Numerical Analysis on Uncoordinated Deformation in Highway Subgrade Widening

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Abstract: Finite element model of widened subgrade by finite element analysis software is established. The uncoordinated deformation rule of the subgrade widening is studied. By considering the different heights of embankment, different excavated slope, uncoordinated deformation is comparably analyzed. It is resulted that the uncoordinated deformation of the high filling subgrade widening is greater than the one of low embankment widening. The steeper original subgrade excavated slope is, the larger deformation will be on the foundation and subgrade. And uncoordinated deformation is more obvious. Moreover, ground settlement is bottomed at the old road center and it increased with distance away from it. Also, the uncoordinated deformation peaked at the original toe.

1. Introduction
The layer-wise summation method is the theoretical method that has been used in calculating settlement of the widening project on both new and old subgrade. However, the method only has the settlement of each layer of the base calculated and the consolidation compression deformation of the roadbed has not been taken into account, which leads to huge differences between measured data on-site and calculation result. Moreover, the layer-wise method failed to consider the interaction between new and old subgrade, which results to a bad cross-section shape as well as the large number of differential settlement on the junction of the subgrade [1-3]. The finite element method (FEM) was used to summarize the pattern of the uncoordinated deformation on the widened subgrade and analyse the parameters that influence the performance of the subgrade, such as subgrade height, cutting slope ratio and excavation steep width. The research results would provide references to the design and construction procedure in engineering practice.

2. Establishment of FEM model and material parameter values
Considering the complex parameters that affect the performance of the widened subgrade, few assumptions have been made. The subgrade is considered to be in plane strain stress state and 2-dimension FEM analysis has been carried out. Also, the filling and foundation soil adopts the Mohr-Coulomb ideal elastoplastic model and no slippage or detachment occurred between the original subgrade and the widened subgrade [4-5].

Based on the results from geological prospecting, the parameters of soil are shown in Table 1. The subgrade height is 8.0 m, 26.0 m wide for the original subgrade and 8.0 m for the widened subgrade on each side, with slope ratio of 1.5H: 1V. The depth of the foundation is 30.0 m, with silty clay, clay
and silt from top to bottom. The width of foundation is 80.0 m and load applied on the subgrade is 20.0 kPa of equivalent uniform live load [6].

| Layers       | Depth (m) | Young Modulus (MPa) | Poisson's ratio | Cohesion (kPa) | Internal friction angle (°) | Unit weight (kN·m⁻³) | Osmotic coefficient (m·d⁻¹) |
|--------------|-----------|---------------------|----------------|---------------|----------------------------|---------------------|-----------------------------|
| Filling soil | 8.0       | 10                  | 0.35           | 30.0          | 26.0                       | 18.5                | —                           |
| Silty clay   | 10.0      | 8                   | 0.30           | 23.0          | 27.0                       | 18.9                | 0.0008                      |
| Clay         | 10.0      | 9.4                 | 0.30           | 29.0          | 30.0                       | 18.7                | 0.0005                      |
| Silt         | 10.0      | 11.2                | 0.30           | 33.0          | 32.0                       | 20.0                | 0.0005                      |

Due to the symmetry of the finite element, half of the structure may be taken, and the center of the old road is calculated for its symmetry plane. The horizontal displacements of the left and right boundaries are constrained, and the horizontal and vertical displacements of the bottom boundary are constrained.

3. Results and discussion

3.1 Foundation settlement
The settlement curve of the foundation is shown in Figure 2. According to the figure, the settlement of the widened part is much larger than that of the original subgrade and the curve of final settlement is a good agreement with the theoretical calculation.

The settlement increased with the distance to the original embankment center and peaked at the foot of the old subgrade, where the additional stress is approximately the maximum, and decreased with the enlarging distance to the subgrade center. Due to the compression to the old foundation from the widened subgrade, the settlement bounced to approximately 1.2 cm at the completion of the construction, meanwhile the differential settlement is 10.8 cm as the maximum settlement is 9.6 cm. The settlement continues to increase with time and most of it happened in the period of 5 years after construction. The settlement gradually turned stable for the next 5 years and the maximum differential
settlement is 10.9 cm with final foundation settlement of 14.0 cm, less than the limitation of 15.0 cm, which requires more attention on the ground treatment.

3.2 Lateral displacement of the foundation
The lateral displacement curve of the foundation is shown in Figure 3. According to the figure, the lateral displacement from embankment center to the centroid of the widened subgrade is negative (i.e., pointing to the center of the subgrade). And it turned positive and increased with distance to the embankment center, peaked at the center of the widened part. The lateral displacement changes fast at the beginning of the completion and turned stable gradually for the next 5 years. As for the final displacement, the widened part displacement is larger than that of the original, which the displacement is in the range of -0.8 cm to 1.5 cm.

![Figure 3. Road surface adding horizontal displacement.](image)

3.3 Settlement of the pavement
The settlement of the pavement is shown in Figure 4. According to the figure, settlement on the old shoulder is larger than that on the center. The settlement on the center bounced for approximately 0.8 cm above because of the foundation deformation, and the settlement peaked on the shoulder with 3.4 cm. The post-construction settlement continued to increase and turned level up for 10 years, formed a maximum settlement of 8.9 cm and the final differential settlement is 5.4 cm. It indicates that widened subgrade is affecting the performance of original subgrade and it should be controlled during construction.

![Figure 4. Settlement of the pavement.](image)

3.4 Parameter study on subgrade height
Due to the topographical change, height of the widened subgrade may various and deformation could be different under the effect of gravity. Hence, height is the key element that affects the performance of the subgrade and foundation. Four cross-sections with different heights from 2.0 m to 8.0 m were selected to analyze the deformation of them in 15 years after construction.
3.4.1 Foundation settlement. Settlement in foundation under different subgrade height is shown in Figure 5. With the same slope ratio, different height may lead to different width of widened subgrade. It indicates that the barycenter of the widened part is out of the old foundation with subgrade height is 2.0 and 4.0 m, where the settlement peaked, while it is inside the old foundation as the height is 6.0 m and 8.0 m, where the maximum settlement located at the old toe. The minimum settlement varied from 1.1 cm to 3.1 cm with 2.0 m to 8.0 m, respectively, while the maximum settlement changes from 6.7 cm with 2.0 m to 14.0 cm with 8.0 m. Based on the patterns above, for subgrade widening project under 5.0 m, the barycenter is where settlement peaked. As for higher subgrade, it is the old toe that should be paid more attention on deformation during construction.

![Figure 5. Deformation curve of road surface adding settlement over subgrade height.](image)

3.4.2 Settlement on the pavement. Settlement on the pavement with different subgrade height is shown in Figure 7. The curves indicate that the settlement increased with longer distance to the center and peaked at the shoulder. Moreover, settlement grows with height increases, differential settlement rises from 3.3 cm with height of 2.0 m to 5.4 cm with it of 8.0 m, indicating that the uncoordinated deformation for high subgrade should be controlled during the period of construction and operation.

![Figure 6. Deformation curve of the old road surface adding settlement over subgrade height.](image)

Overall, height is the key element that affects the deformation of both foundation and subgrade. Hence, measures should be taken to control the deformation for high embankment in widening construction projects.

3.5 Parameter study on excavation slope ratio
In the highway widening project, if the foundation under the slope of the old road needs to be treated or the slope soil is weak, then larger slope soil needs to be excavated. The slope ratio may be the same with the original slope, or larger than that [7]. Different slope ratio has been studied in this paper, as the original subgrade ratio of 1.5H: 1V being excavated to 1H: 1V or 0.5H: 1V.
3.5.1 Foundation settlement. The settlement curve with different slope ratio being excavated is shown in Figure 7. Stepper the slope is, larger the settlement is. The settlement increased from 14.0 cm with 1.5h: 1V to 20.4 cm with 0.5H: 1V. As the barycenter moving to the inner side of the subgrade with stepper slope, differential settlement grows from 10.9 cm to 15.1 cm.

![Figure 7. Road surface adding vertical settlement in the different cutting slope of the old road.](image)

3.5.2 Settlement of the pavement. The settlement of the pavement with different excavated slope is shown in Figure 8. It indicates that stepper the slope is, larger the differential settlement is. The differential settlement increases from 5.4 cm to 8.0 cm with 1.5H: 1V to 0.5H: 1V.

![Figure 8. The old road surface adding vertical settlement in the different cutting slope of the old road.](image)

4. Conclusions
Based on the FEM analysis, some conclusions on the subgrade widening has been revealed.
(1) The minimum settlement of the foundation is located at the original subgrade center, and it increased with longer distance to it and peaked at the original toe. Then, it decreased with more distance. Little rebound appeared at the center right after the construction is completed and differential settlement topped at the old toe. Settlement rises with time as most of it happened in the period of first 5 years after construction, and it turned stable for 5 years after that.
(2) The lateral displacement is changing fast at the beginning after the completion; it showed a trend of moving to the inner side of the subgrade and turned stable for 5 years. The final displacement of widened subgrade is larger than that of original part.
(3) Height is the key parameter to the performance of the widened subgrade that measures should be taken to have the uncoordinated deformation controlled.
(4) The stepper the excavated slope is, the larger the deformation is. More filling soil would be constructed with stepper excavated slope, indicating more uncoordinated deformation would be appeared. So, under the condition of stability, more attention should be paid on the junction between the original and widened subgrade.
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