Stability analysis of an expansive soil-embankment slope with a soft interlayer

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Abstract. The soft interlayer in the foundation is one of the most important factors that induce landslide in the expansive soil-embankment slope. The existence of large soft layers significantly reduces the overall stability of the slope, and they have the tendency to further develop into a sliding surface. To investigate the influence of the soft interlayer on expansive soil slopes, taking the high-fill embankment slope with a soft interlayer in the Baoshan area of Yunnan Province as an example, the causes and strength effects of the soft interlayer are analyzed via landslide investigation, laboratory test, and numerical simulation, and the stability and instability mode of the slope are studied. Results indicate the following: ① The soft interlayer is located at the bottom of the weathering layer within the depth of the atmosphere. Its strength is less than that of the expansive soil on both sides. ② The overall stability of the slope and the shape of the sliding surface are controlled by weak interlayers, and its strength greatly impacts the damage scope of the slope. When the strength is high, it appears as a collapse of the fill area, and when the strength is extremely low, it appears as the overall sliding of the slope. Using the residual strength as the calculation parameter of the weak layer reflects well the actual stability and failure mode of the slope. ③ Results of soil layer parameter sensitivity analysis indicate that the internal friction angle of the soft interlayers has the most significant effect on slope stability. Using the lightweight embankment fill can effectively improve the stability factor of embankments.

Keywords: Embankment Slope, Expansive Soil, Landslide, Soft interlayer

1. Introduction

Expansive soil is a type of special soil that is widely distributed in China. Its unique engineering properties pose serious threat to highway engineering construction. Yang Heping investigated several expansive soil landslides during highway construction in Guangxi Province and found that most of the slope instabilities were caused by the weak layer between the soil layers, particularly in the high consolidation cutting and the filling embankment on the slope[1]. Khan, M.S. investigated an expansive soil highway landslide in Texas and found that weak interlayer can also cause the slope
shallow instability failure [2]-[3]. It was found that the peak strength of the weak layer is far lower than that of the two sides, even lower than the residual strength of the two sides. Therefore, the strength of the weak layer is believed to be extremely important to evaluate the overall strength of expansive soil [4]-[5]. Analysis of the failure mechanism of the slope with a weak layer demonstrates that under the action of excavation or surcharge, the weak layer easily forms a stress concentration area, which further penetrates to form a sliding surface, leading to the instability and failure of the expansive soil slope [6]-[7]. Based on a landslide of a high embankment filled with expansive soil in Yunnan Province, combined with geological investigation, engineering investigation, and numerical modeling, the characteristics of expansive soil-slope instability controlled by the soft layer are analyzed herein. Moreover, it discusses the influence of the filling height, emergency treatment measures, and soil parameters on the overall stability of the slope. This study provides a future reference for the parameter selection and stability analysis of the embankment slope filled with expansive soil.

2. Project overview

2.1. Project background

The slope is located in the southwest part of Yunnan Province and belongs to gentle slope and hilly landform. Farmland, arable land, and forest land basically exist along the line. The ground of the proposed road is simply leveled. The slope exhibits a relatively flat terrain, with a gradient of about 5°–10°, and a large partial gradient, with a maximum gradient of about 18°. The seasonal distribution of rainfall is uneven, and the dry and rainy seasons are distinct. The rock and soil layers along the road are mainly quaternary arable soil (q4pd), quaternary alluvial and proluvial clay (q4al + q4pl), and upper tertiary clay (N2). Moreover, the vegetation is relatively developed, and the bedrock is deeply buried. The test results of the geological drilling exploration show that the strata of the slope in the exploration depth are mainly divided into four layers, namely, thin red clay layer, two layers of medium weak expansive clay with different weathering degrees, and the underlying hard clay layer. The relative height difference of the terrain along the proposed road is large, the excavation and filling are large, and the bearing layers used are different, which belong to a typical uneven foundation site. The mechanical properties of the bearing layer of embankment are general, the shear strength is not high, and it is easy to soften and collapse when it comes in contact with water. Combined with the field investigation and laboratory test, the primary mechanical parameters of rock and soil layers are presented in Table 1, wherein C denotes the cohesion; φ, the internal friction angle; e, the elastic modulus of the soil; and V, Poisson’s ratio.

| Layer                              | c (kPa) | φ(°) | E(MPa) | υ  |
|------------------------------------|---------|------|--------|----|
| Embankment fill                    | 5       | 25   | 50     | 0.35 |
| Spoil                              | 35      | 18   | 30     | 0.35 |
| Weathered layer of expansive soil  | 20      | 12   | 30     | 0.3  |
| Unweathered layer of expansive soil| 38      | 12   | 40     | 0.28 |
| Stiff clay                         | 38      | 20   | 50     | 0.25 |

The design institute provides the design of the embankment based on the strength parameters listed in the survey report. The road and typical vertical section bearing layer are presented in Figure 1, and the design filling embankment elevation is 16 m.

2.2. Landslide process
The designed embankment has a total height of 16 m. In March 2017, the road construction company entered the site for construction and began to fill the subgrade. On July 12, 2017, when the filling was 4.6 m away from the top of the subgrade, it was handed over to the pipe gallery construction company. Then, the filling height of the highest subgrade center of the embankment was approximately 12 m and that of the side was approximately 14 m. On October 19, 2017, after the completion of the pipe gallery construction, the project was transferred back to the road construction unit. The pavement elevation was then filled to approximately 14 m. On November 7, 2017, cracks appeared on the top surface of this section of subgrade, with a width of 1–2 mm. In the morning of September 9, 2017, the deformation suddenly increased, and the crack on the upper edge increased to 30 cm. Moreover, the road surface sank with a sinking amount of about 30–40 cm. In the next five days, the settlement of the embankment reached 1.6 m, as shown in Figure 2.

![Figure 2. Overall shape map of the landslide body](image)

According to the supplementary survey of the landslide, the terrain slope of the landslide area is 25°–36°, and the length of the sliding body is approximately 157.0 m. The front edge of the landslide is approximately 50-m wide, the rear edge is approximately 100-m wide, and the slope of the entire sliding surface is about 150-m long. The landslide plane is irregularly rectangular with an average thickness of approximately 7.20 m. The landslide body mass is 1228 m$^3$, and the maximum relative height difference of the landslide body is approximately 28 m, which is considered a small push landslide. Tensile cracks can be observed running through the back edge of the landslide mass, and there is a significant settlement displacement. The slope body moves outward as a whole, and numerous cross cracks appear on the surface. There is no obvious bulge at the front edge of the landslide mass, and the slope is partially anti-inclined. The borehole indicates that the material composition of the upper part of the landslide body is mainly quaternary artificial backfill accumulation layer with a thickness of 0.80–12.1 m and a loose structure.

2.3. Preliminary analysis

The highway foundation is a typical uneven foundation, and there is a soft layer below the original surface of the fill section, which is located approximately 3 m below the original surface. This soft layer controls the shape of the slip zone. The bottom is moderately broken, and the upper part penetrates the fissure in the fill area. Based on the boreholes and trenches, the slip zone is a soft interlayer inside the expansive clay that is located between the weathered layer and the unweathered clay layer. Moreover, its cracks develop as grayish yellow and light gray clay, the slip zone (surface) soil is wet plastic, the strength is further reduced after immersion in water, and the thickness is 0.1–0.2 m. The sliding surface position is shown in the following figure. The shape resembles the original terrain of the slope, which is relatively gentle, and the inclination of the sliding surface is 4°–6°. The thickness of soft interlayer is small. In engineering investigation, the existence of this layer is ignored. In the previous process of subgrade filling, the layer exhibited local instability under the
action of the filling surcharge. Thus, the soil particles had a certain directional arrangement. During the follow-up filling process, the embankment slope slips along the soft layer, causing a landslide. Furthermore, the rise in the groundwater level and the infiltration of the surface water cause further water absorption and soft-layer softening, accelerating the landslide occurrence.

3. Strength test of the soft layer

3.1 Cause analysis

Geological analysis of the cause of the weak layer reveals that the shallow expansive soil forms a large number of weathered fissures under the action of atmospheric drying and wetting, which is close to the bulk structure and exhibits good water permeability. The permeability of the unweathered expansive soil in the middle and lower parts is much smaller than that of the weathered layer, forming a relatively water-proof layer. The surface water infiltrates through the weathered layer soil that has strong water permeability with the surface of the unweathered soil layer that has weak water permeability, and it is difficult to continue infiltration. The bottom part of the weathered layer is subjected to long-term immersion in surface water, wherein the water content is significantly higher than that of the upper and lower soils. Simultaneously, during the alternating dry and rainy seasons, which affect the repeated rise and fall of the groundwater level, the weathering layer undergoes repeated dry and wet cycles, and a large number of fissures develop. The difference in the structure and water content between the weak layer and the undisturbed soil is the primary reason for its low strength.

3.2 Basic properties

As shown in Figure 4, the drilling holes are arranged at a reasonable location in the landslide section. The borehole depth is 19.2–36.8 m, which is approximately 15-m deep into the underlying hard clay layer. Ten undisturbed soil samples are collected from each layer, and the ring cutter samples are collected from the structural surface through the trench. The basic properties of each layer of the soil sample and the weak layer are tested, and the results are shown in Table 2.

![Figure 4. Landslide boundary and drilling point](image)

![Figure 5. Typical soil samples](image)

| Parameter          | Undisturbed expansive soil | Soft layer  |
|--------------------|-----------------------------|-------------|
| water content (w)  | 37.1                        | 40.05%      |
| natural density (ρ) | 1.83                        | 1.81        |
| porosity ratio (e) | 1.02                        | 1.17        |
Based on the test results, this soft layer is similar to the muddy interlayer that developed between the most weak expansive soil layers. Moreover, the water content, clay content, and free expansion rate are higher than those of the upper expansive soil.

### 3.3 Strength properties of the soft layer

Existing studies [6]-[7] reveal that the strength of the weak layer is not only much lower than the peak strength of the soil on both sides but also even lower than its residual strength, which would most likely develop as a sliding surface. Therefore, undisturbed soil samples should be selected, and the strength properties of the weak layer should be separately tested and evaluated.

In this test, two soft-layer samples in the saturated and natural state are prepared, and the peak value and residual strength of the soil sample in the weak layer are measured through a slow shear test with a shear rate of 0.02 mm/min. The relationship between the peak shear stress and normal stress of the soft layer under different loads is presented in Figure 6. The strength parameters of the soft layer can be obtained through fitting. Test results indicate that the strength of the soft layer is significantly lower than that of expansive soil on both sides.

![Figure 6. Peak shear strength of the soft layer](image)

Figure 7 presents the residual shear stress and residual strength of the soft layer. Test results indicate that compared with the peak strength, the residual strength of the soft layer is further reduced. The cohesion and internal friction angle evidently decreased, indicating the obvious reordering of the soil particles after sliding.
Figure 7. Residual shear strength of the soft layer

Table 4 presents the strength parameters in the natural and saturated states of the soft layer. The internal friction angle and cohesion of the saturated samples significantly decreased, indicating that the strength of the soft layer decreased further under the condition of immersion. Therefore, under the conditions of rainfall, surface water infiltration, and rise of groundwater level, the slope of expansive soil controlled by the soft layer is more prone to instability.

| Parameter       | Natural moisture content | Saturation | Natural moisture content | Saturation |
|-----------------|--------------------------|------------|--------------------------|------------|
| Peak strength   | 12.23                    | 8.92       | 10.36                    | 6.23       |
| Residual strength | 7.77                   | 4.64       | 5.68                     | 4.27       |

4 Stability analysis of the embankment slope

According to the geometric and strength parameters of the weak layer, based on the large-scale finite element calculation software ABAQUS, the slope stability is analyzed using the finite element strength reduction method. The Mohr–Coulomb criterion is selected in the constitutive model, and the soil is assumed to be an ideal elastic–plastic body. When the strength reduction method is applied, the reduction coefficient ranges 0.5–2, and the interval is 0.25, ensuring the accuracy of the final stability coefficient.

4.1 Geometric model

According to the slope survey data, the following typical calculation sections are selected for finite element analysis and calculation. Figure 7 presents the calculation model of this section.

Owing to the large extension range of the slope in the horizontal direction, a 2D model can be used to simulate the slope. The plane strain element is utilized in the slope element without considering the influence of groundwater. The bottom part of the model is set as a fixed boundary to constrain the
displacement in the X and Y directions. Both sides of the model are set as horizontal constraints, and only vertical displacement is allowed.

The survey data suggests that the soft layer in the model is located between the weathered layer and the unweathered layer within the weathered layer expansive clay. The thickness is set as 0.15 m of the approximate average thickness of the soft layer, which is determined through the supplementary survey of the landslide. Moreover, the thickness and range of other soil layers are determined based on the survey data. The parameter value of the soil layer is obtained through a series of laboratory tests (Table 1). In the previous construction process, a local slip occurred in the weak layer, and the soil particle arrangement orientation had changed to some extent. Therefore, the actual strength of the soft layer should be set as the residual strength.

4.2 Stress and displacement of the slope

From the maximum principal stress of the slope (Figure 9), it can be seen that the maximum principal stress is basically parallel to the ground surface direction, and the distribution is relatively regular. In the vicinity of the soft layer, the maximum principal stress appears to be abnormal, the maximum principal stress direction turns and increases several times, and the stress concentration appears. Based on the plastic strain diagram of the slope (Figure 10), a large plastic-deformation area appears in the weak layer position under the action of large stress. It can be seen that the stress change caused by the embankment filling load has a certain impact on the development of soft layer. Moreover, an abnormal stress field appears at the layer. Under the local stress concentration, further sliding and fragmentation of the soft layer finally leads to the formation of a sliding surface.

![Figure 9. Maximum stress distribution of the slope](image)

![Figure 10. Distribution of the slope plastic zone](image)

4.3 Slope stability analysis

In the following, the stability coefficient and sliding surface position of the landslide are calculated and determined using the strength reduction method. The stability coefficient is calculated as 0.96 when there is a soft layer, indicating that the slope is in a state of instability. The sliding surface passes through the soft layer. The back edge of the landslide is located in the middle of the road between the fill area and the spoil area of the front edge of the landslide. From the plastic zone distribution, it can
be seen that the soft layer forms a stress concentration zone under the load of the upper embankment, causing the slope to form a broken line plastic zone along the soft layer, as well as tensile crack in the filling area. This causes the overall instability of the slope.

![Slope with a soft layer (Fs = 0.97)](image1)

b. Slope without a soft layer (Fs = 1.61)

**Figure 11.** Potential sliding surface

![Tension crack at the back edge of the embankment landslide](image2)

**Figure 12.** Tension crack at the back edge of the embankment landslide

The relationship between the vertical displacement of point A (representative observation points at the top edge of the slope in Figure 11) and the strength reduction factor is presented in Figure 13. When the reduction coefficient exceeds 0.97, the displacement of point A suddenly increases. The value of 0.97 can be regarded as the slope stability coefficient.

![Relationship between the vertical displacement of point A and strength reduction factor](image3)

**Figure 13.** Relationship between the vertical displacement of point A and strength reduction factor

By comparison with the field pictures, it can be found that the calculated shape of the landslide resembles the actual situation, which is consistent with the actual situation of slope instability under the stacking height. Calculation results of the stability coefficient indicate that the modeling method and the soft-layer parameters adopted herein are reasonable.

### 4.4 Influence of unloading and slope cutting on the slope

After the embankment slope loses its stability, appropriate emergency measures should be taken, which include removing the packing and piling or brushing the slope to remove the spoil. To evaluate the treatment effect of the emergency measures on the slope, the following conditions are analyzed: unloading 1–5 m of the embankment fill, removing the spoil at the half slope, and analyzing the change rule of the sliding surface and stability coefficient of the embankment slope under several
unloading measures. After the calculation, the stability coefficients that correspond to several treatment measures are presented in Table 5.

| Emergency measures                                      | Stability coefficient |
|---------------------------------------------------------|-----------------------|
| Unload 1 m of the embankment fill                       | 1.04                  |
| Unload 3 m of the embankment fill                       | 1.15                  |
| Unload 5 m of the embankment fill                       | 1.32                  |
| Remove spoil only                                       | 0.95                  |
| Remove spoil and unload 5 m of the embankment fill      | 1.24                  |

After unloading 1–5 m of the embankment fill, the trend of slope instability is controlled, and the stability coefficient increases to more than 1. With the increase in the unloading amount, the stability coefficient evidently increases. After unloading, only shallow sliding occurs in the filling section. After removing the spoil soil from the lower part of the embankment, the slope stability coefficient decreases, and the range of sliding instability increases. This indicates that the existence of spoil load at the bottom of the original sliding surface is conducive to slope stability and plays the role of back-pressure slope toe. After unloading or brushing the slope, the downward trend of the slope can be controlled and is temporarily stable. The unloading height of the filler is limited owing to the presence of pipe corridors at a depth of 3 m below the slope fill. Moreover, the overall stability and sliding surface shape of the landslide after unloading are still mainly controlled by the soft layer. Therefore, for the embankment slope with a pipe gallery, if it is important to further improve the slope stability and ensure the embankment filling construction, it is still necessary to take appropriate reinforcement measures, such as anti-slide pile, for the soft layer.

![Figure 14. Effect of unloading on the slope sliding surface](image)

5 Parameter sensitivity analysis
Owing to the complexity of expansive soil and the uncertainty of soil parameters, the expansive soil parameters are often distributed in a small range in the actual project. Therefore, sensitivity analysis of soil parameters of the slope should be conducted.
Based on the above slope numerical model, the parameters of each soil layer [weight (kN/m$^3$), cohesion (kPa), and internal friction angle ($^\circ$)] are changed for the calculation, and one parameter of the specific soil layer is changed each time using the control variable method. Through the numerical calculation, a large number of data are obtained to achieve the fitting straight line, and the influence level of the each soil layer parameter on the slope stability coefficient is obtained. The change in the gravity parameter is within the range of initial gravity $+/-2$ kN/m$^3$, and the change step is set as 0.5 kN/m$^3$. The change in the cohesion parameter is within the range of initial cohesion $+/-5$ kPa, and the change step is set as 1 kPa. Moreover, the parameter change in the internal friction angle is controlled within the initial internal friction angle of $+/-5^\circ$, and the change step is set to $1^\circ$. After the trial calculation for the embankment slope, the parameter change in the underlying hard clay layer has no significant influence on the slope stability coefficient. Therefore, only the cohesion, internal friction angle, and the corresponding slope stability coefficient of the other four soil layers are presented. Figure 15 presents the calculation results.

![Figure 15. Relationship between cohesion and Fs](image1)

![Figure 16. Relationship between $\varphi$ and Fs](image2)

![Figure 17. Relationship between $\gamma$ and Fs](image3)

By comparing the relationship between the slope stability coefficient and the parameters of each soil layer before reinforcement, the following conclusions are obtained:

1) When the strength of the soil layer changes, the strength parameters of the soft layer have the greatest influence on the slope stability, wherein the internal friction angle has a greater influence on the slope stability than the cohesive force. Reinforcement measures that directly or indirectly increase the strength of the soft layer should be taken to improve the safety of the slope.

2) When the weight of the soil layer changes, the weight of the embankment fill has the greatest impact on the slope stability coefficient. As the weight of the filler increases, the slope stability significantly reduces, and the use of lightweight embankment fills can increase the safety of the slope.

6 Conclusions
Through an engineering geological survey, laboratory experiment, and numerical modeling analysis, taking the high-expansion soil-embankment landslide in Yunnan as an example, a comprehensive analysis of the instability mechanism of the expansive soil-embankment slope with a weak layer was conducted herein, and the following conclusions are obtained:

(1) The shallow expansive soil forms a large number of weathered fissures under the action of dry and wet cycles, and its permeability is much greater than that of the non-weathered layer. After the surface water seeps into the bottom of the weathering layer, it will be difficult for it to continue seeping; therefore, the bottom part of the weathering layer is soaked and forms a broken interlayer with high water content. In the process of subgrade filling, the layer is loaded by the filler to form a stress concentration zone, and the plastic zone is further penetrated to form a failure surface.

(2) The stability and failure mode of the high embankment filled with expansive soil with a soft layer are controlled by the surcharge height and soft layer position. There are two types of failure modes in embankment slope. When a weak layer exists, a large-scale broken line landslide occurs along the weak layer. Conversely, when no weak layer exists, only a shallow landslide with a circular sliding surface occurs in the filling section.

(3) The removal of part of the embankment load temporarily improves the slope stability coefficient. However, the effect is extremely limited, and further reinforcement measures are still required for the weak layer. The spoil load under the fill slope has a certain back-pressure effect on the slope toe, which improves the slope stability. Based on the sensitivity analysis of parameters, the internal friction angle of the soft layer has the greatest impact on the overall stability of the slope. The weight of the embankment fill also has a certain impact. Therefore, in the construction process, care should be taken to prevent water infiltration and further decrease the strength of the soft layer. Moreover, a lightweight embankment fill should be preferably selected.

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