Study on Water Damage Mechanism and Emergency Restore of Fill Subgrade upon Squashy Slope Foundation in Mountain Area

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Abstract. This thesis takes the typical fill subgrade of squashy slope foundation of Qinglong-Xingyi Expressway in Guizhou Province as an example. Through engineering geological analysis, it was found that the topography and geomorphology conditions, formation lithology conditions and highway construction conditions were the basic conditions of water damage to highway subgrade, and hydrometeorological conditions are the direct cause of water damage of highway. Coupling calculation analysis using SEEP/W and SLOPE/W revealed the mechanism of short-term continuous heavy rainfall. When the short-term continuous heavy rainfall reached a certain level, the soil at the geotechnical interface reached saturation. At this time, the surge of pore water pressure at the geotechnical interface led to the sudden drop of effective stress, leading to the sudden decline of side slope stability, which was the starting condition for the formation of landslide caused by the water damage to subgrade. The implementation of emergency restore and the effect evaluation indicated that comprehensive treatment measures of the anti-sliding support combined with integrated drainage should be adopted for the prevention and control of the water damage to the subgrade. Underground drainage measures could effectively drain groundwater, playing a role in reducing groundwater level and pore water pressure in slip soil.

Keywords. Squashy slope foundation, water damage to the subgrade, short-term heavy rainfall, numerical simulation, emergency restore.

1. Introduction
Guizhou Province is located in the southwest mountainous area where mountains are high and deep, ravines and gullies criss-cross, the mountains and hills account for 93% of the total area. A large number of high-filled and deep-buried subgrades are formed in the highway construction, which brings great challenges to road construction and operation [1]. The squashy slope foundation in Guizhou are relatively common. They are mainly distributed in the middle and low mountainous landform areas formed by construction and denudation [2]. They have three distinctive features: first, the surface of the foundation has a certain slope; second, the groundwater in the field is rich; third, the foundation soil is characterized by low strength and high compressibility due to long-term water immersion. Subgrade filling on the squashy slope foundation is likely to cause uneven sedimentation or even overall instability. The fill subgrade section upon the squashy slope foundation for the operating highway is often a high-risk area of water damage.

Highway water damage refers to a series of destruction to highway engineering along highways and the processes of highway destruction under the combined effects of climate, hydrology, and geological environmental factors as well as human activities [3]. Highway water damage is one of the
main problems for the current operating highway, and the side slope water damage of subgrade is the most prominent. On the one hand, the water damage to the subgrade depends on the basic geological conditions of the subgrade side slope and the highway construction conditions; on the other hand, it is influenced by a variety of external factors. Rainfall, especially heavy rainfall, is one of the most important factors inducing water damage to the subgrade [4-5].

Taking the fill subgrade upon squashy slope foundation of Qinglong-Xingyi Highway in Guizhou Province as an example, the deformation characteristics, the causes, and the short-term heavy rainfall action mechanism of the water damage to the subgrade upon the squashy slope foundation, and the targeted emergency restore and treatment measures were put forward, which has important practical engineering significance for the prevention and control of the water damage of fill subgrade upon squashy slope foundation.

2. Project Overview

The Qinglong-Xingyi Highway was completed and opened to traffic on December 31, 2012. The K0+000 - K40+375 section passes through the coal measure strata area, which is the prone area of the water damage to the subgrade. The main forms of water damage to the subgrade include slope surface scouring, subgrade slippage and subgrade sedimentation. The field is subtropical, cool and humid monsoon climate, with an average annual rainfall of 1,561.7 mm, mostly in May to October, and maximum daily rainfall of 186.1 mm.

The left fill subgrade of K13 + 270-K13 + 330 is a secondary fill subgrade. The first and second slope ratios are 1: 1.5 and 1: 1.75 respectively. The slope surface is protected through arched skeleton with a maximum filling height of 12 m. The original terrain of this section was a natural slope, the elevation of the axis position was between 1,341.4 and 1,382.6 m, the relative height difference was 41.2 m, and the natural slope angle was 20°-35°. The overburden is the Quaternary artificial filling (Q₄m), the Quaternary residual and slope sediments (Q₄rend) pebbly silty clay, and the underlying bedrock is the Permian Upper Longtan Formation (P₉l) argillaceous siltstone. The composition of the formation lithology is as follows:

1) Artificial filling (Q₄m): variegated, the composition is gravel soil, the gravel component is mainly limestone with the block diameter of 5-10 cm and the content of 60-70%, among which clay is filled.

2) Pebbly silty clay (Q₄rend): It is grayish black, plasticized-soft plastic, with 15-20% crushed stone content and 20-30 mm particle size.

3) Argillaceous siltstone (P₉l): thin to medium thick layer, occasionally with thin coal seam, the rock layer is monoclinal, and the comprehensive rock formation is 155°< 12°; thick rock joint fissures in strongly weathered layer are very developed, in which the two groups of dominant joints are mainly developed, whose occurrences are 22°< 88°, 282°< 80°, and opening degree is 1-3 mm, with mud interbedded with rock debris filled.

Between July and August 2018, due to repeated heavy rainfall, pavement settlement occurred on the left side of the K13 + 270-K13 + 330 section, resulting in the closure of the left lane, as shown in figure 1.

3. Deformation Characteristics and Causes Analysis of Water Damage to the Subgrade

3.1. Deformation Characteristics of Water Damage to the Subgrade

The water damage to the subgrade formed a landslide. The landslide deformation range included the left fill subgrade of K13 + 270-K13 + 330 section and the squashy foundation soil mass within a certain range of cornfields and paddy fields below the subgrade. The overall landslide form a V shape, the lateral width of the front rim is about 75 m, the longitudinal length is about 90 m, the plane area is about 5,200 m², the average thickness is about 6 m, the sliding volume is about 31,200 m³, and the main sliding direction is 62°. It is a small-sized slumping landslide.

The back edge of the landslide was located in the left foundation. The crack on the highway
pavement was circular arc. The maximum crack was about 3 m from the centerline of the highway, 30 cm wide, and about 10 cm below. After 2 days of asphalt re-laying, the crack appeared again on the pavement, about 25 cm wide, 80 cm deep and 8 cm below. The front edge of the landslide was located in the cornfield and paddy field below the subgrade with many radial bulging cracks on the leading edge, and a small extent collapse. Goose feather shape shear cracks appeared on both sides, the cracks in the subgrade were continuously distributed, and the cracks in the soil mass below the subgrade were intermittently distributed.

**Figure 1.** Engineering geological plane of landslide area.  
**Figure 2.** JCK5 deep displacement monitoring curve.

According to the results of deep displacement monitoring (figure 2), the sliding surface at the rear of the landslide body was 8.6 m deep on a typical section (figure 3), which was located near the contact surface between the fill and the bedrock, and the sliding surface material is filled with soil; the sliding surface depth of the landslide body about 8.5 m, located in the vicinity of the contact surface containing the pebbly silty clay and bedrock, the sliding surface material is composed of pebbly silty clay, which is soft plastic. During the monitoring period, the displacement speed of the landslide is 5-10 mm/d, and the landslide body is in the strong deformation stage as a whole.
3.2. Analysis the Causes of Water Damage to the Subgrade
The main conditions for the water damage to the subgrade are topography and geomorphology conditions, formation lithology conditions, highway construction conditions and hydrometeorological conditions.

(1) Topography and geomorphology conditions determine the size of the surface water area on the one hand, and the existence of slope terrain provides a potential water damage object for water damage. The catchment area of the original watershed area before excavation was about 90,000 m². Some of the water was discharged through the drainage system, and some was infiltrated into the fill subgrade.

(2) Formation lithology conditions determine the characteristics of groundwater distribution, the infiltration route and the softening characteristics of soil water immersion. The Longtan Formation (P₃l) coal measure strata contains carbonaceous mudstone, carbonaceous shale, and coal seams. The characteristics are soft rock, strong water absorption, swelling and softening when meeting water. Strongly weathered rock mass is broken, which is relative aquifer. The pebbly silty clay is a weathering product of coal-bear rock formations. It is easily softened under the long-term action of groundwater, and has the characteristics of high water content and low strength. In addition, the artificial fill of the fill subgrade has the characteristics of relatively large void ratio and strong water permeability, which provides a convenient passage for rainfall infiltration and is a relative aquifer.

(3) The road construction conditions determine the ability of the subgrade to withstand water damage. The subgrade and slope water merged into the platform drainage ditch at K13 + 325. The drainage ditch was made of masonry stone material. During the deformation of the slope, the drainage ditch simultaneously underwent deformation and cracking, which caused the water to enter the slope and accelerate the deformation of the slope itself. In addition, the slope has no underground drainage measures resulted in poor ability of the subgrade slope to withstand water damage.

(4) Hydrometeorological conditions determine the amount of rainfall and surface flow, which is a direct driving factor for road water damage. Long-term rainfall infiltration softened the foundation rock soil, reduced the shear strength parameters of the rock mass of the subgrade slope and reduced the slope stability; there was no surface water body, and rainfall was the main factor affecting the water damage of the subgrade. The rain continued from August 1 to August 10, in which the rain from August 3 to August 7 was moderate rain and heavy rain. This was the direct trigger for the formation of the water damage to the subgrade.

In summary, the topography and geomorphology conditions, formation lithology conditions and highway construction conditions are the basic conditions for highway water damage and the internal cause of water damage. Hydrometeorological conditions are the direct cause of highway water damage, and the external causes of water damage disasters. Long-term rainfall infiltration and softening plays a role in changing the formation lithology conditions; short-term continuous heavy rainfall is the direct predisposing factor affecting the water damage of the subgrade.

4. Mechanism of Short-term Continuous Heavy Rainfall
We applied SEEP/W and SLOPE/W for coupling numerical calculation analysis. The SEEP/W was used to calculate the pore water pressure change inside the slope under strong rainfall, and then import the SEEP/W calculation result into SLOPE/W to calculate the change of the stability coefficient during every rainfall duration.

4.1. Model Establishment and Parameter Selection
The calculation model of the typical section is selected as shown in figure 4. The initial groundwater level line of this model used the groundwater level line during the survey period.

The calculation applied the physical and mechanical parameters of rock and soil as shown in table 1.
**Figure 4.** Numerical calculation model for landslide.

**Table 1.** Values of physical and mechanical parameters of rock and soil.

| Type of the rock or soil                    | Saturated bulk density (kN/m³) | Cohesive force c (kPa) | Internal friction angle φ (°) | Permeability coefficient (cms⁻¹) |
|--------------------------------------------|-------------------------------|------------------------|-------------------------------|---------------------------------|
| Artificial fill                            | 19.5                          | 5.0                    | 30.3                          | 2.5×10⁻²                        |
| Pebby silty clay                           | 18.5                          | 15.0                   | 16.5                          | 7.1×10⁻¹                        |
| Strongly weathered argillaceous siltstone | 22.6                          | 50.9                   | 25.4                          | 1.6×10⁶                         |
| Moderately weathered argillaceous siltstone| 23.5                          | 205.6                  | 35.2                          | 3.2×10⁷                         |

4.2. Transient SEEP/W Simulation Analysis of Subgrade Slope

The SEEP/W finite element program was used to simulate the transient seepage field of the subgrade slope under rainfall conditions. According to the meteorological data during the subgrade water damage, the rainfall intensity was 50 mm/d and the rainfall duration was 48 hours. This study only listed the initial pore water pressure distribution in the initial state, 16 hours, 32 hours, 48 hours, as shown in figure 5.

**Figure 5.** Distribution of Pore water pressure in slopes under different rainfall periods: (a) Initial state, (b) Rain for 16 hours, (c) Rain for 32 hours, (d) Rain for 48 hours.

According to the simulation results, in the initial stage of rainfall, the infiltration rate of the overburden was large, and the subgrade slope was dominated by shallow surface infiltration. The pore
water pressure of the soil increased continuously, and a transient saturation zone was formed in the surface layer. The low terrain of the leading edge was conducive to the accumulation of rainfall. The leading edge groundwater level line rose, and the trailing edge had no obvious change, as shown in figure 5b. As the rainfall time increased, the back edge of the subgrade slope was flat and the cover layer was thin, the rainfall seepage path was short, the soil body was first saturated, the groundwater level rose rapidly, the overburden in the middle part of subgrade slope was thicker, and the groundwater level rose slowly. The leading edge continued to rise, as shown in figure 5c. After the back edge slope reached saturation state, the rainfall was continuously converged at the interface of rock and soil with obvious permeability difference. The front part of the slope was still dominated by rainfall infiltration, while the back edge was dominated by seepage. As time increased, the interface between rock and soil gradually reached full state, the groundwater level rose rapidly, the pore water pressure continued to increase, the floating force increased, and the stability of the slope gradually decreased, as shown in figure 5d.

The positions of a, b and c are shown in figure 5a. It can be seen from figure 6 that the pore water pressure of the leading edge of the slope continued to increase during the whole rainfall process, and suddenly increased after the saturation of the rock-soil interface; the pore water pressure increased earlier than the middle part, and then remained stable. The pore water pressure in the middle part of the sliding body was basically stable within 32 hours of rainfall, similar to the leading edge. When the rock-soil interface was saturated, the pore water pressure increased sharply, and the time preceded that of leading edge.

**Figure 6.** Change trend of pore water pressure.

### 4.3. Analysis of Subgrade Slope Stability

Based on the Morgenstern-Price limit equilibrium stability calculation method, based on the simulation of the instantaneous seepage field of the subgrade slope, considering the influence of the vehicle load on the highway, assuming that the vehicle load was 25 kPa, the stability analysis of the landslide was carried out. The calculation result is shown in figure 7. At the beginning of rainfall, the slope stability coefficient showed a slow downward trend; when the rainfall continued for 32 h, the stability coefficient plummeted and entered the limit equilibrium state, which was also consistent with the SEEP/W simulation results, after which the stability coefficient continued to decline.

### 4.4. Analysis of the Mechanism of Short-Term Continuous Heavy Rainfall

When the rainfall intensity is 50 mm/d, the pore water pressure of the slope increased continuously with time during continuous heavy rainfall, the effective stress decreased, and the stability of the slope gradually decreased. When the rainfall lasted for 32 h, the soil at the geotechnical interface reached saturated state. At this time, the surge of pore water pressure at the geotechnical interface led to the sudden drop of effective stress, which led to the sudden decline of the slope stability, the slope entered
the limit equilibrium state, that is, the Condition for landslide occurring was the 50 mm/d rainfall lasts 32 h.

Figure 7. Curve for stability coefficient vs rainfall time.

5. Emergency Restore and Effect Analysis of Water Damage to the Subgrade

5.1. Emergency Restore Measures
According to the deformation and failure characteristics of the subgrade water damage and the instability mechanism, combined with the topography, highway traffic safety and project schedule requirements, etc., "steel pipe pile + subgrade excavation and replacement + round anti-slide pile + integrated drainage (underground drainage blind ditch, surface drainage ditch) + pavement and slope restoration " comprehensive measures were made for the emergency restore of the subgrade in this section.

(1) Steel pipe pile: In order to ensure the safety of the half-passage of the right subgrade, a row of steel pipe piles is arranged about 1m away from the trailing edge of the left side of the subgrade. The outer diameter of the pile is 159 mm, the wall thickness is 5 mm, and the pile length is 10 m, a total of 82 pieces and 820 m.

(2) Subgrade excavation and replacement: Subgrade excavation and replacement: the upper part is bounded by the crack of the pavement, and the lower part is bounded by the bottom of the first platform.

The sliding body is excavated and replaced, and the graded gravel is used as the filler. The first level of the filling slope is 8 m and the slope rate is 1: 1.5. The first platform is located 12 m to the left of the sideline of the road and 2 m wide.

(3) Round anti-slide pile: A row of round anti-slide piles is arranged on the 13 m first stage platform on the left side of the highway side line. The pile diameter is 1.6 m, the pile length is 18m, and the pile spacing is 4 m, a total of 16 pieces.
(4) Integrated drainage: After the excavation, the foundation is leveled according to the 3% drainage slope and the vertical and horizontal blind ditch is used to drain the groundwater. The total length of the blind ditch is 80 m, the material is C15 concrete and M10 mortar masonry; the drainage is set at the foot of the slope. The ditch will lead the blind ditch and the subgrade side ditch to the outside of the area.

5) Pavement and slope restoration: the pavement is restored according to the current standard and the arched skeleton of the slope is restored.

5.2. Analysis of Treatment Effects
As the construction destroyed the hole for deep displacement monitoring, four deep displacement monitoring holes were re-arranged during the construction phase to provide security for the safety construction, and feedback to guide the engineering construction.

In this thesis, the monitoring data of the JZK2-1 monitoring hole near the anti-slide pile was selected for analysis. According to the construction process and the cumulative displacement trend, the curve can be roughly divided into four stages: In Stage I, before the subgrade excavation, slip body was still in the accelerated creep stage. After the landslide was about 3,000 m³, the displacement was rapidly reduced and the whole was convex. In Stage II, the displacement of the anti-slide piles increased slowly after construction, and the displacement of the anti-slide piles after construction kept stable. In Stage III, after the completion of the anti-slide pile construction, the subgrade was replaced
by the graded gravel. Due to the loading and construction disturbance, the displacement increased in a small range. In Stage IV, after the completion of the construction, the highway was opened to traffic, the overall deformation tended to be stable, and the treatment effect was good.

In addition, the effect of the blind ditch in the slope was good, and the normal water output was about 0.1 l/s.

6. Conclusions
Through the study on the deformation characteristics of water damage to the subgrade, the causes of water damage, the water damage mechanism of short-term heavy rainfall and the effect of emergency repair, the following conclusions are obtained:

(1) Topography and geomorphology conditions, formation lithology conditions and highway construction conditions are the basic conditions for highway water damage and the internal causes of water damage. Hydrometeorological conditions are the direct causes of highway water damage, and the external causes of water damage disasters. Long-term rainfall infiltration and softening plays a role in changing the formation lithology conditions; short-term continuous heavy rainfall is the direct predisposing factor affecting the water damage of the subgrade.

(2) When the short-term continuous heavy rainfall reaches a certain level, the soil at the geotechnical interface reaches saturated state. At this time, the pore water pressure surge at the geotechnical interface leads to the sudden drop of effective stress, which leads to the sudden decline of slope stability, which is starting condition of the landslide caused by water damage to the subgrade. In this thesis, the starting rainfall condition of the landslide caused by the water damage to the subgrade slope is the 50 mm/d rainfall lasts 32 h.

(3) The comprehensive treatment measures of anti-sliding support combined with integrated drainage should be adopted for the prevention and control of water damage to the subgrade. The integrated drainage should be include with underground drainage and surface drainage. Effective drainage of groundwater can reduce the groundwater level and the pore water pressure, serves to improve the shear strength of the slip zone and the overall stability of the slope.

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