Abstract: Numerical analysis of the total energy release of surrounding rocks excavated by drill-and-blast (D&B) method and tunnel boring machine (TBM) method is presented in the paper. The stability of deep tunnels during excavation in terms of energy release is also discussed. The simulation results reveal that energy release during blasting excavation is a dynamic process. An intense dynamic effect is captured at large excavation footage. The magnitude of energy release during full-face excavation with D&B method is higher than that with TBM method under the same conditions. The energy release rate (ERR) and speed (ERS) also have similar trends. Therefore, the rockbursts in tunnels excavated by D&B method are frequently encountered and more intensive than those by TBM method. Since the space after tunnel face is occupied by the backup system of TBM, prevention and control of rockbursts are more difficult. Thus, rockbursts in tunnels excavated by TBM method with the same intensity are more harmful than those in tunnels by D&B method. Reducing tunneling rate of TBM seems to be a good means to decrease ERR and risk of rockburst. The rockbursts observed during excavation of headrace tunnels at Jinping II hydropower station in West China confirm the analytical results obtained in this paper.

Key words: drill-and-blast (D&B) excavation; tunnel boring machine (TBM) excavation; energy release; rockbursts

1 Introduction

Excavation of deep tunnels is often involved in deep mining, hydropower project or traffic engineering. Because of special geophysical environments and high in-situ stresses, various excavation induced hazards, such as rockburst, coal burst and gas outburst, would occur during excavation of deep rocks (He et al., 2005; Tang et al., 2010) and dominate the safety of the engineering construction (Xu et al., 2003).

At present, the drill-and-blast (D&B) method and tunnel boring machine (TBM) method are the main methods for rock excavation. The differences of responses for rock mass induced by the two excavation methods have been comprehensively studied (Cook et al., 1966; Abuov et al., 1989; Carter and Booker, 1990; Barton, 2000; Lu et al., 2007; Yan et al., 2008). Generally speaking, it is noted that D&B method would lead to significant stress adjustment of surrounding rock mass, and the stress of surrounding rock mass is considerably steady by TBM method (Barton, 2000). Cook et al. (1966) found that a sudden release of stress during rock excavation may cause rock over-relaxation and result in tensile stress in rock masses. Abuov et al. (1989) also indicated that the remaining rock masses in the vicinity of excavation working face could be damaged because of rapid unloading of in-situ stresses during blasting. Carter and Booker (1990) showed that tensile stress could be induced by transient unloading of in-situ stresses, and the tensile stress would be increased by the unloading rate of in-situ stresses. Lu et al. (2007, 2008) studied the dynamic unloading of in-situ stresses for rock mass during blasting excavation under high in-situ stresses conditions, and the corresponding prevention,
monitoring and control methods were also established.

However, the rock dynamic responses associated with excavation process actually are the complex mechanical processes, including rock energy’s concentration, storage, release, dissipation and failure (Zhao et al., 2003). So the analysis and assessment of surrounding rocks stability under high in-situ stresses should be considered in the process of energy release during underground excavation (Hua, 2003). In order to evaluate the influence of excavation process, Feng (2000) established a rockburst risk estimation expert system to study the energy release rate (ERR). Guo (2000) proposed an index of effective ERR of rockburst. Su et al. (2005) proposed an index of local ERR of rockburst. Zhao et al. (2003) studied the minimum energy principle of rock dynamic failure. Based on energy dissipation and release in terms of non-equilibrium thermodynamics, Xie et al. (2005) established a strength loss criterion associated with the intensity of energy dissipation and a failure criterion associated with the strain energy release, and the critical stress of rock masses at failure under various confining pressures was analyzed.

Unfortunately, the differences in mechanical effect and ERR induced by D&B and TBM methods are ignored in the above-mentioned studies, in which D&B method is regarded the same as TBM method. In order to address this issue, numerical simulations are conducted to study the energy adjustment process with the two excavation methods in the paper. The stability of deep tunnel is also discussed in terms of energy release speed (ERS).

2 Rock stress adjustment with the two excavation methods

The dynamic adjustment process of initial stress induced by punching a hole quickly in the middle of a circular plate in tensile state was studied by Miklowitz (1960). Yan et al. (2008) studied the stress adjustment process of surrounding rocks during excavation with D&B method. The results reveal that the stress paths of surrounding rocks under TBM (quasi-static unloading) and D&B (transient unloading) excavation conditions are totally different. Significant differences exist in the stress adjustment speed, as shown in Fig. 1, where $\sigma_r$ is the radial stress, $\tau_{rt}$ is the tangential stress, $P_0$ is the initial stress, $t_0$ is the unloading time, $t_u$ is the duration of transient unloading, $t_s$ is the duration of quasi-static unloading, $t_r$ is the calculating time, $a_0$ is the excavation radius, and $r$ is the distance from excavation contour.

In Fig. 1, it can be observed that the stress adjustment process with D&B method is evident, while that with TBM method is steady. The main reason is that the stress unloading speed of the normal stress during blasting is much higher than that during TBM excavation (Yan et al., 2008, 2009).
By using finite difference code (such as FLAC), Cai (2008) simulated the stress adjustment process of rock mass during D&B excavation. Fig. 2 shows the radial stress path, calculated with elastic models in hydrostatic stress field, of the point at the center of the sidewall after transient excavation, and it is basically consistent with the calculation results shown in Fig. 1.

![Stress adjustment path induced by transient excavation calculated with elastic model (Cai, 2008).](image)

In the process of field excavation, two different stress paths corresponding to D&B and TBM methods would cause different mechanical responses of surrounding rocks. Assuming that the surrounding rocks are elastoplastic, the excavation induced stress may exceed the peak strength of rocks, and part of surrounding rocks would be in the post-peak stage. Thus, the difference between excavation damaged zones (EDZs) induced by the two excavation methods would be greater. Fig. 3 shows the simulation results of in-situ stress adjustment during excavation (Cai, 2008).

![Simulation results of in-situ stress adjustment during excavation (Cai, 2008).](image)

3 Rock energy adjustment with the two excavation methods

3.1 Brief introduction to Jinping II hydropower station

Jinping II hydropower station is located on Jinping River bend of Yalong River in West China. The average length of the four headrace tunnels is around 16.7 km. The overburden depth is basically 1 500–2 000 m, and the maximum depth is 2 525 m. The headrace tunnels pass through Jinping Mountain with complex geological conditions, and the main strata along the tunnels consist of Triassic marble, followed by sand slate and hundreds of meters of mud schist (Fig. 4). The maximum in-situ stress is 46.1 MPa, which was measured at the early stage of construction in shallow part of the transportation tunnel parallel to the headrace tunnels. The maximum principal stress at the largest depth of the headrace tunnels could reach 72 MPa after regression (Shan and Yan, 2010).

A combination method of D&B and TBM was used in the construction of the four headrace tunnels at Jinping II hydropower station. The cross-section of the
tunnel excavated by D&B method is of horseshoe-
shape with the width of 13.0 m, while those excavated
by TBM are of circular with the diameter of 12.4 m. In
order to control the high stress induced failure of
surrounding rocks, part cross-section was excavated
by D&B method. For simplicity, the four headrace
tunnels were modeled with circular cross-section.

3.2 Numerical model

As mentioned above, the finite difference method
with explicit integration solving was adopted to
simulate the transient unloading of in-situ stresses
during blasting, and the concept of “elastic excavation
and plastic equilibrium” was adopted in TBM
excavation simulation. It is noted that the effect of
explosive load was not considered in the calculations,
only the in-situ stress adjustment processes were
studied to compare the effect of different stress
processes with various adjustment speeds induced by
the two excavation methods.

The size of numerical model is 85 m×72 m×85 m,
as shown in Fig. 5. The buried-depth of the headrace
tunnel in the model is about 1 700 m, and the in-situ
stress fields are: \( \sigma_{xx} = 43.9 \text{ MPa}, \quad \sigma_{yy} = 50.8 \text{ MPa}, \quad \text{and} \quad \sigma_{zz} = 38.5 \text{ MPa} \). The surrounding rocks are of

class III, and the lithology is mainly marble of
Yantang group. The Hoek-Brown model is used in
the simulations, and the parameters of Hoek-Brown
criterion (Shan et al., 2010) are listed in Table 1.

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<th>Hoek-Brownriterion (Shan et al., 2010)</th>
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<td>Marble</td>
<td>Strength parameters</td>
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<td>Peak state</td>
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<td>III Remnants of brittle fracture</td>
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Note: UCS is the uniaxial compressive strength, \( m \) is the material
constant of Hoek-Brown criterion, and GSI is the geological strength index.

3.3 Energy release process of different excavation
footages

For surrounding rocks excavated by D&B method
under high in-situ stresses, transient crushing and
throwing of rocks under current footage would cause
severe adjustment of the second stress field to
surrounding rocks. As for TBM excavation, it could be
classically considered as a continuous tunneling process
with very little footage. Thus, when simulating tunnel
cavation with FLAC, large tunneling speed or
cavation footage can be considered to simulate the
stress adjustment associated with D&B method (Cai,
2008). If the tunneling speed or excavation footage is
reduced to a certain value, it could be used to simulate
quasi-static excavation process approximately (Shan
and Yan, 2010).

In the paper, six excavation footsteps (0.25, 0.5, 1.0,
2.0, 3.0 and 4.0 m) are adopted to understand the energy
release process of different excavation methods, and
five excavation steps are calculated for each footage. In
order to save computing resources, only the energy in
the zones of 3 times the excavation radius is considered.
Taking excavation footage of 1.0 m for example, the
distribution of energy in surrounding rocks after one
cavation step is shown in Fig. 6. The outside black
area of the model in Fig. 6 does not mean that the
energy change is zero. It only means that the energy
situation is not calculated, so it does not represent the
actual energy situation in the area.

Fig. 7 shows the total energy changes in the zones
of 3 times the excavation radius under six excavation
footages. In Fig. 7, symbols ①, ②, ③, ④ and ⑤ represent the excavation steps, and following
conclusions can be drawn:

(1) The energy release process of each excavation
footage is expressed by the variation curves in terms
of total energy during excavation. It is clear that larger
cavation footage will cause larger energy release
quantity, and the ERS will be increased. As the excavation footage decreases, the influence of excavation on energy release becomes weaker, and the energy release process of surrounding rocks becomes stable and ERR becomes much smaller.

2) When the excavation footage is large (for example, 4.0 or 3.0 m), the excavation process could be considered as a D&B excavation process, and a clear dynamic effect on the energy release process during excavation is observed. The total energy of rocks reduces rapidly at first, and then increases, finally reaches a temporary steady state. The dynamic process of total energy is similar to the transient adjustment of in-situ stresses during D&B excavation, as show in Figs. 1 and 2.

3) When the excavation footage is 0.25 m, which could be regarded as TBM excavation, the impact of each excavation step is not significant, and energy release of rocks changes to a more steady or quasi-static process. With a smaller footage, a weaker dynamic effect of in-situ stress transient unloading during excavation could be expected, which is also true for the case of TBM excavation.

3.4 Energy release process of different simulation methods

For the study of energy adjustment and change process of surrounding rocks, the method of “elastic excavation and plastic equilibrium” was adopted to
simulate the excavation process with D&B method. Because the dynamic effects of the total energy change process are evident in four cases with excavation footages of 1.0, 2.0, 3.0 and 4.0 m, the material substitution method proposed by Cai (2008) is employed in the paper, and the simulation results are shown in Fig. 8.

Fig. 8 Total energy changes in surrounding rocks under different simulation methods.

The bold lines in Fig. 8 are the results obtained by the material substitution method (corresponding to TBM excavation), while the dashed lines are the results obtained by the common simulation method (corresponding to D&B excavation), which considers the influence of transient stress unloading (Cai, 2008). It can be seen from Fig. 8 that the total energy change process induced by each excavation step can be obviously divided into two parts after using the material substitution method. The first part is the energy release caused by the transient excavation with elastic material, which is “elastic excavation”. The second part is the balancing process with plastic material in the elastic stress field, which is “plastic equilibrium”.

After using the material substitution method, the energy release process during the whole excavation becomes stable. The ERR and ERS are significantly reduced. The larger the excavation footage is, the higher the reduction percentages of ERR and ERS are. If the excavation footage is 1.0 m or smaller, the differences between ERR and ERS caused by transient unloading and quasi-static unloading are very small. It indicates that, during D&B excavation, the total energy release process and speed are still significantly different from those during TBM excavation, even though the impact of explosive load is not considered, which is caused by different stress paths and ERSs of surrounding rocks.

4 Relation between energy release speed and rockburst

It is known from previous discussion that different stress paths of surrounding rocks excavated by D&B and TBM methods can lead to significant differences in energy release process, speed and quantity. In addition, the energy release extent and rate of surrounding rocks excavated by D&B method are greater than those of rocks by TBM method. Fig. 9 shows the ERR and ERS of surrounding rocks under different excavation footages. It can be observed that smaller excavation footage means lower ERR and ERS. Besides, after using the material substitution method, the ERR and ERS of same excavation footage are significantly reduced. It indicates that the ERR and ERS under TBM excavation are significantly lower than those under D&B excavation.

Fig. 9 ERR and ERS of surrounding rocks under different excavation footages.

It is well known that when the released energy in
surrounding rocks during tunneling is greater than the dissipated one, rockburst or coal burst may occur (Su et al., 2005). The energy stored in surrounding rocks is the main cause of rockburst. Thus, the frequency and intensity of rockbursts induced by D&B excavation are larger than those by TBM excavation under the same conditions.

Statistical results of rockbursts and high stress induced failures of rocks during the excavation of headrace tunnels at Jinping II hydropower station, between stakes of 10+000 and 17+000, are shown in Fig. 10 (Shan and Yan, 2010). The headrace tunnels #1 and #2 were excavated by TBM and D&B methods, respectively. Following conclusions can be drawn from Fig. 10:

1. The intensity of rockburst increases with the overburden depth, but the overburden depth is not the only controlling factor. The positions of rockburst occurrence have a good relationship with the geological structure along tunnel axis, such as synclines, anticlines or faults. The influence of geological structure on in-situ stresses is clearly one of the key factors for rockburst occurrence.

2. Since the headrace tunnel #2 is excavated by steps using D&B method, the rockbursts as shown in Fig. 10 were frequently encountered during excavation of top half of the tunnel. Therefore, the excavated cross-section of the headrace tunnel #2 is smaller than that of the headrace tunnel #1 excavated by TBM method in fact. But the frequency and intensity of rockburst encountered in the tunnels excavated by D&B and TBM methods are nearly the same according to the statistic results.

The statistic results of rockbursts in the headrace tunnels at Jinping II hydropower station are basically consistent with the calculation results. As a continuous tunneling method, TBM excavation can maintain the physical state of surrounding rocks as possible and minimize the excavation disturbance to surrounding rocks. In brief, the TBM excavation is beneficial to rockburst control.

However, it should be noted that the advantages for rockburst control with TBM excavation may be changed with the variation in operative conditions (He et al., 2005). Under the condition of fast excavation, the total ERR and ERS may maintain at a high level if the tunnel is excavated before complete adjustment of stress and energy (in Fig. 8, with an excavation footage of 3.0 or 4.0 m). Therefore, when TBM advances into intensive rockburst regions, reducing tunneling speed is an initiative way for rockburst control and prevention. On the other hand, the inflexibility of TBM would make it very difficult to deal with rockburst in the rockburst-prone area (Fig. 11). The optimum solution to address this issue is to consider TBM design and manufacture carefully.

5 Conclusions

The stress and energy adjustment processes of surrounding rocks excavated by D&B and TBM methods are analyzed using numerical method. The stability of surrounding rocks in deep tunnel is discussed based on the prevention of rockbursts during excavation of headrace tunnels at Jinping II hydropower station in West China. Following conclusions can be drawn:

1. The surrounding rocks experienced completely different stress paths during D&B and TBM excavation, resulting in significant differences of
energy release process and extent. The energy release process during D&B excavation reveals the dynamic characters, and the ERR and ERS are both large during blasting. Large excavation footage will result in intensive dynamic characters. The energy release process is stable during the TBM tunneling, and the higher the tunneling speed is, the faster the ERR of surrounding rocks is.

(2) The magnitude of energy release during D&B excavation (full-face excavation) is much larger than that during TBM excavation under the same conditions, and the ERR also has a similar trend. So the rockbursts in tunnels excavated by D&B method are always found much more intensive and frequent than those in TBM excavated tunnels.

(3) The intensity of rock energy release is influenced not only by the capacity of energy storage of rocks, but also by excavation method. The rockbursts can be properly controlled with proper measures in D&B excavated tunnels. But for TBM excavated tunnels, because the space behind tunnel face is occupied by the backup system of TBM, the ability of dealing with rockburst is not appreciable. Therefore, rockburst in tunnels excavated by TBM method with the same intensity is more harmful than that in tunnels by D&B method. Reducing TBM tunneling speed seems to be a good way to decrease the ERR and mitigate the risk of rockburst occurrence during TBM excavation. Rockbursts during the excavation process of headrace tunnels at Jinping II hydropower station confirm the conclusions in this paper.

References


