Inversion of the 3D in situ stress field in a complex valley area around the underground cavern group of the Yingliangbao Hydropower Station

Hong Zheng*,1, Shengcun Yan2, Tao Chen2, Quan Jiang1, Xiantao Xiong3, Meng Li2, Chang Liu1

1 State Key Laboratory for Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
2 Sichuan Huaneng Luding Hydropower Co. Ltd., Chengdu, Sichuan 610072, China
3 PowerChina Chengdu Engineering Co., Ltd., Chengdu, Sichuan 610072, China

* Corresponding author: zhengh@whrsm.ac.cn; Tel: +086-87198805

Abstract. The inversion of three-dimensional in situ stress fields in complex river valleys is of great significance for evaluating the excavation stability of deep underground caverns. Based on known in situ stress measurements, it is a major method for obtaining the geostress of the engineering area through the inversion geostress of the whole area with the application of geomechanical mechanics. However, the inversion results are often limited by the geological structure and heterogeneous altered rock, as well as the measurement data reliability. A three-dimensional nonlinear neural network inversion was combined with a simulation of stratigraphic denudation by stages, tectonic compression, and alteration degree in the fault structure. The model was then applied to an underground cavern group of the Yingliangbao Hydropower Station. Comparative analysis showed that the inversion results were in reasonable accordance with the measured in situ stress values. Moreover, the reliability of the three-dimensional in situ stress field obtained using this method was further verified from the stress-induced failure during the cavern excavation. This technique is helpful for optimizing the design of subsequent excavation and reduces the potential instability of surrounding rock during a layered excavation.

Introduction

In large hydropower station engineering, many deep underground caverns are located in the complex river valleys along Yalong River and Dadu River, which produce a complex initial geostress field due to the evolution of the incised valley and complicated tectonic movement. During the excavation of these underground powerhouses, stress-induced failure occurs in the main position[1]. Therefore, the accuracy of magnitude and direction of the stress field influence the prediction and estimation of the failure type and degree of damage to the underground house directly. The initial geostress field, as the stress state inside the natural rock mass, is produced by gravity and various prior geotectonic movements. As a result of different physical properties in the rock mass and transformation from weathering and denudation environment, the geostress field is releasing and subjected to redistribution in residual stress form. However, the measured in situ stress does not reflect the in situ stress field distribution well because of the limited measure points. Therefore, an inversion of the geostress field is crucial for
underground engineering design and calculation analysis\(^{[2,3]}\). Usually, the geostress distribution of the whole region is retrieved through geological mathematics and mechanics based on the characteristics and laws in the measured in situ stress or other field information, such as the displacement\(^{[4-6]}\).

To simulate the in situ stress field in an area with strong geological action, the surface geological action is strong. The surface denudation and unloading effect caused by it significantly influences the distribution of the in situ stress field. Therefore, it is necessary to consider the unloading effect of surface denudation for a correct evaluation of the stress state of the regional in situ stress field\(^{[7-10]}\). Furthermore, the mechanical effects of the fault tectonic movement should be involved in the inversion model. This study developed a nonlinear initial geostress inversion approach by considering the impact of the stratigraphic denudation process and the alteration degree in the fault structure to reflect the unloading effect of the stratigraphic denudation, river erosion on the tectonic stress field, and the heterogeneous alteration in a fault zone. The ancient tectonic and stratigraphic denudation processes of the regional stress field of the valley area around the Yingliangbao underground cavern group were then simulated. The distribution characteristics of the regional stress field of this valley area were analyzed. The results provided a more reasonable stress boundary condition for dynamic feedback analysis of the Yingliangbao underground cavern group excavation.

**Overview of the Yingliangbao underground cavern group**

*Project layout*

The Yingliangbao Hydropower Station is the 14\(^{th}\) level power station in the latest 28-level plan of the mainstream of the Dadu River in Sichuan Province. It adopts the diversion type development, and the project scale is the large (Two) type in the second class. The general layout scheme of this station includes a concrete sluice and face rock fill dam, a left bank diversion system, and an underground powerhouse. Four power units with 270,000-kW and ecological units with 36,000 KW are installed in the powerhouse with a total installed capacity of 1,116,000 KW. This project adopts the water diversion development form. The factory site is located on the left bank of the Dadu River upstream of Huashibao, approximately 1000 m from the Guanyinya factory site (Figure 1). The bank slope lithology is mainly diorite, a medium to hard rock, with the conditions for the layout of large underground caves, so the underground plant type was adopted.

![Figure 1. Location of the Yingliangbao underground cavern group](image-url)
powerhouse, main transformer, and tailrace surge tank caverns, as well as several related connecting tunnels (Figure 2). Two machines, one room, and one hole are used for the indoor intersection. The section shape of the underground powerhouse cavern is a circular arch straight wall. The span of the top arch is 28.20 m; the span below the rock anchor crane beam is 25.40 m, and the maximum height is 66.8 m. The length of the main powerhouse, installation room, and auxiliary powerhouse is 129.50 m, 63.90 m, and 24.00 m, respectively, and the total length is 217.40 m. The main transformer with the section shape of a circular arch straight-wall type is arranged in parallel with the longitudinal axis of the main powerhouse that displays the following details: a span of 18.0 m, a maximum height of 25.80 m, and a total length of 171.50 m. Moreover, tailrace surge tank caverns share a span of 15.0 m, a length of 139.40 m, and a maximum height of 56.75 m.

Figure 2. Schematic diagram of the Yingliangbao underground cavern

Regional tectonic historical process
Yingliangbao underground cavern is located in the Junction compound site of the north head of the Sichuan-Yunnan SN-trending structural belt, the NE Longmenshan fault-fold belt, the NW Xianshuihe fault-fold belt, and the Jintang arc structural belt (Figure 3). The regional geological and structural background is complex. As the southernmost part of the Xianshuihe fault zone, the Moxi fault is approximately 6km away from the underground cavern site. The Regional Detuo fault is mainly controlled by the Detuo fault from the Erzi field on the right bank of the Dadu River to the upper reaches of Huashibao on the left bank. In the underground cavern group site, the II, III, IV, and V structure planes are developed with the main influence of the Detuo fault. Generally, the III and IV weak structure plane is the skeleton with joints and cracks as the matrix. They are distributed mainly in the hanging wall area of the F3 and F4 faults, with NW, NWW, and NEE dips, and middle and steep dips.
As the outcomes of multi-period tectonic movement and regional faults in geological history, the rock mass in the region near the Yingliangbao underground cavern is generally altered, particularly near the regional fault zone. This is because the joints and fractures near the faults are the main channels of hydrothermal solution migration, where hydrothermal alteration occurs in banded or planar form. The rock alteration degree can be divided into four categories according to the weathering degree, mineral composition, mineral arrangement, mineral alteration type, anisotropy, and rock type. In general, the orientation of the minerals is mainly near the Sn direction (NNW~NNE), which is consistent with the main tectonic direction.

There are three main internal and external dynamic factors of the topography, geomorphology, and in situ stress field in the region near the Yingliangbao underground cavern. The first factor is the complex contact relationship between the Proterozoic Jinning-Chengjiang intrusive rock and the surrounding rock. Second, the regional stratum accumulates a large horizontal stress due to the influence of the compression in the regional fault zone. Third, since the Cenozoic, the “U” shaped valley was formed by the severe erosion of the Dadu River, and the horizontal stress in the valley area was released to a certain extent. However, there would still be some residual tectonic stress in the rock mass affected by the topography.

**In situ stresses at the measuring points**

In the feasibility study stage, six groups of in situ stress tests were carried out in the stress relief method at the main exploration tunnels (Figure 4) near Yingliangbao underground cavern group. Table 1 lists the 3D principal in situ stresses at the measuring points around the underground powerhouse. The plunge is with the up-dip angle as positive.
**Figure 4.** Diagram of the location of in situ stress measuring points

| Measuring point | Lithology | Depth (m) | Principal stress | σ1    | σ2    | σ3    |
|-----------------|-----------|-----------|-------------------|-------|-------|-------|
| σPD06-1         | Diorite   | 240       | Magnitude (MPa)   | 16.48 | 6.32  | 3.51  |
|                 |           |           | Trend (°)         | 274.2 | 79.4  | 1.0   |
|                 |           |           | Plunge (°)        | -27.3 | -61.9 | 6.1   |
| σPD06-2         | Diorite   | 415       | Magnitude (MPa)   | 17.96 | 12.38 | 4.25  |
|                 |           |           | Trend (°)         | 299.4 | 51.2  | 354.7 |
|                 |           |           | Plunge (°)        | -31.8 | -30.9 | 42.6  |
| σPD06-3         | Diorite   | 560       | Magnitude (MPa)   | 18.50 | 8.44  | 6.02  |
|                 |           |           | Trend (°)         | 107   | 297   | 205   |
|                 |           |           | Plunge (°)        | 65    | 24    | 4     |
| σPD06-4         | Diorite   | 420       | Magnitude (MPa)   | 21.10 | 12.92 | 5.01  |
|                 |           |           | Trend (°)         | 289.1 | 119.0 | 20.2  |
|                 |           |           | Plunge (°)        | 19.2  | 70.5  | 3.1   |
| σPD11-1         | Diorite   | 150       | Magnitude (MPa)   | 10.83 | 7.46  | 3.16  |
|                 |           |           | Trend (°)         | 260.9 | 116.6 | 23.3  |
|                 |           |           | Plunge (°)        | 69.9  | 16.5  | 11.0  |
| σPD11-2         | Diorite   | 260       | Magnitude (MPa)   | 14.43 | 11.34 | 6.54  |
|                 |           |           | Trend (°)         | 253.1 | 15.2  | 140.8 |
|                 |           |           | Plunge (°)        | 30.5  | 42.1  | 32.8  |

**Table 1** 3D principal in situ stresses at the measuring points around the underground powerhouse

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Nonlinear inversion of the in situ stress considering strata denudation and alteration degree in the fault structure

From the perspective of geological evolution, the in situ stress field originated from an ancient tectonic stress field and formed from a long-term unloading process with strong erosion, denudation, and scouring during the formation of a deep valley. Therefore, it is essential to consider the effects of strata denudation and unloading to correctly understand and evaluate the stress distribution and in situ stress field. The Yingliangbao Hydropower Station project is located in the area of sharp changes in Dadu River topography, with high mountains, deep valleys, and steep slopes, which is a typical in situ stress field of the valley. Based on the principles of uniform design, artificial neural network, and stratum denudation, this chapter simulates the process of river valley formation and stress unloading in the area of the Yingliangbao Hydropower Station and carries out nonlinear inversion of this regional in situ stress field.
Three-dimensional numerical calculation model

The coordinate origin of the three-dimensional initial in situ stress field calculation model was selected at the intersection point of the 0+000 cross-section and the model boundary. The calculation range along the X-axis and Y-axis was 1673 m and 1332 m, respectively, vertically from an altitude of 0 m to the top of the mountain. The azimuths of the three coordinates are as follows: X-axis, S50°E; Y-axis, N40°E. The Z-axis coincides with the geodetic coordinates; Figure 5 presents their regional positions.

Figure 5. Schematic diagram of the numerical calculation model in the valley area

The topography and landform in the region around Yingliangbao underground cavern group reflect the strong internal and external dynamic geological action. The present in situ stress field results from long-term unloading by geological action, such as surface stripping and river erosion in river valley formation based on regional stress field construction in ancient times. The surface in the calculation model was assumed to be flat in ancient times to consider that influence, and the denudation of surface rock mass by external dynamic geological action was then simulated. A three-dimensional model of the calculation region was established, as shown in Figure 6, which contains 4.3 million elements and 3.3 million nodes. The geological conditions in this model are as follows:

1) The lithology in the region around the Yingliangbao underground cavern group is generally Jinning-Chengjiang diorite, which is slightly new with a marginally developed fracture.
2) The characteristics of heterogeneous alteration near the faults are considered, and the graded weakening characteristics of altered rocks are reflected using mechanical parameters.
3) According to the geological slice, four faults with a relatively reliable and non-negligible scale are classified as II structural planes. Inside the fault is the V-level rock mass, and its influence zone is a relatively IV-level rock mass. Because these four regional large faults have a specific influence on the in situ stress field, they are described as solid elements in the model.
Constitutive model and mechanical parameters of the rock mass

In the numerical calculation, it was assumed that the boundary of the engineering object area is gradually loaded. At the initial deformation phase of the rock mass, each rock element will be in an elastic state. When the stress state in rock exceeds the limitation of the elastic state, i.e., reaches the yield condition, further loading may subject the rock element to unrecoverable plastic deformation. The deep valley of the Dadu River at the Yingliangbao Hydropower Station was formed under the comprehensive action of surface denudation, river erosion, and geological tectonic movement in ancient times. The sloping rock of the deep valley has undergone different degrees of unloading process, accompanied by different degrees of elastoplastic deformation of the rock mass. During this process, the rock mass may suffer compressive shear and tensile failure. Therefore, the elastoplastic calculation method was adopted to simulate the unrecoverable deformation in a shallow rock mass caused by external dynamic action with the composite criterion of the Mohr-Coulomb and tensile failure criterion. The mechanical parameters in the calculation are derived from the design recommendations listed in Table 2.

| Parameters          | Diorite | Granite | Alteration degree A | Alteration degree B | Alteration degree C | Alteration degree D | Fault |
|---------------------|---------|---------|---------------------|---------------------|---------------------|---------------------|-------|
| Density (g/cm³)     | 2.6~2.7 | 2.98~   | 2.71~               | 2.75~               | 2.71~               | 2.61~               |       |
|                     |         | 3.01    | 3.06                | 2.77                | 2.75                | 2.74                |       |
| Elasticity modulus (GPa) | 6~15   | 11~18   | 7~12                | 6~10                | 5~9                 | 4~7                 |       |
| Poisson's ratio     | 0.23-0.27 | 0.21   | 0.19~               | 0.24~               | 0.24~               | 0.25~               | <0.2  |
|                     |         |         | 0.26                | 0.25                | 0.28                | 0.3                 |       |
| Shear strength c (MPa) | 0.6~1.4 | 0.44    | 0.3~0.6             | <0.2                |                     |                     |       |
| ψ                   | 0.7~1.3 | 1.06    | 0.5~0.7             | 0.35~0.5            |                     |                     |       |

The influences of the alteration degree of diorite or granite on the geostress distribution are described by considering the mechanical parameters of the affected region as five times the width of the faults and banded dikes as a gradient change from the fault to the surrounding rock.

Various geostress factors and computational conditions in nonlinear inversion

The characteristics of the measured in situ stress and background analysis of the regional geological show that the tectonic models in the Yingliangbao Hydropower Station, which significantly affected the present in situ stress field, are summarized as follows: gravity, compression in the X and Y direction, horizontal shear structure in the XY plane, horizontal shear structure in the YZ plane and ZX plane. Based on trial calculation results, the interval value of each factor could be determined by applying the
uniform design method in Table 3. According to the six factors with five levels in each interval value, the output sample in the neural network train and the test sample could be established.

**Table 3** The interval value of each factor in the uniform design

| Boundary condition | \( \sigma_g \) (m·s\(^{-2}\)) | \( \sigma_x \) \((10^4 m)\) | \( \sigma_y \) \((10^4 m)\) | \( \tau_{xy} \) \((10^4 m)\) | \( \tau_{yz} \) \((10^4 m)\) | \( \tau_{xz} \) \((10^4 m)\) |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Value             | 9~11              | 6~8               | 7.5~9.5           | 8~10              | 5.5~7.5           | 3.5~5.5           |

The balance calculation was performed on the aforementioned three-dimensional grid model and constitutive model with mechanical parameters. Subsequently, the excavation of surface elements was simulated layer by layer as the denudation and unloading process. Finally, the calculated stress at each measurement point was obtained as the input vector, while the corresponding boundary conditions were considered the output vector. The nonlinear mapping relationship between the geostress at the measuring point and boundary conditions in the calculation model was established. The optimal network structure and connection weight of the neural network were optimized using the genetic algorithm. Based on this mature network structure and training times, the measured stress values of in situ stress points were taken as the input vector. The output vector and the applicable boundary conditions were obtained through the neural network, as shown in Table 4.

The calculated data of the in situ stress field at six measuring points around the underground powerhouse could be obtained from the numerical simulation with the applicable boundary conditions. Compared to the measured in situ stress values, there were local minor differences between the calculated and measured values (Figure 7), but they were acceptable.

**Table 4** Calculation boundary conditions recognized by evolution neural network

| Boundary condition | \( \sigma_g \) (m·s\(^{-2}\)) | \( \sigma_x \) \((10^4 m)\) | \( \sigma_y \) \((10^4 m)\) | \( \tau_{xy} \) \((10^4 m)\) | \( \tau_{yz} \) \((10^4 m)\) | \( \tau_{xz} \) \((10^4 m)\) |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Value             | 9.91              | 3.83              | 4.74              | 8.24              | 6.78              | 3.32              |

![Figure 7](image_url). Comparison between the measured stress and calculated stress

**Geostress field Characteristics of the Yingliangbao Hydropower Station and field verification**

**Characteristics of the geostress field in the Yingliangbao Hydropower Station**
Based on the above inversion method, the three-dimensional in situ stress of the Yingliangbao Hydropower Station area was obtained, as shown in Figure 8. Figure 9(a) shows the vector diagram of maximum principal stress in the transverse section of the central axis at the 3# power generation unit. Figure 9(b) shows the vector diagram of maximum principal stress in the elevation section at an altitude of 1149 m. According to the figure, the maximum principal stress in the area near the Yingliangbao main powerhouse was 15 ~ 20MPa. The Yingliangbao underground cavern group area belongs to the middle and highland area and has specific zoning characteristics. The vertical and horizontal stresses were superimposed as the geostress in shallow ground, while the horizontal stress gradually dominates with increasing depth. The direction of the maximum principal stress near the Yingliangbao underground cavern group is consistent with the results of a regional geological survey, which is the EW–NWW direction.

Figure 8. Basic characteristics of the three-dimensional stress field of the river valley area

Figure 9. Vector diagram of the maximum principal stress in (a) transverse section of the central axis at 3# power generation unit and (b) elevation section at an altitude of 1149 m.

Figure 10 shows the contour and isosurface maps of the maximum and minimum principal stress in the longitudinal section of the main powerhouse. The underground powerhouse is located in the transition zone between the stress concentration zone and the stationary stress zone in the valley stress field. Moreover, the geostress contours in the influence zone of the fault or altered rock revealed an inflection shape.
Figure 10. Contour and isosurface maps of the (a) maximum and (b) minimum principal stress in the longitudinal section of the main powerhouse

Preliminary verification of failure mode of the surrounding rock

Rock spalling, as a common stress-induced failure, could occur several hours after excavation. With time, the surrounding rock gradually relaxes, cracks, and peels off from the surface to the inside, and the depth and range of the ganging gradually increase, and the failure can last for several days or longer. According to the maximum principal stress in the transverse section of the main powerhouse in Figure 9(a), it was predicted that rock spalling in the middle guide tunnel could occur mainly in the upstream side shoulder and downstream side foot. During excavation of the middle guide tunnel, obvious rock spalling took place at the upstream side shoulder, as shown in Figure 11.

Figure 11. Rock spalling occurred in the upstream side shoulder of the middle guide tunnel in the main powerhouse
At present, the second phase of the Yingliangbao underground cavern group has been excavated. The inversion of in situ stress conditions is taken as the loading boundary conditions of the numerical calculation model of underground caverns. The stress concentration area of the surrounding rock after excavation of the underground cavern was calculated. The stress concentration area is located mainly in the arch shoulder at the upstream side and the bottom of the downstream sidewall. This is consistent with the fact that the stress-induced spalling and falling blocks in the surrounding rock are mainly concentrated at the bottom of the downstream sidewall during excavation of the second floor of the main transformer chamber (Figure 12). The inversion of in situ stress was reasonable and reliable in terms of quantity and direction.

![Figure 12. Maximum principal stress contours of the main transformer chamber and corresponding stress-induced failure photo](image)

**Conclusions**

In this study, based on the initial measured geostress and other geological data, the boundary conditions of the three-dimensional inversion calculation model of the river valley area around the Yingliangbao underground cavern group were obtained. Considering the historical complex construction and landform characteristics, three-dimensional nonlinear neural network inversion combined with elastoplastic theory was applied in the simulation of stratigraphic denudation by stages and tectonic compression to illustrate the basic characteristics of the initial three-dimensional in situ stress field of rock mass in the complex valley area around the underground cavern group of the Yingliangbao Hydropower Station. The maximum principal stress in the Yingliangbao underground cavern group area was 15 ~ 20MPa. The underground powerhouse was located in the transition zone between the stress concentration zone and the stress–stationary zone in the valley stress field. The direction of the maximum principal stress is relatively consistent with the EW–NWW direction. Comparative analysis of the calculated values and the measured values showed that the inversion results were in reasonable accordance with the measured in situ stresses. The measured data tended to be discrete and restricted by the incomprehensive geological structure and in-site geostress measuring technique. The numerical inversion of the geostress field can only reflect the in-site geostress field in terms of the trends and magnitude. However, the numerical value cannot be entirely consistent with the actual stress field to a precise degree.

Based on the results of nonlinear initial geostress inversion by considering the impact of the stratigraphic denudation process and alteration degree in a fault structure, the stress concentration area of the surrounding rock after the second phase excavation of the underground cavern was calculated. The corresponding stress-induced failure at the bottom of the downstream sidewall verified that the inversion of the in situ stress is reasonable and reliable in terms of quantity and direction.

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