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Inversion analysis of the Three Dimension Geostress Field in **A** Tunnel

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Abstract. The initial geostress field is an important basis for the design and stability analysis of geotechnical engineering. The geostress field of the whole engineering area must be calculated by inversion analysis with the limited geostress data, because there are few measured geostress points. Based on the geological background of a tunnel in northern Hebei province and considering the influence of regional highly weathered, moderately weathered and slightly weathered stratum on the stress field, the 3D finite difference method and multiple linear regression method were used to calculate the three-dimensional geological model of the study region to get the optimal regression coefficient. It is found by comparing the regression value with the field measured value that the two values are equal in magnitude and close in direction, indicating that the geostress field calculated by regression is reasonable, then the distribution law of the geostress field in the study area is further analyzed on this basis. The results show that there is a stress concentration in the tunnel center, z peaking at 50m below the center, and decreasing in the left and right direction with a large stress gradient then getting out of the area of stress concentration and tending to be stable. The study area is a medium geostress area, based on gravity stress, the control effect of gravity stress field is gradually enhanced with the increase of buried depth. The research results have important value in the design and construction of tunnel in special geological conditions.

1. Introduction

The initial geostress of rock-soil mass, a natural stress in the stratum and not affected by engineering, is the fundamental force that causes the deformation of surrounding rock for excavation in the area with complex geostress. It is a necessary precondition for the stability analysis of surrounding rock as well as the excavation design and scientific decision-making of rock engineering. At present, because the geostress analysis in actual engineering areas is usually aimed at conciseness and accuracy, field monitoring of geostress field has been widely used in the study of geostress field for its effectiveness and directness. However, it is often limited by such conditions as regional engineering geological conditions and construction schedule requirements, so the conventional geostress field monitoring can only be used in the areas with complex geostress like fracture zones and faults in the engineering areas. The local stress around points can be reflected to a great extent by the adding of monitoring results from different measuring points. However, the measured results of geostress usually have high discreteness because there are fewer measuring points as well as many complex causes and influencing factors for the geostress field, together with certain human errors, so it is difficult to reflect the initial geostress characteristics of all project areas intuitively. In order to better meet the requirements of engineering design and construction, multiple linear regression method and 3D finite

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difference method were used for the inversion, analysis and research of the initial geostress field in this paper. The results of inversion analysis show that the difference between numerical simulation of inversion value and measured values is smaller. Compared with measured values, the inversion value has high continuity, which can well reflect the distribution of initial geostress field in study area and provide a basis for the design and construction of tunnels and other underground projects in the area with complex geostress.

2. Research on the inversion analysis of initial geostress field

At present, the inversion analysis of initial geostress field of rock-soil mass has been researched in many literature, the results suggest that geostress distribution in rock-soil mass is affected by many factors such as gravity stress field and tectonic stress field in geotechnical engineering area and temperature stress of rock mass, the formation lithology as well as groundwater characteristics, etc. The measured geostress is often taken as a reflect of the combined action of these factors, when the inversion of geostress field is the simulated reconstruction of various factors ^[1]. Due to its small error and high computational efficiency, the multiple linear regression method for geostress field inversion analysis has been well applied and popularized in practical engineering and research. Therefore, this method is used for geostress inversion in this paper.

2.1. Inversion calculation principle of geostress field

The principle of multiple regression method is to take the regression calculation value of geostress as the dependent variable, and the gravity stress field and tectonic stress field calculated by numerical calculation corresponding to the stress calculation value of the measuring point as independent variables. The regression equation is shown below:

$$\sigma_k = \sum_{i=1}^n l_i \sigma_k^i \tag{1}$$

Where k is the number of observation points, σ_k is the calculated regression value of observation point k, l_i is the multiple regression coefficient corresponding to independent variables, σ_k^i is the single column matrix of the calculated value of the corresponding stress component, n is the number of working conditions. For m observation points, the residual sum of squares by least square method is:

$$S = \sum_{k=1}^{m} \sum_{j=1}^{6} \left(\sigma_{jk} - \sum_{i=1}^{n} l_i \sigma_{jk}^i \right)^2$$
(2)

Where k is the number of observation points, σ_k is the calculated regression value of observation point k, l_i is the multiple regression coefficient corresponding to independent variables, σ_k^i is the single column matrix of the calculated value of the corresponding stress component, n is the number of working conditions. For m observation points, the residual sum of squares by least square method is:

$$\sigma_{jp} = \sum_{i=1}^{n} l_i \, \sigma_{jp}^i \tag{3}$$

2.2. Influence factors and boundary constraints of initial geostress field

The study area belongs to the deep valley area, and the geostress field in this area is greatly affected by the structure, weathering and denudation, etc., so the regularity of geostress field distribution is relatively complex. Based on the engineering geological conditions in the study area and inversion technique requirement, the following six factors are selected as basic factors of the initial stress field regression in this paper, which are gravity stress state, east-west horizontal compressive tectonic movement, north-south horizontal compressive tectonic movement, homogeneous shear tectonic movement on horizontal plane, east-west vertical homogeneous shear tectonic movement on the vertical plane and north-south vertical homogeneous shear tectonic movement on the vertical plane. Considering the uncertainty of the magnitude of geological tectonic movement, the tectonic displacement method is used in this paper to simulate and study regional geological tectonic movement ^[2]. Based on the above analysis, the regression of geostress field can be expressed as:

$$\sigma = (l_1 \sigma_1 + l_2 \sigma_{1\Delta}) + (l_3 \sigma_2 + l_4 \sigma_{2\Delta}) + l_5 \sigma_3 + l_6 \sigma_4 + l_7 \sigma_5 + l_8 \sigma_6 + l_9 \sigma^{\nabla} + \varepsilon_k$$
(4)

Where σ is the initial geostress value, σ_1 and σ_2 are 1cm uniform extrusion displacement applied along the east-west and north-south horizontal boundaries respectively, $\sigma_{1\Delta}$ and $\sigma_{2\Delta}$ are triangular distributed extrusion displacements with a vertical depth gradient of 10-2cm /m applied along the eastwest and north-south horizontal boundary, σ_3 and σ_4 are east-west and south-north uniform tangential displacements of 10cm applied on the horizontal plane respectively, σ_5 and σ_6 are east-west and southnorth uniform tangential displacements of 10cm applied on the vertical plane respectively, σ^{Δ} is the gravity stress value, ε_k is a random variable and 11 - 19 are regression coefficients.

3. The geostress inversion analysis model in study area

3.1. Engineering overview of the study area

The tunnel is in the northern mountainous area of Changshen Highway in Hebei Province. Due to the restrictions of special topography and landforms, it is through a mountain. However, because of the steep mountains and the valleys development in the study area, there are many V-shaped valleys with deep cuts and the bedrock is granite. And influenced by weathering in the north Hebei region, the depth of the highly and moderately weathering zone is up to 50m. Thus, there are many technical problems caused by complex stress field in the excavation and construction. Therefore, the above area is taken as an example for the inversion analysis on the regional geostress field to provide a reference for the geostress research in engineering area with similar topography and geology.

3.2. Analysis of geostress measured results

According to the topographic conditions in the study area, the aperture deforming method of 3-hole intersection was used in geostress measurement, that is, holes intersecting in 3 directions were drilled in the testing rock mass, then the pore deformation was measured when the stress is relieved, and the three-dimensional stress state at the measuring point was calculated according to the theoretical relation between pore deformation and stress ^[3].

During the engineering survey period in the study area, 7 holes were drilled in the tunnel excavation area, then three-dimensional geostress measurements were taken on these points respectively. The test results are shown in Table 1, where the measuring points numbered D1-D3 are in the left of the tunnel (the three measuring points are all in the left affected area of the tunnel), and the measuring points numbered D4-D7 are in the right affected area.

Table1 The results of geo-stress measurement in underground powerhousezone						
Number	Location	Height /m	Measured 1 /MPa	Measured 2/MPa	Measured 3 /MPa	
D1	Z01+14	67.6	5.32	10.14	5.05	
D2	Z02+43	76.2	5.24	10.48	4.98	
D3	Z04+62	84.3	5.19	10.10	5.15	
D4	Y01+17	39.1	6.41	10.37	6.33	
D5	Y02+15	36.8	6.59	11.27	6.41	
D6	Y03+35	71.7	5.47	9.64	4.21	
D7	Y04+57	92.1	5.12	8.14	5.42	

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3.3. Calculation scope and calculation model

Based on the engineering and hydrogeologic condition in the study area and the measuring point layout, meanwhile to eliminate the boundary effect of artificial boundary faults on key parts of the inversion model, the inversion calculation scope of the numerical model is as follows: the central axis is along the tunnel, x axis is perpendicular to the tunnel, y axis is along the tunnel, z axis is straight up in the tunnel. Considering the boundary constraint of numerical calculation and the actual engineering geological conditions of the study area, the calculation area is determined as shown in Figure 1. According to the above calculation zone diagram and regional engineering geological conditions, the three-dimensional finite difference calculation method and the More-Coulomb constitutive model were used to establish the three-dimensional geological model and generate the corresponding mesh, with A total of 164,243 tetrahedron elements and 32,484 nodes, shown in Figure 2. The highly, moderately and slightly weathered stratum in the study area is simulated in the calculation area. The specific mechanical parameters of rock mass in stratum is from the results of triaxial tests and parameter inversion, which is shown in the table 2.



Fig1 Sketch map of calculation zone

	Tablez Pal	rameters of rock meet	lanics		
	Unit weight 10 ⁴ N/m ³	Modulus of elasticity GPa	Poisson's ratio	Cohesion MPa	Frictional angle°
Slightly weathered granite	2.7	10	0.25	2.0	45
Moderately weathered granite	2.6	5	0.28	0.50	30
Highly weathered granite	2.6	2	0.35	0.10	22

Table2 Parameters of rock mechanics



Fig2 Three dimensional calculation model

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4. Analysis of geostress field inversion results

4.1. Comparation on regression coefficient analysis and inversion results of initial geostress

Six stress fields are calculated by the 3D finite difference method when six different loads including the gravity stress, the tectonic stress in y direction along the central axis, the tectonic stress in x direction perpendicular to the central axis, τ_{xy} the shear tectonic stress in xy direction, τ_{yz} the shear tectonic stress in yz direction and τ_{xz} the shear tectonic stress in xz direction are taken into account separately[4]. Then, based on the test data of three dimensional Geostress at 7 measuring points from D1 to D7 by the aperture deforming method of 3-hole intersection, multiple linear regression analysis was performed by Least squares, and the correlation coefficient is as follows: $l_1 = 1.3782$, $l_2 = 2.7753$, $l_3 = 0.0053$, $l_4 = -0.2436$, $l_5 = 1.6968$, $l_6 = -0.7389$, $l_7 = 0.8061$, $l_8 = -1.3324$, $l_9 = 1.0003$, $\varepsilon_k = 0.2037$, meanwhile, the multiple correlation coefficient r=0.7372. The regression coefficient is substituted into the regression expression of geostress field (4), which is expressed as:

$$= (1.3782 \ \sigma_1 + 2.7753 \ \sigma_{1\Delta}) + (0.0053 \ \sigma_2 - 0.2436 \ \sigma_{2\Delta}) + 1.6968 \ \sigma_3 - 0.7389 \ \sigma_4 \ (5) + 0.8061 \ \sigma_5 - 1.3324 \ \sigma_6 + 1.0003 \ \sigma^{\nabla} + 0.2037$$

In addition, further calculation shows that the regression residual sum of squares S = 10.9865, the regression sum of squares U = 334.2315, the significance test observation F = 95.3264 and when the level of significance was over 0.1 the critical value F = 1.3784. Therefore, it can be believed that the overall effect of the 9 independent variables is significant.

4.2. Comparation of geostress inversion results

 σ

After the above stress field regression calculation, the regression stress value at measuring points in the computational coordinate system can be further calculated. The comparison between the measured geostress value and the regression principal stress value and the stress component at the measuring point is shown in Figure 3 and Table 2 respectively. According to the analysis in Figure 3 and Table 3, the stress inversion regression analysis value at the measuring point is close to the measured stress value as a whole, fitting well on the magnitude of normal stress and slightly poor on that of shear stress. The main characteristics of the geostress field in the engineering area can be expressed by this inversion regression stress field.



Fig3 The histograms of measured and calculated geo-stresses of measuring points

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Number of	x		у		Z	
measure points	Measured value	Regressive value	Measured value	Regressive value	Measured value	Regressive value
D1	-4.73	-4.55	-9.06	-8.98	-3.95	-3.79
D2	-4.27	-4.88	-9.47	-9.52	-3.86	-3.67
D3	-4.17	-4.59	-9.13	-7.82	-4.10	-2.69
D4	-5.46	-4.86	-9.38	-8.92	-5.36	-3.14
D5	-5.52	-4.71	-10.24	-9.24	-5.44	-2.52
D6	-4.73	-4.63	-8.13	-8.26	-4.64	-3.40
D7	-4.10	-4.81	-7.08	-9.51	-4.42	-4.34

 Table3 (1)
 Comparison between measured and regressive principal stresses of measuring points

 Table3 (2)
 Comparison between measured and regressive principal stresses of measuring points

		F			
xy		yz		XZ	
Measured value	Regressive value	Measured value	Regressive value	Measured value	Regressive value
1.93	1.19	0.09	1.93	1.19	0.09
1.28	1.35	0.38	1.28	1.35	0.38
1.00	1.12	-0.00	1.00	1.12	-0.00
1.48	1.24	0.14	1.48	1.24	0.14
1.73	1.46	-0.08	1.73	1.46	-0.08
-0.23	1.29	0.01	-0.23	1.29	0.01
0.53	0.94	0.20	0.53	0.94	0.20
_	Measured value 1.93 1.28 1.00 1.48 1.73 -0.23 0.53	xyMeasured valueRegressive value1.931.191.281.351.001.121.481.241.731.46-0.231.290.530.94	xy Measured Regressive Measured value value value value 1.93 1.19 0.09 1.28 1.35 0.38 1.00 1.12 -0.00 1.48 1.24 0.14 1.73 1.46 -0.08 -0.23 1.29 0.01 0.53 0.94 0.20	xy yz Measured value Regressive value Measured value Regressive value 1.93 1.19 0.09 1.93 1.28 1.35 0.38 1.28 1.00 1.12 -0.00 1.00 1.48 1.24 0.14 1.48 1.73 1.46 -0.08 1.73 -0.23 1.29 0.01 -0.23 0.53 0.94 0.20 0.53	yyzMeasured valueRegressive valueMeasured valueRegressive valueMeasured value1.931.190.091.931.191.281.350.381.281.351.001.12-0.001.001.121.481.240.141.481.241.731.46-0.081.731.46-0.231.290.01-0.231.290.530.940.200.530.94

4.3. Distribution characteristics of inversion geostress field

Based on above relations between various tectonic stresses with stress field and their regression coefficients, the inversion geostress field is formed by the regression stress values calculated from all points in the entire calculation area by equation (5). Due to space limitation, only the inversion results of three-dimensional geostress, stress nephogram in axis section and stress nephogram in the sections 20m as well as 45m from tunnel axis are presented here, as shown in Figure 4-7.



Fig4 Contour maps of stress in three-dimensional model



Fig5 Contour maps of stress in section(x=50m)



Fig6 Contour maps of stress in section left axis from 20m(x=30m)



Fig7 Contour maps of stress in section left axis from 45m(x=5m)

After the comparation three-dimensional stress nephogram of above model and various sections, it can be seen that the influence of topography and engineering geological conditions on distribution of the geostress field in the engineering area is significant, while the effect of formation lithology (different surrounding rock) is small. Meanwhile, it is shown by the slope stress on two sides of valleys that the stress on the earth surface is relatively small and there is an obvious stress concentration at the bottom. From the earth surface to the bottom, the stress is enhanced with the increase of depth. The stresses near the surface differ greatly in numerical values, while the three values are gradually close from the surface to the buried depth of the tunnel.

4.4. Distribution law of inversion geostress field along buried depth and tunnel axis

Figure 8 shows the distribution of σ_x stress vertical the axis, σ_y stress along the axis, and σ_z stress along the height along the center line of the tunnel. Curves in the figure indicates that stress components decrease linearly as the height increases and the buried depth decreases. Within the buried depth of the tunnel, σ_x is between $3.92 \sim 7.96$ MPa, σ_y is between $3.99 \sim 8.16$ MPa, and σ_z is between $6.93 \sim 12.87$ MPa. Meanwhile, all stress components decrease near the boundary of different stratums. So, it can be further inferred that the influence of different stratums on the geostress is: all stress components drop sharply near the interface of different stratums while the stress components far away from the interface are also affected to some extent but they still have a good linear trend.

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Fig8 Distribution rule of geo-stress of tunnel along altitude

Figure 9 shows the distribution of the various geostress components along the axis of the tunnel at an height of 10m. The curve indicates that along the axis to the central area of the tunnel, the horizontal and vertical stresses, σ_x , σ_y and σ_z increase, but in the central area, the horizontal and vertical stresses, σ_x , σ_y and σ_z keep stable. Numerically, σ_x , σ_y , which indicates that the geostress in the study area is still dominated by the gravity stress, and the above curve also shows the same trend as the measured results. Meanwhile, considering that stress components changes linearly along the buried depth, the buried depth (h) is taken as a variable to fit the distribution of σ_x , σ_y and σ_z along the height in tunnel centerline by the equation of ah b. The fitting coefficients a and b in different conditions are obtained as follows. It is pointed out that the fitted equation is only suitable for height from -20 to 100m.



Fig9 Distribution rule of geo-stress at altitude 10m along powerhouse axis

4.5. Distribution law of side pressure coefficient along the buried depth and the tunnel axis k_x and k_y are the side stress coefficients vertical axis and along axis, which can be calculated by the calculation formula of the side stress coefficient $\begin{cases} k_x = \sigma_x / \sigma_z \\ k_y = \sigma_y / \sigma_z \end{cases}$. Figure 10 shows the distribution

curves of k_x and k_y . It can be observed from the curve that k_y grows with the increase of buried depth in the slightly weathered and moderately weathered rock stratum. However, the increase rate (slope) of k_y . in the moderately weathered stratum is much larger than that in the lightly weathered stratum, with about two times, and increases by 0.121 to 0.139 at the boundary between the lightly weathered stratum and the moderately weathered stratum. In the highly weathered stratum, in general, k_y . decreases as the buried depth increases, and the descending slope is between the increasing slope in the slightly weathered rock stratum and the moderately weathered stratum. Compared with k_y , the overall trend of k_x along the buried depth is more irregular. However, generally, with the increase in buried depth, k_x first decreases and then increases in different rock stratum, and there are repeated fluctuations near the rock stratum interface.



Fig10 Distribution rule of lateral pressure coefficient of tunnel along altitude

Figure 11 shows the distribution of the side pressure coefficient along the tunnel axis at 10m height. It is shown that from the tunnel entrance to the center, the side pressure coefficient gradually increases as the distance to the center decreases. Therefore, along the tunnel axis, the closer to the tunnel center, the stronger the control effect of the tectonic stress field, and the effect of the gravity stress field gradually weakens. However, since the side pressure coefficients are all less than 1, the geostress in this area is still mainly the gravity stress. The value of the side pressure coefficient near the center is obviously greater than that of other locations at the same depth, and there is little change in the side stress coefficient, generally between 0.611 and 0.627.



Fig11 Distribution rule of lateral pressure coefficient at altitude 10m along powerhouse axis

5. Conclusion

(1) Multiple linear regression analysis and finite difference were used for the inversion analysis of the initial geostress field in the study area. The regressive stress value fits well with the measured stress value, providing a reasonable three-dimensional initial geostress field for the design and construction of the tunnel axis layout.

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(2) The study area is a medium geostress area, and geostress in the shallow place is mainly tectonic stress. The control effect of gravity stress field is gradually enhanced with the increase of buried depth. The research results have important value in the design and construction of the tunnel axis layout.

(3) The geostress inversion analysis results show that the rock stratum has a great influence on the geostress field in the engineering area and there is a significant stress release effect near the boundary of the rock stratum. Within the buried depth of the tunnel, x is 6.9-8.6mpa, y is 13.8-17.1mpa and

z is 11.5-13.7mpa. The side geostress coefficient of the tunnel is 0.5-0.6 in vertical axis direction, and 1.1-1.30 in axis direction.

(4) There is remarkable stress concentration at the tunnel center, and the vertical depth of the stress concentration area reaches 30m. $_z$ peaks at 50m below the center, and decreases in the left and right direction with a large stress gradient then gets out of the area of stress concentration and tends to be stable.

(5) The side pressure coefficients in the study area are all less than 1, indicating that the geostress in the study area is mainly gravity stress. In addition, the values of the side pressure coefficients near the stress concentration area at the tunnel center are significantly larger than that at other parts at the same depth, with little change.

(6) The side pressure coefficients in the study area are all less than 1, indicating that the geostress in the study area is mainly gravity stress. In addition, the values of the side stress coefficients near the stress concentration at the center of the tunnel are significantly larger than that at other locations at the same depth, with little change.

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