Large deformation analysis of tunnel-surrounding rock along the expressway from Wenchuan to Maerkang, China

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Abstract. The rock surrounding the Wenchuan–Maerkang Tunnel, which consists of metasandstone, slate, and phyllite (including carbonaceous phyllite), is strongly affected by geological and tectonic factors. The large deformation of the tunnel-surrounding rock is a concerning problem. Based on the analysis of the geological characteristics of the tunnel-surrounding rock, Hoek predictive equation was used to study the relationship between the relative deformation of the tunnel-surrounding rock and the rock strength, geostress, geological strength index, and strength-to-stress ratio. Using the strength-to-stress ratio, we predicted the large deformation of the tunnel-surrounding rock and compared it with the deformation phenomena revealed during tunnel construction. Our study shows that the large deformation of tunnel-surrounding rock along the expressway from Wenchuan to Maerkang occurs primarily in soft rock, such as slate and phyllites, which are strongly affected by the geology and tectonics factors. Deformation of the tunnel-surrounding rock grows rapidly in soft rock with decreasing geological strength index and strength-to-stress ratio and with increasing ground stress. Moreover, the relationship between the schistosity strike of the steeply layered rock mass and the tunnel axis has an important influence on the tunnel-surrounding rock deformation. Tunnels where the schistosity of the surrounding rock has a strike at a small angle with the tunnel axis are more prone to large deformation.

1. Introduction
Mountain tunneling has become more widespread and sophisticated than ever. During tunnel excavations, large deformation of soft rock is always a challenge, disturbing the safety and quality of underground engineering. Squeezing and swelling are the main modes of large deformations [1,2]. Squeezing—large time-dependent convergence during tunnel excavation—occurs when a particular combination of induced stress and material properties forces some rock masses around the tunnel beyond the limiting shear stress at which creep starts [3]. Squeezing is always a serious problem in tunnel engineering in the mountainous area in western China because of high in-situ stress and fractured soft rock due to the tectonic compression. Extensive research has been conducted on the characteristics and mechanisms related to large deformation of tunnel-surrounding rock, combining engineering practice and theoretical analysis [4–6]. However, due to the complexity of geological conditions, the mechanisms and characteristics of large deformations require a specific study of typical engineering cases.

The total length of the Wenchuan–Maerkang section of China National Expressway G4217 (CHN G4217) is 172 km, of which the tunnels account for 55% of the total length. Geologic strata of the...
tunnel-surrounding rock are primarily soft rock, mostly phyllites (including carbonaceous phyllites), slates, and metasandstones. These strata are strongly influenced by geological structure, leading to serious problems with the deformation of the tunnel-surrounding rock. In this study, we investigated the geological characteristics of tunnel rock mass and deformation characteristics of the surrounding rock in tunnel construction and used the results to analyze the relationships among deformation, lithology, structure, and in-situ stress.

2. Background of research area

2.1. Geologic setting
The Wenchuan–Maerkang section of CNH G4217 is located in the eastern part of Tibet. Starting from Wenchuan, it passes through Lixian and Miyaro and ends at Maerkang, which is in the Songpan–Garze fold belt (Figure 1). The Songpan–Garze fold belt is wedged between the Tarim, Qaidam, Yangtze, and Qiangtang blocks and presents an inverted triangle. The Songpan–Ganzi fold belt consists mainly of the Triassic flysch deposits (Figure 1) formed by deep-water turbidity currents along the eastern margin of paleotethys. Strong fold deformation occurred at the end of the Triassic with the paleotethys closure [7].

2.2. Geological strata
Silurian, Devonian, and Triassic metasandstone, phyllites, and slates are the strata in this study area. The Upper Triassic Xinduqiao Formation (T3x) mainly consists of phyllites (including carbonaceous phyllites) with slate and metasandstone. The Upper Triassic Zhuwo Formation (T3zh) primarily consists of metasandstone and slate (~2:1 ratio). The Middle Triassic Zagunao Formation (T2z) mainly consists of metasandstone and slate (~8:1). The Devonian Weiguan Formation (Dwg) principally consists of phyllites (sericitic, sericite-quartz, or carbonaceous) and metasandstone. The Silurian Maoxian Formation (Smx) chiefly consists of sericitic and sericite-quartz phyllites. Table 1 summarizes the mechanical parameters of these rock types.

2.3. Geological structures
The CNH G4217 is mostly within the Xuecheng S-type and northwest-trending Maerkang structures. The structure of the Xuecheng S-type consists of a series of S-type folds and compression faults, and
the northwest-trending Maerkang structure comprises a series of inverted anticlinoria and synclinoria in the Songpan–Garzê fold belt (Figure 1). The Maoxian–Wenchuan and Miyaluo Faults cross the CNH G4217. The Wenchuan No. 1 Tunnel intersects the Maoxian–Wenchuan Fault, and the Miyaluo No. 3 Tunnel is parallel to and within 500 m of the Miyaro Fault (Figure 1).

The northwest-trending Maerkang and Xuecheng S-type structures are characterized by strong extrusion deformation based on field investigations (Figure 2). Most strata are nearly vertical (or even reverse), with a very well developed chevron fold. This type of structural feature, which is common in both macroscopic and microscopic scales, often results in sharp changes in the geological characteristics of a rock mass within a short distance. A fracture zone revealed by the tunnel face of Miyaluo No. 3 shows the structural features of strong bedding-plane shear, fold deformation, and structural lenses.

Table 1. Mechanical parameters of rock types in study area

| Stratum | Rock type                      | Uniaxial compressive strength (MPa) | Range     | Average |
|---------|--------------------------------|------------------------------------|-----------|---------|
| T₃ₓ     | Metasandstone                  | 38.5–111.1                         | 65.1      |
| T₃zh    | Slate                          | 17.6–47.8                          | 31.5      |
| T₂ₓ     | Phyllite                       | 12.8–16.2                          | 14.5      |
| Dₘg²    | Sericite-quartz phyllite       | 27.4–36.5                          | 31.4      |
|         | Carbonaceous phyllite          | 5.14–14.3                          | 9.72      |
|         | Sericitic phyllite             | 16.07–26.61                        | 21.6      |
| Dₘg¹    | Sericite-quartz phyllite       | 11.26–47.36                        | 25.6      |
|         | Carbonaceous phyllite          | 9.81–27.27                         | 19.6      |
|         | Metasandstone                  | 20.43–92.05                        | 51.2      |
| Sₘx     | Sericite-quartz phyllite       | 12.8–55                            | 27.3      |
|         | Sericitic phyllite             | 26.05–35.27                        | 30.66     |

Figure 2. Photos of typical rock mass. (a) Chevron folds and (b) Fractured zone on face of Miyaluo No. 3 Tunnel (ZK162+705).

2.4. Geostress

Geostress was tested in the CNH G4217 drill hole, and we also collected in-situ geostress data in the G317 Zhegushan Tunnel. The location of the test point and direction of maximal principal stress are shown in Figure 1 and tabulated in Table 2. The maximal principal stress is trends the northwest at a small angle of intersection with CNH G4217.
Table 2. Geostress data measured along Wenchuan–Maerkang Expressway

| Test point                  | Test depth (m) | Principal stress (MPa) | Dominant direction of maximal principal stress | Relationship between maximal principal stress and depth |
|-----------------------------|---------------|------------------------|-----------------------------------------------|---------------------------------------------------|
| CA2K50796.5L12.7 of Wenchuan No. 1 Tunnel | 320.28–320.83 | 10.87 7.20 8.49 | N42° to 56°W | S_H = 0.0465H – 4.618 |
| K82+225L15 of Xuecheng No. 1 Tunnel | 345.50–346.10 | 16.69 10.04 8.98 | N65°W to N85°W | S_H = 0.038H + 2.84 |
| CK146930L5 of Shiziping Tunnel | 359.40–360.20 | 14.19 9.02 9.51 | N26°W | S_H = 0.031H + 2.93 |
| Z1-T-3 of Zhegushan Tunnel | 236.0–236.5 | 6.36 4.42 6.25 | N72°W |
| Tunnel of G317           | 500–785       | 11.4–15.3–9.5–11.7–15.1 | N45°W |
| Z1-TW-1 of Zhegushan Tunnel | 500–785      | 23.3 15.5 14.3 | N87°E |

3. Characteristics of large deformation in tunnels on the Wenchuan–Maerkang section of CHN G4217

3.1. Analysis of relationships between tunnel strain and relevant factors

Hoek [8] derived the following approximate relation by applying axisymmetric finite-element analysis to a range of different rock masses, in-situ stresses, and support pressures:

$$\varepsilon_t = 0.15 (1 - P_t/P_0) \left( \frac{\sigma_{cm}}{P_0} \right)^{-(3P_t/P_0+1)(3.8P_t/P_0+0.54)}$$

(1)

where $\varepsilon_t$ is tunnel strain (the percentage ratio of radial tunnel wall displacement to tunnel radius); $P_t$ is the support pressure of the tunnel; $P_0$ is in-situ stress; $\sigma_{cm}$ is rock mass uniaxial compressive strength, which can be determined by the Hoek–Brown criterion [9,10]. A possible way to estimate $\sigma_{cm}$ is given below [11]:

$$\sigma_{cm} = (0.0034m_i^{0.8})\sigma_{ci}[1.029 + 0.025e^{(-0.1m_i)}]^{GSI}$$

(2)

where $m_i$ is the Hoek–Brown constant, determined by triaxial testing of core samples or estimated from a qualitative description of the rock material [9,10]. The geological strength index ($GSI$), which has a range of 0–100 and is based on the Hoek–Brown criterion.

(1) Relationship between tunnel strain and rock strength

Considering the typical lithology revealed by the geological survey for the CHN G4217 section of the Wenchuan–Maerkang Tunnel, we used Equation (1) to calculate the relationship between tunnel strain ($\varepsilon$) and uniaxial compressive strength ($R_s$) at different geostress levels ($GSI = 50, P_0/P_0 = 0.05$) (Figure 3). $R_s$ is inversely proportional to $\varepsilon$: When $R_s > 20$ MPa, $P_0 = 20$ MPa, and $\varepsilon$ is less than 1.5%; however, in particular, when $R_s < 10$ MPa, $\varepsilon$ increases rapidly and significantly with decreasing $R_s$. Furthermore, the higher the geostress level, the faster $\varepsilon$ increases with the decreasing $R_s$. 


(2) Relationship between tunnel strain and geostress
Through extrapolation from the measured geostress, we found that the maximum principal stress on the vertical tunnel axis with the largest tunnel-burial depth along with the Wenchun–Maerkang section of CHN G4217 is ~30 MPa. When geostress was within 5–30 MPa ($GSI = 50, P_i/P_0 = 0.05$), we used Equation (1) to calculate the change of tunnel strain (Figure 4). Our data show that when $R_c = 9.7$ MPa and $R_c = 14.5$ MPa, $\varepsilon$ of the tunnel increases rapidly with increasing geostress, whereas when $R_c = 31.5$ MPa and $P_0 = 30$ MPa, $\varepsilon$ is only 1.4%. This suggests that the deformation of soft rock tunnels increases rapidly with increasing geostress; however, with increasing geostress, tunnel strain for harder rock tunnels does not increase significantly.

![Figure 3. Relationship between tunnel strain and uniaxial compressive strength.](image)

Figure 3. Relationship between tunnel strain and uniaxial compressive strength.

(3) Relationship between tunnel strain and $GSI$
The $GSI$ of a rock mass indicates the integrity of the rock mass and state of its structural plane. From the results of the calculation (Figure 5) of the tunnel strain, as $GSI$ changes ($P_0 = 10$ MPa, $P_i/P_0 = 0.05$), it is obvious that tunnel strain increases with decreasing $GSI$, especially when $GSI < 60$. The tunnel strain in soft rock ($R_c = 9.7$ and $R_c = 14.5$) tunnels increases rapidly with decreasing $GSI$. However, the tunnel strain in hard rock ($R_c = 31.5$ and $R_c = 65.1$) tunnels does not increase significantly with decreasing $GSI$. This indicates that the deformation of tunnel-surfacing rock is not only subject to uniaxial compressive strength and geostress but also to the integrity of the rock mass and the state of the rock mass structural plane, especially for soft-rock tunnels.

![Figure 4. Relationship between tunnel strain and geostress.](image)

Figure 4. Relationship between tunnel strain and geostress.
Figure 5. Relationship between tunnel strain and geological strength index.

(4) Relationship between tunnel strain and strength-to-stress ratio
The ratio of the rock mass uniaxial compressive strength $\sigma_{cm}$ to the in-situ stress $P_0$ is an indicator of potential squeezing problems in tunnels$^{[12]}$. The strength-to-stress ratio is defined as

$$F = \frac{\sigma_{cm}}{P_0}$$ (3)

The change in tunnel strain with the strength-to-stress ratio under different support resistances when geostress is 10 MPa and $R_c = 14.5$ MPa indicates that they are inversely proportional (Figure 6). When $F < 0.5$, $\epsilon$ increases rapidly with decreasing $F$, and when $F < 0.2$, $\epsilon$ increases sharply with decreasing $F$.

The larger the support resistance of the tunnel, the smaller the tunnel strain. For example, when $F = 0.12$, $\epsilon = 7.78\%$ for unsupported tunnels; when $P_i/P_0 = 0.05$, $\epsilon$ decreases to 4.1%; when $P_i/P_0 = 0.1$, $\epsilon$ further decreases to 2.7%.

![Graph showing relationship between tunnel strain and strength-to-stress ratio](image)

Figure 6. Relationship between tunnel strain and strength-to-stress ratio.

3.2. Prediction of deformation in tunnels on the Wenchun–Maerkang section of CHN G4217
According to the above analysis, tunnel strain is subject to several factors, such as geostress, uniaxial compressive strength, and GSI. Overall, the strength-to-stress ratio is a comprehensive reflection of the relationship between the tunnel strain and each relevant factor. Therefore, it is used to analyze and predict a large deformation of tunnel-surrounding rock$^{[6,11,12]}$. 

![Graph showing relationship between tunnel strain and strength-to-stress ratio](image)
According to the design specifications of the highway and railway tunnels in China [13–14], large deformation of tunnel-surrounding rock is generally divided into three classes; namely, slight, medium, and severe. However, there are some differences in the specification standards and among scholars concerning the classification of large deformation grades and for the assessment standards [6,12–14]. By reference to existing literature and based on the above analysis of the relationships between the tunnel wall displacement and relevant factors, we developed the criteria for the analysis and assessment of large deformation of tunnel-surrounding rock on the Wenchun–Maerkang section of CHN G4217 (Table 3).

**Table 3. Classification of large deformation in tunnels on the Wenchun–Maerkang section of CHN G4217**

| Class   | Level  | Tunnel strain (%) | Strength-to-stress ratio |
|---------|--------|-------------------|--------------------------|
| I       | Slight | $2 \leq \varepsilon < 3$ | 0.25–0.5 |
| II      | Medium | $3 \leq \varepsilon < 5$ | 0.15–0.25 |
| III     | Severe | $5 \leq \varepsilon$ | <0.15 |

We used the strength-to-stress ratio approach to analyze large tunnel deformation in the CHN G4217 section of the Wenchun–Maerkang Tunnel. The geostress of sections with different burial depths in each tunnel was analyzed and predicted based on geostress measurement results and regional distribution of geostress fields on the CHN G4217 section of the Wenchun–Maerkang Tunnel. We calculated the uniaxial compressive stress of the rock mass and classified the level of large deformation in each tunnel (Table 3). Based on the strength-to-stress ratio approach, large deformation in tunnels on the CHN G4217 section of the Wenchun–Maerkang Tunnel can be divided into the following types:

- Because of the influence of geologic structures, rock mass in fault fracture zones has a very low GSI value, resulting in low uniaxial compressive strength and strength-to-stress ratio. At greater tunnel-burial depths, large deformation may occur. This tunnel type mostly applies to the Wenchuan Tunnel No. 1 (passing through Maoxian–Wenchuan Fault) and the Miyaluo Tunnel No. 3 (parallel to the nearby Miyaluo Fault). It is assumed that the rock surrounding these two tunnels is characterized by a slight to medium-large deformation.
- Rock mass in the Devonian Weiguan Group consists of carbonaceous phyllite (soft rock) with $R_c = 5.14–14.3$ MPa. Slight to medium-large deformation is likely to occur in sections with great burial depth. This type of tunnel mostly applies to the Gucheng Tunnel, Xuecheng Tunnel No. 1, Ganbao Tunnel, and Weiguan Tunnel.
- Rock mass consisting of phyllite (soft rock) in the Triassic Xinduqiao Formation, with $R_c = 12.8–16.2$ MPa. Lixian Tunnel (maximum burial depth, 976 m), Shiziping Tunnel (maximum burial depth, 1280 m), Zhegushan Tunnel (maximum burial depth, 1393 m), and other tunnels pass-through this suite of strata at large burial depths. It is assumed that the surrounding rock tunnels are characterized by a slight to medium-large deformation.

### 3.3. Characteristics of large deformation revealed in tunnels construction

During the construction of tunnels on the Wenchun–Maerkang section of CHN G4217, evidence of large deformation was found in many tunnels (Table 4).

**Table 4. Characteristics of large deformation in tunnels on the Wenchun–Maerkang section of CHN G4217 based on construction data**

| Tunnel | Maximum tunnel-burial depth (m) | Tunnel length (m) | Tunnel-burial depth in deformation section (m) | Geological characteristics of tunnel-surrounding rock in the deformation section | Characteristic of large deformation discovered during construction |
|--------|---------------------------------|-------------------|-----------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Wenchuan | 630                              | 4777              | 480–630                                      | Rock mass with strong                                                        | Deformation and intrusion                                           |
| Tunnel No. 1 | fold deformation, abundant structural lenses, bedding-plane shear, and powdery rock zones. The strike of the schistosity plane intersects tunnel axis at a small angle. Steeply dipping, thin-layered sericitic phyllite with strong bedding-plane shear and weathering. The strike of the schistosity plane intersects tunnel axis at a small angle. Steeply dipping, laminated phyllites (including carbonaceous). The strike of the schistosity plane intersects tunnel axis at a small angle. Steeply dipping, laminated sericitic, and carbonaceous phyllites. The strike of the schistosity plane intersects tunnel axis at a small angle. Primary lining supports cracking and local deformation. | Significant deformation, intrusion, and damage of Z5j primary support occur. Extrusion of steel frame at joint of upper and lower steps is significant. The tunnel strain is 3.9%–6.9%. Significant deformation, intrusion, and damage of primary lining support occur in section IV2, with local deformation of the secondary lining. The tunnel strain is 0.4%–0.9%. | Deformation of a typical monitoring section is 211–466 mm, and tunnel strain is 2.7%–6.2%. Deformation of a typical monitoring section is 85–360 mm, and tunnel strain is 1.1%–4.8% |
|---|---|---|---|
| Taoping Tunnel | 210 | 2374 | 80–104 |
| Xuecheng Tunnel No. 1 | 485 | 3321 | 382–485 |
| Gamboa Tunnel | 474 | 4140 | – |
| Shipping Tunnel | 1280 | 13,156 | – |
| Miyaluo Tunnel No. 3 | 319 | 4198 | 130–319 |
| Zhegushan Tunnel | 1393 | 8784 | 500–1120 |

4. Analysis and discussion
We compared the predicted results of large tunnel-surrounding rock deformation on the Wenchun–Maerkang section of CHN G4217 with those revealed by construction (Table 4) and found the main influencing factors to be as follows:

4.1. Relationships among deformation of tunnel-surrounding rock, burial depth, and geostress
Generally, the geostress field of shallow crustal regions increases with an increase in the burial depth. Geostress measurements in boreholes also prove that geostress increases with depth. During the construction of the tunnels on the Wenchun–Maerkang section of CHN G4217, the deformation sections cut by tunnels were found to have burial depths of >382 m, except for Taoping Tunnel and Miyaluo Tunnel No. 3, thereby showing that large tunnel-surrounding rock deformation occurs mainly under high geostress. After measuring the maximum deformation of 93 soft rock tunnels, Chen Ziquan et al.[13] found that the correlation between deformation and geostress was irregular; that is, they found no obvious change in the variation of deformation with increasing geostress. The relationship that we found among the large deformation of tunnel-surrounding rock, burial depth, and geostress of the Wenchun–Maerkang section of CHN G4217 is consistent with their research findings. The Wenchuan Tunnel No. 1 and Miyaluo Tunnel No. 3 are the two tunnels exhibiting medium-to-severe deformation, but the maximum burial depth of the deformation section is only 466 m. The Zhegushan Tunnel and Shiziping Tunnel, which have the greatest burial depths, do not show significant large deformation in the surrounding rock, and there is no large deformation of tunnel-surrounding rock in the section with the greatest burial depth. There is also no large deformation of the tunnel-surrounding rock in the Lixian Tunnel, which has a burial depth of 976 m. This shows that the correlation between large deformation of tunnel-surrounding rock and geostress deformation is weak as high geostress does not necessarily result in large deformation.

4.2. Relationship between deformation of tunnel-surrounding rock and strength of rock mass
Most tunnels with large deformation of tunnel-surrounding rock on the Wenchun–Maerkang section of CHN G4217 are in rock masses dominated by slate and phyllites (including carbonaceous) that are soft rock. This indicates that soft rock tunnels are more prone to large deformation of the tunnel-surrounding rock. However, the tunnels with the most intense deformation (Wenchuan Tunnel No. 1 and Miyaluo Tunnel No. 3) were constructed in sections where the tunnel-surrounding rock is characterized by strong fold deformation and strong bedding-plane shear that is affected by the geologic structure. These effects show that the lower the strength of rock mass, the greater the chance of large deformation of the tunnel-surrounding rock occurring in the tunnel, which is also consistent with calculation results from Equation (1). This indicates that soft rock tunnels that are subject to compression due to the geologic structure are more likely to have large deformation characterized by tunnel-surrounding rock.

4.3. Relationship between deformation of tunnel-surrounding rock and strength-to-stress ratio
From the comprehensive analysis of the relationship among large deformation of the tunnel-surrounding rock, geostress, and rock mass strength, we found the strongest correlation between large deformation of the tunnel-surrounding rock and the strength-to-stress ratio. For example, although the burial depth of Wenchuan Tunnel No. 1 and Miyaluo Tunnel No. 3 is not large, the GSI and σ crm are low, thereby resulting in low rock mass strength, low strength-to-stress ratio, and ultimately large deformation.

4.4. Relationship between deformation of tunnel-surrounding rock and rock mass structure
The tunnel surrounding the rocks on the Wenchun–Maerkang section of CHN G4217 is a massive rock comprising interbedded metasandstone, slate, and phyllites. The main structural surface controlling deformation and rock mass stability is the steeply dipping schistosity plane. The tunnel excavation showed that the angle between the strike of the schistosity plane and the orientation of the tunnel axis had a significant effect on the stability of the tunnel-surrounding rock. The stability is good where the schistosity plane intersects the tunnel axis at a large angle, but is poor where they intersect
at a small angle or are parallel to each other. Sections characterizing the tunnel-surrounding rock with large deformation are mostly where schistosity parallels the tunnel axis or intersects it at a small angle. Figure 7a illustrates the deformation of the sidewall in Miyaluo 3 Tunnel, and Figure 7b shows the typical deformation-monitoring section, indicating that sidewall deformation is the largest.

Figure 7a illustrates the deformation of the sidewall in Miyaluo 3 Tunnel, and Figure 7b shows the typical deformation-monitoring section, indicating that sidewall deformation is the largest.

5. Conclusions
The tunnel-surrounding rock on the Wenchun–Maerkang section of CHN G4217 consists mainly of metasandstone, slate, and phyllite (including carbonaceous). The main structures along the expressway are the Xuecheng S-shaped structure in the Songpan–Garzê fold belt and the northwest-trending Maerkang structure, which consists of a series of tight compressional synclines and anticlines. The large deformation of tunnel-surrounding rock occurs mainly in soft rock, such as slate and phyllite (including carbonaceous), which is strongly affected by the geologic structure.

There is no obvious correlation between the large deformation of tunnel-surrounding rock, burial depth, and geostress in tunnels on the Wenchun–Maerkang section of CHN G4217. In soft rock, the tunnel strain increases rapidly with increasing geostress, decreasing GSI, and decreasing rock mass uniaxial compressive strength $\sigma_{cm}$, whereas in hard rock, the tunnel strain does not change significantly with increasing geostress and decreasing GSI and compressive strength $\sigma_{cm}$.

On the Wenchun–Maerkang Expressway, the tunnel-surrounding metamorphic rock is characterized by steeply dipping structure and laminated strata. The relationship between the schistosity strike and tunnel axis plays a significant role in the deformation and stability of the rock since the large deformation of the tunnel-surrounding rock occurs primarily in the section where the schistosity strike intersects the tunnel axis at a small angle. The plate-like rock mass in the sidewall of the tunnel deforms toward the free face of the tunnel under the action of high geostress, thereby resulting in prominent sidewall deformation.

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