Risk analysis of progressive cracking and failure of hard rock around deep underground caverns with high sidewall

Chi Zhou1, Yi Han2, Guo-feng Liu1, 3, Hao-qi Mu1, Ji-Kang Tie1, Guang-liang Feng4
1 School of Highway, Chang’an University, Xi’an 710064, China
2 CCCC Tunnel Engineering Company Limited, Beijing, 100088, China
3 Shanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an 710064, China
4 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

Correspondence should be addressed to Guo-feng Liu; gfliu@chd.edu.cn

Abstract: The progressive cracking of hard rock is more significant under the strong unloading effect of excavation of deep buried large caverns, which often leads to the destruction of surrounding rock, the sharp increase of deformation, support damage and other engineering disasters. Relying on a domestic giant underground hydropower station that faces serious aging crack problems of surrounding rock during the excavation period, the risk analysis methods on the progressive cracking and failure of hard rock around deep underground caverns with high sidewall were presented. Firstly, the formation mechanism of cracking and failure risk of hard rock was revealed from the perspective of risk, based on the analysis of the influencing factors of the cracking behaviour. Secondly, the risk consequences and losses caused by progressive cracking of hard rock were summarized through typical historical observation cases. On this basis, the identification and estimation process of progressive cracking and failure risk of hard rock was put forward, according to the characteristics of complex excavation process of the large caverns and the development characteristics of progressive cracking of hard rock. Thirdly, based on the existing risk assessment guidelines for underground engineering, the risk classification principle of progressive cracking of hard rock for large underground cavern was preliminary proposed, including risk occurrence, risk loss and risk grading, and a set of methods for estimating the risk of progressive cracking and failure of hard rock in the underground powerhouse from Baihetan Hydropower Station project was applied to verify the applicability of the method proposed in this paper. This study has important guiding significance for risk assessment of similar disasters and support optimization design of large and deep underground engineering in hard rock.

Keywords: Large cavern; Progressive cracking; Risk consequences; Risk analysis; Hard rock
1 Introduction

With the implementation of major projects such as West-East Power Transmission and South-to-North Water Diversion in China, dozens of world-class large-scale water conservancy and hydropower projects are being or will be built [1]. For example, Baihetan hydropower station in Jinsha River Basin has the largest underground powerhouse cavern group in the world [2-3] (the size of main powerhouse: 434.0m × 34.0m × 86.7m). The maximum buried depth of the powerhouse is more than 500 m, and the maximum measured geo-stress is 33 MPa. The underground powerhouse cavern groups of Shuangjiangkou hydropower station [4] and Lianghekou hydropower station [5] are more than 400m, and the measured initial geo-stress is more than 20MPa, and the maximum is 38MPa. In the high geo-stress environment, the failure process of rock mass will be controlled by the excavation induced stress. That is, with the increase of geo-stress or excavation induced stress, the surrounding rock will show the mechanical behavior of brittle fracture, and eventually lead to the cracking and failure of surrounding rock.

Cracking and failure of surrounding rock is a kind of static brittle failure, which is often manifested as flake or plate-like cracking relaxation and failure of rock mass. Because this kind of failure often presents a progressive rather than sudden failure characteristics with the excavation of caverns, it can eventually cause large-scale rock mass stripping and instability in the damaged area of cavern excavation, which is harmful to engineering construction. During the excavation of the underground powerhouse for the Baihetan Hydropower Station, the unloading cracking and failure of the surrounding rock is common, and the surrounding rock support system has been damaged many times [6], as shown in figure 1. Martin tracked the brittle failure of surrounding rock during the excavation for Mine-by test tunnel in AECL, and found that spalling of surrounding rock showed obvious progressive failure characteristics from surface to inside with the continuous excavation of tunnel face [7]. The progressive cracking process of surrounding rock in a TBM tunnel excavation damage zone of Jinping II Hydropower Station was observed by Li et al. through pre-buried boreholes and borehole camera technology. The evolution process of the depth and width for the rock cracking cracks in the damage zone with the continuous excavation of the tunnel face was given [8]. Combined with geological, construction, test and numerical analysis data, Liu Guofeng et al. comprehensively summarized and deeply analyzed the mechanism of basalt spalling [6]. Jiang Quan et al. comprehensively revealed the whole evolution process of basalt internal fracture under strong unloading of cavern excavation through statistical investigation of surrounding rock failure and continuous observation of borehole camera [9].

From the perspective of the generalized risk theory, the progressive cracking and failure of surrounding rock is a typical risk event in the construction period of deep underground engineering, which is full of a lot of uncertainty. Once it occurs, it is likely to cause unexpected consequences, such as the delay of engineering progress, the damage of supporting system and so on. In recent years, with the occurrence of hard rock cracking damage disasters in large and deep underground caverns, research on risk loss estimation of cracking damage is urgently needed.

![Figure 1. Cracking and failure of surrounding rock supported by rockbolts in the underground cavern of Baihetan Hydropower Station.](image)

In view of this, on the basis of fully considering the construction characteristics of underground caverns with high geo-stress and the characteristics and mechanism of the risk for cracking and failure of hard rock, this paper draws on and integrates the theoretical ideas of risk management disciplines, and puts forward the
implementation process of risk assessment and the principle of risk assessment classification. Based on the underground cavern project of a large hydropower project in the area of China, the application, verification and improvement of the corresponding risk assessment methods are studied, which provides scientific and reasonable technical support for the prevention and control of cracking and failure disasters in the construction period of deep buried hard rock underground projects.

2 Formation mechanism and evaluation implementation process of progressive cracking failure risk for hard rock

2.1 Risk formation mechanism

From the perspective of risk definition, the risk formation mechanism of progressive cracking and failure during the excavation of underground caverns in deep hard rock can be simply described as follows: During the excavation and construction of caverns in deep underground environments, due to the objective existence of in-situ stress, geological conditions and other pregnant environments, combined with the induction of construction factors such as excavation support, it may lead to the occurrence of risk events for cracking and failure of hard rock, which may cause a series of consequential losses to the disaster bodies, as shown in figure 2.

2.2 Implementation process of risk assessment

Large span and high sidewall underground cavern group is a kind of cavern layout structure which is often used in hydropower underground engineering (such as underground powerhouse, bus hole, tail gate chamber, surge shaft, tailrace tunnel and so on). This kind of cavern group is composed of a series of large underground caverns and small-sized tunnels. The risk assessment of each cavern during construction should be carried out independently and closely combined with the construction process of each cavern, but it is particularly important to emphasize that the influence of adjacent cavern excavation on each other cannot be ignored, and the influence of the adjacent cavern should be considered when the risk assessment of the affected part of the adjacent cavern (such as the cross cavern) is involved. For large underground caverns such as large span and high sidewall, as shown in figure 3, the top-down layered excavation method used in the cavern is not only a risk area of concern in the area near the tunnel face of the excavation layer (risk area A in figure 3), but also a risk area in some parts of the upper excavated layer due to stress adjustment and further intensification of stress concentration (risk area B in figure 3). The corresponding risk assessment ideas and implementation processes are introduced as follows:
2.2.1 Risk assessment process currently under excavation

Taking the disaster-prone areas in the construction process as the risk assessment unit, the risk severity in the assessment unit is estimated in real time with each advance of the excavation face of the current layer, and the potential loss by the risk event is estimated. On this basis, the risk level is determined, the risk level in the unit is evaluated, and the scientific and reasonable local risk response strategy is selected according to the corresponding risk acceptance criteria to ensure the smooth progress of the current layer excavation. Such risk assessment should be accompanied by the construction process of each layer until the completion of the cavern. Based on this idea, the risk assessment process currently under excavation is proposed, as shown in figure 4.

![Figure 3](image1.png)

**Figure 3.** Two different types of risk area concerning the progressive cracking and failure of surrounding rock during the excavation period of the cavern with large span and high sidewall.

![Figure 4](image2.png)

**Figure 4.** Risk assessment process of cracking and failure of hard rock during the excavation of the underground cavern with large span and high sidewall.

2.2.2 Risk assessment process of upper excavated layer

During the excavation of the current layer for the cavern, the upper excavated layer will also have damage risk. We should make full use of all kinds of relevant monitoring information in the cavern, conduct dynamic tracking investigation, monitoring on the risk of the excavated layer of the upper part in real time, and determine the risk level. At the same time, we use numerical simulation and other technical methods to predict whether the risk is acceptable in the subsequent layer excavation process. Finally, the risk response strategy should be comprehensively determined until the acceptance conditions are met, and then the next excavation is carried out, so that the cycle assessment is carried out until the cavern is completed.
3 Classification principle of progressive cracking failure risk assessment for hard rock

The study of risk assessment classification principle includes classification principle of risk severity, risk loss classification principle, risk level principle, risk acceptance criteria and corresponding risk disposal measures. Considering that the in-situ stress conditions of deep underground caverns can basically determine whether they have the occurrence conditions of such disasters, layered excavation of high sidewall caverns may lead to continuous expansion of disasters and increase of corresponding surrounding rock support loss. Referring to the risk assessment classification standards established by the risk assessment norms and guidelines formulated by urban rail, railway, highway and other departments [10-13], this paper preliminarily establishes the risk classification principle applicable to the progressive cracking and failure of deep hard rock in the caverns.

3.1 Classification principle of risk severity

Considering the characteristics of disaster development, the classification principle of risk severity is preliminarily established, as shown in table 1.

| Level | 1         | 2         | 3         | 4         |
|-------|-----------|-----------|-----------|-----------|
| Qualitative description | slight    | moderate  | serious    | catastrophic |
| Depth of the crack (m) | <0.5      | 0.5~1     | 1~3       | >3         |

3.2 Risk loss classification principle

Considering the construction scale, period, importance, construction characteristics and engineering cost of deep-buried caverns, combined with the characteristics of disaster hazard, the classification principle of risk loss for progressive cracking and failure of hard rock is preliminarily proposed, as shown in tables 2-5.

| Level | 1         | 2         | 3         | 4         |
|-------|-----------|-----------|-----------|-----------|
| Qualitative description | slight    | moderate  | serious    | catastrophic |
| Number of casualties | SI or MI≤10 | F≤2 or 1<SI≤5 | 2<F≤5 or 5<SI≤10 | F>5 or SI>10 |

| Level | 1         | 2         | 3         | 4         |
|-------|-----------|-----------|-----------|-----------|
| Qualitative description | slight    | moderate  | serious    | catastrophic |
| Economic losses ($ 10,000) | ≤10       | 10~100    | 100~300   | ≥300       |

| Level | 1         | 2         | 3         | 4         |
|-------|-----------|-----------|-----------|-----------|
| Qualitative description | slight    | moderate  | serious    | catastrophic |
| Delay time (day) | <10       | 10~30     | 30~60     | >60        |

| Level | 1         | 2         | 3         | 4         |
|-------|-----------|-----------|-----------|-----------|
| Qualitative description | slight    | moderate  | serious    | catastrophic |
| Degree of support loss | spray     | spray spalling and extrusion | Bolt suspension failure, steel mesh | Full damage, cable overrun, broken |
| Degree of deformation | cracking   | deformation | failure, arch deformation | over run, broken |

3.3 Risk level principle and risk acceptance criteria

The determination method of risk level is the process of combining the risk severity and the risk loss result. The most commonly used method is the risk matrix method, which is a qualitative risk evaluation method. Referring to the relevant norms and guidelines of underground engineering, the progressive cracking and failure risk of deep hard rock during the excavation of cavern is evaluated as shown in table 6, the risk acceptance criteria corresponding to the risk level principle are shown in table 7.
4 Engineering application

4.1 Engineering background

The Baihetan hydropower station is located in Ningnan County of Sichuan Province and Qiaojia County of Yunnan Province in the lower reaches of the Jinsha River, which belongs to the alpine canyon landform. The valley is a typical asymmetric ‘V’ type valley. The horizontal buried depth of the left bank powerhouse is 600~1000m, the main geological structure distribution is shown in figure 5. The in-situ stress is mainly valley tectonic stress, the detailed description of the project is shown in reference [6].

4.2 Case analysis

Taking the K0+300~350 bore hole section of left bank powerhouse as an example, the progressive development process of cracking and failure of hard rock during the excavation of the cavern with large span and high sidewall is analyzed in detail.

On 29 June 2014, the first floor (I3) on the right side of the left bank powerhouse was advanced to K0+329. According to the selection principle of the risk assessment unit, the arch shoulder of the upstream side K0+329~345 bore hole section was used as risk assessment unit (as shown in figure 6).

| Risk level | acceptance criteria | Risk disposal principles and countermeasures |
|------------|---------------------|--------------------------------------------|
| I          | acceptable          | Low risk, enhanced observation or monitoring to ensure that risk is not increased |
| II         | attention-getting   | Moderate risk, take some measures to reduce risk to an acceptable level |
| III        | unexpected           | High risk, implement risk prevention and monitoring, formulate risk disposal measures to reduce risk, and meet the cost of reducing risk is not higher than the loss after the risk occurs, and strengthen risk monitoring, real-time tracking risk |
| IV         | unacceptable         | Extremely high risk, high priority must be given to the development of risk emergency response plan to reduce risk at least to an undesirable level at any cost |

Figure 5. Distribution map of main geological structure of underground powerhouse on left bank of Baihetan Hydropower Station.

Figure 6. Excavation schedule of the north side of the left bank powerhouse on 29 June 2014 (a)
Observation section(K0+330); (b) The plane graph of excavation schedule.

The three-dimensional numerical model of the local hole section is established, and the numerical simulation is carried out by FLAC, as shown in figure 7. The RFD (Rock Failure Degree) value is an index defined by the plastic shear strain of rock mass to evaluate the degree of damage in the process of rock mass deformation and fracture. The area of RFD≥0.8 can basically characterize the area of relaxation and cracking of surrounding rock, details are given in reference [15]. It can be seen from figure 7 that the splitting failure depth is within 1.47 m. From table 1 in section 3.1, it can be determined that the risk level of progressive cracking and failure for hard rock is level 3. According to the risk loss classification principle given in section 3.2, the risk loss level is determined to be level 1. In summary, the risk level can be finally determined to be level II according to the risk evaluation matrix described in table 6. According to the risk acceptance criteria shown in table 7, it can be seen that the risk belongs to moderate risk and needs to be paid attention.

If the deep anchor+hanging spray layer system support form is not timely applied in the area, the risk of hard rock cracking may continue to grow with the excavation of the face. On September 16, 2014, the bottom plate (I4-D) of the downstream side of the powerhouse began to excavate to the north and south sides of the powerhouse from the K0+325 section. The second sequence expansion excavation face (I5-D) of the downstream side was excavated to both sides along with the I4-D face. Since then, due to the influence of the excavation of multiple nearby faces, the cracking degree of surrounding rock near the K0+330-0-U observation hole has further intensified. According to the cracking depth and loss of the surrounding rock slices at the site, the risk level is finally determined to be level III. According to the corresponding risk acceptance criteria, this risk is not expected to occur and belongs to high risk. On October 3, 2014, the borehole camera results showed that the cracking depth of rock mass was 2.78m. The borehole photography results are shown in figure 8, and compared with the results on June 29.

Figure 7. RFD distribution nephogram of surrounding rock for K0+330 section after I3 expansion of upstream side was completed on June 29, 2014.

Figure 8. Comparison of borehole photography results for K0+330-0-U borehole on arch roof.

The above analysis shows that if the excavation continues, there will be a huge risk to the project. Therefore, the RFD distribution nephogram of surrounding rock after the excavation of the III layer is simulated, as shown in figure 9. It can be seen from the figure that the cracking depth of surrounding rock is more than 3 meters. According to table 1, the risk severity level can be determined as level 4, and the
corresponding risk level will also reach level IV. This is extremely high risk and must be highly valued. The risk emergency response plan should be prepared to reduce the risk at least to an unexpected level at any cost.

According to the results of risk analysis, if the surrounding rock of deep caverns fails to take timely measures to deal with the cracking of surrounding rock in the early stage, it will cause unexpected loss consequences in the subsequent excavation.

5 Conclusion

(1) The formation mechanism of progressive cracking and failure risk for deep hard rock in the excavation of cavern is expounded. The implementation process of risk assessment for progressive cracking and failure of deep hard rock in the excavation of cavern is proposed.

(2) The classification principle of risk assessment for progressive cracking and failure of deep hard rock in the excavation of cavern is preliminarily established, including the classification principle of risk severity, the classification principle of risk loss, the risk level principle and the corresponding risk acceptance criteria.

(3) Based on the underground cavern project of a large hydropower station in the southwest mountainous area of China, the dynamic evaluation of progressive cracking and failure for deep hard rock during the construction period of underground cavern is carried out. The evaluation results are in good agreement with the actual results, which verify the applicability of this method and provides scientific and reasonable technical support for the prevention and control of cracking and failure disasters during the construction period of underground engineering in deep hard rock.

Acknowledgement

Authors wishing to acknowledge the financial support from the Fundamental Research Funds for the Central Universities (Grant No.300102210110), the Open Fund of Shaanxi Key Laboratory of Safety and Durability of Concrete Structures (Grant No. XJKFJJ201806), and the National Natural Science Foundation of China (Grant No. 42077265).

Reference

[1] Xiating F, Chuanqing Z, Shaojun Li, et al. Dynamic design method for deep hard rock tunnel [M]. Science Press, 2013.

[2] Guotao M, Yilin F, Yali J, et al. Research on key rock mechanics problems and engineering countermeasures of giant underground caverns in Baihetan Hydropower Station [J]. Rock mechanics and engineering, 2016,35(12): 2549-2560.

[3] Quan J, xiating F, Yilin F, Yali J, et al. Under high geo-stress, the hard rock is unloaded and ruptured: an example analysis of basalt cracking observation of underground powerhouse of Baihetan Hydropower Station [J]. Rock mechanics and engineering, 2017,36(5): 1076-1083.

[4] Ning L, Weishen Z, Xiaoli X. Shuangjiangkou hydropower station initial stress field inversion regression analysis [J]. Journal of Shandong University Engineering Edition, 2008,38(6): 121-126.

[5] Zeze L. Study on surrounding rock stability of underground powerhouse of Lianghekou hydropower
station in Yalong River [D]. Chengdu University of Technology, 2010.

[6] Guofeng L, Xiating F, Quan J, et al. The failure characteristics, laws and mechanisms of surrounding rock spalling in large underground powerhouse excavation at Baihetan [J]. Rock mechanics and engineering, 2016, 35(05): 865-878.

[7] Martin C D. Seventeenth Canadian Geotechnical Colloquium: The effect of cohesion loss and stress path on brittle rock strength [J]. Canadian Geotechnical Journal. 1997, 34(5): 698-725.

[8] Shaojun L, Xiating F, Zhanhai L, et al. Evolution of fractures in the excavation damaged zone of a deeply buried tunnel during TBM construction [J]. International Journal of Rock Mechanics and Mining Sciences, 2012, 55(10): 125-138.

[9] Quan J, Yilin F, Xiating F, et al. Unloading rupture of hard rock under high geo-stress: Case study on basalt cracking observation of underground powerhouse of Baihetan Hydropower Station [J]. Rock mechanics and engineering, 2017, 36(05): 1076-1087.

[10] National standard of the People's Republic of China. Risk management specification for underground engineering construction of urban rail transit (GB 50652-2011) [S]. Beijing, 2011.

[11] Industrial standards of the People's Republic of China. Interim regulations on risk assessment and management of railway tunnels [S]. Beijing, 2007.

[12] Xigang Z. Guide for Safety Risk Assessment of Highway Bridge and Tunnel Engineering Design [S]. Beijing, 2010.

[13] National standards of the People's Republic of China. Risk management norms for construction of large and medium-sized hydropower projects (GB/T50927-2013) [S]. Beijing, 2012.

[14] National standard of the People's Republic of China. Classification standard of casualties among enterprise employees (GB6441-1986) [S]. Heilongjiang, 1986.

[15] Quan J, Xiating F, Shaojun L, et al. Fission-inhibition method for stability design optimization of large hard rock underground caverns under high geo-stress and its application [J]. Rock mechanics and engineering, 2019, 38(06): 1081-1101.