Close Feedback Stability Analysis and Design Optimization under EPC Condition for Large Underground Caverns

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Abstract. To prevent stability risks and improve the optimal design capability for large underground caverns under the Engineering Procurement Construction (EPC) convention, an improved feedback analysis model is presented to adapt the integration of design and construction model for large underground engineering. A close stability optimization design and corresponding technical flowchart under EPC pattern were initially established by considering the cooperated-building parties. Some key optimization methods, including 3D monitoring, real-time stability warning, and cracking-restraint design, are proposed. Finally, a typical stress-structure case in the Baihetan underground cavern shows this optimizing process of close feedback analysis under EPC pattern, indicating the advantages of the presented method in opening and supporting optimizations.

1. Introduction

Large underground caverns, due to their complicated geological conditions, large sizes, high sidewalls, and multi connections, undergo typical failures during their opening, such as time-dependent deformation, inner cracking, large-scale collapse, and brittle rockburst [1, 2]. For example, more than 200 mm deformation occurred in the underground main transformation caverns of Jinping I hydropower station during its excavation [3]; a collapse of more than 3000 m³ in the Dagangshan main powerhouse occurred due to β80 weak discontinuity, causing a substantial increase in supporting cost [4]. In addition, several inner cracks had been observed in the Baihetan right underground powerhouse [5]. Similarly, spalling failures have also been observed in the “Mine-by tunnel of AECL” and “Äspö Hard Rock Laboratory” of SKB [6, 7]. To prevent and overcome these stability issues, an integrated coordination model by coupling the dynamic design and construction, i.e., Engineering Procurement Construction (EPC), may improve underground engineering safety management in practice [8]. Thus, a scientific feedback analysis method under EPC conditions is the key to preventing rock failure and ensuring the global stability of the large underground caverns.

In recent years, engineering, procurement, and construction have been extended in many fields, such as transportation, municipal engineering, water conservancy project, and hydropower engineering, with high efficiency and economical cost [8, 9]. Yet, the EPC practices indicated that the integrated design and construction for large hydropower underground caverns still faces new challenges in theoretical methods and technical management, such as:

1. Realizing the integrated and rapid response for underground caverns’ stability evaluation, excavation, support construction, early safety warning, and dynamic control needs to be further explored by sharing multiple in situ monitoring and geological information.
2. Finding the best balance between the caverns’ stability and economic benefits under the EPC pattern requires more profound theoretical innovation in the aspect of feedback stability, analysis, and design optimization for larger underground caverns.
3. Sharing multiple information to realize the maximization of surrounding rock stability and construction efficiency in the “integrated construction process” needs further practice.
Thus, it is crucial to establish a feedback method of stability analysis under the EPC condition to realize the integrated optimization of excavation and support for a large underground cavern group. Zhong [10] proposed an underground cavern group construction system analysis method and software by integrating cyclic network computer simulation, visualized resource-oriented modeling, and dynamic demonstration. Wang [11] discussed the information management of underground powerhouse cavern group construction of Tianhuangping pumped storage power station. In another study, a practical method for fast feedback analysis of large underground cavern groups during construction based on interval analysis and hierarchical optimization was proposed [12]. Jiang [13] proposed a calculation method for the overall safety factor of large multi-cavity structures. Hu [14] used microseismic monitoring to carry out safety early warnings for several underground powerhouse cavern groups. Therefore, it is urgent to establish an independent early-warning and dynamic optimization for cavern excavation and support models under EPC conditions.

Hence, this study proposed a new closed-loop feedback analysis mode under EPC (FA-EPC) condition to solve the collaborative design and construction integration problem for large cavern caverns. Furthermore, several monitoring and analysis technologies under the EPC mode were developed. Finally, the implementation process of the method was executed through the optimized application of the weil C4 shear belt’s stability and supporting the right underground cavern of the Baihetan hydropower station.

2. Close feedback analysis method under EPC condition

The engineering mandate of EPC generally consists of project design, procurement, and construction, with the core goal of controlling cost and improving efficiency, but faces key challenges in the integration of design and construction. Therefore, necessary to realize the advanced integration between design, procurement, and construction in EPC general contracting project. Thus, the dynamic design and construction of large underground cavern groups under EPC conditions drive the excavation and support optimization of underground caverns jointing more close connections.

However, the safety risk of large underground cavern groups is high due to unclear geological conditions and high construction speed in EPC patterns, which requires a more reasonable method for economic support, scientific excavation, and optimization. Furthermore, multi geological units, complicated geological conditions, the overlapping effect of cavern groups, and high opening rate (40 to 50%) result in intensive stress adjustment, complex stress-path transfer, diverse deformation, and failure behavior of surrounding rock. Thus, a feedback analysis method under EPC condition (CFA-EPC) must be proposed. In this method, the mechanical behavior of the surrounding rocks in caverns is predicted from previous construction experience and theoretical analysis of the caverns. The excavation and support scheme of the next caverns are also optimized to realize the optimal management to support the design of the next construction, purchase materials in advance, and reasonable construction organization, as Fig.1.

In the dynamic feedback analysis flowchart, it is necessary to fully use the characteristics of caverns’ excavation stages and follow the feedback analysis mode of “excavation phase $i$, analysis phase $i$, the optimization phase $i$, and prediction phase $i+1$”. That is, the looping progress of CFA-EPC mainly includes the following steps:

Step 1: Real-time observation of the excavation process of phase “$i$”. During the phase “$i$” opening, the geological conditions of surrounding rock will be revealed continuously with the advance of the excavating face. Thus, it is necessary to understand the possible real-time changes of geological state, the deformation and failure responses of the surrounding rock, the response characteristics of the caverns’ blasting, supporting process, etc.

Step 2: A feedback analyzes of the stability of caverns during the opening “$i$” phase. First, an intelligent inversion is carried for gaining the equivalent mechanical parameters of rock mass, such as deformation modulus, cohesion, and internal friction angle, based on the accumulated multi-information during the construction “$i$” process. At the same time, the simulation analysis of the excavating and supporting process was carried out using the mechanical model considering the degradation of rock mass for exposing the global and local stability of the surrounding rock. Then, the strengthened supporting scheme for the local zone with high unstable risk is suggested.
**Step 3**: Optimize the phase “i” excavating and supporting design. During the excavation of phase “i,” the integrity and scientific characteristics of the opening parameters, including opening bench height, cyclical footage, opening sequence, blasting parameters, shotcrete thickness, bolt supporting form, bolt spacing, bolt length, anchor cable’s prestress, supporting time, are audited and be optimized.

**Step 4**: Predict the mechanical stability and adjust the construction scheme for the phase “i+1” excavation. Based on the reliable mechanical parameters of rock mass and detailed engineering geological information, the stability of the phase “i+1” excavation of the cavern group can be further predicted by detail numerical simulation, such as the deformation increment of the surrounding rock and the damage evolution of rock. What is more, the proper excavation sequence, reasonable support parameters, and realistic stability management standards for the phase “i+1” of underground caverns are suggested to effectively organize the resource-input planning of the phase “i+1” construction and the advance implementation of auxiliary construction, signifying that the advanced and efficient organization of the phase “i+1” excavation is realized in the EPC pattern.

![Dynamic close feedback analysis and construction optimization flowchart for large underground caverns under EPC condition](image)

During the dynamic feedback analysis, the global and local stability of surrounding rock can be judged based on the following aspects: monitored deformation and failure tendency, the health state of the supporting system, numerical analysis results, and global stability factor (Table 1).

| Index                                      | Detail proof                                                                 |
|--------------------------------------------|-----------------------------------------------------------------------------|
| (1) Monitored deformation and failure tendency | A. Monitored deformation tends to stable convergence, and the total deformation value is acceptable.  
   B. Tested loosed depth of surrounding rock tends to stable convergence, and the rock’s damage degree trends to convergence. |
| (2) Health state of supporting system       | A. Tested loosening depth of surrounding rock < Length of supported rock bolt.  
   B. The relatively large deformation zone and significant break zone of surrounding rock are effectively reinforced.  
   C. Monitored load of supporting system < Designed loading capability of supporting system |
(3) Numerical analysis results
A. The calculated deformation and failure depth are in the acceptable range.
B. The damage/yield zone is not connected between caverns.

(4) Global stability factor
The global safety factor is large in 1.5.

3. Key analysis technologies under FA-EPC pattern
The key points of dynamic feedback analysis for large underground caverns depend on the reasonable rock performance observation method, reliable warning technology of rock stability, and scientific optimization technology of excavation and support under the FA-EPC pattern.

3.1 3D multi-monitoring technique
A reasonable and effective in situ monitoring method should synchronously observe the co-evolution process of rock’s failure and deformation during excavation to provide primary data for warning on the surrounding rock’s stability. Therefore, it is essential to reveal the mechanical response behavior of surrounding rock in multiple aspects during the excavation process of a large underground cavern by adopting coupled a 3D monitoring mode, including microseismic monitoring, borehole camera, multi-point displacement meter, and other means. For example, the position of deep fracture on the profile has a good relationship with the direction of the maximum principal stress in an underground cavern; hence the borehole for a digital camera should be perpendicular to the direction of the maximum principal stress, and its length should not be less than 0.5 times of the cavern’s span. Likewise, the borehole for the multi-point displacement meter should be perpendicular to the direction of the maximum principal stress. At the same time, the spatial array of microseismic sensors should be surrounded as much as possible in the risk area of a deep fracture of large underground caverns to obtain the best micro-break information (Fig.2a). In this way, the deformation of surrounding rock and surface cracking and deep fracture can be observed detailly (Fig.2 b, c).

Fig.2 On-site 3D multi-monitoring for cavern’s deformation and failure (a. Layout method for surrounding rock; b. Monitored MS events; c. Observed break by digital borehole camera)

3.2 Stability warning technology
To realize the automation and real-time safety monitoring of the surrounding rock in a large cavern group, it is necessary to further establish the automatic monitoring and remote data analysis technology for underground caverns. This technology adopts the “wired + wireless” networking scheme to construct a new type of remote online telemetry system architecture, which mainly includes: an information acquisition and transmission subsystem, a management and analysis subsystem, and a remote receiving subsystem of monitoring data (Fig.3).
Fig. 3 Automatic gather and analysis processing of surrounding rock’s monitoring data

The outcome of a hard rock subject to high stress is cracking and breaking [15]. Therefore, the critical safety management index for surrounding rock in a large underground cavern should consider the break information of the surrounding rock, i.e. loosed depth or damaged depth. Thus, the loosed depth of surrounding rock should be considered as a control index of its safety. In addition, the deformation index is also taken as the primary control indicator in China’s current codes (GB50086-2001, SL279-2002). The surrounding rock is regarded as unstable in these codes when the measured displacement value exceeds the safety range. However, its threshold of early warning is still lacking for specific geological conditions. In addition, the rate of rock mass deformation is also an important criterion to judge the instability state of surrounding rock. In summary, we define the break depth, deformation increment, and deformation rate as the indexes of the warning method for the stability of surrounding rock in a large underground cavern and proposed stability management standards for large underground caverns with a layer-by-layer excavation process (Table 2). In this table, the safety levels for management is divided into three levels, i.e. Safety, Warning, and Danger.

| Stability level | Surrounding rock | Safety | Warning | Danger | Layer |
|-----------------|------------------|--------|---------|--------|-------|
| Loosed depth $D_{\text{RFD tested}}/D_{\text{RFD limitation}}$ in layer $i$ | $<1$ | $1-1.25$ | $>1.25$ | |
| Deformation increment $\delta_{\text{tested}}/\delta_{\text{limitation}}$ in layer $i$ | $<1$ | $1-1.25$ | $>1.25$ | $i$ |
| Deformation rate $(\Delta\delta/L_i)/\varepsilon_{\text{limitation}}$ in layer $i$ | $<1$ | $1-1.25$ | $>1.25$ | |

Note: $D_{\text{RFD}}$ is the rock failure depth, $\delta$ is the deformation increment, $\Delta\delta/L_i$ is the deformation rate.

It is noted that thresholds for each level of safety management in Table 2 cannot be fixed entirely. Instead, they should be determined and gradually adjusted through multiple on-site feedback based on engineering analogy, numerical analysis, and monitoring results based on specific engineering characteristics, lithology characteristics, construction parameters, etc.

3.3 Cracking-restraint method for excavating and supporting design under EPC condition

Excavation by layers or sections in large underground caverns with hard rocks will inevitably induce three-dimensional stress states ($\sigma_x$, $\sigma_y$, $\sigma_z$) adjustment in a certain depth range of surrounding rock, including stress concentration and stress unloading in the same area, resulting in a break of surrounding rock. Therefore, cracking is the essential cause of the large deformation and catastrophic failure of surrounding rock, inelastic deformation is the external manifestation of the accumulation of cracks inside hard rock, and total deformation of the surrounding rock is the accumulated result of internal
cracks developing to a certain extent. So, the key to maintaining the stability of large underground caverns under high-stress conditions is to inhibit internal cracking inside rock mass. When the extension of cracks inside rock mass is effectively restrained, surrounding rock deformation tends to converge spontaneously.

The main work of the stability design for underground caverns during construction is to systematically optimize the excavation scheme (opening bench step height, opening sequence, opening method) of the cavern group to reduce the damage/losing depth and degree of surrounding rock. By systematic optimization of supporting parameters (shotcrete thickness, type and length of rock bolt, anchor cable’s length, and prestress), rock bolts and anchor cables can be supported, and the scale, depth, and degree of surrounding rock cracking reduced and avoided in a global design viewpoint. Furthermore, these active supports can restrain the cracking process of surrounding rock and strengthen the structural integrity of the loosed/damaged surrounding rock (Eq.1). In this way, the damaged surrounding rock can be transformed from the supported object into a bearing structure. As a result, the full bearing capacity of surrounding rock can be actualized, and the safety, efficiency, and economic goals of engineering stability design are achieved.

\[ \min(D, RFD) = f(S, P, T) \]  
(1)

Where, “S” is the opening scheme, “P” is the supporting parameters, “T” is the supporting opportunity, “D” is the damage depth, RFD is the failure index, and the limitation condition for the Eq.1 is the construction realizability.

(1) From the view of excavation, the key is to find a feasible construction scheme with moderate excavation disturbance to reduce the rock’s break range, intensity, and depth of stress adjustment, by optimizing the opening bench and opening sequence between caverns \{S\}. Thus, the path, process, depth, and energy release degree of stress concentration inside the surrounding rock is harmonious. That is, the rock mass fracture depth \{D\} will be within the acceptable range of engineering experience or theoretical analysis (Eq.2). Thus, a reasonable excavation scheme can effectively reduce the damage depth and range of surrounding rock for a large cavern (Fig.4).

\[ \text{Optimize} \{S\} = \min \{D_{\max}[RFD(0.8,1.0)]\} \leq \{D_{\text{acceptable}}\} \]  
(2)

Where, \{S\} is the opening sequence, D is the break depth.

(2) The purpose of optimizing the support parameters of the caverns is to reduce the mobilizing depth and stress concentration degree of concentrated stresses as much as possible, reduce the depth and degree of the rock’s damage, maintain or reconstruct the self-bearing arch of the surrounding rock through the connection of the supporting structure, and restrain the transfer of the inside cracking extension (Eq.3).

\[ \text{Optimize} \{L, P, T\} = \min \{D_{\max}[RFD(0.8,1.0)]\} \leq \{D_{\text{acceptable}}\} \]  
(3)

Where, L is the depth of rock bolt or anchor cable.
4. Case interpretation for weak C4 shear belt in the Baihetan underground hydropower cavern

4.1 Engineering background

The Baihetan hydropower station, located at the Sichuan and Yunan provinces boundary, is the second-largest water-power engineering in China. There are two underground powerhouses with a combined electrical capacity of $16 \times 10^6$ kW located on the respective banks of the Jinshang valley, i.e., the right underground caverns and the left underground caverns. The size of the underground powerhouse is $438.88 \times 734$ m (length × height × width). These represent the largest underground hydroelectric caverns in the world (Fig. 5).

The stratigraphic rock surrounding the underground cavern inside the right bank is a basaltic formation originating from magmatic and volcanic eruptions, belonging to the Emei mountain group of the Permian system ($P_{2\beta}$). The direction of the maximum principal stress at the site, whose measured value is approximately 26 MPa in average and 30 MPa in a local position, is nearly parallel to the axis of the main powerhouse [16, 17]. According to the Chinese “Standard for engineering classification of rock mass” [18], the rock mass quality is ranked as “II” and “III,” which are acceptable for constructing underground tunnels or caverns. According to the Barton’s Q system and GSI classifications [19, 20], the quality indices of rock mass are 20–50 and 70–80, respectively.

The C4 shear belt is exposed in the right underground cavern. This shear belt cuts the side of the auxiliary powerhouse, with an exposed thickness of about 10–20 cm with a mixture of mud and debris (Fig. 6), meaning this weak shear belt can easily soften under groundwater conditions.

4.2 Failure performance of C4 shear belt in the main transformer chamber

During the excavation of the main transformer chamber, three typical collapse failures occurred on the sidewall and top arch induced by C4 shear belt, which mainly belongs to stress-structural failure, as shown in Fig. 7.
4.3 Close feedback analysis

Because this weak geological structure resulted in the instability of the surrounding rock, it is necessary to carry out dynamic feedback analysis for the stability state and predict the mechanical performance during the subsequent excavation for the main transformer chamber. Thus, section k0-20.4 m was selected as a monitoring section to analyze the evolution process of damage range and depth of surrounding rock around C4 shear belt. **Fig.8** shows the evolution curve of the maximum failure depth of rock, advancements in the opening face during the step-by-step excavation of the first layer in the main transformer chamber, and the three-dimensional RFD evolution cloud map of this cavern affected by the C4 shear belt. This numerical simulation indicated that: (i) the surrounding rock did not experience significant damage when the opening face was advanced to 8 m away from the monitoring section; (ii) the surrounding rock experienced a disturbance when the opening face continued to advance to 4 m from the monitoring section, and its damage depth was about 0.5 m (RFD > 0.8 fracture range); (iii) The range of damage zone around the shear belt increased sharply with the maximum damage depth about 3.4 m, and was gradually connected when the opening face exceeded 4 m across the monitoring section; (iv) The damage depth of surrounding rock in the observance section continued to increase until the opening face passed 24 m over the monitoring section.

**Fig.8** Evolution process of damage depth and RFD index during the excavation of cavern around C4 shear belt

4.4 Close feedback analysis

The above analysis indicated that adequate supporting strength is needed to restrain the various deformation and failure problems of surrounding rock induced by the C4 shear belt during subsequent excavation of the main transformer chamber. Therefore, the supporting parameters decided by the design
department and supporting opportunities determined by the construction department should be incorporated into the EPC pattern. In addition, it is necessary to control the convergence deformation of surrounding rock around the C4 shear belt and the development of rock’s tensile and shear fractures in the progressive failure process, i.e. the development of damage degree of the surrounding rock.

Therefore, based on cracking-restrain methods, the prestress rock bolt and anchor cable should pass through the dislocation zone, and the supporting length and density of the rock bolt/anchor cable must restrain the rock mass from dropping into the rock’s unstable expansion and post-peak softening stages. That means a surrounding rock with an RFD value of more than 0.8 should be reinforced. In this case, the density of rock bolt and anchor cable should be increased appropriately in the high-risk zone of collapse failure zone. Moreover, the support intervention of bolt and cable should not be later than the rock’s sudden increase of stress and the rapid development of cracks, i.e. 4 m distance to the opening face. Thus, a reinforced supporting scheme is determined, and the support time is determined 4 m near the opening face (Fig.9a). The application of these schemes using monitored data indicated that this supporting and excavation scheme is reasonable and reliable (Fig.9b).

![Fig.9 Reinforced supporting scheme and corresponding monitored deformation of chamber’s arch after optimization design](image)

5. Conclusions

An improved closed-loop feedback analysis mode (CFA-EPC) under the EPC condition is presented to enhance the integration of design and construction for a large underground cavern group. In this CFA-EPC model, the dynamic design and construction of large underground cavern groups were integrated. Several key analysis technologies under the CFA-EPC model, including reasonable observation method of rock performance, reliable warning technology of rock stability, and scientific optimization technology of excavation and support, are also proposed to improve design and construction efficiency.

Finally, the implementation process of the method is deduced through a case analysis of the weak shear belt stability in the right underground cavern of Baihetan hydropower station, which indicated that this close feedback stability analysis and design optimization under EPC condition is reasonable and reliable.

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