Stress state of the Shangri-La–Bangda section of
Yunnan–Tibet Railway and its implication for route alignment

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Abstract. A multisource comprehensive analysis method based on geomechanical trace
analysis, focal mechanism solution, and measured data is utilized to analyze the direction of in
situ stress field of the Shangri-La–Bangda railway. Based on the Hoek–Brown strength
criterion and modified Sheorey theory, the rock mass strength parameters and in situ stress
magnitude are estimated and predicted. The results show that the directions of maximum
horizontal principal stress are N0°W–N40°W in the Shangri-La–Deqin stress district and
N60°E–N80°E in the Mangkang–Bangda stress district. The maximum and minimum
horizontal principal stresses ranges are 25.93–28.80 MPa and 15.85–17.60 MPa when the
buried depth is about 1000 m, and 50.77–52.50 MPa and 31.03–32.09 MPa when the buried
depth is about 2000 m. By combining the comprehensive analysis of in situ stress state, and the
principle of disaster prevention and reduction, suggestions on railway alignment are presented.

Keywords: Yunnan–Tibet Railway; Stress state; Stress prediction; Route alignment

1 Introduction

The Yunnan-Tibet railway is an essential trunk artery in China's medium- and long-term railway
network planning and construction. It starts from Kunming City, Yunnan Province, and ends in Lhasa
City, Tibet Province. Based on the comparison and selection of engineering, operation, risk, and other
aspects, authorities plan to connect the Yunnan–Tibet railway with the Sichuan–Tibet Railway in
Bangda [1], as shown in figure 1. In addition, the railway line from Kunming to Lijiang was
completed, and the Lixiang railway from Lijiang to Shangri-La has just been completed and will be
put into operation this year. Therefore, the direction of the remaining Yunnan–Tibet railway line is
mainly from Shangri-La to the northwest, through Deqin, Mangkang, and Zuogong, connecting with
the Sichuan-Tibet railway at Bangda, and then through Bomi, Linzhi, Lang County, Gongga, and
Lhasa.

The geotectonic movement of the Shangri-La–Bangda section of the Yunnan–Tibet railway is
particularly strong because of the pushing effect of the Indian plate on the Eurasian plate. There are
many tributaries along the railway, with an average altitude greater than 3000 m, and the relative elevation difference between snow mountains and rivers is 4700 m. Because of the long-term intense geologically tectonic activity and crisscrossing active faults, the rock mass in this area is broken and has poor stability [2–3]. Besides, deep-buried and long tunnels occupy a significant proportion in this railway where significant geological disasters may occur under a high in situ stress state. Therefore, the stress state analysis of the Shangri-La–Bangda section of Yunnan-Tibet railway is vital for geological disaster protection and line alignment.

Recent research reveals that the stress state in Yunnan and Tibet regions is complicated [4–8]. Qian et al. [4] studied the recent tectonic stress field in the Yunnan region based on focal mechanism solutions and indicated three main sources of force controlling the regional stress state. Li et al. [5] analyzed the in situ stress state in Northwest Yunnan based on in situ stress measurement, where the maximum horizontal stress direction is around NEE. Zhang et al. [6] measured the in situ stress in the region of Yangbajain–Kangmar in Tibet and indicated that the direction of maximum principal stress is mainly NW–NNW, while the direction of maximum principal stress is around E–W [7]. However, most of the previous works are focus on the in situ stress state in Yunnan and Tibet regions, and there are few systematic studies on the in situ stress state along the Yunnan-Tibet railway. Combined with the previous research results, the in situ stress orientation along the Shangri-La–Bangda section of Yunnan–Tibet railway was analyzed based on the geomechanical trace analysis, focal mechanism solutions, and measured data. The in situ stress magnitudes were predicted on the basis of the Hoek–Brown strength theory and the modified Sheorey model. Finally, the study presented some suggestions on line alignment of the Shangri-La–Bangda section of Yunnan–Tibet railway based on the comprehensive analysis of the stress state and the principle of railway disaster prevention and reduction.

![Figure 1](image-url)

**Figure 1.** Geological structure and the general trend of the Shangri-La–Bangda section of the Yunnan–Tibet railway. The regional divisions of stress district are from Xie et al. [8].

2 The direction of the stress field

2.1 Stress district

The stress district is defined based on the fundamental database of in situ stress environments in the Chinese mainland and the characteristics of modern tectonic stress fields [8]. The Shangri-La–Bangda
2.2 Characteristics of tectonic stress
The Yunnan–Tibet railway's geological structure includes three main fault zones: Jinshajiang, Langcangjiang, and Nujiang. The resultant direction of the Jinshajiang and Lancangjiang fault zones is NS. However, the detailed direction of the Jinshajiang fault zone changes from NNE in the southern segment to NNW in the northern segment [9]. Contrarily, the strike of the Lancangjiang fault zone is NS–NW–NS from north to south [10–12]. The Nujiang fault zone is a large-scale regional fault at the boundary of the Baoshan and Tengchong blocks. Its strike is distributed along the Nujiang River. The direction of its northern section is NW, and that of its southern section is NS [13].

Based on the comprehensive analysis of the primary faults along the Shangri-La–Bangda section, the fault strike is NW–NNW. Anderson's theory holds that the fault plane is coplanar with the intermediate principal stress. The friction coefficient on the fault plane is generally 0.6–1.0, meaning that the angle between the directions of the maximum principal stress and the fault plane is generally 23°–30° [14–15]. Therefore, the main fault strike of the Shangri-La–Bangda section is NW. Therefore, according to this theory, the maximum principal stress direction should be NWW–NNW, consistent with Xie's results [16–17] by inversion of fault slip data. However, the neotectonic movement in the Shangri-La–Bangda section is strong. Besides tectonic evolution, many external dynamic factors are also present. Thus, the actual direction of the principal stress may also vary greatly.

2.3 The direction of in situ stress
The results of the geomechanical trace estimation primarily characterize a paleotectonic stress field. Therefore, He et al. [18] analyzed the focal mechanism of the 2013 Diqing M5.9 earthquake in Yunnan, and the obtained dominant azimuth of the P-axis is NNW. Gao et al. [19] analyzed the focal mechanism of the 2013 Zuogong–Mangkang MS6.1 earthquake using P-wave initial motion. Their results showed that the dominant azimuth of P-axis is NE–NEE.

In determining the direction of in situ stress, geomechanical trace analysis, multisource stress data, focal mechanism solution, and measured data are used for analysis. By consulting the basic database of Xie et al. [20], the focal mechanism solution data of the Shangri-La–Bangda section are obtained. The P-axis azimuth is shown in figure 2 by analyzing these data.

The stress state of the Shangri-La–Deqin stress district is relatively complex. The maximum horizontal principal stress direction is NWW–NNW with a dominant orientation of N0°W–N20°W. The maximum principal stress direction of the Mangkang–Bangda stress district is NEE, with a dominant orientation of N60°E–N80°E. Combined with hydraulic fracturing and stress relief data in this area and referring to the results of Xie et al. [20], the maximum principal stress azimuths of the measured data in these two studied stress zones are shown in figure 3.

According to the measured data in the Shangri-La–Deqin stress district, the horizontal maximum principal stress direction is NNW with a dominant orientation of N20°W–N40°W. On the other hand, the horizontal maximum principal stress direction in the Mangkang–Bangda stress district is NEE–EW with a dominant orientation of N60°E–N80°E. These results are consistent with the focal
mechanism solutions.

Figure 2. Statistical charts of the P-axis azimuth of focal mechanism solutions in each stress district. (a) Shangri-La–Deqin stress district (b) Mangkang–Bangda stress district.

Figure 3. Statistical charts of the maximum principal stress azimuth of the measured data in each stress district. (a) Shangri-La–Deqin stress district (b) Mangkang–Bangda stress district. About 51.82% of the fault stress state in the Shangri-La–Bangda section is strike-slip, indicating that the stress regime is $S_H > S_V > S_h$. Conversely, approximately 22.73% of the fault stress state in the research area is normal, indicating that the stress regime is $S_V > S_H > S_h$. There are more focal mechanism data in the Shangri-La–Deqin stress district; the analysis results are shown in figures 4 and 5. The statistical results show that the direction of the maximum principal compressive stress is NW, and the stress ratio $R$ ranges from 0.62 to 0.88. These show the minimum and medium principal stress magnitudes are close to each other.

Figure 4. Orientation of the principal stress axis reflected by the focal mechanism solution in the Shangri-La–Deqin stress district. Figure 5. Statistics of the stress ratio $R$ in the Shangri-La–Deqin stress district.
Based on the comprehensive analysis of the geomechanical trace, focal mechanism solution and measured data, the horizontal maximum principal stress direction of the Shangri-La–Deqin stress district is NNW with a dominant orientation of N0°W–N40°W. The maximum horizontal principal stress direction in the Mangkang–Bangda stress district is NEE, with a dominant orientation of N60°E–N80°E.

3. Estimation of stress field magnitude

3.1 Stress prediction method

The measured in situ stress data of the Shangri-La–Bangda section are few and discrete. Therefore, based on the Hoek–Brown strength criterion and the modified Sheorey theory, the rock strength parameters and in situ stress in the research area are estimated, predicted, and combined with the measured data to better reflect the in situ stress. The Earth is assumed to be a spherical shell in the Sheorey model. The in situ stress state is analyzed with the elastic modulus, Poisson's ratio, density, and thermal expansion coefficient of rock mass in the crust and mantle increasing with depth [21]. The Sheorey model can normalize discrete data. Based on the limited measured data, if the stress magnitude in one buried depth and place is known, the stress state in the other buried depths and places can be predicted using the following equation [22]:

$$k_2 = k_1 \frac{0.25 + 7E_{\text{m1}}(0.001+1/Z_1)}{0.25 + 7E_{\text{m2}}(0.001+1/Z_1)}$$

(1)

where $Z_1$ and $Z_2$ are the depths from the surface, $E_{\text{m1}}$ and $E_{\text{m2}}$ are the elastic moduli of rock mass at $Z_1$ and $Z_2$, and $k_1$ and $k_2$ are the ratios of horizontal stress to vertical stress at $Z_1$ and $Z_2$. In the equation, $Z_1$, $E_{\text{m1}}$ and $k_1$ are used as references to predict the values of $k_2$ at different depths by changing the value of $Z_2$.

3.2 Horizontal-to-vertical stress ratio

Combined with the measured data of the Shangri-La–Deqin stress district and the results of Xie et al. [20], the in situ stress data of the research area are shown in figure 6. Figure 6 shows that when the buried depth exceeds 400 m, the maximum and minimum principal stresses show certain regularity. According to the stress data of the research area, the horizontal-to-vertical in situ stress ratios are calculated using the formulas $k_{11} = S_{h1}/S_{v1}$, $k_{0} = S_{h0}/S_{v0}$ and $k = (S_{h1}+S_{h0})/(2S_{v0})$, as shown in figure 7.

**Figure 6.** In situ stress measurement data of the Shangri-La–Deqin stress district.

**Figure 7.** $k$-value fitting and data graph based on the Hoek–Brown formula.
The stress data are fitted according to the modified Sheorey equation in figure 7. When the buried depth is shallow, the horizontal-to-vertical in situ stress ratio is relatively discrete because of the influence of topography, landform, and weathering degree. When the buried depth is greater than 200 m, the discreteness of this ratio decreases. For improving the accuracy of the results, the following fitting values of the horizontal-to-vertical in situ stress ratio at 500 m are used as a reference to predict the stress magnitude: $k_H=1.80$, $k_V=1.10$, and $k=1.46$.

### 3.3 Estimation of stress value

The modified Sheorey model [22] is used to predict the magnitude of the stress field, and the rock mass strength is estimated according to the Hoek–Brown strength criterion and RocLab software [23]. The Shangri-La–Bangda section belongs to the Deqin–Weixi stratigraphic division of the Qiangtang–Changdu stratigraphic area. The lithology along the line mainly comprises limestone, sandstone, and slate. Therefore, the stress magnitudes of the Shangri-La–Bangda section are predicted considering these three kinds of lithology and four surrounding rock grades (II, III, IV, and V). Compared with the results in figure 6, the predicted stress magnitudes in the limestone and sandstone strata with a grade of IV and slate formation with a grade of V agree well with the measured data. The typical predicted results are shown in table 1. The maximum and minimum horizontal principal stress ranges are 25.93–28.80 MPa and 15.85–17.60 MPa at a buried depth of 1000 m. The maximum and minimum horizontal principal stress range are 50.77–52.50 MPa and 31.03–32.09 MPa at a buried depth of 2000 m.

#### Table 1. Typical prediction results of stress value.

| Depth/m | Limestone IV | Sandstone IV | Slate V |
|---------|--------------|--------------|---------|
|         | $S_h$/MPa    | $S_v$/MPa    | $S_h$/MPa | $S_v$/MPa | $S_h$/MPa | $S_v$/MPa | $S_h$/MPa | $S_v$/MPa |
| 400     | 11.19        | 14.58        | 8.91     | 10.84     | 14.30     | 8.74     | 10.40     | 12.24     | 7.48      |
| 700     | 19.58        | 21.94        | 13.41    | 18.97     | 21.68     | 13.25    | 18.20     | 18.91     | 11.55     |
| 1000    | 27.97        | 28.80        | 17.60    | 27.10     | 28.60     | 17.48    | 26.00     | 25.93     | 15.85     |
| 1200    | 33.56        | 33.37        | 20.39    | 32.52     | 33.20     | 20.29    | 31.20     | 30.84     | 18.85     |
| 1500    | 41.96        | 40.38        | 24.68    | 40.65     | 40.26     | 24.60    | 39.00     | 38.55     | 23.56     |
| 1800    | 50.35        | 47.59        | 29.08    | 48.78     | 47.50     | 29.03    | 46.80     | 45.91     | 28.06     |
| 2000    | 55.94        | 52.50        | 32.09    | 54.20     | 52.42     | 32.04    | 52.00     | 50.77     | 31.03     |
| 2200    | 61.53        | 68.85        | 42.07    | 59.62     | 57.43     | 35.10    | 57.20     | 55.71     | 34.04     |
| 2500    | 69.93        | 65.18        | 39.83    | 67.75     | 65.11     | 39.79    | 65.00     | 63.26     | 38.66     |

### 3.4 Evaluation of in situ stress state

The rock strength-stress ratio method modified using the Hoek–Brown criterion can be used to evaluate the in situ stress [24], and the results are shown in figure 8. When the buried depth exceeds 400 m, limestone and sandstone's in situ stress state may be high. Likewise, when the buried depth exceeds 300 m, the in situ stress state of the slate may be high.

### 4 Line alignment suggestions

The geological structure of the Shangri-La–Bangda section is complex. In avoiding the risk of major geological disasters [25] and according to the detour and short distance principle, the route should avoid the high mountains, valleys, and broken rock areas. In areas with a significant height difference,
the maximum slope should be used in the design, or the speed of the railway should be reduced to increase the minimum curve radius for line extension.

![Figure 8. Stress evaluation of the limestone, sandstone, and slate strata.](image)

The Shangri-La–Bangda section's stress state is $S_h > S_v > S_p$, favoring a strike-slip faulting stress regime. Therefore, the strike of the tunnel axis should be parallel to the direction of the maximum horizontal principal stress, or the included angle should be less than 30°. However, the normal faulting stress regime in the research area accounts for 22.73% of the line, and its stress state favors $S_v > S_h > S_p$, which is rarely distributed in the Shangri-La, Deqin, and Zuogong areas. Therefore, the strike of the tunnel axis should be parallel to the direction of the minimum horizontal principal stress or the included angle should be less than 30° [5, 26]. The maximum horizontal principal stress directions are NNW in the Shangri-La–Deqin section and NEE in Mangkang–Bangda section. Because there are many tunnel projects along the railway, the Shangri-La–Deqin section should be in the NNW direction. In contrast, the Mangkang–Zuogong section, which crosses the Lancangjiang fault area, should be in the NEE direction.

Because of the influence of the significant height difference, tunnels along the Shangri-La–Bangda section are at great depths. According to the above results, when the buried depth is around 1000 m, the maximum and minimum horizontal principal stress are 25.93–28.80 MPa and 15.85–17.60 MPa, respectively. Therefore, the effect of high in situ stress along the railway is significant, with associated rock burst or large deformation risks. Thus, the buried depth and lithology should be considered in route selection to minimize the influence of high in situ stress.

5 Conclusion

Based on the geological conditions, stress field direction analysis, stress field value prediction, comprehensive analysis of the stress field, and the significance of railway route selection for the Shangri-La–Bangda section, the following conclusions are drawn:

(1) The directions of horizontal maximum principal stress are N0°W–N40°W in the Shangri-La–Deqin stress district and N60°E–N80°E in Mangkang–Bangda stress district. The tectonic movement is strong along the railway, and the stress direction deflects in some areas, showing complex and dynamic characteristics.

(2) The maximum and minimum horizontal principal stress ranges are 25.93–28.80 MPa and 15.85–17.60 MPa at a buried depth of 1000 m, and 50.77–52.50 MPa and 31.03–32.09 MPa at a buried depth of 2000 m. Thus, the Shangri-La–Bangda section is affected by high in situ stress.

(3) The Shangri-La–Deqin section should be in the NNW direction, whereas the Mangkang–Zuogong section, which crosses the Lancangjiang fault area, should be in the NEE direction. When the height difference
significant, the maximum slope should be fully used, or the speed of the railway should be reduced to increase the minimum curve radius for line extension. In areas of high in situ stress, the impact of buried depth and lithology should be considered.

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