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Numerical simulation analysis of excavation response of counter-tilt rock slope

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***Abstract*—With the development of the rock mass joints and the increase in the excavation depth of the slope, the failure of the anti-dipping rock slope has occurred from time to time, which has attracted the attention of scholars. Taking a proposed highway cutting slope as the research object, establish a finite element model for the excavation of a high anti-dipping rock slope. The strength reduction method is used to calculate the safety factor of the slope, stability and excavation response are also analyzed. The results show that the horizontal displacement of the rock mass caused by excavation is small, the vertical displacement is mainly concentrated near the excavation area of the slope, and the upward unloading rebound is mainly; As the excavation progresses, the maximum shear strain develops from the silty clay and strongly weathered sandy mudstone in the shallow ground to the slope toe. In the actual construction process, it is recommended to pay attention to the failure of the rock mass at the step slope toe. The safety factor of the slope gradually decreases as the excavation progresses. When the first-level slope is excavated, it is still in a stable state. The research results can provide a reference for anti-dipping slopes with similar characteristics.**

Keywords-counter-tilt rock slope; slope excavation; safety factor; stability

I. INTRODUCTION

The excavation of high rock slope is an important concern and control point in the mountain road construction process. The counter-tilt slope is considered more stable, because the dip of rock stratum is opposite to the direction of the slope. Nevertheless, with the development of rock joints and the increase of the excavation depth of the slope, the destruction of counter-tilt rock slopes occurs from time to time. It has attracted the attention of scholars. Zhu Cunjin[1] derived a formula for calculating the fractured depth in toppling failure of counter-tilt rock slopes on the basis of cantilever beam limit equilibrium model. Zheng Da[2] conducted physical simulation on the excavation of the upper-hard soft counter-tilt slope, studied the deformation characteristics and damage mode of the slope during the excavation process, and suggested to avoid the large cutting of the dumped rock mass at the foot of the slope. He Qian[3] analyzed the stability and damage mechanism of the counter-tilt rock slope based on PFC^{2D}. This paper takes the cutting high slope of a proposed highway as the research object, uses finite element analysis software to numerically simulate the excavation and support process. The safety factor of the slope is calculated by applying the strength reduction method. The displacement, stress and shear strain in the step excavation are analyzed.

II. PROJECT OVERVIEW

The proposed highway is located in Dazhou City, Sichuan Province. The site is a hilly area formed by tectonic erosion, the terrain is undulating, overall terrain is high in the west and low in the east, ground elevation is between 302m~366m, the relative difference of elevation is approximately 64 m. The strata consists mainly of Q_4^{el+dl} and J_2s bedrock. Surface distribution thickness of about 2.5m~3.5m silty clay, slightly wet, soft plastic-flow plastic. The lower part is J_{2s} sandy mudstone, sandstone and siltstone. It is unequal thickness and interlayered shape, degree of weathering gradually decreased with increasing depth. The ground elevation of left slope excavation point of K0 + 740 is 361.24m. The total excavation heights is 56m, and the slope is cut into six levels from top to bottom. Excavate the slope step by step and carry out the anchoring construction in time. The anchor rod adopts 20mm diameter steel bar. Slope surface spacing 2.5m × 2.5m, the incident angle is 20 degrees, anchor rod length is 4m~8m. After the anchor rods reach the design strength, cut the next slope and finally spray the anchor. The height of the 6th and 5th grade slope are 8 meters, both slope ratios are 1:1. The height of the 4th to 1th grade slope are 10 meters, both slope ratios are 1:0.75. Set a horse track width of 1.2m. The central elevation of the proposed highway is 305.24m. The excavation section of the cutting slope is shown in Figure 1.

III. FINITE-ELEMENT ANALYSIS MODEL

According to the slope excavation section diagram, the height of the slope formed after the excavation is 56m. In the finite element calculation, in order to ensure the calculation accuracy and eliminate the influence of the boundary effect. The model size is shown in Figure 1

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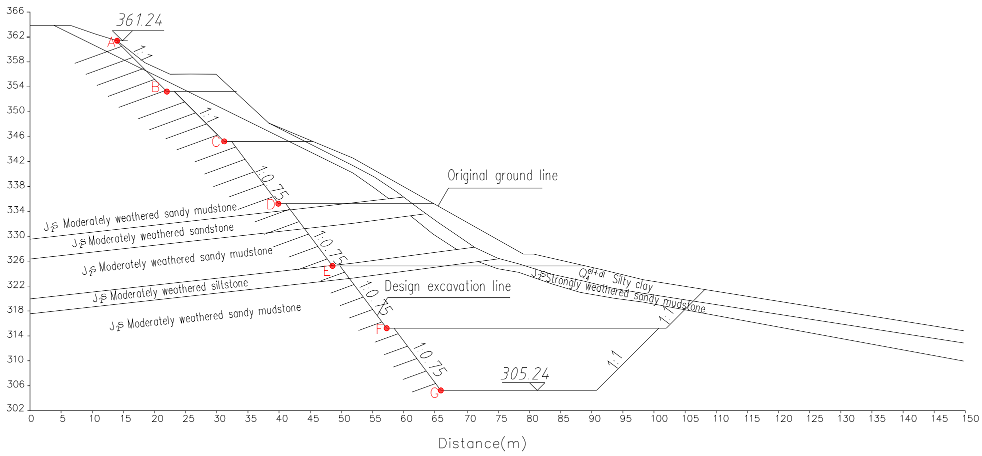

Fig.1 Excavation section view of cutting slope

In the calculation model, the rock and soil are regarded as isotropic elasticoplasticity materials. The mohr-coulomb yielding criteria is adopted. The anchor rod is regarded as the ideal elastic material and simulated using implanted truss unit. The boundary conditions are the lower fixed end constraints, and the left and right are horizontal constraints. The grid size of the excavation area is controlled as 1m, as the distance from the excavation area, the rest of grid size gradually transitions from 1m to 2m according to a linear gradient. Excavation calculation model shown in Figure 1, seven ABCDEFG points are selected on the slope excavation surface for monitoring, and the deformation of the slope during excavation is analyzed.

According to the drilling data, combined with the results of in-situ tests and indoor tests, the physical and mechanical parameters of the rock and soil in the calculation model are determined. The specific values are shown in Table 1.

TABLE 1 PHYSICAL AND MECHANICAL PARAMETERS OF ROCK AND SOIL

Type	Elastic Modulus (kPa)	Poisson's ratio	Bulk weight (kN/m^3)	Cohesion (kPa)	Angel of internal friction(°)
Silty clay	3×10^4	0.30	18.2	19	15
Strongly weathered sandy mudstone	1×10^6	0.28	23.4	150	21
Moderately weathered sandy mudstone	1.5×10^6	0.25	24.7	500	36
Moderately weathered sandstone	2.3×10^6	0.20	24.8	700	38
Moderately weathered siltstone	1×10^6	0.33	23.9	250	28
anchor rod	2.1×10^8	0.20	77.0	/	/

IV. SIMULATION CALCULATION AND RESULT ANALYSIS

A. *Deformation Analysis*

It is stipulated that the horizontal displacement of the monitoring point is positive to the right, and the vertical displacement is positive to the upward. The horizontal and vertical displacement of the seven monitoring points was extracted with the increased excavation depth. As the excavation depth increased, the horizontal displacement of the seven monitoring points gradually increased. But the horizontal displacement value is relatively small. As shown in Figure 2, the maximum horizontal displacement does not exceed 3mm, indicating that the horizontal displacement of the rock mass caused by excavation is small. From the horizontal displacement cloud Figure 4, during the whole excavation process, the horizontal displacement to the left is mainly distributed in the top area of the slope, the right horizontal displacement is mainly distributed in the lower part of the excavated slope and the toe of slope, the development of horizontal displacement conforms to the deformation characteristics of slope sliding failure.

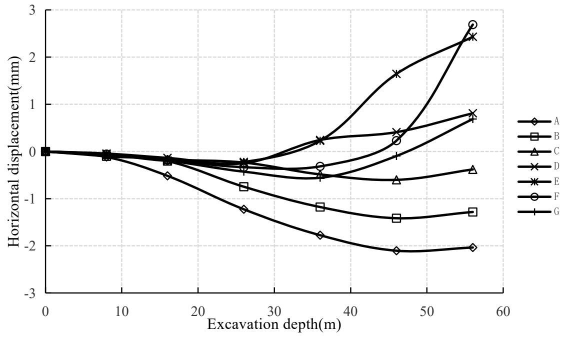

Fig.2 Variation curve of horizontal displacement with excavation depth

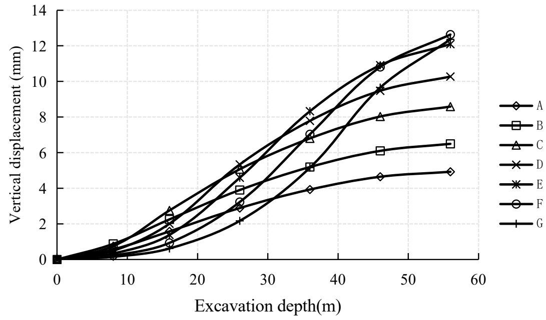

Fig.3 Variation curve of vertical displacement with excavation depth

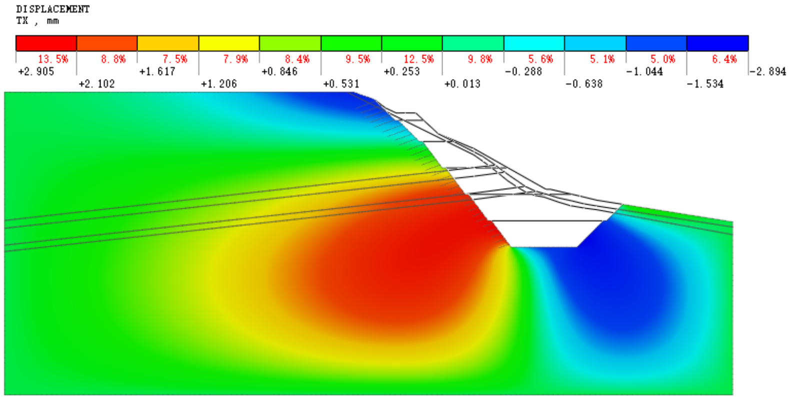

Fig.4 Horizontal displacement cloud diagram under first-level excavation

The overlying rock layer is unloaded due to excavation, the slope rock mass is relieved, and the shallow rock mass produces upward or outward expansion, which is manifested as the unloading rebound of the rock mass. As shown in Figure 3, the vertical displacement of the monitoring point increases with the excavation depth, and the direction points upward, manifested as the rebound deformation to the free surface. In the process of excavation from level 6 to level 1, the maximum vertical displacement of the excavation area is 1.05mm, 2.92mm, 5.85mm, 9.40mm, 12.55mm, 14.43mm, and the positions where the maximum appears in each level of excavation Underside . It is shown by the vertical displacement cloud figure 5 under the first-level excavation, vertical displacement mainly occurs near the slope excavation area, and mainly upward loading rebound, the maximum value appears in the sixth excavation undersurface (road pavement design elevation), the maximum value is 14.43mm. The vertical displacement of the rock mass away from the excavation area is mainly the downward settlement.

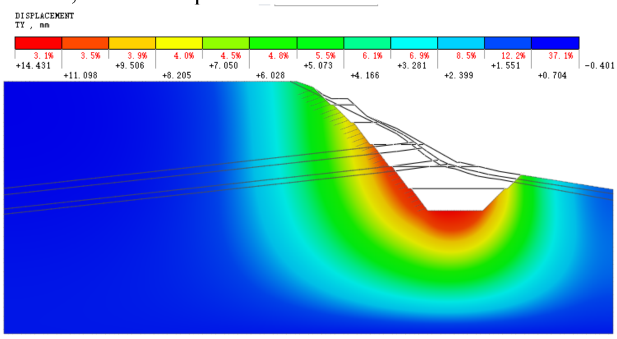

Fig.5 Vertical displacement cloud diagram under first-level excavation

B. Stress and strain analysis

With the excavation of the cutting slope, the stress field has changed, and the maximum shear stress increases with the excavation depth. The maximum value is increased from 0.4MPa to 0.89MPa. The maximum shear stress occurs near the toe of the slope, and the smaller its value near the free surface of the slope top.

During the sixth-level to the fourth-level excavation, the maximum shear strain is concentrated in the shallow formation in the middle of the slope, as shown in Figure 6. This is because 2m thick silty clay and 3m thick strongly weathered sandy mudstone are distributed in the shallow stratum. The weathered fissures are extremely developed, and the core is broken.

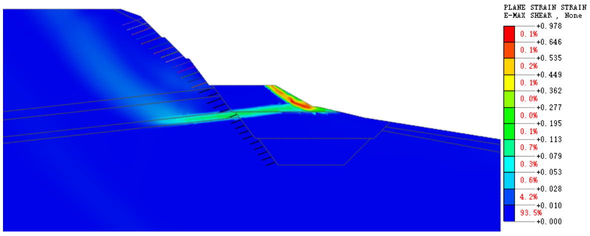

Fig.6 Maximum shear strain cloud diagram under fourth-level excavation

During the third-level to first-level excavation process, the maximum shear strain distribution is shown in Figure 7, and stress concentration occurs at the slope toe. In the actual construction process, it is recommended to pay attention to the failure of the rock mass at the step slope toe.

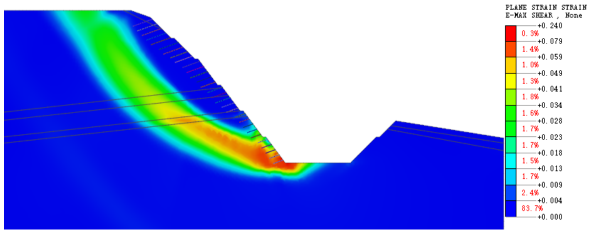

Fig.7 Maximum shear strain cloud diagram under first-level excavation

C. stability analysis

According to the Specifications for Design of Highway Subgrades: JTG D30-2015[4], calculation of subgrade stability should consider normal operating conditions and abnormal operating conditions (heavy rains and earthquake conditions), The seismic fortification intensity of the cutting area is located is 6 degrees[5], therefore, the dynamic slope analysis is not conducted. The cutting slope is calculated under the normal and rainstorm conditions, and the safety factor during the excavation is shown in Table 2, and the position and shape of the sliding surface are determined.

It can be seen from Table 2 that the safety factor of the slope under the sixth-level excavation has increased compared with the original state. This is because the excavation of the sixth-level slope has the effect of "cutting the head", reducing the weight of the upper part of the slope and increasing slope stability. With the subsequent slope excavation, the slope stability gradually decreases. During Grade III excavation, the safety factor reached the maximum, 20% under normal working conditions and 27% under rainstorm conditions. This is because the bottom surface and the toe of tertiary excavation are the contact surface of moderately weathered sandy mudstone and moderately weathered siltstone, especially after immersion, it is easy to soften and form a potential sliding surface. With the subsequent slope excavation, the slope stability gradually decreases. In the third-level excavation, the decrease in the safety factor reached the maximum, 20% under normal conditions and 27% under rainstorm conditions. This is because the bottom surface and slope toe of the third-level excavation are the contact surfaces of moderately weathered sandy mudstone and moderately weathered siltstone, especially after being immersed in water, it is easy to soften and form a potential sliding surface. After the first-level excavation, the slope safety factor was reduced to 1.96 (normal conditions) and 1.39 (heavy rain conditions). For each level of excavation, the anchor rods were constructed in time for reinforcement, and the slopes were in a stable state.

TABLE 2 SAFETY FACTOR DURING EXCAVATION OF ROAD CUTTING SLOPE

Slope excavation	Accumulated excavation depth	safety factor	
		normal conditions	heavy rain conditions
Original slope	0m	3.01	2.17
Sixth-level	8m	3.09	2.25
Fifth-level	16m	3.00	2.23
Fourth-level	26m	2.82	2.15
Third-level	36m	2.26	1.58
Second-level	46m	2.16	1.54
First-level	56m	1.96	1.39

Comparing the shear strain distribution cloud diagrams of the cutting slope at each level of excavation in the critical state, as the excavation depth increases, the shear band moves to the back of the slope, and when the excavation depth is 36m at the third level, The cutting slope will produce a certain degree of shear failure in the moderately weathered siltstone layer, and the shear outlet is at the foot of the third-level excavation slope.

As can be seen from the distribution of the first-level excavation plastic zone (Figure 8), the tensile failure is mainly concentrated within the range of 30m from the slope surface. It is recommended to arrange monitoring points in this area during the excavation process to pay close attention to the displacement changes.

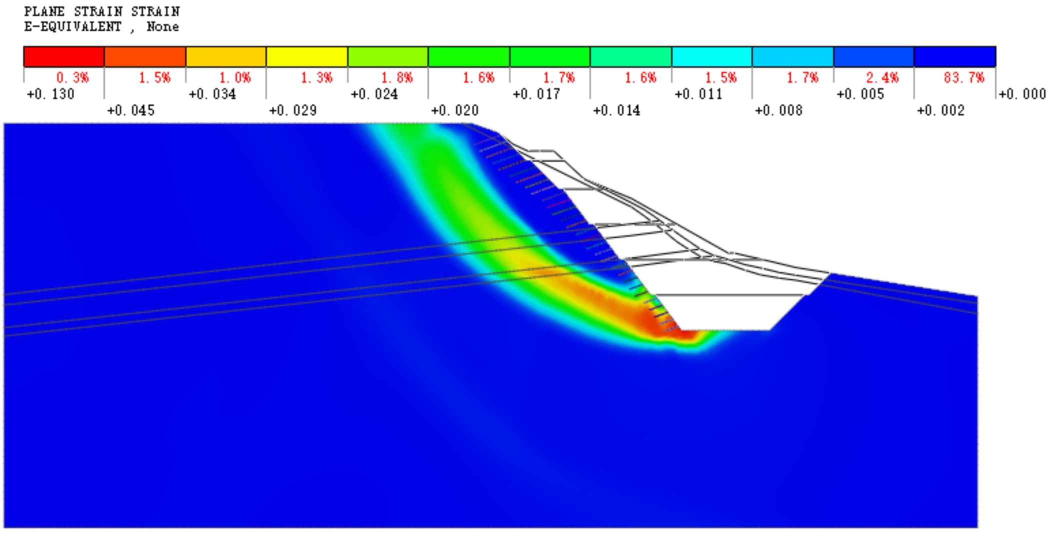

Fig.8 Equivalent strain cloud diagram under first-level excavation

V. CONCLUSION

This paper presents the numerical simulation of the excavation and support process of the high slope of a highway cutting, draws the following conclusions.

(1) The slope displacement increases with the excavation depth. The horizontal displacement of the rock mass caused by excavation is relatively small. The horizontal displacement to the left is mainly distributed at the top area of the slope, and the horizontal displacement to the right is mainly distributed at the lower part of the slope and the toe; the vertical displacement is mainly Occurs near the excavation area of the slope, and is dominated by upward unloading rebound.

(2) The maximum shear stress increases with the excavation depth. During the excavation process of the cutting slope, the maximum shear strain develops from the silty clay and strongly weathered sandy mudstone of the shallow formation to the slope toe. In the actual construction process, it is recommended to focus on the destruction of the rock mass at the step slope toe.

(3) As the excavation depth increases, the stability of the slope gradually decreases. Under normal and rainstorm conditions, when excavated to the first-level slope, the safety factor still meets the specification requirements and is in a stable condition.

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