Analysis of Initial Geostress Field of a Hydropower Project without Measured In-situ Stress

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Abstract. Initial geostress field is an important factor affecting the stress distribution, displacement and failure mode of surrounding rock of underground engineering, and is also one of the important indexes of design for underground works, especially large hydropower projects. At present, the method to obtain the geostress field is mainly based on measured in-situ stress, however some projects are lack of in-situ stress measurement data. To solve this problem, we inversed regional tectonic stress field firstly, and then extracted the boundary load of the project area from the fitted regional tectonic stress field and embedded the underground cavern to be studied in the calculation model to carry out the numerical calculation of the geostress field of the project area. The results show that the direction of regional tectonic principal stress is NNE~NE, and the average maximum horizontal tectonic stress is about 5.0MPa. The direction of the maximum principal stress in the project area is generally the same as that of the regional tectonic stress field, which indicates that the valley stress field is determined by the regional tectonic stress field. However, due to the influence of river incision, the geostress field of the project area redistributes, and has the basic characteristics of principal stress direction deflection and stress differentiation. The research results provide a basis for the subsequent study of the stability of underground caverns, and have a certain reference value for the method of obtaining initial geostress field of a project without measured in-situ stress.

1. Introduction
Geostress field is one of the important basic data for the evaluation of geological environment and crustal stability [1], engineering design and construction. It is also one of the occurrence environments of rock mass and one of the fundamental differences between rock mass and other materials. It affects and controls the mechanical properties of rock mass to a great extent, and is the load source of stress and displacement release in engineering activities (such as excavation) [2]. In a word, geostress field is an important aspect to determine the basic load and mechanical parameters of rock mass. Therefore, it is necessary to grasp the characteristics and distribution law of geostress field in the project area accurately and reasonably.
The measured in-situ stress is the most direct way to provide geostress field in project area, however due to the limitation of the number of measuring points, it can only reflect the local stress situation. At the same time, the measurement error will also cause obvious dispersion characteristics, which is difficult to reflect the macroscopic law of in-situ stress field [3]. In view of this problem, the existing ideas can be summarized as follows: Based on the measured data of in-situ stress [4], combined with the geological conditions of the project area, the geostress field inversion is carried out by using the numerical analysis method to obtain the accurate and wide range of in-situ stress distribution characteristics. At present, the commonly used methods include multiple regression analysis method [5-10], lateral pressure coefficient method [11, 12], stress back analysis method [13], artificial neural network method [9].

It can be seen that the current geostress field inversion is mainly based on the measured in-situ stress data, and there is a lack of research on the inversion method without measured value. However, due to the limitation of geographical environment and economic conditions, some projects lack in-situ stress measurement data. Therefore, it is of great theoretical value and practical significance to study the method of obtaining geostress field in project area without measured in-situ stress data. Based on the attitude of fault and fault throw, Ke Li et al. [14] established the numerical solution of displacement discontinuity method (DDM) of fault structure by considering fault deformation mode in the DDM program, and then used the DDM computational kernel for the initial stress field inversion. In this paper, based on a large hydropower project, combined with the terrain and geological conditions, a three-dimensional geological model of the project area is established, and the boundary load of the project area is extracted from the fitted regional tectonic stress field. Taking the boundary load as the initial condition, and embedding the underground cavern to be studied into the calculation model, the numerical calculation of in-situ stress in the project area is carried out. Thus, the initial geostress field of the project area is obtained, and its basic characteristics are analyzed accordingly, so as to provide the basis for the research on the stability and layout optimization of the main caverns in the project area.

2. Materials and Methods

2.1. Regional tectonic setting.

The project area is located in the east-central part of Qinghai-Tibet Plateau, which belongs to the Nagqu-Luolong Yenshanian depression of Biru terrane in terms of tectonic units. It is adjacent to Southern Qiangtang depression of Qiangtang terrane in the north, Namco-Sangba late Yanshanian granite uplift belt of in the south, Shenzha-Duoxueku basement uplifted belt in the west and Jiayuqiao landmass in the east.

2.2. Regional stress field

The in-situ stress and modern tectonic activities in the western part of China are mainly determined by the collision of Indian and Eurasian plates and the compression of nearly S-N direction, and the tectonic stress is generally close to S-N direction. For specific parts, affected by lithology and structure, the direction of maximum principal stress in each region has changed, however the direction of maximum principal stress in large area has a strong control effect on it. Affected by the northward thrust of the Indian plate, the maximum principal stress direction of the tectonic stress field in the main part of the Qinghai-Tibet Plateau is NNE. On its northern and eastern edges, from the northern edge to the southeast to the southeast of the plateau, the direction of the principal stress gradually changes from NNE to NE, NEE, near E-W, SE to SSE directions (Fig. 2). The project area is located in the east-central part of Qinghai-Tibet Plateau, and the direction of regional tectonic stress is NNE~NE.
2.3. In situ stress measurement in adjacent area

There is no measured in-situ stress in the project area. According to the data retrieval, there are reports of in-situ stress measurement data in Yangbajing tunnel [17] and Bangpu mining area [18] near Lhasa area, and the locations of the two measuring points are shown in Fig. 2.

Figure 1. Geotectonic division of the study area [15].

Figure 2. Recent tectonic stress field in China and adjacent area [16].
It can be seen from the measured data of two places mentioned above that the direction of regional principal stress is NNE~NE, with an average of 37.9°. The maximum principal stress is 3.3~10.4MPa (including tectonic stress and gravity stress). If the gravity stress and Poisson's horizontal stress are simply deducted, the maximum horizontal tectonic stress is 3~10MPa, with an average of 5.0MPa.

In conclusion, the direction of the maximum principal stress of tectonic stress in this area is NNE~NE, and the value is about 5.0MPa.

2.4. Overview of the project area
The macro geomorphic morphology of the project area is characterized by large surface elevation difference and complex landform morphology. The factory area has abundant mountains and complete terrain. Small faults and fractures are developed in the project area, the extension length is generally less than 100m, and the width of fracture zone is generally 5cm-30cm. The scale of faults and fractures is so small that they are negligible compared with abundant mountains.

According to the survey data (Fig. 3 and Fig. 4), the stratum in the hydropower plant area is relatively single, and the main exposed strata are Quaternary (Q3, Q4) and Jurassic lagongtang formation (J2~3). The Quaternary (Q3, Q4) deposits are mainly distributed at the foot of mountain and gentle slope, and the accumulation thickness is thin. The lagongtang formation (J2~3) is mainly composed of gray black sandy slate locally mixed with metamorphic sandstone band, and the sandy slate is in thin layer structure.

2.5. Inversion model and parameters of regional tectonic stress field
In view of the main research purpose of regional tectonic stress, the topographic factors affecting the self-weight stress are not considered. Therefore, the blue box part in Figure 1 is taken as the calculation area, including the project area, Yangbajing tunnel and Bangpu mining area (Fig. 5). The physical and mechanical parameters of rock mass (Table 1) in each area are selected according to the regional stratigraphic data. The stress back analysis method is used to inverse the regional tectonic stress field, and the stress field is obtained, which provides the basis for the numerical calculation of the in-situ stress field in the project area.

| Number | Block belonging to | Elastic modulus $E$ (GPa) | Poisson's ratio $\mu$ | Cohesion $c$ (MPa) | Internal friction angle $\phi$ (°) |
|--------|--------------------|--------------------------|----------------------|-------------------|-----------------------------|
| I1     | Qiangtang block    | 35                       | 0.29                 | 0.9               | 36                          |
| I2     | Qiangtang block    | 35                       | 0.29                 | 0.9               | 36                          |
| I3     | Qiangtang block    | 35                       | 0.29                 | 0.9               | 36                          |
| II     | Nierong block      | 39                       | 0.28                 | 1.0               | 40                          |
| III1   | Lhasa block        | 45                       | 0.28                 | 1.2               | 45                          |
| III2   | Lhasa block        | 45                       | 0.28                 | 1.2               | 45                          |
| III3   | Lhasa block        | 45                       | 0.28                 | 1.2               | 45                          |
| III4   | Lhasa block        | 45                       | 0.28                 | 1.2               | 45                          |
| III5   | Lhasa block        | 45                       | 0.28                 | 1.2               | 45                          |

2.6. Calculation model and parameters of in-situ stress field in project area

2.6.1. Calculation range and coordinate system. The geometric range of the model includes the whole underground powerhouse system and diversion tunnel on the right bank, and the spillway tunnel on the left bank. At the same time, in order to ensure sufficient boundary influence range, the calculation area includes all the parts in Fig. 3, and the local extension is 300~400m. The lithology of the extended part is extrapolated based on the existing engineering geological research results (Fig. 3 and Fig. 4).
According to the characteristics of regional tectonic stress field revealed by regional geological data, the in-situ stress direction of the study area is mainly near S-N~NE direction, and the model is easy to produce displacement along the direction of in-situ stress after loading. Therefore, the E direction is taken as the positive direction of $x$-axis in the model coordinate system, the N direction as the positive direction of $y$-axis, vertical upward as the positive direction of $z$-axis, so as to ensure that the model coordinate system is consistent with in-situ stress coordinate system.

2.6.2. Calculation model. The lithology of the project area is relatively simple, mainly composed of medium and thin bedded slate, not much meta sandstone developed, and the overburden is thin, so all the lithology is represented by sandy slate in calculation. The faults in the project area are not developed and the rock mass is relatively complete, so it can be regarded as continuous medium.

In order to provide a basis for the subsequent stability study of underground caverns, the cavern to be studied is embedded in the calculation model. Due to the consideration of rock mass and main engineering, and considering terrain and geomorphic conditions, the calculation model adopts hexahedral and tetrahedral mixed discrete grid, as shown in Figure 6 (the blue part in the figure is the underground powerhouse system area).

![Figure 3. Engineering geological plan of the project area.](image)
2.6.3. Calculation parameters. In order to give consideration to the stability research of underground cavern, elastic model and elasto-plastic coupling constitutive model are used in the calculation. In order to speed up the calculation, elastic calculation is adopted first, and then the elastic-plastic calculation is adopted after the calculation convergence and balance (the same for cavern stability study). In the numerical calculation of natural stress field in the engineering area, the physical and mechanical parameters of rock mass (Table 2) are selected according to the previous research results.

| Lithology  | Density $\rho$ (kg/m$^3$) | Poisson's ratio $\mu$ | Elastic modulus $E$ (GPa) | Cohesion $c$ (MPa) | Internal friction angle $\phi$ (°) | Tensile strength $T$ (MPa) |
|-----------|---------------------------|-----------------------|---------------------------|-------------------|-----------------------------------|--------------------------|
| Sandy slate | 2600                      | 0.27                  | 7.83                      | 0.91              | 51.15                             | 0.72                     |

2.6.4. Boundary conditions and initial conditions.

(1) Boundary conditions

The top surface of the model is a free boundary.

The bottom of the model is taken as the fully constrained boundary, that is, there is no displacement in the horizontal and vertical directions.

The north and east sides of the model are sliding boundaries, that is, there is no northward horizontal displacement outside the northern boundary, but vertical displacement and east-west horizontal displacement can occur, while there is no eastward horizontal displacement outside the eastern boundary, but vertical displacement and north-south horizontal displacement can occur.

The south and west sides of the model are stress boundaries. The boundary stress is composed of initial tectonic stress and gravity stress, which is determined by its initial conditions.

(2) Initial conditions

Since the stress boundary conditions are adopted in the south and west sides of the model, the initial conditions should be determined in advance.

The self-weight stress of the south and west boundary of the model is considered according to the gravity of fresh sandy slate and Poisson effect, which is calculated and determined according to the boundary elevation.
The horizontal tectonic stress of the south and west boundary is mainly based on the research results of the regional tectonic stress field. The coordinate system (Fig. 5) adopted for the inversion of regional tectonic stress is the same as that used here (Fig. 6). Therefore, the stress $\sigma_x$ in the $x$ direction (E-W), the stress $\sigma_y$ in the $y$ direction (S-N) and the shear stress $\tau_{xy}$ of the boundary can be directly extracted from the results of the regional tectonic stress, which can be used as the horizontal tectonic stress of the west boundary and the south boundary respectively.

3. Results

3.1. Regional tectonic stress field
The calculation results (Fig. 7) show that the in-situ stress calculation results of Yangbajing tunnel and Bangpu mining area are basically consistent with the measured data, regardless of the magnitude or direction.
The calculated maximum principal stress values of Yangbajing tunnel and Bangpu mining area are 4.45~9.46MPa and 3.98~7.62MPa respectively, which are basically consistent with measured data. In the direction of the maximum principal stress, the calculated direction is also consistent with the measured data basically. The direction of Yangbajing tunnel is NE~E-W, and that of Bangpu mining area is near NE. In addition, the direction of the maximum principal stress in most areas near project area is NNE~NE (Fig. 7), which is basically consistent with the regional geological data, indicating that the calculation results well reflect the characteristics of regional tectonic stress field, and can be used to analyze the characteristics of in-situ stress field in the engineering area.

It can be concluded that the maximum principal stress direction of the project area is near NNE direction, and its variation range is NE13° to NE29°, and the maximum principal stress of tectonic stress field is $\sigma_1$=4.9MPa, and the minimum principal stress is $\sigma_3$=3.8MPa. Therefore, in the regional tectonic stress field of the project area, the direction of horizontal principal compressive stress is mainly NNE~NE, and the maximum horizontal tectonic stress is about 5.0MPa.

3.2. Initial geostress field of project area

In order to analyze the characteristics of the geostress field in the project area more intuitively, the calculation results (Fig. 8) are cut and analyzed, and the following rules are obtained.
The stress trace (Fig. 9a) shows that the direction of the maximum principal stress in the project area is near S-N~NE, which is consistent with the characteristics that the main compressive stress direction of the regional tectonic stress field is mainly NNE~NE, which indicates that the stress field of the project area is determined by the regional tectonic stress field.

However, due to the change of topography and geomorphology in the process of river undercutting, stress redistribution occurs, resulting in the deflection of principal stress direction. The stress trace on the dam axis section (Fig. 10a) shows that due to the stress redistribution, the principal stress trace near the slope surface deflect obviously, which shows that the closer to the free surface, the closer is the maximum principal stress parallel to the free surface and the minimum principal stress orthogonal to the free surface. With the increase of the depth into the slope, the stress gradually changes and tends to the gravity stress field.

In addition, stress concentration is obvious at the junction of slope and riverbed, and the difference of principal stress is large, which makes it easy to shear failure. Stress concentration also occurs in the riverbed, which is also shown that the maximum principal stress increases and the minimum principal stress decreases. However, the direction of principal stress is different from that of bank slope. The maximum principal stress is nearly horizontal, while the minimum principal stress is nearly vertical.

(2) Principal stress value

At the same elevation, the maximum principal stress on the surface of the bank slope decreases to a certain extent, and gradually increases inward and approaches to the natural stress (Fig. 9b, Fig. 10b). The results show that the stress field on both sides of the river is adjusted or redistributed due to river downcutting, which shows that the in-situ stress is not only partially released but also partially transferred to the deep, which leads to the stress differentiation of the bank slope, showing stress decreasing zone, stress increase zone and normal stress zone.
The physical and mechanical properties of rock mass are deteriorated due to the decrease of in-situ stress due to the existence of stress reduction area on the surface of bank slope, which accelerates the evolution process of external forces of rock mass, such as weathering, relaxation unloading, etc. As a result of these external forces, the physical and mechanical properties of rock mass in the valley area further deteriorate, and gradually develop into the interior of rock mass, forming different weathering zones and unloading zones with certain depth (Fig. 4).

At the same time of releasing the shallow stress of the bank slope, part of the stress transferred to the deep part of the bank slope, resulting in a certain degree of stress increasing area within the stress reduction area on both banks, which is the reason for the development of flaky stripping (Fig. 11) on the sandy slate layer at a certain depth range of some exploration adits. Moreover, the sandy slate with a certain thickness intersecting with the wall at a small angle in these parts is generally tensioned along the bedding plane (Fig. 12).

4. Conclusion
(1) The study area is located in the composite part of geotectonics, which is significantly affected by regional tectonic stress. Comprehensive analysis of regional tectonic stress field and in-situ stress measurement data of some projects in adjacent areas shows that the direction of regional tectonic principal stress is NNE~NE, and the average maximum horizontal tectonic stress is about 5.0Mpa.

(2) The direction of the maximum principal stress in the project area is generally the same as that of the regional tectonic stress field mentioned above, that is, NNE~NE direction is the main direction, which indicates that the valley stress field is generally determined by the regional tectonic stress field.

(3) Due to the influence of river incision, the in-situ stress field in the project area redistributes, resulting in the deflection of the principal stress direction. It is shown that the closer to the free surface, the closer is the maximum principal stress parallel to the free surface and the minimum principal stress orthogonal to the free surface. With the increase of the depth into the slope, the in-situ stress changes gradually and tends to self-weight stress field.
(4) At the same elevation, the principal stress on the surface of the slope decreases to a certain extent, and gradually increases inward and approaches to natural stress state, showing stress reduction zone, stress increase zone and normal stress zone. In addition, the stress concentration from the slope toe to the riverbed is obvious, and the difference of principal stress is large, which makes it easy to shear failure.

(5) Initial geostress field of the project area is a local stress field formed by the influence of river incision and other factors on the basis of comprehensive superposition of gravity stress and regional tectonic stress, which has the basic characteristics of deflection of principal stress direction and obvious stress differentiation.

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