ANALYSIS OF INFLUENCING FACTORS ON SETTLEMENT OF WIDENED SUBGRADE BASED ON DIFFERENCES IN WORKING CONDITIONS

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ABSTRACT

The finite element method is used for numerical simulation analysis to explore the settlement characteristics of widened subgrade under the influence of different working conditions and factors. The research results show that at the end of the construction period, the maximum total settlement of the subgrade surface of the project of simultaneous widening and raising of the original subgrade is 1.97 cm, the maximum differential settlement of the subgrade surface is 0.21 cm, and the cross slope of the road arch increases by 1.4%. The maximum total settlement of the subgrade surface of the project of only widening of the original subgrade is 2.35 cm, which is an increase of 19.3% compared with the maximum total settlement of the subgrade surface of the project of simultaneous widening and raising of the original subgrade. The total settlement of the subgrade surface under the two working conditions varies with the change of filling materials and increases with the width, height, and slope ratio. When the width increases from 3.5 to 14 m, the maximum uncoordinated deformation of the subgrade surface of the project of simultaneous widening and raising of the original subgrade is increased from 0.54 to 1.31 cm, and the value of the subgrade surface settlement curvature of the splicing area for the project of only widening of the original subgrade is increased from 0.13 to 0.97. The obtained results can provide a reference for subgrade widening projects in the future.

Keywords: filling materials, heights, settlement working condition differences, slope ratios, widened widths.

1 INTRODUCTION

The settlement of new and original subgrade after widening is affected by numerous factors due to the complexity of engineering practices. Domestic and foreign scholars have carried out analysis and research on the widening method [1–7], widened width [8–12], height [13–16], slope ratio [17–18], elastic modulus of subgrade soil [19–21], compression modulus of ground soil [22–25], and lightweight embankment filling material [26–28].

Nowadays, the widening of subgrade is not only integrated on both sides of the original subgrade but also influenced by factors, such as the clearance of bridges and culverts and the longitudinal slope index of the route, so the original subgrade is raised. Different from the only widening of the original subgrade, the simultaneous raising and widening of the original subgrade needs to consider and analyze the settlement of the subgrade at the widening place and the settlement caused by the heightening of the upper part of the original subgrade. Relying on numerical simulation, Tao *et al*. [29] comparatively analyzed the final settlement of the subgrade surface, the horizontal displacement of the subgrade surface, and the lateral displacement of the ground surface under the two conditions of raising and widening the original subgrade and directly widening the original subgrade without raising it. Xiaoli *et al.*

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[30] analyzed and discussed the treatment measures of the junction between the new and original subgrade under the raised and widened subgrade and a method to ensure the smooth flow of the road when the subgrade widened. Jianrong *et al*. [31] explored the influence of the elastic modulus of the subgrade soil, the compression modulus of the ground soil, and the height of the upper part of the original subgrade on the settlement and deformation of raised and widened subgrade.

In this work, based on previous research, the reconstruction and extension project of the Lalinhe–Harbin section of the Beijing–Harbin Expressway is used as a case study. Finite element numerical simulation is employed to analyze and discuss the total settlement of the subgrade of the project of simultaneous widening and raising of the original subgrade, the total settlement of the subgrade of the project of only widening of the original subgrade, and the total settlement of the subgrade surface with the two working conditions under the influence of different factors.

2 BASIC CONDITIONS FOR CALCULATION

2.1 The basic structure and size of the subgrade

The width of the original subgrade was 28 m. The height of the original subgrade in the project of only widening of the original subgrade was 4 m. In the project of simultaneous widening and raising of the original subgrade, the height of the original subgrade was 3 m, and the height of the upper part of the original subgrade was 1 m. The slope ratio of the new and original subgrade under the two working conditions was the same at 1:1.5. The original subgrade was evenly widened on both sides, and the widened width was 7 m. The calculated width of the ground was 54 m, and the calculated depth was 20 m. Considering the symmetry of the two-sided widened subgrade, half of the calculation area was employed for the analysis. The model of subgrade widening is shown in Fig. 1.

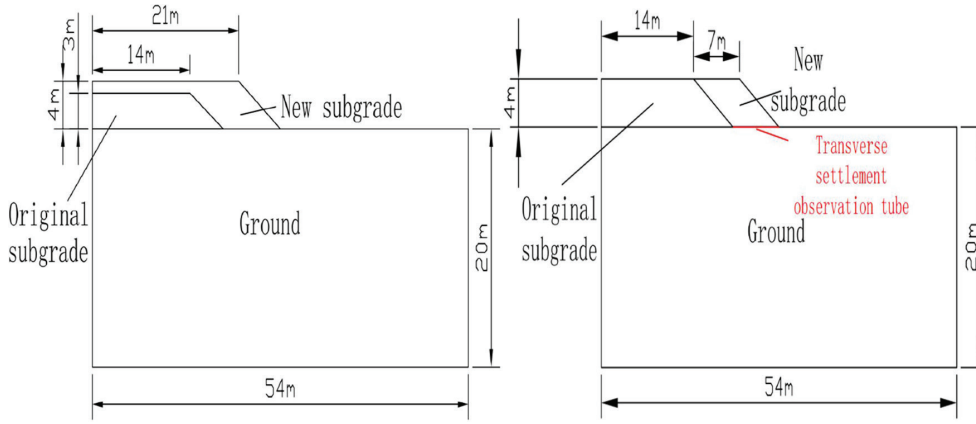

Figure 1: Structure model diagram of widened subgrade: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

2.2 Model calculation assumption of widening subgrade

Subgrade and ground soils are homogeneous, continuous, and isotropic elastoplastic materials. The Mohr–Coulomb ideal elastoplastic constitutive model is used as the constitutive model of soil in this work. Simultaneously, the plastic potential function is introduced into the model. The consolidation and settlement of the original subgrade and the original ground had been essentially completed in the case study. The contact between the subgrade soil and the ground soil was continuous and completely bonded. In addition, the new and original subgrade would not experience relative slippage during construction.

2.3 Model constraints and grid element types

The left and right sides of the ground are subject to horizontal constraints, the bottom of the ground is subject to horizontal and vertical constraints, and only the surface of the ground has drainage. The 4-node bilinear plane strain quadrilateral, reduced integral, hourglass controlled unit (CPE4R) governs the subgrade part, and the 4-node plane strain quadrilateral, bilinear displacement, bilinear pore pressure unit (CPE4P) governs the ground part.

3 SETTLEMENT ANALYSIS OF SUBGRADE UNDER DIFFERENT WORKING CONDITIONS

The settlement change of the cross section of the widened subgrade at the end of the construction period is shown in Fig. 2, and the vector diagram of the settlement of the widened subgrade is shown in Fig. 3. According to Figs. 2 and 3, it can be seen that under the action of the additional load, the subgrade and ground of the two working conditions have a large settlement. The deformation of the ground at different depths is different under the two working conditions. For the project of simultaneous widening and raising of the original subgrade, the shallow ground settlement is approximately basin-shaped, the maximum settlement is below the widened part of the subgrade, the deep ground settlement is approximately W-shaped, and the maximum settlement is located at the foot of the original subgrade. For the project

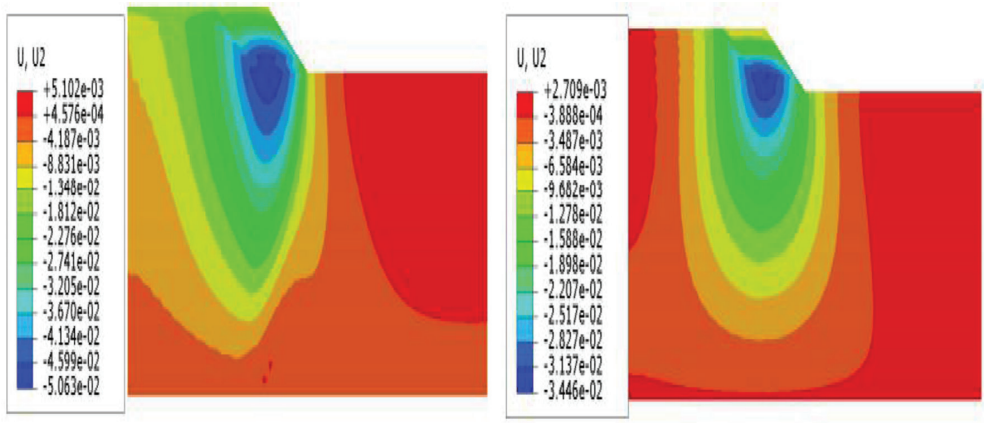

Figure 2: Settlement cloud diagram of widened subgrade: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

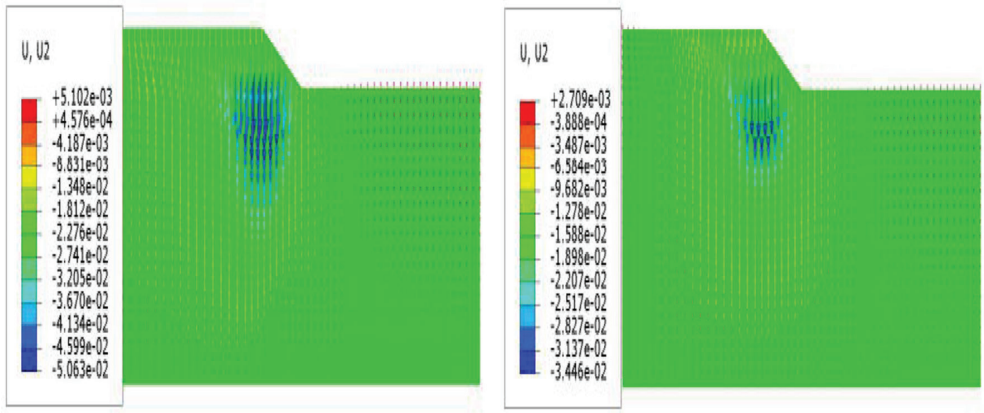

Figure 3: Settlement vector diagram of widened subgrade: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

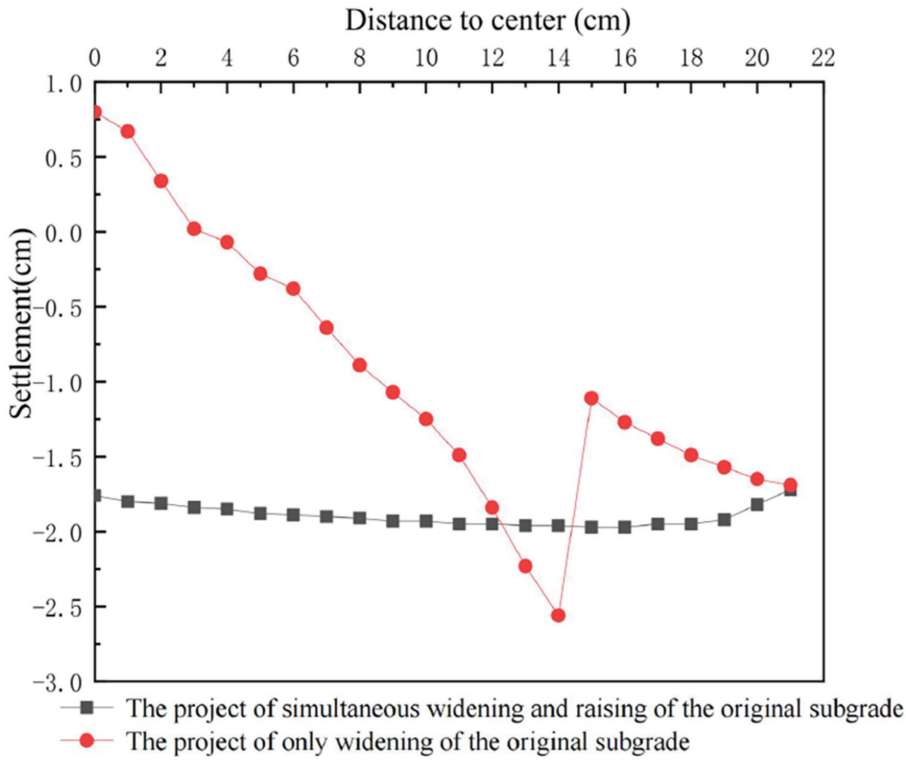

Figure 4: The total settlement diagram of the subgrade surface at the end of the construction.

of only widening of the original subgrade, under the filling load, the original subgrade and the underlying ground are uplifted near the center of the subgrade, the widened part of the subgrade displays subsidence, and the maximum settlement at the cross section of the subgrade appears near the toe of the original subgrade.

It can be observed in Fig. 4 that the shape of the total settlement curve on the surface of the project of simultaneous widening and raising of the original subgrade is like a basin. The settlement first increases and then decreases. The maximum settlement is 1.97 cm, the maximum differential settlement is 0.21 cm, and the cross slope of the road arch increases by 1.4%. The total settlement of the subgrade surface of the project of only widening of the original subgrade increases significantly at the junction of the new and original subgrade. The maximum settlement is 2.35 cm, and the road surface is prone to damage at the junction. Compared with the project of simultaneous widening and raising of the original subgrade, the maximum total settlement of the subgrade surface of the project of only widening of the original subgrade is increased by 19.3%. As shown in Fig. 5, the additional settlement on the ground surface is approximately in the shape of a 'spoon' under the two conditions, and the position of the maximum settlement point of the ground surface is different under the two conditions. For the project of simultaneous widening and raising of the original subgrade, the maximum settlement point of the ground surface is the projection point of the outer edge of the shoulder of the new subgrade. Different from the project of simultaneous widening and raising of the original subgrade, the maximum settlement point of the ground surface in the project of only widening of the original subgrade is mainly located at the foot of the original subgrade. The maximum settlement of the ground surface is 3.36 and 4.93 cm.

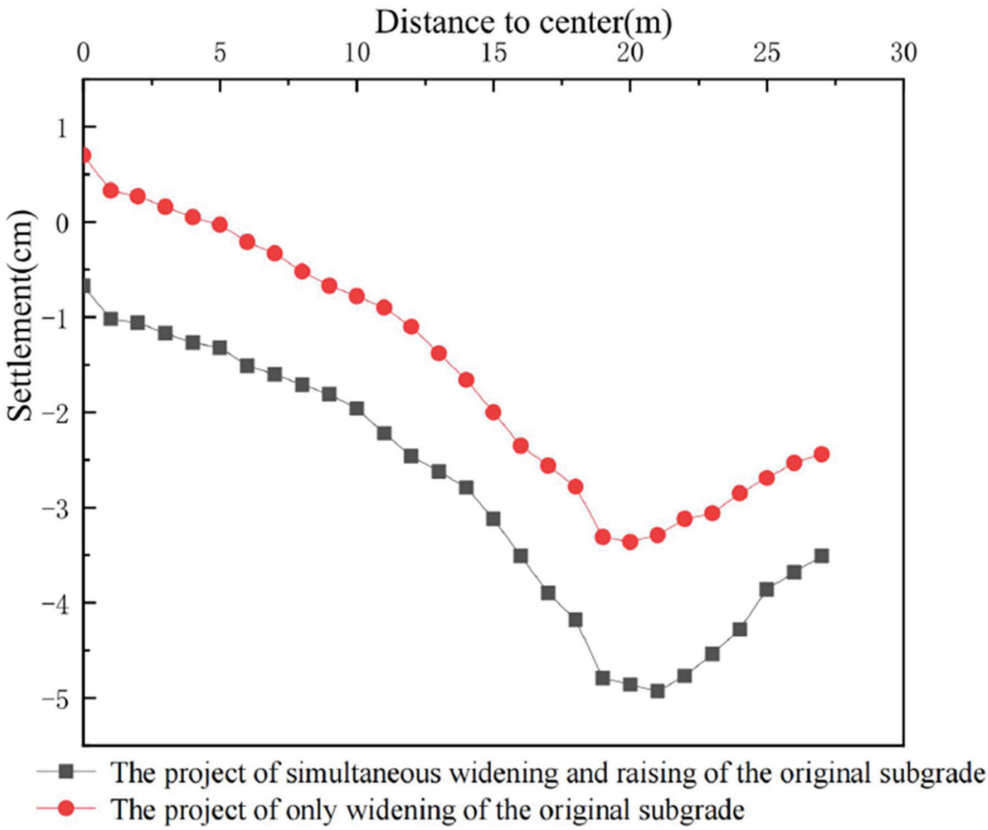

Figure 5: The settlement diagram of the ground surface at the end of the construction period.

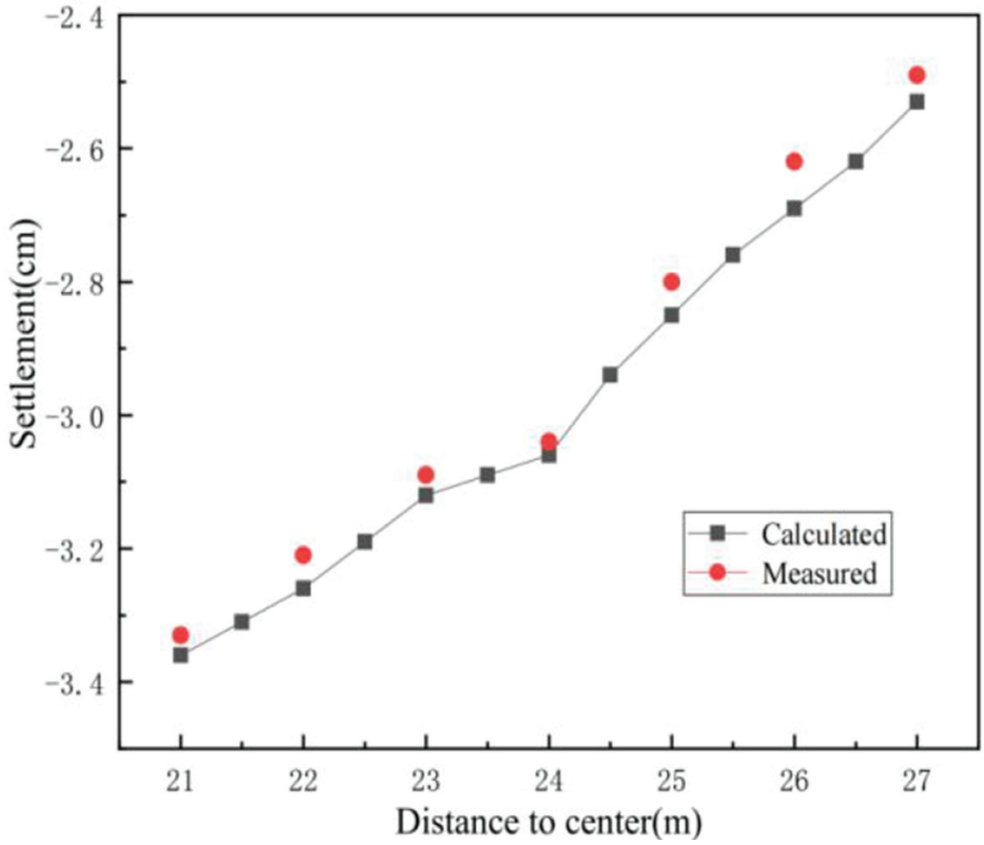

Figure 6: Calculated value and measured value of settlement.

The measured and the calculated values of the settlement are shown in Fig. 6. As shown in Fig. 6, the settlement of the ground under the two methods is similar. Therefore, the numerical simulation is accurate and can be used in our subsequent analysis.

4 ANALYSIS OF SUBGRADE SETTLEMENT INFLUENCED BY DIFFERENT FACTORS IN DIFFERENT WORKING CONDITIONS

4.1 Widened widths of subgrade

The basic conditions for the subgrade widening remain unchanged. Only the width of the subgrade widening is altered, considering that the width of both sides of the original subgrade is widened at the same time at 3.5, 7, 10.5, and 14 m.

The curve diagram of the total settlement of the project of simultaneous widening and raising of the original subgrade at different widths is shown in Fig. 7a. It can be seen from the figure that when the widening width is 3.5 m, the overall uncoordinated deformation of the subgrade surface is ‘concave’. At this time, the settlement curve characteristics of the subgrade surface are similar to that of the newly built subgrade. When the width of the subgrade is 7, 10.5, and 14 m, the uncoordinated deformation of the subgrade surface (0–14 m) at the

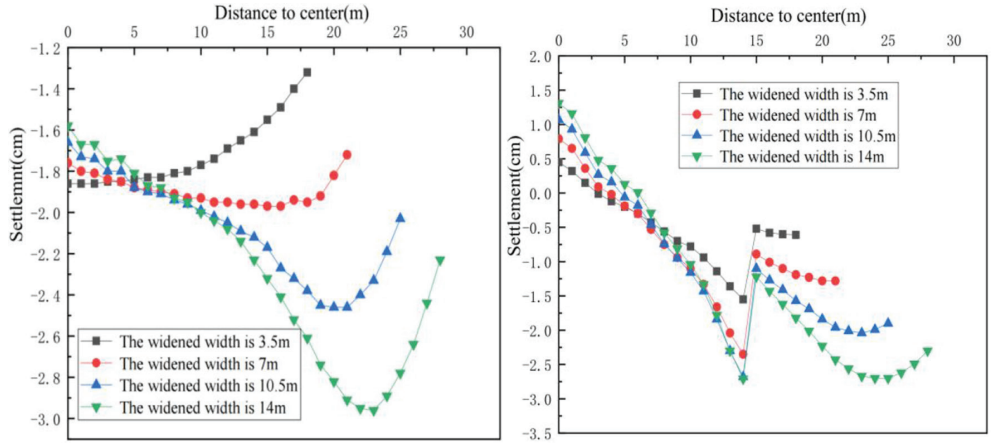

Figure 7: Curve diagram of the total settlement of the subgrade surface under different widened widths: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

raised position is 'upwardly convex', the uncoordinated deformation of the widened subgrade surface is 'downwardly concave', and the overall deformation of the subgrade surface is in the shape of '~'. With the increase of the widening width on both sides of the original subgrade, the settlement within 0–4 m of the raised subgrade surface gradually decreases and the settlement gradually increases within the range of 4–14 m. With the increase of the widening width, the maximum uncoordinated deformation value of the subgrade surface gradually increases. When the widened width is 3.5 m, the maximum uncoordinated deformation value of the subgrade surface is 0.54 cm; when the widened width is increased to 14 m, the maximum uncoordinated deformation value of the subgrade surface is 1.31 cm. As the width of the widening increases, the maximum deformation of the settlement of the subgrade gradually moves to the widened side. When the widening width is 3.5 m, the maximum settlement deformation of the subgrade occurs at the center of the subgrade. When the widening width is 14 m, the maximum settlement deformation of the subgrade is included on the inner side of the new subgrade shoulder. At this time, the subgrade surface on the widened side appears as a 'reverse slope'. It can be seen from Fig. 7b that with the continuous increase of the widened width, the overall uncoordinated settlement of the original and new subgrade in the project of only widening of the original subgrade gradually increases. The maximum total settlement of the subgrade surface appears at the splicing area of the original and new subgrade. At the same time, the subgrade surface settlement curvature of the splicing area increases most obviously. When the width of the subgrade is widened from 3.5 to 14 m, the value of the settlement curvature of the subgrade surface at the splicing area increases from 0.13 to 0.97.

For the project of simultaneous widening and raising of the original subgrade, when the width of the subgrade widening is small, the additional stress acting on the slope of the original subgrade by the additional load is small but the additional stress acting on the center of the subgrade is large. Therefore, when the width is widened by 3.5 m, the settlement at the shoulder of the subgrade is small, and the settlement at the center of the subgrade is large. After years of operation of the original subgrade and the underlying ground, the properties of the soil are significantly improved, and the improvement of the ground soil under the new

subgrade is much smaller than that of the original. Therefore, as the width of the widening increases, the settlement on the widened side of the subgrade increases significantly. For the project of only widening of the original subgrade, the junction of the original and new subgrade is the location where the additional stress is the largest. Therefore, as the widening increases, the maximum settlement also occurs at the junction.

4.2 Heights of subgrade

The basic conditions for widening the subgrade remain unchanged, and only the height of the subgrade is changed. In the calculation and analysis, the height of the upper part of the original subgrade for the project of simultaneous widening and raising of the original subgrade is taken as 1, 2, 3, and 4 m, and the height of the subgrade for the project of only widening of the original subgrade is taken as 4, 5, 6, and 7 m.

The curve diagram of the total settlement of the subgrade surface of the project of simultaneous widening and raising of the original subgrade is shown in Fig. 8a. It can be observed from the figure that the settlement at each point on the surface of the subgrade increases with the increase in height of the upper part of the original subgrade. When the original subgrade is raised by 1, 2, 3, and 4 m, the maximum total settlement of the subgrade surface increases to 1.97, 2, 2.04, and 2.15 cm, respectively. The position of the maximum total settlement point thus moves from the widened side of the subgrade to the center of the subgrade.

As shown in Fig. 8b, for the project of only widening of the original subgrade, both uplift and settlement occur on the surface of the subgrade at different heights. The uplift is mainly located in the center of the subgrade, and the amount of uplift increases with the increase in height of the subgrade. When the height of the subgrade increases from 4 to 7 m, the uplift value increases from 0.79 to 1.45 cm. The maximum total settlement of the subgrade surface occurs at the junction of the new and original subgrade. The maximum total settlement value of the subgrade also gradually increases with the increase in the subgrade height. The maximum total settlement is 2.35, 2.59, 2.79, and 2.94 cm, respectively.

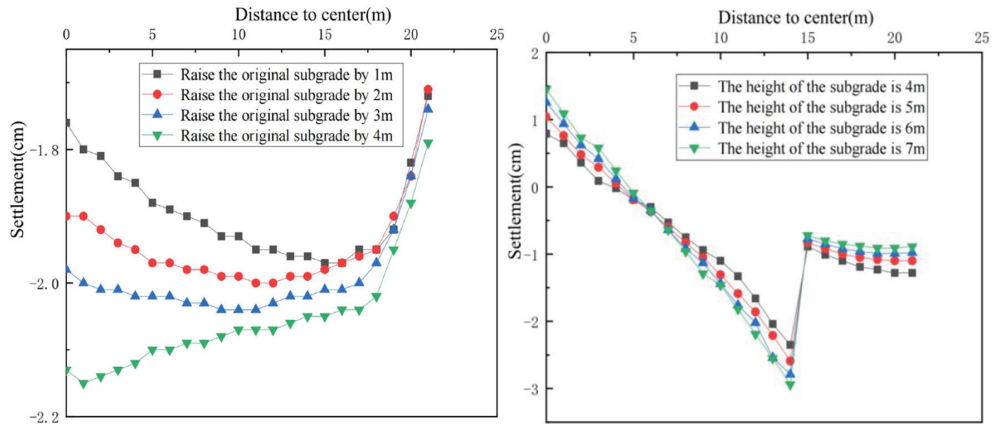

Figure 8: Curve diagram of the total settlement of the subgrade surface under different heights: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

For the project of simultaneous widening and raising of the original subgrade, the higher the upper part of the original subgrade, the greater the weight of the upper part of the ground soil, and the stronger the additional effect of the new subgrade on the original subgrade. When the raised height of the upper part of the original subgrade is less than the height of the original subgrade, the additional stress is mainly concentrated on the subgrade connection (14 m). When the raised height of the upper part of the original subgrade exceeds the height of the original subgrade, the additional stress is redistributed to the vicinity of the center of the subgrade. For the project of only widening of the original subgrade, the additional stress is mainly concentrated at the junction of the original and new subgrade.

4.3 Slope ratios of subgrade

The basic conditions for widening the subgrade remain unchanged; only the slope ratio of the new subgrade is changed. The slope ratio of the new subgrade is considered in this analysis as 1:1, 1:1.5, and 1:2.

The total settlement curve diagram of the subgrade surface under different slope ratios at the end of the construction period of two working conditions is shown in Fig. 9. It can be seen from the figure that with the increase of the slope ratio of the new subgrade, the total settlement of the subgrade surface under the two working conditions has an increasing trend. For the project of simultaneous widening and raising of the original subgrade, when the slope ratio of the new subgrade is 1:1, the maximum total settlement of the subgrade surface is 1.93 cm; when the slope ratio of the new subgrade is 1:2, the maximum total settlement of the subgrade surface is 1.99 cm; when the slope ratio of the new subgrade increases from 1:1 to 1:1.5 and from 1:1.5 to 1:2, the maximum total settlement of the subgrade surface increases by 2.07% and 0.51%, respectively.

For the project of only widening of the original subgrade, when the slope ratio of the new subgrade is 1:1, the maximum total settlement of the subgrade surface is 2.22 cm and the maximum differential settlement is 2.17 cm. When the slope ratio of the new subgrade is

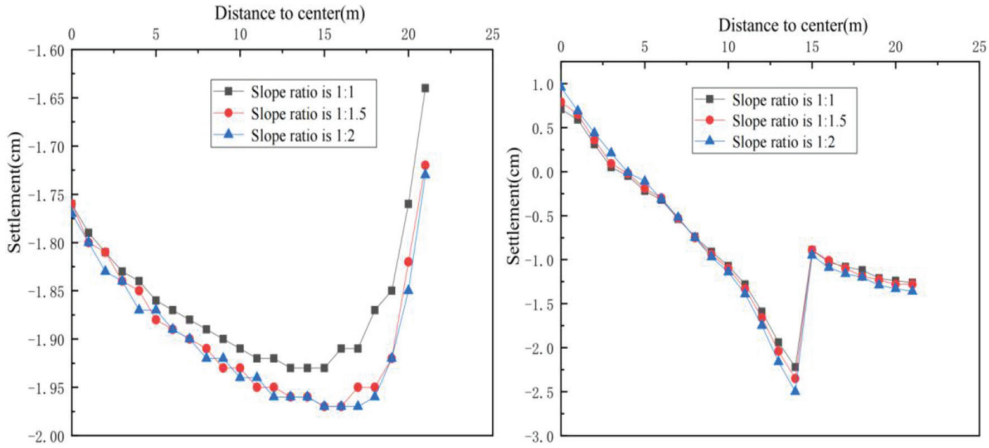

Figure 9: Curve diagram of the total settlement of the subgrade surface under different slope ratios: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

1:1.5, the maximum total settlement of the subgrade surface is 2.35 cm, an increase of 5.86%, and the maximum differential settlement is 2.33 cm, an increase of 7.37%. When the slope ratio of the new subgrade is 1:2, the maximum total settlement of the subgrade surface is 2.5 cm and the maximum differential settlement is 2.49 cm, an increase of 6.87%.

4.4 Filling materials of new subgrade

In this subsection, the basic conditions for widening the subgrade remain unchanged, and only the filling material of the new subgrade is altered. On the basis of the existing filling material, this article employs two other filling materials (filling material 1 and filling material 2). The existing filling material, filling material 1, and filling material 2 are silty clay, stone soil, and medium sand, respectively. The specific parameters of the existing filling material, filling material 1, and filling material 2 are shown in Table 1.

Table 1: The specific parameters of filling materials.

Name	Modulus of elasticity (MPa)	Poisson's ratio	Soil unit weight (kN/m^3)	Cohesion (kPa)	Angle of internal friction (°)
Filling material 1	900	0.25	21.3	–	–
Filling material 2	21.5	0.21	19.4	24	42.5
Existing material	32.5	0.3	18.2	31.5	32

Source: Lixiao (2014) and Lin (2007).

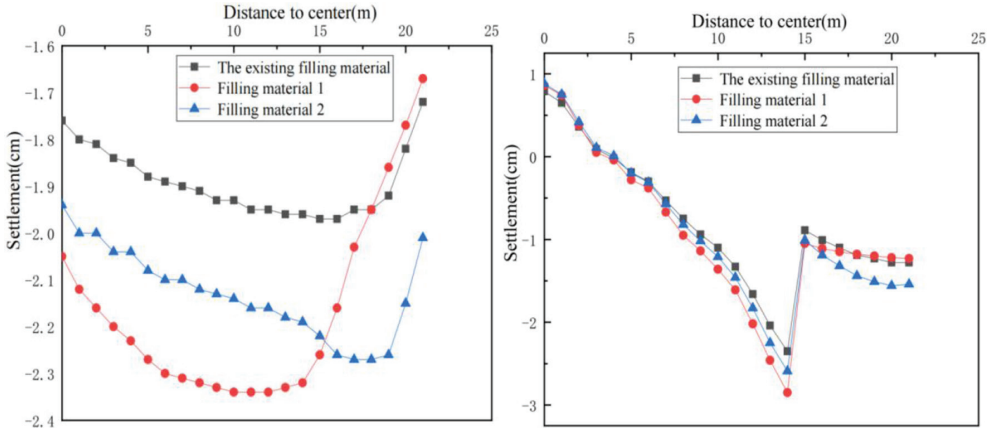

Figure 10: Curve diagram of the total settlement of the subgrade surface under different filling materials: (a) simultaneous widening and raising of the original subgrade and (b) only widening of the original subgrade.

The total settlement curve diagrams of the subgrade surface with different filling materials under two working conditions are shown in Fig. 10. As can be seen from the figure, different filling materials have an impact on the total settlement of the subgrade surface for both the project of simultaneous widening and raising of the original subgrade and the project of only widening of the original subgrade. In addition, among the three types of filling materials, filling material 1 (stone soil) has the greatest impact on the total settlement of the subgrade surface. For the project of simultaneous widening and raising of the original subgrade, the maximum total settlement of the subgrade surface under the influence of filling material 1 is 2.34 cm and the maximum differential settlement is 0.67 cm. When the original subgrade is only widened, the maximum total settlement of the subgrade surface under the influence of filling material 1 is 2.85 cm and the maximum differential settlement is 2.81 cm.

5 CONCLUSION

Based on finite element numerical simulation, this paper analyzed the total settlement of the subgrade of the project of simultaneous widening and raising of the original subgrade, the total settlement of the subgrade of the project of only widening of the original subgrade, and the total settlement of the subgrade surface with the two working conditions under the influence of different factors. The following conclusions were obtained:

1. There were differences in the settlement at different depths of the ground surface under the two working conditions. At the same time, the total settlement of the subgrade surface and the ground surface were different in the two working conditions. Compared with the project of only widening of the original subgrade, the maximum total subgrade surface settlement of the original subgrade simultaneous raising and widening project was relatively smaller and the maximum total ground surface settlement was relatively larger. Compared with the simulated value of the total settlement of the ground surface with the measured value, the settlement values in the two cases were relatively close, which further demonstrated the correctness of the finite element simulation.
2. Under the two working conditions, the total settlement of the subgrade surface increased with the increase of the width. However, with the increase in the width, the maximum total settlement point of the subgrade surface in the project of simultaneous widening and raising of the original subgrade gradually moved to the widening side of the subgrade, and the maximum total settlement point of the subgrade surface in the project of only widening of the original subgrade was still concentrated at the junction of the new and original subgrade.
3. Under the two conditions, the total settlement of the subgrade surface increased with the increase of the height of the subgrade. However, with the increase in the height, the maximum total settlement point of the subgrade surface in the project of simultaneous widening and raising of the original subgrade gradually moved to the center of the original subgrade, and the maximum total settlement point of the subgrade surface in the project of only widening of the original subgrade was still concentrated at the junction of the new and original subgrade.
4. Under the two conditions, the total settlement of the subgrade surface gradually increased with the increase of the new subgrade slope ratio.
5. Under the two working conditions, the total settlement of the subgrade surface varied with the change of filling materials, and the use of the filling material 1 (stone soil) had a greater impact on the total settlement of the subgrade surface of the two working conditions.

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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