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Research Article

Analysis of the Embankment Settlement on Soft Soil Subgrade with a Cement Mixed Pile

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The settlement of the widening of soft soil subgrade highways is typically associated with different treatment positions of cement mixed piles. In order to overcome this, in the current paper we employ the finite element method to simulate and analyze the influence of piles under an existing road slope and under an existing subgrade and new embankment on the settlement characteristics of the subgrade and foundation. In particular, we focus on the influence of the pile length and pile spacing on the subgrade and foundation settlements based on a northern high-speed reconstruction and expansion project. The subgrade and foundation soils in the finite element analysis are considered to be homogeneous, continuous, and isotropic elastoplastic materials. The Mohr–Coulomb ideal elastoplastic constitutive model is implemented as the constitutive soil model. The impact of piles under an existing subgrade and new embankment on the settlement is observed to be more significant than that of piles under the existing road slope. Moreover, the subgrade and foundation settlements increase with the pile spacing under the existing road slope and under the existing subgrade and new embankment. More specifically, an increase of the pile spacing from 200% to 400% of the pile diameter is associated with an increase in the maximum settlement of the foundation surface from 1.76 to 1.85 cm (existing road slope) and from 1.44 to 1.96 cm (existing subgrade and new embankment). In addition, the subgrade and foundation settlements decrease for increasing pile lengths under the existing road slope and under the existing subgrade and new embankment, the pile length increases from 4.7 to 9.2 m, and the maximum foundation surface settlement is reduced from 6.2 to 5.52 cm and from 9.73 to 5.43 cm, respectively. The results can provide reference for future subgrade widening projects.

1. Introduction

The reconstruction and expansion of highways typically pass through areas of soil, with high natural moisture content and compressibility and a low bearing capacity. In addition, following years of operation, the physical and mechanical properties of the old subgrade vary greatly to those of the new subgrade and foundation soil. This results in great differences in the settlement, as well as the additional stress of the widened subgrade and pavement. Thus, soft soil foundation treatment is currently the focus of much academic interest [1–3].

Tan et al. employed the finite element method to analyze the settlement deformation of the widening subgrade with PTC piles and compared the results with measured values [4]. Based on the Beijing-Zhuhai high-speed expansion project, Sun et al. compared the deformation of the widening subgrade of the composite foundation with cement mixed piles, CFG piles, and prestressed concrete pipe piles and observed a minimal settlement under the prestressed concrete pipe piles [5]. Xu et al. analyzed the differential settlement, horizontal displacement, and pavement structural stress under the widening of soft soil subgrade in coastal areas via the finite element method [6]. Jiang et al. conducted finite element simulations on the deformation law of new and old subgrade and foundations in the widening of expressways across soft soil areas [7]. Nie et al. analyzed the mechanical properties of subgrade under varying heights, widths, and filling parameters via the finite element method [8]. Based on the reconstruction and expansion project of the G320 National Road, Wang evaluated the widened subgrade settlement and the additional stress induced by the pavement structure under differential settlements [9]. Ke monitored a settlement under the widening of soft soil subgrade based on the reconstruction and expansion of the Shian Section project of Beijing, Hong Kong, and Macao and simulated the additional stress of the subgrade widening under varying settlements [10]. Pan investigated the settlement characteristics of widening subgrade under a pile-composite foundation via centrifugal tests [11]. The aforementioned studies generally focus on the settlement and stress of widening soft subgrades, soft foundation treatments, and influencing factors of soft soil subgrade.

Based on the properties of thick soft soil foundation, reconstruction and expansion projects often lay reinforcing piles on the old roadside slope to reduce the uneven settlement of the widening subgrade. In their study of the Guangsan high-speed reconstruction and expansion project, Yu et al. compared the settlement characteristics of the widening subgrade of two pile treatments of the foundation (the pile treatment under new subgrade and simultaneous pile treatment under new and old subgrade) and analyzed the impact of the lightweight embankment filler on the settlement of the subgrade [12]. Liu et al. investigated the deformation of new and old subgrades at the Zhenjiang section expansion of the Huning Expressway under the influence of powder jet piles (on the slope and nonslope) on piles length, distance, and side friction [13]. Current research generally jointly considers slope piles and new or old subgrade piles, while there is a lack of studies that separately focus on either the side slope or nonside slope piles. In order to fill in this gap in the literature, in the current paper we take the northern high-speed reconstruction and expansion project as the case study to perform finite element numerical simulations. In particular, we compare the settlement characteristics of cement mixed piles (of varying lengths and distances) under the following cases: (1) the existing road slope and (2) the existing subgrade and new embankment.

2. Subgrade Finite Element Model

2.1. Model Assumptions. In order to simulate the overall structure of the subgrade and pavement, we make the following assumptions. (1) The subgrade and foundation soils are homogeneous, continuous, and isotropic elastoplastic materials. (2) The yield criterion of the material is combined with the Mohr–Coulomb ideal elastoplastic constitutive model to form a constitutive soil model [14, 15]. (3) The contact between the subgrade and foundation soil is continuous and completely bonded. (4) The new and old subgrade do not experience relative slippage during construction. (5) The left and right sides of the foundation are subject to horizontal constraints, while the bottom of the foundation is subject to horizontal and vertical constraints. (6) Only the surface of the foundation has drainage. (7) The pavement load is equivalent to a 1 m high-fill load [16, 17], and the vehicle load is equivalent to a uniformly distributed 10 kPa load [18, 19].

2.2. Widening of the Subgrade Mold Construction. Figures 1 and 2 present the widening model of the subgrade and the corresponding finite element model of the widened subgrade.

The old subgrade had a height and width of 3.47 m and 28 m, respectively, with a silty clay filling. Following a 7 m widening on both sides, the new subgrade has a height of 4.1 m, with a stone soil filling. The slope ratio of the new and old subgrade is 1 : 1.5. The foundation width and depth are determined as 29.15 m and 20 m, respectively, with a 0.5 m sand cushion, 7.2 m muddy clay, and 12.3 m mild clay. In addition, the foundation water lies 1 m below the foundation surface. Considering the symmetry of the two-sided widened subgrade, we employed half of the calculation area for this work [20, 21].

Based on the Technical Guidelines for Design and Construction of Highway Embankment on Soft Ground (JTG/T D31-02-2013), the diameter of the reinforced soil pile should not be less than 0.5 m and the distance between adjacent piles should not be greater than 4 times the pile diameter [22]. The muddy clay foundation is reinforced by cement mixed piles of a 7.2 m length and 0.5 m diameter. The pile spacing is 1.5 m (300% of the pile diameter). The whole structure is arranged in an equilateral triangle.

2.3. Basic Parameters of the Subgrade Materials. Table 1 reports the stone soil, old subgrade soil, and mild clay key parameters [23], Table 2 lists the sand cushion parameters [24], and Table 3 details the soft soil parameters [25].

The settlement of the subgrade in the reconstruction and expansion of the expressway is mainly caused by the soil, and the constitutive relationship of the soil is the stress-strain relationship, so the plane strain model is considered in the finite element simulation to analyze the settlement of the subgrade. The nonlinearity in the field of engineering includes material nonlinearity and geometric nonlinearity, among which the former is the most influential [24]. In the current paper, the muddy clay foundation is strengthened by cement mixed piles with an elastic modulus of 100 MPa and Poisson's ratio of 0.25 [26, 27]. The cement mixed pile contains Portland cement with a compressive strength of 42.5 MPa. Table 4 reports the key parameters of the Portland cement. Plain strain analysis reveals the piles to be equivalent to plane plates [28]. Simplifying the three-dimensional pile to a two-dimensional plate requires the strength reduction to be accounted for. The strength reduction coefficient is calculated as follows [29]:

$$n = \frac{\pi r^2/2}{\sqrt{\left(3D^2/2\right)/2}} : \frac{R}{D}, \tag{1}$$

where r is the cement mixed pile radius (0.5 m), R is the cement mixed pile diameter (1 m), and D is the pile spacing (1.5 m). Following conversion, the reduction coefficient of the mixed pile strength (n) is derived as 0.605.

We determined the setting time, soundness, compressive strength, and rupture strength of cement according to the Test Methods for Water Requirement of Normal Consistency, Setting Time, and Soundness of the Portland Cement (GB/T1346-2011) and Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005) [30, 31].

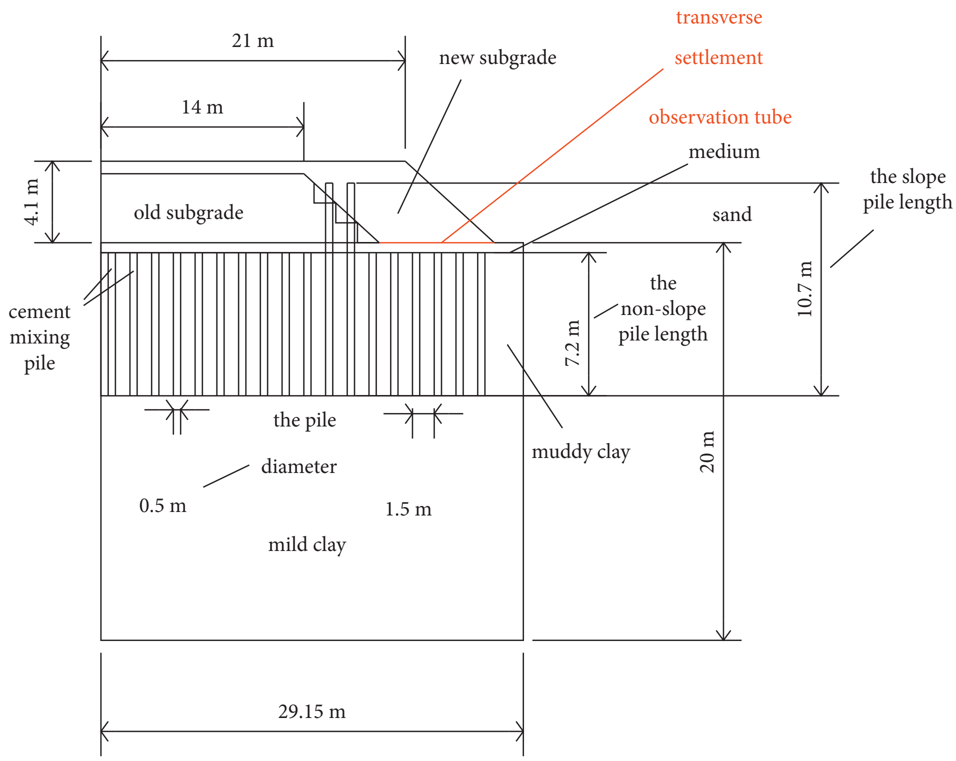


FIGURE 1: Widening subgrade engineering design.

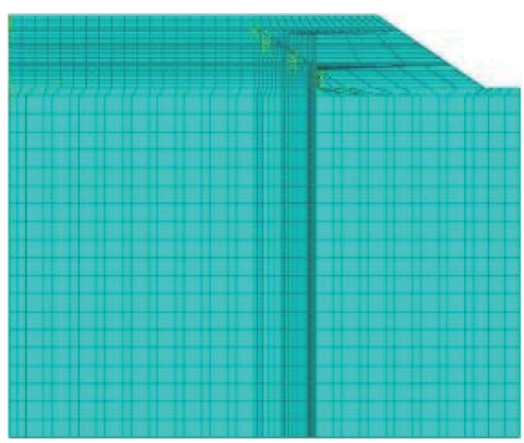


FIGURE 2: Finite element mesh diagram of the widened subgrade.

TABLE 1: Stone soil, old subgrade soil, and mild clay parameters [23].

Name of soil	Thickness (m)	Modulus of elasticity (MPa)	Poisson's ratio	Soil unit weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (°)
Stone soil	4.1	900	0.25	21.3	—	—
Old subgrade soil	4.1	34	0.35	18.4	46	25.2
Mild clay	12.3	18	0.35	16.7	16.4	26.6

2.4. Loading Time History. We adopt the Technical Specification for Construction of Highway Subgrades (JTG/T 3610-2019) and consider the actual construction of the reconstruction and expansion project to determine the filling thickness and filling time of each layer as 20–30 cm and 1-2 d, respectively [32].

Table 2: Medium sand parameters [24].

Name of soil	Thickness (m)	Modulus of elasticity (MPa)	Poisson's ratio	Soil unit weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (°)
Medium sand	0.5	21.5	0.21	19.4	24	42.5

Table 3: Muddy clay parameters [25].

Name of soil	Thickness (m)	Modulus of elasticity (MPa)	Poisson's ratio	Soil unit weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (°)
Muddy clay	7.2	1.2	0.35	14	23.1	22

Table 4: Portland cement parameters.

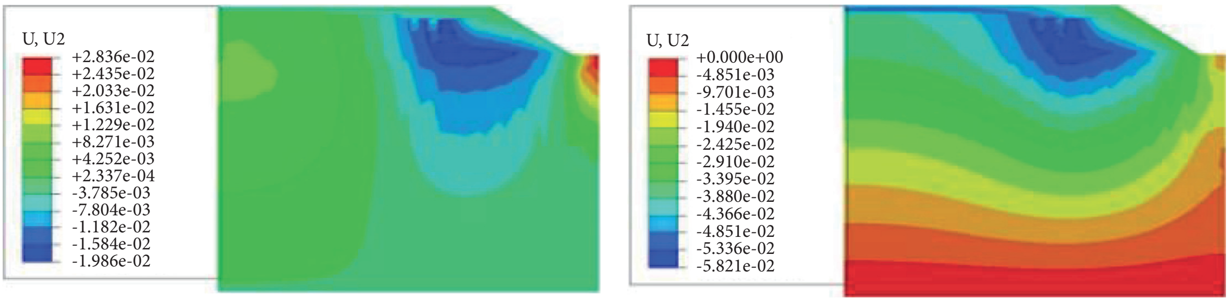
Name	Initial setting time (min)	Final setting time (min)	Soundness (mm)	3 days' rupture strength (MPa)	28 days' rupture strength (MPa)	3 days' compressive strength (MPa)	28 days' compressive strength (MPa)
Portland cement	160	287	1.5	4.5	7.7	24.7	49.1

3. Settlement Calculation Results of the Widening Subgrade

3.1. Comparative Analysis of the Settlement under Different Pile Spacings. The diameter of the pile is 0.5 m. Under the slope of the existing road, the pile is observed to have a length of 10.7 m, while under the existing subgrade and new embankment, the length is 7.2 m. In order to analyze the influence of the cement mixed pile spacing on the settlement of the new and old subgrade, we investigate the following two conditions. (1) The pile spacing of the cement mixed piles under the existing road slope is fixed to 300% of the pile diameter, while the pile spacing of the cement mixed piles under the existing subgrade and new embankment varies. The proposed pile spacing is 200%, 300%, and 400% of the pile diameter, respectively. (2) The pile spacing of the cement mixed piles under the existing subgrade and new embankment is fixed to 300% of the pile diameter, while the pile spacing of the cement mixed piles under the existing road slope varies, and the proposed pile spacing is 200%, 300%, and 400% of the pile diameter, respectively. For the subgrade settlement corresponding to the time of the layered filling and completion, only the additional effect of the filled soil load needs to be considered, while at the time of post-construction, the additional effects of pavement load and vehicle load must be accounted for.

Figure 3 presents the settlement variations of the widened subgrade cross section when the pile spacing under the existing road slope is 300% of the pile diameter. Figure 4 depicts the settlement vector diagram of the widened subgrade when the pile spacing under the slope of existing road is 300% of the pile diameter. The subgrade and foundation are observed to have a large settlement under the action of the additional load. Moreover, the foundation deformation is similar across different depths and the settlement curve follows an approximate basin-shape. The maximum settlement at the cross section of the subgrade appears near the toe of the old subgrade. Figure 5 depicts the layered settlement of the widened subgrade surface under different piles spacings. When the new subgrade is filled at 1 m, the entire old road exhibits an uplift trend that is maximized at the center of the old road. When the fill height increases to 3 m, the old subgrade surface follows a "reverse deflection basin" shape [9] and once again the old road center exhibits the largest uplift. As the distance from the center of the old road increases, the uplift amount of each point on the old road surface gradually decreases, with the uplift equal to 0 at 1.3 m from the shoulder of the old road. Further increases in the distance result in the gradual settlement at each point, and the maximum settlement is achieved at the old road shoulder. The maximum settlement of the old road surface increases with the pile spacing of the existing road slope. In particular, at the 3 m filling height, the maximum settlement value increases from 0.33 to 0.38 cm. The same trend is also observed under the existing subgrade and new embankment for the maximum settlement of the old road surface, with an increase from 0.27 to 0.38 cm at the 3 m filling height. As the new subgrade load increases and its height reaches 4.1 m, the surface settlement of the widened subgrade gradually forms a "deflection basin" shape, whereby the old road center exhibits the largest settlement. As the distance from the center of the old road continues to increase, the surface settlement of the widened subgrade gradually decreases and a turning point appears at 1 m from the new shoulder. This is followed by the uplift of the widened subgrade.

Figure 6 depicts the settlement of the old subgrade surface once the new subgrade is completed. At completion, the center of the old subgrade is uplifted under all cases, and the demarcation point of the uplift and settlement occurs at 3 m inside the old road shoulder. The closer it is to the demarcation point, the smaller the uplift value is, while the closer it is to the old road shoulder, the larger the settlement value is. The settlement reaches a maximum value of 1.16 cm at the old road shoulder. The pile spacing is observed to be positively correlated with the surface settlement of the old road. The larger the pile spacing under all two cases, the



(a) (b)

Figure 3: Settlement cloud diagram of the widened subgrade for a pile spacing under the existing road slope equal to 300% of the pile diameter. (a) Settlement cloud diagram of subgrade completion. (b) Settlement cloud diagram 15 years after subgrade construction.

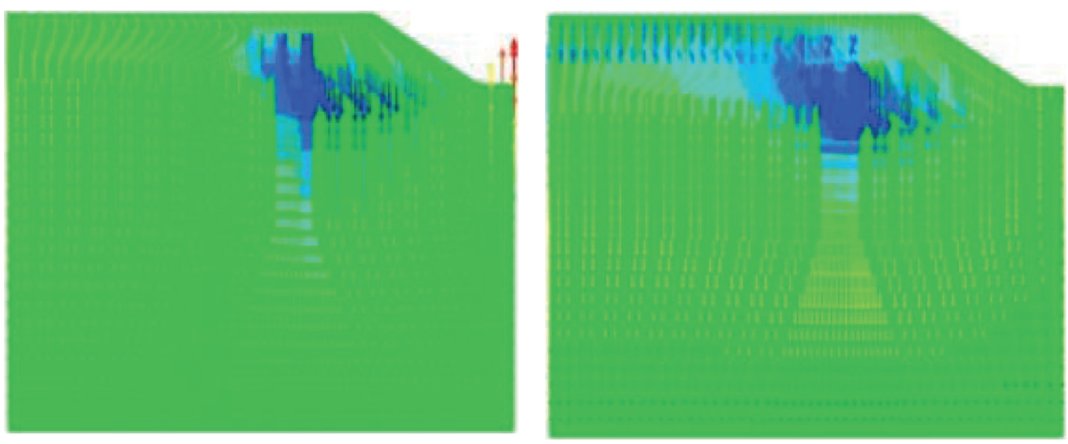


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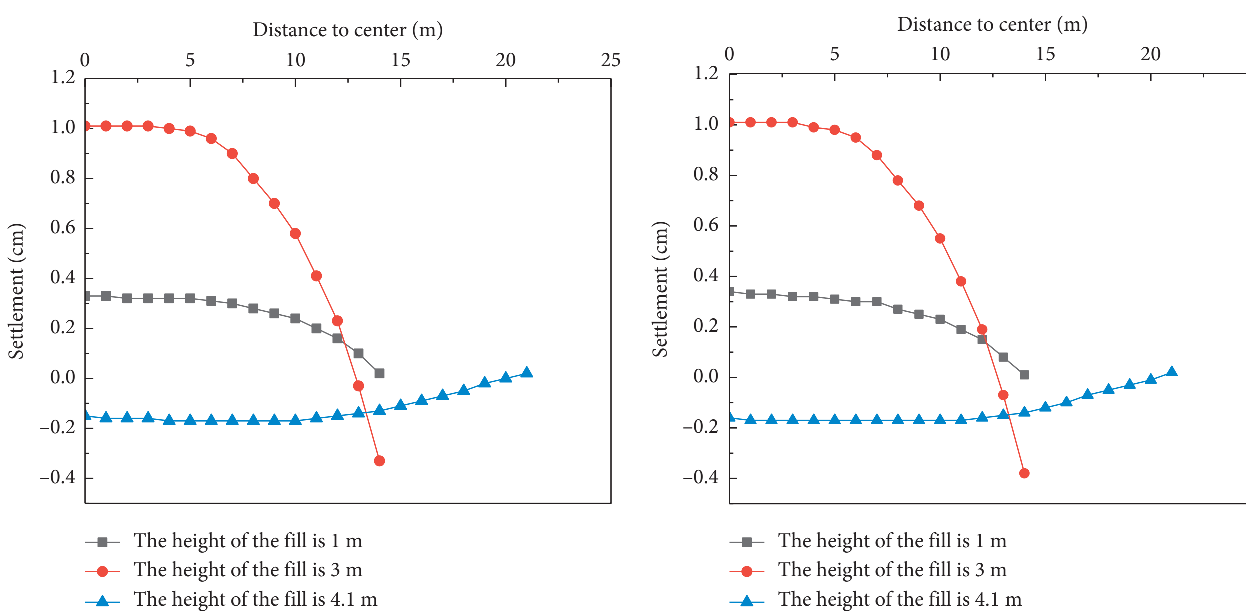
Figure 4: Settlement vector diagram of the widened subgrade for a pile spacing under the existing road slope equal to 300% of the pile diameter. (a) Settlement vector diagram of subgrade completion. (b) Settlement vector diagram 15 years after subgrade construction.



(a) (b)

Figure 5: Continued.

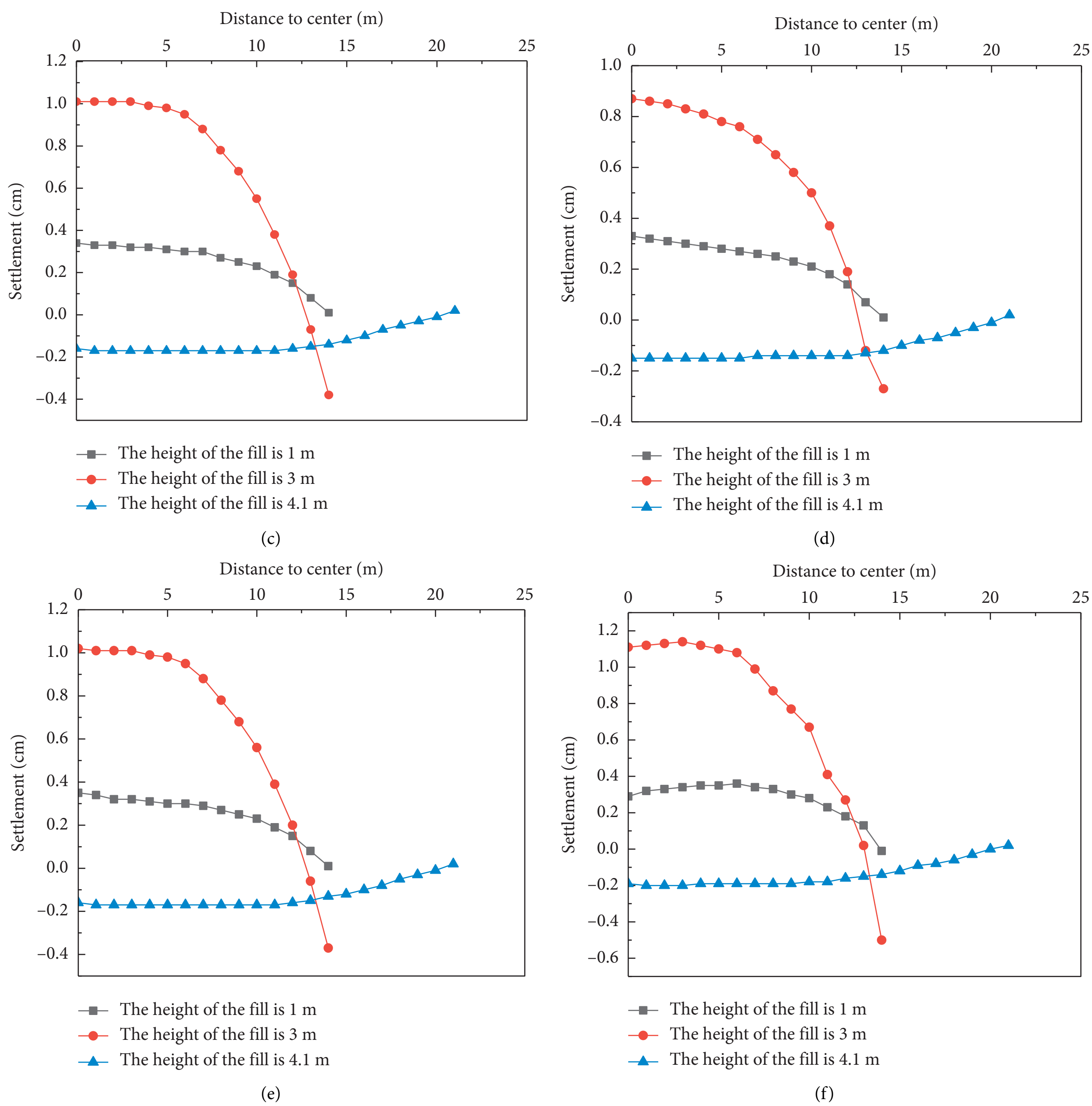


FIGURE 5: Layered settlement diagram of subgrade surface under different piles spacings. (a) Pile spacing under the slope of the existing road equal to 200% of the pile diameter. (b) Pile spacing under the slope of the existing road equal to 300% of the pile diameter. (c) Pile spacing under the slope of the existing road equal to 400% of the pile diameter. (d) Pile spacing under the existing subgrade and new embankment equal to 200% of the pile diameter. (e) Pile spacing under existing subgrade and new embankment equal to 300% of the pile diameter. (f) Pile spacing under existing subgrade and new embankment equal to 400% of the pile diameter.

greater the settlement increase. The maximum settlement of the old road surface exhibits an increase from 0.8 to 1.16 cm following the change in the pile spacing under the existing subgrade and new embankment and from 0.92 to 0.98 under the existing road slope. Figure 7 presents the post-construction differential settlement curve of the subgrade surface with the different pile spacings relative to the old road center. The curve is observed to present an "inverted bell" distribution; the closer the widened subgrade is to the new road shoulder, the greater the difference settlement will be. The maximum difference settlement is achieved at the new road shoulder. Comparing the maximum differential settlement of the subgrade surface under the change of slope piles spacings and the maximum differential settlement of

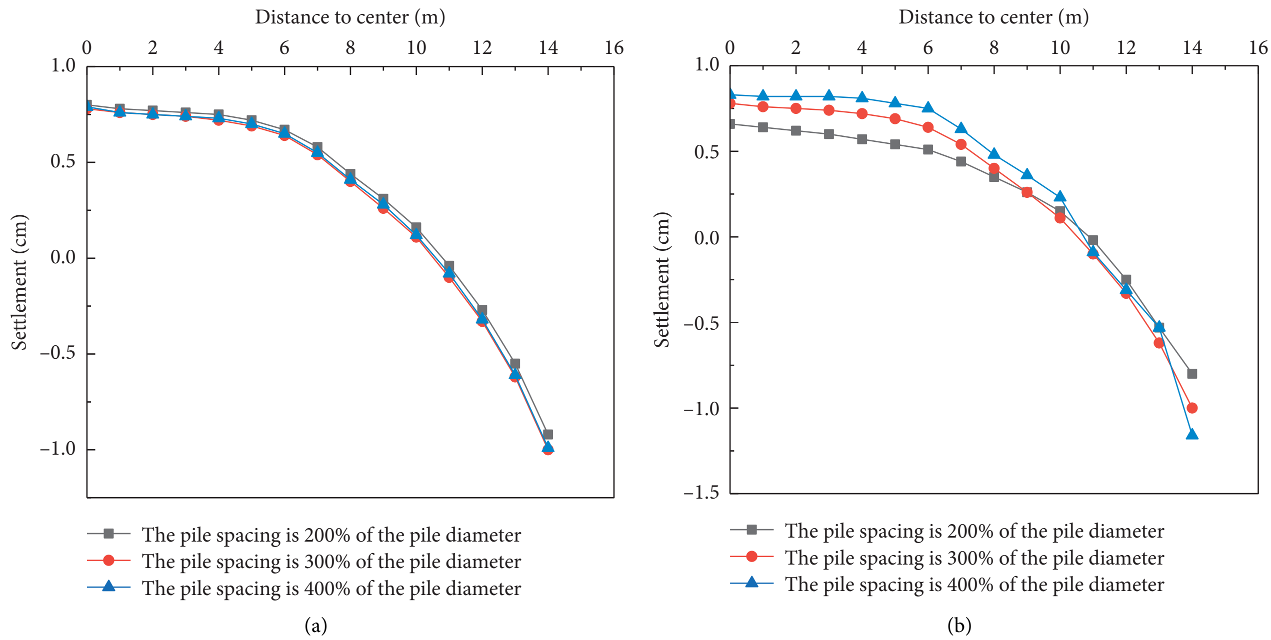


Figure 6: Completion settlement diagram of the old subgrade surface under different piles spacings. (a) Varying pile spacing under the existing road slope. (b) Varying pile spacing under the existing subgrade and new embankment.

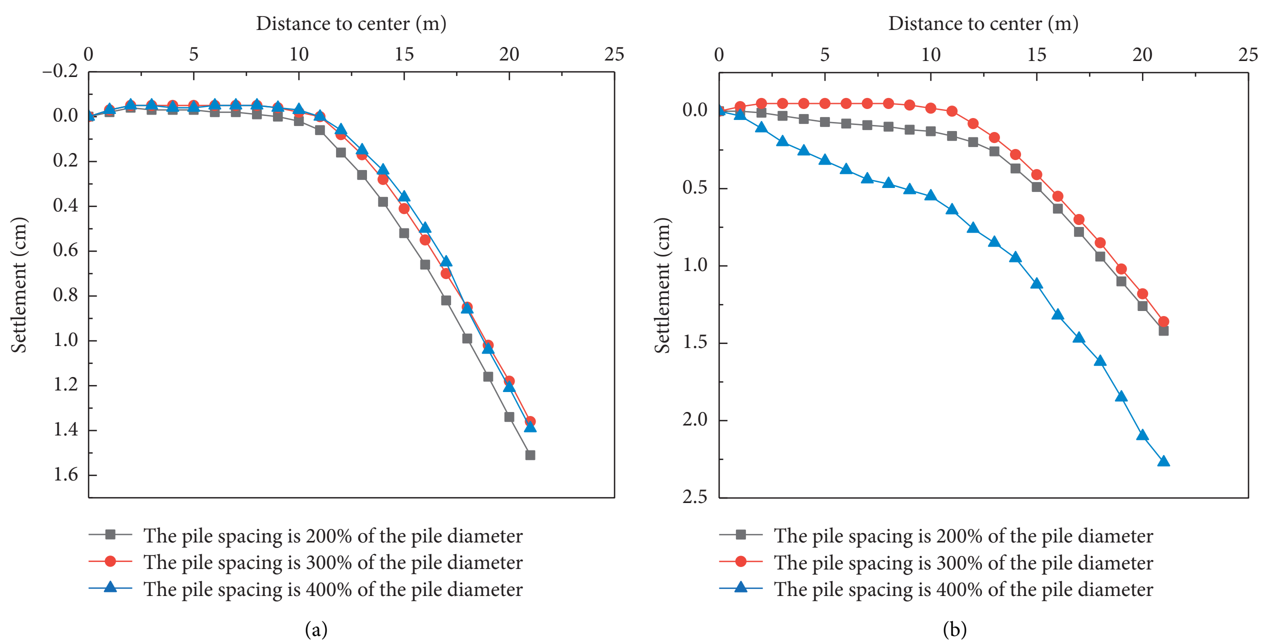


Figure 7: Postconstruction differential settlement diagram of the subgrade surface under different piles spacings. (a) Varying the pile spacing under the existing road slope. (b) Varying the pile spacing under the existing subgrade and new embankment.

subgrade surface under the change of piles spacings under existing subgrade and new embankment reveals that, with the variation of the pile spacing, the maximum differential settlement of the widening subgrade surface is enhanced from 1.36 to 1.51 cm and from 1.36 to 2.27 cm, respectively.

Following the completion of the new subgrade, the foundation under the new and old subgrade is observed to be deformed (Figure 8). Variations in the mixed pile spacing under the existing road slope or the existing subgrade and new embankment are not observed to affect the foundation settlement. In general, the foundation at the center of the old subgrade exhibits an uplifting trend, and the foundation close to the widening side is settled. The turning point of the uplift and settlement is located 6 m inside the toe of the old

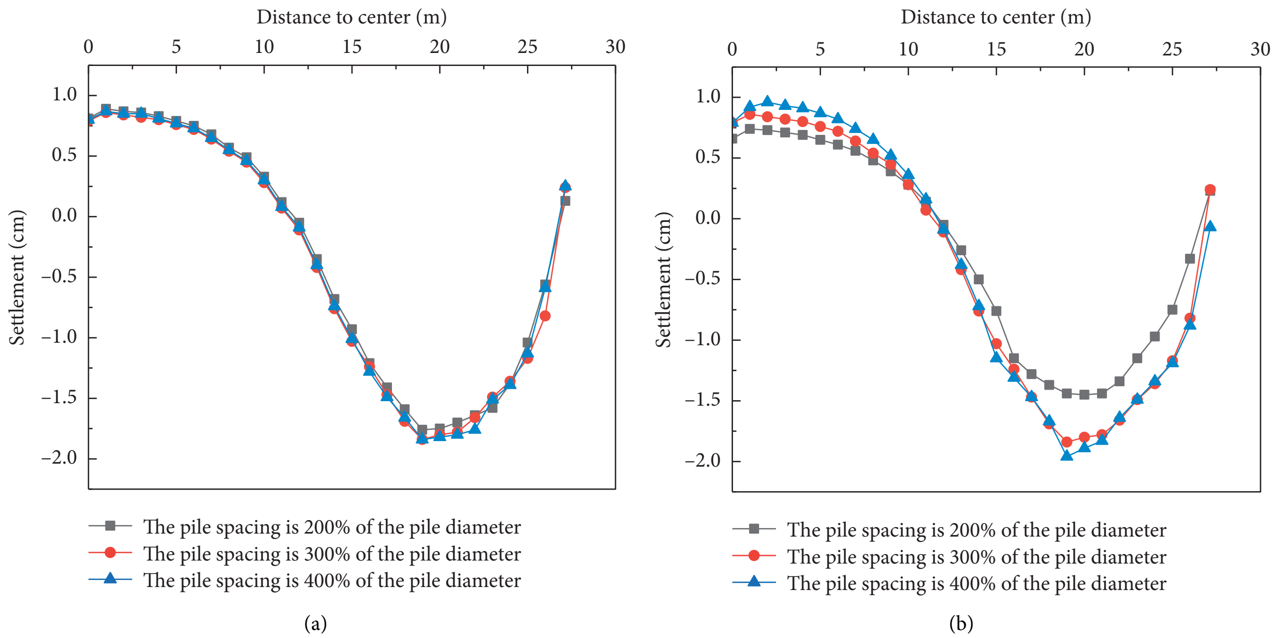


FIGURE 8: Settlement diagram of the foundation surface at completion under different piles spacings. (a) Varying the pile spacing under the existing road slope. (b) Varying the pile spacing under the existing subgrade and new embankment.

subgrade, while the foundation settlement is maximized at the junction of the new and old subgrade, followed by a gradual reduction and subsequent uplift at the foot of the new subgrade. As the pile spacing increases, the maximum settlement of the foundation surface under changing slope piles spacings increases from 1.76 to 1.85 cm, and from 1.44 to 1.96 cm for changing piles spacings under the existing subgrade and new embankment. Figure 9 depicts the differential settlement curve of the foundation under the old and new subgrades at different piles distances relative to the foundation at the old road center following 15 years of construction. As the distance from the old road center increases, the postconstruction differential settlement of the foundation under the new and old subgrades initially increases, followed by a subsequent decrease, and finally exhibits a gradual rise. The maximum differential settlement is concentrated close to the foot of the old road slope. The variations of the mixed piles spacings under the existing road slope and under the existing subgrade and new embankment result in changing of the maximum differential settlement of foundation surface from 1.63 to 1.84 cm and 0.99 to 1.84 cm, respectively.

The degree of compression deformation is determined by the elastic modulus of the component material and the compressive stress acting on the component [33]. At a constant subgrade width and height, the soil weight on the upper region of the foundation remains unchanged; that is, the compressive stress is constant. At this time, the tighter the piles, the greater the overall elastic modulus of the foundation, the higher the compression resistance, and the smaller the settlement. Comparing the pile spacing at different positions on the subgrade and foundation settlements reveals that the pile spacing under the existing subgrade and new embankment on the settlement exerts a greater influence compared to the pile spacing under existing road slope. This can be attributed to the larger improved foundation area under the piles of the existing subgrade and new embankment compared to the existing road slope.

3.2. Comparative Analysis of the Settlement under Different Piles Lengths. The pile spacing is 300% of the 0.5 m pile diameter. In order to comprehensively analyze the influence of cement mixed pile lengths on the settlements of the new and old subgrades, we adopt the following two conditions. (1) The side slope pile length at the muddy clay remains unchanged (7.2 m), while the foundation pile length under the existing subgrade and new embankment varies (4.7 m, 7.2 m, and 9.7 m). (2) The foundation pile length under the existing subgrade and new embankment remains unchanged (7.2 m), while the side slope pile length at the muddy clay varies (4.7 m, 7.2 m, and 9.7 m). When the subgrade settlement occurs at the time of layered filling and completion, only the additional effect of the filled soil load requires consideration, while for the subgrade settlement at the time of postconstruction, the additional effects of pavement load and vehicle load must be taken into account.

Figure 10 presents the settlement variations of the widened subgrade cross section for a pile length under the existing subgrade and new embankment equal to 4.7 m, while Figure 11 depicts the corresponding vector diagram of the widened subgrade settlement at the same pile length. The maximum settlement at the subgrade cross section typically appears close to the toe of the old subgrade. Figure 12 presents the influence of the pile length at different positions on the subgrade surface layered settlement curve. The trends in the subgrade surface settlement are consistent whether the side slope pile length is changed or the pile

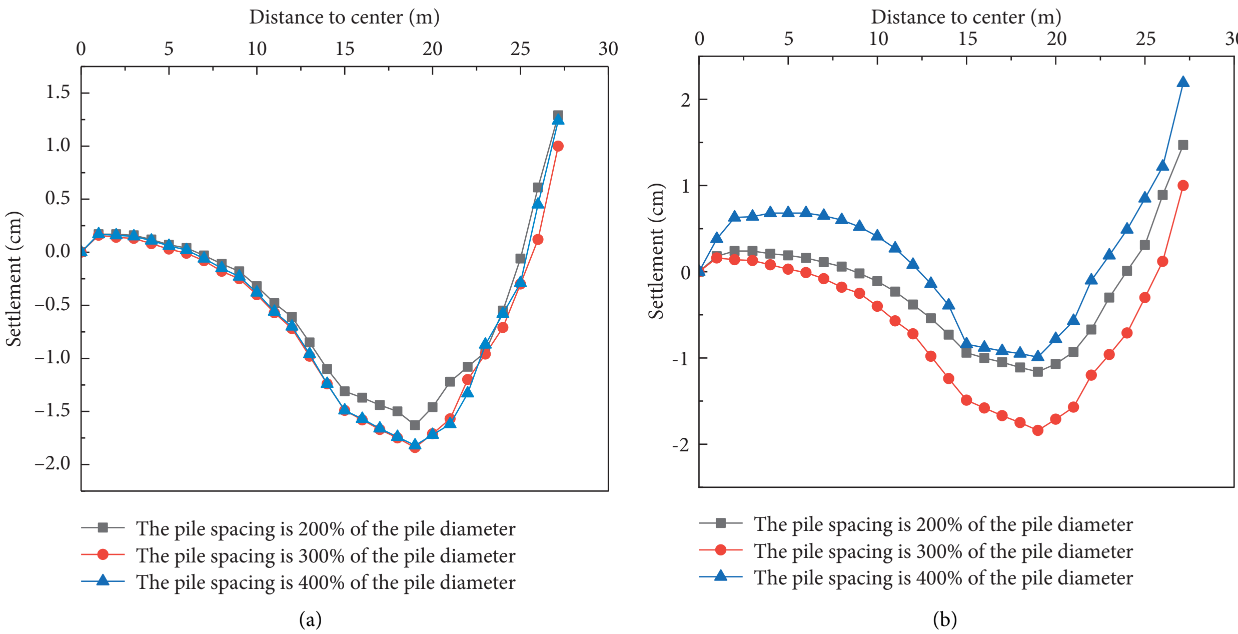


Figure 9: Postconstruction differential settlement diagram of the foundation surface under different piles spacings. (a) Varying the pile spacing under the existing road slope. (b) Varying the pile spacing under the existing subgrade and new embankment.

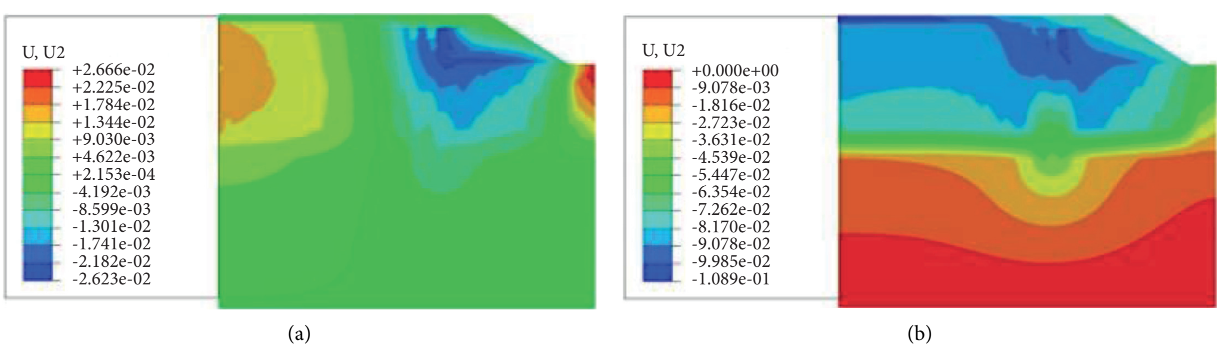


Figure 10: Settlement cloud diagram of widened subgrade for a pile length under the existing subgrade and new embankment equal to 4.7 m. (a) Settlement cloud diagram of subgrade completion. (b) Settlement cloud diagram 15 years after subgrade construction.

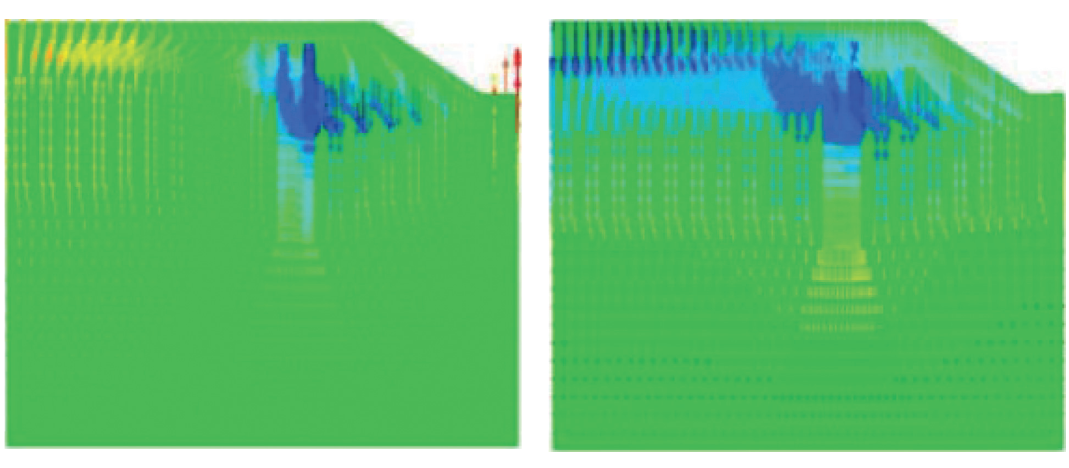


Figure 11: Settlement vector diagram of widened subgrade for a pile length under the existing subgrade and new embankment equal to 4.7 m. (a) Settlement vector diagram of subgrade completion. (b) Settlement vector diagram 15 years following subgrade construction.

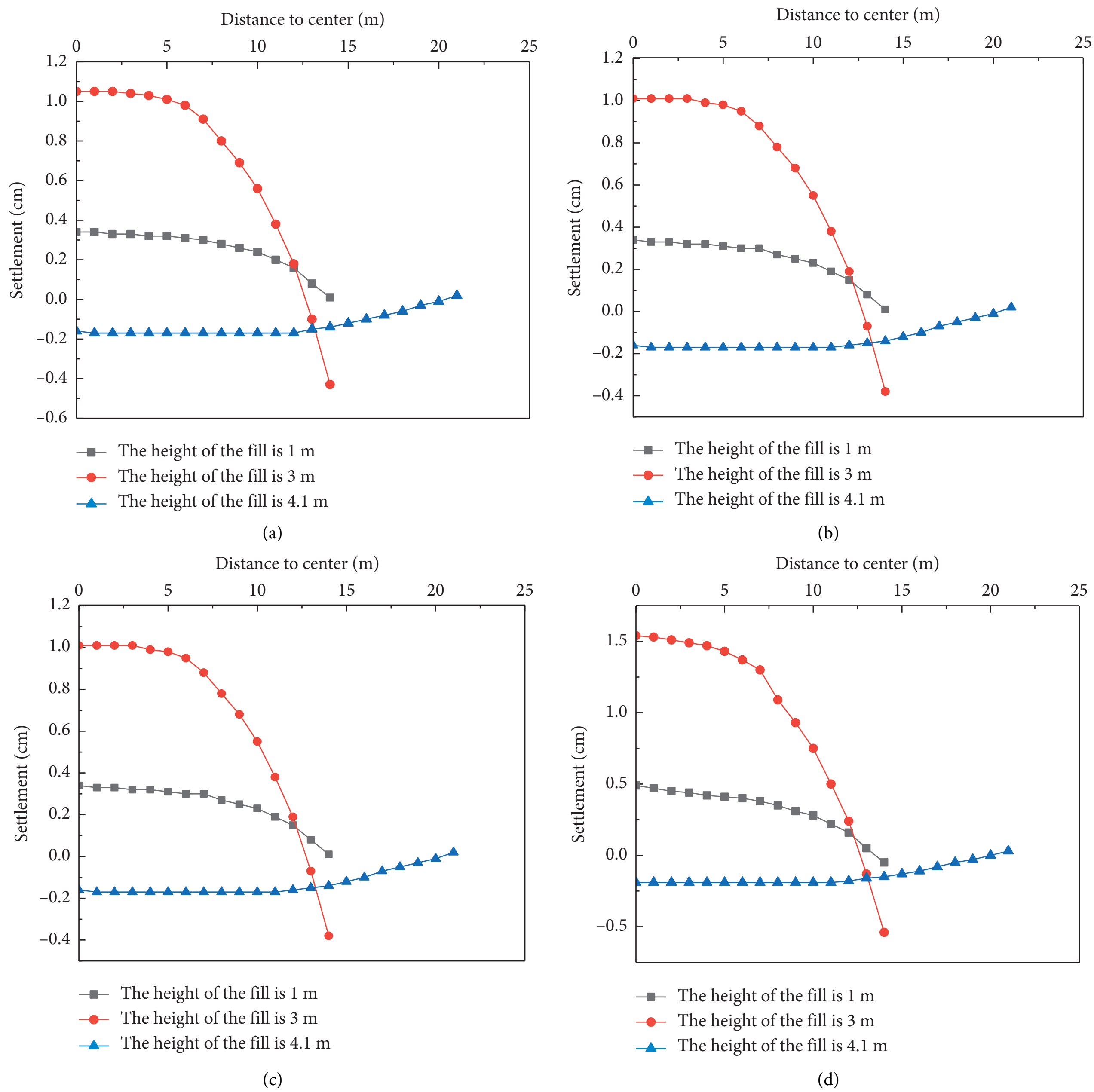


Figure 12: Continued.

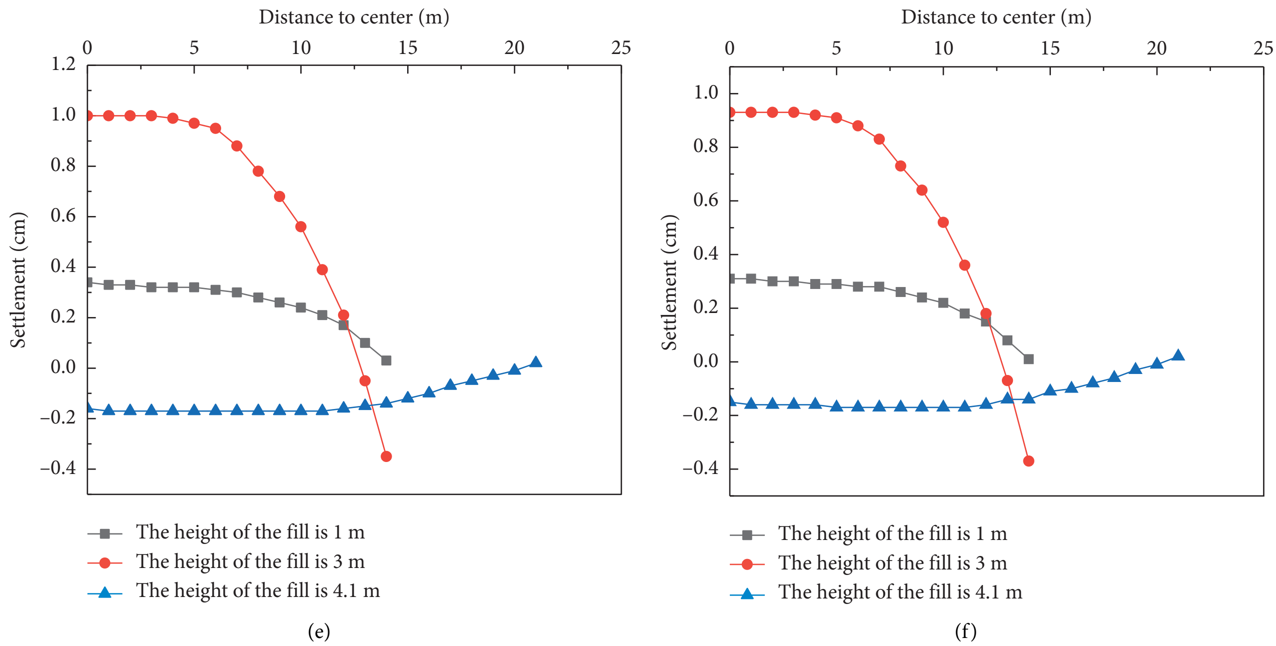


Figure 12: Layered settlement diagram of subgrade surface under different piles lengths. (a) Pile length under existing road slope equal to 4.7 m. (b) Pile length under existing road slope equal to 7.2 m. (c) Pile length under existing road slope equal to 9.7 m. (d) Pile length under existing subgrade and new embankment equal to 4.7 m. (e) Pile length under existing subgrade and new embankment equal to 7.2 m. (f) Pile length under existing subgrade and new embankment equal to 9.7 m.

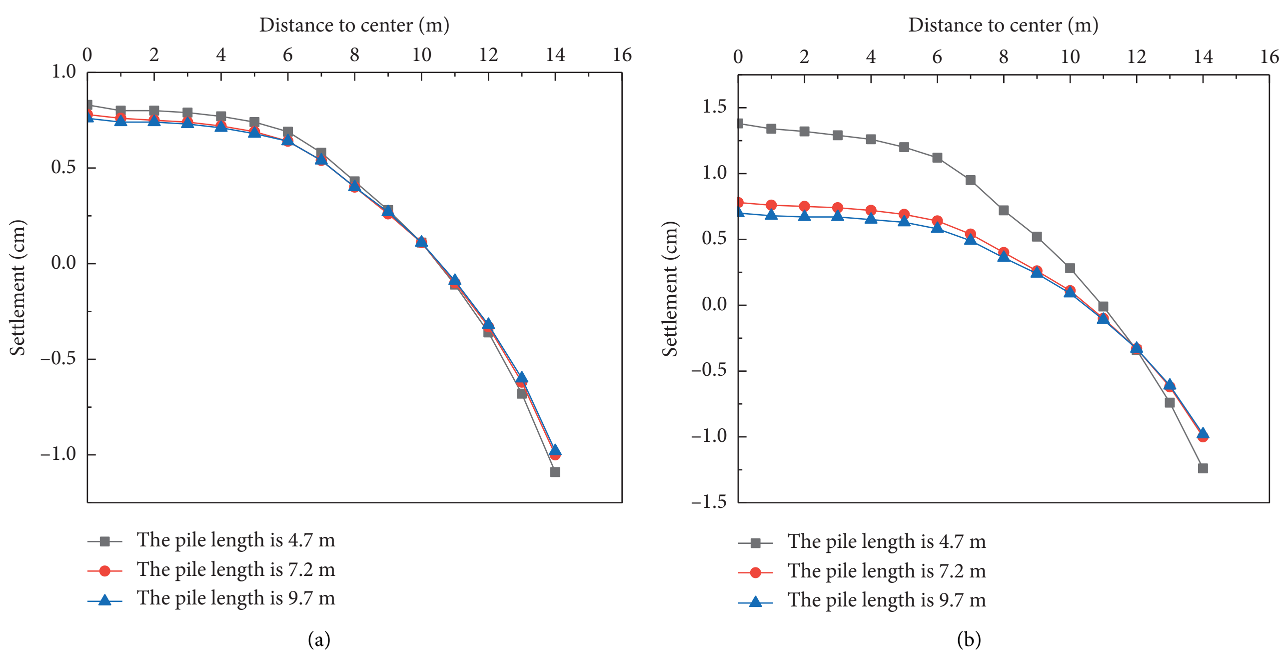


Figure 13: Settlement diagram of old subgrade surface completed under different piles lengths. (a) Varying pile length under the existing road slope. (b) Varying pile length under existing subgrade and new embankment.

length under existing subgrade and new embankment is changed. In general, when the new subgrade filling height is low, the old road surface is uplifted, and when filling load increases, the old road surface begins to subside. The settlement is maximized at the old road shoulder; when stopping new subgrade soil load, the center of the old road has the largest settlement, while the new shoulder has a smaller settlement. Figure 13 depicts the completed settlement diagram of the old subgrade surface under different piles lengths. At side slope pile lengths in the muddy clay

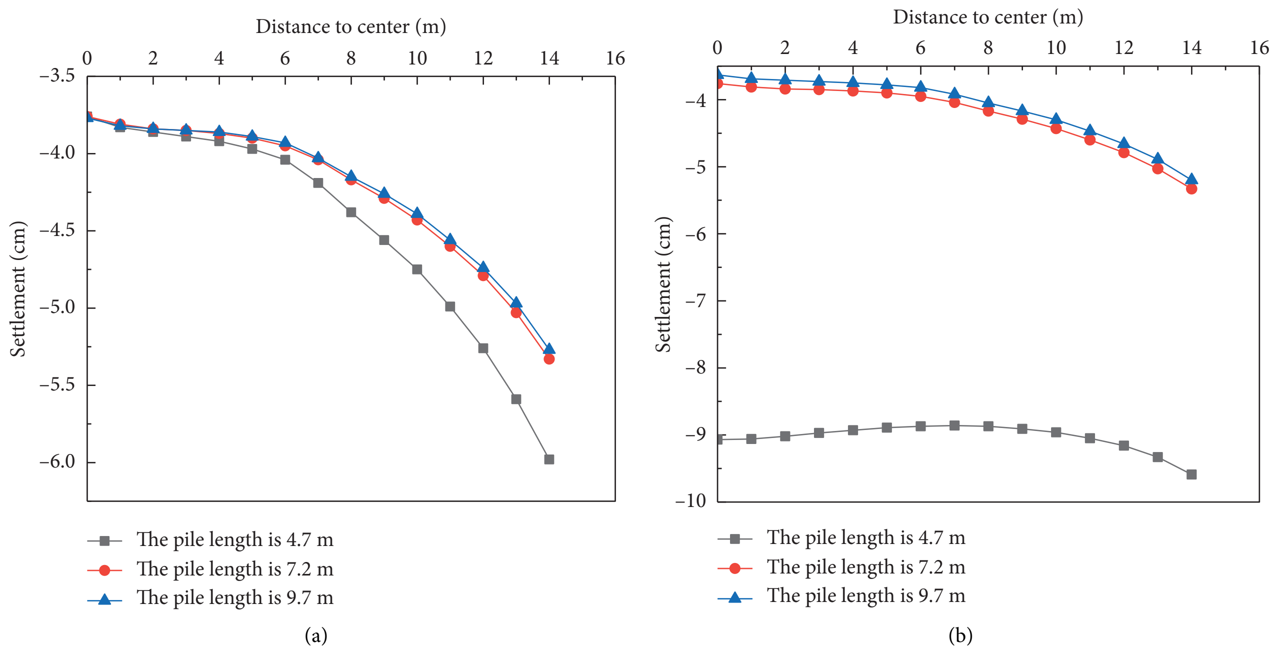


Figure 14: Postconstruction settlement diagram of the old subgrade surface under different piles lengths. (a) Variations in the pile length under the existing road slope. (b) Variations in the pile length under the existing subgrade and new embankment.

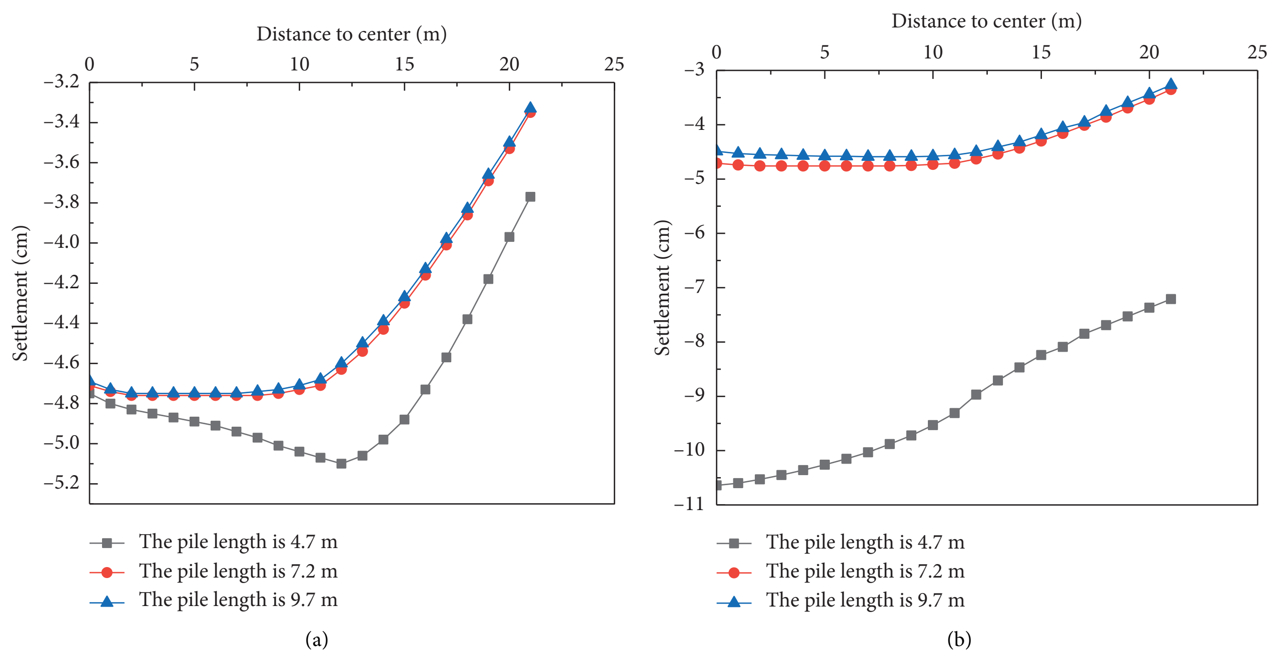


Figure 15: Postconstruction settlement diagram of the subgrade surface widened under varying piles lengths. (a) Variations in the pile length under the existing road slope. (b) Variations in the pile length under the existing subgrade and new embankment.

equal to 4.7 m, 7.2 m, and 9.7 m, the maximum settlement on the surface of the old subgrade is determined as 1.09 cm, 1 cm, and 0.98 cm, respectively. In addition, when the foundation pile lengths under the existing subgrade and new embankment are equal to 4.7 m, 7.2 m, and 9.7 m, the maximum settlements on the surface of the old subgrade are 1.24 cm, 1 cm, and 0.98 cm, respectively.

Figure 14 illustrates the postconstruction settlement of the old subgrade surface under different piles lengths. Varying the pile length (side slope piles and piles under the existing subgrade and new embankment) does not affect the parabolic settlement curve shape of the old subgrade surface. However, changing the pile length at different positions alters the maximum settlement value of the postconstruction

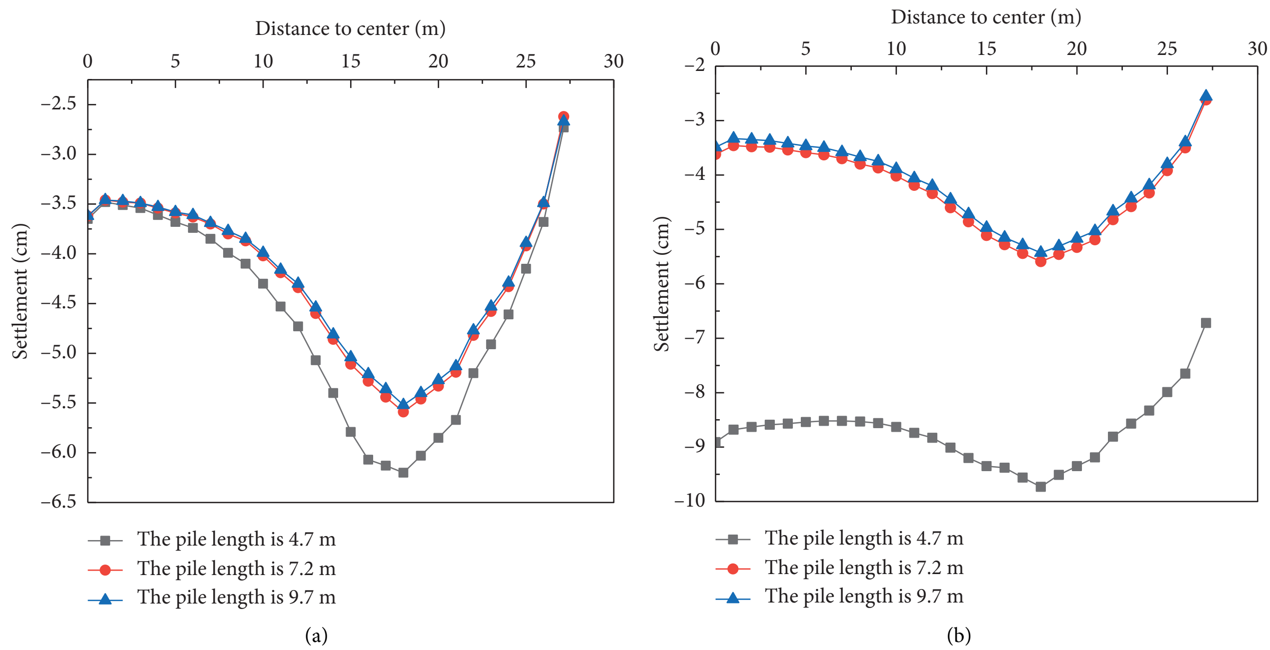


Figure 16: Postconstruction settlement diagram of the foundation surface under different piles lengths. (a) Varying the pile length under the existing road slope. (b) Varying the pile length under the existing subgrade and new embankment.

old subgrade surface. An increase in the side slope pile length from 4.7 to 9.2 m is associated with a reduction in the postconstruction maximum settlement from 5.98 to 5.27 cm. Moreover, enhancing the pile length under the existing subgrade and new embankment from 4.7 to 9.2 m reduces the postconstruction maximum settlement of the old subgrade surface from 9.59 to 5.2 cm. Figure 15 depicts the postconstruction settlement diagram of the widened subgrade surface under different piles lengths. As the pile length increases, the postconstruction maximum settlement of the subgrade widened surface is equal to $5.1 \longrightarrow 4.76 \longrightarrow 4.75$ cm and $10.64 \longrightarrow 4.76 \longrightarrow 4.59$ cm, respectively.

Varying the piles length is observed to induce the deformation of the old and new foundations. Figure 16 presents the postconstruction settlement diagram of the foundation surface, which exhibits a “spoon-shaped” trend [14]. The maximum settlement is located close to the joining of the old and new subgrade (foot of the old subgrade slope). Increasing the pile length (side slope and nonside slope piles) subsequently reduces the maximum settlement following the surface construction from 6.2 to 5.52 cm and 9.73 to 5.43 cm, respectively.

For short piles, the whole pile body is located in the soft soil. Due to the large compression settlement of the soft soil, the mixed pile will settle with the soft soil. This consequently results in large subgrade and foundation settlements. When the pile is long, the bearing capacity of the mixing pile can improve the subgrade stability. The length of the pile under the new and old subgrades is observed to exert a greater influence on the settlement, particularly following construction. This is linked to the greater number of piles under the existing subgrade and new embankment compared to that of the existing road slope, with an improved ability to transmit the upper load downward.

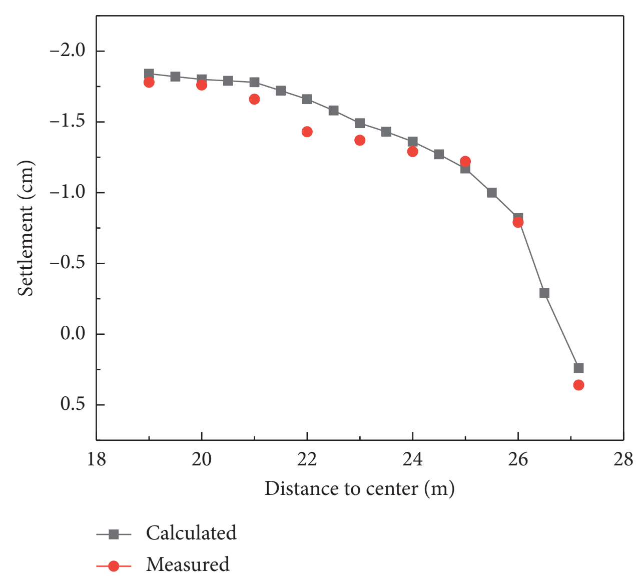


Figure 17: Calculated and measured settlement values.

4. Discussion

We employed the transverse settlement observation tube to monitor the foundation surface settlement. Figure 17 presents the corresponding measured and calculated values of the settlement, demonstrating a strong agreement between the two sets of values. This verifies the accuracy of the proposed numerical simulation and its applicability in future research.

5. Conclusion

In the current paper, we adopt finite element numerical simulations to analyze the settlement characteristics of the subgrade and foundation under different disposal positions of the soft soil foundation mixed piles in an expressway widening project. Based on the results, we obtained the following key conclusions:

(1) The maximum settlement of the widened subgrade cross section is located at the toe of the old subgrade, irrespective of whether the piles under the existing road slope or under the existing subgrade and new embankment are changed.

(2) The subgrade and foundation settlements are observed to increase with the pile spacing both under the existing road slope and under the existing subgrade and new embankment. However, the impact of the pile spacing under the existing subgrade and new embankment on the settlement exceeds that of the existing road slope.

(3) The subgrade and foundation settlement increases with the pile length under the existing road slope and under the existing subgrade and new embankment. However, the impact of the pile length under the existing subgrade and new embankment on the settlement is more significant than that of the existing road slope and the impact on settlement is more prominent after construction. Under the existing road slope, an increase in the foundation pile length from 4.7 to 9.2 m reduces the post-construction maximum old subgrade surface settlement, widening subgrade surface settlement and foundation surface settlement from 5.98 to 5.27 cm, 5.5 to 4.75 cm, and 6.2 to 5.52 cm, respectively. Increasing the foundation pile length under the existing subgrade and new embankment from 4.7 to 9.2 m induces a decrease in the postcontraction maximum old subgrade surface settlement, widening subgrade surface settlement and foundation surface settlement from 9.59 to 5.5 cm, 10.64 to 4.59 cm, and 9.73 to 5.43 cm, respectively.

Data Availability

The data used to support the results of this study are included in the article.

Conflicts of Interest

The authors state that there are no conflicts of interest in the publication of this paper.

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