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# Tempo-spatial characteristics and influential factors of rockburst: a case study of transportation and drainage tunnels in Jinping II hydropower station

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**Abstract:** Jinping II hydropower station is located in a high in-situ stress region in Southwest China. During the excavations of the transportation and drainage tunnels, more than 460 rockburst events were recorded in the transportation tunnel and 110 in the drainage tunnel, which has a serious and negative influence on the tunnels' construction and the safety of staff and equipment. In the paper, the characters of rockburst patterns are analyzed for the transportation and drainage tunnels. The results are illustrated as follow: (1) Most of intensive rockbursts occur in the layer $T_{2b}$, and continuous occurrences of rockbursts are more frequently observed than those in other layers. (2) The critical overburden depth of rockburst in the transportation tunnel is 600 m, and the length of the continuous occurrence section of rockburst is smaller than 25 m. The damaged depth of the rockburst has the tendency to increase with the increasing overburden depth, and the maximum damaged depth is over 3.5 m. (3) From east to west (west to east) in Jinping II hydropower station, the rockburst usually takes place in the right (left) side of tunnel working face, and then the left (right) or roof of the tunnel. The total length of the continuous occurrence section of rockburst is 57.4%–62.2% of the overall rockburst length, followed by the rockbursts of flake-splitting type and other types. (4) Compared with the transportation tunnel, the intensity of rockburst in the drainage tunnel is higher while the length of the continuous occurrence section of rockburst is smaller. The rockburst section with length less than 10 m and depth of 1 m mainly occurs in the layer at a depth of 1 800–2 000 m. The influences of opening geometry and excavation method on the characteristics of the adjacent zone are great, but the influence of the stress among the tunnel group induced by excavation is relatively low.

**Key words:** Jinping II hydropower station; rockburst; developing pattern; influential factor

## 1 Introduction

Rockburst is a kind of geological hazard triggered by the brittle rupture of surrounding rocks during unloaded excavation in high in-situ stress environments. It is basically accompanied by a sudden release of elastic strain energy and some other phenomena, such as slabbing, spalling, ejecting or throwing [1]. Rockburst has tremendous and potential threats to both the safety of staff and equipment, and may cause a series of casualty and property loss as unexpected.

Jinping II hydropower station is located in the boundary zone between Qinghai—Tibet Plateau and Sichuan Basin in Southwest China. The phenomenon of rock core disking frequently occurred during drilling in this field. The maximum principal stress measured is approximately 42.1 MPa. The four drainage tunnels, each about 16.7 km in length running parallel to and crossing the Jinping Mountain, connect the sluice gate and the plant units. The cross-section of two transportation tunnels A and B is U-shaped with sizes of 5.5 m $\times$ 5.7 m and 6.0 m $\times$ 6.25 m (width $\times$ height), respectively. In addition, the round drainage tunnel has been constructed for water inrush or dewatering. The transportation tunnels are excavated by blasting, with more than 460 rockbursts recorded during excavation. The drainage tunnel is excavated by TBM, with more than 110 rockbursts recorded from the beginning of excavation.

Since the first rockburst record of the England Tin

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Mine was reported in 1783, many researchers have conducted studies on the rockburst. A great number of rockburst forecast and prevention methods have been proposed, such as Erlang mountain method [1], Tao Zhenyu criterion [2], Qinling method [3], Hou Faliang criterion [4], Norway Barton criterion [5], Russense criterion, Turchaninov criterion, Kidybinski method and Hoek criterion [6, 7]. These methods or criteria have been employed with local monitoring data and laboratory tests to study the mechanical characters of rockbursts [8, 9]. However, the problem is strongly site-specific, depending upon many factors such as the magnitude and direction of in-situ stresses, the strength of rock mass, the geometry of the tunnel, as well as the relative positions and excavation methods.

The transportation tunnels have been completed and the drainage tunnel is partly completed, around 6 km at present. Due to the high in-situ stresses, various levels of rockbursts happened during excavation [10, 11]. This paper focuses mainly on the tempo-spatial characteristics of rockburst in the transportation and the drainage tunnels. Meanwhile, the characteristics of spatial distribution and the influences of the tunnel geometry, interaction of stress and excavation methods are also discussed.

## 2 Rockburst patterns and analysis

A rough illustration of the local geology is presented in Fig.1. The rockburst classification of Jinping II hydropower station is based on the “Code for water resources and hydropower engineering geological investigation” (GB50287-2006) [12] in China, as shown in Table 1.

### 2.1 Rockburst patterns in the transportation tunnels

The location and intensity of rockburst in the transportation tunnels are shown in Fig.2. During excavation, there were 460 rockburst events recorded, among which 229 and 231 happened in transportation tunnels A and B (those in the same position are not included), respectively. Among them, 181 rockbursts of grade I occurred in the tunnel A and 172 in the tunnel B, 79.04% and 74.46% of total rockbursts, respectively. 33 rockbursts of grade II occurred in the tunnel A and 41 in the tunnel B, 14.41% and 17.75% of total rockbursts, respectively. 15 rockbursts with grade greater than II happened in the tunnel A and 18 in the tunnel B. The rockbursts in the transportation tunnels are mainly observed in the layers $T_{2b}$ (Baishan marble), $T_{2z}$ (Zagunao marble) and $T_{2y}$ (Yantang marble). The rockbursts of grade IV are also mainly observed in the layer $T_{2b}$, such as in the sections of AK9+671–676 and AK9+696–706 in the tunnel A, and BK9+457–509 in the tunnel B. For the maximum principal stress in these regions is 60–70 MPa and the strength of the layer $T_{2z}$ is very high, elastic strain energy is easily stored to create good conditions for the occurrence of intensive rockburst.

Figure 3 illustrates the length of rockburst section in the transportation tunnels A and B. Normally, this length is less than 25 m. There are 198 points in the transportation tunnel A and 214 in the tunnel B, of which 31 points have a length larger than 25 m in the tunnel A and 17 in the tunnel B.

Figure 4 shows the relation between the length of rockburst section and the overburden depth of rockburst location in the transportation tunnels A and B. The critical overburden depth of rockburst location in the transportation tunnels is almost 600 m and there is no correlation between the length of rockburst section and the overburden depth.

The relation between the depths of rockburst location in the transportation tunnels with the stake number is shown in Fig.5. The depths of rockbursts location are basically less than 1 m. However, there

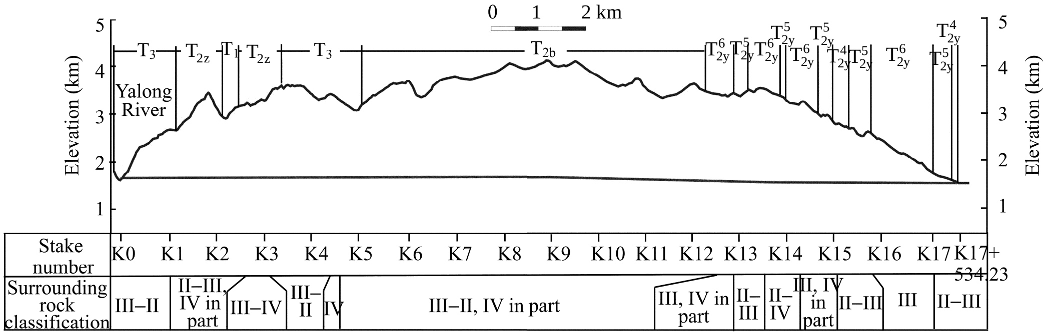


**Fig.1** Rough engineering geology along the transportation tunnels of Jinping II hydropower station.

**Table 1** Classification of rockburst.

| Grade of rockburst | Uniaxial compressive strength/ maximum stress ($R_c/\sigma_{max}$) | Failure depth (m) |
|---|---|---|
| Slight | 4–7 | < 0.5 |
| Moderate | 2–4 | 0.5–1.0 |
| Intensive | 1–2 | 1.0–2.0 |
| Extremely intensive | <1 | > 2.0 |

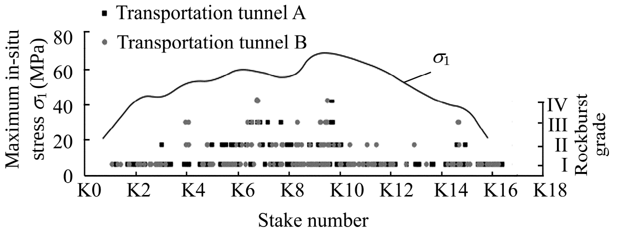



**Fig.2** Rockburst in the transportation tunnels.

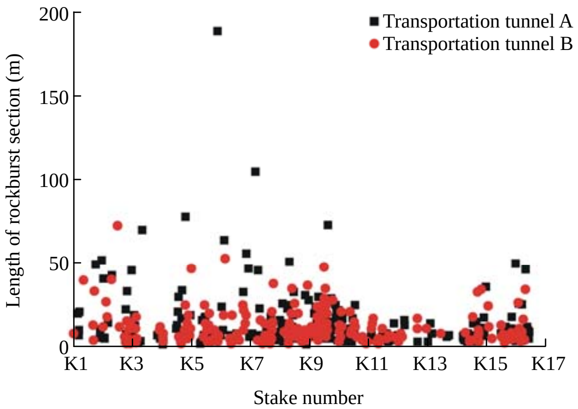



**Fig.3** Relation between length of rockburst section and stake number for the transportation tunnels.

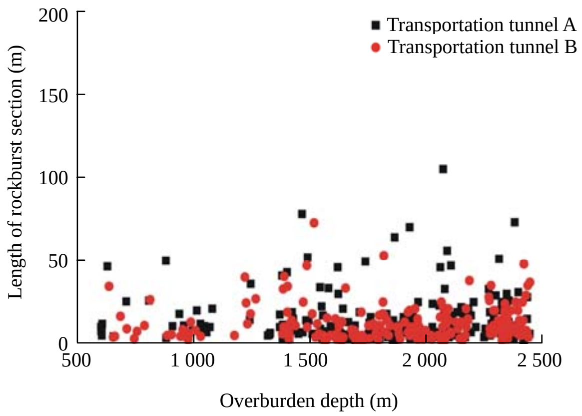



**Fig.4** Relation between length of rockburst section and overburden depth for the transportation tunnels.

were 18 spots recorded with depths over 1 m in the transportation tunnel A and 31 in the transportation tunnel B. Larger values of depths were mainly observed in the sections of K6+000–K10+000.

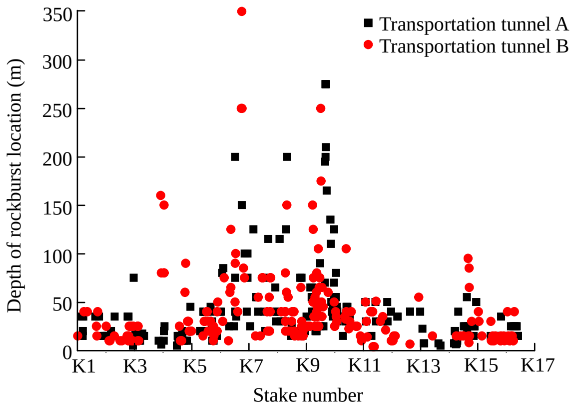



**Fig.5** Relation between depth of rockburst location and stake number for the transportation tunnels.

Figure 6 shows the depth of rockburst location in the transportation tunnels with the varying overburden depths. It is obvious that the depth of rockburst location increases with the overburden depth.

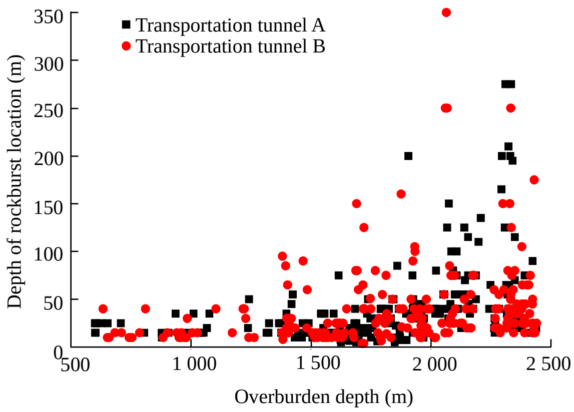



**Fig.6** Depth of rockburst location varying with overburden depth.

In the transportation tunnels, from east to west (from west to east), the rockbursts mainly occurred in the right (left) side of the tunnel face, which were 38.1%–52.6% of the total events. The rockbursts at the left side of the tunnel face and the crown were 23.3%–38.8% and 24.1% of the total rockburst events, respectively. The length of continuous occurrence section of rockburst was the maximum, which was 57.4%–62.2% of the total length of rockburst; flake-splitting rockburst was in the second place; the occasional rockburst was 14.1%–16.3%. Due to the slight alteration in the in-situ stress environment and the rock mass strength, the flake-splitting and continuous occurrence of rockburst occurred more frequently in the layer $T_{2b}$, then the layers $T_{2z}$ and $T_{2y}^5$. When the excavation of the headrace tunnels reaches those strata, special methods should be adopted to release the elastic strain energy stored in rock masses, such as pilot drilling and other methods. Meanwhile, proper supporting measures should be considered to prevent the continuous occurrence or flake-splitting rockbursts and help to keep the staff and equipment safe.

### 2.2 Rockburst in the drainage tunnel

The relations among the length of rockburst section, the depth of rockburst location in the drainage tunnel, and the stake number are illustrated in Fig.7. The length of rockburst section is usually less than 10 m, while only the length of 3 spots is over 10 m, which takes up 2.61% of total events. Except the 3 rockbursts, the depth of other rockbursts is basically less than 200 cm. It can be observed from comparison of Figs.3 and 7 that the length of rockburst section in the transportation tunnels is much longer than that in the drainage tunnel at the adjacent stake, but the depth shows an opposite trend. The variations in length of rockburst section and depth of rockburst location in the drainage tunnel are illustrated in Fig.8, indicating that the rockbursts with length less than 10 m and depth of 1 m are predominately located at the overburden depth of 1 800–2 000 m. This is totally different from that in the transportation tunnels.

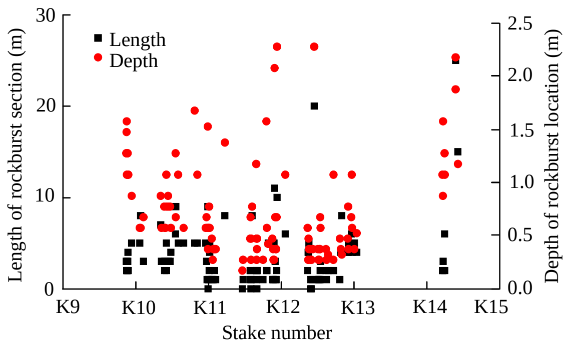



**Fig.7** Length of rockburst section and depth of rockburst location varying with stake number for drainage tunnel.

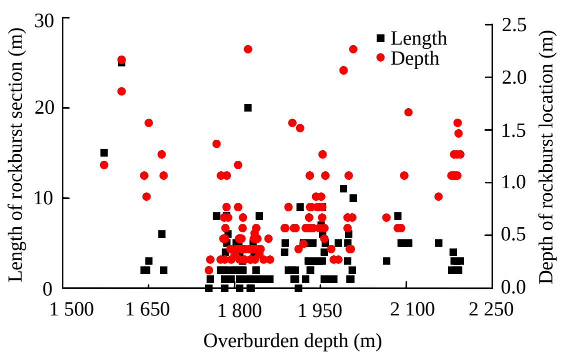



**Fig.8** Length of rockburst section and depth of rockburst location varying with overburden depth for drainage tunnel.

Based on the above analyses, we can get the results as follows: (1) As the transportation tunnels are excavated by the drill and blast method and the drainage tunnel by TBM, the perturbation to the rock masses in the transportation tunnels is greater than that in the drainage tunnel. The drill and blast method will cause great damage to the rock masses in direction parallel to the tunnel axis. The explosion releases part of the initial strain energy stored in rock masses. Therefore, the typical characteristic of rockburst in the transportation tunnels is of low grade, great extent and continuous occurrence of rockburst with collapse. However, the TBM method will induce lighter perturbations on the rock masses, thus rockbursts with high level and short length are observed. (2) Different geometries of the tunnels have varying impacts on the stress redistribution of rock mass. (3) The in-situ stress may be changed during the excavation of the transportation tunnel. Due to different geo-environments, those factors have different impacts on the characteristics of rockbursts.

## 3 Influential factors of rockbursts

The section of AK11+100 is taken as the typical cross-section for numerical analysis by finite element software, Phase2 [13]. The rock mass in this simulation is mainly regarded as the medium thick marble of grade II. The parameters are shown in Table 2, while parts of them are referred to the Hoek-Brown criterion and Refs.[14–16].

**Table 2** Rock mechanical parameters of rock mass.

| Young's modulus (GPa) | Poisson's ratio | Cohesion (MPa) | Friction angle (°) | *D* |
|---|---|---|---|---|
| 26.94 | 0.21 | 9.442 | 35.79 | 0 |

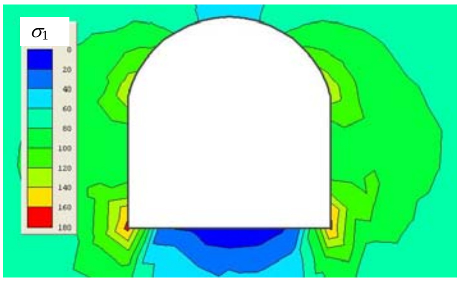
| Uniaxial compressive strength (MPa) | Tensile strength (MPa) | Density (g/cm$^3$) | *GSI* |
|---|---|---|---|
| 120 | 2.205 | 2.7 | 75 |

The in-situ principal stress field is $\sigma_1$ = 64 MPa, $\sigma_2$ = 36 MPa, and $\sigma_3$ = 36 MPa [17].

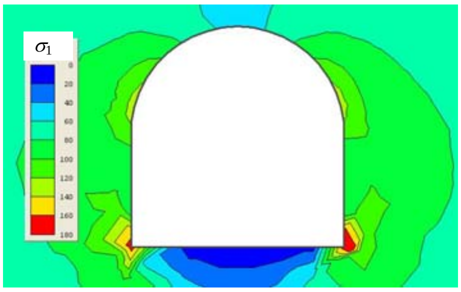
### 3.1 Influence of the cavity shape

The cross-section of the transportation tunnels A and B is U-shape, while the drainage tunnel is circular. Different shapes have different influences on the characteristics of the stress redistribution [18]. Based on the hypothesis of elastic material, the influence of different shapes of openings on the stress redistribution is analyzed.

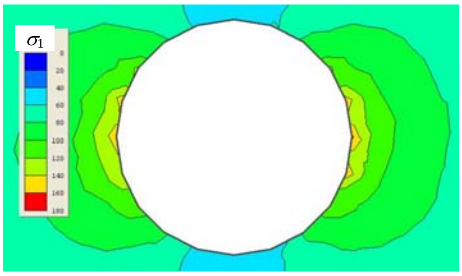
Figure 9 illustrates the maximum principal stress around the transportation and the drainage tunnels. It




(a) Transportation tunnel A.




(b) Transportation tunnel B.




(c) Drainage tunnel.

**Fig.9** The maximum principal stresses around various tunnels (unit: MPa).

shows that the distributions of the maximum principal stress around the transportation tunnels are similar, with small diversity on average. The value of the maximum principal stress at the sides of the transportation tunnels is much lower than that of the drainage tunnel, which means that the intensity of the rockburst in the transportation tunnels is much lower than that in the drainage tunnel.

### 3.2 Mutual impacts of tunnels

The excavation damaged zone (EDZ) will be generated during tunnels excavation. With the increasing distance from the tunnel wall, the maximum principal stress will go through four typical zones, namely, stress relaxation zone, stress concentration zone, stress transition zone and stress stability zone. These zones have their radius of influential extent, thus small distances between tunnels will have great effects on each other. Based on the marble's brittle characteristics in Jinping II hydropower station, the stress effects between the transportation tunnels and the drainage tunnel are analyzed under the postulations of material's brittle characteristics. The mechanical properties are shown in Table 2.

After excavations of the transportation tunnels A and B, the maximum principal stress distribution in surrounding rocks is shown in Fig.10. We can learn that the excavation of the tunnel A has little effect on the tunnel B and the drainage tunnel. In the same way, the excavation of the tunnel B also has little effect on the tunnel A and the drainage tunnel. Consequently, the stress effect among tunnel groups is not the main factor that gives rise to different macroscopic characteristics of rockburst in the region of the transportation and the drainage tunnels.

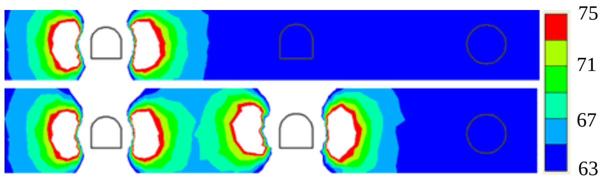



**Fig.10** Distribution of the maximum principal stress around openings (unit: MPa).

### 3.3 The effects of construction methods

Compared with TBM method, the drill and blast method has more perturbations on the surrounding rock, which are mainly including the following two aspects:

(1) The characteristics of stress wave's propagation will induce damage to the surrounding rocks.

(2) The transient stress wave will have an effect on the stress distribution and strain energy release of the surrounding rocks. In this paper, only the damage induced by the drill and blast method, which has an effect on the characteristics of rockburst, is analyzed.

The Hoek-Brown criterion has undergone several modifications since it was put forward in 1980. Hoek et al. [19] gave the current edition of this model, named generalized Hoek-Brown criterion, in 2002:

$$\sigma_1' = \sigma_3' + \sigma_{\mathrm{ci}}\left(m_{\mathrm{b}}\frac{\sigma_3'}{\sigma_{\mathrm{ci}}} + s\right)^a \tag{1}$$

$$m_{\mathrm{b}} = m_{\mathrm{i}}\exp\left(\frac{GSI-100}{28-14D}\right) \tag{2}$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right) \tag{3}$$

$$a = \frac{1}{2} + \frac{1}{6}(\mathrm{e}^{-GSI/15} - \mathrm{e}^{-20/3}) \tag{4}$$

where $\sigma_1'$ and $\sigma_3'$ are the maximum and minimum effective stresses at failure, respectively; $\sigma_{\mathrm{ci}}$ is the uniaxial compressive strength of the intact rock obtained from laboratory tests; $m_b$ is the value of the constant $m$ for the rock mass; the empirical constants $a$ and $s$ are based on the rock mass quality; $GSI$ is the geological strength index; and $D$ is a factor that depends upon the degree of disturbance, to which the rock mass has been subjected by blasting damage and stress relaxation.

Using RocLab software [20], the effect of $D$ on the rock mass strength in a specified situation is studied and the result is shown in Fig.11. With the increase in stress perturbation factor, the modulus, cohesion, friction angle and tensile strength reveal the reducing tendency significantly. Therefore, blasting has evident damage effects on the rock mass strength.

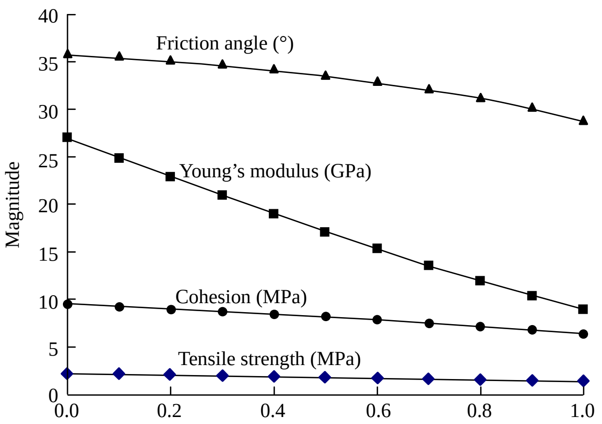



**Fig.11** Parameters of rock mass with different values of *D*.

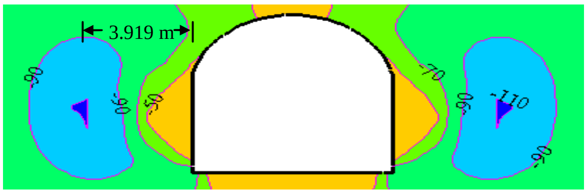
According to the quality of surrounding rocks during the excavation of the transportation tunnels A and B by the drill and blast method, and the relationship between rock mass quality and the parameter $D$ recommended by Hoek et al. [19], the perturbation factor $D$ is set as 0.2. The rock mechanical parameters of the surrounding rocks are shown in Table 3, where the effect of the drill and blast method has been considered.

**Table 3** Rock mechanical parameters by the dill and blast method.

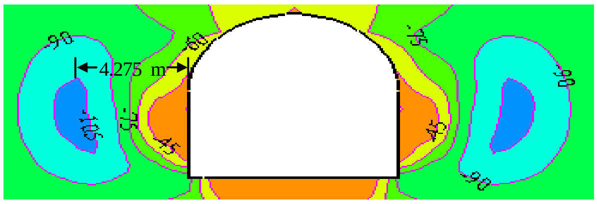
| Young's modulus (GPa) | Cohesion (MPa) | Tensile strength (MPa) | Friction angle (°) | $D$ | $GSI$ |
|---|---|---|---|---|---|
| 22.89 | 8.955 | 1.997 | 35.03 | 0.2 | 75 |

Table 3 indicates that blasting has significant effects on the rock mass strength. The cohesion drops from 9.442 to 8.955 MPa, the friction angle drops from 35.79° to 35.03°, and the Young's modulus decreases from 26.94 to 22.89 GPa.

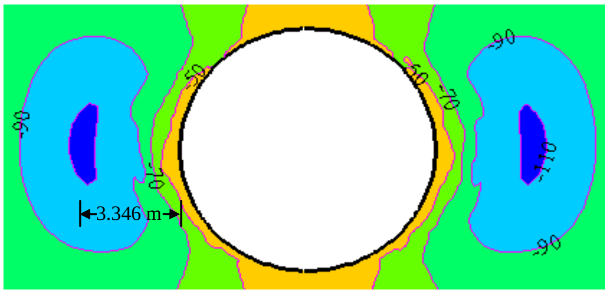
In deep underground rock engineering, the zones of rockburst can be divided into several parts, namely stress-relief failure zone in shallow strata, potential rockburst source zone, deteriorated rockburst source zone, and elastic deformation zone [21]. As illustrated in Fig.12, the maximum principal stress occurred at 3.919, 4.275 and 3.346 m away from the sidewall of the tunnels for the three tunnel profiles. The maximum principal stress has the least distance from the sidewalls of the drainage tunnel, and the magnitude is larger than those of the transportation tunnels. Thus, compared with the rockburst characteristics in the drainage tunnel, the rockburst in the transportation tunnels has the overall characteristics of lower grade and larger length in rockburst sections.




(a) Transportation tunnel A.




(b) Transportation tunnel B.




(c) Drainage tunnel

**Fig.12** The maximum principal stresses around openings with different excavation methods (unit: MPa).

## 4 Conclusions

(1) High elastic strain energy is more easily accumulated due to the high overburden depth and high strength of layer $T_{2b}$ in Jinping II hydropower station. It creates a perfect condition for the occurrence of high-grade or intensive rockbursts. The intensive rockbursts mainly happen in the layer $T_{2b}$ and the continuous occurrences of rockbursts in this layer are more frequent than in other layers.

(2) The critical overburden depth of rockburst in the

transportation tunnels is 600 m, and the length of continuous occurrences section of rockburst is smaller than 25 m. The failure depth of the rockburst has the tendency to increase with the increasing overburden depth. From east to west (west to east), the rockburst usually happens in the right (left) side of the excavation working face, and then the left (right) and roof of the tunnels. The accumulated length of the continuous rockburst is larger, and then the lengths of flake-splitting rockburst and occasional rockburst are consequently observed.

(3) Compared with the rockburst in the transportation tunnels, the rockburst in the drainage tunnel has the overall characteristics of higher grade and shorter length. Moreover, the rockburst sections with length less than 10 m and depth of 1 m mainly occurred at the overburden depth of 1 800–2 000 m.

(4) The excavation of the transportation tunnels has little effect on the stress redistribution of the drainage tunnel, but the geometry and the excavation methods have somewhat great effects. The rockburst in the drainage tunnel shows the characteristics of higher grade and smaller length in terms of macro-scale.

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