Anchorage design analysis and field monitoring of large key blocks in high and steep rock slope

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Abstract: One of the main failure modes of rock slope is the instability of the key block formed by cutting combination of structural planes. In view of the block stability and control problem caused by the combination of structural planes in the high and steep rock slope in Southwest China, the key block theory method and on-site monitoring method are used to study the stability of the key block after the excavation of the slope, the optimization of the design parameters of anchor cable support, and the deformation characteristics and change laws of the slope with the construction process are analyzed. The research results show that the large block formed by the discontinuity layer and layer fracture of the slope reaches 26000 m³, sliding along the structural plane on both sides, with low safety factor. The safety monitoring data show that the block is stable after the reinforcement with anchor cable.

Key words: slope engineering; key block theory; optimization design; anchor cable; field monitoring

1. Introduction
The rock mass has certain structural characteristics. There are different types and scales of structural planes in the rock mass, including faults, planes, staggered zones, joints and fissures. The spatial combination of various structural planes forms the rock mass structure. The rock mass structure controls the deformation, failure and mechanical properties of rock mass.

The large-scale slope engineering of hydropower project takes rock mass as engineering structure. In the support design idea, it is required to give full play to the strength and bearing capacity of rock mass itself. Due to the complex variability of the development of rock mass discontinuities and the incomplete information of early exploration, the large block formed by the combination of discontinuities in the layered excavation process of large-scale slope is not easy to be predicted and found in time, This kind of block is easy to cause rock deformation and failure, even large collapse, threatening the safety of the project.

Since Shi Genhua and Goodman put forward the Key Block Theory, the theory has been widely used in fractured rock engineering, and a lot of important research progress has been
made. However, most of them focus on the analysis and prediction of random block and semi positioning block before excavation or in the stage of test tunnel, which is lack of pertinence. In the process of large-scale slope construction, it is closely combined with geological analysis, design and monitoring, There are few reports about block analysis integrating dynamic design, prediction and timely adjustment. This paper introduces the key block theory, fine construction geological description and deformation monitoring method, which is applied in the dynamic anchoring support, feedback and regulation of step-by-step excavation of large slope engineering. It is fully applied in the high slope of Wudongde Hydropower Station in Southwest China to ensure the stability of the high slope.

2. Key Block Theory
The core of the key block theory can be attributed to finding the key blocks on the excavation free face. For the rock engineering which requires to maintain the stability of excavation, the engineering treatment measures should be taken before the unstable key blocks are completely exposed in the excavation process to keep them stable.

(1) Full space stereographic projection
Different from the general stereographic projection, the full space stereographic projection is used to extend the projection arc of each group of planes limited in the equatorial circle into a full circle. In this way, each direction of the space corresponds to the point of the projection plane one by one, so as to study the collapse caused by the combined cutting of the upper and lower walls of the spatial structural plane and the free surface on the projection plane.

(2) The finite theorem of block
In the analysis of block theory, each group of structural plane and free surface in space are translated to pass through the coordinate origin, and each space plane will form a series of pyramid with the coordinate origin as the vertex. The purpose of converting a block into a pyramid is to facilitate mathematical analysis. Based on this concept, fracture cone (JP), excavation cone (EP), spatial cone (SP) and block cone (BP) are defined.

The sufficient and necessary condition for a block to be finite is that its fracture cone is a spatial cone: \( JP \subset SP \).

(3) Movable theorem of block
If the block composed of structural plane and free surface is finite and the crack block composed of structural plane is infinite, the block is movable; If the block composed of structural plane and free surface is finite, and the fracture block composed of structural plane is finite, the block is immovable. In other words, the infinite fracture block is the premise of the movable block.

The necessary and sufficient condition for the block to move is: \( JP \neq \emptyset \lor EP \cap JP = \emptyset \).
3. Analysis method of key blocks across multiple layers of high slope

After the movable block is determined by topological method, the mechanical analysis model is established, that is, after the combination of structural plane and the resultant force of active force are known, the movement form of the movable block is judged, and then according to the physical and mechanical characteristics of structural plane, which movable block is the real key block or the block that may lose stability is judged. There are three types of block movement: breaking away from rock mass (falling), one-sided sliding and two-sided sliding. Block theory can be divided into two ways: full space stereographic projection analysis and space vector analysis. The whole space stereographic projection of different structural plane combination and excavation free surface is carried out to analyze the block finiteness and mobility; The types of movable blocks are analyzed, and then the safety factor is calculated according to the residual sliding force of block mechanical analysis to determine the key blocks.

In the process of layered and step-by-step excavation of large slope, after the excavation of the current layer, the stability of key blocks is checked and new key blocks are searched according to the newly revealed structural plane properties and extension changes, and the geological and monitoring information is timely analyzed and sorted out to judge the rationality of the design; If the structural plane of the key block exposed by the next excavation does not extend downward and the block support meets the requirements, the check of the block will be stopped, otherwise the volume, safety and support force of the block will be calculated dynamically, and the spiral cycle operation will be repeated until the end of the whole excavation(See Fig. 2).
4. Project overview

Wudongde Hydropower Station is the lower reaches of Jinsha River in China, with an installed capacity of 10200MW, which is the second largest hydropower station under construction in the world. The project is mainly composed of dam, spillway tunnel energy dissipation, water diversion and power generation system. The dam is a concrete double curvature arch dam with the maximum dam height of 270m. The tailrace outlet slope on the left bank of Wudongde belongs to grade I slope in the project area, with the maximum excavation height of 160m (See Fig. 3~Fig. 4). The rock mass quality of slope is mainly grade III1, and that of fault f1 tectonite and its hanging wall is mainly grade III2~IV1. The slope is very steep, and there is a vertical slope with a height of 55m at the bottom. The rock mass of the slope is thin bedded to interbedded steep bedded structure, and is cut by fault F1 and f1-1; At the same time, three large tailrace tunnels are excavated at the foot of the slope, the local excavation rate of the vertical slope section is high, and the interaction between the excavation of the slope and the cavern is significant. These adverse factors make the safety problems of the slope during the construction period very prominent.

During the excavation of the left bank tailrace outlet slope, there are many phenomena, such as the bedding collapse of shallow rock mass, the cracking of shotcrete layer and rock mass on the slope surface, the deformation of the lower tailrace tunnel top and rock column, and the cracking and deformation of the upper stripping body; The internal and external safety monitoring shows that the blasting excavation in the rock plug section of the lower cavern leads to the rapid growth of slope deformation and the obvious increase of anchor cable supporting force, most of which are 10-30m deep structural plane deformation, and the maximum deformation depth can reach 40m. Geophysical test results show that the unloading relaxation of slope rock mass is very significant, the wave velocity of rock mass is significantly reduced, and the strong unloading relaxation depth of slope is large.
5. Unloading deformation of slope and control effect of structural plane

The deformation of the slope is -1.8-174.0mm, the direction of parallel slope is -1.7-82.4mm, the vertical direction is -0.7-192.8mm, and the vertical slope is outside the slope and the settlement deformation is larger. The monitoring of deep deformation of slope shows that the deformation of the hole is generally -0.35-73.99mm, and the maximum deformation is 83.50mm. Among them, 9 measuring points are over 50mm, accounting for 33.3% of the total. The slope is mostly of structural surface control type. In contrast with the relative relationship between the rock structure surface and multi-point displacement meter in the geological section of the slope, the deformation section in the deep part of the slope is closely related to the deformation of the rock structure surface.

6. Stability analysis of large key blocks across multi-layer of slope

Ze98 block is mainly composed of fault f1 and large steep structural plane T446 (298° -81°) as the sliding surface, the relatively large fracture T1 (201) exposed near the elevation of 900m (89°) (See Fig. 5). As the structural plane is gradually exposed with the layered excavation, the extensiveness of the structural plane is the key factor. In the process of slope excavation, the detailed geological survey is carried out for each excavation step, and the structural plane combination analysis is carried out. Through Analysis of full space stereographic projection (See Fig. 6), the block is a movable block, 000 shape, double-sided...
sliding. Considering the most dangerous conditions, the buried depth of the block in the slope is 41.9m. The volume of block formed by cutting is about 26000 m³ (See Fig. 7). The safety factor of the slope should reach 1.15, and the required supporting force is 63000 kN; The safety factor of the slope should reach 1.25, and the required supporting force is 101000 kN. This will be a huge amount of anchorage support, which is almost difficult to achieve. Along with the excavation process, the author continues to analyze, feedback and optimize. Finally, due to the limited extension length of large and steep structural plane T446, there is no special reinforcement for the block, but structural anchorage, and the anchorage design is carried out according to the slope deformation.

Fig.6. Full space stereographic projection

Fig.7 Three dimensional shape map of key blocks across multiple layers

7. Slope support scheme and dynamic design adjustment
(1) Excavation parameters: the slope above EL835 is excavated for 15m, with a grade I berm
with a slope of 1:0.3 and a berm width of 3m; The vertical slope below EL850.

(2) Support parameters: two rows of 3ф28mm. L = 12m, with horizontal spacing of 2m;

(3) The slope is systematically supported by 6m / 9m anchor bolts with a row spacing of 2m; Two rows are arranged on the shoulder of each slope, ф28mm, L = 9m locking bolt;

(4) The slope surface is hung with machine-made galvanized wire mesh, and the thickness of C20 concrete spraying is 10cm;

(5) Two rows of 2000kN, 30m system anchor cables (with spacing of 4m) are arranged for each slope x 6m );

(6) Dynamic design adjustment: in order to ensure the stability of tailrace slope, according to the results of slope block analysis and stability analysis, a large number of system long anchor cables and anchor reinforced piles are added on the high slope. In the elevation of 850.5m ~ 880m, the system anchor cables are increased to 2000kN, 60m, with a total length of 112 unbonded prestressed anchor cables. Two rows of 2000kN system anchor cables with L = 40m ,72 system anchor cables are added below elevation 850.5m(See Fig. 8).

![Design drawing of anchor cable for tailrace outlet slope](image)

**Fig. 8** Design drawing of anchor cable for tailrace outlet slope

8. conclusion
Based on the large-scale slope of Wudongde Hydropower Station, the dynamic feedback and design control of local stability of rockmass in layered excavation are studied by using key block theory, fine construction geological description, deformation monitoring and other methods, and the local stability control method of rock structure control in large-scale rock engineering is obtained. The results show that:

(1) The dynamic feedback and process control analysis method of key blocks is a set of local stability analysis method for surrounding rock of slope, which forms a complete set of cycle closed analysis process, including rapid feedback, on-site theoretical calculation, on-site monitoring, inspection and verification, and optimization design.

(2) Similar to Wudongde Hydropower Station, there are large faults, long cracks and extension in large slope, which can form local key large blocks in multiple layers. Slope
excavation has a great disturbance on block structural plane, causing rapid displacement growth, spray layer cracking and other phenomena. With the excavation and structural plane extension, the block boundary is gradually clear.

(3) Combined with the structural plane and surrounding rock deformation, the dynamic feedback and dynamic control of block stability are carried out to effectively ensure the safety and stability of key blocks. The research methods and results can provide a useful reference for the stability analysis and control of local large blocks in rock slope engineering.

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