Inversion analysis of the complex initial stress field of an extra-long tunnel based on “overlapping partition-integration”

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Abstract: Tunnels in Tianshan are high-altitude highway tunnels, which are extra-long and high-cold. The distribution characteristics of the in-situ stress field of the entire project are crucial to the design and construction of the tunnel. Therefore, this paper first analyzes the hydraulic fracturing in-situ stress test results obtained during the preliminary and detailed survey stages of the engineering area. Second, the inversion of in-situ stress field of the super-long tunnel is proposed based on “overlapping partition-integration,” and a large-scale three-dimensional numerical model with overlapping partition is established. Finally, the in-situ stress field regression of the “overlapping partition-integration,” for inversion and stress field characteristic analysis of the entire engineering area are carried out based on the finite difference method. The results showed that the engineering area is primarily dominated by horizontal tectonic stress in the NNE-NE direction. When the buried depth of the tunnel is less than 300 m, between 300 m and 800 m, and greater than 800 m, the three principal stresses ($\sigma_1$, maximum horizontal principal stress, $\sigma_2$, minimum horizontal principal stress, $\sigma_3$, gravity stress of overlying strata) showed the characteristics of $\sigma_1 > \sigma_3 > \sigma_2$, $\sigma_1 > \sigma_2 > \sigma_3$, and $\sigma_2 > \sigma_1 > \sigma_3$, respectively. The “overlapping partition-combination” for inversion method of in-situ stress field could provide a reference for inversion of in-situ stress field of extra-long tunnel engineering.

1. Introduction
In-situ stress is an important basis for excavation design and construction of underground engineering. In the engineering field, in-situ stress testing is the most direct way to determine the stress field [1-2]. However, when in-situ stress is measured, a large number of tests cannot be performed due to the limitation of site conditions and fund constraints. Only a limited number of measuring points can be arranged in a local area for testing, and the test results can only reflect the stress field near the measuring points. Due to large buried depth and long line in extra-long tunnels, full-line testing from the surface before construction may be impossible. Therefore, it is extremely difficult to predict the distribution of in-situ stress field in the whole line of extra-long tunnel by relying solely on the measured in-situ stress.

At present, with the continuous development and progress of numerical simulation technology, scholars generally use systematic and effective numerical simulation methods to invert the distribution of in-situ stress field in the entire project area based on the measured in-situ stress results and geological data. Guo Huazhi[3] studied the determination of the calculation domain and the treatment
of boundary conditions in the numerical analysis of the initial stress field of rock masses and simplified the initial stress field as a linear superposition of the self-weight stress field and the tectonic stress field. Simultaneously, he pointed out that the calculation domain should generally be selected in the symmetry of the terrain, such as river valleys, watersheds, and the force of tectonic movement is reflected by the force or displacement exerted on the boundary. Dai Cong⁴, You Zhemin⁵, Wang Bo⁶, and Z. Zhang⁷ used the three-dimensional finite element multiple regression analysis method based on the hydraulic fracturing method data; they inverted and analyzed the stress field characteristics of super-large buried and extra-long highway tunnels such as Lanjiayan, Dapingshan, Cangling, and Daxiangling. A couple of cases provide a good reference for the stress field research of extra-long tunnel engineering when simulating the tectonic stress field in the axial direction of tunnel. Fig.1(a) presents the application of boundary load. Although the calculation domain covers the entire tunnel, the boundary load does not directly act on the engineering area within the tunnel axis under this working condition, inevitably weakening the structural action of the tunnel in the axial direction. Moreover, the stress at both ends of the tunnel entrance and exit will be abnormal due to the boundary effect, contrary to the engineering practice. In order to reduce this effect, the tunnel entrance and exit with shallow buried depth are abandoned, and the tectonic stress field in the axial direction of the tunnel is simulated, as shown in Fig.1(b). However, it is not difficult to find that the terrain of tunnel crossing is high in the middle and low at both ends, showing a hump shape. In either way, applying a boundary load to the end of the tunnel to simulate the tectonic stress field in the axial direction weakens the tectonic effect of the mountain above the highest point of the load.

In view of this, this paper takes the Tianshan Shengli extra-long highway tunnel in Xinjiang as the engineering background and puts forward the inversion method of in-situ stress field in the whole line of the extra-long tunnel. Based on the in-situ stress test results of the hydraulic fracturing method in the preliminary and detailed investigation stages, a large-scale three-dimensional numerical analysis model with overlapping partition is established, and the in-situ stress field in the whole engineering area is regressed and inverted based on the three-dimensional finite difference method to obtain the continuous stress field distribution along the axis of the entire tunnel.

2. In-situ stress test

2.1. Engineering situation

The Tianshan Shengli Tunnel is an extra-long high-cold and high-altitude highway tunnel with a total length of 22.035 km. It will become the longest highway tunnel in the world after completing the project. Simultaneously, it will become the transportation barrier between the north and south of the Tianshan Mountains, creating a safe, comfortable, fast, and efficient road transportation channel connecting northern and southern Xinjiang. The tunnel has a clearance of 11.0 m (width) × 5.0 m (height), a maximum buried depth of about 1120.0 m, and an overall axis direction of about 233°~210°. The area is located at a high altitude (2777.0~4113.0 m above sea level) and has medium to high mountainous area with tectonic denudation. The topography is undulating with strong rock weathering and developed glacier landforms.

The surrounding rocks of the tunnel consist of tuffaceous siltstone, carbonaceous slate, quartz schist, granite, granodiorite, granite porphyry, sandy slate, marble, and gneiss. The surrounding rock at the outcrop of the fault is Grade V, and the surrounding rock of the remaining tunnel sections is composed of Grade III and Grade IV with Variscan structure. Nearly 18 faults along the line strike in the NWW direction and intersect the tunnel axis at a large angle. Among them, the structures that have a great
influence on the tunnel are Bolokenu Aqikekuduke Fault(F6), Bingdaban Fault(Fw2), and thrust strikeslip fault(F7). Fig.2 shows the longitudinal section of the Tianshan Shengli Tunnel, where SZK-NO, and SKTS-NO are borehole locations.

![Schematic diagram of geological section and borehole location.](image)

**Figure 2.** Schematic diagram of geological section and borehole location.

### 2.2. Results of in-situ stress test

In order to obtain the distribution of in-situ stress field in the tunnel site, a total of 102 in-situ stress tests were completed in 12 holes near the tunnel axis in the locations shown in Fig.2. Among them, 25 directions of the maximum horizontal principal compressive stress were obtained. In view of a large amount of test data, the author has made statistics on all in-situ stress test results based on different lithology and depth (300 m as the boundary). Table 1 presents the statistical results.

| Lithology          | B.H. | H/m | H'/m | σ<sub>1</sub>/MPa | σ<sub>2</sub>/MPa | λ<sub>1</sub> | α<sub>1</sub> |
|--------------------|------|-----|------|-------------------|-------------------|------------|------------|
| Carbonaceous shale | SKTS05 | 407.0 | 306.1–383.1 | 22.2–25.7 | 13.5–16.8 | —/2.6–3.0 | N41°E    |
| Granodiorite       | SKTS05 | 407.0 | 195.1–278.3 | 16.8–22.6 | 9.3–13.2 | 3.2–3.4 | N36°E    |
|                    | SKTS07 | 610.4 | 119.8–583.9 | 12.1–28.1 | 7.4–18.5 | 2.7–3.7 | N28°E–N32°E |
|                    | SKTS14 | 658.0 | 210.8–574.8 | 6.8–17.8 | 4.3–12.0 | 1.1–1.2 | N17°E–N22°E |
|                    | SZK02  | 525.0 | 243.5–511.8 | 9.9–16.3 | 6.8–11.4 | 1.7/1.2 | N31°E    |
| Granite            | SKTS10 | 724.0 | 242.4–533.4 | 4.6–13.5 | 4.5–9.3 | 0.7/0.9 | N30°E    |
|                    | SKZK04 | 806.0 | 351.6–775.1 | 11.5–21.8 | 8.7–15.7 | —/1.1 | N31°E–N34°E |
|                    | SKZK05 | 778.0 | 231.8–762.4 | 8.4–20.2 | 5.7–12.7 | 1.5/1.1 | N36°E–N44°E |
|                    | SKZK06 | 381.5 | 327.2–353.4 | 11.7–12.3 | 8.1–8.5 | —/1.5 | N53°E    |
|                    | SKZK07 | 384.6 | 235.4–372.5 | 10.8–13.6 | 7.5–9.6 | 1.9/1.5 | N43°E–N51°E |
| Quartz schist      | SKZK02 | 525.0 | 341.1–492.7 | 11.6–14.8 | 8.0–10.5 | —/1.2 | N37°E    |
|                    | SKZK03 | 598.0 | 242.4–533.4 | 9.8–15.6 | 5.5–12.6 | 1.5–1.8 | N33°E–N36°E |
|                    | SKZK06 | 381.5 | 208.5–360.1 | 9.5–10.9 | 6.1–7.2 | 1.8–1.9 | N42°E    |
| Marble             | SKTS15 | 532.0 | 311.0–511.4 | 7.1–23.0 | 5.2–14.8 | 1.8–2.4 | N20°E–N46°E |
| Tuffaceous silstone| SKTS19 | 131.0 | 34.2–115.2 | 1.8–7.1  | 1.6–4.3  | 1.5–2.6 | N12°E–N23°E |

a borehole number; b borehole depth; c test depth; d maximum horizontal principal stress; e minimum horizontal principal stress; f lateral compression coefficient of maximum horizontal principal stress (σ<sub>1</sub>/σ<sub>2</sub>); g maximum horizontal principal stress direction.

The measured results show that the maximum horizontal principal stress σ<sub>1</sub> in the project area was found to be 1.8–28.1 MPa, whereas the minimum horizontal principal stress σ<sub>3</sub> was about 1.6–18.5 MPa. The maximum horizontal principal stress value near the pavement design elevation can reach 28 MPa. For the measured depth <300 m, the relations between three principal stresses are σ<sub>1</sub> > σ<sub>2</sub> > σ<sub>3</sub> (σ<sub>2</sub>-gravity stress of overlying strata). For the measured depth >300 m, the relations are σ<sub>1</sub> > σ<sub>2</sub> ≈ σ<sub>3</sub>. The maximum principal stress is horizontal whereas the predominant direction of the maximum horizontal principal stress measured in each borehole has a good consistency and is NNE to NE, consistent with the direction of the regional tectonic stress field. However, the stress results of each borehole are quite different. For example, the stress magnitudes of different lithologies are quite
diverse, as the stress magnitudes of the same lithology (such as SKTS05, SKTS07, SKTS14 boreholes). Based on the layout position of each borehole, the boreholes were arranged at the half slope of the valley due to the limitation of site topographic conditions. The comprehensive analysis shows that the difference in measured stress results fully reflects the influence of lithology, topography, geological structure, and other factors on in-situ stress, and the test results only represent the local stress field near the borehole. In view of the long tunnel, it is extremely difficult to predict the distribution law of the in-situ stress field in the whole line range, relying on the measured in-situ stress results with high discreteness.

3. Inversion of in-situ stress field with “overlapping partition-integration” method

In this research, the multiple regression analysis method is used for simulating the stress field. The in-situ stress field is considered the superposition of the gravity stress field, and the tectonic stress field and details are described in reference[8].

3.1. Inversion method of in-situ stress field based on “overlapping partition-integration”

In the conventional multiple regression inversion of the in-situ stress field and the simulation of the tectonic stress field in the axial direction of the tunnel, the boundary load is applied to the entrance and exit of the tunnel with low terrain, which weakens the tectonic effect of the mountain above the highest point of the load. Moreover, the regression stress values near the tunnel entrance and exit are distorted due to the boundary effect. In order to avoid these disadvantages, boundary loads should be applied from the side with high terrain to maintain the tectonism of the engineering area. For tunnel engineering with high terrain in the middle and low terrain at both ends, it is necessary to divide the tunnel engineering area at the watershed to ensure that the boundary load is applied from the high terrain in the middle of the engineering area to obtain a reasonable stress field distribution. Zhao De’an[9] divided Wushaoling extra-long tunnel into two subregions with shared boundary at the watershed and used the three-dimensional finite element multiple regression analysis method to analyze the in-situ stress field in the tunnel area. In this method, the in-situ stress field in the subregion is independent of each other. Although the distribution of in-situ stress field in each subregion is reasonable, due to the boundary effect, the stress at the shared boundary of subregions is unequal and has an undesirable staircase effect. Therefore, the stress field of each tunnel section can only be analyzed separately by region. Later, Yu Yunyan[10] divided the tunnel engineering with curved tunnel axis into two regular subregions with overlapping areas due to the limitation of geological map data of Liangshui Tunnel in which in-situ stress measuring holes appeared in zone I; however, zone II did not have. In order to analyze the stress field in the engineering area, a virtual measuring hole is created in the overlapping area of the two subregions. Based on the measured in-situ stress data, the in-situ stress field in zone I is obtained first by inversion. Afterward, the in-situ stress value at the virtual borehole in zone I is taken as the known stress point in the expansion analysis of zone II, thus

Figure 3. The calculation process of the “overlapping partition-combination” inversion method of in-situ stress field. Z1 and Z2 stand for two subregions. C1 stand for overlapping area. B1 and B2 stand for the boundary of C1.
expanding the in-situ stress field in the entire tunnel area. The method of virtual borehole provides a good idea for obtaining the stress field without in-situ stress measurement data in the adjacent area. However, due to the boundary effect, the stress field in the overlapping area of the two subregions is quite different. It is unreasonable to take the average as the in-situ stress field in the overlapping area. Therefore, based on previous studies, the author has put forward the inversion method of in-situ stress field on “overlapping partition-integration.” In order to briefly describe this method, the implementation process is illustrated by two simplest cases of overlapping partitions, and in turn, the multiple overlapping partitions can be recursively calculated. Fig. 3 shows the calculation flow chart of this method in detail as follows: (1) divide an extra-long tunnel into two subregions $Z_1$ and $Z_2$ with overlapping area $C_1$ at the watershed, ensuring that each subregion has measured boreholes; (2) set up a virtual in-situ stress borehole in the $C_1$ area; (3) regression and inversion of the in-situ stress field in $Z_1$ area; (4) the stress value of the virtual borehole of the $C_1$ area in the $Z_1$ area is used as the known stress data in the $Z_2$ area to invert the in-situ stress field in the $Z_2$ area; (5) the stress of the boundary $B_1$ of the $C_1$ area in the $Z_1$ area and the boundary $B_2$ of the $C_1$ area in the $Z_2$ area are respectively extracted as the stress boundary conditions of the $C_1$ area and the stress field in the $C_1$ area is calculated; (6) the stress fields of $(Z_1-C_1)$, $C_1$, and $(Z_2-C_1)$ areas are imported into the overall calculation model for balance calculation, and a continuous and reasonable stress field in the engineering area is finally obtained.

Notably, (a) when the project is partitioned, the overall calculation model should be directly partitioned, and the calculation units should be uniformly divided; (b) based on the principle of multiple linear regression, when the in-situ stress field is inverted for subregions $Z_1$ and $Z_2$, the boundary loads in the direction of horizontal tectonic action are applied from the side with high terrain, and the regression coefficients of self-weight conditions should be consistent.

3.2. Calculated partition and physical mechanical parameters

Based on the inversion method of in-situ stress field of “overlapping partition-integration,” the entire calculation domain of the engineering model covers the whole line of Tianshan Shengli Tunnel with a plane range of $X \times Y = 23\,000\,m \times 4\,000\,m$, including subregions $Z_1$ and $Z_2$ and overlapping area $C_1$. The calculation range of $Z_1$ area is $X \times Y = 14\,000\,m \times 4\,000\,m$, and there are eight measured in-situ stress boreholes in this range, including SZK02-SZK05, SKT05, SKT07, SKT10, and SKKT19. The calculation range of $Z_2$ area is $X \times Y = 10\,000\,m \times 4\,000\,m$, and there are four measured in-situ stress boreholes in this range, including SZK06-SZK07 and SKT14-SKT15. The overlapping area of $C_1$ has a width of 1000 m, which is the watershed area of the topography of the tunnel and has a virtual borehole in the middle. Seventeen faults and the types of surrounding rocks reflected in the geological profile are considered in the model. The $X$-axis is positive in the direction of pile number increase, and the azimuth is $212.5^\circ$. The $Y$-axis is positive, with the right line of the tunnel pointing to the left line. The $Z$-axis remains vertical with the bottom elevation is 0 m (subject to the right-hand rule). When the calculation model has mesh, the principle of “whole-partition” is strictly applied.
followed, and the elements near the tunnel and the measured in-situ stress boreholes are encrypted. Fig.4 presents the specific calculation range, partition, and elements. The surrounding rocks of the tunnel are composed of tuffaceous sandstone, quartz schist, granite, granodiorite, granite porphyry, sandy slate, marble, and gneiss. The surrounding rock at the outcrop of the fault has Grade V, and the surrounding rock of the remaining tunnel sections has Grade III and Grade IV. In this research, the initial stress field in the engineering area is inverted using three-dimensional finite difference software FLAC³D and Mohr–Coulomb elastic-plastic constitutive model. The mechanical parameters of rock were tested in the laboratory, and the recommended parameters are shown in Table 2.

| Lithology                        | Density (g/cm³) | Deformation Modulus (GPa) | Poisson’s ratio | Internal friction angle (°) | Cohesion (MPa) |
|----------------------------------|----------------|---------------------------|----------------|-----------------------------|----------------|
|                                  | III | IV | V  | III | IV | V  | III | IV | V  | III | IV | V  | III | IV | V  | III | IV | V  |
| Granite and granodiorite         | 2.79 | 18.5 | 5.5 | 1.2 | 0.25 | 0.30 | 0.35 | 48 | 39 | 27 | 1.40 | 0.65 | 0.20 |
| Marble                           | 2.75 | 13.0 | 4.5 | 1.1 | 0.25 | 0.32 | 0.40 | 45 | 37 | 26 | 1.20 | 0.62 | 0.15 |
| Quartz schist and gneiss         | 2.73 | 14.0 | 4.6 | 1.2 | 0.25 | 0.32 | 0.35 | 46 | 38 | 27 | 1.30 | 0.63 | 0.20 |
| Tuffaceous siltstone             | /   | 2.76 | /   | 4.2 | 1.1 | /   | 0.32 | 0.40 | /   | 36 | 25 | /   | 0.58 | 0.15 |
| Carbonaceous slate               | /   | 2.65 | /   | 4.0 | 1.0 | /   | 0.32 | 0.42 | /   | 34 | 25 | /   | 0.45 | 0.12 |
| Sandy slate                      | /   | 2.71 | /   | 4.0 | 1.1 | /   | 0.33 | 0.44 | /   | 32 | 25 | /   | 0.35 | 0.12 |

3.3. Results of stress field inversion

Based on the measured in-situ stress data of 12 boreholes (excluding the measured stress anomaly points) and the principle of multiple linear regression, the initial in-situ stress field of the Tianshan Shengli Tunnel project area was inverted according to the method of “overlapping partition-combination.” Due to a large amount of data, Table 3 compares only the measured values and calculated values of some measuring points with a depth >300 m and an impression direction. The results show that the error between measured and calculated values for some measuring points is relatively large due to the large difference in the lateral pressure coefficient (or stress value) of the maximum horizontal principal stress of each borehole. The measured value only reflects the characteristics of the local in-situ stress field near the borehole; however, the strata and faults were generalized in the numerical calculation model. The measured values of most measuring points have minor errors compared with the calculated values, and the stress values of some measuring points are even close to the same. Simultaneously, the measured values of the maximum horizontal principal stress azimuth for each borehole are consistent with the calculated values. Therefore, the in-situ stress field in the calculated area obtained by the regression is reasonable.

| B.H.     | H/m | Measured value/Calculated value | σH/MPa | σV/MPa | αH/° | B.H.     | H/m | Measured value/Calculated value | σH/MPa | σV/MPa | αH/° |
|-----------|-----|---------------------------------|--------|--------|------|-----------|-----|---------------------------------|--------|--------|------|
| SKTS05    | 383.1 | 25.0/25.0 | 16.8/15.8 | 41/33 | | SKZ02    | 492.4 | 14.8/22.0 | 10.5/15.0 | 37/39 |
| SKTS07    | 583.9 | 28.1/20.8 | 18.5/15.1 | 28/39 | | SKZ03    | 523.0 | 15.6/21.0 | 12.0/13.8 | 33/37 |
| SKTS14    | 429.2 | 15.3/16.7 | 10.3/11.4 | 17/14 | | SKZ04    | 475.1 | 15.6/23.2 | 11.7/17.4 | 34/63 |
| SKTS15    | 538.4 | 16.0/16.4 | 10.4/11.5 | 20/8  | | SKZ05    | 762.1 | 20.2/23.7 | 12.7/18.0 | 44/33 |
| SKTS16    | 511.4 | 23.0/22.9 | 14.3/13.0 | 34/26 | | SKZ06    | 327.5 | 10.9/16.7 | 7.2/14.0 | 42/51 |

Table 3. Comparison of measured and calculated values of in-situ stress
4. Analysis of stress field characteristics of the tunnel axis

The left-line tunnel is considered an example to analyze the characteristics of the stress field along the tunnel due to word constraints in the manuscript. Fig.5 depicts the contour map of horizontal principal stress distribution along the tunnel, and the stress distribution on the tunnel axis is presented in Fig.6. When the buried depth <300 m, the three principal stresses are characterized by \( \sigma_H > \sigma_\theta > \sigma_Z \). When the buried depth is in the range 300–800 m; the three principal stresses are characterized by \( \sigma_H > \sigma_Z > \sigma_\theta \). When the buried depth >800 m, the three principal stresses are characterized by \( \sigma_Z > \sigma_H > \sigma_\theta \). The stress distribution varies with the undulations of the topography, and the stress value in the fault-affected zone is significantly lower than that in the surrounding rock mass.

![Figure 5. Horizontal principal stress isochromatic cloud diagram of tunnel axis section.](image1)

![Figure 6. Principal stress distribution along the axial direction of the tunnel.](image2)

The maximum horizontal principal stress is less than 7 MPa at the tunnel entrance with a buried depth less than 100 m, which is equivalent to the stress value of SKTS19 borehole at the entrance. The maximum horizontal principal stress ranges from 7.5 MPa to 32.5 MPa, the minimum horizontal principal stress ranges from 3.3 MPa to 23.3 MPa, and the vertical stress ranges from 2.8 MPa to 31.0 MPa at pile numbers 76 + 000 m to 97 + 500 m with tunnel buried depth greater than 100 m. The stress of granite with tunnel pile number 84 + 900 m–86 + 000 m is higher, and the buried depth is 800–1000 m. This section lies between the compressional faulting of \( F_{w-11} \) and \( F_{w-12} \), and the compressive tectonism is the main reason for the high stress value. The maximum buried depth of the tunnel (about 1115 m, lithology is granite) is located near pile number 88 + 700 m, with the maximum horizontal principal stress of about 22.2 MPa, the vertical stress of about 24.7 MPa, and the minimum horizontal principal stress of about 15.5 MPa. For the tunnel exit with a buried depth less than 100 m, the maximum horizontal principal stress value near pile number 97 + 100 m is higher than other tunnel sections due to the influence of reverse fault \( F_{w-14} \). Moreover, the stress value of other tunnel exit sections is less than 5MPa, which is smaller than the entrance section. The topography is the main factor leading to this difference.

The azimuth angle of the tunnel route shows a “W” change trend of \( 57^\circ \rightarrow 25^\circ \rightarrow 41^\circ \rightarrow 28^\circ \rightarrow 40^\circ \) from the entrance to the exit. The azimuth angle of the maximum horizontal principal stress obtained by
inversion shows the “N” trend of $20^\circ \rightarrow 32^\circ \rightarrow 45^\circ \rightarrow 10^\circ \rightarrow 50^\circ$ in turn. The entrance section has a large intersection angle, which is not conducive to the stability of the tunnel surrounding rock. It is primarily influenced by the topography and geological structure of the deep-cut gully. The intersection angle of other tunnel sections is relatively small, which has a relatively weak influence on the stability of the surrounding rock of the tunnel.

5. Conclusion

An inversion method of “overlapping partition-integration” is proposed to obtain the distribution of the in-situ stress field of the entire tunnel line based on the engineering background of Tianshan Shengli Tunnel and the principle of multiple linear regression. The main conclusions are as follows:

(a) The measured stress in different boreholes has significant differences, owing to topography, geological and rock mass characteristics.

(b) When the buried depth of the tunnel is less than 300 m, between 300 m and 800 m, or greater than 800 m, the three principal stresses have shown the characteristics of $\sigma_1 > \sigma_h > \sigma_2$, $\sigma_1 > \sigma_2 > \sigma_h$, and $\sigma_2 > \sigma_1 > \sigma_h$, respectively. The engineering area is dominated by horizontal tectonic stress, with the maximum horizontal principal stress direction of NNE–NE.

(c) At the tunnel entrance, the angle between the maximum horizontal principal stress and the axial direction is large, which is not conducive to the stability of the surrounding rock of the tunnel.

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7. References

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