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Stability Analysis of Embankment Slope Considering Water Absorption and Softening of Subgrade Expansive Soil

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Abstract: With the rapid development of road engineering today, a large number of high-grade highways need to pass through expansive soil distribution areas. At present, the research on expansive soil slope mainly focuses on the newly excavated cutting slope. However, according to engineering experience, a landslide of fill embankment on expansive soil foundation is also very common. The expansive soil layer is heterogeneous. There are many weak intercalations or large fissures under the ground, which are generally parallel to the trend, with low strength and high permeability. After rainfall, the strength of the weak interlayer and large fissures will be further reduced after moisture absorption, and the sliding surface is easily formed under the load of filler, which is the main factor inducing embankment landslide. On the basis of landslide investigation and a laboratory test, a FORTRAN calculation program is developed in this paper, which can comprehensively consider the special moisture absorption and softening characteristics of expansive soil. Taking a high fill embankment slope with a soft interlayer in the Baoshan area of Yunnan Province as an example, the stability and instability characteristics of the fill slope on the expansive soil foundation are analyzed, and the influence of moisture absorption and softening on the expansive soil slope is emphatically discussed. Finally, this paper puts forward the reinforcement method of the high fill embankment slope on the soft expansive soil foundation, which is proven to have a good reinforcement effect through calculation analysis and field practice. For expansive soil foundation with weak interlayer, it is better to directly reinforce the weak layer through rigid piles.

Keywords: expansive soil; landslide; failure mode; rainfall infiltration

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1. Introduction

Expansive soil is a kind of special cohesive soil with expansibility, fissures, and moisture absorption softening. Its special engineering properties often bring great harm to local water conservancy channels and road projects, among which the instability of embankment built on expansive soil foundation is a more common engineering disease. Different from ordinary clayey soil, the shallow layer of expansive soil often has a broken structure and dense cracks. There are weak layers and structural planes below a few meters deep. Under the action of rainfall infiltration and groundwater level rise, the strength of the foundation expansive soil further softens after moisture absorption, which induces the slope of expansive soil to slide and lose stability along the weak layer.

Engineering accidents caused by the instability of expansive soil subgrade are very common in the process of road construction. During the construction of Qingbao highway in Yunnan Province, serious slope instability accidents occurred in many embankment sections on expansive soil foundation. Different from the instability mechanism of the expansive soil cutting slope, the stability of the filling embankment slope on expansive soil foundation is not only affected by the properties of expansive soil in the bearing layer but the weak interlayer in the expansive soil layer is also very developed, which is generally expansive. When there is a large filling load on the expansive soil foundation, these weak intercalations are prone to slip failure under the load, which has become the main factor inducing embankment landslide. If there is rainfall infiltration and groundwater level rise at the same time, and the strength of the weak interlayer becomes softer after moisture absorption, it is more likely to lead to the instability of the embankment slope on the expansive soil subgrade, which will seriously affect the highway construction.

Scholars have carried out a lot of research on this problem from two aspects: the change of hygroscopic softening strength of expansive soil and its impact on slope stability. In terms of strength softening, Zhang [1,2] found that the two main factors affecting the strength of expansive soil are water content and crack ratio. Zhou [3] found that the strength of expansive soil decreases with the increase in water content, the cohesion and internal friction angle have a logarithmic relationship with water content, and the cohesion and saturation of soil have a quadratic parabola relationship. Yang [4,5] simulated the cracks of expansive soil through the interface element, analyzed the relationship between the softening path length of cracks and slope stability with the seepage of rainwater along the cracks, and better predicted the time of critical failure of the slope. Xu [6] found that the cohesion of expansive soil is close to 0 in the completely softened state, and the strength is mainly determined by the internal friction angle at this time, in terms of the influence of moisture absorption and softening on slope stability. Later, by analyzing an unstable expansive soil slope, Gyasi-Agyei [7,8] found that the actual strength of the expansive soil after moisture absorption is very low, and the residual strength of the high water content remolded soil should be used as a reference parameter for the design of the expansive soil slope. At present, a lot of research has been carried out on rainfall-type landslide, but the research on embankment slope destabilization model on expansive soil foundation needs to be further studied [9–12]. The above research on slope stability is based on the softening strength and the pre-specified area. In fact, this kind of slope instability is dynamic. With the infiltration of rainfall and the rise of the groundwater level, the strength of soil decreases, and the stability of slope decreases. The above research has not been able to analyze this dynamic process well.

To sum up, this paper develops a program that can automatically realize the decline of expansive soil strength with the increase in saturation. Based on a high fill embankment slope on a fissured expansive soil foundation in Yunnan Province, combined with laboratory tests, the influence of moisture absorption and softening on slope stability and the instability mode is discussed.

2. Calculation Program of Moisture Absorption and Softening

Due to the high clay content of expansive soil, the moisture absorption softening of expansive soil is more obvious and violent than that of common clayey soil. With the difference in clay content, the moisture absorption and softening characteristics of different expansive soils are also quite different. Therefore, the applicability of the above methods is limited, and it is necessary to explore a new method.

This paper designs a simple analysis method of moisture absorption and softening of expansive soil slope, which is realized by the following three steps:

(1) Firstly, the strength of undisturbed expansive soil with different water content is measured by a laboratory test, and the relationship between water content (saturation) and strength is obtained.
(2) The boundary conditions are imposed on the slope model, and the shear strength parameters of expansive soil are automatically modified and calculated through subroutines, according to the saturation change of soil, during the change of rainfall or groundwater level.
(3) Finally, the new stability coefficient and potential sliding surface are obtained by using the strength reduction method in the finite element analysis.

2.1. Analysis of Moisture Absorption and Softening Characteristics

The shear strength of expansive soil will decrease significantly with the increase in water content because the cohesion of unsaturated expansive soil is affected by the adsorption between soil particles and matrix suction. With the increase in saturation, the thickness of water film between soil particles increases, which reduces the adsorption and matrix suction. Therefore, the law between strength and moisture content of expansive soil should be studied through experiments.

At the landslide site, undisturbed soil samples of shallow expansive soil (main failure layer) are taken through boreholes. The moisture content is measured by the drying method, and the internal friction angle and cohesion c of expansive soil sample is measured by the direct rapid shear test. The relationship between the cohesion c value of the undisturbed sample of the expansive soil and the saturation, Sr, can be obtained by converting the water content into saturation, as shown in the following Figure 1.

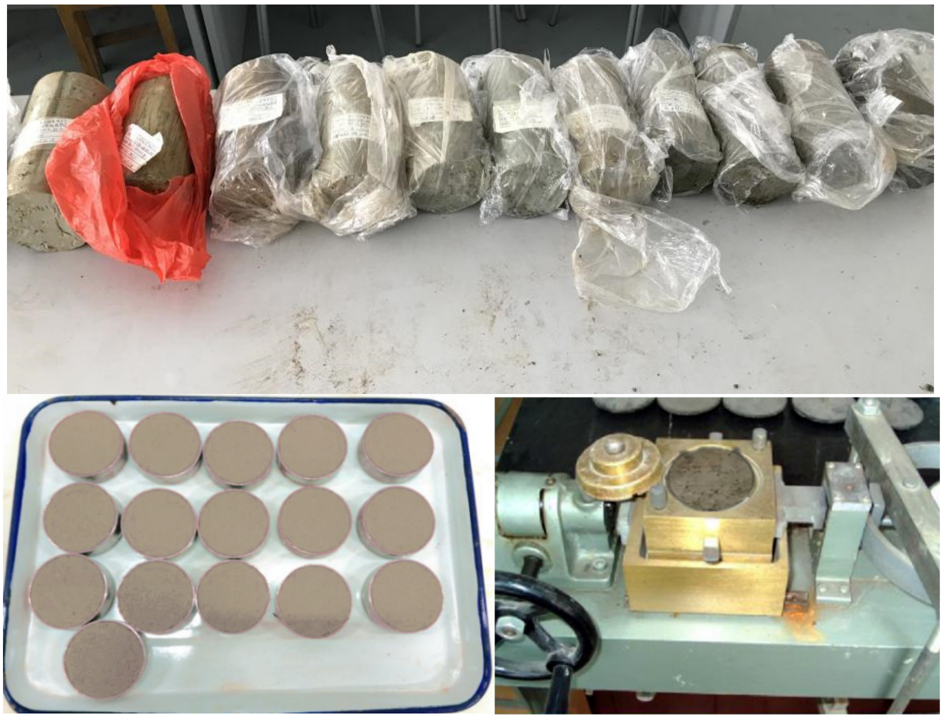

Figure 1. Strength test of the undisturbed soil sample.

According to the test, the internal friction angle of expansive soil basically does not change with saturation, and it can be regarded as a fixed value in the process of moisture absorption. As shown in Figure 2, the cohesion of expansive soil decreases, obviously, with the increase in saturation. When the saturation is greater than 93%, the cohesion suddenly decreases, indicating that the hygroscopic softening phenomenon of expansive soil is significant. When the saturation exceeds 97%, the cohesion decays to stability. Therefore, in the calculation process, when the saturation of the soil in the unweathered area is less than 93%, the cohesion value of the soil is taken as the average value of 38.9 in the natural state. When the saturation is greater than 97%, the cohesion has basically reached the strength of complete saturation, so it is set to the saturated cohesion of 29.8 kpa. When the saturation is between 93% and 97%, the cohesion is determined by the fitting relationship ($y = -3.2423x + 338.8$). The above process is realized by the independently written FORTRAN subroutine, which is called ABAQUS in the calculation process, to realize that the cohesion of soil changes with the change of saturation.

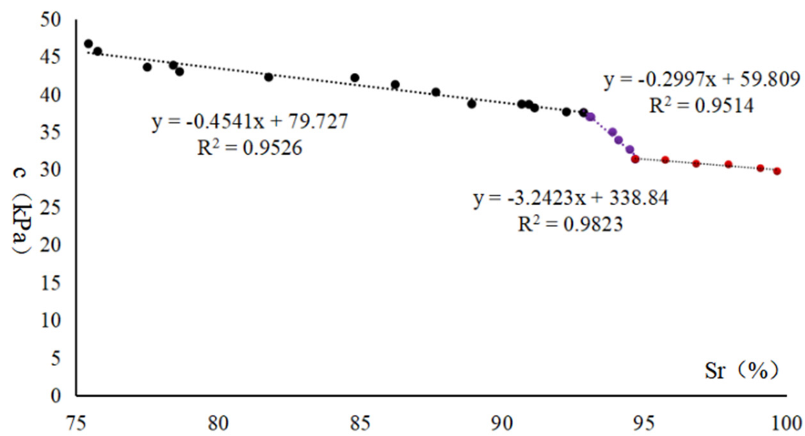

Figure 2. Relationship between humidity and cohesion c.

2.2. Development of ABAQUS Subroutine

Through the development of the ABAQUS applet, the automatic change of expansive soil strength with saturation in the calculation process is as follows:

(1) Apply rainfall load boundary on the top and outside of the slope, and calculate the slope saturation field and groundwater level after rainwater infiltration.
(2) According to the calculation results of the new slope saturation after rainfall, the strength of the soil element is updated.
(3) Based on the new soil element strength, the stress field and displacement field of the slope are updated, and the stability is calculated by the finite element strength reduction method.

The detailed flow chart of the calculation process is, as follows, in Figure 3:

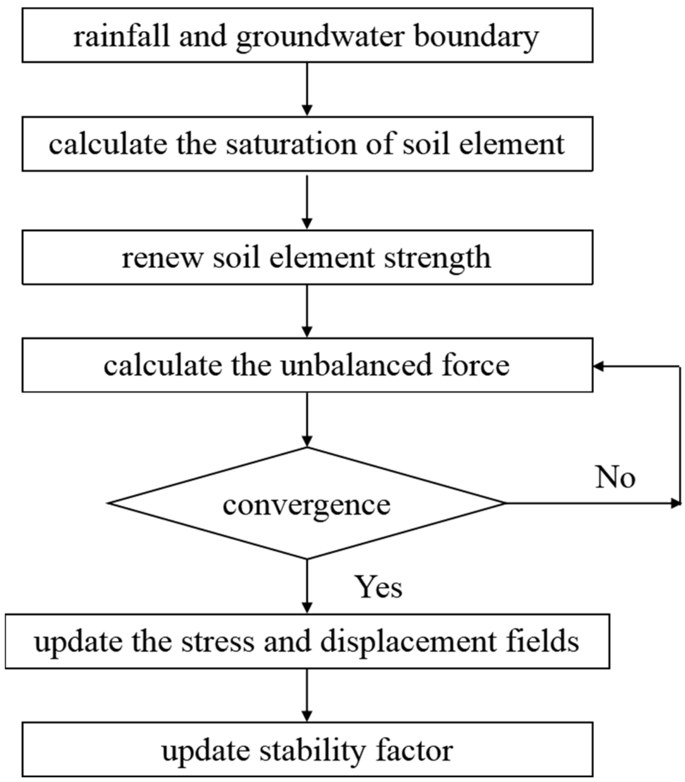

Figure 3. Calculation flow chart.

3. Engineering Examples

3.1. Landslide Survey

The landslide is located in Baoshan City, Yunnan Province, and it belongs to a gentle slope and hilly landform with gentle terrain. The rainfall is concentrated in the rainy season from June to September. The designed filling height of embankment is 16 m. The construction period just passes through the local rainy season, and cracks occur on the top surface of the subgrade when the filling reaches 12 m, with an initial joint width of 1–2 mm. The construction unit did not take treatment measures to continue the construction, and the embankment deformation increased suddenly. Two days later, the upper edge crack increased to 30 cm, and the top of the embankment sank, with a sinking amount of 30–40 cm. In the next five days, the top of the embankment sank by 1.6 m, as shown in the Figure 4 below.

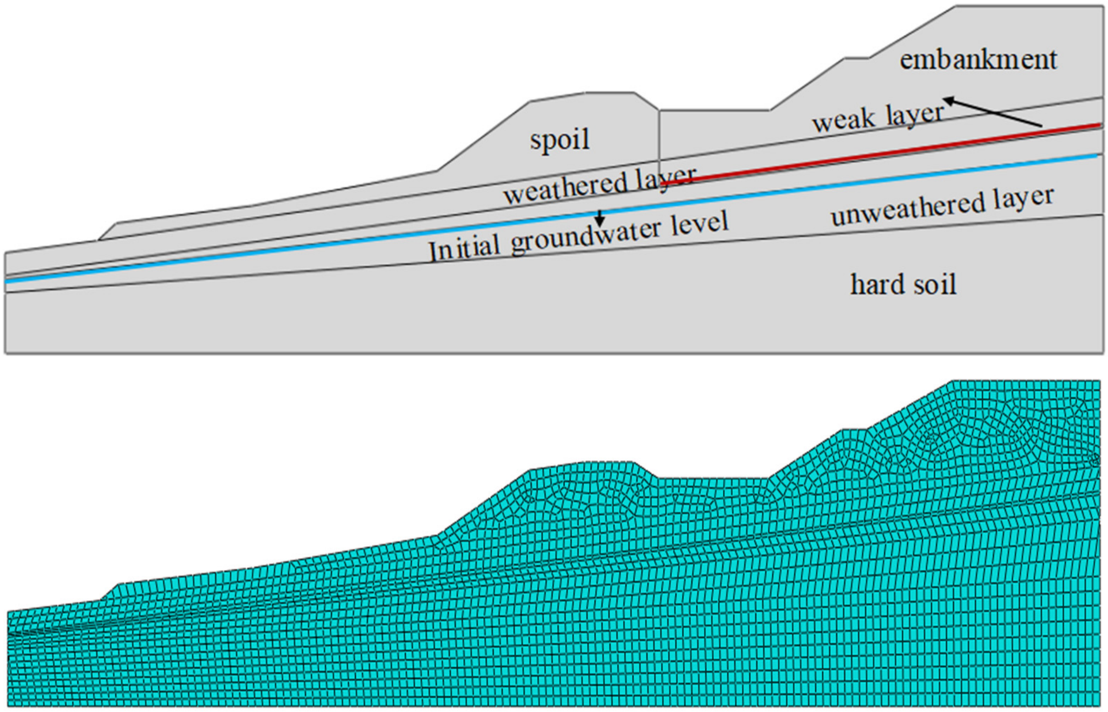

Figure 4. Basic model of slope.

The bedrock along the road is deeply buried, and the main foundation-bearing layer is a medium to weak expansive soil layer. Some sections along the line have large topographic height difference, large excavation and filling, and different bearing layers, which belong to typical uneven foundation. According to the results of geological drilling exploration test, there are four layers of soil in the depth of the bearing layer, as Table 1. The mechanical properties of the rock and soil layer are general, the shear strength is not high, and it is easy to soften and collapse in case of water. The parameters of rock and soil layers are shown in Table 2.

Table 1. Values of cohesion parameters.

(Sr %)	c (kPa) (Matrix Suction Has Been Considered)
75~93	38.9
93~97	−1.925 Sr + 217.925
97~100	31.2

Table 2. Calculation parameters of soils.

Soil Layer	Strength Parameters			
	c (kPa)	φ (°)	E (MPa)	υ
embankment	10	25	50	0.35
spoil	35	18	30	0.35
③$_1$ weathered layer of expansive soil	20	12	30	0.3
soft layer	12	8	20	0.35
③$_2$ unweathered layer of expansive soil	38	12	40	0.28
④ hard soil	38	20	50	0.25

After supplementary exploration and analysis, the main causes of the embankment landslide can be summarized as follows:

(1) The strength of the weathered layer of the shallow expansive soil is low, and there is a weak interlayer, at the depth of 2.5 m, from the original surface. The inclination of the interlayer is approximately the same as that of the stratum, and the dip angle is slightly larger than that of the stratum.
(2) The long-term rainfall in the rainy season infiltrates through the weathered layer of expansive soil with high permeability, raising the groundwater level, and the weak interlayer further softens to form a potential sliding surface. The lower slope toe has higher humidity and low strength, which reduces the binding force on the upper soil mass.

3.2. Slope Model Considering Rainfall Moisture Absorption Softening of Foundation Soil

Since the moisture absorption and the softening of the weak layer and the slope foot are the most important reasons for the instability of the slope foundation, the following analyzes the foundation slope through the subroutine of the second part.

(1) Basic model

According to the supplementary survey results of the embankment landslide, the section located in the middle of the landslide is selected as a typical section for analysis. The soil layer distribution of this section is determined according to the supplementary drilling data. The depth and distribution range are shown in the Figure 4, and the parameter values are shown in Table 1. Before the construction of embankment surcharge, there is a weathered layer with a thickness of 2~2.5 m on the surface, and an unweathered layer below the depth of 2.5 m. Both layers come from the medium to weak expansive soil layer with stable thickness and wide distribution on the site. The weak layer is located between the weathered layer and the unweathered layer inside the expansive clay. The thickness is set as the approximate average thickness of the weak layer determined by the supplementary survey of the landslide is 0.2 m. The thickness and range of other soil layers are determined according to the survey data. Below the hard clay is the bedrock surface, and the strength and elastic modulus are much larger than the soil layer. Therefore, the bottom of the hard clay at the bottom of the model is set as a fixed boundary, and the horizontal displacement on both sides of the slope model is fixed.

(2) Analysis of groundwater rising process caused by rainfall infiltration

After a long period of intermittent rainfall in the rainy season, the groundwater level continues to rise, which is quite different from the water level determined during the survey before the rainy season. In order to reasonably analyze this process, the rainfall infiltration groundwater level rise process is analyzed in combination with the local measured rainfall in the rainy season. The boundary conditions are set as follows:

(1) Initial boundary conditions: before embankment construction, the groundwater level was observed after site leveling and before the rainy season in June 2017. It is located at 3.5–5 m underground. This water level line is set as the initial water level before rainfall. The long-term rainfall in the rainy season corresponds to a process of

continuous rise in the groundwater level of the slope. When the groundwater level exceeds the ground during the rise process, it becomes runoff and will not generate excess pore pressure. Therefore, the surface of the slope should be defined as the boundary of pore water pressure-free dissipation. The bottom and both sides of the slope are defined as impervious boundaries to simulate the process of groundwater rise. The long-term rainfall in the rainy season corresponds to a process of continuous rise in the groundwater level of the slope. When the groundwater level exceeds the ground during the rise process, it becomes runoff and will not generate excess pore pressure. Therefore, the surface of the slope should be defined as the boundary of pore water pressure-free dissipation. The bottom and both sides of the slope are defined as impervious boundaries to simulate the process of groundwater rise.

(2) Rainfall infiltration process: The embankment filling of this section began on 2 July 2017, and the slope began to lose stability when the elevation of the road construction unit was filled to 17 m on November 6. In order to get the impact of real rainfall on the overall humidity field, it is necessary to determine the amount of rainwater infiltration according to the local rainfall data. The permeability of the fill is large, so it is assumed that the rainfall will directly infiltrate into the foundation soil layer through the fill. The leveled ground surface is selected as the rainfall infiltration boundary. The infiltration intensity and time of the boundary is the rainfall minus evaporation. According to the theory of unsaturated soil infiltration, the permeability of unsaturated soil is modified according to saturation. In the process of rainfall, when the rainfall amplitude is less than the unsaturated permeability coefficient of expansive soil, all rainwater infiltrates. When it is greater than the unsaturated permeability coefficient, the actual infiltration intensity is equal to the unsaturated permeability coefficient, and the rest of the rainfall is discharged by generating surface runoff.

In ABAQUS, the rainfall process during the whole construction period can be defined by a time amplitude function. The whole process is divided into several 24 h segments (single day), and the flow boundary of each segment is equal to the rainfall of that day minus the evaporation. After the definition of the whole rainfall process is completed, the rainfall process of the whole rainy season is applied to the surface of the slope model as the flow boundary, that is, the definition of the rainfall process is completed.

(3) Consideration of moisture absorption and softening

The moisture absorption softening characteristics of the weathered layer, unweathered layer, and weak interlayer of expansive soil are mainly considered. In the process of rainfall infiltration, the soil strength changes, with saturation, through the subroutine. The value of strength is determined according to the indoor strength test of undisturbed soil, as shown in Table 3. When the soil saturation is less than 92%, the strength of the soil layer is set as the natural strength; When the soil saturation exceeds 97%, adjust the strength parameter of the soil layer to saturation strength; When the soil saturation is between 92% and 97%, the strength is adjusted, by linear interpolation, between natural strength and saturated strength through the program, and then, the overall stress-strain state of the slope is recalculated on this basis.

Table 3. Strength parameters.

Soil Layer	Natural Strength		Saturation Strength	
	c (kPa)	φ (°)	c (kPa)	φ (°)
Weathering layer	20	12	17	10.5
Unweathered layer	38	12	29	10.5
Weak layer	10.8	6.5	7.6	5.2

3.3. Stability Analysis of Embankment Slope

(1) Verification of groundwater rise calculation results

The Figures 5 and 6 shows the overall humidity field of the slope. The lower part of the slope reaches and remains fully saturated early after the rainy season. As the rainy season continues, the saturated area of the soil in the middle and upper part of the slope continues to move up, and the rise of the saturation in the middle of the slope is more obvious. The saturation of the soil in the middle and lower part of the slope increases and leads to strength softening, which reduces the support of the filling section, and the impact on the occurrence of landslides cannot be ignored. The blue line is the groundwater level determined by the supplementary survey immediately after the landslide, and the red line is the calculated water level (pore water pressure is 0 line). The calculated groundwater level basically coincides with the measured results of the supplementary survey of the landslide. Therefore, the humidity field of expansive soil slope can be better predicted by setting rainfall infiltration intensity and soil parameters, which is basically consistent with the groundwater level determined by the landslide supplementary survey.

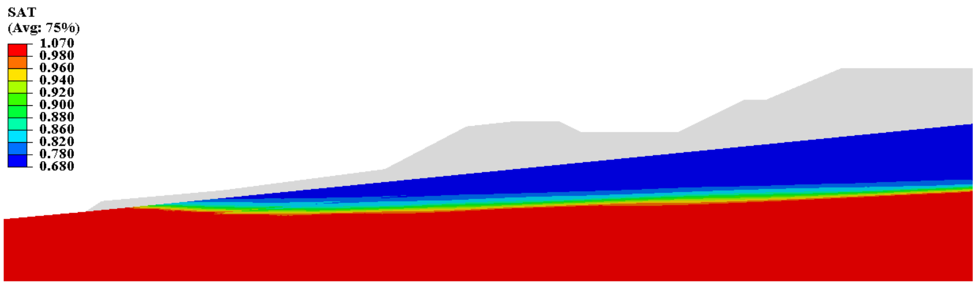

Figure 5. Overall saturation of slope.

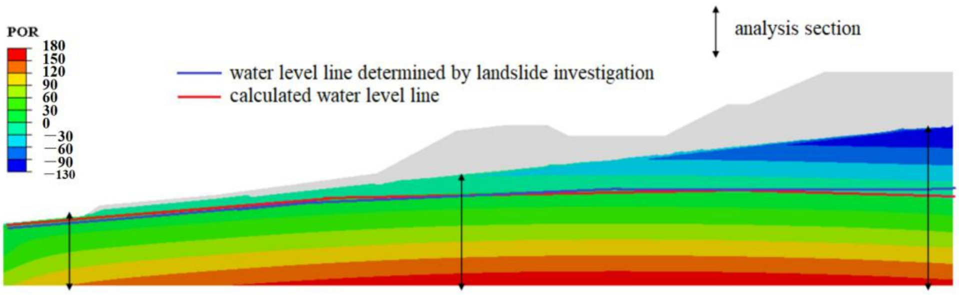

Figure 6. Overall pore pressure of slope.

(2) Analysis of slope stress and displacement and comparison of monitoring data

Figure 7 shows the plastic strain zone of the slope. Under the action of fill load, a large plastic deformation zone appears at the position of the weak layer. The abnormal stress field appears in the weak layer, and the further sliding fragmentation of the weak layer, under the action of local stress concentration, finally forms the sliding surface. It can be seen that the stress change caused by filling soil load has a certain impact on the development of weak layers.

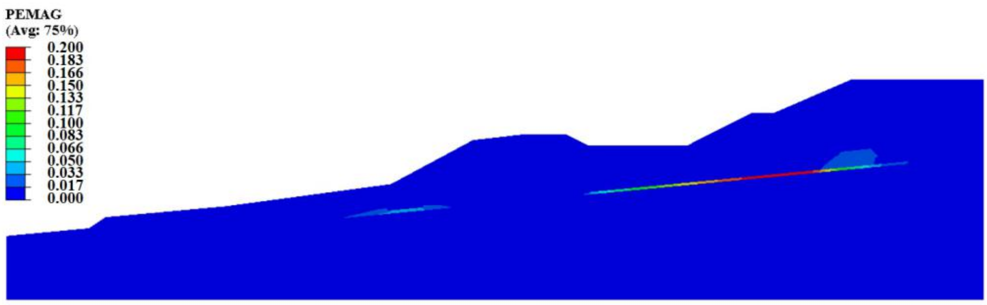

Figure 7. Slope plastic zone.

It can be seen from the overall displacement of the slope, in Figure 8, that the area with large vertical displacement is located at the crack on the top of the slope, and the Embankment Filler, on both sides of the crack, has a large relative dislocation. The horizontal displacement mainly occurs near the weak layer, indicating that the soil layer on the upper side of the weak layer has a large bedding displacement. The area with large lateral displacement is close to the plastic area. According to the above analysis, the stress change caused by the embankment-filling load has a certain impact on the development of the weak layer. Under the load, it has a horizontal displacement and further fragmentation, finally forming a sliding surface.

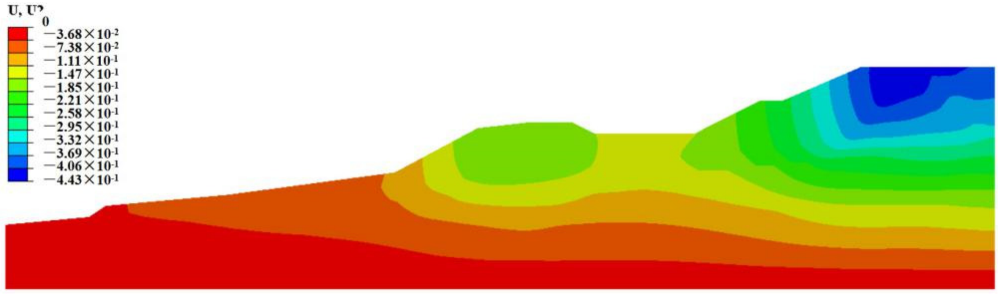

Figure 8. Vertical displacement of slope.

(3) Site landslide analysis

After the vertical tension cracks appear on the top of the embankment, ZK1–ZK9 observation points are set on the site (Figure 9), which are respectively arranged at the upper, middle, and lower positions of the landslide for monitoring the vertical displacement of the slope. The settlement displacement of representative slope displacement monitoring points ZK2 (top of slope), ZK5 and ZK6 (middle of slope), as well as ZK8 (toe of slope) is shown in the following Figure 10. With the expansion of vertical cracks, the settlement increases rapidly in the initial stage and gradually stabilized in the later stage. The monitoring data was stopped after the 15th. According to the monitoring results, the settlement value of the rear edge of the landslide is large, while the change of the front edge is not obvious.

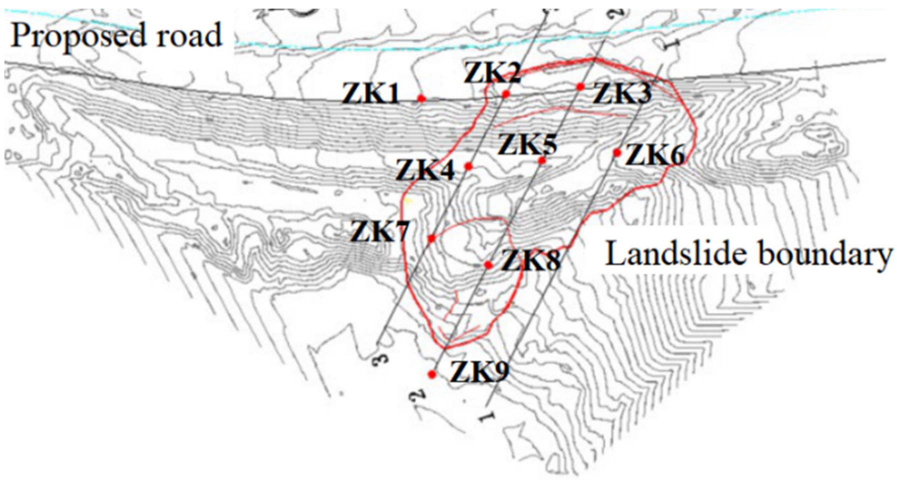

Figure 9. Scope of landslide.

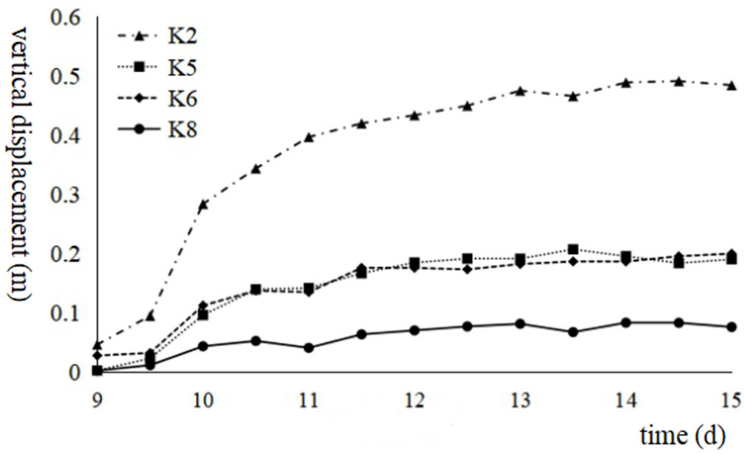

Figure 10. Vertical displacement of slope monitoring point.

Table 4 below shows the calculation results of the overall vertical displacement of the slope when the landslide is stable. From the Table 4, it can be found that the calculated value of the vertical settlement at the three measuring points of the slope is relatively close to the measured value, indicating that the method proposed in this paper can better describe the real displacement field of the slope.

Table 4. Comparison of displacement calculation results.

Monitoring Point	Slope Crest	Middle	Slope Toe
Monitoring value	0.47 m	0.19 m	0.09 m
calculated value (Consider moisture absorption and softening)	0.45 m	0.18 m	0.10 m
calculated value (Moisture absorption softening is not considered)	0.051 m	0.022 m	0.13 m

(4) Landslide site analysis

In the stability analysis of the embankment slope, in order to verify the influence of moisture absorption and softening, the calculation is divided into two cases: without considering moisture absorption and softening and considering moisture absorption and softening. In the process of rainfall, the subroutine automatically updates the strength of the soil element according to the saturation change of the slope, and then, it uses the finite element strength reduction method to solve the stability coefficient and potential sliding surface of the slope.

The calculation results are as follows in Table 5. Without considering moisture absorption and softening, the calculated stability coefficient is 1.15, indicating that the slope is in a stable state. After considering the moisture absorption and softening, the stability coefficient of the slope decreases to 0.97, and the filling section has been in an unstable state. The lower sliding surface passes through the weak layer, and the rear edge of the landslide is located in the middle of the pavement, between the filling area and the spoil area at the front edge of the landslide, as shown in Figure 11. From the distribution of the plastic zone (Figure 8), it can be seen that the weak layer forms a stress concentration zone under the action of the upper embankment load, forming a broken line plastic zone along the weak layer inside the slope, resulting in tensile cracks in the filling area and causing the overall instability of the slope. Compared with the field picture (Figure 12), it can be found that the calculated landslide shape is relatively close to the actual situation, which is in line with the actual situation of slope instability under the surcharge height. According to the calculation results of the sliding surface and stability coefficient, the modeling method and parameter used in this paper are reasonable.

Table 5. Influence of the calculation method on the stability coefficient.

Computing Method	F_s (Before the Rainy Season)	F_s (After the Rainy Season)
calculated value (Consider moisture absorption and softening)	1.23	1.15
calculated value (Moisture absorption softening is not considered)	1.19	0.97

Figure 11. Potential sliding surface of slope (Fs = 0.97).

Figure 12. Tensile Cracks at the rear edge of Embankment Landslide.

In order to analyze the rationality of the method proposed in this paper, it is compared with the stability coefficient calculated by the conventional method that expansive soil is regarded as ordinary cohesive soil (without considering moisture absorption and softening). The slope stability coefficient calculated by the conventional method is 1.15, indicating that the embankment slope is stable. Therefore, the stability coefficient calculated by the conventional method is obviously larger. Due to the high groundwater level after the rainy season, as well as the moisture absorption and softening of expansive soil itself, the softening of the weathered layer and weak layer is the most important reason for the instability of the embankment slope.

The calculation results are shown in Table 5. In order to analyze the rationality of the method proposed in this paper, it is compared with the stability coefficient, calculated by the conventional method, that expansive soil is regarded as ordinary cohesive soil (without considering moisture absorption and softening). The slope stability coefficient calculated by the conventional method is 1.15, indicating that the embankment slope is stable. Therefore, the stability coefficient calculated by the conventional method is obviously larger. Due to the high groundwater level after the rainy season and the moisture absorption and softening of expansive soil itself, the softening of the weathered layer and weak layer is the most important reason for the instability of the embankment slope.

4. Emergency Disposal and Reinforcement Measures

4.1. Analysis of Emergency Response Measures

After the landslide of the embankment slope, appropriate emergency treatment measures shall be taken. Common emergency measures include unloading the fill or brushing the slope to eliminate the spoil. In order to evaluate the treatment effect of emergency measures on the slope and provide reference for scheme selection, the following working conditions are analyzed: unloading 1m–5m Embankment Filler, unloading the spoil at the half slope, and analyzing the variation law of the embankment slope sliding surface and stability coefficient under these unloading measures. After calculation, the stability coefficients corresponding to several treatment measures are shown in Table 6 and Figure 13.

Table 6. Stability coefficient after taking emergency treatment measures.

Emergency Treatment	F_s
unload 1 m of fill	1.04
unload 3 m of fill	1.15
unload 5 m of fill	1.32
remove spoil only	0.95
remove spoil and unload 5 m	1.24

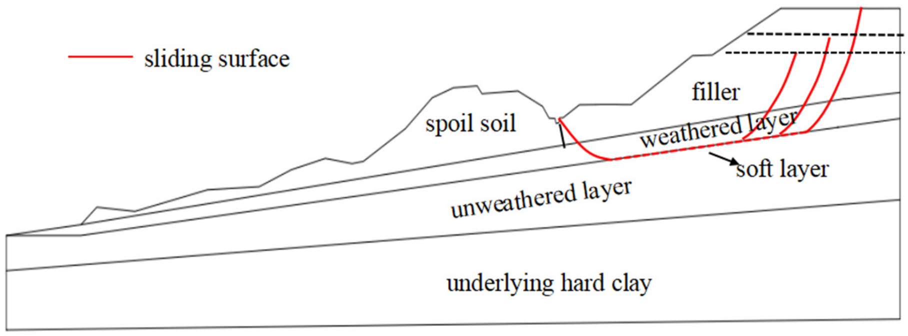

Figure 13. Influence of different unloading heights on slope sliding surface.

According to the calculation results in the above Table 6, the slope instability trend is controlled after unloading 1–5 m Embankment Filler. With the increase in the height of the removed filler, the stability coefficient increases slightly, and the scope of embankment sliding failure decreases. After removing the spoil at the toe of the embankment, the stability coefficient of the slope decreases, and the range of sliding instability increases. This shows that the spoil load at the toe of the slope is conducive to the stability of the slope and plays a certain role in restricting the displacement of the toe of the slope. After removing part of the fill, the slope sliding trend can be controlled and is in a temporary stable state, but the degree of improvement of the stability coefficient is very limited. At the same time, after unloading measures, the overall stability of the landslide and the shape of the sliding surface are still controlled by the weak layer.

4.2. Design of Slope Reinforcement

According to the previous section, for this slope, the effect of removing the fill is very limited. If it is necessary to further improve the stability of the slope and ensure the smooth construction of embankment filling, targeted reinforcement measures should still be taken for the weak layer.

According to the instability characteristics and engineering characteristics of the embankment slope, the selection of reinforcement measures needs to consider the following three aspects:

(1) restricted by the site conditions, the design height and grading gradient of the pavement cannot be changed;
(2) it is necessary to ensure the long-term stability of highway traffic;
(3) the uneven settlement shall be strictly controlled to protect the highway pavement and the pipe gallery facilities 3 m below the pavement.

Based on the above points, the final reinforcement scheme design of this slope adopts the method of combining anti-slide piles with reinforced soil for slope reinforcement. The upper fill is reinforced to improve the strength and integrity of the fill. There are two rows of piles set under the fill to pass through the weak layer, which can directly transfer the upper load to the deep hard soil layer with high strength. The reinforcement scheme of anti-slide pile, reinforced soil, and waterproof and drainage is designed as follows (Figure 14):

(1) Layout of reinforced soil in the filling area: excavate the steps at the top of the subgrade, lay the geogrid at a spacing of 0.7 m, and the tensile strength is ft = 70 kn/m. A total of 10 layers of geogrid are laid.
(2) Anti-slide pile: two rows of manually dug piles (with a section size of 2 × 2.5 m, a spacing of 5 m, and a pile length of 12–16 m) are arranged 10 m away from the step. A row of bored cast-in-place piles (pile diameter 1.2 m, pile length 25 m, longitudinal pile spacing 4 m, horizontal pile spacing 3 m) are arranged at the lower part of the slope.
(3) Drainage: due to the moisture absorption and softening characteristics of expansive soil, drainage channels are excavated on the east and west sides of the road before the construction of anti-slide piles. During the construction process, attention should be paid to the sealing and waterproof of the surface to prevent the infiltration of surface water.

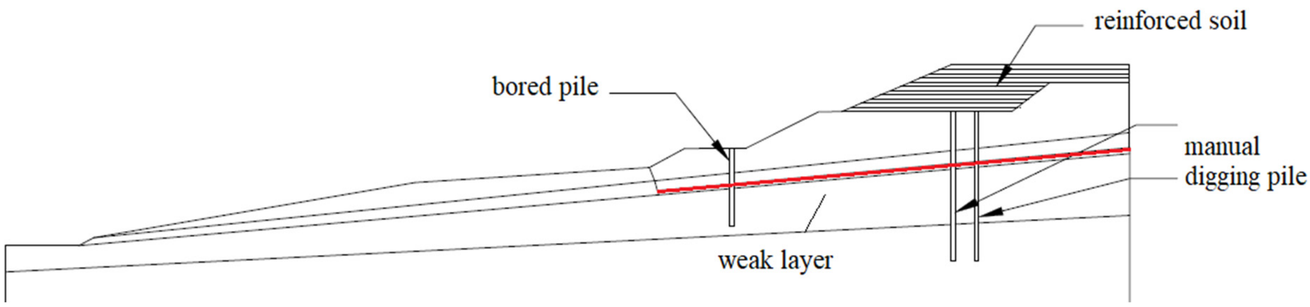

Figure 14. Final reinforcement scheme of slope.

According to the previous calculation method, the stability coefficient and potential failure mode of the reinforced slope are verified. The calculation results are shown in Table 7 below. The stability coefficients obtained by the two methods meet the requirements of relevant specifications (the slope stability coefficient under non-seismic conditions is greater than 1.3, and the slope stability coefficient under seismic conditions is greater than 1.1). The reinforcement scheme is reasonable and feasible, and it has good engineering economic benefits.

Table 7. Stability coefficient after reinforcement.

Conditions	Fs (After Reinforcement)	Fs (Not Reinforced)
normal condition	1.42	0.97
8 degrees of earthquake	1.20	0.86

As shown in the Figure 15, after the anti-slide pile reinforcement, the instability form of the slope changes. The failure mode is limited between the front and rear rows of anti-slide piles. At present, the reinforcement scheme has been implemented in the field, and the site construction is shown in Figure 16.

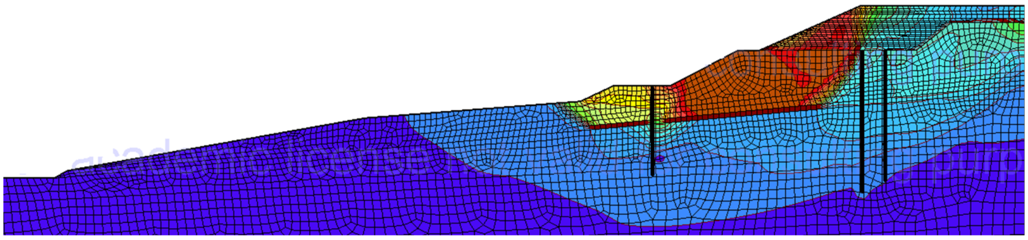

Figure 15. Potential sliding surface after reinforcement.

Figure 16. Site construction of reinforcement scheme.

5. Conclusions

After landslide geological investigation, landslide investigation, and numerical analysis, taking a high fill embankment landslide of expansive soil in Yunnan as an example, the instability mechanism of expansive soil embankment with low strength of shallow soil and moisture absorption softening is analyzed, and the conclusions are as follows:

(1) The shallow foundation soil is fractured by weathering, has low strength, and is absorbed and softened in rainy season, which is the main cause of the embankment landslide. Considering the strength reduction caused by moisture absorption, the true stability of slope can be better evaluated.

(2) For high fill embankment on weathered expansive soil, its stability and failure mode are mainly affected by the shallow weathered layer and weak layer. With the increase in the filling height, the most dangerous sliding of the embankment slope moves towards the inner side of the embankment, and the instability and failure range increase, but the failure surface still develops along the bottom of the weathered layer.

(3) In the case of strict site conditions, the scheme of anti-slide pile-reinforced soil has better practicability for this kind of embankment slope. At the same time, attention should be paid to prevent the infiltration of surface water during the construction process to avoid the further decline in the strength of the expansive soil foundation.

For expansive soil foundation with weak interlayer, it is better to directly reinforce the weak layer through rigid piles. However, the cost of rigid piles is relatively high, and there are certain requirements for construction equipment. For the survey of road engineering in the expansive soil area, attention should be paid to the analysis of the strength and distribution range of soft interlayer. If necessary, the road can avoid the soft layer distribution area.

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