Numerical Simulation of Reinforced Soil Slope in Subgrade Widening of Expressway

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Abstract:
The finite difference element software FLAC3D was used to simulate the reconstruction and expansion project of Xinle-Yuanshi expressway. The model of reinforced soil slope widening subgrade was established. Based on the comparison of the simulation data of the sections with different heights and structural forms, the structural behavior of reinforced soil structure in subgrade widening project was analyzed. The law of structural deformation and construction control technology were summarized.

1. Introduction

With the increase of the traffic flow of the expressway, some of the original expressways need to be reconstructed and expanded. The expansion construction in the area with poor geological conditions puts forward higher requirements for the widening structure[1-2]. How to ensure the overall stability of the widened subgrade structure, reduce the differential settlement between the old and the new subgrade joint, and prevent the occurrence of pavement longitudinal cracking has become the focus of research[3]. Reinforced soil slope is widely used in subgrade widening engineering for its advantages of reducing land occupation, good seismic resistance, strong adaptability of foundation conditions and cost saving[4].

The anchoring mechanism of anchoring bar and the function mechanism of geogrids in the joining between the new and the existing subgrade are analyzed by Wang[5]. Through the 3D finite element analysis, Qian[6] studied the mechanical performance and influence of geosynthetic-reinforced and pile-supported (GRPS) embankment in the soft soil subgrade widening project. Ling[7] studied the performance and treatment method of low liquid limit silty clay widening subgrade through laboratory test and numerical simulation. Combined with the experimental section of Fangzhen-Harbin section of Tongjiang Sanya expressway, Yang[8] analyzed the stability of unilateral widening embankment in the process of step excavation of old road slope and construction of new embankment. Sivathasan[9] introduced the geotechnical engineering challenges encountered in the widening project of Expressway and the methods to solve these challenges. In order to know the effect of freeze-thaw action and soil compression on the post-construction deformation of widening high embankment in seasonal frozen regions, Shan[10] combined with the survey of Fangzheng-Harbin section of Tongshan highway.

In this paper, based on the reconstruction and expansion project of Xinle-Yuanshi expressway, FLAC3D software is used to carry out three-dimensional numerical simulation to analyze the structural state of widened structure in the construction process and after completion.
2. Project overview and numerical model

2.1. Project overview

Xinle-Yuanshi expressway has been open to traffic for 25 years. The original subgrade is 27 m wide and 4 m-4.4 m high. After widening, the subgrade wide is 34.5 m, the subgrade high is 4.8 m-6.4 m, and the slope rate is 1:0.75. The foundation soil is composed of silt and medium sand from bottom to top, with thickness of 10 m and 5 m, respectively. The foundation of the newly widened part is treated with geocell, and the treatment depth is 0.6m. The connection between the new and the original subgrade shall be excavated by benching. The step high is 0.8m and the step wide is 1.2m. The original subgrade filler is sandy soil, and the reinforced soil slope is filled with gravelly soil. The return package structure is used in reinforced soil slope. The reinforcement is TGDG-65 one-way tensile plastic geogrid with the vertical spacing of 0.4m.

2.2. Numerical model

The Mohr-Coulomb model is adopted for foundation soil and subgrade filler. The elastic model is adopted for geogrid. Material parameters are shown in table 1-2.

| Material                      | Density (kN·m⁻³) | Bulk modulus (MPa) | Shear modulus (MPa) | Poisson's ratio | Cohesion (kPa) | Internal friction angle (°) |
|-------------------------------|------------------|--------------------|---------------------|----------------|---------------|---------------------------|
| Medium sand of foundation     | 18.2             | 30                 | 13.8                | 0.3            | 0             | 36                        |
| Silt of foundation            | 19.5             | 43.3               | 14.4                | 0.35           | 6             | 37                        |
| Original subgrade filler      | 18.7             | 25                 | 18                  | 0.28           | 10            | 35                        |
| Natural grading subgrade filler | 19              | 25                 | 18.6                | 0.28           | 20            | 32                        |
| Reinforced soil subgrade filler | 20.8            | 16.7               | 18.1                | 0.2            | 29.5          | 33.1                      |

| Model                        | HDPE TGDG 65     |
|------------------------------|------------------|
| Tensile modulus(kN·m⁻³)      | 825              |
| Poisson's ratio              | 0.2              |
| Thickness(mm)                | 1.0              |
| Cohesion of coupling spring(kPa) | 4.9         |
| Friction angle of coupling spring (°) | 5.7         |
| Stiffness per unit area of coupling spring(kPa) | 1300          |

The depth of the foundation is 15 m and the width is 30 m. Two sections with subgrade height of 4.8 m and 5.6 m are selected. Half of the subgrade model is established for simulation analysis, as shown in Figure 1.
3. Simulation results of reinforced soil slope subgrade

3.1. Vertical displacement

The vertical displacement distribution after the filling of reinforced soil slope subgrade structure is shown in Figure 2. It can be seen from the figure that the vertical displacements of two kinds of reinforced soil slopes increase with the increase of subgrade height. The maximum vertical displacement in Figure 2 (a) and Figure 2 (b) are 14.8 mm and 18.5 mm, respectively. Compared with the original subgrade, due to the small degree of compaction at the reinforced slope, a large vertical displacement occurs within a certain range of the reinforced slope. The gravity center of the new subgrade lies between the new subgrade shoulder and the original subgrade shoulder, where the displacement is large. During the design and construction process, the excavation depth of the original subgrade slope shall be controlled, and the compaction quality of the connection between the new subgrade and the original subgrade shall be ensured.

![Figure 2. Vertical displacement distribution of subgrade.](image)

The change of foundation surface settlement with filling height is shown in Figure 3. It can be seen from the figure that the foundation surface settlement increases with the increase of filling height. When the subgrade with 4.8m-high is filled, its surface settlement is 14.2mm. When the subgrade with 5.6m-high is filled, its surface settlement is 17.4mm. With the increase of overburden, the foundation is gradually consolidated and the settlement rate of the foundation is gradually reduced.

![Figure 3. Change of foundation surface settlement with filling height.](image)
3.2. Horizontal displacement

The horizontal displacement curve of slope is shown in Figure 4. The horizontal displacement distribution of subgrade is shown in Figure 5.

After the construction of reinforced soil slope subgrade, the horizontal displacement is small. The horizontal displacement increases first and then decreases along the slope from bottom to top. The horizontal displacement of the reinforced soil slope is negative, that is to say, the displacement of the slope toward the center of the subgrade is generated. The horizontal displacement of the section with subgrade height of 5.6m is large, and the maximum displacement is -2.2mm. The horizontal displacement of the original subgrade is larger than that of the new one. The maximum horizontal displacement at the original subgrade shoulder is 3.4mm.

3.3. Structural stability analysis

The safety factors of the two sections are calculated by strength reduction method. The safety coefficients of the two sections are 2.56 and 2.39, respectively, with high overall stability. This kind of structural form and reinforcement arrangement method are suitable for the roadbed widening structure.
The shear strain increment of reinforced soil slope is shown in Figure 6. The maximum shear strain of the two kinds of section is basically distributed in circular arc from the original subgrade shoulder to the new subgrade toe, and the maximum shear strain point appears at the toe of the slope. Because there is no reinforced material in the original subgrade, compared with the reinforced part, the shear strength is lower, so the shear strain is larger. In the process of design and construction, the shear strain can be reduced by increasing the treatment depth of the foundation and the strength of the reinforcement at the junction of the subgrade.

4. Conclusion

According to the simulation results, the structural state after the completion of subgrade construction is analyzed, including the vertical displacement, horizontal displacement and safety stability of the structure. Some conclusions are drawn.

(i) For the reinforced soil slope structure, the displacement of the new subgrade changes little, and the horizontal displacement of the subgrade slope surface to the inner side of the subgrade is produced.

(ii) The settlement of the foundation surface in the widened part increases with the increase of the filling height, and the growth rate decreases when the filling height reaches 3.5m.

(iii) The maximum increment of shear strain of reinforced soil slope occurs at the toe of original subgrade.

(iv) The reinforced soil structure becomes a composite structure due to the grid, and the deformation is more uniform. The safety factor of reinforced slope is high.

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Reference

[1] Alpysova, V.A., Bushuev, N.S., Shkurnikov, S.V., et al. (2017) The impact of engineering-geologic conditions on the development of railway subgrade design solutions. Procedia Engineering, 189:752-758.

[2] Lee, E.B., Harvey, J.T., Thomas, D. (2005) Integrated design/construction/operations analysis for fast-track urban freeway reconstruction. Journal of Construction Engineering and Management, 131:1283-1291.

[3] Shen, Ai-quin , Zheng et al. (2003) Study of compacting mechanism and construction technology of filling road bed with bearing sand silt of low liquid limit. China Journal of Highway and Transport, 13:12-15.
[4] Li, Y., Yang, J.Sh., Gao, Y.X., et al. (2006) Numerical analysis of geosynthetics treatment in old road widening. Chinese Journal of Geotechnical Engineering, 25:1670-1675.

[5] Wang, H., Yang, G.Q, Liu, W.Ch., et al. (2014) Research on the anchorage-reinforced technology in the highway subgrade widening projects. In: Ground Improvement and Geosynthetics, WuHan. pp.452-463.

[6] Qian, J.S, Ling, J.M. (2009) 3D finite element analysis of geosynthetic-reinforced and pile-supported widening of embankment over soft soil. In: Road Pavement Material Characterization and Rehabilitation, WuHan. pp.124-132.

[7] Ling, J.M, Li, W.Y, Huang, Q.L, et al. (2014) Subgrade performance and treatment of silty clay with low liquid limit in widening. In: Ground Improvement and Geosynthetics, WuHan. pp.278-288.

[8] Yang, L., Shan W. (2010) Stability finite element analysis in the process of one side widened-embankment construction. ICCTP: Integrated Transportation Systems: Green, Intelligent, Reliable, ShangHai. pp.3095-3101.

[9] Sivathasan, S.K., Benson, T.C.. (2011) Geotechnical challenges in freeway widening project-case study. In: Geo-frontiers: Advances in Geotechnical Engineering, BeiJing, pp.2958-2967.

[10] Shan W., Guo Y., Liu, H.. (2009) The compaction for widening high embankment and its distribution along the height of roadbed in seasonal frozen regions. In: International Conference on Transportation Engineering, ShangHai. pp.3368-3374.