Numerical Analysis and Application of Uncoupled Coefficient of Water Sealed Blasting on Blasting Effect

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Abstract: To study the influence of axial and radial uncoupling coefficient on blasting effect when air and water are used as spacer in surrounding holes of tunnel water seal blasting, and the optimal charge coefficient is determined for construction. Combined with numerical simulation and field test, the research results show that: (1) When the air and water are used as the interval medium in the peripheral hole for multi-hole blasting, the optimal value range of axial uncoupling coefficient is 2.2~2.5. The optimal value range of radial uncoupling coefficient is 1.5~1.6. (2) The concept of composite uncoupling coefficient is proposed, and the optimal decoupling charge coefficient is determined. Finally, the axial decoupling coefficient is 2.2 and the radial decoupling coefficient is 1.6, which can meet the blasting requirements. (3) The simulation results are verified by field test. It is proved that the axial decoupling coefficient is 2.2 and the radial decoupling coefficient is 1.6, which is better than the research results of axial decoupling coefficient of 2.07 and radial decoupling coefficient of 1.5 used in conventional blasting. The results show that the air and water media used in engineering construction can improve the blasting effect and reduce the explosive unit consumption.

Keywords: Water sealed blasting, peripheral hole, uncoupling coefficient, numerical simulation.

1. Introduction
Smooth blasting, as a feasible method to improve the blasting effect, has been widely used in tunnel blasting construction. The charge coefficient of surrounding holes has an important impact on the blasting effect. At present, air interval charging is widely used. [1-2] Zhu et al. [3] compared and analyzed the damage distribution characteristics of air space charge structure on rock mass by using the method of numerical simulation and field test. Zhu et al. [4] used the detonation wave theory to analyze the interaction of one-dimensional unsteady shock wave inside the blast hole with air interval, the reflection process at both ends of the blast hole, and the time history change of pressure at each point in the hole and obtained the design parameters of air interval charging. Zong et al. [5] took the rock as an example to calculate and discussed the calculation method of the axial uncoupled charge coefficient of the air cushion from a theoretical perspective.

However, the dust concentration after blasting with the air interval charge is large, which is not conducive to the follow-up construction and affects the construction progress. Therefore, water seal blasting, as an efficient, energy-saving, and environmental protection construction technology, has been paid attention to. Liu et al. [6] discussed different water seal blasting charge structures through numerical simulation and field test and concluded that the blasting effect of water interval charging...
structure at both ends is the best, and it can effectively reduce dust. Cai et al. [7] elaborated the mechanism of coal breaking by water pressure blasting according to the damage and fracture propagation morphology, compared and analyzed the influence of water and air two uncoupled media on coal blasting, and finally proved that the fracturing effect of hydraulic blasting was better. Xia et al. [8] combined the crack guidance of slotting blasting with the efficiency of hydraulic blasting, and compared and analyzed the three blasting modes of coupling charge, slot air decoupling, and slotted water pressure through experiments, and obtained the change characteristics of cracks and stress changes. Yang et al. [9] explained the mechanism of safe blasting with water-filled and pressure-bearing cracks in surrounding rock holes by combining theory with experiments, and established a crack propagation model during pressure-bearing blasting in surrounding rock cracks, thus revealing the pressure inside the blast hole. After the water is “wedge”, the cracks expand regularly.

The above-mentioned research mainly studies the blasting effect when the single medium of air or water is an uncoupled charge spacer. When water-sealed blasting is used in the actual construction process, the charge structure is more complicated, and both air and water media are involved. As a spacer, when these two media exist at the same time, the influence of the change of the charge uncoupling coefficient on the blasting effect needs further study. Taking the WenQuan tunnel of YanChong expressway as the engineering background, this paper uses LS-DYNA to simulate and analyze the influence of axial uncoupling coefficient (ratio of hole length to charge length) and radial decoupling coefficient (ratio of hole diameter to charge diameter) on surrounding rock blasting effect when air and water exist at the same time In engineering construction, it provides a reference for the application of water seal blasting in tunnel excavation.

2. Model Establishment and Parameter Selection

2.1. Model Establishment

As the surrounding holes directly affect the overall blasting effect of the tunnel, this paper takes the surrounding holes of WenQuan tunnel excavation blasting as the research object. To achieve the research purpose and ensure the simulation accuracy, the axial uncoupled model is shown in figure 1 (a). The size of the model is 8 m × 5 m × 2 m. The left and right sides and the lower boundary are non-reflective boundaries, and the upper boundary is defined as the free boundary. According to the setting parameters of the field blasting test of the WenQuan tunnel, the blast hole length is 3.3 m (the cyclic footage is 3 m), the diameter is 0.042 m, the filling length is 0.5 m, and the distance between the surrounding holes is 0.6 m. The radial uncoupling model is shown in figure 1 (b), the model size is 5 m×4 m× 3.5 m, and the blasthole plugging material parameters are set to be consistent with the surrounding rock. The blasthole uses reverse simultaneous detonation, as shown in figure 1.

![Blasting model (unit: m).](image-url)
2.2. Material Constitutive Model And Parameters

To reduce the calculation workload, the model is simplified and an asymmetrical model (right half of figure 1) is established. Multi-material ALE algorithm is adopted for explosive and water medium, and Lagrange algorithm is used for surrounding rock. The specific parameters are as follows:

(1) Surrounding rock

In the process of explosive explosion, some rocks near the explosive yield and form a fracture zone. At this time, the rock strain is very large and the strain rate effect is very obvious. JHC model is suitable for concrete and rock with a high strain rate and large deformation. The relevant parameters are shown in table 1.

| Parameter          | Value | Parameter          | Value |
|--------------------|-------|--------------------|-------|
| Density/kg·m⁻³     | 2586  | P_crush/GPa        | 0.016 |
| Shear modulus/GPa  | 6.52  | u_crush            | 0.001 |
| A                  | 0.79  | Pロック/GPa        | 0.8   |
| B                  | 1.6   | uロック             | 0.1   |
| C                  | 0.007 | D₁                 | 0.04  |
| N                  | 0.61  | D₂                 | 1     |
| f₁/GPa             | 0.048 | k₁/GPa             | 85    |
| T/GPa              | 0.004 | k₂/GPa             | -171  |
| E₁min              | 0.01  | k₃/GPa             | 208   |
| Smax               | 7     | EPS₀               | 1E-6  |

Note: f₁, T, E₁min, Smax, P_crush, u_crush, Pロック, uロック, k₁, k₂, k₃, EPS₀ are pressure parameters [11].

(2) Constitutive model and state equation of explosives

The material model of explosive is MAT_HIGH_EXPLOSIVE_BURN, the material model should be combined with the JWL equation of state. Related parameters: Density ρ=1240 kg·m⁻³, Detonation velocity D=3200 m·s⁻¹, Explosion pressure PCJ=7.4 GPa, A=214.4 GPa, B=0.182 GPa, R₁=4.2, R₂=0.9, ω=0.15, E₀=4.192 GPa, V=1.0. A, B, R₁, R₂, and ω are independent constants describing the JWL equation [11].

(3) Water

The constitutive model of water is MAT_NULL and the state equation adopts the Gruneisen equation. The related parameters are: density ρ = 1000 kg/m³, C = 1480, S₁ = 2.56, S₂ = -1.986, S₃ = 0.227, GAMAO = 0.5, A= 1.3937, E₁ = 256, V₀ = 1.0. Where C, S₁, S₂, S₃, GAMAO and A are software parameters; E₁ is the initial internal energy; V₀ is the initial relative volume [11].

(4) Air

The constitutive model of air is MAT_NULL and the state equation adopts the LINEAR_POLYNOMIAL_TITLE. The related parameters are: Density ρ=1.29 kg/m³, Cₐ=0.4, Cₜ=0.4, Initial internal energy E₀=0.25 MPa.

3. Influence of Axial Decoupling Coefficient on the Blasting Effect

Based on the relevant crushing theory of the medium crushing area, it can be seen that after the explosion of explosives, cracks with radial distribution are formed outside the crushing zone [12]. Under the premise of radial coupling charge and without considering the initial stress of rock mass, the blasting effect is simulated according to different axial decoupling coefficients K₁ = 1.4, 1.7, 2.0, 2.2, 2.5, and 2.7 (the distance between the black line and the free boundary is 3 m, indicating the blasting cycle footage). The numerical simulation results are shown in figure 2.
It can be seen from figure 2 that after the explosive explosion, an obvious blasting cavity is formed around the explosive column, and cracks are formed between adjacent blast holes, and the blasting cavity radius at the bottom of the blast hole is slightly larger than that at the hole opening. This is because the explosive energy at the bottom of the blast hole has no loss compared with the explosive at the hole hole hole, which completely acts on the wall rock of the hole, strengthening the damage to the surrounding rock. When the axial coupling coefficient increases from $K_1=1.4$ to $K_1=2.7$, the length of the cavity decreases continuously, the distribution density of surrounding rock crack decreases, and the block size of the crushed stone generated by blasting increases with the decrease of the charge quantity and the length of water interval at both ends of the explosive. When the axial uncoupled coefficient $K_1=2.7$, the cyclic footage required by the design can not be reached, so the value range of the axial uncoupled coefficient is 2.2-2.5.

4. Influence of Radial Decoupling Coefficient on the Blasting Effect
In addition to the axial uncoupling coefficient, the radial uncoupling coefficient also has a great influence on the blasting effect. Therefore, when the axial decoupling coefficient is 2.5, the simulation results are shown in figure 3.
It can be seen from figure 3 that after the explosion of explosive, radial cracks appear around the blast hole and continuously expand to form a fracture area. The above simulation results are similar to those in reference [13]. Besides, due to the simultaneous initiation of multiple blast holes, the cracks formed develop along the direction of the connecting line of the blast hole center, and there are also cracks in the direction perpendicular to the connecting line of the blast hole center, which indicates that the stress wave superposes in the middle of adjacent holes when multiple holes are detonated at the same time. When the radial uncoupling coefficient $K_2 = 1.6$, the fracture between the blast holes reaches the critical point.

In this paper, the decoupling coefficient of charge in the water seal blasting process is simulated according to the actual engineering. Based on the above simulation results, when the axial decoupling coefficient of the peripheral hole is 2.2 ~ 2.5, and the radial decoupling coefficient is 1.5 ~ 1.6, the smooth blasting effect is good and the tunnel profile is neat.

**5. Determination of Composite Uncoupling Coefficient**

To further determine the uncoupling coefficient of water sealed blasting charge, the concept of composite uncoupling coefficient is introduced. The composite uncoupling coefficient refers to the axial decoupling coefficient and radial uncoupling coefficient jointly used when the blasting effect is achieved. According to the results of the first half, the axial decoupling coefficient of water seal blasting is 2.2 ~ 2.5, and the radial decoupling coefficient is 1.5 ~ 1.6. The composite uncoupling coefficients that can be composed are shown in table 2.

| Category                    | I    | II   | III  | IV   |
|-----------------------------|------|------|------|------|
| Axial uncoupling coefficient| 2.2  | 2.2  | 2.5  | 2.5  |
| Radial uncoupling coefficient| 1.5  | 1.6  | 1.5  | 1.6  |

Other model parameters remain unchanged. The blasting effects of four water encapsulated charges in table 2 are simulated. The results are shown in figure 4.
Figure 4. Different composite uncoupling coefficients correspond to blasting effects.

It can be seen from figure 4 that among the four kinds of composite uncoupling coefficient charging structures, charging structures (I) and (II) can not only achieve the required blasting cycle footage after blasting, but also form a through between the blast holes, and the surrounding rock fragmentation degree of the hole is the best, which can effectively reduce the rock and stone size after blasting. However, the blasting of charge structure (III, IV) forms the base, and the surrounding rock of the hole is not broken, which leads to the larger rock fragmentation after blasting, which affects the subsequent construction progress. Therefore, considering the construction cost and reducing the unit consumption of explosives, when water seal blasting is used in tunnel excavation blasting construction, the axial decoupling coefficient of surrounding holes is 2.2, and the radial decoupling coefficient is 1.6, which can meet the construction requirements.

6. Engineering Application
To verify the above results and compare with the research results in references [5, 14], the WenQuan tunnel is selected as the water seal blasting test site, and the blasting test is carried out at the construction site. As one of the supporting projects for the 2022 Winter Olympic Games, the surrounding rock is mainly porphyry granite. Figure 5 (a) shows the blasting effect of field test (the surrounding rock has no obvious cracks, most of which are porphyritic granite, and there are a few other quality granites in the lower right corner. The mechanical properties of the two kinds of granites are similar, and their influence on the blasting effect can be ignored). The left side is the conventional charging structure, with the axial decoupling coefficient of 2.07 and the radial decoupling coefficient of 1.5; the right side adopts the above-mentioned mode The structure of water encapsulated charge with simulated results is as follows: the axial decoupling coefficient is 2.2, and the radial decoupling coefficient is 1.6 (emulsion explosive is used in blasting construction, to meet the demand of uncoupled charging of peripheral holes, the charge is processed on-site), and figure 5 (b) shows the corresponding numerical simulation blasting effect.

As can be seen from figure 5, through field test and numerical simulation, the effect of conventional blasting and water sealed blasting is compared. Using the charge uncoupling coefficient obtained from the above research for water sealed charging can better control the over-excavation and under excavation phenomenon after initiation, and achieve good smooth blasting effect, and the
fragmentation of blasting pile rock is uniform and the distribution is reasonable. However, the conventional blasting charge structure appears obvious to the overbreak phenomenon that brings inconvenience to the follow-up construction.

![Conventional blasting and Water seal blasting](image)

(a) Field test comparison

![Simulation comparison](image)

(b) Simulation comparison

Figure 5. Blasting effect.

To sum up, when the air and water media are used as the spacer of uncoupled charge in the peripheral hole for water seal blasting, the axial decoupling coefficient of the peripheral hole is 2.2, and the radial decoupling coefficient is 1.6, which can not only reduce the explosive unit consumption and control the construction cost, but also only need to fill water bags at both ends of the charge column, compared with using a single water medium as a spacer for water seal blasting, the filling process is simple and can improve the construction progress.

7. Conclusions

In this paper, taking the WenQuan tunnel as the engineering background, in view of the selection of the coupling coefficient of the surrounding hole charge in the process of water seal blasting, the method of combining numerical simulation with field test is used to analyze the problem. The following conclusions are obtained:

1) When the axial uncoupling coefficient increases from $K_1 = 1.4$ to $K_1 = 2.7$, due to the decrease of charge and the increase of water interval length at both ends of the explosive, the length of the surrounding hole blasting cavity decreases, the distribution density of surrounding rock fissures at the hole opening decreases, and the fragmentation of blasting generated gravel increases. According to the construction requirements, the reasonable value range of the axial decoupling coefficient is 2.2 $\sim$ 2.5.

2) When multiple blast holes are detonated at the same time, the explosion crack develops along the direction of the connecting line of the blast hole center, and the stress wave superposes in the middle of the adjacent blast hole, and cracks are also generated in the direction perpendicular to the central line of the blast hole. When the radial decoupling coefficient $K_2 = 1.5 \sim 1.6$, the smooth blasting effect is good and the tunnel contour is neat.

3) Based on the concept of composite uncoupling coefficient, the axial and radial decoupling coefficients are comprehensively analyzed, and the field tests are compared. Finally, when water seal blasting is used in tunnel excavation blasting construction, the axial decoupling coefficient of surrounding holes is 2.2, and the radial decoupling coefficient is 1.6, which can meet the construction requirements.

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