Effect of joint characteristics on surrounding rock stability and stress mechanism of bolt under blasting excavation

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Abstract. Joint characteristics of rock mass are the key factors of tunnel surrounding rock failure. This paper relies on the two-lane mountain tunnel project and takes the IV class surrounding rock as the research object. By means of on-site investigation, numerical simulation and on-site monitoring, the effects of different joint development characteristics under blasting vibration on tunnel surrounding rock deformation, instability mode and force mechanism of rock bolts are studied. It is found that the instability mode of tunnel is obviously affected by the larger joint dip angles. When the dip angle of one group of consecutive joints is kept unchanged and the dip angle of another group of joints is changed, the vault settlement decreases first and then increases with the increase of joint dip angles. The influence of horizontal joint spacing on surrounding rock deformation and vault settlement is much greater than that of vertical joint. Under the most disadvantageous working conditions of the two sets of consecutive joints, the effective range of the axial force of rock bolts depends on joint dip angles and has little correlation with joint spacing. The axial force of rock bolts decreases with the increase of horizontal joint spacing, while the influence of vertical joint spacing on bolt is less.

1. Introduction
Rock mass undergoes the destruction and transformation of various internal and external forces during its formation process. It contains discontinuous structural planes such as faults, joints and fractures. The structural planes divide the rock mass into blocks of different shapes and sizes, resulting in damage to the integrity and mechanical properties of rock mass (Xu et al., 2013; Bahaaddini et al., 2012). The rock mass cut by joints is a common surrounding rock in mountain tunnel construction. The occurrence, spacing and track length of joints are important factors affecting the stability of surrounding rock after tunnel excavation (Jia et al., 2007; Madkour, 2012). Under the influence of blasting vibration in tunnel excavation, the block slides along the joint surface, the support is not timely, or the strength of rock mass is insufficient or there are no targeted measures, which can easily cause large deformation or even collapse, seriously threatening the safety of highway tunnel
construction. In addition, the current highway tunnel industry norms and engineering experience are not enough to estimate the blasting vibration effect in the construction process. In construction and design, bolt parameter design and full-face support are mainly based on surrounding rock grade, but the influence of joint occurrence and developed degree on bolt force has not been deeply studied. The rationality and economy of bolts design scheme are difficult to effectively guarantee. Most of the current studies focus on the analysis of the influence of blasting vibration or joint characteristics on the stability of surrounding rock and tunnel (Yeung et al., 1997; Ramulu et al., 2008; Shin et al., 2010; Xia et al., 2013; Jing et al., 2018). There is a lack of comprehensive consideration of the two influencing factors, and a lack of research on the stress mechanism of bolts (Duan et al., 2017).

In this paper, based on the Luohanpo Tunnel of Duping Expressway in Guizhou Province, the characteristics of IV class surrounding rock joints are elaborated by means of on-site testing and mathematical statistics, and the characteristic parameters of dominant structural planes are counted and analyzed. According to the blasting parameters in site, the stress time history curve of the tunnel wall element is obtained by analyzing the blasting model of surrounding rock excavation. Based on the occurrence parameters of dominant joints, the tunnel blasting excavation simulation of surrounding rocks with different joint dip angle and spacing is studied by means of the tunnel discrete element model including blasting stress wave. The deformation and instability modes of surrounding rock and the stress characteristics of rock bolts under different joint characteristics are analyzed, which provides theoretical support for revealing the joint characteristics under blasting excavation to the stability of surrounding rock and the stress mechanism of rock bolts.

2. Project profile
Duping Expressway starts from Maliu, Mawan Town, Dushan County, and connects with Pingtang County Town through Luohanpo and Lahai Tunnels to the terminal punch. The geological conditions of each section of tunnel are complex, the joints and fractures of rock mass are well developed, the rock mass is fragmented to extremely fragmented, the rock mass is soft, showing loose and fragmented structure, and the surrounding rock grade of tunnel is grade III, IV and V, respectively.

In this paper, the IV surrounding rock is taken as the research object. According to the characteristics of the site structural plane, three surrounding rock sections (YK4+889, YK4+892, YK4+897) of Luohanpo Tunnel are selected to collect the joint characteristics. Combined with data statistical analysis and geological sketch (see figure 1), the fine description of geological characteristics is realized. The excavation section of IV class surrounding rock is shown in figure 2, and the spatial parameters of the dominant structural plane of the tunnel are shown in Table 1.

![Figure 1. Geological sketch of Luohanpo tunnel (YK4+897).](image)

![Figure 2. IV class surrounding rock joint development](image)

| Dip angle/θ (°) | Trend/σ (°) | Trace length/ L (m) | Spacing/ D (m) |
|-----------------|-------------|---------------------|----------------|
| 13.1            | 262.6       | 1.31                | 3.35           |
| 40.9            | 254.0       | 2.62                | 0.34           |
| 78.1            | 341.0       | 1.38                | 0.78           |
3. Effect of joint characteristics on stability of surrounding rock and mechanical behaviour of rock bolts under blasting excavation

3.1. Study on blasting stress time-history curve of tunnel wall

In the blasting calculation model, the rock mass is 24 m wide, 17 m high and the excavation diameter of the opening is 11.72 m, as shown in figure 3. The model consists of explosive, rock and air elements, which are two-dimensional solid elements with four nodes. ALE algorithm and plane strain equation are used. With the help of HYPERMESH software, the model is built and meshed to avoid the use of triangular elements, and the edge length and inner angle of quadrilateral elements are optimized. Gravity is not considered in the calculation, and the boundary condition is set as non-reflective boundary to simulate infinite rock mass.

According to the blasting parameters of single hole charge and depth of explosive in site (see table 1), the equivalent radius of explosive in the calculation model can be calculated by using formula (1). The surrounding hole is 0.66 cm, the auxiliary hole is 1.2 cm, and the cut hole is 1.36 cm. In the formula, \( m \) is the quantity of single hole explosive; \( l \) is the depth of hole; and \( \rho \) is the density of explosive.

\[
R = \frac{m}{\sqrt{\pi l \rho}}
\]

(M_PLASTIC_KINEMATIC model provided by LS-DYNA is selected for the rock. Referring to the field survey results, the material parameters are shown in Table 2. The failure of rock mass is simulated by adding element failure criterion. When the stress of element exceeds the set limit of tensile stress or compressive stress, the element fails.

| Material property | Value |
|-------------------|-------|
| Elastic modulus   | 2300  |
| Poisson ratio     | 3.5   |
| Yield stress      | 0.3   |
| Tangent modulus   | 40    |
| Hardening parameter | 0.75 |
| Compressive strength | 1    |
| Tensile strength  | 44.9  |
| (GPa)             | (MPa) |
| (MPa)             | (GPa) |
| (MPa)             |       |
| (MPa)             |       |

In the process of tunnel blasting simulation, the JWL equation of state in LS-DYNA is used to calculate the unit pressure inside the explosive. The high-performance material MAT_HIGH_EXPLOSIVE_BURN is selected for the explosive. The parameters of explosive and JWL equation of state are shown in Table 3, the blast hole adopts the method of uncoupled charge, MAT_NULL material is selected as the air, and formula (2) is used to calculate the air pressure. In the formula, \( C_i \) (\( i = 0 \sim 6 \)) is a constant related to gas properties, \( C_0 = C_1 = C_2 = C_3 = 0 \), \( C_4 = C_5 = 1 \); \( \rho_0 \), \( \rho \), \( E \) and \( \gamma \) are the initial density, density, internal energy per unit volume and adiabatic index of air respectively. The parameters of air pressure equation are: \( \rho = 1.293 \text{ kg·m}^{-3} \), \( E = 2.5 \times 10^5 \text{ J} \), \( \gamma = 1.4 \).
Table 3. Explosives and JWL equation of state parameters.

| Density \( \rho \) (kg·m\(^{-3}\)) | Explosion rate \( v \) (m·s\(^{-1}\)) | Initial internal energy \( E \) (GPa) | Bombardment Pressure Coefficient | Coefficient of equation of state \( \omega \) |
|-------------------------------|---------------------------------|-------------------------------------|---------------------------------|-----------------|
| 1000                          | 3600                            | 1.82                                | 4                               | \( 1.4 \times 10^{10} \times 10^{8} \) |

\[ P = C_0 + C_1 m + C_2 m^2 + C_3 m^3 + (C_4 + C_5 m + C_6 m^2)E \]  

\[ (2) \]

The blasting vibration analysis is carried out by establishing the blasting excavation model of the upper and lower steps of the fourth grade surrounding rock, and then the stress time history curve generated by the blasting of the upper and lower steps is extracted. The blasting stress wave of the tunnel wall is applied symmetrically to the wall of the subsequent discrete element model. As shown in figure 4, the blasting vibration stress curves of the upper and lower benches include 9 and 18 elements (red virtual frame) on the right side of the central axis in the figure, respectively. The action range of each stress-time curve is the area of the wall with the center of the element and the spacing of the elements as the diameter.

![Figure 4. Blasting stress unit distribution around tunnel wall.](image)

Taking the vault unit of tunnel wall as an example, the stress time history curves of x, x y and y directions at the vault during the blasting process of the upper bench of the IV class surrounding rock are analyzed. As shown in figure 5, the peak value of the horizontal direction of the vault is about 1.5 MPa, the vertical direction is 2.3 MPa, and the peak value of the shear stress is about 0.5 MPa.

![Figure 5. Stress-time-history curve at vault top of step blasting in IV class surrounding rock.](image)

3.2. Discrete element model and parameters

![Figure 6. Tunnel model and local enlargement.](image)
Based on the joint information characteristics of IV class surrounding rock in situ, the calculation model is established. The depth of the tunnel is 47 m, and the height and width of the cavern are 9.31 m and 12.62 m, respectively. Considering the influence range of the boundary of the underground cavern, the upper boundary of the model is taken to the surface, the lower boundary is taken from the centre of the cavern down to 15 m (about 1.5 times the height of the cavern), and the two sides are taken from the centre of the cavern outward to 32.5 m (about 3 times the width of the cavern). It can be inferred that the height of the strata is 45 meters and the width of the strata is about 65 meters. The boundary conditions are fixed constraints in x direction on both sides and fixed constraints in y direction on the bottom. The model schematic is shown in figure 6. In the local enlargement map, three points A, B and C are the monitoring points of settlement and convergence.

In the two-dimensional discrete element model, the joint trend of surrounding rock should be considered according to the most disadvantageous principle, and the direction of tunnel should also be considered. The occurrence parameters (see Table 4) of surrounding rock structure plane are obtained by projecting the occurrence of surrounding rock to the tunnel excavation face. At the same time, according to the site geological sketch, the structural plane with smaller length of rock bridge is treated as rock bridge connection. The normal and tangential boundary conditions of tunnel wall are displacement boundary conditions and viscous boundary conditions.

Table 4. Discrete element model structure surface occurrence table.

| Structural plane | Angle (°) | Spacing (m) | consecutive or non-consecutive joint |
|------------------|-----------|-------------|--------------------------------------|
| Group 1          | 13        | 0.4         | consecutive joint                    |
| Group 2          | 96        | 0.8         | consecutive joint                    |
| Group 3          | 2         | 3.4         | non-consecutive joint                |

Mohr-Coulomb elastic-plastic model is used for rock mass and joint surface. According to field geological survey data, the mechanical parameters of grade IV surrounding rock joints are listed in Table 5, and the support parameters are listed in Table 6 and Table 7.

Table 5. Mechanical parameters of surrounding rock structural plane.

| Angle (°) | Normal stiffness (GPa·m⁻¹) | Tangential stiffness (GPa·m⁻¹) | Cohesive force (kPa) | Internal friction angle (°) |
|-----------|----------------------------|-------------------------------|----------------------|---------------------------|
| 13        | 12.0                       | 4.0                           | 110                  | 37                        |
| 2         | 6.0                        | 2.0                           | 92                   | 31                        |
| 96        | 4.0                        | 1.3                           | 87                   | 29                        |

Table 6. Shotcrete parameters.

| Name       | Density (kg·m⁻³) | Poisson ratio | Elastic modulus (GPa) | Compressive strength (MPa) | Tensile strength (MPa) | Residual strength (MPa) |
|------------|------------------|---------------|-----------------------|---------------------------|-----------------------|-------------------------|
| Shotcrete  | 2200             | 0.3           | 21                    | 10                        | 1.1                   | 0.55                    |

Table 7. Rock bolt parameters.

| Name       | Cross-sectional area (m²) | Density (kg·m⁻³) | Ultimate tensile strain | Compressive strength limit (kN) | Tensile strength limit (kN) | Elastic modulus (kPa) |
|------------|---------------------------|------------------|-------------------------|---------------------------------|---------------------------|----------------------|
| Rock bolts | 4.9e-4                    | 7857             | 0.01                    | 164                             | 164                       | 2.1e8                |

3.3. Effect of joint inclination on stability of surrounding rock and stress mechanism of rock bolts
Based on the information collected from the field geological characteristics and the dip angle of joints as the calculation variable, the calculation model of two groups of penetrating joints under the IV grade surrounding rock is established. The dip angle of joints is chosen randomly in two groups of 0°,
30°, 60°, 90°, 120° and 150°, and symmetrical joint occurrences are considered in one group, such as 0°-30° and 0°-150°. The values of the parameters of the two groups are the same. The calculation conditions are shown in Tables 8 and 9.

Table 8. First to fifth working conditions in calculation.

| Condition | Angle (°) | Spacing (m) | Supporting form |
|-----------|-----------|-------------|-----------------|
| 1         | 0-30      | 0.6         | No support, original design (bolt length 3m, spacing 1.2m, range 200 degrees) |
| 2         | 0-60      |             |                 |
| 3         | 0-90      |             |                 |
| 4         | 30-60     |             |                 |
| 5         | 30-90     |             |                 |

Table 9. Sixth to ninth working conditions in calculation.

| Condition | Angle (°) | Spacing (m) | Supporting form |
|-----------|-----------|-------------|-----------------|
| 6         | 30-120    | 0.6         | No support, original design (bolt length 3m, spacing 1.2m, range 200 degrees) |
| 7         | 30-150    |             |                 |
| 8         | 60-90     |             |                 |
| 9         | 60-120    |             |                 |
Comparisons between two groups of surrounding rock collapse areas without support under different joint dip angle combinations are shown in figure 7. From the analysis of the figure, under the condition of 0°-30°, after the tunnel blasting excavation, the surrounding rock bending capacity at the right vault is not strong, resulting in bending and tension damage, local block falling, and the overall performance of the condition of 30°-60° is relatively stable. Under the conditions of 0°-60° and 30°-120°, after blasting excavation, the jointed rock mass moves along the direction of larger joint dip angle, resulting in bedding slip and local collapse in the tangent direction between joint dip angle and tunnel contour. Under the condition of symmetrical joint dip angle (30°-150° and 60°-120°), symmetrical cutting occurs at the vault. After excavation, the rock mass falls under the action of gravity, and the displacement in the vertical direction is dominant. Under the conditions of 0°-90°, 30°-90° and 60°-90°, the tunnel has bedding slip phenomenon. Under the condition of 0°-90°, the collapse is most serious from the tunnel vault to the surface.

The relationship curves of settlement, convergence deformation and joint dip angle of tunnel vault are shown in figure 8. From the graph, the settlement of tunnel vault is the smallest (13.18 mm) and the convergence deformation is the largest (10.7 mm) under the condition of 60°-90°. However, the settlement of tunnel vault is the largest (17.78 mm) and the convergence deformation is the smallest (1.95 mm) under the condition of 0°-30°. The settlement and convergence deformation of tunnel vault first decrease and then increase with the increase of joint dip angle under the conditions of 0°- (30°-150°). Under the conditions of 30° (0°-180°), the settlement of tunnel vault decreases first and then increases with the increase of joint dip angle, and the convergence deformation decreases first and then increases with the counter clockwise rotation of joint dip angle. Under the conditions of 60°- (0°-180°) and 90°- (0°-180°), the settlement of tunnel vault first decreases and then increases with the increase of joint dip angle, and the convergence deformation first increases, then decreases and then increases with the increase of joint dip angle. When one group of joint dip angle is kept unchanged and the other group of joint dip angle is changed, the settlement of tunnel vault shows a change rule of decreasing first and then increasing with the increase of joint dip angle.

Figure 8. Relation curve between tunnel deformation and joint angle.
Figure 9. Relationship between loosening range and joint angle.

Figure 10. Axial force of two groups of rock bolts with different joint angles. (unit: N) (part)

The relationship between the area of the loosening range (settlement greater than 9 mm) and the joint dip angle is shown in figure 9. From the figure, the loosening range of surrounding rock is the largest under the conditions of 0°-90° and 30°-150°. The loosening area is 835 m² and 842 m², respectively, while the loosening range is the smallest under the condition of 60°-120° (467 m²). The height of the loosening range is the greatest under the condition of 0°-90°, and the width of the loosening range is the greatest under the condition of 30°-150°. Under the conditions of 0°-(30°~180°), the loosening range decreases first, then increases, then decreases and then increases with the increase of the dip angle of the second group of joints. Under the condition of 0°-60°, the loosening range of surrounding rock is the smallest, and the loosening range of surrounding rock is the largest under the condition of 0°-90°. Under the conditions of 30°-(30°~150°), the loosening range is the smallest under the condition of 0°-60°, 30°-90°, 150°-120° and other conditions is similar. Under the conditions of 90°-(0°~180°), the range of loosening is the largest except for the condition of 0°-90° and the range of loosening is similar in other working conditions. Keeping one group of joint inclination unchanged, when the other group of joint inclination is 60° or 120°, compared with 0°, 30°, 90°, 150° and other conditions, the surrounding rock loosening range is the smallest and the tunnel is safer.
Table 10. Distribution range of bolts with small axis force at different joint dip angles.

| Angle 0°  | Angle 30°  | Angle 60°  |
|-----------|------------|------------|
| Angle 30° | 11°~43°    |            |
| Angle 60° | 32°~85°    | 22°~106°   |
| Angle 90° | 74°~106°   | 53°~117°   |
| Angle 120°| 96°~127°   | 22°~53°    |
| Angle 150°| All axial forces are larger. | 32°~148° |

The axial forces of two groups of bolts with different dip angles are shown in figure 10. For all conditions, the bolt axial force of the left and right-side walls is relatively large. Under the condition of 0°~90°, the smaller range of anchor axial force is NO.13~10, i.e. 74°~106°, on both sides of 90°. Under the condition of 30°~120°, the smaller range of the axial force of bolts is 96°~127°, 22°~53°, and the smaller range of the axial force is on both sides of the positions of 120° and 30°. Under the condition of 30°~150°, the axial force distribution of bolts is more uniform, and the axial force is larger. When the included angle between the two sets of through joints is less than or equal to 60°, the smaller range of the axial force of bolts is generally as follows: when the joint dip angle is asymmetrical "A°-B°" type and A° is closer to 90° than B°, the smaller range of the axial force is on both sides of A° and the range is generally 50°~80°. When the joint inclination angle is symmetrical "A°-(180-A)°" type, the smaller range of anchor axial force is the combination of A° and (180°-A°). The range is generally 90°~120°. The range of axial force of rock bolts under different joints is shown in Table 10.

Figure 11. Relation between axis force of rock bolts and joint dip angles.

The curves of the relationship between the axial force of bolt, the axial force of vault bolt and the dip angle of different joints are shown in figure 11, respectively. Based on the analysis of the relationship curve between the axial force of the vault bolt and the joint dip angle, the axial force of the vault bolt decreases first and then increases with the increase of the joint dip angle under the conditions of 0°-(30°~150°). Under the conditions of 30°-(0°~180°), the axial force of arch vault bolt decreases first and then increases with the increase of joint inclination. Under the conditions of 60°-(0°~180°) and 90°-(0°~180°), the axial force of vault bolt decreases first and then increases with the increase of joint inclination. The stress of bolts under various working conditions is analysed. When the orientation of bolts is at a certain included angle with the surrounding rock joints, the axial force of bolts is larger. When the orientation of bolts is nearly parallel to the surrounding rock joints, the axial force of bolts is smaller.

3.4. Effect of joint spacing on stability of surrounding rock and stress mechanism of bolt

Based on the calculation results of different joint dip angles of two groups of developed joints in grade IV surrounding rocks, the joint dip angle of 0°~90° is taken as the most typical working condition. The variables for calculating working conditions are joint spacing, as shown in Table 11.
Table 11. Working conditions for calculating spacing between two groups of developed joints

| Vertical spacing | 0.2m | 0.4m | 0.6m | 0.8m |
|------------------|------|------|------|------|
| 0.2 m            | ✓    | ✓    | ✓    | ✓    |
| 0.4 m            | ✓    | ✓    | ✓    | ✓    |
| 0.6 m            | ✓    | ✓    | ✓    |      |
| 0.8 m            | ✓    | ✓    |      |      |

Under different joint spacing conditions, the relationship between settlement and loosening area (settlement greater than 1.5 cm) of tunnel vault and horizontal spacing is shown in figure 12. Overall, the settlement and loosening range of vault gradually increase with the decrease of joint spacing. Under the same vertical joint spacing, according to figure 12, the smaller the horizontal joint spacing, the larger the settlement and loosening range of the vault, except for the 0.6-0.2 m spacing group. When the horizontal spacing is 0.2 m, the range of settlement and loosening of vault is much larger than other working conditions. When the horizontal spacing is 0.4m, 0.6m and 0.8m, the difference of vault settlement and loosening range is relatively small. At the same horizontal joint spacing, the smaller the vertical joint spacing is, the larger the settlement and loosening range is.

The distribution pattern of bolts is basically the same in different working conditions. The distribution pattern of bolts is that the vault and side walls are smaller, and the waist of the arch is larger on both sides. The peak values of bolt axial force are all located at the boundary of different areas in the vertical displacement nephogram. The following is an example of 0.2-0.6m spacing, as shown in figure 13.

As can be seen from the figure, the axial force of bolts in No. 4, No. 5, No. 6, No. 7, No. 16, No. 17, No. 18 and No. 19 is larger than that of other bolts, and the peak point is obvious (marked with white lines in the figure). The peak positions of bolts are all located at the green-yellow-red boundary in the nephogram, and these boundary lines are also the joint positions where the surrounding rock slips. The closer the peak value of the bolt is to the midpoint of the bolt, the larger the peak value of the bolt is. For example, bolts No.7 and No.16 are the largest, followed by No.6 and No.17, and others are smaller. The other bolts have smaller axial force and smooth curve, and the peak value usually appears at the midpoint of the bolt.
The maximum tension of rock bolt usually appears at the arch waist position. The relationship curve between the spacing of different joints and the maximum tension of rock bolt is shown in figure 14. From the figure, the tension of rock bolt decreases with the increase of horizontal joint spacing, while the influence of vertical joint spacing on rock bolt is small, especially in the case of dense horizontal joint. For example, under the horizontal joint spacing of 0.2m and 0.4m, the vertical joint spacing basically has no effect on the axial force of the rock bolt.

4. Conclusion
In this paper, discrete element software is used to study the influence of different joint dip angle and spacing on deformation, instability mode of surrounding rock and stress mechanism of rock bolt under blasting vibration. The following conclusions are drawn:

(1) The instability mode of IV class surrounding rock tunnel is obviously affected by the larger joint dip angle. When the included angle between two groups of joints is less than or equal to 30° and asymmetric, the failure mode of rock mass is bending and tension failure at tunnel wall parallel to joints. When the inclination angle between the two groups of joints is greater than 30° and asymmetric, the failure mode of rock mass is bedding slip around two joints and the contour of the tunnel wall. Under symmetrical joints, the failure mode of rock mass is that the vault collapses occur in the area surrounded by two joints at the vault and the contour line of the cave wall, while the roof collapses occur in the horizontal and vertical joints.

(2) Under two sets of consecutive joints of IV class surrounding rock, keeping one group of joint dip angle unchanged and changing the other group of joint dip angle, the vault settlement decreases first and then increases with the change of joint dip angles of 0°, 30°, 60°, 90°, 120° and 150°. For the area of loosening range with settlement greater than 9 mm, when the dip angle of one group of joints
remains unchanged and the dip angle of the other group of joints is 60° or 120°, the loosening range is the smallest and the tunnel is safer than the four groups of working conditions of 0°, 30°, 90° and 150°.

(3) When the angle between the two groups of consecutive joints of IV class surrounding rock is less than or equal to 60°, the range of the small axial force of rock bolts is generally as follows: When the joint dip angle is asymmetric, the smaller range of rock bolts is on both sides of steep joint, and the range is generally 50°–80°. When the joint dip angle is symmetrical, the range of rock bolts axial force is small in the middle area of the two joints and the two sides of the joints, and the range is generally 90°–120°.

(4) Under the most disadvantageous working condition (0°–90°) of two groups of consecutive joints in IV class surrounding rock, the smaller the distance between horizontal joints, the larger the vault settlement and the loosening range (settlement greater than 1.5 cm) of surrounding rock. The influence of horizontal joint spacing on surrounding rock deformation and vault settlement is much greater than that of vertical joint.

(5) When the joint spacing increases from 0.2 m to 1.0 m, the distribution of the bolt axial force basically remains unchanged. The effective range of the bolt axial force depends on the dip angle of the joint, which has little correlation with the spacing. Under the most disadvantageous working condition (0°–90°) of two groups of consecutive joints, the change rule of bolt axial force is that the bolt axial force decreases with the increase of the horizontal joint spacing. Vertical joint spacing has little effect on bolt, especially in the case of dense horizontal joints. Under the horizontal joint spacing of 0.2m and 0.4m, the vertical joint spacing has little effect on the bolt axial force.

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References
[1] Xu T, Ranjith P G, Wasantha P L P, Zhao J, Tang C A, Zhu W C 2013 Influence of the geometry of partially-spanning joints on mechanical J. Eng. Geol. 167 134-47
[2] Bahaaeddini M, Sharrock G, Hebblewhite BK 2012 Numerical investigation of the effect of joint geometrical parameters on the mechanical properties of a non-persistent jointed rock mass under uniaxial compression properties of rock in uniaxial compression J. Comput. Deotech. 49 206-25
[3] Jia P, Tang C A 2007 Numerical study on failure mechanism of tunnel in jointed rock mass J. Tunn. Undergr. Sp. Tech. 23 500-7
[4] H. Madkour 2012 Parametric analysis of tunnel behavior in jointed rock J. Ain. Shams. Eng. J. 3 79-103
[5] Yeung M R, Leong L L 1997 Effects of joint attributes on tunnel stability J. Rock. Mech. Min. Sci. 34 3-4
[6] Ramulu M, Chakraborty A K, Sitharam T G 2008 Damage assessment of basaltic rock mass due to repeated blasting in a railway tunnelling project – A case study J. Tunn. Undergr. Sp. Tech. 24 208-21
[7] Shin J H, Moon H G, Chae S E 2010 Effect of blast-induced vibration on existing tunnels in soft rocks J. Tunn. Undergr. Sp. Tech. 26 51-61
[8] Xia H B, Xu Y, Zhang Y J 2013 Numerical Simulation and Experimental Analysis of Roadway Surrounding Rock Loose Circle under Blasting Vibration 4th. Int. Conf. on Digital Manufacturing and Automation (Qingdao) pp 850-4
[9] Jing H D, Li Y H, Li K M 2018 Study on the Deformation Mechanism of Soft Rock Roadway under Blasting Disturbance in Baoguo Iron Mine J. Shock. Vib. 2018
[10] Duan B F, Xia H L, Yang X Xu 2017 Impacts of bench blasting vibration on the stability of the surrounding rock J. Tunn. Undergr Sp. Tech. 71 605-22