Article

Evaluation of Differential Settlement of Subgrade for Highway-Widening Projects

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Abstract: Highway widening is an important way to improve the existing expressway capacity and promote the development of transportation systems. The differential settlement between the old and new subgrade is the key factor to evaluate whether it is necessary to carry out ground improvement for the new foundation, which will cause longitudinal pavement cracking and even subgrade instability. Therefore, the most critical task in the highway expansion project is controlling differential settlement, particularly post-construction differential settlement. In this study, a fluid-structure coupling settlement analysis model was developed based on FLAC3D, and a modified Cam-clay (MCC) model was used to describe the difference between new and old foundation parameters. The working conditions of different subgrade heights and groundwater levels were simulated to analyze their influence on the differential settlement during and after construction. With the increment value of the transverse slope ($\Delta i$) and maximum slope ($k$) of new and old subgrade settlement curves as evaluation indexes, the differential settlement size of widened subgrade under different working conditions is evaluated, which provides a basis for the design of widened foundation engineering and provides suggestions on whether reinforcement measures should be taken. The results show that the post-construction differential settlement increases with the increase in groundwater level and subgrade height. Under the requirement of $\Delta i \leq 0.5\%$, it is not necessary to take reinforcement measures under the condition of local water levels under a 2 m subgrade height and $-9$ m and $-11$ m groundwater levels under a 4 m subgrade height. However, when the water level rises further, or the height of the subgrade increases further, it is necessary to take foundation reinforcement measures. Meanwhile, for the requirement of $k \leq 0.5\%$, foundation reinforcement measures should be taken for all working conditions regardless of the water level or subgrade height. The research results can provide theoretical value and reference for foundation treatment in roadbed-widening engineering.

Keywords: highway widening; differential settlement; groundwater level; numerical analysis

1. Introduction

In recent years, rapid economic development has driven the progress of the transportation industry, resulting in the constant growth of the traffic volume on the highway. To satisfy the current road capacity and traveler demand, it is imperative to take road-widening and renovation measures. However, the influence of traffic load on subgrade settlement cannot be ignored [1]. The settlement deformation of the existing subgrade is stable under the long-term consolidation of the foundation due to dead weight and traffic load. However, since the newly built subgrade and foundation have not been subjected to the long-term overburden surcharge, large settlement deformation may occur, resulting in the obvious differential settlement between the new and old subgrade [2]. In addition, it has been shown that excessive differential settlement will lead to longitudinal cracking...
of the joints between old and new pavement [3], thus affecting the normal operation of the roads [4,5]. Therefore, it is of great significance to study post-construction differential settlement for highway-widening projects.

At present, most studies on post-construction differential settlement are performed through laboratory tests [6] or numerical simulation [7–9]. It has been shown that the differential settlement generated by widening and reconstruction projects is related to many factors, such as the construction method, widening the width of new subgrade, subgrade height, subgrade soil properties, etc. [2,10–12]. ANSYS was used to build a subgrade settlement model, and the unilateral widening and bilateral widening were compared to analyze the differential settlement [13]. Fu et al. established a differential settlement calculation model for the analysis of differential settlement characteristics of widened subgrade [14]. The effects of the subgrade height, subgrade compression modulus, the widening method [15], and the width of the subgrade on differential settlement and settlement curve characteristics were also investigated [16]. In addition, the finite element program PLAXIS was used to evaluate the mechanical and deformation characteristics of the roadbed in a highway-widening project [14,17]. Through numerical simulation, the influence of widening the plateau subgrade on the final settlement, horizontal displacement, and surface transverse displacement were analyzed [18]. The development of settlement [19], horizontal displacement, and pore water pressure during highway widening [20] were also analyzed by a centrifuge model test [21] and numerical analysis. Han et al. [8] established a two-dimensional model of subgrade widening based on FLAC 3D and verified it with engineering examples. At the same time, they further analyzed a series of problems such as the vertical and horizontal displacement, the maximum settlement, subgrade lateral movement, and additional stress distribution caused by widening. In addition, the criteria for differential settlement control are also not consistent [7,22,23]. Zhen et al. studied the classification of differential settlement control standards according to the requirements of the pavement structure and function [24]. They proposed taking the post-construction settlement curve slope rate as the control standard of differential settlement. Moreover, the splitting strength was proposed as the pavement dynamic response index [17].

At present, there is research on how to control differential settlement [5,24–28]. However, it can be found that the influence of groundwater on subgrade differential settlement is not very clear, and the control index of subgrade differential settlement is not universal. In this study, a fluid-structure coupling settlement analysis model was developed with FLAC3D, and the modified Cam-clay model was used to describe the difference between the new and old foundation parameters. The effects of subgrade height and groundwater level on the differential settlement during and after construction are analyzed through the simulation results. The increased values of the transverse slope ($\Delta i$) and the maximum slope ($k$) of new and old subgrade settlement curves are used as key indexes to evaluate the differential settlement of widened subgrade under different working conditions. This study provides the basis for foundation reinforcement design in roadbed-widening projects.

2. Settlement Analysis Model Establishment and Verification

To verify the accuracy and reliability of the study of soil consolidation settlement by FLAC 3D, the engineering case of Forsman et al. [29] was adopted for validation (Figure 1). Huang et al. [30] carried out a numerical simulation of the settlement of each profile for the whole construction and post-construction process. The numerical model established is shown in Figure 2. Settlement calculation model of Huang et al. [30] was based on FLAC 3D, and a road settlement calculation model considering groundwater seepage and consolidation settlement was also established in this study, as shown in Figure 3.

A comparison between the numerical simulation results at points 327.5, S1, and S2 of the extracted profile with Huang’s calculation and monitoring results is shown in Figure 4. By comparing the settlement curve shape of the subgrade bottom and the settlement process of the representative points, the numerical simulation results of this study are consistent
with that of Huang et al. [30] and the field measurement results. As such, the reliability of the fluid-structure coupling analysis method adopted in this study was validated.

![Figure 1. Project case diagram: (a) subgrade cross profile; (b) mixing column layout in the foundation.](image1)

![Figure 2. Settlement calculation model of Huang et al. [30].](image2)

![Figure 3. Settlement calculation model: (a) subgrade and foundation model; (b) mixing column in the foundation.](image3)
A comparison between the numerical simulation results at points 327.5, S1, and S2 of Figure 4. Comparison of the simulation results of this paper with the measured and simulated results from previous publications: (a) settlement at profile 327.5; (b) settlement at S1, S2. Huang et al. [30].

3. Establishment and Parameter Determination of Post-Construction Settlement Model

3.1. Parameter Determination

3.1.1. Typical Soil Parameters

Particle analysis tests, compaction tests, and Atterberg limit tests were carried out to obtain the basic characteristics of subgrade soil samples, and the results are as shown in Table 1. According to the analysis, the subgrade soil belongs to silty clay.

Table 1. Basic characteristics of subgrade soil.

<table>
<thead>
<tr>
<th>Optimum Moisture Content (%)</th>
<th>Maximum Dry Density (g/cm³)</th>
<th>Liquid Limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plasticity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>1.91</td>
<td>31.19</td>
<td>19.98</td>
<td>11.21</td>
</tr>
</tbody>
</table>

3.1.2. Parameters of Foundation

The foundation soil in this study is typical silty clay, with a permeability coefficient of $10^{-8}$ m/s. The modified Cam-clay (MCC) model was used to characterize the soil behavior, and the corresponding parameters are shown in Table 2.

Table 2. MCC model parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>normal consolidation line slope</td>
<td>0.04934</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>unloading/reloading line slope</td>
<td>0.00474</td>
</tr>
<tr>
<td>$p_0'$</td>
<td>preconsolidation pressure</td>
<td>1000 Pa</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>specific volume</td>
<td>1.85</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson ratio</td>
<td>0.35</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>bulk modulus</td>
<td>$5 \times 10^9$ Pa</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>1623 kg/m³</td>
</tr>
<tr>
<td>$M$</td>
<td>critical state line slope</td>
<td>1.24</td>
</tr>
</tbody>
</table>

3.1.3. Subgrade Parameters

The Mohr–Coulomb model was adopted for subgrade soil, with the model parameters shown in Table 3.
3.2. Establishment of the Numerical Model

Based on a general subgrade-widening project, the numerical model adopted is as shown in Figure 5. A subgrade height of 4 m is taken as an example, and the total width of the existing subgrade is 28 m. According to the symmetry rule, 14 m of half subgrade is used for modeling. The width of the widened subgrade is 7 m, and the slope rate is 1:1.5. The width of the foundation is 40 m, and the depth is 30 m. The water table’s depth is h.

Table 3. Subgrade soil parameters.

<table>
<thead>
<tr>
<th>Position</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E$ (MPa)</th>
<th>$\nu$</th>
<th>$\phi$ (°)</th>
<th>$c$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old subgrade</td>
<td>1950</td>
<td>37.1</td>
<td>0.30</td>
<td>27.0</td>
<td>47.0</td>
</tr>
<tr>
<td>New subgrade</td>
<td>1950</td>
<td>29.7</td>
<td>0.30</td>
<td>25.0</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Figure 5. Model of settlement calculation.

First, the settlement analysis model is established, elastic parameters and boundary conditions are set, and the initial stress field is obtained by the initial stress balance. Then, according to the construction procedure, the soil element is activated step by step, or the load is applied, to simulate the construction process of roadbed widening and to calculate the settlement value during construction.

For the static boundary, the subgrade is considered long enough to be considered a plane strain problem. Therefore, the normal displacement of each side of the model was constrained in FLAC 3D. The degree of freedom in the vertical direction was retained to simulate symmetry conditions and plane strain conditions. The bottom of the model was completely constrained and in a fixed state. In terms of seepage boundary, the left interface and bottom boundary were set as an impervious boundary. The right boundary was the continuous seepage boundary, and the pore pressure was maintained as static pore pressure. The water surface was a permeable boundary, and the pore pressure was always maintained at 0, allowing the pore water pressure to dissipate. Moreover, to further improve the calculation accuracy while taking into account the calculation efficiency and model aesthetics, a hexahedral grid with a side length of 0.5 m was adopted in this paper.

4. Results and Discussion

4.1. Influence of Groundwater Level on Subgrade Settlement

The settlement in the case of a subgrade height of 4 m and groundwater level depths of $-3\, \text{m}$, $-5\, \text{m}$, $-7\, \text{m}$, $-9\, \text{m}$, and $-11\, \text{m}$ was taken as an example to analyze the influence of...
groundwater level depth on subgrade settlement. Figure 6 shows the settlement value as a function of the distance from the old subgrade center for different groundwater level depths. It can be seen that the variation trend was the same; the subgrade settlement increases with the increase in the distance from the old subgrade center. With the decrease in groundwater level, the slope of the settlement curve increases gradually during the construction period. Meanwhile, the post-construction settlement and total settlement curve deviate downward, which shows that the subgrade settlement increases overall. The slope of the settlement curve following the installation of a new subgrade is smoother than the total settlement curve during construction when the groundwater level remains constant. The root cause of this phenomenon is that part of the settlement of the new subgrade has been eliminated during the construction period, so that the settlement in the later period is not significant.

It is generally accepted that the post-construction settlement is the total settlement minus the settlement during construction. In this paper, the total settlement of the old subgrade is the post-construction settlement, and the post-construction settlement of the new subgrade is the total settlement minus the settlement during construction. Generally,
the maximum value of the settlement curve occurs near the shoulder of the new subgrade, and the minimum value occurs at the center of the old subgrade. The differential settlement value is the difference between the maximum value and the minimum value of the settlement curve. For the 4 m subgrade, calculation results of the differential settlement in each working condition are shown in Table 4. The post-construction differential settlement is reduced by about 30% relative to the total differential settlement, which is because part of the differential settlement of the new subgrade has been eliminated during the construction, and this is why it is more in line with the actual engineering situation. It also shows that the post-construction settlement analysis method adopted in this study can accurately calculate the post-construction differential settlement of the widening subgrade, which lays a good foundation for the later evaluation of the subgrade settlement.

Table 4. Calculation results of differential settlement at different groundwater levels.

<table>
<thead>
<tr>
<th>Groundwater Level (m)</th>
<th>Differential Settlement during Construction (m)</th>
<th>Post-Construction Differential Settlement (m)</th>
<th>Total Differential Settlement (m)</th>
<th>Percentage of Post-Construction Differential Settlement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−3</td>
<td>0.0825</td>
<td>0.1176</td>
<td>0.1640</td>
<td>71.67</td>
</tr>
<tr>
<td>−5</td>
<td>0.0969</td>
<td>0.1213</td>
<td>0.1637</td>
<td>69.07</td>
</tr>
<tr>
<td>−7</td>
<td>0.1045</td>
<td>0.1231</td>
<td>0.1617</td>
<td>69.12</td>
</tr>
<tr>
<td>−9</td>
<td>0.1081</td>
<td>0.1063</td>
<td>0.1572</td>
<td>67.65</td>
</tr>
<tr>
<td>−11</td>
<td>0.1082</td>
<td>0.1052</td>
<td>0.1552</td>
<td>67.74</td>
</tr>
</tbody>
</table>

The percentage of post-construction differential settlement is the ratio of post-construction differential settlement to total settlement.

The variation in the differential settlement is shown in Figure 7. The differential settlement steadily rises during construction as the groundwater level falls, whereas the post-construction differential settlement and overall differential settlement marginally decline. This is because the soil above the water table is unsaturated, and the compression deformation develops rapidly, mainly during the construction period. Meanwhile, the main cause of the post-construction settlement is the drainage consolidation of soil below the groundwater level. Therefore, the groundwater level is one of the important factors affecting subgrade differential settlement. The fraction of unsaturated foundation deformation increases with lower groundwater levels, which causes more differential settling during construction. In addition, the additional stress caused by the new subgrade will decay with depth, and the groundwater level will decrease, which means that the influence of some underwater soil is reduced. As the consolidation settlement caused by pore pressure dissipation becomes less obvious, the post-construction differential settlement decreases. At the same time, the change in the curve shows that the decrease in the groundwater level gradually slows down, which indicates that the influence of the groundwater level on the settlement is gradually reduced. According to the actual working conditions, the differential settlement below the groundwater level is calculated so that appropriate actions can be taken to control the differential settlement of the subgrade in engineering practice, improve the service performance of the road, and lengthen its service life.

4.2. Influence of Subgrade Height on Settlement

The settlement in the case of the groundwater level of −5 m with subgrade heights of 2 m, 4 m, 6 m, and 8 m was taken as an example to analyze the influence of the subgrade height on the settlement. Figure 8 shows the total settlement curves of the top surface of the new and old subgrade during and after construction. It can be seen that with the increase in subgrade height, the slope of all settlement curves will increase, the post-construction settlement curve and the total settlement curve will move down, and the differential settlement is more significant. When a certain subgrade height is maintained, compared with the slope of the total settlement curve during construction, the slope of the post-construction settlement curve of the new subgrade is much gentler.

The calculation results of the settlement difference under different working conditions with the groundwater level of −5 m are shown in Table 5. As can be seen, with the increase
in subgrade height, the proportion of post-construction differential settlement relative to the total differential settlement gradually decreases by 25–33%. A reasonable evaluation of the differential settlement will directly affect the selection of foundation treatment approaches for the widening foundation. Therefore, post-construction differential settlement replaces full differential settlement as the control criterion, which reasonably reduces the cost of foundation treatment, especially for high-fill subgrade.

Figure 7. Variation in differential settlement with groundwater level.

Figure 8. Calculation of settlement at different subgrade heights: (a) 2 m; (b) 4 m; (c) 6 m; (d) 8 m.
Table 5. Calculation results of differential settlement at different subgrade heights.

<table>
<thead>
<tr>
<th>Subgrade Height (m)</th>
<th>Differential Settlement during Construction (m)</th>
<th>Post-Construction Differential Settlement (m)</th>
<th>Total Differential Settlement (m)</th>
<th>Percentage of Post-Construction Differential Settlement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0586</td>
<td>0.0955</td>
<td>0.1252</td>
<td>76.28</td>
</tr>
<tr>
<td>4</td>
<td>0.0969</td>
<td>0.1131</td>
<td>0.1637</td>
<td>69.09</td>
</tr>
<tr>
<td>6</td>
<td>0.1225</td>
<td>0.1276</td>
<td>0.1905</td>
<td>66.98</td>
</tr>
<tr>
<td>8</td>
<td>0.1388</td>
<td>0.1570</td>
<td>0.2022</td>
<td>67.42</td>
</tr>
</tbody>
</table>

The variation in the differential settlement under different working conditions with a groundwater level of $-5$ m is shown in Figure 9. With the increase in subgrade height under the same groundwater level, the total differential settlement increases gradually during construction. On the one hand, the increase in subgrade height leads to the increase in the load borne by the foundation, increasing deformation. On the other hand, the subgrade construction period is positively correlated with the subgrade height. For projects with high subgrade, the settlement has a longer development time in the construction process, which further promotes the occurrence of differential settlement during construction. In addition, with the increase in subgrade height, the differential settlement after construction also increases slightly. This is mainly due to the large excess pore pressure generated by the high subgrade and the wide affected area, which leads to the large consolidation settlement. This guides the setting of the subgrade height in broadening engineering design.

![Figure 9. The variation in differential settlement with subgrade height.](image)

4.3. Evaluation of Post-Construction Differential Settlement

4.3.1. Differential Settlement Coupling Analysis

Figure 10 illustrates the coupling effect of the subgrade height and groundwater level on post-construction differential settlement. It can be seen that the post-construction differential settlement increases with the increase in the groundwater level and subgrade height. The maximum post-construction differential settlement (14.25 cm) occurs at a subgrade height of 8 m and a groundwater level depth of $-3$ m, whereas the minimum post-construction differential settlement (9.02 cm) occurs at a subgrade height of 2 m and a groundwater level depth of $-11$ m.

4.3.2. Evaluation Index $\Delta i$

Both the Technical Rules for Design and Construction of Highway Embankment on Soft Soil Foundation (JTG D31-02-2013) and the Code for Design of Highway Subgrade (JTG D30-2015) indicate that the increased value of the arch slope of existing subgrade and widened subgrade should be controlled within 0.5% after construction. For the calculation of the increased value of the transverse slope of the road crown, the following indicator has commonly been used:
\[ \Delta i = \frac{(z_1 - z_2)}{l_{12}}, \]  

(1)

where \( z_1 \) is the central settlement of the old subgrade, \( z_2 \) is the shoulder settlement of the new subgrade, and \( l_{12} \) is the total width of the new and old subgrade. The index \( \Delta i \) is adopted to evaluate the increased value of the road crown transverse slope of the post-construction settlement curve under different subgrade heights and groundwater levels, and the results are shown in Figure 11. As can be seen, the increased value of the road crown transverse slope \( \Delta i \) increases with the increase in the groundwater level and subgrade height, which is consistent with the trend of post-construction differential settlement. When the subgrade height is 8 m, and the groundwater depth is \(-3\) m, the maximum value of \( \Delta i \) is 0.68%. Meanwhile, the minimum \( \Delta i \) is 0.4% when the working conditions include a subgrade height of 2 m and a groundwater level depth of \(-11\) m. The corresponding \( \Delta i \) of each water level under 2 m subgrade height does not exceed the limit value. However, if the water level rises further, or the subgrade increases further, \( \Delta i \) exceeds the limit of 0.5%, and the corresponding foundation reinforcement measures need to be taken.

Figure 10. Analysis of post-construction differential settlement.

4.3.3. Evaluation Index \( k \)

The increased value of the transverse slope is controlled not more than 0.5% to reduce the cracking damage of the pavement structure. When \( \Delta i \leq 0.5\% \), this only indicates that the increased value of the overall transverse slope of the subgrade meets the requirements. However, some local parts may still exceed the limit, which may cause the risk of pavement cracking. In order to strictly control the differential settlement of the highway-widening project, the maximum slope of the settlement curve is proposed as the evaluation index \( k \) to control the differential settlement. As can be seen from the above settlement curves (Figure 8), all post-construction settlement shows a similar S shape, and the junction of the old and new subgrade is the boundary. The slope of the maximum tangent line can be
obtained from the side of the old subgrade approaching the reverse bend point, denoted by \( k \):

\[
k = \lim_{x \to l_0} \frac{z(x) - z_0}{x - l_0}
\]

where \( x \) is the \( x \)-axis coordinate of the post-construction settlement curve, \( z(x) \) is the curve expression, \( z_0 \) is the settlement at the joint of the new and old subgrade, and \( l_0 \) is the width of the old subgrade. Formula (2) is used to evaluate the maximum slope \( k \) of the post-construction settlement curve under different subgrade heights and groundwater levels, and the calculation results are shown in Figure 12. It can be seen that under all working conditions considered in this study, the index \( k \) of the post-construction settlement curve exceeds the limit value of 0.5%, which is quite different from using the index \( i \).

**Figure 11.** Evaluation of \( \Delta i \), the increase in the road crown slope.

**Figure 12.** Evaluation of the maximum slope \( k \).
5. Conclusions

Based on the FLAC 3D analysis model considering the difference between new and old foundation parameters, this study has analyzed the influence of the groundwater level and the subgrade height on the differential settlement during and after construction for highway-widening projects. The main goal of evaluating the differential settlement of wider subgrade is to determine the best means and criteria for foundation remediation. The settlement control indexes of the increased value ($\Delta i$) of the transverse slope of the road crown and the maximum slope $k$ of the settlement curve as the evaluation index are proposed in this study. These indexes can effectively control the differential settlement of the new and old subgrade and have great guiding significance on whether to take reinforcement measures in the widening project. The following main conclusions can be drawn:

- Part of the differential settlement of the new subgrade could be eliminated during the construction process, and the post-construction differential settlement of the subgrade accounts for about 70% of the total differential settlement;
- With the decrease in groundwater level, the differential settlement increases gradually during the construction period, whereas the post-construction differential settlement decreases slightly. For 4 m high subgrade, when the groundwater level decreases from $-3$ m to $-11$ m, the corresponding differential settlement during construction increases from 8.25 cm to 10.82 cm, and the post-construction differential settlement decreases by 11%;
- With the increase in subgrade height, the differential settlement increases gradually during and after construction. For a $-5$ m groundwater level, when the subgrade height increases from 2 m to 8 m, the corresponding differential settlement during construction increases from 5.86 cm to 13.88 cm, and the differential settlement after construction increases by 43%;
- The transverse slope of the road arch shall not rise by more than 0.5% on either the enlarged or existing subgrade. Taking the increased value ($\Delta i$) of the transverse slope of the road crown as the evaluation index, there is no need to reinforce the new foundation for 2 m high subgrade or 4 m high subgrade with an underground water level deeper than $-9$ m. For other cases with lower groundwater levels or higher subgrade, the corresponding foundation reinforcement measures should be taken;
- The maximum slope $k$ of the settlement curve, as the evaluation index, was more than 0.5% for all the cases considered in this study, so that corresponding foundation reinforcement measures are recommended for differential settlement control. Compared with index $\Delta i$, index $k$ is more rigorous in terms of quality control. In real highway-widening projects, the evaluation index should be determined according to specific situations and requirements.


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