Mechanical behaviors of tunnel lining in uneven temperature field of high geothermal surrounding rock

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Abstract: Because of large temperature difference between inside and outside of tunnel lining in high ground temperature environment, thermal stress is easy to occur in the structure, which affects the stability of tunnel lining. In this paper, a three-dimensional thermo-mechanical coupled numerical model of rock stratum-tunnel is established based on a tunnel project with high geo-temperature, and the stress of tunnel lining under high geo-temperature environment is calculated and analyzed, the influence of temperature distribution on lining stress is analyzed. The results show that the principal stress and surrounding rock pressure increase with the increase of temperature at the initial stage of lining. When the temperature field is not uniform, the stress concentration is easier at the corner of the initial support of the high temperature side. When the temperature difference between the left and right sides of the lining is constant, the surrounding rock pressure ratio between the high temperature side and the low temperature side is basically the same. However, the pressure difference of surrounding rock increases with the increase of the initial temperature value. Therefore, the unfavorable temperature field distribution of surrounding rock should be carefully handled in tunnel design and construction. The research results of this paper will provide some reference value for the design and construction of similar tunnel with temperature and heat damage in highland.

Keywords: High geothermal tunnels; Inhomogeneous temperature field; Primary support
1 Introduction

The high temperature phenomenon of rock is remarkable under the influence of geological structure, tunnel depth, radioactive heat-generating elements, etc. In recent years, along with the tunnel construction scope and the mileage unceasing increase, the construction often meets the high temperature adverse geology which is difficult to avoid\(^1\)-\(^2\), the maximum ground temperature of the completed Sangzhuling and Gaoligong Mountains railway tunnels reached 90 °C and 75 °C respectively. In tunnel construction, the tunnel with air temperature higher than 28 °C is considered as high ground temperature tunnel. The working environment in high ground temperature tunnel is difficult, the safety risk is high, and the construction efficiency is low. Generally, it is necessary to use cooling measures to control the construction environment temperature inside the tunnel at 28 °C. However, the temperature difference between the external surrounding rock and the internal air will reduce the bond strength of the concrete lining and make it difficult to spray, the safety of tunnel and the stability of surrounding rock are seriously affected\(^3\).

Scholars have done a lot of research on the surrounding rock temperature field and lining stress field formed by high ground temperature tunnel construction. Shao et al.\(^4\) took the stress-strain constitutive relation of thermo-elasticity into consideration to establish the simultaneous elastic equations. By using the method of dimensionless and series solution of differential equations, the thermoelastic problems of the circular cross-section tunnel were analyzed, and the thermoelastic theoretical solutions including temperature field, displacement field and stress field were obtained. Lai et al.\(^5\) simplified the thermo-hydro-mechanical coupling equilibrium differential equation by using the non-dimensional method and the perturbation method, and deduced the finite element calculation formula of tunnel temperature field and the approximate analytic solution of temperature effect on lining. Shao\(^6\) takes the surrounding rock layers of tunnel into consideration, and obtains the stress field and displacement field of each surrounding rock layer under the thermal-mechanical coupling by the equilibrium equation. Liu et al.\(^7\) proposed that the tunnel temperature stress could be divided into two groups: the spontaneous temperature stress and the elastic confinement temperature stress, which were obtained respectively according to the theory of infinite long and thick wall cylinder\(^8\) and Lame stress formula. Li\(^9\) considered the influence of boundary conditions on the heat conduction differential equation, and compiled a program according to the tunnel temperature field and the lining stress calculation formula, and analyzed the influence of the change of high ground temperature and related parameters on the lining stress field. In the field test and numerical simulation, Zhan et al.\(^10\) established a thermo-hydro-mechanical coupling model considering the phase transition, and analyzed the temperature, pore water pressure and temperature deformation based on the COMSOL partial differential equation. Taking Xiluodu non-pressure-release Hongdong County as the research object, Chen et al.\(^11\) set up a three-dimensional model to simulate the construction of the tunnel chamber under different initial ground temperature. Wang et al.\(^12\)-\(^13\) based on the project of Sangzhuling Super High Geothermal Tunnel on
Sichuan-tibet railway, analyzed the main stress, load pattern and factor of safety of the high geothermal lining with the change of temperature through numerical simulation, the fitting formula of the uniform load and temperature on the lining is given. It is found that the higher the temperature, the greater the surrounding rock pressure and the faster the rate of increase. However, when scholars consider the initial temperature of surrounding rock, they only consider the surrounding rock as a given temperature, then the resulting stress field and temperature stress are distributed symmetrically along the middle line of tunnel. The temperature of the surrounding rock is not invariable in the actual project. It is very likely that the tunnel will pass through the area near the heat source, resulting in a higher temperature on the side near the heat source and a lower temperature on the side far away from the heat source, then the uneven temperature stress is produced in the lining, and the weak part of the structure is easy to be destroyed.

In this paper, FLAC3D finite difference software is used to analyze the thermal-mechanical coupling of high ground temperature tunnel. Taking the Red River Tunnel project in Yunnan as the background, considering the distribution of non-uniform temperature field with heat source around the tunnel section, the thermal-mechanical coupling calculation is carried out and verified according to the literature, observe the non-uniform difference between the non-uniform stress produced by lining and the surrounding rock pressure. At the lower corner of the supporting Factor of safety in the initial stage of high geo-temperature excavation, the stress on the high temperature side is more concentrated under the non-uniform temperature field distribution, and it is easier to be destroyed. Taking the temperature field as the variable, the parameters of the initial lining force are analyzed to provide the mechanical basis for the different surrounding rock temperature in the project.

2 Validation of numerical simulation for high geothermal tunnels

2.1 Principle of thermo-mechanical coupling analysis

The thermal-mechanical coupling of FLAC3D can get the change of stress by calculating the element strain caused by the change of temperature. The calculation of the temperature field is based on Fourier’s law of heat conduction, that is, the rate of change of a point temperature in space with time is positively correlated with the rate of thermal diffusivity. In FLAC3D, the equation of Conservation of energy is:

\[-q_{i,j} + q_v = \rho C_v \frac{\alpha T}{\alpha t}\]  \hspace{1cm} (1)

where \( q_{i,j} \) is the heat flux (W/m²); \( q_v \) is the body heat source intensity (W/m²); \( \rho \) is the density (kg/m³); \( C_v \) is the amount of heat in a given volume [J/(kg·°C)]; \( T \) is the temperature (°C);\( t \) is the time(s).

In addition to the definition of heat transfer between solid and solid, by means of FLAC3D, the
convection heat transfer between fluid, and the combination of the two can be simulated as that the wall rock-lining-air heat transfer process. The temperature field is calculated by explicit method. And after each complete temperature time period calculation, carries on this stage thermodynamic calculation, so the cycle calculation.

2.2 Comparison with the in-situ monitoring data

The parameters of the model are set in the reference text, in which a grid is divided every 0.5 m longitudinally, and the circumferential grid is divergent around the center of the tunnel. Considering that the parts where the temperature exchange is most intense usually occur around the tunnel, the grid around the tunnel is encrypted. The computational model is shown in Figure 1. The mechanical boundary conditions and the thermal field boundary conditions are consistent with those given in the paper. Simulation of the original 40 °C, 50 °C, 60 °C, 80 °C high ground temperature, the simulation calculation.

![Fig. 1 The 3D thermo-mechanical coupling numerical model](image)

The side wall, spandrel and vault of the lining are monitored according to the monitoring points in the original text, and compared with the field measurement in the paper. The temperature of surrounding rock is measured at 45 °C, and the working condition of surrounding rock with high ground temperature is taken at 40 °C. The results are shown in Figure 2.

![Fig. 2 Comparison of in-situ measurement and numerical simulation of cross-section concrete stress (MPa)](image)

(a) Test Point results  (b) Simulation results

Fig. 2 Comparison of in-situ measurement and numerical simulation of cross-section concrete stress (MPa)
Observation test data, 2 test section test data by geology, construction and other factors, there will be some fluctuations. However, the overall stress trend and distribution of the two test sections are relatively consistent, which can reflect the reliability of the field test. It is found that the maximum compressive stress of lining in field test and numerical simulation occurs at the side wall, and the maximum tensile stress occurs at the arch waist, in this paper, the numerical simulation shows that the maximum tensile stress is about 15% less than the field test, and the maximum compressive stress is about 7% less than the field test.

In addition, the distribution of stress nephogram obtained from 4 simulated high geo-temperature conditions is compared with the numerical values as shown in table 1 and 2.

Table 1 Comparison of the maximum tensile stress under different working conditions

| Working condition | Reference\(^{[11]}\) /MPa | Distribution position | Simulation results /MPa | Distribution position | Difference value |
|-------------------|---------------------------|----------------------|------------------------|----------------------|------------------|
| No temperature field | 0.4 | Corners, vaults | 0.56 | Corners | 28.0% |
| 40°C | 1 | Spandrel, side wall, back arch | 1.14 | Corner, Spandrel | 12.3% |
| 50°C | 1.85 | Spandrel, side wall, back arch | 1.97 | Corner, Spandrel | 6.1% |
| 60°C | 2.68 | Spandrel, side wall, back arch | 2.92 | Corner, Spandrel | 8.2% |
| 80°C | 4.30 | Spandrel, side wall, back arch | 5 | Corner, Spandrel, invert | 14.0% |

Table 2 Comparison of the maximum compressive stress under different working conditions

| Working condition | Reference\(^{[11]}\) /MPa | Distribution position | Simulation results /MPa | Distribution position | Difference value |
|-------------------|---------------------------|----------------------|------------------------|----------------------|------------------|
| No temperature field | 8.9 | side wall | 9.8 | side wall | 9.2% |
| 40°C | 10.58 | Side wall, arch waist | 10.75 | Side wall | 1.6% |
| 50°C | 13.01 | Side wall, arch waist | 12.61 | Side wall, arch waist | 3.2% |
Due to the difference between the internal air thermodynamic parameters and the construction site parameters such as the heat transfer coefficient, there is a difference in the numerical value, but it is still controlled within a reasonable range. The distribution of the main stress in the lining is approximately the same. It is proved that the numerical simulation method is reasonable and can reflect the actual situation well.

3 Stress distribution on tunnel under uneven temperature field

In practical engineering, heat source is one of the important reasons for high geothermal environment. In the high ground temperature environment, the temperature on the side near the heat source is higher, and the temperature on the side far from the heat source is lower. This leads to stress concentration and failure on the side lining near the heat source. Based on the tunnel engineering in Red River, Yunnan Province, and based on the distribution of non-uniform temperature field, the thermal-mechanical coupling analysis is carried out by FLAC3D to study the influence of non-uniform temperature on the stress of lining.

3.1 Solution of temperature field

In the calculation of the temperature field, the one-dimensional unsteady heat conduction differential equation\[14-16\] in polar coordinates is usually used to solve the temperature field distribution after the excavation of the multi-layer composite tunnel. The control differential equation is:

\[
\frac{\partial u}{\partial t} = a \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right)
\]

where \( u \) is the temperature (°C); \( t \) is the heat conduction time (s); \( a = \frac{\lambda}{c \rho} \), \( \lambda \) is the thermal conductivity of medium [W/(m²·°C)], \( c \) is the specific heat capacity of medium [J/(kg·°C)]; \( \rho \) is the density of medium (kg/m³); \( r \) is the polar radius (m).

The solution of the equation is greatly influenced by the initial conditions and the boundary conditions, considering the temperature field generated for the soil affected by one of the heat sources, and the temperature is not affected by the heat source at infinite distance, the boundary radius length is assumed to be 0, based on the following assumptions:
1) the heat source is simplified to a point, and the gradient curvature of surrounding rock temperature due to heat transfer is circular, but near the tunnel excavation is infinitesimal.

2) the thermal conductivity of surrounding rock is homogeneous and isotropic, and the density, specific heat capacity, thermal conductivity and other thermodynamic parameters do not change with temperature.

3) the heat transfer between the surrounding rocks is heat conduction, and the temperature exchange caused by heat radiation is not considered.

4) the surrounding rock medium is closely bonded, and there is no thermal resistance in the medium.

Laplace transformation and Bessel expansion for the equation:

$$
\begin{cases}
Ali(\chi r) + BK(\chi r) + \frac{f(\rho)}{a} = u,

\alpha I(\chi r) - BK(\chi r) + \frac{f(\rho)}{a} = 0
\end{cases}
$$

$$
\tilde{\mu} = \frac{\chi K_1(\chi r)\left(u_i - \frac{f(\rho)}{a}\right) - K_0(\chi r)\frac{f(\rho)}{a}}{(\chi K_1(\chi r)I_0(\chi r) + \chi I_1(\chi r)K_0(\chi r))} + \frac{\chi K_1(\chi r)\left(u_i - \frac{f(\rho)}{a}\right) + I_0(\chi r)\frac{f(\rho)}{a}}{(\chi K_1(\chi r)I_0(\chi r) + \chi I_1(\chi r)K_0(\chi r))} + \frac{f(\rho)}{a}
$$

The Crump code is compiled and calculated. The rock temperature at 600m from the heat source center is about 82 °C, and the rock temperature at 780m is about 57 °C. Therefore, when calculating the non-uniform temperature field, one side of the model boundary is approximately set at 80 °C and the other at 60 °C, in which the initial temperature field distribution inside the model is generated by the calculation of the thermal field after the temperature boundary is fixed. The distribution of the generated initial temperature field is shown in Fig. 3.

![Fig. 3 Distribution of the temperature](image-url)
3.2 Establishment of the Model

The width of the tunnel model is 12.08 m, the height is 8.6 m, the depth of the tunnel is 80 m, the thickness of the bottom surrounding rock is 40 m, the distance between the two ends of the tunnel and the boundary of the two ends of the model is 50 m, and the longitudinal dimension of the model is 30 m, the in-plane model grid extends outwards from the center of the tunnel. The computational model is shown in Figure 4. The thermodynamic parameters of tunnel surrounding rock and lining are listed in Table 3.

Table 3 Table of the physical and mechanical parameters

| Materials          | Density / (kN·m⁻³) | Young's Modulus / GPa | Poisson ratio | Cohesive / MPa |
|--------------------|---------------------|-----------------------|---------------|----------------|
| Surrounding rock   | 20                  | 1.5                   | 0.4           | 0.1            |
| C25 shotcrete      | 22                  | 23                    | 0.2           | -              |

| Materials          | Angle of internal friction / (°) | Thermal conductivity / [W·(m·°C)]⁻¹ | Coefficient of linear expansion / (°C⁻¹) | Specific heat capacity / [J·(kg·°C)]⁻¹ |
|--------------------|----------------------------------|--------------------------------------|----------------------------------------|---------------------------------------|
| Surrounding rock   | 24                               | 2.3                                  | 6x10⁻⁷                                 | 707                                   |
| C25 shotcrete      | -                                | 1.60                                 | 1.02x10⁻⁵                              | 911                                   |

All the boundary conditions except the upper boundary are set as constraint boundary, and the initial stress field generated by self-weight is considered. In order to simulate the influence of surrounding rocks on the thermal conductivity of surrounding rocks, a temperature load is applied at the boundary of the model to generate the initial temperature field. In the calculation, the air temperature in the model is fixed at 28 °C after each excavation of 2 m, and the initial lining is applied after stress release. The heat exchange mode between air and lining is defined as convective heat transfer, and the coefficient of convective heat transfer is 10 W/(m² °C). Taking the boundary effect
Fig. 4 The 3D thermo-mechanical coupling numerical model into account, the stress of the lining in the middle of the excavation is analyzed. The internal force monitoring points are set at the section corner, side wall, arch waist, arch shoulder and arch crown of the tunnel. The monitoring points are arranged as shown in Figure 5.

Fig. 5 Layout of monitoring points of tunnel section

3.3 Analysis of calculation results

Figure 6 shows the maximum compressive stress and the maximum tensile stress nephogram of the lining structure, and figure 7 shows the stress and pressure values of the monitoring points.

Fig. 6 The stress nephogram of the tunnel lining (MPa)

(a) The 3rd principal stress (b) The 1st principal stress
As can be seen from the diagram, all points of the primary lining are under pressure. The maximum compressive stress of lining is mainly distributed at the side wall and the arch waist, and the maximum tensile stress is mainly distributed at the spandrel and the arch waist. However, the surrounding rock has less pressure at the side wall, and the compressive stress at the side wall is mainly produced by the internal thermal expansion extrusion of the lining. The comprehensive stress and pressure diagram shows that the surrounding rock pressure and stress at the corner of the lining wall are relatively large and belong to the most disadvantageous position.

**Fig. 7 Distribution diagram of the stress and pressure at monitoring points**

**Table 4 Comparison of compressive stresses on the left and right side of tunnel lining**

|       | Maximum compressive stress on the left (MPa) | Maximum compressive stress on the right (MPa) | Difference of the compressive stress | Rock pressure on the left (10^5Pa) | Rock pressure on the right (10^5Pa) | Difference of the surrounding rock pressure |
|-------|--------------------------------------------|-----------------------------------------------|-------------------------------------|-----------------------------------|-------------------------------------|-------------------------------------------|
| Spandrel | -12.79                                    | -12.51                                         | 2.2%                               | 4.40                              | 4.35                                | 1.1%                                      |
| Arch waist | -13.52                                   | -12.91                                         | 4.6%                               | 4.48                              | 4.24                                | 5.6%                                      |
| Side Wall | -13.42                                   | -12.70                                         | 5.6%                               | 3.63                              | 3.45                                | 5.2%                                      |
| Corner    | -11.87                                    | -10.58                                         | 12.2%                              | 8.03                              | 7.66                                | 4.8%                                      |

Comparison of the two sides of the lining force table, as shown in table 4. It is found that the change of the maximum compressive stress is obvious, and the increase of the maximum compressive stress at the left side is obvious compared with that at the right side, and the increase of the maximum compressive stress at the corner is 12%. The difference of surrounding rock pressure increases from the top of the arch to the corner of the wall, and the difference of the corner is 0.37 × 10^5Pa. This is because the distribution of temperature field decreases from the left side to the right side, so the temperature difference at the left side wall and corner of the lining is large, and the temperature difference at the spandrel is small. Combined with the distribution of principal stress and pressure, it is found that the lining corner is the most serious area of non-uniform force. According to the existing research conclusion, the corner of the initial support is the lowest area of the Factor of safety, which is the most
vulnerable area. In the case of non-uniform temperature distribution in the actual project, more attention should be paid to the weak area at the corner of the high-temperature side wall of the initial support.

3.4 Temperature parameter analysis

Considering that the non-uniform temperature field distribution is more likely to cause the damage of the weak corner of the early supporting wall, the non-uniform temperature field is set as a variable. The influence of temperature gradient and initial temperature on the mechanical properties of tunnel lining is investigated. The temperature on both sides of the temperature boundary of the design model (where the high temperature side is on the left) is fixed at 20-20 °C, 20-30 °C, 20-40 °C, 20-50 °C, 20-60 °C, 30-30 °C, 30-40 °C, 30-50 °C, 30-60 °C, 40-40 °C, 40-50 °C, 40-60 °C respectively, the initial temperature field is calculated by FLAC3D and then the excavation calculation is carried out. The parameters and dimensions of the model are consistent with the above simulation.

Table 5 is used to calculate the pressure value of the surrounding rock on the contact surface. It is found that when the temperature distribution is uniform, the pressure distribution of each storey in the surrounding rock is approximately the same. With the increase of the boundary temperature gradient of the model, the temperature difference between the two sides of the tunnel becomes larger, and the pressure difference between the two sides of the lining becomes larger. At the spandrel, the temperature of the left and right spandrel is similar, and the additional surrounding rock pressure caused by the temperature difference is negligible. It shows that the temperature difference has a great influence on the additional surrounding rock pressure. Therefore extract the temperature difference under the circumstances of the wall at the foot of the rock pressure and temperature ratio, as table 6.

Table 5 Comparison of surrounding rock pressure under different working conditions (10^5Pa)

| Spandrel | Arch Waist | Side Wall | Corner |
|----------|------------|-----------|--------|
| Left     | Right      | Left      | Right  | Left  | Right  | Left  | Right  |
| wall     | wall       | wall      | wall   | wall   | wall   | wall   | wall   |
| rock     | pressure   | pressure  | pressure| pressure| pressure | pressure| pressure |
| 20-20    | 3.98       | 3.98      | 2.13   | 2.11   | 2.07   | 2.09   | 1.82   | 1.83   |
| 20-30    | 4.30       | 4.15      | 2.19   | 2.14   | 2.24   | 2.18   | 1.95   | 1.95   |
| 20-40    | 4.67       | 4.36      | 2.29   | 2.20   | 2.44   | 2.30   | 2.12   | 2.09   |
| 20-50    | 5.09       | 4.65      | 2.42   | 2.27   | 2.68   | 2.43   | 2.33   | 2.27   |
| 20-60    | 5.55       | 4.92      | 2.62   | 2.33   | 2.94   | 2.57   | 2.60   | 2.51   |
| 30-30    | 4.63       | 4.62      | 2.29   | 2.28   | 2.41   | 2.43   | 2.12   | 2.14   |
| 30-40    | 5.02       | 4.86      | 2.39   | 2.33   | 2.62   | 2.56   | 2.34   | 2.35   |
| 30-50    | 5.45       | 5.15      | 2.53   | 2.40   | 2.90   | 2.73   | 2.60   | 2.57   |
| 30-60    | 5.93       | 5.46      | 2.74   | 2.50   | 3.20   | 2.89   | 2.89   | 2.84   |
| 40-40    | 5.38       | 5.39      | 2.50   | 2.53   | 2.85   | 2.87   | 2.63   | 2.63   |
| 40-50    | 5.85       | 5.69      | 2.71   | 2.63   | 3.17   | 3.06   | 2.93   | 2.92   |
| 40-60 | 6.36 | 6.03 | 2.94 | 2.76 | 3.47 | 3.26 | 3.26 | 3.22 |
|-------|------|------|------|------|------|------|------|------|

Table 6 Temperature at wall corner and rock pressure under non-uniform temperature field

|  | Left corner temperature°C | Right corner temperature°C | Difference value°C | Left rock pressure (10^5 Pa) | Right rock pressure (10^5 Pa) | Ratio |
|---|--------------------------|---------------------------|-------------------|----------------------------|----------------------------|-------|
| 20-30 | 26.1 | 24.1 | 2.0 | 4.30 | 4.15 | 1.03 |
| 20-40 | 30.6 | 26.8 | 3.8 | 4.67 | 4.36 | 1.07 |
| 20-50 | 35.2 | 29.5 | 5.7 | 5.09 | 4.65 | 1.09 |
| 20-60 | 39.8 | 32.1 | 7.7 | 5.55 | 4.92 | 1.09 |
| 30-40 | 34.2 | 32.3 | 1.9 | 5.02 | 4.86 | 1.03 |
| 30-50 | 38.8 | 35.0 | 3.8 | 5.45 | 5.15 | 1.06 |
| 30-60 | 43.4 | 37.6 | 5.8 | 5.93 | 5.46 | 1.09 |
| 40-50 | 42.4 | 40.4 | 2.0 | 5.85 | 5.69 | 1.03 |
| 40-60 | 46.9 | 43.1 | 3.8 | 6.36 | 6.03 | 1.05 |

As can be seen from Table 6, the additional wall rock pressure caused by temperature has a positive correlation with the temperature difference. When the temperature difference is constant, the ratio of wall rock pressure on the high temperature side is basically the same as that on the low temperature side, but because of the same temperature difference, under different temperature initial value, the higher the temperature initial value is, the greater the surrounding rock pressure is, so the additional surrounding rock pressure is also greater. These two factors should be fully taken into account in construction.

4 Conclusions

Based on the experimental data and numerical simulation, this paper considers the inhomogeneity of initial temperature field of surrounding rock, and observes the influence of lining force under inhomogeneous temperature field distribution. In addition, the temperature field distribution was taken as a parameter to conduct the parameter analysis. The following conclusions are obtained:

(1) After tunnel excavation, high temperature of surrounding rock and low temperature of construction environment in tunnel cause temperature stress in initial support. Among them, the initial lining points are under pressure, the maximum compressive stress distribution in the side wall, the arch waist. Under the condition of non-uniform temperature field, the maximum compressive stress in the high temperature side increases obviously compared with that in the low temperature side, and the increase amplitude is positively related to the temperature difference.

(2) The surrounding rock pressure on the initial support is affected by temperature, the higher the temperature, the greater the surrounding rock pressure. Under the non-uniform temperature field
distribution, when the temperature difference between left and right sides of the lining is constant, the ratio of the surrounding rock pressure is basically the same between the high temperature side and the low temperature side, but the magnitude of the surrounding rock pressure difference increases with the increase of the initial temperature value.

(3) Under the condition of non-uniform temperature distribution, the stress at the high temperature side wall corner is more concentrated, and the surrounding rock pressure at the corner is the biggest, which is affected most by the temperature, the additional surrounding rock pressure produced is the largest, more prone to failure.

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