Simulation study on rock slope reinforced by anti-slide pile: a case study

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Abstract: For the collapse of bedding rock slope in Yuqian Expressway, by using simulation software FLAC-3D this paper established simulation models bedding rock slope before and after reinforced by combined supporting, i.e., “slide-resistant pile+ diagonal bracing wall+ anchor cable”, and collected parameters such as deformation and shear stress through three monitoring points established. As simulation results compared with field monitoring data, bedding rock slope before reinforced was unstable, belonging pull-type failure model, and this failure model was sudden; the displacement contour map after the slope was reinforced by combined supporting showed that there existed one bigger shear zone in the rock interface, and the shear zone was disappeared after this slope was reinforced, then maximum deformation was decreased; the displacement vector map of slope showed that this slope slipped along the rock interface before it was reinforced, but the whole slope slid along one arc after it was reinforced; shear stress concentration phenomenon in the rock interface was disappeared obviously after this slope was reinforced. As monitoring deformation compared with simulation deformation, slope deformation was less; and the slope was stable; the reinforcement measure of combined supporting has the better retaining effects.

1. Introduction
Bedding rock slope is a rock slope with a dip angle of the rock layer that is close to or consistent with the dip angle of the slope. The excavation caused the excavation of the highway is very common in the southwestern region, and it has a serious impact on the construction and operation of the motorway. At present, there are many engineering and technical measures for remediation of bedding rock slope disasters, such as anti-slide piles [1], anchor rods [2], prestressed anchor cables [3], retaining walls [4], etc. The engineering cases of supporting measures to deal with bedding rock slope disasters are rare, and the slope evaluation methods before and after treatment are not complete. Therefore, it is urgent to carry out research on the reinforcement of bedding rock slope by combined support structure [5].

2. Engineering background

2.1. Project Introduction
The Yuqian road RK1058+500–RK1058+650 section is a roadside slope with a slope length of 75m.
The height is about 15–45m. The expressway has a roadbed width of 24.5m and a two-way four-lane road. The original slope design adopts 1:0.5 grading treatment and there is no protective measures. On April 28, 2014, a small amount of collapse occurred in the middle part of the slope, the square volume was about 1000m$^3$, and the collapsed body was massive sandstone. The largest bulk volume was more than 60m$^3$. After the instability, the sandstone block in the middle of the slope produced a thickness of about 8m., and the unloading crack appears in the joint crack surface along the side slope. Under the combination of the sandstone layer and the joint fissure, the sandstone in the middle of the slope forms a separator, which may slide and become unstable at any time, as shown in Figure 1(a). At about 2 am on April 29, 2014, the sandstone block in the middle of the slope (shown in Figure 1) was further collapsed and unstable along the mudstone contact surface. The largest block was 4×4.5×4.5 m and the collapse amount was about 2000 m$^3$. As shown in Fig. 1(b), the unloading crack distribution is found at the top of the slope at the same time. Several collapsed blocks are piled up on the slope, and dangerous rock mass is formed in the upper part of the slope, which may further destabilize. Continued collapse will result in a two-way closure of the Yuqian highway, causing serious economic losses and extremely adverse social impacts. On April 30, 2014, in order to ensure the safety of traffic and the safety of construction personnel and equipment, the owner carried out the blasting and removal work of dangerous rock mass, and the removal amount was about 300m$^3$, as shown in Figure 1(b). During the blasting process at the top of the slope, an unloading crack with a penetration depth of about 4 m was found, and the unloading crack did not penetrate the mudstone contact surface. After blasting part of the dangerous rock mass, the hidden dangers of the upper dangerous rock for construction safety is improved.

![Figure 1. Full view of the slope](image)

2.2. Analysis of the damage mechanism

The tendency of the layered structural plane of the rock slope is less than the inclination of the slope. When the layered structural surface, especially the weak structural surface, is exposed to the slope due to engineering activities, it forms a potential sliding surface. It is easy to form a slip. Such slope damage can be attributed to the type of slip damage, that is, the slope body slides down the slip surface in different ways, or the disintegration is a block-like caving.

After the slope collapse and slippage studied in this paper, sandstone dangerous rock mass is formed on the slope surface, which is in an unstable state. Once the trailing edge unloading crack penetrates, under the continuous influence of atmospheric rainfall, the slip surface strength value will continue to decrease. If it is not treated in time, the sandstone experience will fall again along the structural plane, forming a secondary collapse disaster, which poses a great threat to road safety. Once destabilized, it will lead to the continuous disconnection of the Yuqian expressway, which will bring great interference to the economic and social development of the two places. Therefore, in order to ensure the safety of roads, ensure social stability and economic development, the instability will be permanent. Sexual governance projects are very urgent and necessary.

3. Joint support measures and model establishment

3.1. Joint support measures

According to the comparison and selection of the plan for the bedding rock slope of the Yuqian expressway, the joint support measures of “anti-slide pile + diagonal wall + anchor cable” were
established, as shown in Figure 2. According to the stability calculation, the design sliding force of the bedding rock slope reaches 720kN/m, and only the anti-slide pile or anchor cable is difficult to bear the residual sliding force of the bedding rock slope, and the bedding rock edge below the slope is the Yuqian expressway, the section area of the anti-slide pile should not be too large. Therefore, considering the comprehensive consideration, the joint support measures of “anti-slide pile + diagonal wall + anchor cable” were selected. The anti-slide pile and the anchor cable play a combined anti-slide role, and the diagonal bracing wall can transfer the remaining sliding force that the anchor cable fails to support to the anti-slide pile. The specific dimensions and related parameters are as follows:

Figure 2. Combined supporting engineering sketch map of bedding rock slope in Yuqian expressway(unit: m)

1) Anti-slide pile: anti-slide pile adopts round section anti-slide pile with a diameter of 2.0m, pile length is 12.0~22.0m, pile spacing is 4.0m, HRB400 steel bar is adopted, pile body adopts C30 concrete, mechanical hole forming process;

2) Anchor cable: The anchor cable adopts 6φ15.2 steel stranded wire, the vertical row spacing of anchor cable is 2.5m, the horizontal spacing is 3.0m, the length of anchoring section is 10.0m, the anchoring force is designed to be 350kN, the M30 cement mortar is poured, and the drilling diameter is 150mm. The anchor pier structure is adopted, the anchor pier is made of C30 concrete, and the HRB400 steel bar is adopted. The anchor pier size is 1.0m*1.0m, the height is 60cm, and the embedded rock is not less than 35cm;

3) Diagonal bracing wall: The supporting inclined column is cast by C30 concrete, and the structural steel bar is evenly arranged along the circumference of the column. The HRB400 steel bar with a diameter of 25 is used, the spacing is 250mm, and the stirrups are made of HRB400 steel bars with a diameter of 12, with a spacing of 200mm.

3.2. Model establishment:
In order to study the deformation and failure rule of the bedding rock slope of the Yuqian expressway before construction and the supporting effect of the joint support structure after construction, the FLAC-3D simulation software was used to establish the simulation model before and after the construction, the model mainly consists of the upper sandstone stratum, the lower mudstone stratum and the structural plane. It is imported into ANSYS software and adopted by CAD drawing, and then transferred to FLAC-3D to mesh the pre-construction slope model. Dividing, and then using the anchor cable unit, the elastomer unit, and the pile unit for joint support simulation, as shown in Figure 3.
The constitutive model used in the simulation is the Mohr-Coulomb model. The physical and mechanical parameters of sandstone, mudstone, structural plane, anchor cable, diagonal bracing wall and anti-slide pile in Figure 3 are shown in Table 1 and 2.

| Mechanical parameter                      | Mudstone | Sandstone | Structural surface |
|------------------------------------------|----------|-----------|--------------------|
| Bulk modulus (GPa)                       | 75       | 100       | -                  |
| Shear modulus (GPa)                      | 27       | 30        | 25                 |
| Internal friction angle (°)              | 35.15    | 44.67     | 20                 |
| Cohesion (MPa)                           | 1.81     | 5.47      | 0.3                |
| Strength of extension (MPa)              | 0.41     | 1.38      | 0.3                |
| The normal stiffness (MPa/m)             | -        | -         | 10                 |
| Shear stiffness (MPa/m)                  | -        | -         | 10                 |

| Mechanical parameter                      | Anchor cable | Brace wall | Anti-slide pile |
|------------------------------------------|---------------|------------|-----------------|
| Elasticity modulus (GPa)                 | 200           | -          | 80              |
| Stiffness (GPa/m)                        | 10            | -          | 130             |
| Internal friction angle (°)              | 25            | 35.15      | 10              |
| Cohesion (MPa)                           | 200           | 1.9        | -               |
| Strength of extension (MPa)              | 10000         | 1.38       | -               |
| Physical modulus (GPa)                   | -             | 530        | -               |
| Poisson's ratio                          | -             | -          | 0.3             |
| Shear modulus (GPa)                      | -             | 320        | -               |

4. Numerical simulation and comparative analysis before and after joint reinforcement

4.1. Deformation law of slope before reinforcement

From the simulated displacement curves of Figure 4, it is known that the simulated slope displacement curve is basically consistent with the monitoring data, which increases sharply in a short period of time, accelerates in the later period, and tends to a stable value. The only difference is that the monitoring point 1 and the monitoring point 2 monitor the displacement curve undergo a slow growth process, while the monitoring point 1 and the monitoring point 2 simulate the displacement curve undergo a process of decreasing and then significantly increasing, which is due to the structural plane of sandstone and...
mudstone. The shear displacement is mainly generated. When the displacement reaches a certain value, the continuity of the FLAC-3D deformation mesh hinders the deformation process of the structural surface, resulting in a downward displacement of the front edge of the structure, which in turn drives the deformation displacement of the monitoring point 2. When the deformation of the mesh is large, the original shape of the mesh is changed, and the displacement is rapidly increased, showing a sharp increase. For the monitored displacement and simulated displacement of the monitoring point 3 of Figure 4, the curves are substantially similar.

For the monitoring displacement and simulated displacement of the three monitoring points, the maximum displacement data are not much different. Although the displacement data of the three monitoring points are stable, it does not mean that the slope tends to be stable, because FLAC-3D cannot produce a damaged mesh. Therefore, for a hard rock slope, the displacement of 2.69 cm is enough to cause the slope to collapse. At the same time, the phenomenon of collapse of bedding rock slope occurred during the on-site monitoring process. The bedding rock slope of the Yuqian expressway is in an unstable state and needs to be treated urgently.

From the monitoring displacement and the simulated displacement, it can be found that the displacement curve sharply increases in a short time, undergoes a slow growth phase, and then rapidly increases, eventually reaching a stable value. It can be seen that the bedding rock slope is rapidly deformed under the condition of the lower part of the rainfall, and the tensile strength of the rear rock mass is slowly increasing. When the tensile strength of the slope cannot withstand the deformation of the rock mass, sudden damage occurs during strength, so it can be concluded that this slope belongs to the traction bedding rock slope, and the damage is sudden.

4.2. Evaluation of slope treatment after combined support and reinforcement

4.2.1. Comparative analysis of slope displacement before and after joint support reinforcement. Figure 5 is the contour map of the displacement before the slope reinforcement. It can be found that the deformation of the slope body is down to the slope. The deformation at the interface of the rock layer is the largest, reaching 2.08cm, and a large shear is formed at the interface of the rock layer. The deformation of the slope after the crack at the trailing edge of the slope is small, and the deformation is between 0.75cm and 1cm, which produces a significant displacement separation from the leading edge slope. As shown in Figure 5, after the slope is reinforced with the joint supporting structure, the contour map of the displacement of the slope is obviously deflected, and there is no obvious shearing surface at
the interface of the rock stratum; Under the combined action of “anti-slide pile + diagonal wall + anchor cable”, the displacement at the foot of the slope is small, only 4mm–6mm, and the deformation of the trailing edge slope is large under the action of gravity, up to 1cm~1.2cm. The joint support structure effectively restrains the further deformation of the slope, and the maximum deformation is reduced from 2.08cm to 1.2cm, which can prevent further slip deformation of the slope.

From the vector diagram of the slope displacement before and after the reinforcement of the joint supporting structure in Figure 6, the displacement before the reinforcement is along the oblique slope of the rock interface, and the direction is basically parallel with the interface of the rock stratum. The maximum displacement rate is $1.268 \times 10^{-8}$. The deformation rate of other parts of the slope is basically 0; After the joint support structure is strengthened, the direction of the slope displacement vector diagram changes, the deformation rate of the upper part of the slope is larger, the lower part is smaller, and the maximum displacement rate is $2.07 \times 10^{-9}$. The reinforcement of the anchor cable and the anti-slide pile acts to combine the lower and rear slopes, thereby reducing the deformation of the leading edge slope and reducing the deformation rate of the slope. From the displacement vector diagram before and after the reinforcement of the joint support structure, the joint support structure can effectively reduce the displacement deformation rate and play the role of reinforcing the bedding rock slope.

### 4.2.2. Comparative analysis of slope deformation and on-site monitoring data after reinforcement.

In order to test the effect of the joint support construction, the slope after construction (Figure 7) is quantitatively monitored. Comparing the monitoring displacements of the slope foot monitoring point 1, the slope top monitoring point 2, the trailing edge monitoring point 3 and the simulated displacement, it is found that the monitoring displacement and the simulated displacement are basically similar, and the effect is good, the displacement curves of the three monitoring points all showed a tendency of becoming stable after increasing rapidly. The displacement value of the slope monitoring point 1 is small, the maximum is 4.2mm; The displacement value of the slope top monitoring point 2 and the trailing edge monitoring point 3 is large, and the maximum value is 9.8mm and 11.9mm. At the same time, the gap between the monitoring displacement and the simulated displacement is small, which meets the engineering requirements, and the combined supporting structure can better support the bedding rock slope.
5. Conclusion

(1) The FLAC-3D model before and after the reinforcement of the bedding rock slope along the Yuqian Expressway was established. Three monitoring points were set up to collect the displacement and shear stress and other parameters of the bedding rock slope before and after the anti-sliding key reinforcement. Compared with the on-site monitoring data, it was found that the maximum displacement of the slope before reinforcement reached 2.69 cm and was in an unstable state. It was concluded that the slope belonged to the traction failure mode and was sudden.

(2) The frontal displacement contour map of the slope with anti-sliding key reinforcement shows that a large shear zone is formed at the interface of the rock stratum, and the shear zone disappears after the reinforcement, and the deformation is reduced; The displacement vector diagram of the slope shows that the slope slides along the rock interface before reinforcement, and the slope is stable when the reinforcement is completed. The shear stress concentration on the interface of the rock layer disappears obviously after reinforcement. The comparison between the field monitoring displacement and the simulated displacement after reinforcement shows that the slope deformation is small and in a stable state.

(3) The design data of anti-slide piles, diagonal bracing walls and anchor cables are larger than the simulated data, and all of them have not yielded. The joint support structure reinforcement measures have better-supporting effect.
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