Construction of 3D geological model and multi-scale numerical analysis of in-situ stress field of long tunnel in fault development area

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Abstract. Affected by faults of different scales, there is a big difference between the local stress and regional stress in the crust. The Xianglushan tunnel of Central Yunnan Water Diversion Project is located in the Sichuan-Yunnan block with violent tectonic activity, and the tunnel passes through complex strata and fault development areas. Due to the limitations of testing methods, the measured stress data in Xianglushan tunnel project are mainly distributed in the relatively intact rock mass, so it is difficult to reflect the stress characteristics in the fault-affected area. Therefore, based on the tectonic geological data of Xianglushan tunnel, this article explores the construction method of multi-scale 3D geological model of fault development area. The corresponding information processing mechanism is established to realize the interactive interpretation, supplement and correction of fault data, and then gradually approach the actual situation of the geological body in the modeling process. According to the modeling method, a generalized large-scale model and a refined sub-model were established separately for the whole Xianglushan tunnel project area and the Longpan-Qiaohou fault affected area. At the same time, combined with the stress test data of Xianglushan tunnel, the first-stage stress field inversion calculation of large scale model is carried out based on multiple regression analysis method. The macroscopic stress field distribution characteristics of the strata and fault zones along the tunnel are preliminarily explored. From the first-stage inversion result, the displacement boundary conditions of the sub-model can be obtained by interpolation in the displacement field, which is applied to sub-model for the secondary elastic-plastic iterative calculation. Finally, the construction of the refined sub-model and the secondary elastic-plastic iterative calculation not only optimize the detail features of the initial stress field obtained by the first-stage
inversion analysis, but also reveal the disturbance law of the complex strata and
the Longpan-Jiaohou fault on the initial stress state, which has a high guiding
significance for the construction and support of tunnel engineering.

1. Introduction

Active faults have strong disturbance effects on crustal stress field, the change of stress state
is the direct cause of the instability and destruction of the underground caverns. Therefore,
exploring the distribution of in-situ stress in active fault zones is a key issue in tunnel design
and construction.

The Xianglushan tunnel of the Central Yunnan Water Diversion Project is located in the
western part of the Sichuan-Yunnan Rhombic Block. The entire tunnel passes through many
fault zones of different properties and scales. Each fault zone has experienced a long history
of geological development, and most of them are inherited faults. Among them, Longpan-Qiaohou fault, Lijiang-Jianchuan fault, and Heqing-Eryuan fault are all regional
active fault zones, which directly intersect the tunnel line and are closely related to the stress
distribution characteristics in the study area[1].

As we all know, active fault zones are the areas with high stress concentration or stress
release in the current in-situ stress field. Accompanied by continuous regional tectonic
movement, the faults will lead to the redistribution of in-situ stresses nearby. Therefore, the
variation rules of principal stress value and direction near the active fault are very complex. In
view of the limitations of in-situ stress testing, it is necessary to study the influence law of
active faults on the in-situ stress field through effective numerical simulation methods, and to
explore its internal mechanism.

2. Construction method of multi-scale 3D geomechanical model in active fault zone

2.1 Construction of large-scale complex geomechanical model crossing active fault area

In order to describe the geometric shape of fault structures and the contact relationship
between them, the main content of active fault modeling includes the generation of fault plane
and the cutting between fault planes[2]. Firstly, we need to obtain the geometric data and
activity properties of faults. These data mainly come from the geological plane and profile
data ( such as the occurrence, scale and spatial extension of the fault plane ), the underground
fault feature point data exposed by drilling or flat hole excavation and the profile data
obtained by geophysical prospecting method. How to make these data complement each other
and jointly control the spatial boundary characteristics of geological bodies is the focus of our
research.

By extracting the boundary intersection feature points of line elements and plane elements,
the topological relationship between each element can be established[3]. It should be noted that
the expression of geological profile is 2D information. Therefore, in the 3D modeling of
complex geological body, it is necessary to interpolate and encrypt the feature points of
stratum line and fault line based on drilling hole and excavation cavern data to form a 2D
profile close to the real stratum distribution. Then, multiple 2D profiles are mapped to 3D
space through coordinate transformation and arranged in accordance with a certain depth, so
that the corresponding stratum lines and fault lines of adjacent geological profiles are merged.
In addition, multiple fault planes often exist in complex fault networks, the contact relationship between fault planes should be hierarchically processed. According to the active property and active age, we can define the cutting path and use the path cutting algorithm to realize various intersecting relationships\(^4\). And the specific implementation process is shown in Figure 1 and Figure 2. Because the accuracy and reliability of borehole and tunnel excavation data are higher than other data, which can be used to correct the fault plane, thereby approaching the real fault plane\(^5\).

![Figure 1. Implication diagram of stratum and fault plane modeling](image1)

![Figure 2. Flow chart of complex fault network modeling](image2)

### 2.2 Construction of small-scale refined geomechanical model of fault zone

In the traditional modeling method, the fault zone is usually treated as a plane without thickness or volume. In this case, the fault structure and properties cannot be clearly expressed. In fact, the generation of fault has a time process. When the shearing force of the crust rock exceeds its own strength limit, micro-cracks first begin to appear. Under continuous action, microcracks gradually develop and unite, and strata dislocation occurred, eventually manifested in the form of fault\(^6\). In this process, fracture zones are formed along the sliding plane of the fault. At the same time, the rock mass near the sliding fracture zone also produced a large number of fissures due to stress changes, forming an induced fissure zone. Therefore, the internal structure of the active fault should include two parts: the sliding fracture zone and the induced fissure zone, as shown in Figure 3(a).

![Figure 3. Fault internal structure and modeling simplification method](image3)
In the process of 3D modeling, this paper simplifies the fault structure based on the influence degree on the stability of tunnel engineering. Active faults are generally large in scale and have the greatest impact on engineering. In order to reflect the nonlinear mechanical properties of active faults, the sliding fracture zone and induced fissure zone of active faults are completely constructed according to the geological data. The non-active fault does not slide for a long time, and its internal rock mass forms a complete fault disturbance zone after long-term geological cementation, which can be simplified as a single geological body. The specific modeling method is shown in Figure 3(b) and 3(c).

3. Multiple regression analysis of stress field in large-scale model of Xianglushan tunnel

Combining with geological survey data and rock physical mechanical parameters, the 3D geomechanical model of Xianglushan tunnel project area is constructed based on the above modeling method, as shown in Figure 4. As the model scope is 70km long and 35km wide, in order to avoid the calculation speed being too slow or even the calculation error caused by too much model grid element division, the strata and faults are greatly simplified and the elastic assumption is used for calculation.

Affected by the influence of three Holocene active faults in the study area, the measured stress statistical data have obvious zoning characteristics, and the maximum horizontal principal stress direction distribution\(^1\) is shown in Figure 5. In order to reasonably reflect the stress field difference along the tunnel, the study area is preliminarily divided into four sub-regions with the three Holocene active faults as boundary. And then the corresponding initial loading is performed on each sub-region boundary according to the stress value and direction. The stress field zoning and loading mode are shown in Figure 6.
According to the in-situ stress test results in 9 boreholes and the multivariate linear stress field regression analysis principle[7,8], nine independent variables can be obtained, namely regression coefficients (Respectively corresponding to gravity stress P0, north-south compressive tectonic stress P1 and P2, horizontal plane shear stress S1 and S2, east-west compressive tectonic stress P3 and P4, horizontal plane shear stress S3 and S4). Then the real boundary conditions can be obtained by combining the regression coefficients. Finally, the rock mass stress distribution in engineering area can be obtained by forward calculation.

The Xianglushan tunnel is more than 60 kilometers long and passes through different geological tectonic units, resulting in a complex distribution of stress fields along the tunnel. According to the stress field simulation results and the corresponding interpolation command, the stress component of Xianglushan tunnel line is extracted., and the variation curve of the principal stress with the stake number is shown in Figure 7. In the maximum buried depth of Xianglushan tunnel (more than 1400 m), the maximum horizontal principal stress are as high as 38 MPa, and the minimum horizontal principal stress is 27 MPa.

![Figure 5](image1.png)  
**Figure 5.** Direction distribution of measured maximum horizontal principal stress

![Figure 6](image2.png)  
**Figure 6.** Schematic diagram of boundary loading considering stress division

![Figure 7](image3.png)  
**Figure 7.** Distribution of principal stress value along Xianglushan tunnel
However, due to the stress release effect of active fault, the fault zones along the tunnel show that the vertical stress is greater than the maximum horizontal principal stress. And the original rock of tunnel sections mostly show the characteristics of \( \sigma_v > \sigma_h \), indicating that the stress field of the tunnel is dominated by horizontal stress. In this paper, the maximum horizontal principal stress lateral pressure coefficient is abbreviated as \( \lambda_h \), and the minimum horizontal principal stress lateral pressure coefficient is abbreviated as \( \lambda_h \). For the entire tunnel, in the depth range of 300-400m, \( \lambda_h \) is 1.3~1.8, and \( \lambda_h \) is 0.7~0.9; In the depth range of 400~800m, \( \lambda_h \) is 1.1~1.5, and \( \lambda_h \) is 0.6~0.8; when the depth exceeds 800m, \( \lambda_h \) is 1.0~1.1, and the \( \lambda_h \) is 0.6~0.8.

Figure 8. Contour cloud of maximum horizontal principal stress in Longpan-Qiaohou fault zone

The blocking and disturbance effect of active faults on stress field is clearly presented in Xianglushan tunnel, and there are obvious stress differentiation phenomena in the fault and its surrounding area. Due to space limitations, only the stress cloud profile of maximum horizontal principal near the Longpan-Qiaohou fault is shown in Figure 8. The stress value in this fault zone is significantly reduced, and the direction of the maximum horizontal principal stress is also deflected to varying degrees. The stress direction of the rock mass on both sides of the fracture is in NNE direction, while the internal stress direction distribution in the fracture zone is more complicated, ranging from NW5° to NW75°.

4. Refined simulation of stress field in Longpan-Qiaohou fault sub-model area

Due to the large scale of the calculation model in the above-mentioned study area, there is a large degree generalization for strata and faults, so that the first-stage simulation results cannot reasonably reflect the actual stress distribution characteristics of some tunnel sections, especially near active faults. In order to obtain a more reasonable stress field near the Longpan-Jiaohou fault zone, a refined geomechanical model is established as shown in Figure 9. In order to further improve the calculation accuracy, the fault zone composed of fracture zone and induced fissure zone is separately constructed by assigning different geological mechanics parameters. At the same time, the Mohr-Coulomb constitutive model is used for the secondary elastic-plastic iterative calculation, which can reflect the stress adjustment law of soft geological body when plastic deformation occurs.
Based on the first-stage simulation results, the displacement boundary conditions of the Longpan-Jiaohou fault sub-model can be preliminarily achieved by interpolating in the boundary node coordinate\(^9\). Then the sub-model is loaded and calculated, and comparing the calculated value with the measured value again to further verify the rationality of the calculated result of the sub-model\(^10\). If the error between the calculated value and the measured value is large, the boundary load is multiplied by the unit coefficient, and the measured value and the calculated value are subjected to a secondary fitting analysis to obtain the optimized sub-model boundary load. It should be noted that the secondary fitting analysis of the sub-model is completed on the basis of first-stage regression analysis results. Usually, only a little adjustment of the boundary load coefficient needed we can obtain satisfactory stress field simulation results in the sub-model area.

Figure 10 is the maximum principal stress cloud diagram of the tunnel profile in Longpan-Qiaohou fault zone. It can be seen that the fault produces a large disturbance to the stress field near it, and the stress value in the fracture-affected zone is significantly reduced, only 4–8 MPa. The upper plate stress of Longpan-Jiaohou fault is obviously lower than that of the lower plate, which reveals the general stress characteristics of active normal faults. The maximum principal stress value of the intact rock mass along Xianglushan tunnel is mainly 10–38 MPa, which is closely related to the stratum lithology. The stress value of hard rock (such as limestone, dolomite, basalt, etc.) is significantly higher than that of soft rock (such as slate, argillaceous sandstone, etc.). Therefore, the surrounding rock of tunnel at stake number DL15+300–DL16+500 is limestone and basalt with high strength, and the stress value is significantly higher than that of other tunnel sections.

Figure 10. Cloud diagram of maximum horizontal principal stress in Longpan-Qiaohou fault zone
The vector distribution of horizontal principal stress at tunnel elevation in Longpan-Jiaohou fault zone is shown in figure 11. It can be seen that the dominant direction of the maximum horizontal principal stress in the original rock along the tunnel is generally NNE-NE, which is consistent with the measured stress direction near the Longpan-Qiaohou fault. The figure also shows that the local position of the active fault zone is subjected to tension or compression, resulting in great differences on the principal stress direction inside the fault zone. The local stress direction is distributed in the NEE-EW direction and intersects with the fault trend at a large angle, indicating that this local fault zone is subjected to strong compression, such as the fault zone near the XLZK4 borehole. In addition, the local stress direction is distributed in the NNE-SN direction, which tends to be parallel to the fault trend, indicating that the fault zone is significantly stretched, such as the fault near XLP3ZK2 and XLP3-1ZK3 borehole. Therefore, the refined sub-model and secondary simulation can better reflect the complexity of the stress field characteristics in the Longpan-Qiaohou fault zone.

5. Conclusion
Based on the Xianglushan tunnel project, this article has carried out research on the three-dimensional modeling technology of complex geological bodies containing faults, systematically explored the implementation process of fault 3D modeling, and established a set of fault modeling technology scheme, thus realizing interactive interpretation, supplement and correction of fault data. It provides basic support for stress field simulation with different scales and accuracy.

In order to improve the accuracy of the large-scale stress field inversion of Xianglushan Tunnel, the model boundary conditions is made reasonable partitions according to the measured data and the active fracture distribution, and then the multiple regression analysis method is used for the stress field inversion calculation. The calculation results not only reveal the basic stress distribution law of the whole tunnel, but also provide a more accurate displacement boundary condition for the stress field refined simulation in the local active fault zone, which further realizing the effective transition from large-scale rough simulation to small-scale fine simulation.

The sub-model of Longpan-Jiaohou fault zone fully considers the geometric and mechanical properties of the local geological structure. Moreover, the in-situ stress field obtained by the second elastic-plastic iterative calculation based on the boundary condition interpolating from the first-stage inversion result is closer to the actual in-situ stress field, and
better reflects the influence of local fault structure on crustal stress, which can also provide
technical support for the excavation and support of tunnels crossing fault zones.

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