Random block stability and anchoring design for underground caverns in a hydro-power station

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Abstract: Random blocks in underground tunnels and in grand power caverns are the unstable blocks cut by random joints or fractures in the bedrock. Designers often reinforce these blocks by using systematic anchors however their length and space are difficult to determine because of the randomness of blocks position and the indeterminacy of the blocks geometric characters. By the study of geological conditions and the rock structure of the underground caverns in the hydropower station, the regularities of distribution of the possible random joints were concluded. This enabled the random blocks to be orientated by combining joints with other joints, or combining joints with I and II definite structural planes. The geometric characteristics and stabilities of the random blocks were determined by using stability calculations according to block theory. From this the optimal anchor length could be defined, which could be referred to as a theoretical base for the length of the systematic anchors.

Résumé: Des blocs randoms dans le tunnel sont les blocs incertains qui ont composés par les joints randoms ou les fractures dans le bedrock. Dans les centrales hydrauliques déjà construites, il existe beaucoup de cets blocs. Sa stabilité influence la sécurité de l'exécution des travaux du tunnel. Dans la conception, cets blocs sont souvent renforcés par le jas d'ancrage. Mais, à cause de la randomination de la position et l'indétermination de la caractère géométrique des blocs, il est difficile de déterminer la longueur de jas d'ancrage et la distance de l'ancrage. L'objet basé à étudier le tunnel d'une centrale hydraulique quelconque, sur la base d'étude profondement de la condition géologique et de la caractère de structure de roche, on recherche le règle distribué qui est possible de composer le joint random. Et ensuite, on analyse la combinaison entre les joints, les joints avec la structure déterminée de I et II qui sont possible de former. On obtient les blocs randoms possibles. Fin, on utilise la théorie de roche pour évaluer la stabilité des blocs randoms. On obtient la caractère géométrique et la stabilité des blocs randoms pour résumer la longueur optimale de jas d'ancrage. On livre la férérence théorique de la longueur de jas d'ancrage systématique pour le tunnel souterrain.

Keywords: underground cavern, random block, block stability, systematic anchor, block theory

INTRODUCTION

It is planned to build a dam for a hydropower station, which will be 261.5 meters high, with a power capacity of 5850MW over the Lancang River. The power generation system will be seated inside the left bank, which mainly consists of the major power house (418m×31m×77m), the major switching house (345m×19m×22.6m) and the rear water pressure regulation well. The span and height of the power generation system are amongst the greatest for both the built and planning to be built hydropower stations throughout the world for the current time.

The rock on the left bank dates from the Permian and Triassic periods while the rock above 690-810m comprises sandstone and mudstone. There are F1, F3, F9, F19, F20, F21, F22, F23 faults in the research area, and so on, among which F1 and F3 are the largest. Also, there are lots of discontinuous planes throughout the complex rock mass structure. So according to the systematic analysis of the earth stress, the greatest principal stress is 6.55-11.41Mpa, and the direction of strike, between which and the factory building axis direction is less than 20°, is nearly N20°-65°E.

The natural unexcavated rock in a state of field stress, which is formed by self-weight and tectonic activity, is relatively stable however, it will become unstable when the tunnel is excavated and the stress of the surrounding rock is redistributed, furthermore, the larger the tunnel, the wider the range of influence. This is especially so in the case of a large size tunnel, where the redistribution of stress will have a major effect upon the stabilities of the surrounding rock. .Rock mass is a structure composed of rocks containing many structural planes. During and after excavation of the underground tunnel, the unstable or possibly unstable blocks will be made up of several groups of structural planes and because of the free face existence of some blocks will bring serious danger to the underground construction. So, the block's location, geometric shape, interrelation's definition of the blocks, the underground structure, and block stability criterion are the main problems for design and construction of the wide-span underground factory building with the rock structural feature being the basic factor which produces blocks and controls block stability.

STRUCTURAL PLANES CLASSIFICATION AND ENGINEERING PROPERTY

From studying the process of structural plane building and tectonic reworking, the author investigated lots of structural planes on site and classified the exposed structural planes in conjunction with setting up a property description system for closely studying the engineering geological properties and the engineering effects.

The structural planes are mainly divided into three types according to the difference of their macro properties, i.e. controlling fault or packing plane, general fault or unpacking plane and fitfully extended plane, which correspond to structural plane type I, II and III respectively.

Structural plane Type I: Controlling fault; the features of the fracture surface are continually distributed with some thick soft filling, therefore its mechanical effect and strength are controlled by the filling's properties and thickness, such as F1, F3, F9, F19, F37.

Structural plane type II: General fault, including exposed small faults, zone of tensile fracture and excursion-crushed zone, which is usually distributed discontinuously, so its mechanical property is commonly controlled by its side's geometric property and material's quality.

Structural plane type III: mainly involved in all kinds of discontinuously extending fractures, this type exists largely in rock and is randomly distributed and was generally a solid plane with no fillings of semisolid plane with a small thickness (<1mm). According to the size, it could be further divided into III-1 long-large size fissures and III-2 random fissures. These fissures mostly exist in the research district, i.e.108 strips III-1 and 2000 strips III-2 fissures in the power house.

Table 1. Geological properties of typical type I Joint

Number	**Strike/dip direction /dip**	**Fractured zone**			**Entire feature description**
		Width (cm)	**Structure**	**Material composition**	
F20	N29E/NW/26	20-40	Fractured simple fissure with mud	Breccias 70%, bad rock 20%, fault mud 10%	
F22	N6W/SW/48	130	Fractured both fissures with mud	block 82%, mud 2%, debris 1%,breccias 3%	Mud distributing through fault
F23	N29E/NW/80-82	0.1-0.3	Fractured both fissures with mud	Breccias 60－70%, debris, mud 30－40%	Mud distributing continuously

Table 2. Geological properties of typical type II structural planes

Number	**Strike/dip direction/dip**	**Fractured zone**		
		Width (cm)	**Structure**	**Material composition**
f204-12	N6W/SW/70	1.0-8.0	Simple gravel with mud	Breccias 20%，debris 20%, mud 30%
f204J-1	N10E/SE/72	2	Simple gravel with mud	Breccias 70%，debris 20%，mud 2%，quartzite 2%
F204J-2	N2E/NW/63	10.0-12.0	Fractured simple fissure with mud	Rock mass60%，Breccias 20%，debris 10%，fault mud 10%
F204J-3	N38E/NW/84	26-36	Fracture with debris	Breccias 80%，debris 10%，fault mud 10%
f204-791	N11W/SW/63	26	Fractured both fissures with mud	Rock mass 70%，Breccias 20%，debris、mud 10%
g204-233	N22W/SW/73	20	Fractured simple fissure with mud	Breccias 70%，mylonite 20%，debris、mud 2%
g204－313.4	N10W/SW/72	0.2-6	Simple gravel with mud	Hoar quartzite、Breccias、argillan
g204J-1	N10W/SW/71	12	Fracture with mud	Hoar quartzite、Breccias
g204-372.7	N6E/NW/80	0.2-0.2	Simple gravel with mud	Quartzite 60%，Breccias 30%，iron argillan 10%
g204J-2	N24W/SW/62	0.2-1	Simple fracture	Quartzite 80%，argillan 20%
g204J-3	N2E/NW/72	0.2-0.2	Fracture with mud	Breccias 80%、mud 20%

From the above, it was concluded that type I structural plane characteristics are not only governed by length, but also by some thick fault zones which comprise tectonites with poor properties. The rock mechanics and strength characteristics are effected by the infilling properties and thickness as well. II structural planes comprise exposed small faults, tensile fracture zones and excursion-crushed zones, which usually have an interrupted distribution or thin infilling, therefore its mechanical property is commonly controlled by the geometric property and infilling.

(III-1): The fissure, with some extended structural plane or little infillings, is the stiff structural plane not the controlling property. From the statistics, the structural planes with strike angle NNW dominate, next NNE, the most common dip angle is middle and the fissure's average spacing was 8.05m.

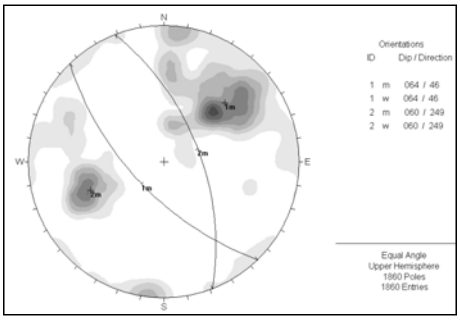


Figure 1. Dominant orientations of random joints

(III-2): This fissure, which is randomly distributed, was the basic forming layer of the rock structure. It was also the important foundation for evaluating the rock quality. From the statistical analysis on random joint's attitude, the development of NNW was dominant, one was NW44°/NE∠64°, the other was NW21°/SW∠60°(Figure 1). The average spacing of random joints was 1.4m; the biggest visible length was not more than 8m because of the limit of the random joint's development.

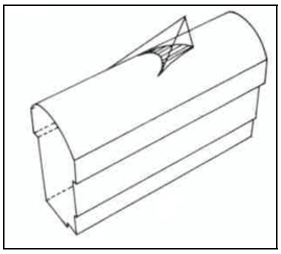


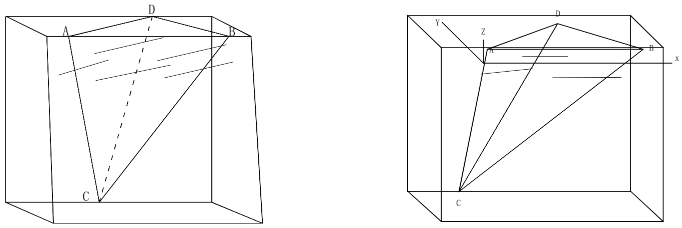
Figure 2. Directly cave-in mode of blocks from vault

BLOCK UNSTABLE MODES AND BOUNDARY DEFINITION

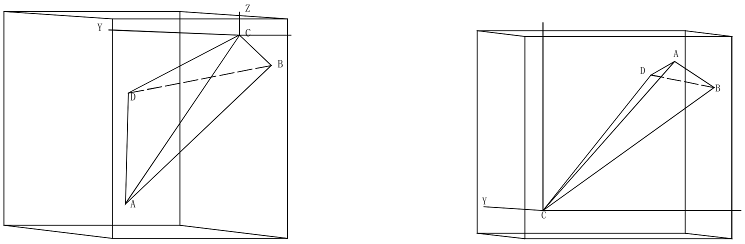
Based on the analysis of the rock structural properties; I and II structural planes with extension, poor engineering properties and distributing features, contributes to form movable blocks which play a controlling role on tunnel stability. Because these blocks are large and located at fixed positions, if their stabilities could not reach the design level, the tunnel had to be specially supported. For structural plane III, not only the size but also the mechanical properties are better than structural planes I and II, however as it is randomly distributed, the intercombinations of them form some small volume and poor stability movable blocks. By finding out the unstable mode of these movable blocks and estimating their stability, the designer could reinforce with systematic anchors and enhance the executive security.

Generally speaking, there are four unstable modes for the blocks of the underground tunnel, named as direct collapse, single-slide (sliding through only one structural plane), double-slide (sliding through two structural planes) and tri-slides. How to judge whether or not these can form blocks and which mode they correspond too, refer to the second reference.

All kinds of structural planes form the block boundary, which is mainly divided into three types: free face, slide plane and cut surface. The possible unstable blocks in the side wall and arch position of the underground tunnel are formed by taking a side cut surface as a free face, taking all kinds of faults with middle low dip angles and middle high dip angles or fissures with a better perforation as a slide plane and taking these faults with high dip angles or fissures with low dip angles as a cut surface of the side or the top. According to block theory, if blocks become possibly unstable, they must be limited, also be movable. There were lots of structural planes forming the slide boundary in the research region, judging from the investigation of all classes of faults and fissures, besides, there are lots of low dip fissures and low congesting zones, so it was availed to block stability. In the natural condition, it is little possible to make the whole top perforated, but in cutting or bursting condition, it is easy to perforate. When calculating the top stability, we considered the top completely perforated, and ignored the effects which the mechanical strength had on it. Besides, it was difficult to form direct collapse (Figure 2) as a result of only two sets of random fissures. There is the direct collapse mode of top block (Figure 2), random joints and low fissures, structural planes I and II form the movably unstable mode (Figure 3).



a. Double-slide formed by low dip fissure b. Single-slide formed by low dip fissure



c. Double-slide formed by I and II structural plane d. Single-slide formed by structural plane I and II

Figure 3. Directly cave-in mode of blocks in vault

RANDOM BLOCK STABILITY COMPUTATION AND EVALUATION

The block theory put forward by Shi_Genhua is the dominant theory for cuniform block stability analysis and uses stereographic projection and vector analysis as the main analytic methods, this plays an important role on spatial block stability analysis. There is some software that has used the cuniform block stability analysis throughout the world, for example, the UNWEDGE used by the Toronto University, National Laboratory of Geo-Hazards Prevention and Geo-Environment Protection, Chengdu University of Technology succeeded in using "Stability Analysis of Slope Wedges", (SASW), by combining a lot of engineering practices comprising block theory, vector analysis, permutation and combination and analytical geometry of three dimensions with modern computer technologies. This paper mainly discusses to use SASW to evaluate the block stability.

From the above statistical analysis for random joints, the main workshop developed dominantly to NW44°/NE∠64°and NW21°/SW∠60°. The combinations of these two groups of random fissures with air condition for tunnel cutting could form two types of blocks as shown on figure 3a & 3b and at the same time, form movable blocks as shown on figure 3c & 3d directly with structural planes I, II and III -1. But because the whole III-1 fissure mostly directs to NNW, and the components of its dip angle and random joints are mostly formed of high and narrow blocks, coupled with the cutting level rising, it was difficult for this random block to be unstable and therefore has not been specially studied. Otherwise, how to stabilise random blocks composed of random fissures and movable blocks formed by random fissures with type structural planes I and II is explained in the following text.

The random blocks composed of random fissures with each other

The block modes possibly formed by these fissures are as shown on figure 3a & 3b and the stabilities of these blocks are shown in Table 3. In this mode, it was only unstable for blocks where the low fissures were within the top cutting boundary, otherwise, it was stable as its dip angle was small and mechanical parameter was great when the low fissures were located as bottom slide planes.

From the table below, it can be seen that the coefficient is not related to the fissure's spacing and the stabilities of blocks composed of only random joints are well.

Table 3. List of factor of stabilities for random blocks combined by joints

Random fissure spacing(M)	dip direction/dip	Block weight (KN^3)	Stable coefficient	Biggest thickness(M)
2	46/64 , 249/60	23.88	2.98	2.22
3	46/64, 249/60	80.59	2.98	3.33
4	46/64, 249/60	191.04	2.98	4.44
5	46/64, 249/60	644.75	2.98	6.67
6	46/64, 249/60	373.12	2.98	5.55
8	46/64, 249/60	1528.3	2.98	8.89

Random blocks composed of fissures and structural planes I and II

Just random block stability indicates that the block stable coefficient has no independence in the slide plane spacing. Considering the long-great joint's average spacing of 8.05m, we adopted the biggest horizontal spacing, 8m, of random blocks formed by random fissures and structural planes I or II, then got the coefficients (Table 2) of random blocks with largest volume, and the deepest depth in the tunnel.

Seen from Table 4, the stable coefficient of eight blocks in all formed by the first group of random joints (46∠64) ranged from 0.39 to 1.2, and the greatest thickness from 5.3 to 8.68, which couldn't achieve the design level by taking its safe coefficient as 1.25. For the blocks composed of the second group (249∠60), there are three blocks that couldn't reach its safe co-efficients because their stable coefficient is from 0.43 to 0.93 and thickness from 4.15 to 7.99.

From Table 5, the stability coefficient of the blocks composed of the same group of fractures in the top or bottom wall has a greater difference in that the top's are always better than the bottom's, and seven blocks couldn't satisfy the design level

Table 4. List of factor of stabilities for random blocks combined by single dominant joint, light pitched joint, and type I, II structure planes

Number	**Position**	**Strike/dip dirction**	**Random joint (46∠64)**			**Random joint (249∠60)**		
			Slide mode	**Stable coefficient**	**Biggest Thickness(m)**	**Slide mode**	**Stable coefficient**	**Biggest Thickness(m)**
f204-12	291.5	N6W/SW∠70	Double	1.68	11.14	Double	3.26	30.38
f204J-1	451.5	N10E/SE∠72	Single	0.36	7.82	Double	2.26	14.08
F20	395.6	N29E/NW∠56	Double	0.69	5.3	Unmovable block		
F204J-2	508	N5E/SE∠63	Single	0.36	8.68	Double	2.95	17.3
F204J-3	563	N28E/NW∠88	Double	0.5	5.41	Double	0.93	7.82
F23	572	N29E/SW∠80-85	Double	0.5	5.3	Double	0.73	7.99
f204-791	791	N15W/SW∠60	Double	2.56	14.29	Double	0.43	4.15
g204-313.4	313.40	N10W/SW∠72	Double	1.97	12.36	Double	5.64	41.54
g204J-1	341.00	N10W/SW∠71	Double	1.99	12.36	Double	5.64	41.51
g204-372.7	372.70	N6E/NW∠80	Double	1.03	8.5	Double	1.95	16.44
g204J-2	387.30	N24W/SW∠65	Double	3.91	19.95	Unmovable block		
g204J-3	400.14	N5E/NW∠72	Double	1.2	8.68	Double	1.51	17.13
G204J-1	428.00	N10W/SW∠66	Double	2.09	12.36	Double	4.06	41.51
g204J-7	451.50	N10E/SE∠75	Double	0.39	7.82	Double	2.28	14.08
g204J-10	562.00	N41E/NW∠71	Double	2.71	6.77	Double		

Table.5 List of factor of stabilities for random blocks combined by two random joints, and type I, II structure planes

Number	**Position**	**Strike/dip**	**Up side**		**Down side**		
			Slide mode	**Stable coefficient**	**Slide mode**	**Stable coefficient**	**Biggest Thickness(m)**
F20	395.6	N29E/NW∠56	Unmovable block		Double	11.36	64.53
F22	533	N6W/SW∠48	Unmovable block		Double	4.32	62.06
F23	572	N29E/SW∠80-85	Double	5.57	Double	2.75	23.49
f204-12	291.5	N6W/SW∠70	Double	2.89	Double	1.47	37.36
f204J-1	451.5	N10E/SE∠72	Double	1.99	Single	0.36	8.53
F204J-3	563	N28E/NW∠88	Double	0.6	Double	0.93	3.27
f204-791	791	N15W/SW∠60	Double	11.27	Double	0.43	4.15
g204-313.4	313.40	N10W/SW∠72	Double	5.93	Double	2.01	31.25
g204J-1	341.00	N10W/SW∠71	Double	5.73	Double	2.02	33.82
g204-372.7	372.70	N6E/NW∠80	Double	1.98	Double	1.05	8.16
g204J-3	400.14	N5E/NW∠72	Double	2.1	Double	1.08	8.39
G204J-1	428.00	N10W/SW∠66	Double	4.12	Double	2.12	28.62
g204J-7	451.50	N10E/SE∠75	Double	2.31	Double	0.39	9.14

SUGGESTION FOR RANDOM BLOCK ANCHORING

The unstable block surrounding the underground cavern is often supported by means of pre stress anchor rod or spouting anchor. For III structural plane (especially some smaller sizes), designers often support it by combining systematic anchors with enforced anchor. It is concluded that the unstable block's minimum value of largest thickness is 4.15m and the maximum value is 8.68m from the stable coefficient. So they anchor the random block by using systematic anchor rods at 8-12 m length, and determine the optimal spacing by making allowance for typical block's remained slide force, anchor rod's diameter and mortar's intension.

CONCLUSIONS

Breakdown of random blocks often occurs during the building period of underground caverns, and the support work is usually undertaken and built up mostly based on human experience. The author defined and confirmed the random block's boundary plane on the base of completely studying the geological conditions and rock structural features of some planning-built underground tunnels. Finally, the stabilities of potentially unstable blocks were calculated by using block theory and some preliminary conclusions are drawn as follows.

(1) The blocks combined by random joints are more stable than those made up of structural planes with type I and II, in the research area.

(2) The random blocks with large volume and wide thickness are more stable than those with small ones.

(3) By taking the biggest spacing of the random joints as 8m and the safety factor as 1.25, the author calculated that the depth of unstable blocks is 4.15m to 8.68m and the optimal length of underground tunnel systematic anchor is proposed to be 8m to 12m according to the criteria for anchor design.

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