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A new numerical model of rock bolts used in jointed rock

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ABSTRACT: In tunnel and underground engineering, the grouted rock bolts are simulated as bolt element in finite element analysis. Usually, 2-node or 3-node element is used to represent the effect of the bolts in jointed rock mass. But the traditional type of element is not convenient to represent the true effect of bolts. In this paper, a new numerical model of rock bolts is proposed. This type of element is especially suitable for simulating the bolts in jointed rock. The new numerical model can be widely used in the finite element analyses of tunnel and underground engineering because of its efficiency, simplicity and flexibility.

1 INTRODUCTION

In tunnel and underground engineering, grouted bolts are important in excavation and the construction of structures. By using the finite element method, the process of constructing and excavating is simulated. Usually, 2-node or 3-node element is used to represent the effect of the rock bolts. But this type of numerical model is not appropriate to reflect the real function of the bolts. In this paper, a new numerical model of rock bolts is proposed. This type of element can consider the shear resistance and the bend resistance of the bolts, so it can indicate the real instance well.

2 NUMERICAL MODEL

2.1 *Traditional method*

The grouted bolts are good means to strengthen the jointed rock, yet the finite element simulation is not always satisfiable. Recently the truss element model is usually used in finite element analysis. When the rock is jointed, the deformation caused by the joints is all-important. So when the bolt impenetrate the jointed rock, the conventional type of element is not convenient to represent the true effect of bolts. In geotechnical engineering, the effect of joints in rock cannot be neglected.

Some other methods are used to resolve the problem. For example, to adjust the C or Φ of the joints and the rock mass can reduce the displacement of the excavated zone.

2.2 *Analysis model*

To develop numerical model based on reasonable experiment and site observation is our main principle to follow. By experiments and site observation we can know that the shear displacement mainly concentrate in the zone near the joint face. The connection of the bolt and the rock is not all damaged. The length of evident part on shear deform of the bolt is about 3~4 times of the diameter of it, as shown in figure 1(Ge, Liu, 1988). The shear resistant behavior is the one of the main functions of the bolt in jointed rock. The pattern of the interactivity between the bolt and the hole wall is shown in figure 2.

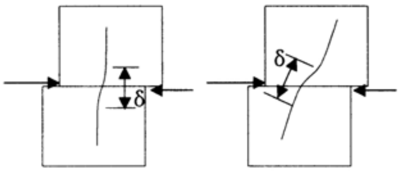


Figure 1. The deformation pattern of bolt.

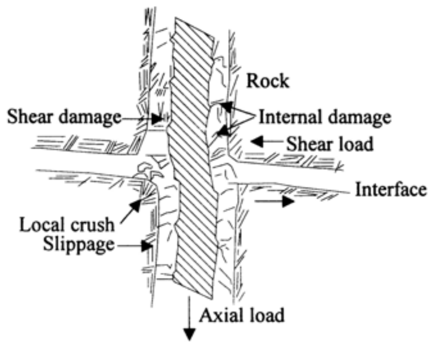


Figure 2. The pattern of the interactivity between the bolt and the hole wall.

2.3 *New numerical model of rock bolts*

In 2D finite element analysis, the 4-node model of rock bolt is proposed in this paper. Between the middle 2 nodes of the 4-node element a joint is passing through. In initial state the 2 nodes are coincide with the nodes of joint element. The middle two nodes of rock bolts model can move according to the process of joint shear deformation. If there is no joint, the 4-node element can be replaced by 3-node element.

This 4-node finite element model can consider the drawing, bending and shearing strength of the bolt. Every node has 2 degrees of freedom as follows:

v_i—the displacement in axial direction

w_i—the displacement in normal direction

Based on these variables, the additional angle of the bolt caused by the shear effect and the angle of the normal direction can be determined. The angle of the normal direction is shown in formula 1.

$$\theta = \left(\frac{\partial w}{\partial x} \right) + \phi \tag{1}$$

where ϕ=effective shear angle, $\left(\frac{\partial w}{\partial x} \right)$=slope of the neutral axis.

The displacement can be written as the vector δ^e, as follows:

$$\delta^e = [v_1, w_1, v_2, w_2, v_3, w_3, v_4, w_4]^T \tag{2}$$

The shape functions are:

$$N_1 = -\frac{2}{3}\left(\xi^3 - \xi^2 - \frac{1}{4}\xi + \frac{1}{4}\right) \qquad N_2 = \frac{4}{3}\left(\xi^3 - \frac{1}{2}\xi^2 - \xi + \frac{1}{2}\right)$$

$$N_3 = -\frac{4}{3}\left(\xi^3 + \frac{1}{2}\xi^2 - \xi - \frac{1}{2}\right) \qquad N_4 = \frac{2}{3}\left(\xi^3 + \xi^2 - \frac{1}{4}\xi - \frac{1}{4}\right) \tag{3}$$

The total potential energy can be written as follows

$$\pi=\frac{1}{2}\int EA\left(\frac{\partial v}{\partial x}\right)^2 dx+\frac{1}{2}\int EI\left(\frac{\partial \theta}{\partial x}\right)^2 dx+\frac{1}{2}\int S\phi^2 dx-\int q_w w dx-\int q_v v dx-P_w\cdot w-P_v\cdot v-C\cdot\theta \quad (4)$$

where EA= axial stiffness, EI= bending stiffness, S= shear stiffness, $\frac{\partial\theta}{\partial x}$= pseudo curvature, ϕ = effective shear angle, q= distribute load, P= concentrated load, C= concentrated force couple.

According to the principle of minimum energy, $\frac{\partial \pi}{\partial u}=0$, there is:

$$\left(\int [B]^T D[B]\ dx\right) u - \int [N]^T q_w dx - \int [N]^T q_v dx - \left(\sum (P_w + P_v) N_i\right) = 0 \quad (5)$$

The stiffness matrix can be written as follows:

$$K^e = \int [B]^T D[B]\ dx \quad (6)$$

The sub-matrix links the node i and the node j can be written as follows:

$$K^e_{ij} = \int [B_i]^T D[B_j] \det J d\xi \quad (7)$$

where J means the Jacob matrix.

In a similar way, stiffness matrix of the 3-node element can be developed although the shape functions are not same:

$$N_1 = -0.5\xi(1-\xi) \qquad N_2 = (1-\xi)(1+\xi) \qquad N_3 = 0.5\xi(1+\xi) \quad (8)$$

2.4 *The simulation of deformation*

The models above can descript the effect of the bolt impenetrate in the joint because it can not only consider the deformation caused by drawing, bending and shearing but also can portray the damage process of the connection between the bolts and the rock. The nodes of the numerical model can be moved. We use two coordinate systems, the global coordinate system and the local coordinate system. In local coordinate system, node 1 has ξ=-1; node 2, ξ=-0.5; node 3, ξ=+0.5; node 4, ξ=+1; as shown in figure 3.

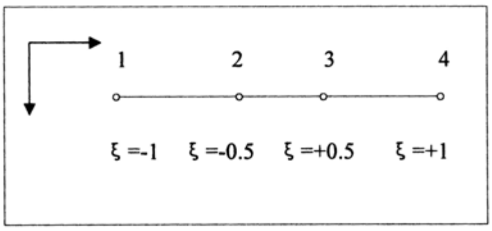


Figure 3. Local coordinate

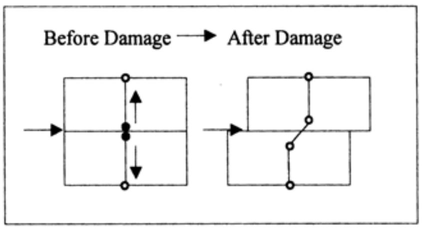


Figure 4. The Simulation of the Deformation.

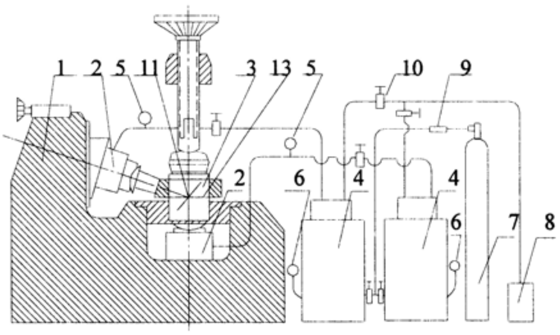
As shown in figure 4, when the damage does not occur, the two middle nodes overlap with the two nodes of the joint element. After the damage develops, the nodes that overlap depart progressively. The two middle nodes leave far away from the joint faces. At last, these two nodes stop in the certain place that can be determined by the diameter of the bolt. This consideration can avoid the shortcomings of the element such as the traditional numerical models discussed above. In fact, this process creates no new node. The moved modified nodes are generated by interpolation.

3 TEST AND VERIFY

3.1 *General situation*

The direct shear test is made to observe the shear resistant behavior of the bolted joints. The direct shear testing machine for rock sample was used in this test. The test sample is made by cement and sand. Between the upper and lower parts of the sample there is a "joint interface". The reinforcing steel bar of 5mm diameter stands for the bolt. This sample is equivalent to the situation of 25mm steel bolt in 1 m^2 of rock mass. According the settle angle of the bolt, the samples are separated into 4 groups for the angle is respectively 90° , 60° ,45° ,30° .

The schematic diagram of the instruments is shown in figure 5.



1 boxshear apparatus
2 leaning jack
3 rock sample
4 voltage regulator
5 oil pressure gauge
6 pressure gauge
7 air supply
8 oil pump
9 reducing valve
10 valve
11 bolt
12 joint interface

Figure 5. The schematic diagram of the instruments.

3.2 *FEM analysis of tests*

The finite element analysis is made according to the test. Because the settle angle of the bolt is 90° , 60° ,45° ,30° and the vertical stress is 0.5MPa, 1.5MPa, there are 8 calculation conditions.

The analysis section is 200mm×200mm, in the middle of the section there is a horizontal joint interface.

The parameters of calculation are: (Rock Element) $E=7.0\times10^3$MPa, $\mu=0.25$, C=1MPa, $\phi=30°$, (Joint Element) $Kn=6.0\times10^4$MPa/m, $Ks=1.5\times10^3$MPa/m, C=0.1MPa, $\phi=30°$, (Bolt Element) $\phi=5$mm, $E=2.0\times10^5$MPa.

3.3 *Comparison of Results*

The comparisons of shear stress-displacement of test and finite element analysis are shown as figure 6 and figure 7.

From the comparison we can see that the new numerical model of bolt is reasonable because the results of the calculation tally the test results well. It has advantages by comparing with the conventional 2 or 3-node element.

There are some errors between the test results and the FEM results. In fact, because of the preparation technology of the sample, the C of sample may not be estimated precisely. If the C of FEM analysis is modified slightly, the results of test and analysis tally very well as shown in figure 7.

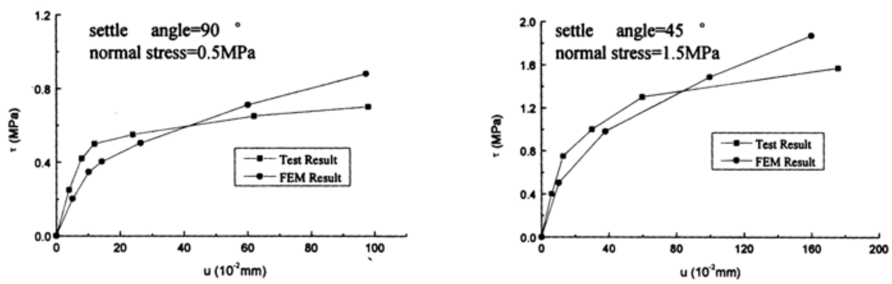


Figure 6. Shear Stress-Displacement (1).

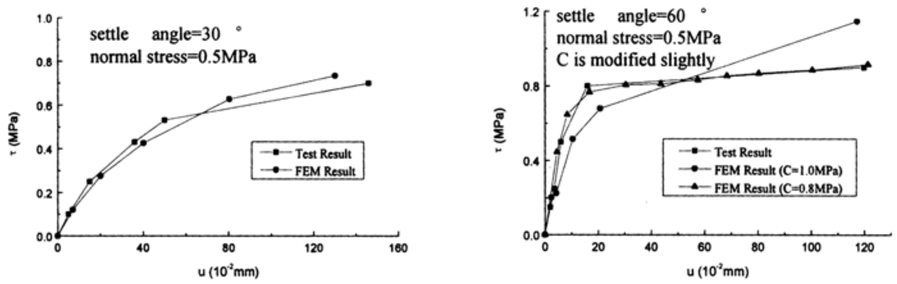


Figure 7. Shear Stress-Displacement (2).

4 APPLICATION

4.1 *Engineering introduction*

An underground powerhouse of pumped storage hydraulic power station is 186m long, 23m wide and 53.3m high. The rock mass lay over the underground house is about 180m deep. The rock is unweathered granite.

4.2 *Condition of calculation*

The bolted and unbolted models are used to analysis and make comparison. The parameters of calculation are: (Rock Element) $E=2\times10^4$MPa, $\mu=0.2$, C=3.0MPa, $\phi=50°$, $\gamma=24.72KN/m^3$, σr=3MPa, (Joint Element) $Kn=7.5\times10^4$MPa/m, $Ks=3.0\times10^3$MPa/m, C=0.2MPa, $\phi=30°$, (Bolt Element) ϕ=25mm, $E=2.0\times10^5$MPa. The gravity and the boundary stress determine the initial ground stress. The boundary stress is set as P_y=5.0582MPa. The bolt installation and the joint are shown in figure 8.

4.3 *Results and analysis*

The deformation of the boundary of excavation and the characteristic points are shown as figure 9.

The table 1 shows the displacements of the characteristic points in two different calculation conditions. Figure 10 shows the difference of the plastic zones between the two conditions.

From the comparison, we can see that the displacements of unbolted model are larger than that of the bolted model. And the plastic zone of the unbolted model is bigger than that of the bolted one.

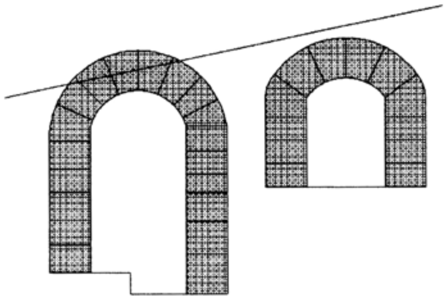


Figure 8. The bolt installation and the joint

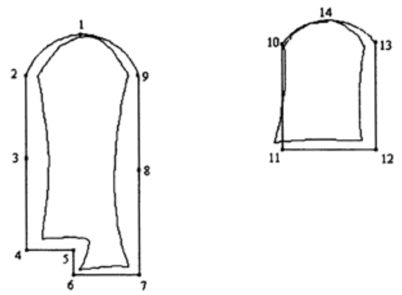


Figure 9. The deformation of the boundary of excavation and the characteristic points

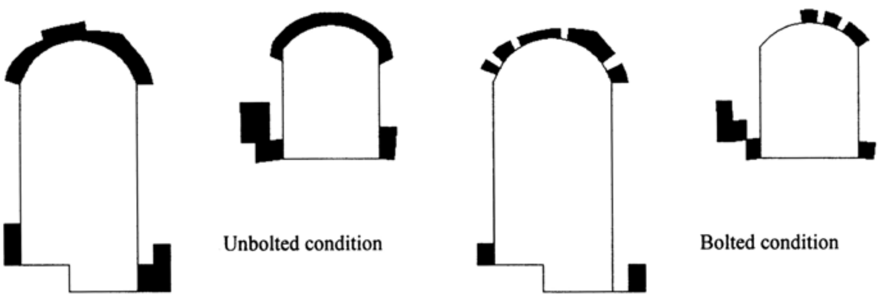


Figure 10. Plastic zone (unbolted condition and bolted condition).

Table 1. Displacements of characteristic points (Unit: cm).

point	Unbolted		Bolted		point	Unbolted		Bolted	
	x-Disp	y-Disp	x-Disp	y-Disp		x-Disp	y-Disp	x-Disp	y-Disp
1	0.04	-0.37	0.03	-0.21	8	-2.13	0.16	-1.67	0.17
2	1.48	-0.09	1.21	-0.03	9	-0.98	-0.03	-0.71	-0.01
3	2.07	0.13	1.54	0.11	10	0.21	-0.38	0.10	-0.17
4	1.62	1.22	1.23	0.94	11	-0.53	0.73	-0.77	0.53
5	1.52	1.11	1.14	1.07	12	-1.30	0.94	-0.99	0.61
6	1.03	0.69	0.73	0.53	13	-1.28	-0.50	-0.97	-0.31
7	-1.24	0.87	-0.92	0.71	14	-0.01	-0.05	-0.01	-0.03

5 DISCUSSION AND CONCLUSIONS

Test evidence and FEM analysis results show that this new kind of bolt element proposed in this paper can indicate the real instance well when the jointed rock is bolted. The new numerical model can be widely used in the FEM analysis of tunnel and underground engineering because of its efficiency, simplicity and flexibility.

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