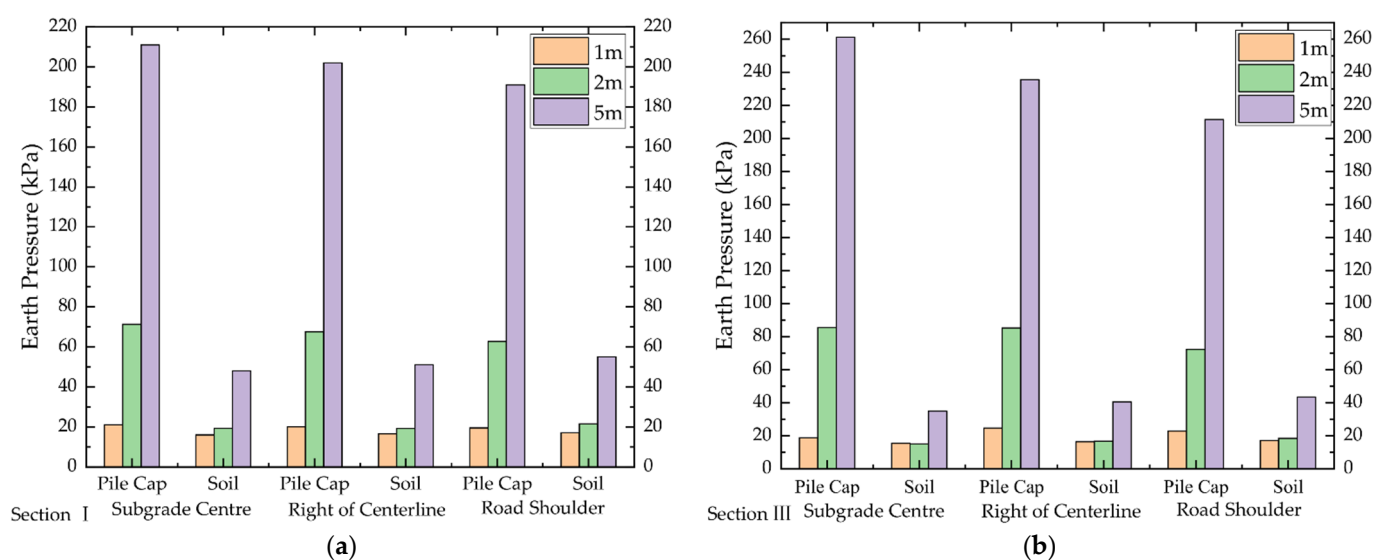


Figure 4. Earth pressure distribution of subgrade cross-sections. (a) Earth pressure distribution of Section I. (b) Earth pressure distribution of Section III.

As shown in Figure 5, with the increase in embankment height, the pile–soil stress ratio increased gradually and the degree of soil arching effect increased gradually. In the same test section, the pile–soil stress ratio gradually decreased from the embankment centerline to the road shoulder. It shows that the soil arch effect is the strongest at the embankment centerline and the soil arch effect is the weakest at the shoulder.

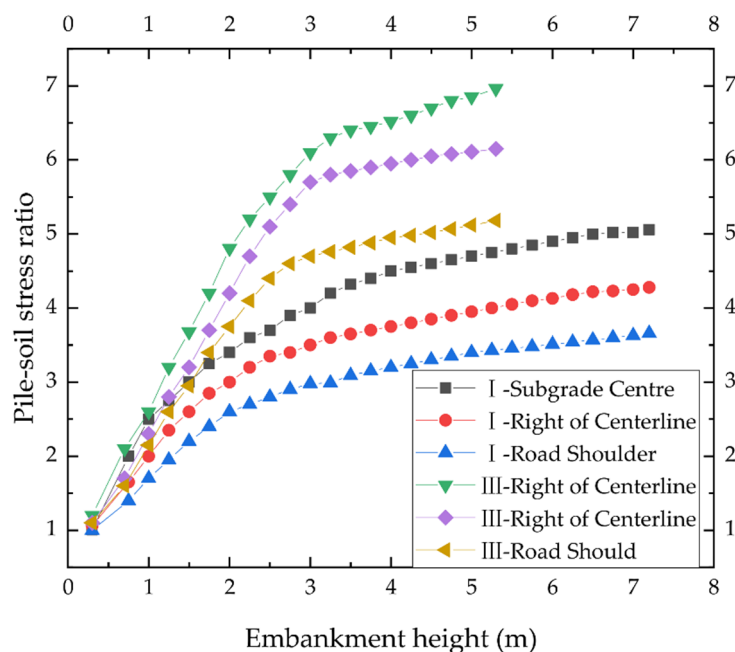


Figure 5. Variation law of pile–soil stress ratio in subgrade cross-sections.

In other words, the stress concentration effect of the pile-supported embankment is not only related to the height of embankment filling, but also to the position of the test point. From the centerline of the embankment to the shoulder, the stress concentration effect gradually decreases. The shoulder is on the free surface of the slope, and so the stress state is different from that at the center of the subgrade.

3. Numerical Simulation

To further analyze the variation of the cross-sectional load of wide subgrades under different influencing factors, this section is analyzed by the finite element method.

3.1. Numerical Model

3.1.1. Model Establishment and Parameter Selection

In this paper, a two-dimensional, full-section model is established by using ABAQUS. In the cross-section shown in Figure 6, the subgrade width is 42 m and the slope ratio is 1:1.5. To reduce the influence of the boundary effect, the foundation is widened by 25 m on both sides, and the depth of the soft soil foundation is 30 m. In the finite element model, the soft soil foundation is divided into five layers. As groundwater depth is 10 m, consideration is given to drainage consolidation of the foundation soil below the groundwater level [19]. The cushion thickness is 0.3 m, and the embankment fill's height is in 3–7 m placement in layers.

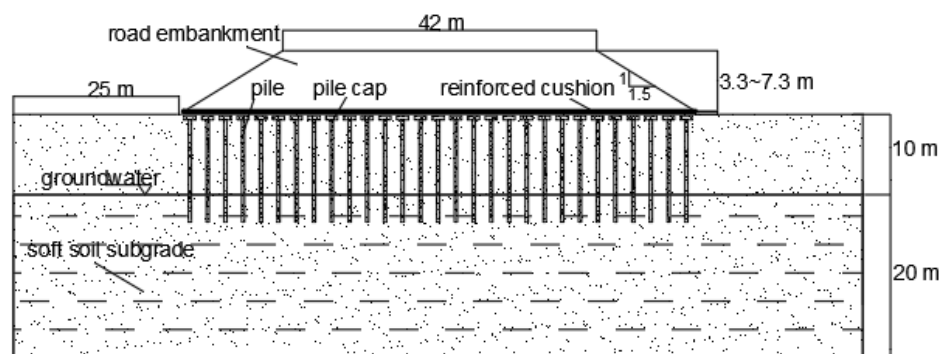


Figure 6. Cross-section of the geosynthetic-reinforced piled embankment.

The soft soil adopts the modified Cambridge constitutive, the road embankment adopts the Mohr-Coulomb model, and both the piles and geogrid use a linear elastic model. The parameters are shown in Table 3. The interaction between the geogrid and the embankment filler, pile, and soft soil foundation is simulated by normal hard contact and tangential ‘penalty’ contact. The contact friction angle between the geogrid and embankment is the same as that of the embankment filler. The friction angle between the pile and soft soil is $\varphi = 0.7\varphi'$, where φ' is the internal friction angle of the soft soil [20,21].

Table 3. Material parameters used in the finite element model of the piled embankment.

Material	Thickness (Length) (m)	Volume Weight (kN/m ³)	E (MPa)	Poisson Ratio	Internal Friction Angle (°)	Cohesion (kPa)	Moisture Content (%)	Void Ratio	Permeability Coefficient (10 ^{−5} m/d)
Pile	12–20	25	20,000	0.2	-	-	-	-	-
Geogrid	-	-	10	0.2	-	-	-	-	-
Cushion	0.3	20	20	0.3	37	6	-	-	-
Embankment	3–7	18.5	15	0.35	30	6	-	-	-
1. silty clay	4	19.2	6.3	0.34	13.8	24.5	24.9	0.778	6.1
2. silt	6	19.1	8.7	0.28	20.8	11.5	21.2	0.718	5.9
3. silty clay	3	19.6	5.9	0.28	12.9	24.7	24.2	0.737	5.8
4. silty clay	9	18.9	4.1	0.28	15.5	18.5	33.5	0.932	6.3
5. silt	8	20.4	8.8	0.28	21.3	12.8	19.8	0.588	6.2

The normal displacement is constrained on both sides of the model, and the bottom is a fixed constraint. The pore water pressure, p_w , is zero on the top of the groundwater simulating the free drainage boundary. The finite element calculation model is shown in Figure 7. In the numerical model, the unit type of the embankment and pile is CPE4, the unit type of the soft soil foundation above groundwater level is CPE4P, and the unit type of the soft soil foundation below groundwater level is CPE4P. The geogrid adopts the Truss element, and the element type is T2D2.

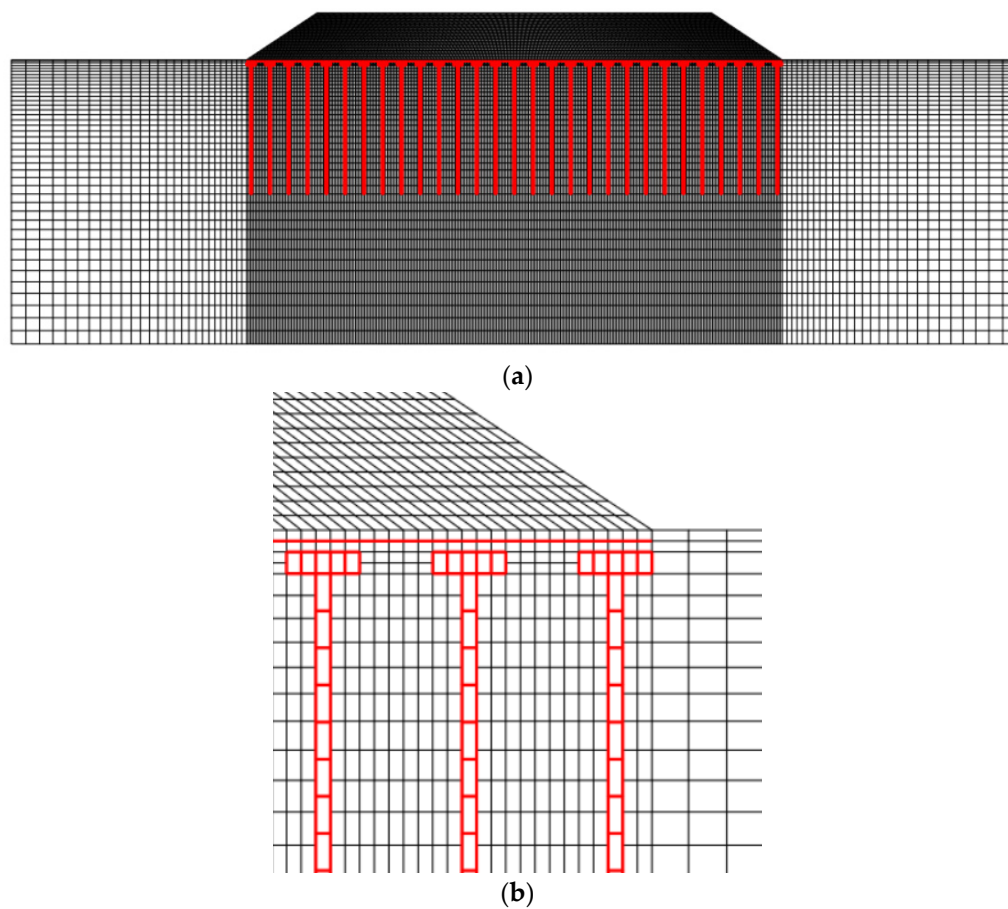


Figure 7. The meshing of the numerical model. (a) The meshing of the whole model. (b) Local amplification of the model.

3.1.2. Model Validation

Calculation model 1 is established according to the field test section (Section III). As shown in Figure 8, the calculated value of the subgrade settlement has the same variation as the measured value. At the center of the subgrade, the calculated value of the model is slightly higher than the measured value, and the maximum error is 0.5%. The calculated value of the model at the shoulder is slightly lower than the measured value, and the maximum error is 16%. The numerical simulation results are consistent with the field test results, which proves the rationality of the model.

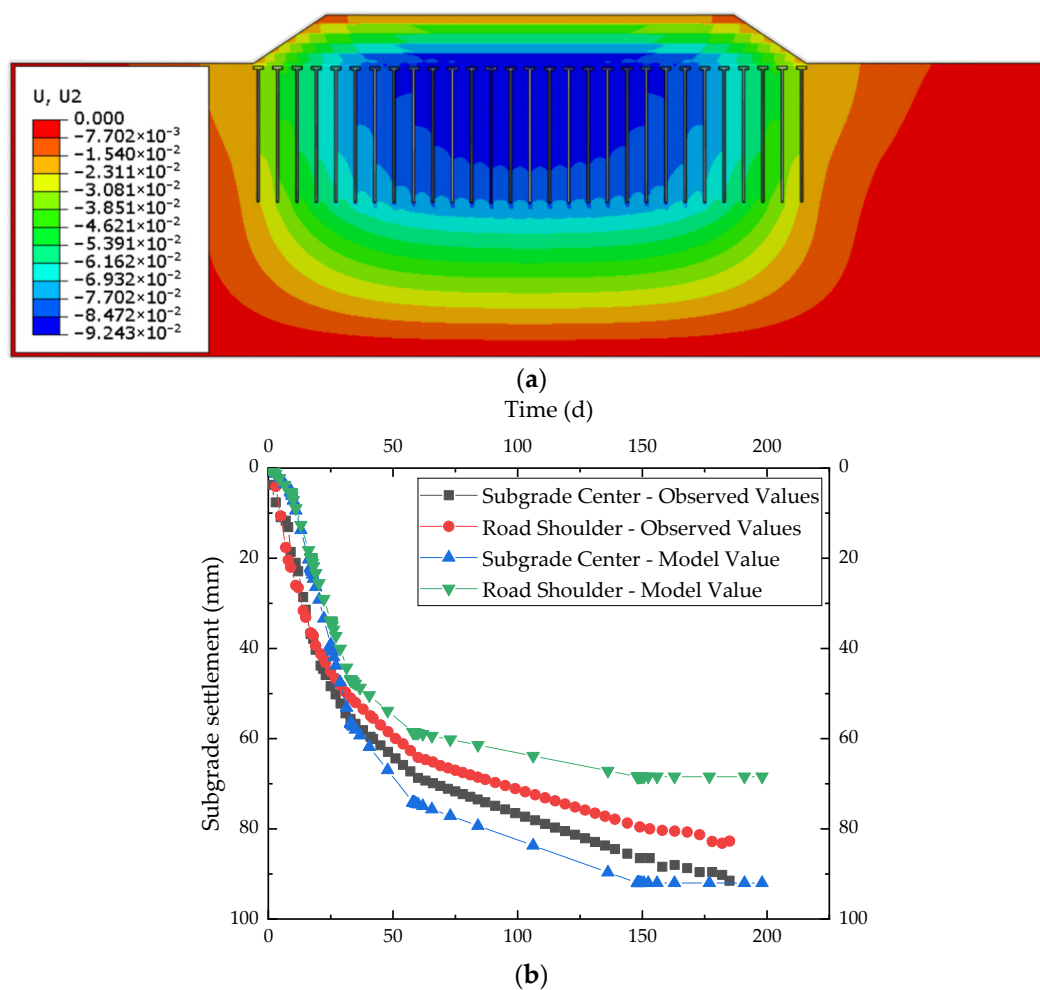


Figure 8. Numerical model verification. (a) Cloud image of the embankment settlement. (b) Comparison of field-measured values and the numerical simulation results of the subgrade settlement.

Based on model 1, the pile length, pile spacing, pile cap width, and embankment height were changed, respectively, for comparative analysis. As shown in Table 4, we set up 17 comparison models to analyze and compare the load variation law at the subgrade center, the right side of the centerline, and the road shoulder in completing our research on the load transfer mechanism of wide subgrade cross-sections.

Table 4. Parameter settings of the finite element model.

NO.	Influencing Factor				Declaration
	Embankment Height (m)	Pile Spacing (m)	Pile Cap Width (m)	Pile Length (m)	
1	5.3	2	1	14	Model validation
2	5.3	2	1	12	Models 1, 2, 3, 4, and 5 analyze the effect of pile length
3	5.3	2	1	16	
4	5.3	2	1	18	
5	5.3	2	1	20	
6	5.3	2.2	1	14	Models 1, 6, 7, 8, and 9 analyze the effect of pile spacing
7	5.3	2.4	1	14	
8	5.3	2.6	1	14	
9	5.3	2.8	1	14	

Table 4. Cont.

NO.	Influencing Factor				Declaration
	Embankment Height (m)	Pile Spacing (m)	Pile Cap Width (m)	Pile Length (m)	
10	5.3	2	0.8	14	Models 1, 10, 11, 12, and 13 analyze the effect of pile cap width
11	5.3	2	1.2	14	
12	5.3	2	1.4	14	
13	5.3	2	1.6	14	
14	3.3	2	1	14	Models 1, 14, 15, 16, and 17 analyze the effect of embankment height
15	4.3	2	1	14	
16	6.3	2	1	14	
17	7.3	2	1	14	

3.2. Analysis of the Numerical Simulation Results

We analyzed the internal stress redistribution of pile-supported reinforced embankments under embankment loads. The soil arching effect and the membrane effect are the comprehensive reflections of the load transfer and the interaction of each component. The load transfer efficacy reflects the bearing capacity of the pile and the load transfer degree under the combined action of the soil arching effect and membrane effect. Therefore, this section analyzes the load transfer law of pile-supported reinforced embankments through load transfer efficacy and clarifies the contribution of the soil arching effect and membrane effect to load transfer through load sharing ratios.

3.2.1. Variation Law of Load Transfer Efficacy

Figure 9 shows the load transfer efficacy variation under the influence of embankment height in model 1. When the filling height is less than 0.3 m, the load transfer efficacy at different positions of the cross-section is less than 35%. At this time, the embankment load borne by a single pile is approximately equal to the load shared by the pile cap, according to the area ratio. When the embankment height is less than 1.3 m, the load transfer efficacy increases rapidly with the increase in filling height. It indicates that with the increase in fill height, the pile–soil differential settlement increases gradually, and the soil arch begins to form and remains stable under the small differential settlement, and so the load transfer efficacy increases rapidly. When the embankment height is greater than 1.3 m, the growth rate of load transfer efficacy decreases significantly. It indicates that with the continuous development of the differential settlement, a stable soil arch structure is formed gradually inside the embankment and the load transfer efficacy tends to be stable.

The load variation law of the subgrade center and that of the right of the centerline are basically the same. When the height of the embankment is greater than 1.3 m, the load transfer efficacy between the subgrade center and the road shoulder begins to differ. When the embankment is filled, the load transfer efficacy at the road shoulder is significantly smaller than that of the subgrade center. The main reasons are that the road shoulder is the free surface of the slope and the stress state is different from the subgrade center, and with the increase in filling height, the load state difference increases gradually.

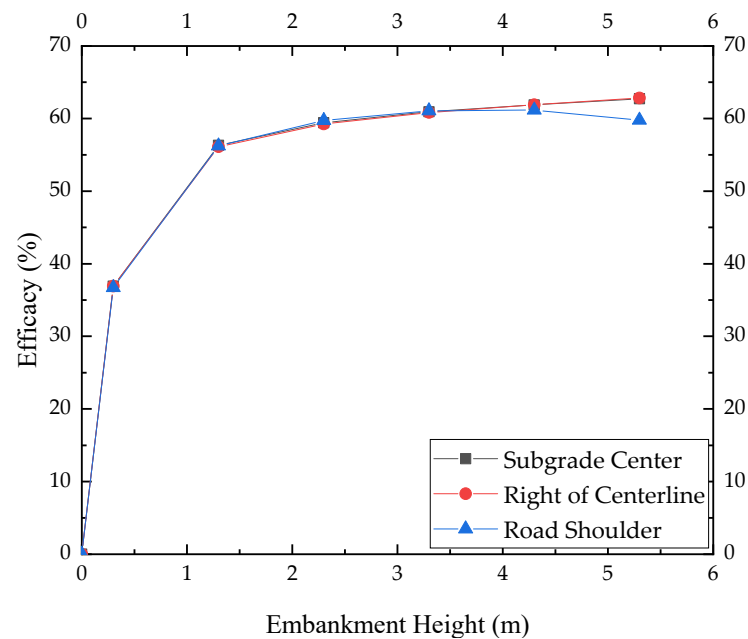


Figure 9. Variation of the load transfer efficacy under the influence of the embankment height.

3.2.2. Load Variation Law of Subgrade Cross-Sections

The pile-supported reinforced embankment transfers the embankment load to the pile through the combined action of the soil arching effect and the membrane effect. To clarify the load shared by the soil arching effect and the membrane effect in the process of embankment load transfer, as shown in Figure 10, the average soil stress σ_u at the upper part of the geogrid and the average soil stress σ_l at the lower part of the geogrid at the pile cap were extracted, respectively.

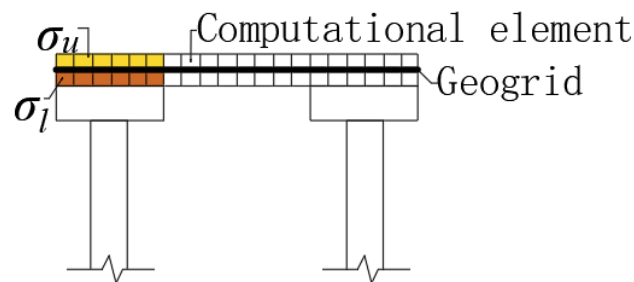


Figure 10. Calculation diagram of the load sharing ratio.

After data processing, the development law of the load sharing ratio of the soil arching effect and the membrane effect can be obtained. The calculation formula is as follows:

$$\begin{aligned}
 \sigma_s &= \sigma_u - \gamma H \\
 \sigma_m &= \sigma_l - \sigma_u \\
 n_s &= \frac{\sigma_s}{\sigma_s + \sigma_m} \\
 n_m &= \frac{\sigma_m}{\sigma_s + \sigma_m}
 \end{aligned} \tag{1}$$

where σ_s , is the load transferred by the soil arching effect, σ_m is the load transferred by the membrane effect, γ is the unit weight of the embankment fill, H is the embankment height, n_s is the load sharing ratio of the soil arching effect, and n_m is the membrane effect charge ratio.

Pile Length

As shown in Figure 11a, with the increase in pile length, the load transfer efficacy gradually increases. Compared with the load transfer efficacy at the shoulder, the load transfer efficacy at the center of the subgrade and on the right side of the centerline increases greatly. As shown in Table 5, with the increase in the pile length, the pile–soil differential settlement at the center of the subgrade and the right side of the centerline increases gradually, while the differential settlement at the shoulder is basically unchanged. It can be seen that the variation law of pile–soil differential settlement is basically the same as that of the load sharing ratio, indicating that the exertion degree of the soil arching effect is directly related to the differential settlement.

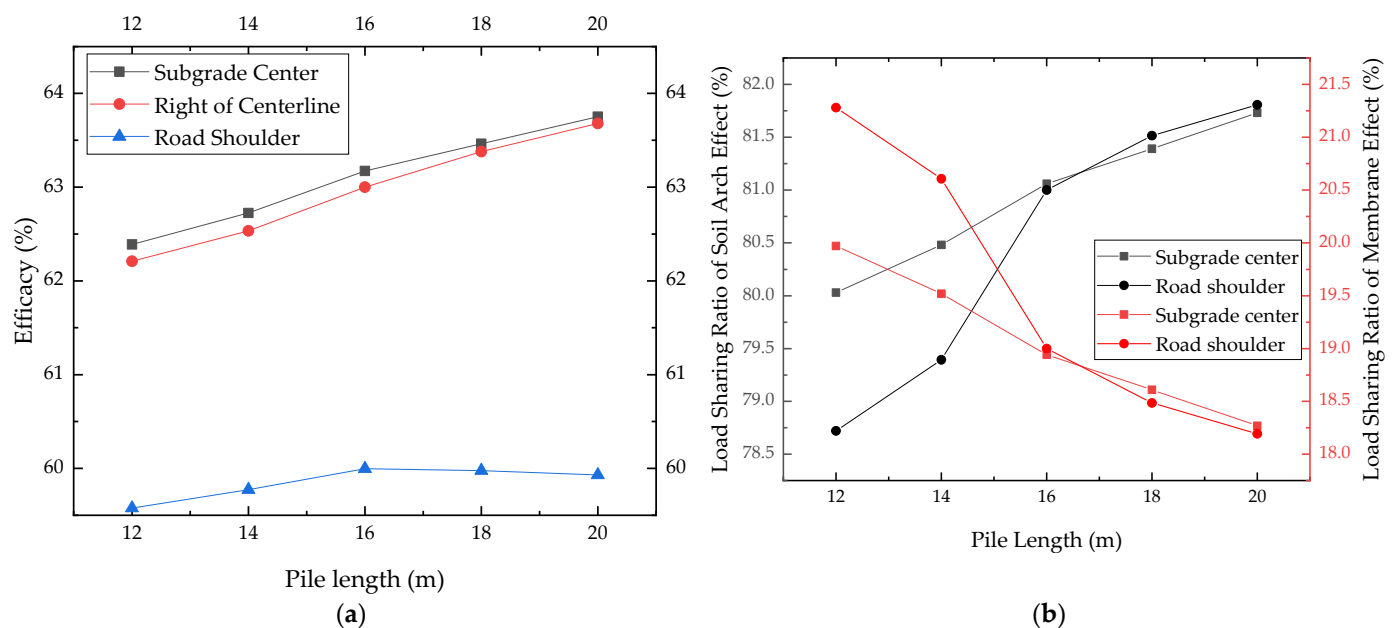


Figure 11. Load transfer law under the influence of pile length. (a) Variation law of the load transfer efficacy. (b) Variation law of the load sharing ratio.

Table 5. The pile–soil differential settlement with different pile lengths.

Pile Length (m)	Pile–Soil Differential Settlement (mm)		
	Subgrade Center	Right of Centerline	Road Shoulder
12	6	5	1
14	6	5	2
16	6	5	1
18	7	6	1
20	7	6	1

As shown in Figure 11b, the load sharing ratio of the soil arching effect at the center of the subgrade is greater than that at the shoulder. With the increase in pile length, the load sharing ratio of the soil arching effect increases gradually while the load sharing ratio of the membrane effect decreases gradually. When the pile length is greater than 16 m, the load sharing ratio of the soil arching effect at the center of the embankment is basically the same as that at the shoulder. The main reason is that the pile–soil differential settlement at the center of the subgrade is large, and so the soil arching effect is exerted to a high degree. While the stress state at the shoulder is complex, the deformation of the reinforcement is large under the combined action of the vertical load of the embankment and the lateral thrust of the slope, and so the load sharing of the membrane effect is relatively large. With

the increase in pile length, the reinforcement area gradually increases and the uneven settlement of the subgrade cross-section is basically stable. Therefore, when the pile spacing is greater than 16 m, the load sharing ratio of the subgrade cross-section is basically stable.

Pile Spacing

As shown in Figure 12a, the larger the pile spacing, the smaller the load transfer efficacy. It shows that when the pile cap size is the same, the pile spacing increases and the single pile treatment range increases. Therefore, the total load of the embankment within the bearing range of a single pile increases and the load transfer efficacy of the pile decreases.

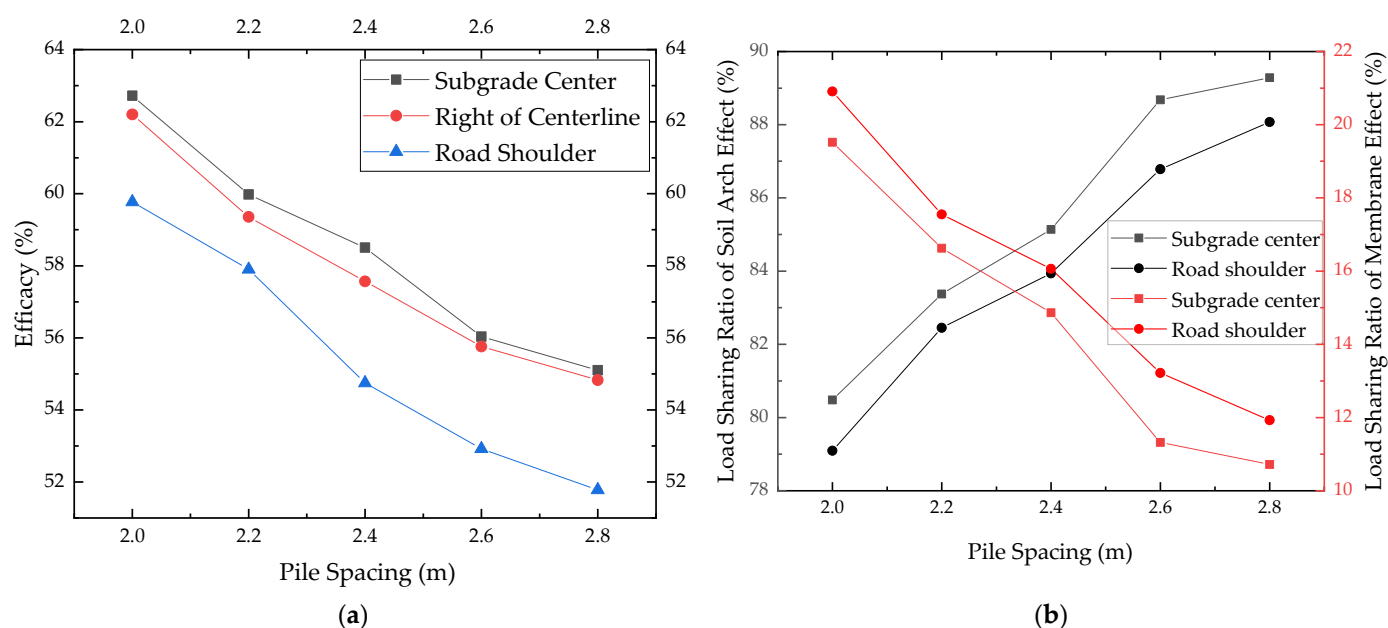


Figure 12. Load transfer law under the influence of pile spacing. (a) Variation law of the load transfer efficacy. (b) Variation law of the load sharing ratio.

As shown in Figure 12b, when the pile spacing increases, the load sharing ratio of the soil arching effect increases, which is consistent with the variation law of the pile–soil differential settlement shown in Table 6. However, compared with Figure 11a, under the combined action of the soil arching effect and the membrane effect, the load transfer efficacy of each observation point gradually decreases with the increase in pile spacing. The main reason is that as the pile spacing increases, the single pile treatment range increases, but the increase in embankment load in the single pile bearing range is much larger than that transferred to the pile cap by the soil arching effect. The load increase in the embankment within the bearing range of the single pile is much larger than the load transferred to the pile cap by the soil arching effect. Therefore, the load transfer efficacy decreases. It can be seen that the increase in the pile spacing promotes the soil arch effect, to a certain extent, but from the bearing capacity of a single pile, as the pile spacing increases, the bearing capacity of a single pile decreases.

Table 6. The pile–soil differential settlement with varied pile spacing.

Pile Spacing (m)	Pile–Soil Differential Settlement (mm)		
	Subgrade Center	Right of Centerline	Road Shoulder
2	6	5	2
2.2	8	7	3
2.4	10	8	2
2.6	11	9	4
2.8	13	11	5

Pile Cap Width

As shown in Figure 13a, with the increase in the pile cap width, the load transfer efficacy increases. The load transfer efficacy at the center of the subgrade and on the right side of the centerline is basically the same, though slightly larger than that at the shoulder. It shows that the load does not change uniformly in the subgrade cross-section, and the load changes greatly at the shoulder. When $a = 0.8$ m, the load transfer efficacy at the embankment center is 57.5%, and when $s = 2.2$, the load transfer efficacy at the embankment center is 60% (as shown in Figure 12a). That is, when the net pile spacing ($s-a$) is the same, the model with the larger pile cap has a larger load sharing because when the net spacing of piles is the same, the model with the larger pile cap has the greater pile cap coverage, and so a single pile bears a greater embankment load. Therefore, in the design of pile-supported embankments, a large pile cap design is recommended in order to bear a greater embankment load when the net spacing of the piles is the same.

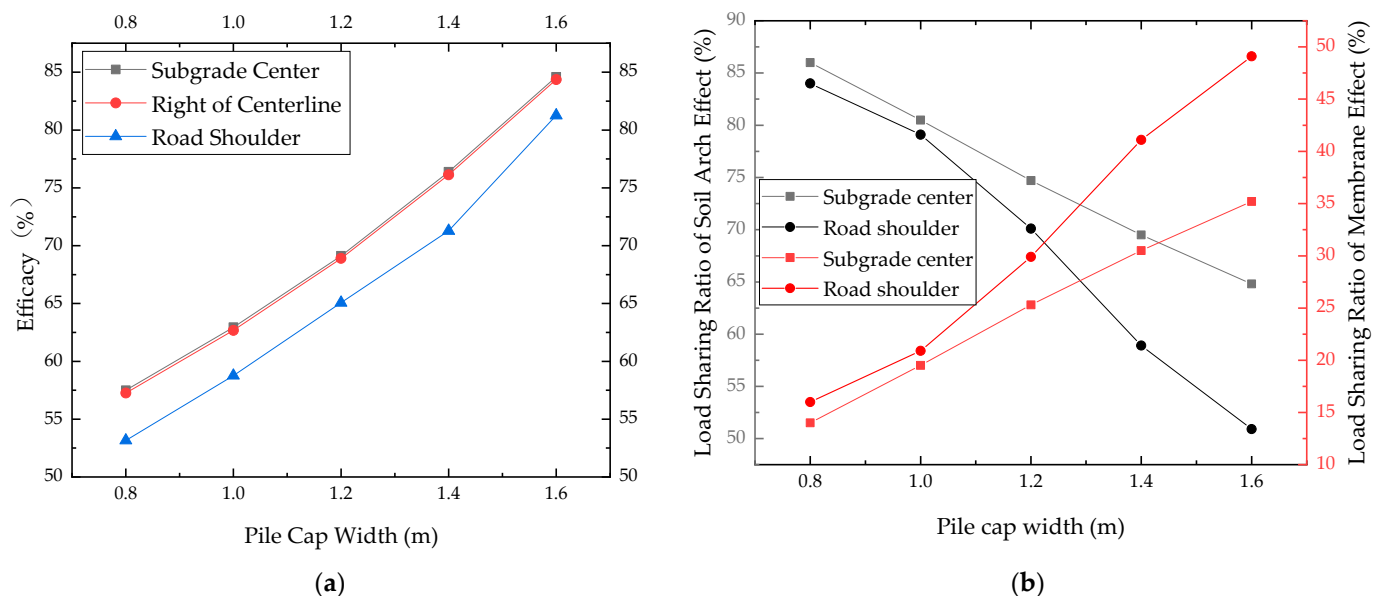


Figure 13. Load transfer law under the influence of pile cap width. (a) Variation law of the load transfer efficacy. (b) Variation law of the load sharing ratio.

As shown in Figure 13b, with the increase in the pile cap width, the load sharing ratio of the soil arching effect decreases, and when the pile cap width is greater than 1.2 m, the gap between the load sharing ratio of the soil arching effect at the center of the subgrade and the road shoulder gradually increases. The main reason is that with the increase in the pile cap width, the pile–soil differential settlement at each observation point decreases, to a certain extent (as shown in Table 7). That is, the soil arching effect is decreased. When the pile cap width is greater than 1.2 m, the differential settlement at the road shoulder is very small, and so the soil arching effect is weakened and the load sharing ratio of the soil arching effect is reduced.

Table 7. The pile–soil differential settlement with different pile cap widths.

Pile Cap Width (m)	Pile–Soil Differential Settlement (mm)		
	Subgrade Center	Right of Centerline	Road Shoulder
0.8	8	7	2
1	6	5	2
1.2	5	4	2
1.4	4	3	1
1.6	3	2	1

In the comprehensive analysis shown in Figure 13a,b, the load transfer efficacy of each observation point increases gradually with the increase in pile cap width. Although the stress transferred to the pile cap through the soil arching effect is reduced, due to the increase in the pile cap width, the coverage rate of the pile cap increases, the bearing capacity of the single pile increases, and the load transfer efficacy increases.

Embankment Height

As shown in Figure 14a, with the increase in embankment height, the load transfer efficacy increases gradually. The main reason is that the embankment height increases and the pile–soil differential settlement increases, which promotes the soil arching effect, to a certain extent. Because the geogrid has a “pocket lifting effect” on the upper soil, the increase in the upper load increases the deformation of the geogrid, thereby promoting the load transfer to the pile top. Therefore, the load transfer efficacy increases.

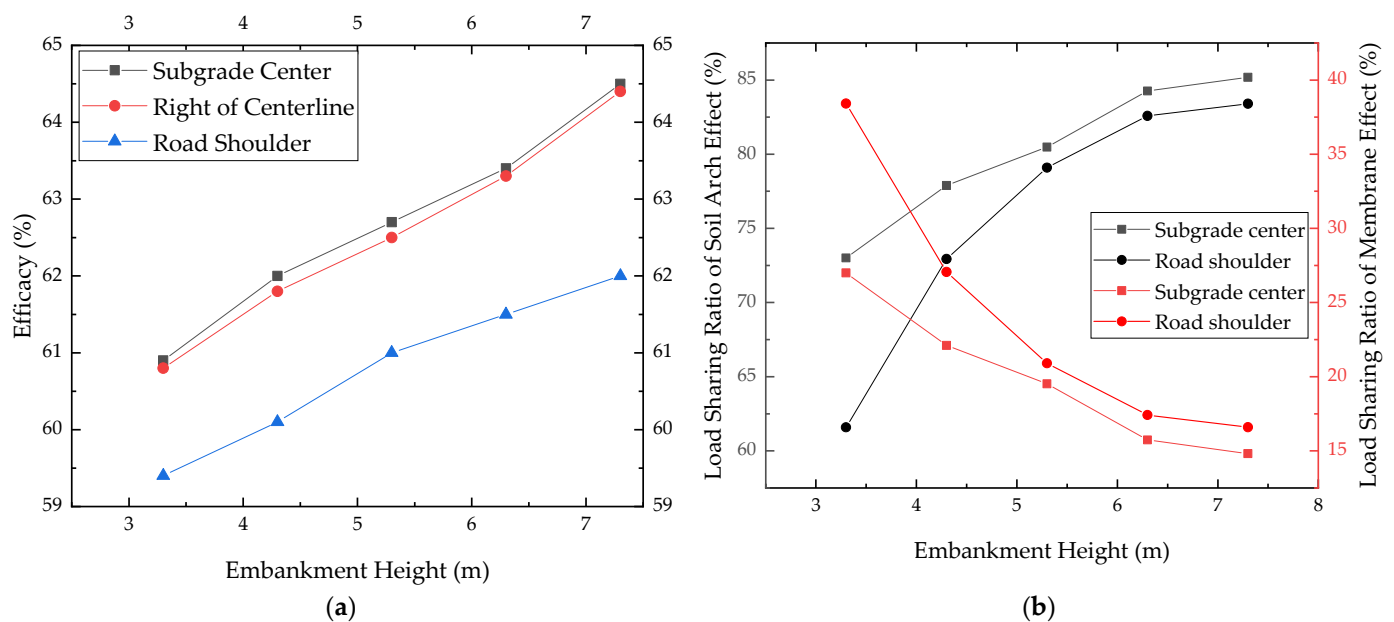


Figure 14. Load transfer law under the influence of embankment height. (a) Variation law of the load transfer efficacy. (b) Variation law of the load sharing ratio.

As shown in Figure 14b, with the increase in embankment height, the load sharing ratio of the soil arch effect at each observation point gradually increases. When the embankment height is greater than 5.3 m, the load sharing ratio at the center of the subgrade is close to that at the shoulder. The main reason is that with the increase in embankment height, the pile–soil differential settlement at each observation point gradually increases (as shown in Table 8), and so the soil arching effect increases. The soil arch forms and remains stable under certain differential settlements. Therefore, the pile–soil differential settlement at the center of the subgrade increases gradually, but the increased range of the load sharing ratio of the soil

arching effect is small. However, the initial value of the differential settlement at the shoulder is small. With the increase in the pile–soil differential settlement, the degree of the soil arching effect increases, and so the load sharing ratio of soil arching effect increases rapidly.

Table 8. The pile–soil differential settlement with different embankment heights.

Embankment Height (m)	Pile–Soil Differential Settlement (mm)		
	Subgrade Center	Right of Centerline	Road Shoulder
3.3	4	3	1
4.3	5	4	1
5.3	6	5	2
6.3	7	6	2
7.3	9	8	2

Macroscopic view: Increasing the pile length, pile cap width, and embankment height, and reducing the pile spacing can increase the bearing capacity of a single pile. Compared with the subgrade center, the load transfer efficacy at 10 m on the right side of the central line decreases by 0.1–1.6% and the load transfer efficacy at the shoulder decreases by 2.5–7.5%. It can be seen that the laws obtained by numerical simulation and field tests are basically the same. That is to say, the variation of the load transfer efficacy of the subgrade cross-section is related to the position of the observation point. From the subgrade center to the shoulder direction, the load transfer efficacy decreases gradually and the load transfer efficacy at the shoulder decreases significantly.

Variation law of load sharing ratios of subgrade cross-sections: Macroscopically, increasing the pile length, pile spacing, and embankment height, and reducing the pile cap width can improve the soil arch effect load sharing ratio. The variation of the load sharing ratio of the soil arching effect is consistent with the variation law of the pile–soil differential settlement, which shows that the differential settlement of pile–soil directly affects the exertion degree of the soil arching effect. The load sharing ratio of the soil arch effect at the shoulder is smaller than that at the center of the subgrade, indicating that the deformation of the geogrid at the shoulder is large and the membrane effect is significant. In comparing the load sharing ratio of the soil arching effect of each calculation model, the load ratio of the embankment center is 65–90% and that of the shoulder is 51–88%. It can be seen that the load transfer of the embankment is mainly based on the soil arch effect and supplemented by the tensile membrane effect.

3.2.3. Sensitivity Analysis of the Influencing Factors

The influence of pile spacing and embankment height on load transfer is analyzed through a field test, which shows that pile spacing has a great influence on load transfer. Due to the limitations of the field tests, the sensitivity coefficient is used for supplementary analysis in this section to evaluate the influence of various influencing factors on load transfer. The sensitivity coefficient S_{AF} represents the sensitivity of the influence factors such as pile length and pile spacing to the evaluation index (the load transfer efficacy E). The calculation formula is shown below. The larger the $|S_{AF}|$ is, the more sensitive the evaluation index A is to the influencing factor F , as follows:

$$S_{AF} = \sum_{i=1}^n \frac{\Delta A_i / A_0}{\Delta F_i / F_0} \quad (2)$$

where $\Delta F_i / F_0$ is the change rate of the influencing factors, as a percentage, ΔF_i is the amount of change in the influencing factors, F_0 represents the corresponding parameters in model 1, $\Delta A_i / A_0$ is the corresponding change rate of the evaluation index, A , when the influencing factor F changes in ΔF_i , ΔA_i is the amount of change in the evaluation index, and A_0 is the value of the evaluation index in model 1.

As shown in Table 9, the pile cap width has the greatest impact on the load transfer efficacy, followed by the pile spacing, while the pile length and embankment height have less impact on the load transfer efficacy.

Table 9. Sensitivity coefficient of each calculation model.

Influencing Factor	Evaluation Scope	Sensitivity Coefficient $ S_{AF} $
Pile length (m)	12–20	0.17
Pile spacing (m)	2.2–2.8	1.43
Pile cap width (m)	0.8–1.6	2.03
Embankment height (m)	3.3–7.3	0.27

3.3. Comparison between Theoretical Value and Calculated Value

3.3.1. Analysis of Calculation Methods

To further analyze the influence of various response factors on the load transfer, this section compares the model calculation results with the theoretical results of Chinese Specification [22], BS8006-1 [23], EBGEO [24], and Nordic Guidelines [25], and evaluates the applicability of various methods.

The load transfer efficacy E of the piles is defined as the ratio of the embankment load borne by a single pile to the total embankment load within the bearing range of a single pile. The load transfer efficacy can measure the degree of soil arching effect, as follows:

$$E = \frac{P}{\gamma HS^2} \quad (3)$$

where P is the embankment load acting on the pile cap (kN), S is the pile spacing (m), H is the embankment height (m), and γ is the unit weight of the embankment fill (kN/m³).

(1) British Standard

In the revised British Standard BS8006-1, the first calculation method uses Marston's theory and the second calculation method uses the Hewlett and Randolph soil arch model.

The first algorithm, based on Marston's theory in BS8006-1, uses Marston's formula to calculate the distribution load on the reinforced material, the ratio of the pile top stress, and the average stress at the bottom of the embankment, as shown in Formula (4):

$$\frac{p'_c}{\sigma'_v} = \left[\frac{C_c a}{H} \right]^2 \quad (4)$$

where p'_c is the earth pressure at the top of the pile cap (kPa), C_c is the arch coefficient, the end bearing pile can be expressed as $C_c = 1.95H/a - 0.18$, the floating pile can be expressed as $C_c = 1.5H/a - 0.7$, and $\sigma'_v = (f_{fs}\gamma H + f_q W_s)$ is the average earth pressure of the foundation base (kPa).

The second algorithm in BS8006-1 is based on the Hewlett and Randolph theory. Hewlett and Randolph believed that the hemispherical model consists of three-dimensional spherical arches between four piles and four flat soil arches on a strip between two piles. It is assumed that the soil element at the top of the vault or the foot of the arch will be damaged only when it is in a limited state, and then the stress borne by the pile and soil can be obtained.

The load transfer efficacy when the plastic point appears on the vault is as shown in Formula (5):

$$E_{crown} = 1 - \frac{(S^2 - a^2)}{S^2 \gamma H} \left[\sigma_i + \gamma(S - a)/\sqrt{2} \right] \quad (5)$$

where S is the pile spacing between adjacent piles (m), σ_i is the pressure acting under the surface of the hemispherical dome (kPa), γ is the unit weight of the embankment fill (kN/m³), H is the height of the embankment (m), and a is the size of the pile caps (m).

The load transfer efficacy when the plastic point appears on the pile top is as shown in Formula (6):

$$E_{cap} = \frac{\beta}{1+\beta};$$

$$\beta = \frac{2K_p}{(K_p+1)(1+\frac{a}{s})} \left[\left(1 - \frac{a}{s}\right)^{-K_p} - \left(1 + K_p \frac{a}{s}\right) \right] \quad (6)$$

The smaller value E_{min} between the two was taken as the load transfer efficacy in the design.

(2) Chinese Specification

Chen Yunmin believed that when the embankment filling height is low, the soil element at the top of the soil arch and pile cap is not necessarily in a plastic state, and the calculation using the limit equilibrium state is inconsistent with the actual situation. Therefore, parameter α is introduced to modify the Hewlett and Randolph model.

The load pressure F_{cap} on the top of the pile and the soil stress σ_{su} between the piles can be calculated according to Formula (7):

$$F_{cap} = \frac{2\alpha K_p}{\alpha K_p + 1} S^2 \sigma_{su} \left[(1 - \delta)^{1-\alpha K_p} - (1 - \delta)(1 + \delta \alpha K_p) \right]$$

$$\sigma_{su} = \gamma \left[H - \frac{S}{\sqrt{2}} \left(\frac{2\alpha K_p - 2}{2\alpha K_p - 3} \right) \right] (1 - \delta)^{2(\alpha K_p - 1)} + \gamma(S - b) \sqrt{2} \left(\frac{\alpha K_p - 1}{2\alpha K_p - 3} \right) \quad (7)$$

where σ_{su} is the soil stress between piles (kPa), K_p is the coefficient of passive earth pressure, γ is the unit weight of the embankment fill (kN/m³), S is the pile spacing between adjacent piles (m), b is the size of the pile caps (m), δ is the ratio of pile cap width to pile spacing ($\delta = b/S$), and α is the undetermined coefficient.

The load transfer efficacy R_p of a rigid pile can be calculated according to Formula (8):

$$R_p \begin{cases} \frac{F_{cap}(\alpha)}{\gamma H S^2 \eta}, (\alpha < 1) \\ \frac{F_{cap}(1)}{\gamma H_{cr} S^2 \eta}, (\alpha \geq 1) \end{cases} \quad (8)$$

where η is the coefficient, and when the square pile arrangement $\eta = 1$ and when the triangle pile arrangement $\eta = 0.866$.

(3) Nordic Guidelines

Based on the wedge-shaped soil arch model, the load on the soil between the piles is always equal to the soil weight of the wedge, which is independent of the embankment height. The weight of wedge-shaped soil in a two-dimensional state is shown in Formula (9):

$$W_{2Dd} = \frac{(c - b)^2}{4 \tan 15^\circ} \gamma_d = 0.93(c - b)^2 \gamma_d \quad (9)$$

The weight of wedge-shaped soil in a three-dimensional state is shown in Formula (10):

$$W_{3Dd} = \frac{1 + \frac{c}{b}}{2} \cdot W_{2Dd} \quad (10)$$

where H is the height of the embankment (m), b is the size of the pile caps (m), and c is the pile spacing between adjacent piles (m).

(4) German Standard

In the calculation method of the soil arching effect in the German standard, it is assumed that the shape of the soil arching is hemispherical, with a radius of $0.5s$. The stress analysis of the arch structure under a three-dimensional state is carried out to obtain the

average stress on the pile cap and the soil between piles. The soil stress between piles can be calculated according to Formula (11):

$$\sigma_{zok} = \lambda_1^\chi \left(\gamma_k + \frac{P_K}{h} \right) \left\{ h \left(\lambda_1 + h_g^2 \lambda_2 \right)^{-\chi} + h_g \left[\left(\lambda_1 + \frac{h_g^2 \lambda_2}{4} \right)^{-\chi} - \left(\lambda_1 + h_g^2 \lambda_2 \right)^{-\chi} \right] \right\}$$

$$\chi = \frac{d(K_{crit}-1)}{\lambda_2 s}$$

$$\lambda_1 = \frac{1}{8}(s-d)^2$$

$$\lambda_2 = \frac{s^2 + 2ds - d^2}{2s^2}$$
(11)

The earth pressure at the top of the pile cap can be calculated according to Formula (12):

$$\sigma_{zsk} = [(\gamma_k h + P_K) - \sigma_{zok}] \frac{A_E}{A_S} + \sigma_{zok}$$
(12)

where A_S is the cross-sectional area of a single pile (m^2), A_E is the influence range of single pile (m^2), K_{crit} is the critical principle stress ratio, γ_k is the unit weight of the embankment fill (kN/m^3), P_K is the characteristic value of the permanent distributed load on the top of the reinforced earth structure (kN/m^2), h_g is the arch height (m), $\begin{cases} h_g = s/2, h \geq s/2 \\ h_g = h, h < s/2 \end{cases}$, and s is the diagonal distance between two adjacent piles when the pile is square (m).

3.3.2. Analysis of Calculation Results

As shown in Figure 15, when the pile spacing increases, the variation trend of the load transfer efficacy obtained according to the Nordic Guidelines is basically the same as that calculated by the model, while the load transfer efficacy obtained according to other specifications decreases greatly. From the analysis of the coincidence between the calculated value and the theoretical value, when the pile spacing is small ($s < 2.2$ m), the first algorithm recommended by BS 8006-1 (BS8006-1-1) is suitable, and when the pile spacing is large ($s > 2.2$ m), the Chinese specification is suitable.

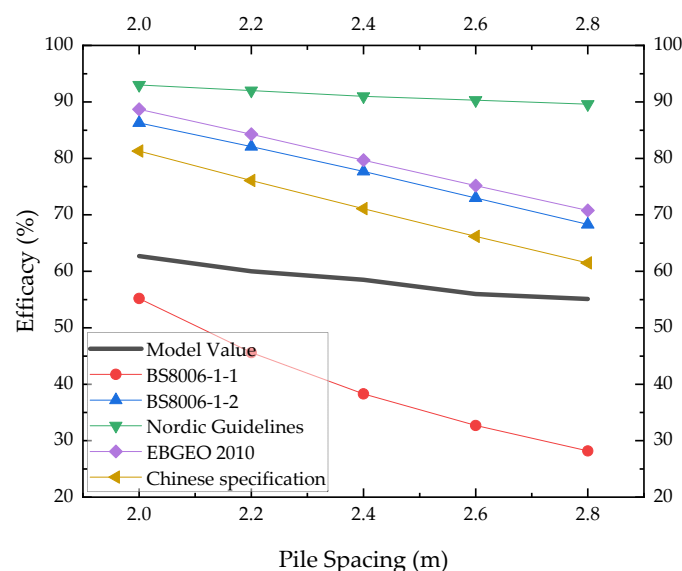


Figure 15. Calculation and theoretical value of the load transfer efficacy under varied pile spacing.

As shown in Figure 16, when the pile cap width increases, the load transfer efficacy calculated according to BS8006-1-1 increases greatly compared with the other specifications. From the analysis of the coincidence between the calculated value and the theoretical value, it is suitable to adopt the Chinese specification.

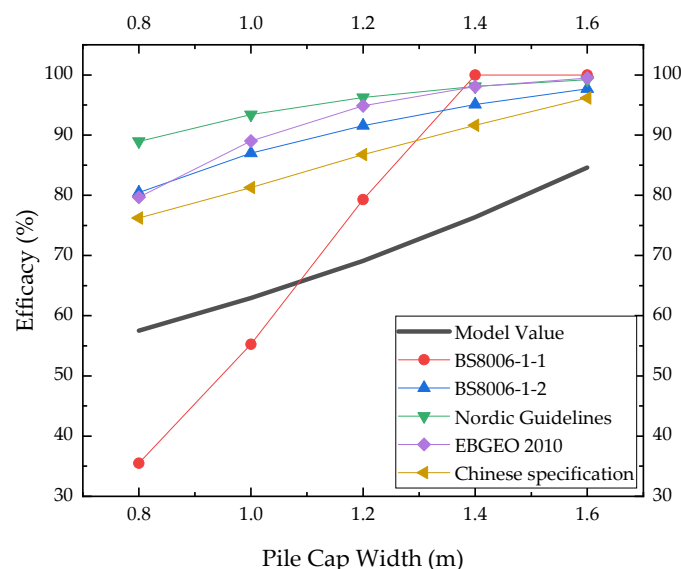


Figure 16. Calculation and theoretical value of the load transfer efficacy under different pile cap widths.

As shown in Figure 17, when the embankment height increases, the load transfer efficacy according to the Chinese code and the second algorithm recommended by BS 8006-1 (BS8006-1-2) increases greatly. From the analysis of the coincidence between the calculated value and the theoretical value, it is suitable to adopt the BS8006-1-1 method.

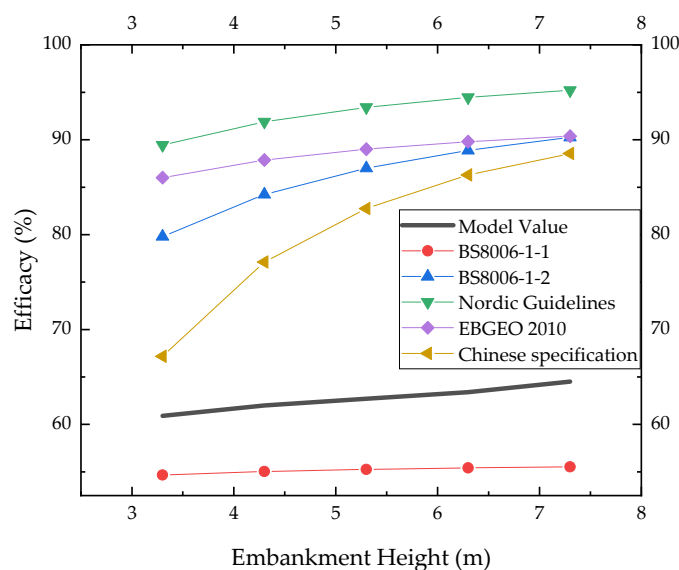


Figure 17. Calculation and theoretical value of the load transfer efficacy under the embankment height.

For the same calculation model, the theoretical values obtained by the different specifications are different, to some extent, and the main reason is that the theoretical basis of the different algorithms is different. BS8006-1-2 is based on the Hewlett and Randolph [26] soil arch model, which is a calculation formula for the load transfer efficacy obtained at the limit state. In fact, neither the element at the top of the pile cap nor the element at the top of the soil arch has entered the limit state. Therefore, Chen Yunmin [27] introduced the parameter α to judge whether the soil has entered a plastic state, and then revised the Hewlett and Randolph soil arch model. Therefore, the theoretical value obtained according to the Chinese specifications is less than that of BS8006-1-2. BS8006-1-1 adopts Marston's [28] theory, as it considered that the plane of equal settlement is formed when the embankment height is greater than 1.4 times the net spacing. Therefore, the BS8006-1-1 method is suitable

for high embankments. EBGeo is based on the multi-arch model proposed by Zeaske and Kempfert [29], which assumes that the soil arch is a system composed of a series of spherical shell elements with different centers and radii. The model is suitable for the calculation of the soil arching effect of pile-supported reinforced embankments, and it is not suitable for the evaluation of unreinforced pile-supported embankments. The Nordic Guidelines adopt the wedge-shaped soil arch model with a top angle of 30° , as proposed by Carlsson [30], and assumes that the load acting on the soil between piles is equal to the weight of the wedge under an embankment height. The calculation model is simple, but it has a large deviation from the measured value.

In summary, compared with other codes, the load transfer efficacy calculated according to the Chinese specification and BS8006-1-1 is in good agreement with the simulated value. In the embankment design, if the pile cap width changes greatly, it is recommended to calculate according to the Chinese specification. If the embankment height changes greatly, it is recommended to calculate according to BS8006-1-1.

4. Conclusions

This paper is based on a two-dimensional finite element model that analyzes the load transfer law under the action of different influencing factors, the variation of the load-sharing ratio of the soil arch effect and membrane effect, and research on the load variation law of wide subgrade cross-sections. Based on the analysis and discussion of the results, the following conclusions can be drawn:

- (1) Analysis of influencing factors: Increasing the pile length, pile cap width, and embankment height and reducing the pile spacing will increase the pile load transfer efficacy, that is, a single pile's bearing capacity will be improved. The pile cap's width has the greatest influence on the load transfer efficacy, followed by pile spacing, while the pile length and embankment height have less influence on the load transfer efficacy.
- (2) Variation law of the load sharing ratio of subgrade cross-sections: Macroscopically, increasing the pile length, pile spacing, and embankment height and reducing the pile cap width can improve the soil arch effect's load sharing ratio. The load sharing ratio of the soil arch effect at the shoulder is smaller than that at the center of the subgrade, indicating that the deformation of the geogrid at the shoulder is large and the membrane effect is significant. Comparing the load sharing ratio of the soil arch effect of each calculation model, the load ratio of the embankment center is 65–90% and that of the shoulder is 51–88%. It can be seen that the load transfer of the embankment is mainly based on the soil arch effect and supplemented by the tensile membrane effect.
- (3) Load variation law of subgrade cross-sections: Compared with the center of subgrade, the load transfer efficacy at 10 m on the right side of the central line decreases by 0.1–1.6% and the load transfer efficacy at the shoulder decreases by 2.5–7.5%. This shows that the variation of the load transfer efficacy of subgrade cross-sections is related to the position of the observation point. From the center of the subgrade to the shoulder, the load transfer efficacy decreases gradually and the load transfer efficacy at the shoulder decreases significantly.
- (4) Compared with other codes, the load transfer efficacy calculated according to the Chinese specification and BS8006-1-1 is in good agreement with the simulated value.

In this paper, the mechanical behavior of pile-supported reinforced embankments is studied by field tests and numerical simulations. According to the research results, the following suggestions are put forward for the engineering application of pile-supported reinforced embankments: There are many influencing factors for pile-supported reinforced embankments. In an embankment design, the design parameters can be adjusted according to the sensitivity analysis results of the influencing factors, and the maximum economic benefit can be achieved while satisfying the load transfer efficiency. Further, in an embankment design, different design schemes can be adopted for the center and shoulder of the subgrade according to the load variation law of the subgrade cross-sections. In the

theoretical calculation, different methods should be adopted for comprehensive analysis, according to the characteristics of the project.

Author Contributions: Writing—original draft preparation, X.W. (Xin Wang); writing—review and ending, X.W. (Xizhao Wang); funding acquisition, G.Y.; validation, X.Y. and D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (Grant No. 52079078); the Key Research and Development Projects in Hebei Province (Grant No. 20375504D); the Hebei Provincial Department of Transportation Science and Technology Project (Grant No. RW-202014); and the Innovation Funding Project for Postgraduates in Hebei Province (Grant No. CXZZBS2022121).

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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