Parametric Influences of Stability and Settlement Pattern of Embankment on Slope Foundation

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Abstract. Building a subgrade on the slope foundation is common for highway constructions in China. Under different hydrogeological conditions, the stability and differential settlement are the main problems for the construction of the subgrade. In order to study the parameters that influence the stability and deformation of subgrade, based on the cross-section of a mountainous region highway, those simulations were conducted to study the influence of subgrade height, subgrade width, embankment slope angle, and slope foundation angle on the stability and pattern of embankment. The results showed that the allowable filling height is 15 m; otherwise, there is a large risk of the slope sliding. Further, it was found that the maximum vertical deformation on the right shoulder of the embankment increases with an increase in the angles of the slope of the foundation. These results provide references for future highway constructions and design works in mountainous areas.

1. Introduction

The stability and settlement of the subgrade are the two most important factors in the construction and service period. For the construction on a slope, which is very different from the construction on plain ground, a large differential settlement or small-scale landslide may occur in the service period.

Based on the complex foundation conditions, it is necessary to identify a method to control the differential settlement so as to prevent it from being too large as it can increase the risk of stability. To solve the problem, it is necessary to analyse the parameters that affect the subgrade stability and deformation such as height, width, subgrade slope ratio, foundation ratio, and soil characters.

Nowadays, design and construction methods of subgrade on plain foundation have been studied comprehensively[1-4]. However, for the slope foundation, parameters such as the slope angle and character of the filling on both sides method affect the construction. Several damages occur on the subgrade during or after the construction, which incur high costs[5-6]. This has become a major
problem to building highways in mountainous areas owing to the unstable subgrade and differential settlement. Therefore, in this paper, the effects of the parameters affecting subgrade stability are analysed along with the prediction of the deformations.

2. Numerical modelling

The Mohr–Coulomb model is used to numerically analyse the subgrade of the slope foundation highway using the Lagrange finite difference method. The tensile separation point, tensile stress yield function, and shear yield function, are the Mohr–Coulomb yield criteria, which corresponds to the failure envelope.

The soil was modelled as a linearly-elastic perfectly-plastic material using the Mohr–Coulomb criterion. The parameters of the Mohr–Coulomb model are friction angle ($\phi$), cohesion ($c$), elastic modulus ($E$), and Poisson's ratio ($\nu$). Based on the lab test results from the Hebei Provincial Communications Planning and Design Institute, the parameters are listed in Table 1.

| Category   | Poisson's ratio | Density (kN/m$^3$) | Elastic Modulus (MPa) | Cohesion (kPa) | Friction Angle (°) |
|------------|-----------------|--------------------|-----------------------|----------------|--------------------|
| Filling    | 0.30            | 22                 | 30                    | 24             | 20                 |
| Foundation | 0.25            | 25                 | 50                    | 90             | 44                 |

The model is based on the cross-section, the width of the subgrade is 24.5 m, the central separation bandwidth is 2.0 m, the traffic lanes are 2 × 3.75 m on each side, the left curb is 0.5 m, the right hard shoulder is 2.5 m (including the curb with 0.5 m), and the right dirt shoulder is 0.75 m. The height of the subgrade is 4.0 m, embankment slope angle is 33.7°, and the foundation angle is 14°. The model of subgrade is shown in Figure 1 and the meshing model is shown in Figure 2.

According to the Technical Standard of Highway Engineering (2014), the acceptable ratio of differential settlement is 0.4%. Results showed that the subgrade function and structure would be in a good condition if the ratio is below 0.4%. In order to study the differential settlement of the subgrade, nine monitoring points were selected. Set the coordinate of the leftmost point as zero; point No.1 is 0.25 m to the zero point, and the distance between each point is 3.0 m (see Figure 3).
3. Parameters study
In order to study the influences of the parameters such as height \(H\) and foundation angle \(m\) to the slope foundation, a series of simulations were carried out. The simulation scheme is summarized in Table 2.

| No. | Height (m) | Foundation angle (°) |
|-----|------------|----------------------|
| 1   | 4          | 14.0                 |
| 2   | 6          | 14.0                 |
| 3   | 8          | 14.0                 |
| 4   | 10         | 14.0                 |
| 5   | 12         | 14.0                 |
| 6   | 4          | 11.3                 |
| 7   | 4          | 12.5                 |
| 8   | 4          | 14.0                 |
| 9   | 4          | 16.0                 |
| 10  | 4          | 18.5                 |

3.1 Effect of subgrade height
In order to understand the influence of height on subgrade stability, the calculation was performed considering the embankment slope, subgrade width, and foundation angle constant, and the deformation of the shoulders on both left and right side were monitored, along with the toe on the left side. Based on these deformations, the stability of the subgrade was studied. It is suggested that the horizontal, vertical, and vertical directions of the x, y, and z directions are positive values.

According to Figure 4, vertical deformation on the left toe increased from 10.0 mm to 14.0 mm, with the subgrade height rising from 4.0 m to 12.0 m; however, the changing rate is very small. This is because the hill stones are beneath the subgrade, which are rigid materials compared to the filling.
Thus, the deformation of the foundation is little, which shows that the settlement on the left toe is small. Settlement on both shoulders, however, significantly increase with an increase in the height, and the settlement increased by about 53.2 mm and 36.4 mm for the subgrade height increase of 8.0 m from 4.0 m on both the left and right shoulder, respectively. In addition, the maximum settlement is on the left shoulder; the settlement is 78.2 mm when the height is 12.0 m, and 311.5% when the height is 4.0 m. Therefore, the influence of the subgrade height is large owing to the vertical settlement. In addition, extra caution is required during the construction on the settlement.

The monitoring settlement curve, settlement grades between the monitoring points, and the centre of embankment (monitoring point 5) are shown in Figures 5.

Based on curves shown in Figure 5, the vertical settlement increased with a higher subgrade. The maximum value appears to be at the monitoring point No.3 and this is because the barycentre is about 6.0 m from the centre of the subgrade. The resultant force is larger than the other points that would take the lead at the settlement of the subgrade. In addition, the minimum is near the right shoulder, which is the monitoring point 9 for the subgrade height, and the dead load is the lowest at that point. Further, the foundation under the right shoulder appears to be at the origin, such as at the rock foundation in the mountain, and its rigidity and deformability are much larger than the soil foundation. The differential settlement at the centre of the monitoring points 8 and 9 are 2.52 cm and 2.70 cm, respectively, when the height is 10.0 m. When the height is 12.0 m, those values are 2.32 cm and 2.77 cm, respectively. According to the Technical Standard of Highway Engineering (JTG B01-2014), the allowable differential settlement is 2.0 cm, and therefore, the high fill embankment needs to be re-designed.

3.4 Effect of foundation angle
The mountainous terrain is complex and often encounters different slopes. Therefore, it is imperative to study the angles of different slopes. The deformation of embankment under different foundation angles has been simulated.

Figure 5. Monitoring point settlement value under different filling heights.

Figure 6. Settlement at different locations under different ground slopes.
According to Figure 6, as the slope foundation angle increases, the vertical deformation of the embankment shows an increasing trend. This is because a larger foundation angle would lead to a higher embankment on the left side, which would cause a large settlement on the left shoulder as well as on the left toe. Therefore, the vertical settlement of the embankment on the steeper slope is still the primary consideration.

Under different foundation angles, the settlement curve of the monitoring point and the settlement grade curve related to the centre of the subgrade are shown in Figures 7.

![Figure 7. Settlement value of monitoring points under different ground slopes.](image)

It can be seen from Figure 7 that as the foundation angle increases from 11.3° to 14°, the settlement of the left and right sides of the fill embankment increases. However, when the foundation angle increases from 14° to 18.5°, the settlement on the left side of the fill embankment increased and the embankment on the right side of the embankment became closer to the original foundation. The difference in quantity leads to a decrease in the amount of sedimentation caused by the elastic mode of the filler and the original foundation. As the foundation angle increases from 11.3° to 14°, the settlement difference of the monitoring point on the left side of the embankment increases, and the settlement difference on the left side of the embankment decreases. However, if the slope increases from 14° to 18.5°, the settlement difference of each monitoring point of the embankment increases.

4. Conclusions
The differential settlement and settlement grade of embankment under different filling heights are simulated by the control variable method.

- The settlement of the embankment is proportional to the height of the fill, and the maximum settlement point appears near the centre of the subgrade. Since the minimum settlement appears near the shoulder of the right side of the embankment, the settlement difference and the settlement slope difference are the largest.
- The embankment settlement under different foundation angles, the embankment settlement difference, and the embankment settlement slope difference are simulated by the filling embankment. It can be seen from the simulation results that the embankment settlement is reduced when the original foundation angle decreases from 14° to 18.5°. When the original foundation angle decreases from 11.3° to 14°, the settlement at the left side of the embankment centre is still decreasing, but the settlement near the right side of the embankment shows an increasing trend. Therefore, it can be concluded that the difference in physical properties between the embankment filler and the original foundation is the main factor affecting uneven settlement.

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