IOP Conference Series: Earth and Environmental Science

Analysis of stress state of transversely isotropic weak rock stratum

To cite this article: Li Zhe *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **692** 042116

EMCEME 2020 IOP Publishing
IOP Conf. Series: Earth and Environmental Science **692** (2021) 042116 doi:10.1088/1755-1315/692/4/042116

Analysis of stress state of transversely isotropic weak rock stratum

Li Zhe$^{1, 2, *}$, Zhang Guangze^{3}, Chen Enyu^{4}

^{1}Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, 430071, China
^{2}University of Chinese Academy of Sciences, Beijing, 100049, China
^{3}China Railway Eryuan Engineering Group Co., Ltd,Chengdu,Sichuan, 610031, China;
^{4}The third engineering company of China Gezhouba Group, Xian, Shanxi, 710000, China

*Corresponding author: lizhe18@mails.ucas.ac.cn

Abstract. In geotechnical engineering excavation and design, in-situ stress field is a factor that engineers must consider. However, in practical engineering, the testing method of in-situ stress in weak rock stratum is not mature, and how to obtain the distribution of in-situ stress field in weak rock stratum efficiently and accurately has become a research hotspot. According to the in-situ stress test results of known rock strata, based on the principle of deformation coordination of adjacent rock strata, the stress state of rock strata which is difficult to carry out in-situ stress test is deduced. It is considered that considering the transverse isotropy of rock strata will greatly improve the prediction accuracy, which is verified by ABAQUS finite element model. The results show that the transverse isotropic model is far superior to the isotropic model in predicting the distribution of ground stress field in rock strata (shale, slate, etc.) with obvious anisotropy. However, the greater the ratio of elastic modulus between horizontal and vertical direction, the smaller the ratio of elastic modulus between horizontal and vertical direction, and the greater the difference between the predicted and measured rock stress states. The obtained conclusions are applied to the estimation of ground stress of Que Ge Ka fault in Litang Tunnel, sichuan-tibet railway, which provides sufficient theoretical basis for the classification of large deformation in the process of tunnel excavation and design.

Keywords: Ground stress; Transverse isotropy; Soft and hard interbedding.

1. Introduction

In-situ stress is an important basis for stability analysis of surrounding rock in underground engineering construction. Obtaining in-situ stress field is the premise of rock burst and large deformation prediction and classification, and its reasonable value is particularly critical in the design of excavation and support in geotechnical engineering [1-4]. At present, the commonly used in-situ stress testing methods include hydraulic fracturing method and stress relief method, both of which require rock to be relatively complete, especially the stress relief method requires drilling and coring to have higher requirements on rock mass integrity, so the existing in-situ stress testing is mostly carried out in intact rock mass, and its in-situ stress testing results are difficult to reflect the real in-situ stress status of weak rock mass such as fault fracture zone [5-6]. With the development of engineering construction, more and more attention has been paid to the in-situ stress measurement of weak rock mass, and new in-situ stress measurement methods have been put forward continuously, such as rheological stress recovery method to determine the stress state of measuring points based on the rheological properties of soft rock. However, this method has high requirements for the depth of in-situ stress test and rheological properties of rock mass, and the process is complex and the monitoring time is long, so it has not been fully popularized [7-8]. Therefore, the current method is difficult to accurately estimate the in-situ stress field of weak rock mass, which leads to a big difference between the predicted results of large deformation and the measured results. It is necessary to propose a method to accurately estimate the in-situ stress of soft rock in fault fracture zone based on the in-situ stress test results of complete rock mass.

Liu Jiang [9] completed the original rock stress measurement at 10 measuring points in Yitai mining area by using the small hole hydraulic fracturing in-situ stress measurement device, and emphatically analyzed the relationship between in-situ stress value and buried depth. Li wenping [10] gives the estimation results of the in-situ stress values of adjacent coal seams according to the measured in-situ stress results of a small number of hard layers. Yang Jianping et al. [11] deduced the relationship between stress distribution and rock mechanical properties, which was verified by finite element method and field measurement results. Li Jing [12] analyzed the in-situ stress distribution law and its influencing factors under the seepage-stress coupling action, and studied the influence of fault occurrence on the orientation and magnitude of in-situ stress. Xu Hailiang [13] studied the influence of the maximum horizontal principal stress on tunnel deformation and settlement, and thought that when the horizontal principal stress was greater than the vertical principal stress, the change of the maximum horizontal principal stress had little influence on its horizontal displacement. When the vertical principal stress is greater than the horizontal principal stress, the change of the maximum horizontal principal stress has little effect on its vertical displacement. Sharla Cheung et al. [14] simulated and calculated the initial geostress field in the tunnel site area according to the field geostress measured data and the structural environment of the tunnel site area, and predicted the rock burst disaster in the tunnel site area based on the strength theory. Scholars have proved through numerical simulation technology, theoretical formula derivation and in-situ stress measurement that the in-situ stress in fractured zone is lower than that in surrounding intact rock area, but few scholars consider the transverse isotropy of rock when analyzing the in-situ stress distribution. Both coal seam rock mass and shale and slate rock mass, which are common in long and deep tunnels, can be regarded as typical transversely isotropic materials. Considering its transversely isotropic properties, the estimation of its stress state can be made more accurate.

In this paper, it is considered that under the condition of elastic rock mass, based on the principle of deformation coordination and consistency of soft and hard rock, the transverse isotropy of horizontal rock in elastic state is fully considered, and the stress state of soft rock mass is reasonably speculated, which is extended to non-horizontal rock mass based on coordinate transformation. It provides a theoretical basis for in-situ stress estimation of weak rock strata which is inconvenient to measure in-situ stress.

2. Stress state analysis of soft and hard interbedded rock mass

2.1. Basic assumptions

As shown in Figure 1, a horizontal interbedding model of soft and hard rocks is given. Superscript w and s of stress component represent weak rock stratum and hard rock stratum respectively. To simplify the analysis, the following assumptions are adopted: (1) The x and y directions (horizontal direction) are much larger than the z direction (vertical direction).(2) Rock is homogeneous and transversely isotropic with five independent elastic parameters.(3) The rock mass is above the critical buried depth, so the linear elastic theory is applicable. It is considered that the stress state of any two points in the same rock stratum is the same.

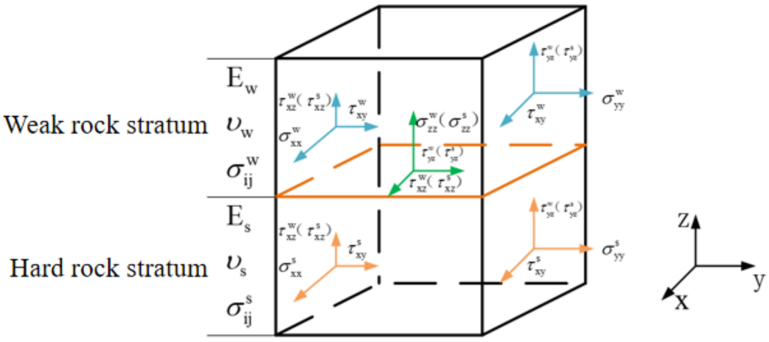


Figure 1 Schematic diagram of soft-hard interface

2.2. *Stress analysis and strain analysis*

Obviously, according to the static equilibrium equation, if the force F on the interface between soft and hard rock is the same, the three stress components σ_z, τ_{xy} and τ_{xz} produced by F in xy plane must be equal in both hard rock and weak rock.

$$\begin{aligned} \sigma_{zz}^{w} &= \sigma_{zz}^{s} \\ \tau_{xz}^{w} &= \tau_{xz}^{s} \\ \tau_{yz}^{w} &= \tau_{yz}^{s} \end{aligned} \tag{1}$$

Because the rocks are continuous and uniform, the strains of adjacent soft and hard rock interbeds must be the same.

$$\begin{aligned} \varepsilon_{x}^{w} &= \varepsilon_{x}^{s} \\ \varepsilon_{y}^{w} &= \varepsilon_{y}^{s} \\ \varepsilon_{z}^{w} &= \varepsilon_{z}^{s} \end{aligned} \tag{2}$$

Literature [9] has deduced the stress state of the weak rock adjacent to the hard rock according to the stress-strain relationship curve of isotropic rock mass, as shown in formula (3)

$$\begin{aligned} \sigma_{xx}^{w} &= \frac{\frac{E_w}{E_s}[(1-\upsilon_s\upsilon_w)\sigma_{xx}^{s}-(\upsilon_s-\upsilon_w)\sigma_{yy}^{s}-\upsilon_s(+\upsilon_w)\sigma_{zz}^{s}]+\upsilon_w(1+\upsilon_w)\sigma_{zz}^{w}}{1-(\upsilon_w)^2} \\ \sigma_{yy}^{w} &= \frac{\frac{E_w}{E_s}[(1-\upsilon_s\upsilon_w)\sigma_{yy}^{s}-(\upsilon_s-\upsilon_w)\sigma_{xx}^{s}-\upsilon_s(1+\upsilon_w)\sigma_{zz}^{s}]+\upsilon_w(1+\upsilon_w)\sigma_{zz}^{w}}{1-(\upsilon_w)^2} \\ \tau_{xy}^{w} &= \frac{E_w(1+\upsilon_s)}{E_s(1+\upsilon_w)}\tau_{xy}^{s} \end{aligned} \tag{3}$$

The stress state in soft rock area obtained by using the stress-strain relationship of transversely isotropic rock mass is as shown in Formula (4). It can be seen from Formula (4) that the transversely isotropic material mechanical properties of rock stratum will only affect the presumed values of σ_{xx}^{w}

and σ_{yy}^{w}, but have no effect on the value of τ_{xy}^{w}. However, in underground engineering construction, the value of principal stress will have a greater impact on the engineering construction area, so the influence of mechanical properties of transversely isotropic rock mass on its stress state is studied.

$$\begin{aligned}
\sigma_{xx}^{w} &= \frac{\frac{E_w}{E_s}[(1-\upsilon_s\upsilon_w)\sigma_{xx}^{s}-(\upsilon_s-\upsilon_w)\sigma_{yy}^{s}-\upsilon_s'(\frac{E_s}{E_s'}+\upsilon_w)\sigma_{zz}^{s}]+\upsilon_w'(\frac{E_w}{E_w'}+\upsilon_w)\sigma_{zz}^{w}}{1-(\upsilon_w)^2} \\
\sigma_{yy}^{w} &= \frac{\frac{E_w}{E_s}[(1-\upsilon_s\upsilon_w)\sigma_{yy}^{s}-(\upsilon_s-\upsilon_w)\sigma_{xx}^{s}-\upsilon_s'(1+\frac{E_s}{E_s'}\upsilon_w)\sigma_{zz}^{s}]+\upsilon_w'(1+\frac{E_w}{E_w'}\upsilon_w)\sigma_{zz}^{w}}{1-(\upsilon_w)^2} \\
\tau_{xy}^{w} &= \frac{E_w(1+\upsilon_s)}{E_s(1+\upsilon_w)}\tau_{xy}^{s}
\end{aligned} \tag{4}$$

Note: E is elastic modulus perpendicular to isotropic plane, E' is elastic modulus parallel to isotropic plane, υ is Poisson's ratio in isotropic plane, and υ' is Poisson's ratio of strain in isotropic plane caused by elastic symmetry axis.

2.3. *Influence analysis of strata occurrence*

Generally speaking, the rock stratum encountered in engineering construction is often not horizontal. To satisfy the hypothesis, it is necessary to transform the coordinate system of stress state into a plane coordinate system with the strike of rock stratum or fault plane as X axis, the inclination as Y axis and the vertical direction as Z axis. The principle of coordinate transformation is as follows:

Let x, y and z be the original coordinate system, and x', y' and z' be the new coordinate system. Let $l_{ij}=\cos(x_i', x_j)$ be the cosine of the angle between x_i' axis and x_j axis, such as $l_{12}=\cos(x', y'), l_{32}=\cos(z', y)$. The matrix expression of stress component transformation formula for the same point in different coordinate systems is:

$$[\sigma']=[\beta][\sigma][\beta]^T \tag{5}$$

Note: $[\sigma']$ is the stress state matrix in the new coordinate system,

$[\beta]$ is the transformation matrix of coordinate transformation

$[\sigma]$ is the stress state matrix in the original coordinate system

Among them, the stress matrix [σ']and transformation matrix [β] of the new coordinate system are:

$$[\sigma']=\begin{pmatrix} \sigma_x' & \tau_{xy}' & \tau_{xz}' \\ \tau_{xy}' & \sigma_y' & \tau_{yz}' \\ \tau_{xz}' & \tau_{yz}' & \sigma_z' \end{pmatrix}$$

$$[\beta]=\begin{pmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{pmatrix} \tag{6}$$

The angle γ between S_H, S_h, S_V and S_v and due north direction can be generally obtained from the traditional in-situ stress test results of small fracturing, and its stress state is:

$$[\sigma_s]=\begin{pmatrix} S_H & 0 & 0 \\ 0 & S_h & 0 \\ 0 & 0 & S_v \end{pmatrix} \tag{7}$$

Considering that the transversely isotropic plane (soft-hard interface plane) is the horizontal plane of the new coordinate system, the inclination of the plane is α, the inclination is β, the direction of the plane is set as X' axis, the inclination is Y' axis, and the direction of the vertical plane is Z' axis, then its transformation matrix is

$$[\beta']=\begin{pmatrix} \sin(\alpha-\gamma) & -\cos(\alpha-\gamma) & 0 \\ -\cos(\alpha-\gamma)\cos\beta & -\sin(\alpha-\gamma)\cos\beta & \sin\beta \\ \cos(\alpha-\gamma)\sin\beta & \sin(\alpha-\gamma)\sin\beta & \cos\beta \end{pmatrix} \tag{8}$$

It is not difficult to find that according to the azimuth angle of the maximum horizontal principal stress in the survey area and the occurrence of the soft and hard interbedded layers, the stress state of the survey points in the plane coordinate system can be obtained. Under the plane coordinate system, the transversely isotropic plane of rock stratum can be regarded as horizontal plane to solve the stress in weak rock stratum area analytically.

3. Numerical verification

3.1. Finite element model

The dimensions of the finite element model in x, y and z directions are 200m × 200m × 600m respectively. Along the z axis, there are interbedded layers of hard rock and weak rock. The thickness of each layer is 100m. There are three layers of hard rock and three layers of weak rock. The boundary conditions are set as ground and side displacement constraints. Considering the practical engineering application background, the lateral pressure coefficient is set as 1.2. The finite element model is shown in Figure 2, and a total of 3000 meshes are generated.

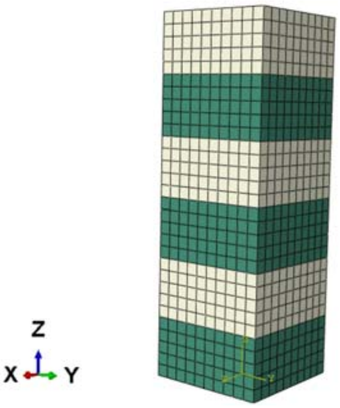


Figure 2 Three-dimensional finite element model

3.2. Attribute assignment of isotropic and transversely isotropic materials

According to the mechanical parameter selection of Class III and Class V surrounding rocks suggested in the project, the isotropic and transversely isotropic rock material properties are given to hard rock and weak rock respectively [13]. The stress distribution of isotropic rock mass and transversely isotropic rock mass under the same conditions is studied. Its parameters are shown in Table 1.

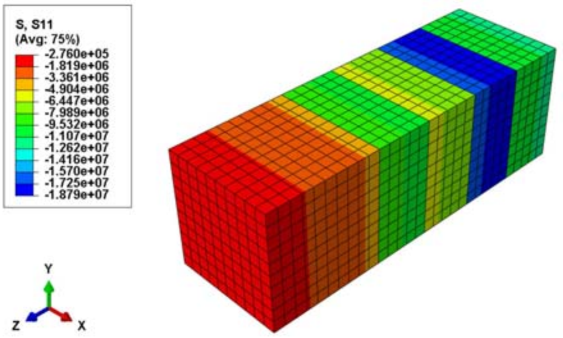
Table 1 Transversely isotropic and selection of mechanical parameters of isotropic materials

Model	Rock character	Serious	Modulus of elasticity(MPa)		Poisson's ratio	
			E1	E2	V1	V2
Isotropy	V	1700	1	1	0.4	0.4
	III	2300	6	6	0.3	0.3
Transversal homogeneity	Weak rock stratum	1700	1	1.5	0.4	0.37
	Hard rock stratum	23000	6	7.2	0.3	0.28

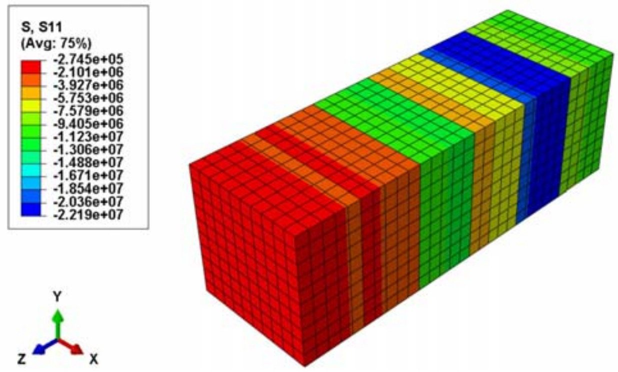
In-situ stress field is generally linearly superimposed by self-weight stress field and tectonic stress field. In reverse faults with complex stress conditions, the stress state is generally SH > SH > SV [14-15]. By applying horizontal load to simulate the tectonic stress field, the lateral pressure coefficient is about 1.2, which is linearly superimposed with the self-weight stress field to simulate the in-situ stress field in the engineering construction area. As shown in Table 2 and Figure 3, on the whole, the simulation results are good and close to the calculation results. The horizontal stress of weak rock stratum is smaller than that of hard rock stratum. The σ_{xx} and σ_{yy} of isotropic materials are exactly the same, and the σ_{zz} distribution of isotropic materials is the same as that of transversely isotropic materials.

Table 2 Numerical simulation results and calculation errors of in-situ stress values of transversely isotropic and isotropic models

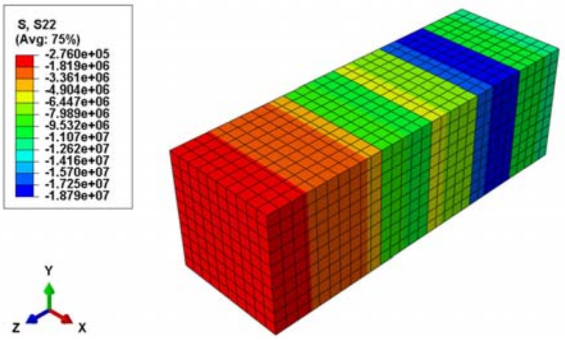
Rock character	Depth of burial	Horizontal stress of isotropic rock stratum/MPa			Horizontal stress of transversely isotropic rock stratum/MPa					
		Analog value	Computed value	Error /%	xx analog value	xx calculated value	Error /%	y y analog value	y y calculated value	Error /%
Hard layer	90	-2480230			-2480110			-2480000		
Soft layer	110	-1660180	-1663709	0.21	-1850320	-1853550	0.17	-2080000	-2082333	0.11
Hard layer	290	-12290500			-11400100			-10600000		
Soft layer	310	-5158820	-5163418	0.09	-5540130	-5543101	0.05	-6000000	-6000647	0.01
Hard layer	490	-22188300			-20387900			-18788200		
Soft layer	510	-8680950	-8663127	-0.21	-9251000	-9232651	-0.20	-9900950	-9924000	0.23



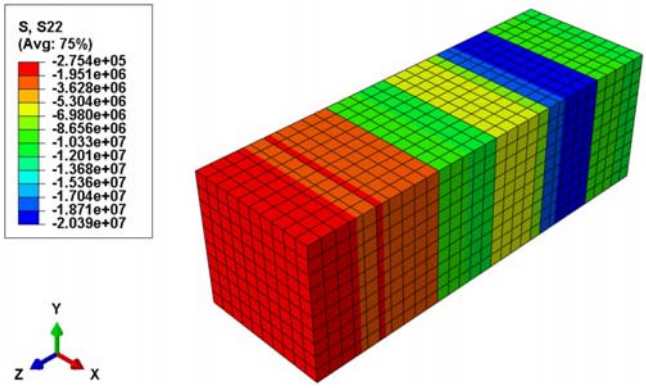
(a) σ_{xx} of isotropic rock formation



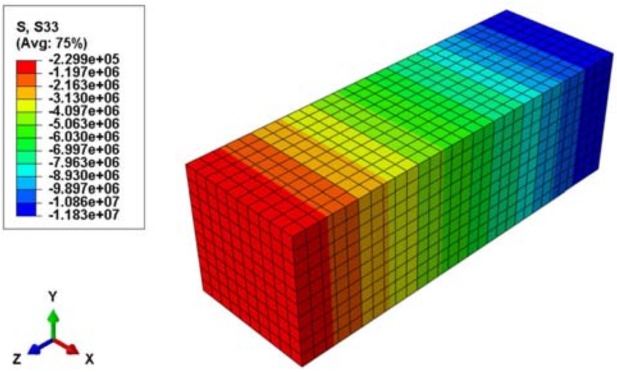
(b) σ_{yy} of transversely isotropic rock strata



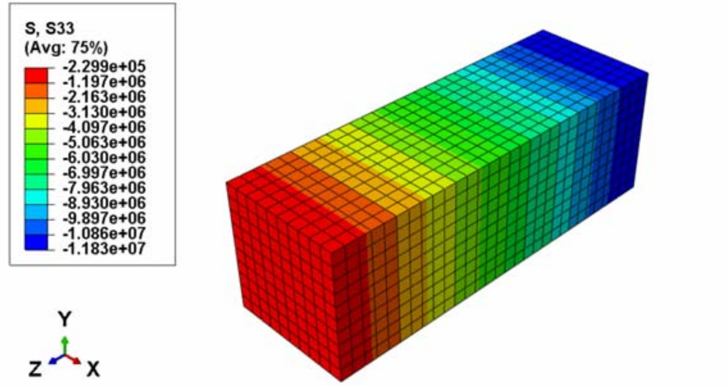
(c) σ_{yy} of isotropic rock formation



(d) σ_{yy} of transversely isotropic rock strata



(e) σ_{zz} of isotropic rock formation



(f) σ_{zz} of transversely isotropic rock strata

Figure 3 Simulation results of in-situ stress field in transversely isotropic and isotropic rock mass mechanics

A center point is extracted from the grid with the same buried depth, and its principal stress value is extracted to observe the law of different models changing with buried depth stress. As shown in Figure 4, the trend of principal stress value of different material models increases with buried depth. Compared with isotropic materials, the horizontal stress of transversely isotropic materials is smaller in weak rock stratum, while it is larger in hard rock stratum, and the difference is more with the increase of buried depth, which means that in the process of deducing the stress state of weak rock stratum by using the known stress state of hard rock stratum, ignoring the transversely isotropic property of rock stratum will make the predicted stress state of weak rock stratum larger than the real stress state, and the greater the buried depth, ignoring the transverse isotropy of rock stratum will make the calculation result.

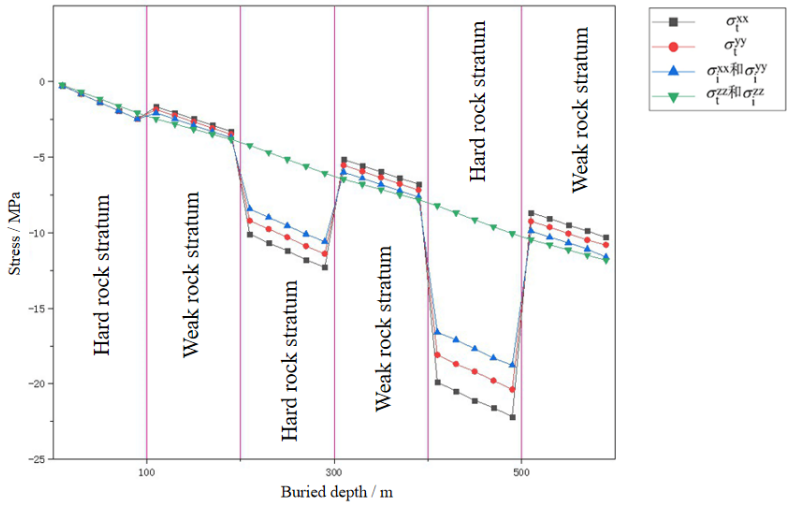


Figure 4 Cross-isotropic rock mass with different buried depths and in-situ stress simulation values show that subscript i is isotropic rock mass and t is transversely isotropic rock mass.

4. Engineering application

4.1. Engineering survey

Litang Tunnel in Ya 'an-Linzhi section of sichuan-tibet railway is about 9190 meters in length and 523 meters in maximum depth. The surrounding rocks in the tunnel site area are mainly sandstone and slate, sandstone is massive structure with good lithology, and the surrounding rocks are mostly Grade III. Slates are mostly plate-like structures with poor lithology, and the surrounding rocks are mainly Grade IV and Grade V.

Faults and folds are developed in this area, and the structural features are mainly NW-trending. The main faults are Balonghai fault, Mo Masang Qian fault, Hula longba fault, Quege ka fault, etc. Most of the faults are thrust, and the adjacent strata have strong compression deformation, and wrinkles, traction folds and joints are developed. In-situ stress measurement at fault is inconvenient, especially at Quege ka fault, as shown in fig. 5. It is measured that the occurrence of Quequegeka fault is n52 W ∠ 55 SW, and the fault is characterized by strong cleavage, which indicates that the type of in-situ stress field is tectonic stress field, as shown in the figure. In-situ stress test was carried out around Quege ka fault and the stress state of Quege ka fault was inferred.

Figure 5 The fault characteristics of Quege ka fault (F27)

4.2. Field measured in-situ stress and stress transformation

In-situ stress test of small fracturing is carried out at a distance of about 20m from Quege ka fault (F27) (mileage CK510+010). Single-loop in-situ stress testing system is used for testing, and the design depth is 230 meters. According to the actual drilling situation, in-situ stress tests were carried out at 104m, 152m and 204m respectively. The test results are shown in Table 3

Table 3 In-situ stress test results of small fracturing

Serial number of measuring point	Depth /m	Rock character	Principal stress value/MPa			Points of the compass
			SH	Sh	Sv	
1	204.0~204.7	Malmstone	8.40	5.58	5.30	N55W
2	152.0~152.7	Malmstone	6.42	4.35	3.95	N48W
3	104.0~104.7	Malmstone	6.12	3.68	2.70	N53W

Note: Sh is the maximum horizontal principal stress, SH is the minimum horizontal principal stress and Sv is the vertical principal stress.

The values of γ, α, β are substituted into the geodetic coordinate system transformation to obtain the stress state of three measuring points in the geodetic coordinate system as shown in the following table, and the stress state of Quege ka fault is inferred according to the transversely isotropic and isotropic properties as shown in the following table.

Table 4 Analytical estimation of stress in Quege ka fault

Stress value/measuring point	1				2				3			
	Hard layer stress	Transversal homogeneity	Isotropy	Error	Hard layer stress	Transversal homogeneity	Isotropy	Error	Hard layer stress	Transversal homogeneity	Isotropy	Error
Sxx	8.39	3.78	4.78	26.5%	5.78	2.55	3.22	26.2%	5.43	2.22	2.78	25.2%
Syy	5.39	3.77	4.31	14.3%	3.74	2.54	2.91	14.6%	2.68	2.05	2.35	14.6%
Sxy	0.08	0.01			0.84	0.13			0.85	0.13		
Szz	5.49				3.67				3.04			
Sxz	-0.12				-2.65				-2.69			
Syz	-0.13				-1.12				-1.14			

From the above table, it can be concluded that compared with isotropic model, the transverse isotropic model is used to predict the stress field of weak rock stratum, and the stress decreases more obviously along the strike direction of fault plane, that is, in the direction of larger horizontal principal stress in plane coordinate system. The errors of considering isotropy and considering transverse isotropy are almost the same in the survey area with different buried depths but the same transverse isotropy mechanical properties, which shows that this index has nothing to do with buried depth.

5. Discussion

In order to discuss the distribution of elastic mechanical parameters between soft and hard rocks on stress field, the ratio of elastic modulus and Poisson's ratio between soft and hard rocks, elastic modulus and Poisson's ratio between transversely isotropic plane of soft rock and vertical elastic symmetry axis, and the influence of elastic modulus and Poisson's ratio between transversely isotropic plane of hard rock and vertical elastic symmetry axis on the calculated value of in-situ stress in soft rock are considered. It is assumed that the maximum horizontal principal stress and the minimum horizontal principal stress and self-weight stress are 12MPa, 10MPa and 8MPa, respectively, which meet the aforementioned basic assumptions. The elastic parameters of hard rock and weak rock are shown in Table 1. First, keep the elastic modulus of transversely isotropic plane and vertically isotropic plane of weak rock stratum and hard rock stratum at 1.5 and 1.2, respectively. As the elastic modulus of hard rock stratum gradually increases, the calculated value of in-situ stress in soft rock area gradually decreases, as shown in Figure 6, which shows that the greater the difference in mechanical properties between soft and hard rock stratum, the greater the difference in stress state.

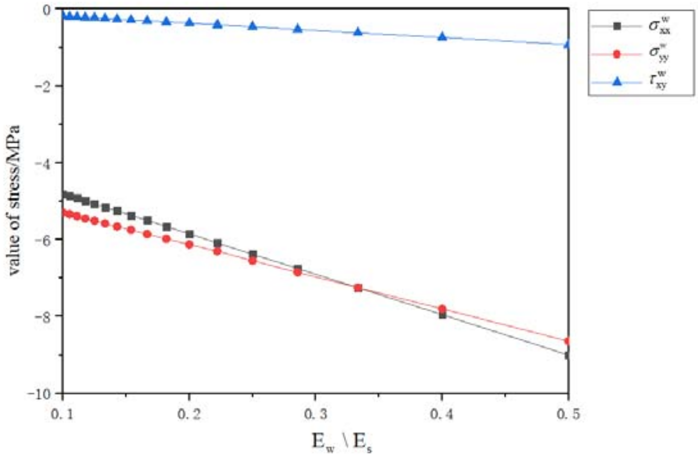
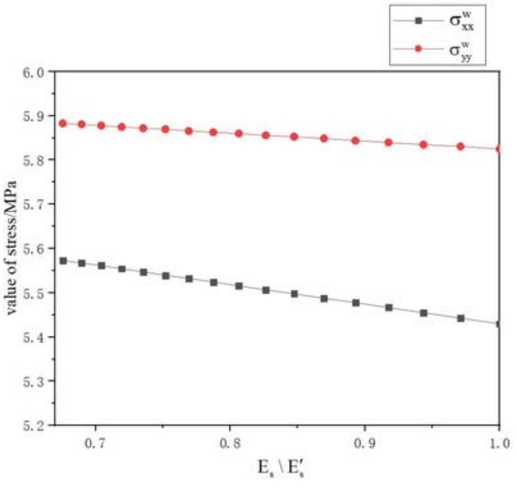
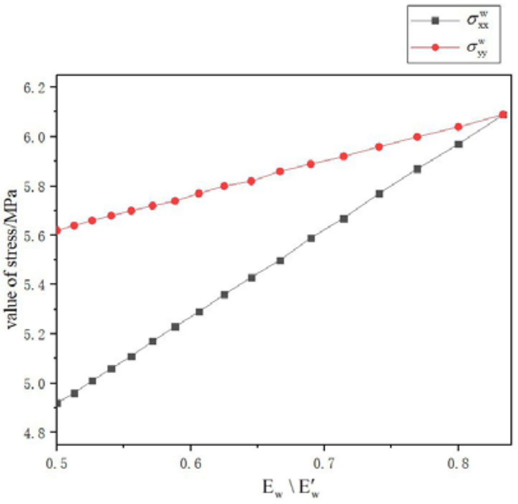


Figure 6 Influence of the ratio of elastic modulus of weak rock stratum on the calculated value of in-situ stress of weak rock stratum

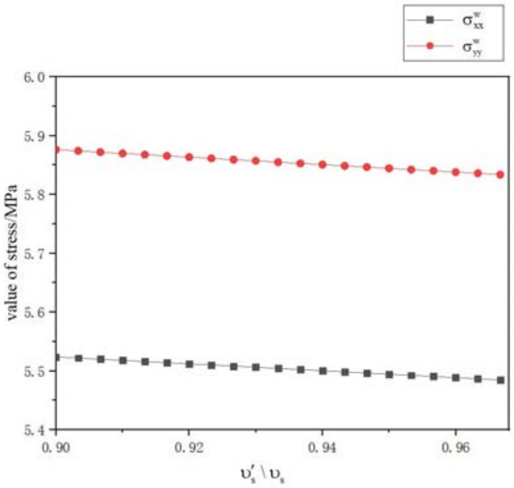
By adjusting the elastic modulus and Poisson's ratio of transversely isotropic plane, the degree of rock anisotropy can be changed. As shown in fig. 7, with the increase of elastic modulus and the decrease of poisson's ratio of transversely isotropic surface of weak rock, the stress of weak rock gradually decreases; With the increase of elastic modulus and the decrease of Poisson's ratio in transversely isotropic plane of hard rock, the stress in weak rock gradually increases. This shows that ignoring the transversely isotropic mechanical properties of weak rock stratum will make the stress estimation value of weak rock stratum higher, while ignoring the transversely isotropic properties of hard rock stratum is just the opposite.



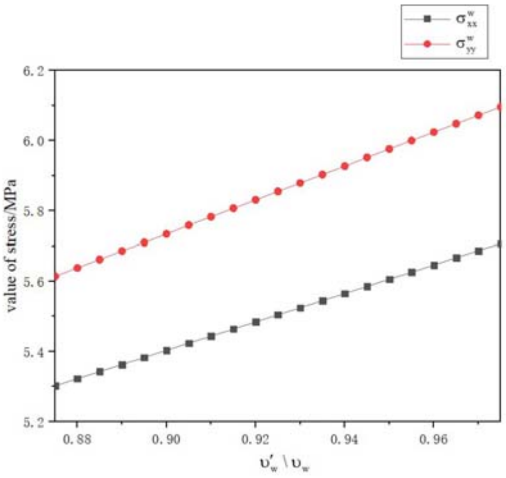
(a)Elastic modulus anisotropy of hard rock stratum



(b) Anisotropy of elastic modulus in weak rock stratum



(c)Poisson's ratio anisotropy in hard rock



(d) Poisson's ratio anisotropy in weak rock strata

Figure 7 Influence of anisotropic characteristics of hard rock and weak rock on analytical estimation of in-situ stress in weak rock

Conclusions

The in-situ stress testing method of weak rock is not mature, and the existing analytical estimation of in-situ stress is only for isotropic rock mass. Therefore, considering the transversely isotropic property of rock mass, the in-situ stress of weak rock mass is estimated analytically and verified by numerical simulation technology. The in-situ stress of Quege ka fault is estimated according to the measured in-situ stress data of Litang Tunnel in sichuan-tibet railway. Get the following conclusions:

(1) Compared with the isotropic model, the transverse isotropic model is used to predict the in-situ stress field, and its stress value can better represent the real situation of the in-situ stress field. The greater the difference between elastic modulus of rock with unknown geostress and rock with known geostress, the greater the difference in stress state.

(2) The more obvious the anisotropic characteristics of weak rock stratum and the more obvious the isotropic characteristics of hard rock stratum, the greater the difference in stress state. The rocks with obvious anisotropy include shale and slate, while marble and sandstone have obvious isotropic properties.

(3) The real distribution of in-situ stress field is also restricted by many factors, such as tectonic action, surface topography, etc. In engineering application, in-situ stress test should be carried out as much as possible as the theoretical basis of geotechnical engineering excavation design.

References

[1] Jing Feng, Sheng Qian, Zhang Yonghui, Liu Yuankun. Research progress of in-situ stress measurement and in-situ stress field analysis in China [J]. Rock and Soil Mechanics, 2011,32(S2):51-58.
[2] Sun Yi. Overview of in-situ stress and its application in mining engineering [J]. Western Prospecting Engineering, 2017, 29(07):127-129+134.
[3] Qu Hongluo, Liu Zheyan, Yang Long, Zhang Yong, Li Biao. Study on tunnel rockburst prediction and evaluation based on stress criterion [J]. chinese journal of underground space and engineering, 2020,16(S2):934-938+956.
[4] Han Changling, Xia caichu, Xu Chen. research progress of large deformation control technology in soft rock tunnel [J]. chinese journal of underground space and engineering, 2020,16(S1):492-505.
[5] Wu aiqing, Zhu jiebing. summary of deep rock engineering mechanical properties and in-situ stress test [J]. journal of yangtze river scientific research institute, 2014,31(10):43-50.
[6] Zhang Zhongyuan, Wu Manlu, Chen Qunce, Liao Chunting, Feng Chengjun. Overview of in-situ stress measurement methods [J]. Journal of Henan Polytechnic University (Natural Science Edition), 2012,31(03):305-310.
[7] Yang zhanbiao. in-situ stress measurement technology and application of rheological stress recovery method in deep weak surrounding rock [J]. coal engineering, 2016,48(07):71-74.
[8] Zhang Fang, Liu Quansheng, Zhang Chengyuan, Jiang Jingdong. In-situ stress test and device by rheological stress recovery method [J]. Rock and Soil Mechanics, 2014, 35(05):1506-1513.
[9] Liu Jiang. Study on in-situ stress measurement and stress field distribution characteristics in Yitai mining area [J]. Journal of Coal Science, 2011, 36(04):562-566.
[10] Li wenping. Preliminary estimation method of in-situ stress in coal and soft rock strata [J]. Journal of Rock Mechanics and Engineering, 2000(02):234-237.
[11] Yang J, Chen W, Tan X, Yang D. Analytical estimation of stress distribution in interbedded layers and its implication to rockburst in strong layer. Tunnelling and Underground Space Technology, 2018(81): 289-295.
[12] Li Jing, Liu Chen, Liu Huimin, Yanchao Xu, Xie Li, Huang Guipeng. In-situ stress distribution and its influencing factors in complex fault structural areas [J/OL]. Journal of China University of Mining and Technology, 2021 (01): 1-15 [2021-01-08]. https://doi.org/10.13247/.

[13] Xu hailiang, Qin Jining, Guo Xu, ren hehuan. analysis of the influence of horizontal geostress on the mechanical properties of tunnels in weak surrounding rock [J]. journal of north china university of technology, 2020,32(05):112-117+134.

[14] Sharla Cheung, Jian Huang, Ju Nengpan, Zhang Yulu, Zhang Guangze. Inversion analysis of in-situ stress field of long and deep buried tunnels in sichuan-tibet railway [J]. chinese journal of underground space and engineering, 2019,15(04):1232-1238+1257.

[15] TB 10003—2016, code for design of railway tunnel [s].

[16] Meng Wen, Guo Changbao, Mao Bangyan, Lu Haifeng, Chen Qunce, Xu Xueyuan. Current tectonic stress field of Sino-Nepalese railway traffic corridor and its engineering influence [J/OL]. Modern Geology: 1-16 [2021-01-08]. https://doi.org/10.19657/J. Geoscience

[17] Zhang Jian, Kang Hongpu, Liu Aiqing, Cheng Peng, Si Linpo, Li Zhongwei. Distribution of in-situ stress field in Xishan Mining Area, Shanxi Province [J]. Journal of China Coal Industry, 2020,45(12):4006-4016.