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Analysis of Slope Excavation Deformation and Stability Under Different Excavation Stages

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***Abstract*—The excavation stage of slope is a common consideration in the actual project, which has a certain impact on the stability and deformation of the slope. Based on this, taking the soil-rock dual slope of a highway in Guizhou as the research background, the finite difference method is applied to simulate the whole process of slope excavation and the validity of the numerical simulation is verified by comparing with the field monitoring data. The influence of excavation stages on slope displacement field and stability factor of safety is further discussed. The results show that increasing the number of stages can effectively improve the stability and reduce the displacement value during slope excavation. However, after the excavation is completed, there is no significant difference in the stability and displacement of the slope under different excavation stages. It is recommended to increase the number of excavation stages reasonably and appropriately when excavating slopes to ensure excavation stability and reduce the amount of displacement. The relevant research can provide a useful reference for the construction stability analysis, monitoring and design of similar slope projects.**

Keywords-stability safety factor; finite difference method; multistage excavation; field monitoring;

I. INTRODUCTION

In the actual practice of slope excavation engineering, excavation stages, slope ratio, and slope height are all important influencing factors on the stability and deformation of slope excavation process. In-depth understanding of the deformation process of rock and soil body during the excavation, mastering the law of deformation and destruction, and providing a basis for the actual engineering construction, can effectively reduce the landslide disaster in the construction of the project, and is of great significance to ensure the safety of the slope engineering construction.

There is a lot of literature at home and abroad on the stability analysis and research of the slope during construction process. Lu Kunlin [1], Zhang Baolong [2], et al. studied the effect of slope morphology on slope stability. Huang Junhui [3], Zhang Baolong [4], Zhang Qianqi [5], etc. used numerical simulation methods to study the influence of slope height, excavation stages, slope ratio and other factors on slope stability. Shao Yinlong [6], Ye Shuaihua [7], Geng Zhao [8], Su Peidong [9] and others studied the destabilization deformation mechanism and failure mode of different structural types of slopes during excavation.

In the previous research on the stability of slope excavation, various types of slopes have been involved, and there are more studies on the excavation slope ratio and slope height. However, there is relatively little literature that relies on actual soil-rock dual slope excavation projects and explores the effect of excavation stage on slope stability and deformation during multi-stage excavation.

Therefore, this paper takes the soil-rock dual slope of a highway in Guizhou as an engineering example, and uses the finite difference method to simulate the whole process of prototype slope excavation, and compares numerical simulation results with the actual monitoring data to verify the effectiveness of the model. Further study the change characteristics of displacement field of soil-rock dual slope and rocky slope under different excavation stages during multi-stage excavation process, and solve the factor of safety of slope by strength reduction method. Based on this, a proposal is made for disaster prevention and control during the excavation of soil-rock dual slope and rock slope.

II. ENGINEERING BACKGROUND AND FINITE DIFFERENCE METHOD NUMERICAL SIMULATION SCHEME

A. Engineering geological conditions and project overview

The overall terrain of the slope is steep and gentle, and there is a continuous step-like scarps between the middle and upper parts of the slope. The slope cover is mainly composed of silty clay, bedrock is moderately weathered and strongly weathered basalt and limestone. The average annual precipitation is 1133mm, and there is no perennial surface water at the slope. Surface water is mainly surface runoff formed by atmospheric precipitation, which is mainly discharged through atmospheric evaporation and surface runoff. Groundwater is mainly quaternary loose rock pore water and bedrock weathering fissure water, recharged by atmospheric precipitation; leakage along fissures in the lower slopes or low-lying areas. The seismic fortification intensity of the site area is 6 degrees, the engineering site category is class II, the peak acceleration of the ground motion is 0.05g, and the

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characteristic period of the peak acceleration response spectrum of the ground motion is 0.40s.

The maximum height difference between the front and rear edges of the landslide is about 40 m, and the length is about 110 m. The landslide is irregular tongue-shaped on the plane. The average thickness of the landslide body is about 8m, the total area is about 14400 square meters, and the landslide body is about 115200 cubic meters. It is a middle-sized traction landslide. It is designed as a four-level excavation slope, and the slope rates of the first to fourth levels are 1: 0.75,1: 1.00,1: 1.25, and 1: 1.25, respectively.

Figure 1. Construction site of slope

B. Calculation conditions

In order to verify the validity of the model, i.e., to compare the numerical simulation results with the monitoring data, combine the geological exploration data to design the model corresponding to the prototype slope, i.e., condition no. 1. The conditions 2~11 is designed to further explore the characteristics of the displacement field and the change of factor of safety in the multi-stage excavation of soil-rock dual slope and rock slope under different excavation stages. To ensure a single variable, all excavation slope ratio is 1:1 and the excavation range is consistent. The specific numerical calculation conditions are shown in Table 1. The displacement field used in the following analysis is obtained by using the software solve statement; the factor of safety and the maximum shear strain increment cloud diagram are obtained by the strength reduction method built in the software.

TABLE I. NUMERICAL CALCULATION CONDITIONS

Number	*Excavation stage*	*slope type*
1	Four stage	Prototype
2	Three stage	Soil-rock dual slope
3	Four stage	Soil-rock dual slope
4	Five stage	Soil-rock dual slope
5	Six stage	Soil-rock dual slope
6	Seven stage	Soil-rock dual slope
7	Three stage	Rock slope
8	Four stage	Rock slope
9	Five stage	Rock slope
10	Six stage	Rock slope
11	Seven stage	Rock slope

C. Calculation parameters

Combining the engineering background and geological investigation data, and referring to relevant engineering codes and manuals, the parameters are formulated as shown in Table 2.

TABLE II. NUMERICAL CALCULATION PARAMETERS

Number	*Density*	*Young's modulus*	*Friction*	*Cohesion*	*Poisson ratio*
	kN/m3	*MPa*	°	*kPa*	
Soil	***18***	***8***	***18***	***25***	***0.4***
Dual slope rock type 1	***23***	***250***	***35***	***45***	***0.35***
Dual slope rock type 2	***28***	***1250***	***45***	***350***	***0.25***
Rock of rock slope	***23***	***250***	***35***	***45***	***0.35***

D. Calculation models

The three-dimensional numerical calculation model is established with the help of $FLAC^{3D}$, a large geotechnical numerical simulation software, as shown in Figure 2 (condition 1). The model for conditions 1 has 7908 nodes and 4098 cells; the dimensions are 150m×1.25m×90m. The models for conditions 2 to 11 have 7757 nodes and 4084 cells; the dimensions are 150m×1.25m×90m.

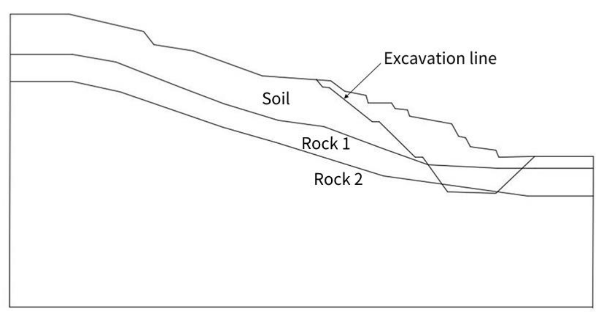


Figure 2. Numerical calculation model

III. VALIDATION AND ANALYSIS OF THE NUMERICAL SIMULATION RESULTS OF THE PROTOTYPE SLOPE

A. Comparison of the results of actual monitoring and numerical simulation

In the actual project, surface displacement monitoring equipment (BeiDou GNSS monitoring station) was set up on the second platform and the top of the slope to monitor the surface deformation of the slope. Deep displacement monitoring was carried out on the third platform. The data from the valid monitoring points on site were selected and compared with the numerical simulation results of the corresponding monitoring points, as shown in Figure 3. Comparing the horizontal displacements of the surface displacement monitoring, it can be seen that the difference is small, no more than 5 mm. The upper sensor in the deep displacement monitoring data differs from the numerical simulation by approximately 50 mm, while the middle and lower sensors differ from the numerical model by 5 mm and 1 mm respectively. The reason for the large discrepancy between the monitoring data and the numerical simulation in the upper part of the deep displacement monitoring is that the sensor is very close to the soil-rock interface, an area of sharp displacement changes.

It can be seen that the difference between the actual monitoring data and the results of the numerical simulation is small, and the numerical simulation matches well with the actual monitoring results, indicating that the establishment of the numerical calculation model and the selection of parameters, etc. and the analysis of the factors affecting the stability of slope excavation carried out based on this are reasonable and reliable.

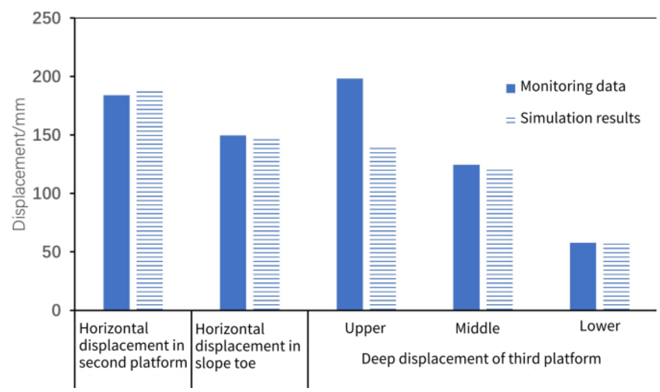


Figure 3. Comparison of monitoring data with numerical simulation results

B. *Analysis of numerical simulation results*

During the excavation of the prototype slope, the excavation area in the first step is small, and the overall displacement of the slope body is concentrated in the shallow surface soil body; the excavation in the third step forms two levels of higher free slope, and the position of the maximum horizontal displacement corresponds to the second level slope body, and there is an obvious partition interface at the soil-rock intersection. In the fourth step, when excavating the underlying rock body, the displacement of the overlying soil body has a certain growth, and the displacement of the rock body is relatively small. The cloud diagram of the horizontal displacement of the completed slope body is shown in Figure 4(a).

Figure 4(b) shows the cloud diagram of the maximum shear strain increment after the excavation is completed. The maximum shear strain increment zone of the slope is vertically above the soil-rock interface, the shear outlet is located at the foot of the second stage slope, the concentration of the foot of the first stage slope is smaller, and the shape of the increment zone is controlled by the soil-rock interface.

Through the change of the maximum shear strain increment zone combined with displacement analysis, it can be deduced that the destabilization mode of the soil-rock dual slope during excavation is that the leading edge is excavated, loses support, and the soil slides out along the soil-rock intersection, which is a traction landslide, and the structural characteristics and lithology of the stratum determine its destabilization mode; this conclusion is consistent with the conclusion reached by using engineering geological analysis, which again verifies the validity of numerical simulation analysis.

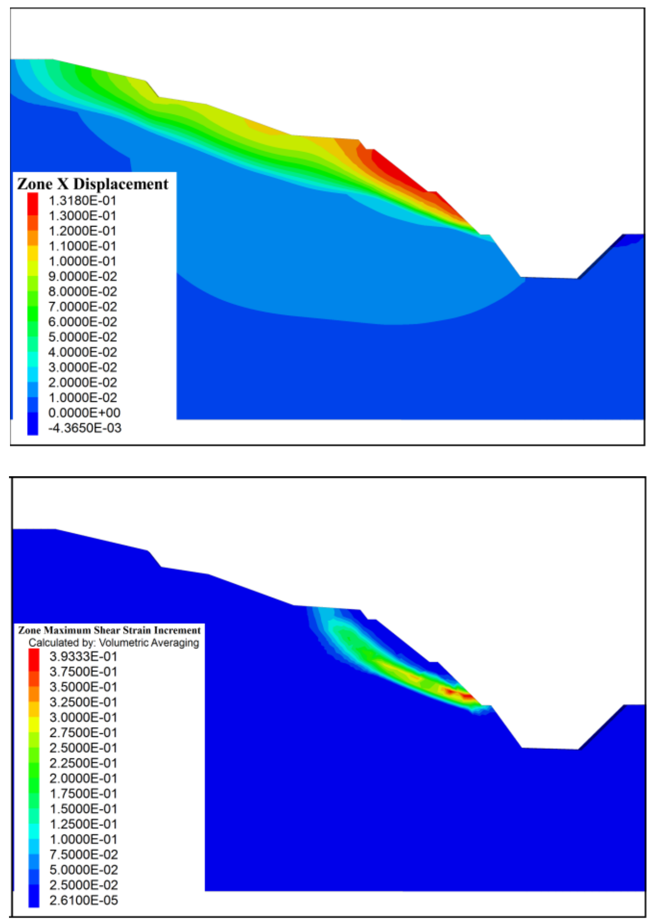


Figure 4. (a) Horizontal displacement after excavation(unit :m); (b) Maximum Shear Strain Increment Contour after excavation

IV. INFLUENCE ANALYSIS OF EXCAVATION STAGE

As an important factor of slope design and construction, excavation stage has a certain influence on slope stability and deformation field. In the following, through the numerical simulation method, by comparing and analyzing the factor of safety, maximum shear strain increment and displacement field of homogeneous rock slope and soil-rock dual slope during excavation, the influence law of excavation stage on the excavation process of slope is obtained, which provides theoretical support and practical guidance for similar projects.

A. *Homogeneous Rock Slope*

The change trend of factor of safety of the rock slope excavation process is shown in figure 5(a), and the overall change rule is gradually decreasing. The more excavation stages, the greater the factor of safety. However, the difference of factor of safety is mainly reflected in the excavation process, and the difference of factor of safety after excavation is very small.

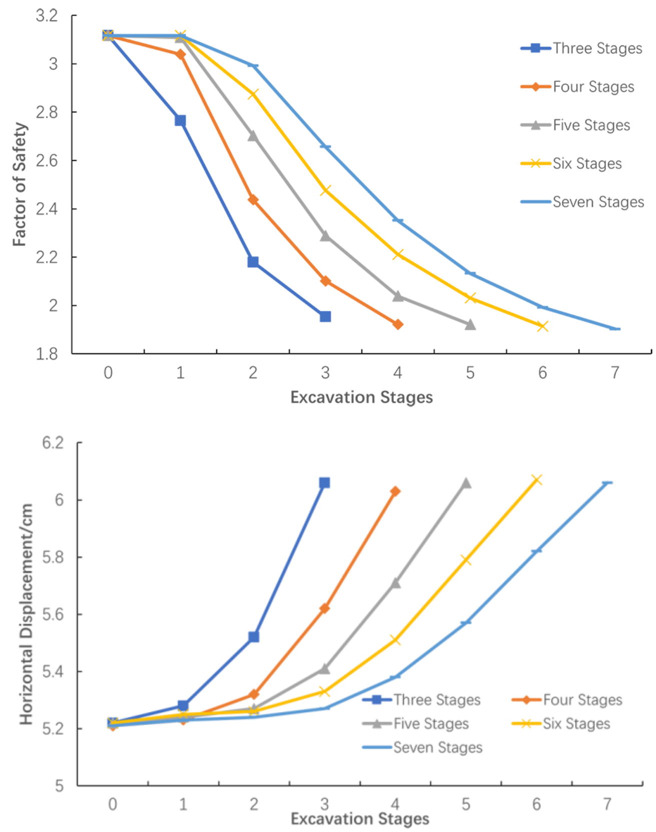
Comparing the maximum shear strain increment cloud diagram of rock slope under different excavation stages conditions, it is found that the distribution of the maximum shear strain increment band is not affected by the stage. After the excavation is completed, the shape of the maximum shear strain increment zone is consistent under different excavation stages. The right edge is located at the toe of the excavation slope and extends in an arc shape to the top of the slope. The maximum shear strain increment cloud map after the excavation of the rock slope is shown in Fig.5 (b) (taking the calculation condition 3 as an example).

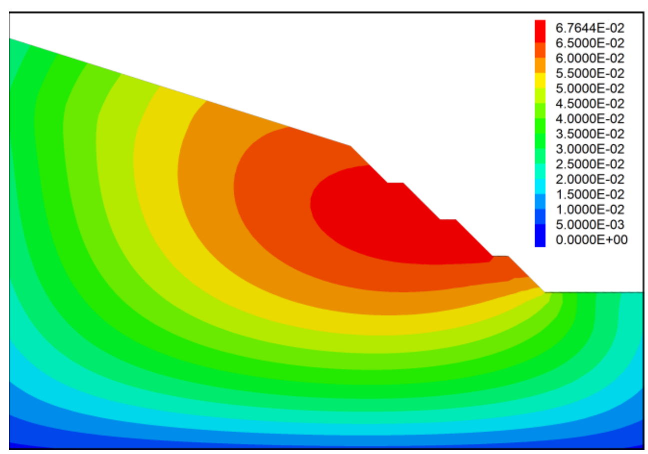
As a characteristic point of slope deformation, the slope top is often used as the layout point of displacement monitoring facilities in practical engineering and the monitoring point in numerical simulation to analyze the deformation of slope. The curve of the horizontal displacement of the slope top monitoring point of the rock slope with the excavation is shown in Fig.5 (c). It can be seen that the overall trend of the curve is gradually increasing, the early change is slow, and the displacement increases rapidly with the excavation. Comparing each curve, it can be seen that with the increase of the excavation stages, the horizontal displacement gradually becomes smaller. The difference is very small after the excavation.

By comparing the displacement cloud diagram of rock slope during excavation, the characteristics are consistent, and there are only some differences in value, indicating that the excavation stage has no effect on the mechanism and range of slope deformation. The cloud diagram of the calculation displacement after the excavation of the rock slope is shown in Fig.5 (d) (taking the calculation condition 3 as an example), and it can be seen that the displacement contour is arc distribution. The largest horizontal displacement occurs in the middle of the slope, and the displacement to the slope becomes smaller. There are some differences in the horizontal maximum displacement under each working condition, but the difference is small. The minimum is 6.76 cm of the four-stage excavation, and the maximum is 6.85 cm of the five-stage excavation.

The reason for the decrease of the factor of safety is that with the excavation, the free slope surface is formed, the slope toe loses support, and the excavation disturbance stress release and displacement adjustment, the potential deformation is cut out at the toe of the slope, and the slope body continues to deform during the last step of excavation, resulting in a continuous decrease of the factor of safety.

At the displacement level, under the condition of the same excavation range, the more stages the excavation is divided into, the less the volume of each excavation is, the shorter the free slope is, and the smaller the disturbance to the slope is. Therefore, in the process of rock slope excavation, with the increase of excavation stages, the displacement of slope in each step of excavation is smaller. After the excavation is completed, because the volume of the excavation is consistent, there is little difference in the displacement of the slope after the excavation is completed.





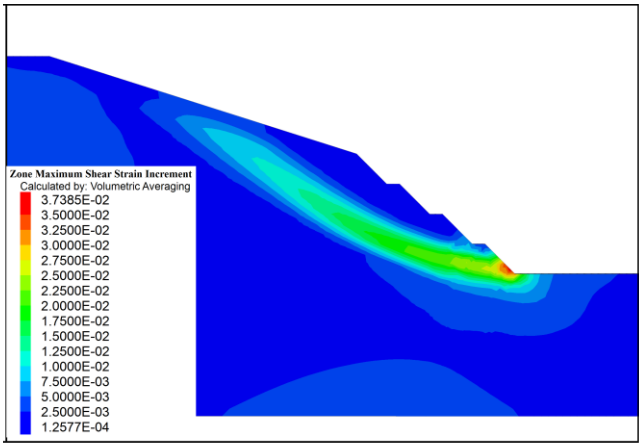


Figure 5. (a) Excavation stage - safety factor; (b) Excavation stage - Horizontal displacement;(c) Horizontal displacement after excavation(unit :m);(d) Maximum Shear Strain Increment Contour after excavation

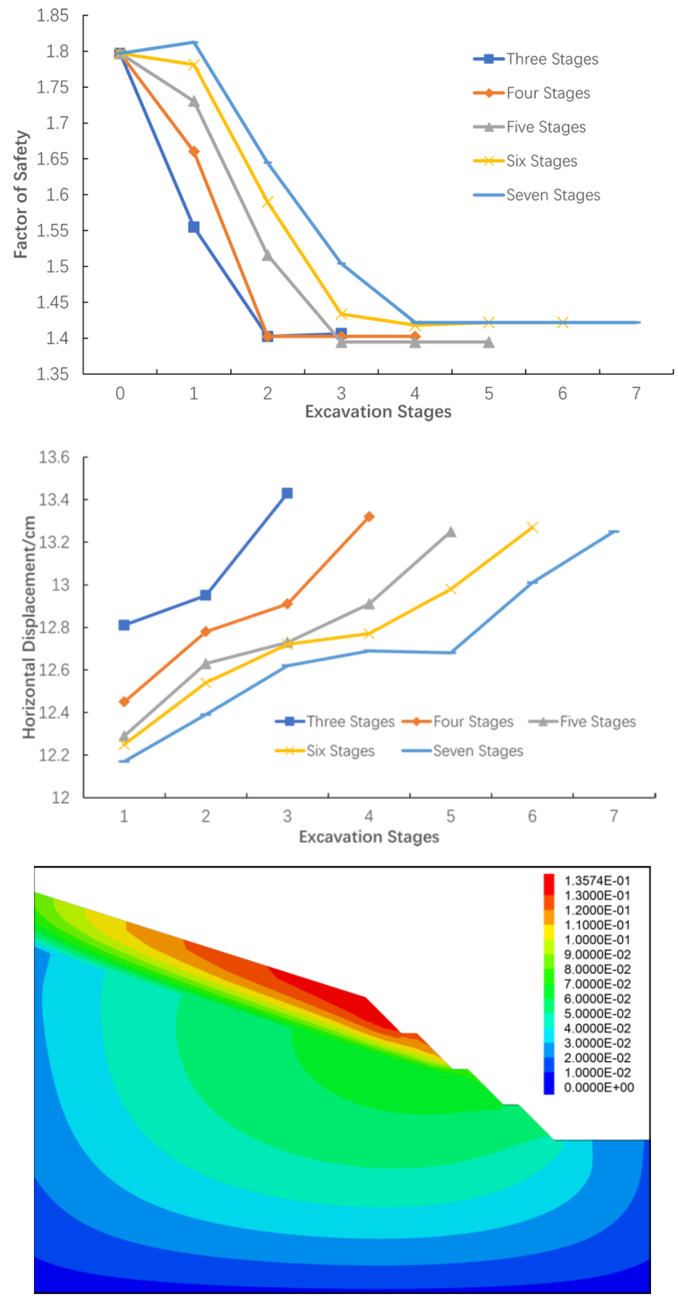
B. Soil-rock Dual Slope

The change of factor of safety in the excavation process of the soil-rock dual slope is similar to rock slope. As shown in figure 6 (a), the law of the overall change of the curve is reduced to stable. The difference is that the factor of safety of the soil-rock dual slope tends to be stable in the last few steps of excavation; it decreases when excavating overlying soil and remains unchanged when excavating rock mass.

Comparing the maximum shear strain increment cloud diagram of soil-rock dual slope under different excavation stages, it is found that the distribution of increment zone is not affected by the excavation stages. The maximum shear strain increment cloud map after the slope excavation is completed is shown in Figure 6 (b) (taking the calculation condition 8 as an example). The right edge of the maximum shear strain increment zone is located above the soil-rock interface in the slope and controlled by it, distributed in a straight line, and extended to the top of the slope in an arc shape at a deeper depth.

The change curve of the horizontal displacement of the monitoring point at the top of the soil-rock dual slope during the excavation is shown in Figure 6 (c). The change trend of the curve is overall growth. Different from the rock slope, the curve corresponding to the excavation of four, five, six and seven stages increase slowly in the middle period and increases rapidly in the early and late periods. The difference of each curve is the same as that of rock slope. With the increase of excavation stages, the horizontal displacement decreases gradually during excavation. After the excavation is completed, the difference is small, which is ' concave '. When the excavation is completed in five stages, the displacement of the slope top monitoring point is the smallest.

By comparing and observing the cloud diagram of horizontal displacement in the excavation process of soil-rock dual slope, the characteristics are consistent, indicating that the excavation stage has no effect on the mechanism and range of slope deformation, and only has some differences in value. The cloud diagram of the horizontal displacement after the completion of the slope excavation is shown in Fig.6(d) (calculation the working condition 8 as an example). It can be seen that the soil-rock interface is a clear dividing line. The displacement of the overlying soil is large, and the shallow soil slides out along the soil-rock interface, while the displacement of the deep soil is small. The displacement value of the rock after the formation of the free slope surface is also relatively small. With the increase of stages, the sliding range of soil has no obvious change, but the maximum value of free displacement decreases from 13.73 cm to 13.46 cm.



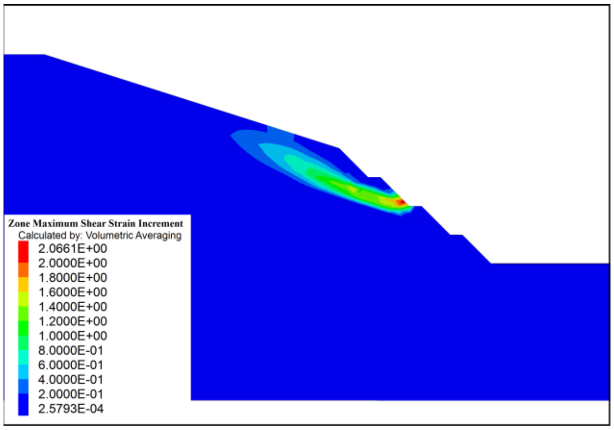


Figure 6. (a) Excavation stage - safety factor; (b) Excavation stage - Horizontal displacement;(c) Horizontal displacement after excavation(unit :m);(d) Maximum Shear Strain Increment Contour after excavation

In the process of soil-rock dual slope excavation, the factor of safety is reduced first, the same as rock slope. After the excavation is completed, combine the maximum shear strain increment zone with the displacement cloud map to infer that the potential sliding surface of the slope is still located in the soil and is above the soil-rock interface. It can be seen that the deformation of the slope is that the overlying soil slides out from the shear outlet along the soil-rock interface, with only a small displacement. The underlying rock can remain stable during the excavation process; therefore, the factor of safety remains stable.

At the level of calculation theory, the physical and mechanical parameters of soil and rock are quite different and the strength of soil and rock is reduced at the same time. After the excavation is completed, the soil has been destroyed before the rock loses stability due to the strength reduction, the higher free slope surface and the slope toe lose support, and the calculation reaches the termination condition, so the calculated factor of safety will remain unchanged. The displacement of the slope verified that the rock slope did not have a large displacement, and confirmed the correctness of the factor of safety results based on the strength reduction calculation and the validity of numerical simulation analysis.

V. SUMMARY

By researching the influence of excavation stages on the stability and displacement field of rock slope and soil-rock dual slope during excavation, the following conclusions are drawn within the scope of this study: ① Increasing the excavation stages can reduce the displacement of slope during excavation process and make the factor of safety larger, but it has no effect on the deformation mechanism of slope. After the excavation, the deformation and factor of safety of the slope are not affected by the excavation stages; ② When excavating the lower part of rock mass of soil-rock dual slope, the displacement value of rock mass is small, and the factor of safety of slope is stable.

Based on the above results, suggestions for excavation, support and monitoring in similar slope projects are proposed: ① Under the condition that the excavation range is consistent and the total amount of excavation is constant, appropriately increasing the number of excavation stages to improve the stability of the slope during excavation and reduce the deformation of the slope. ② When excavating the soil-rock dual slope, because the rock mass can still maintain high stability during the excavation process, when designing the slope deformation monitoring scheme, more attention should be paid to the overlying soil, and relatively more monitoring facilities should be arranged in the overlying soil.

Since the rock and soil structure has a significant impact on the stability of the slope, in the subsequent research, the influence of different design factors should be explored for different structural types of slopes.

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