STRESS AND ENERGY TRANSFER OF WATER COUPLING BLASTING①

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ABSTACT Using the equivalent wave impedance method, the numerical analyses were given about uncoupling coefficient's effects on transfer course of explosive pressure and energy on hole wall in water coupling blasting. The result was verified by the experiments of blasting fragmentation and fracture law on water coupling blasting at different coupling coefficients. This result is valuable to the project design on water coupling blasting under different conditions.

Key word water coupling blasting equivalent wave impedance method match of explosive and rock fragmentation experiment fracture law experiment

1 INTRODUCTION

In blasting project, people always expect to fragmentate the media as effectively as possible, and meanwhile not to destroy the surroundings near blasting object, so uncoupling blasting charge and deck charge are often used to improve blasting effect. Water coupling blasting is a kind of uncoupling blasting loading. In this method water is used as coupling medium between charge and hole wall. Compared with the air coupling blasting, because of high density, high viscosity and no expansibility of water, the water coupling blasting has advantages of high parastatic pressure, well-distributed fragmentation, and high utilization rate of explosive energy[1].

As early as 1964, Mothias had made a study of mould experiment of presplitting blasting through three kinds of coupling media: air, water and dry sand, and found that water coupling blasting increased in spacing by a factor of 60% ~ 70%. In Japan, this way was called as AB tube, which is made of iron or plastics, filled with explosive and water, sealed and plugged in a borehole. It has a good blasting effect in smooth and presplitting blasting. In 1980s, the main result of several Chinese researchers is that the reduction of water coupling blasting stress is smaller than that of air coupling blasting. Chen Shihai analysed the explosive amount, charge structure, and destroy feature of the pressure in borehole wall on water coupling blasting[2].

Therefore water coupling blasting is often used as a control blasting method, but its mechanism of transfer of stress and energy is not known clearly; and on the other hand, the study on the effect of uncoupling coefficient in the blasting process is not enough. Most research works are just confined to the mould test and the suitable coupling blasting coefficients between rock and explosive, so it is difficult to obtain an agreeable relationship between experiments and theory. In this paper, the authors attempt to use the equivalent wave impedance method to study the transfer of explosive energy to rock in water coupling blasting, meanwhile have done simulated experiment for this purpose.

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2 EQUIVALENT WAVE IMPEDANCE METHOD

The equivalent wave impedance method[3] is a new method which can be used to calculate elastic longitudinal wave that propagate perpendicularly to many layers of media or without considering the transverse wave effect. Using this method it is very simple to get the effect of strain waves passing media: water and rock.

2.1 Principle of equivalent wave impedance method

Fig. 1 shows the calculation principle of equivalent wave impedance method. Interface 1 defines the relationship between explosive and water, interface 2 defines the relationship between water and rock. z_0, z_1, and z_2 are the wave impedance of blasting charge, water, blasted media(rock), respectively. Based on the successive condition of stress and velocity, all the parameters on interfaces are expressed as Eqn. (1)

$$\left.\begin{aligned} v_0 &= v_0^+ + v_0^- = v_{11}^+ + v_{11}^- \\ \sigma_0 &= \sigma_0^+ + \sigma_0^- = z_1 v_{11}^+ - z_1 v_{11}^- \end{aligned}\right\} \quad (1)$$

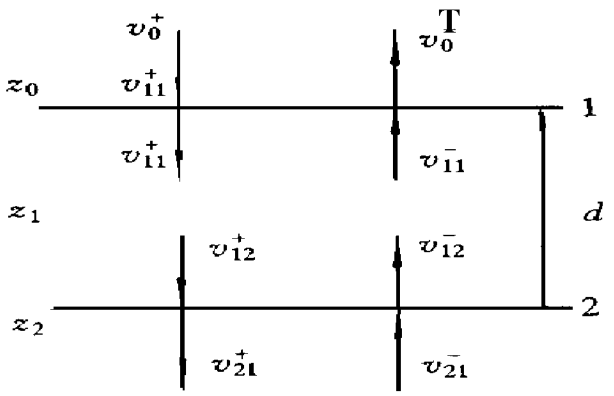

Fig. 1 Calculation principle of equivalent wave impedance method

Based on the formula of Finer(physical optics), the vibration phase of reflection wave (σ) is a half wave lose, which is changed sharply as π phase corresponding to the incident wave. According to this principle, the instantaneous state is determined when wave phase factor is changed only. The phase factor of positive advance should multiply $e^{-i\delta_1}$, and that of negative direction advance should multiply $e^{i\delta_1}$, as Eqn. (2):

$$\left.\begin{aligned} v_{12}^+ &= v_{11}^+ e^{-i\delta_1} \\ v_{12}^- &= v_{11}^- e^{i\delta_1} \end{aligned}\right\} \quad (2)$$

where $\delta_1 = wt_1 + 2\pi d_1/\lambda_1$, d_1 is the thickness of water layer, λ_1 is the wavelength.

Based on Eqns. (1) and (2), the relationship can be shown as Eqn. (3):

$$\left.\begin{aligned} v_0 &= v_{12}^+ e^{i\delta_1} + v_{12}^- e^{-i\delta_1} \\ \sigma_0 &= z_1 v_{12}^+ e^{i\delta_1} - z_1 v_{12}^- e^{-i\delta_1} \end{aligned}\right\} \quad (3)$$

Eqn. (3) can be changed into matrix:

$$\begin{vmatrix} v_0 \\ \sigma_0 \end{vmatrix} = \begin{vmatrix} e^{i\delta_1} & e^{-i\delta_1} \\ z_1 e^{i\delta_1} & -z_1 e^{-i\delta_1} \end{vmatrix} \begin{vmatrix} v_{12}^+ \\ v_{12}^- \end{vmatrix} \quad (4)$$

According to the same principle, there is Eqn. (5) on interface 2:

$$\left.\begin{aligned} v_2 &= v_{12}^+ + v_{12}^- \\ \sigma_2 &= z_1 v_{12}^+ - z_1 v_{12}^- \end{aligned}\right\} \quad (5)$$

Based on Eqn. (5), it can be changed as

$$\left.\begin{aligned} v_{12}^+ &= \frac{1}{2} v_2 + \frac{1}{2z_1}\sigma_2 \\ v_{12}^- &= \frac{1}{2} v_2 - \frac{1}{2z_1}\sigma_2 \end{aligned}\right\} \quad (6)$$

It can also be changed into matrix as:

$$\begin{vmatrix} v_{12}^+ \\ v_{12}^- \end{vmatrix} = \begin{vmatrix} \frac{1}{2} & \frac{1}{2z_1} \\ \frac{1}{2} & -\frac{1}{2z_1} \end{vmatrix} \begin{vmatrix} v_2 \\ \sigma_2 \end{vmatrix} \quad (7)$$

Based on Eqns. (4) and (7), the result is

$$\begin{vmatrix} v_0 \\ \sigma_0 \end{vmatrix} = \begin{vmatrix} \frac{1}{2}(e^{i\delta_1} + e^{-i\delta_1}) & \frac{1}{2z_1}(e^{i\delta_1} - e^{-i\delta_1}) \\ \frac{z_1}{2}(e^{i\delta_1} - e^{-i\delta_1}) & \frac{1}{2}(e^{i\delta_1} + e^{-i\delta_1}) \end{vmatrix} \begin{vmatrix} v_2 \\ \delta_2 \end{vmatrix}$$

The index function is changed to trigonometry function with Eular formula:

$$\begin{vmatrix} v_0 \\ \sigma_0 \end{vmatrix} = \begin{vmatrix} \cos\delta_1 & \frac{1}{2} i\sin\delta_1 \\ z_1 i\sin\delta_1 & \cos\delta_1 \end{vmatrix} \begin{vmatrix} v_2 \\ \delta_2 \end{vmatrix} \quad (8)$$

2.2 Equivalent wave impedance

Fig. 2 shows the sketch map of the equivalent wave impedance. Y is defined as the equivalent wave impedance through interpace of water layer. So there are formulas:

$$\sigma_0 = z_0 v_0^+ - z_0 v^- = Y v'_2$$

$$v'_2 = v_0^+ + v'_0 = v_0$$

then

$$\sigma_0 = Y v_0 \tag{9}$$

$$\sigma_2 = z_2 v_2 \tag{10}$$

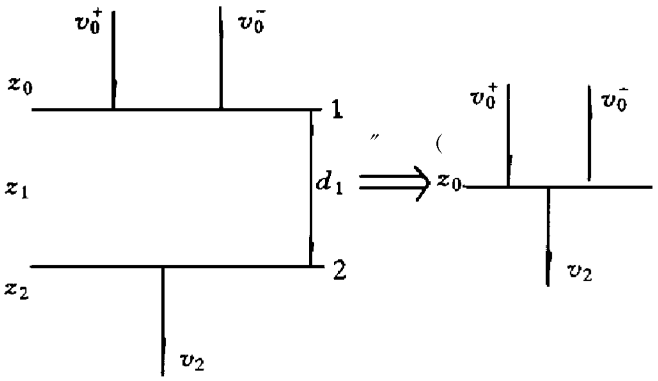

Fig. 2 Sketch map of equivalent wave impedance

Based on Eqns. (8), (9) and (1):

$$\begin{vmatrix} v_0 \\ \sigma_0 \end{vmatrix} = \begin{vmatrix} v_0 \\ Y v_0 \end{vmatrix} = \begin{vmatrix} \cos\delta_1 & \frac{1}{2} i\sin\delta_1 \\ z_1 i\sin\delta_1 & \cos\delta_1 \end{vmatrix} \begin{vmatrix} 1 \\ z_2 \end{vmatrix} v_2 \tag{11}$$

Let

$$\begin{vmatrix} B \\ C \end{vmatrix} = \begin{vmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{z_1} \\ i z_1 \sin\delta_1 & \cos\delta_1 \end{vmatrix} \begin{vmatrix} 1 \\ z_2 \end{vmatrix} \tag{12}$$

so

$$Y = \frac{\sigma_0}{v_0} = \frac{B v_2}{C v_2} = \frac{B}{C} \tag{13}$$

2.3 Calculation of coefficient of explosion stress and energy transfer[4]

For most rocks, the effect scope of impact wave is narrow so it can be ignored, meanwhile because most rocks are brittle, the collision between explosion wave and rock can be considered as the elastic collision approximately, and the elastic stress wave is generated directly from rock. Considering the middle layer, it is impossible for the charge to slide and the blasting wave is propagated out with little angle θ between two sides, so the effect of transverse wave is not considered. According to the equivalent wave impedance method, the transfer coefficient of stress is

$$T_\delta = \frac{2(z_2 \cos\delta_1 + i z_1 \sin\delta_1)}{(z_0 + z_1)\cos\delta_1 + i\left(\frac{z_1^2 + z_0 z_1}{z_1}\right)\sin\delta_1} \tag{14}$$

The energy transfer coefficient is

$$T_e = \frac{4 z_2 z_0}{(z_0 B + C)(z_0 B + C)^*} \tag{15}$$

$$\begin{vmatrix} B \\ C \end{vmatrix} = \begin{vmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{z_1} \\ i z_1 \sin\delta_1 & \cos\delta_1 \end{vmatrix} \begin{vmatrix} 1 \\ z_2 \end{vmatrix} \tag{16}$$

3 CALCULATING OF STRESS AND ENERGY TRANSFER ON WATER COUPLING BLASTING

In water coupling blasting, the uncoupling coefficient k is an important parameter, which is the ratio of hole diameter to charge diameter. The water thickness is expressed with k as

$$\delta_1 = \frac{2\pi r(k-1)}{\lambda_1} \tag{17}$$

where r is the charge diameter and the wave length (λ_1) can be gotten from Refs. [5, 6], as Eqn. (18):

$$\lambda_1 = 7 c_1 w_c^{0.5} k^{-0.45} \times 10^{-4} \tag{18}$$

where c_1 is sound velocity of water, c_1 = 1 460 m/s; w_c (kg/m) is TNT equivalent weight of explosive, $w_c = w_{cs} Q_{ws} / Q_{wt}$. According to above mentioned definition, w_{cs} ($w_{cs} = \pi r^2 \rho_0$) is the density of the explosive charge, and Q_{ws} (4.186 × 10^3 J/kg) is the explosion heat of the explosive charge, Q_{wt} is the mass of TNT and Q_{wt} = 4.186 × 10^6 J/kg. To RDX, ρ_0 = 1 270 kg/m^3, Q_{ws} = 6.279 × 10^6 J/kg. Based on these parameters and Eqn. (18), the wave length λ_1 can be calculated[7].

According to different kinds of explosive wave impedances, they are classed as high explosive, for z_0 = 70 MPa/s; the middle explosive, for z_0 = 45 MPa/s; and the low explosive, z_0 = 30 MPa/s. Rocks are classified as the high hard rock, z_2 = 150 MPa/s; the hard rock, z_2 = 80 MPa/s; and the soft rock, z_2 = 30 MPa/s, the values of transfer coefficient of stress and energy as a function of k can be obtained form different kinds of wave impedance.

4 TRANSFER ANALYSIS OF STRESS AND ENERGY ON WATER COUPLING BLASTING

Through theoretical calculation, the results are showed on Figs. 3~ 6, in which curve 1 means the high hard rock, curve 2 represents the hard rock and curve 3 represents the soft rock.

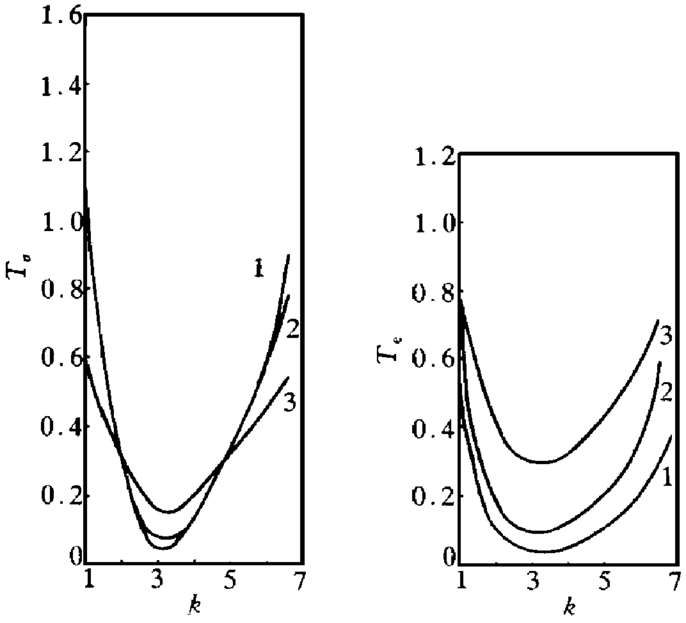

Fig. 3 Stress and energy between high explosive and rocks

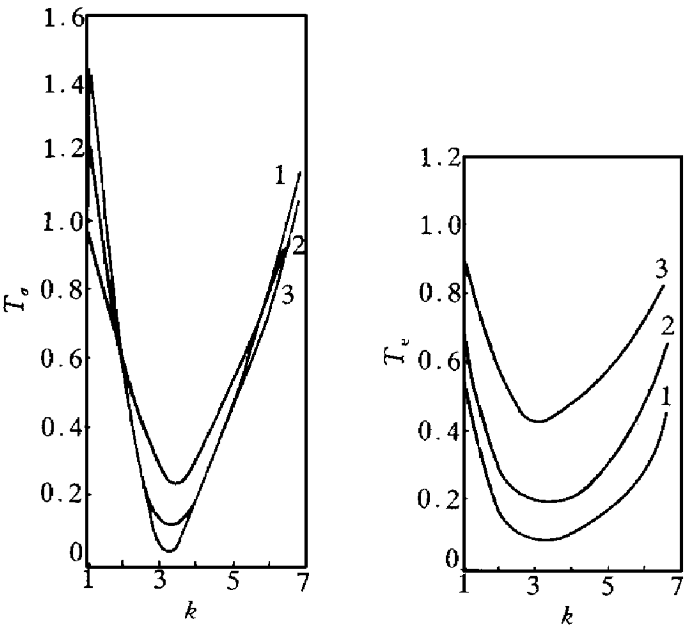

Fig. 4 Stress and energy between mid-high explosive and rocks

In Fig. 6, RDX: z_0= 54. 3 MPa/ s and the concrete model: z_2= 64. 7 MPa/ s.

From Figs. 3~ 6, we can conclude:

(1) There are two phases about the changes of the transfer coefficient T_σ of stress and the energy transfer coefficient T_e as a function of the uncoupling coefficient k in the water coupling blasting. When k is less then 3. 5, T_σ and T_e decrease with k increasing. When k is bigger than 3. 5, two coefficients increase with k reducing. When k = 3. 5, two coefficients are minimums.

(2) Because the minimums of two coefficients are 3. 5, when 3. 5< k< 7. 0, the change

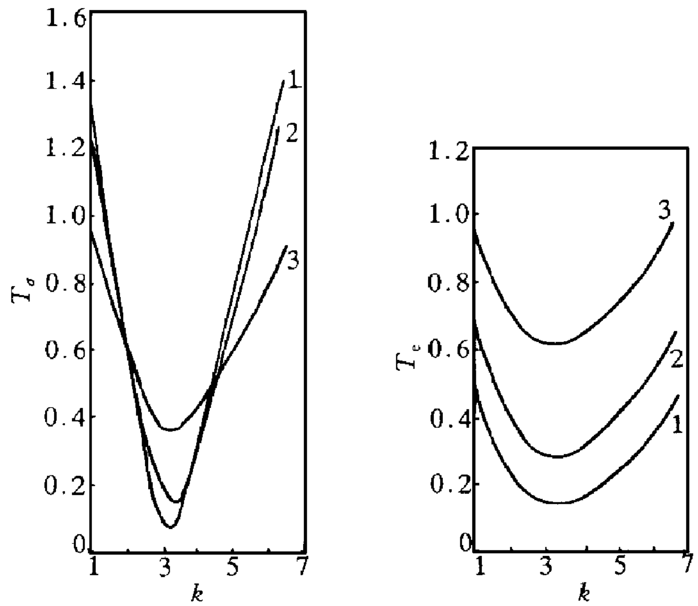

Fig. 5 Stress and energy between low explosive and rocks

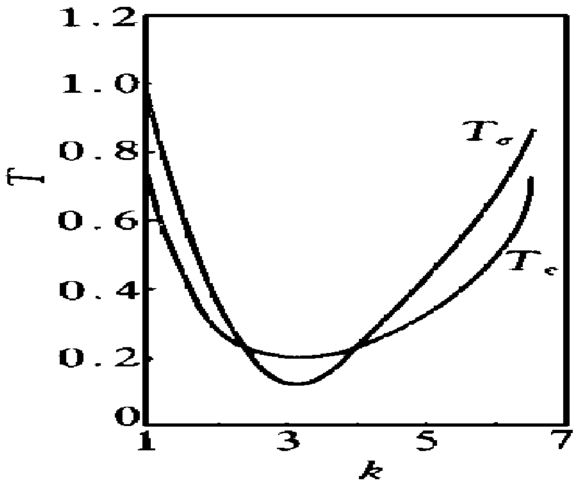

Fig. 6 Stress and energy between RDX and concrete

law of the two coefficients(T_σ and T_e) are opposite to that law when 1.1< k < 3.5, and the curves are shown roughly symmetrical patterns. The descending of the two coefficients is faster when k is less than 3.5, and the ascend rate of that is slower when 3.5< k < 7.

(3) The changes of the two coefficients(T_σ and T_e) in hard rock are bigger than that in soft rock. So in order to maintain high coefficients in the high rock, when k is less than 3.5, it should be less than 1.5. Otherwise, when the value of k increases, the two coefficients decline greatly and it is a bad blasting effect.

(4) The energy transfer coefficient T_e in the soft rock is higher than that in the hard rock. It means that blasting effect in the soft rock is better than in hard rock.

(5) The energy transfer coefficient T_e of high explosive is higher than that of low explosive in water coupling blasting. It shows that the declining of energy in low explosive is slower than that in high explosive.

5 EXPERIMENT STUDY ON WATER COUPLING BLASTING

5.1 Experiment study of fragmentation on water coupling blasting

5.1.1 Experiment conditions

The mould of blasting was made of concrete which has 22.5 MPa in compressive strength. The mass ratio of water: cement: sand was 0.5∶1.0∶2.5. The wave impedance of mould was 64.7 MPa/s. The height of mould was 300 mm and its diameter was 300 mm. The uncoupling coefficient k was 2.0, 2.75, 3.375 or 3.875, respectively. The explosive was RDX. It was detonated by electric detonator. The diameter of the explosive charge which weights 8 g is 8 mm. Considering the smaller volume of the mould and the experiment results affected by the size of boundary, the air coupling blasting with similar k values were tested for compared with the water coupling blasting.

5.1.2 Results of experiment

The results of experiment are showed in Table 1. From Table 1, when k is equal to 2.75 or 3.375, the size of fragment is bigger and the blasting effect is worse than that of the other process, in which fragment size is smaller when k is 2.0 or 3.875. The result does coincide with that of theory with calculating. In order to contrast with the water coupling blasting, the blasting effect on air coupling is worse when k value increases. It means that the effect of boundary on mould experiment has little influence on the fragment size.

Table 1 Relationship of fragment size and k

Type	Index	k			
		2.000	2.750	3.375	3.875
Water coupling blasting	Average size/mm	52	57	56	50
	Fine size (x < 80 mm) /%	76.7	69.0	69.5	76.2
	Coarse size (x > 80 mm) /%	23.3	31.0	30.5	22.8
	R-R curve Y50/mm	44.4	61.4	58.3	42.7
Air coupling blasting	Average size/mm	63.7	70.7	79.1	83.3
	Fine size (x < 80 mm) /%	59.2	47.8	40.6	25.1
	Coarse size (x > 80 mm) /%	40.8	52.2	59.4	74.9
	R-R curve Y50/mm	92.2	141.2	101.0	161.2

5.2 Development law of fracture in water coupling blasting

5.2.1 Condition and index of experiments

The mould of blasting was made of concrete which had 23.3 MPa compressive strength. The mass ratio of water: cement: sand was 0.5∶1.0∶2.0. The side of the mould was 400 mm. The explosive was RDX, which was detonated by electric detonator. The diameter of 350 mg explosive charge was 8.5 mm. Because the mould was flat and the charge space was narrow, in order to avoid leaking of the explosive gas, both ends of the hole must be stemmed. The uncoupling coefficient in water coupling blasting was

2, 3, 4 or 5, respectively. The coefficient of air coupling was 2, 3 or 4. In order to contrast with water coupling blasting, the hole, which had a distance of 100 mm to the bottom side of the mould, was designed on the middle line. And the guided hole was located in the centre of mould. The indexes of experiment are: the number of fractures developping on hole wall, total length of fracture (mm), original splitting time (μs), stagnant time of hole splitting (μs), and description of blasting state. The time, which the explosive wave transmits from the centre of hole to the hole wall, is considered as the stagnant time of hole splitting. The time, during which the exposion wave breaks the sensor located in a place with a distance of 20mm to the hole wall, is considered as the original splitting time. The experiment results of fracture development is showed in Table 2.

5.2.2 Result of fracture experiment

From Table 2, the original splitting time and stagnant time of the hole splitting both increase with increasing of k. The number of fracture developed on the hole wall reaches its maximum when $k=2.0$, and equals to its minimum when $k=3.0$, and increases again along with $k=4.0$ or 5.0. The number of fracturre with $k=2.0$ or 5.0 is more than that when $k=1.0$. Because the energy transfer on oversmash energy of hole is more than the latter coupling blasting process, the number of fracture of coupling blasting ($k=1$) is less than the one of water coupling blasting with $k=2.0$ or 5.0. Meanwhile, with k increasing, the total length of fracture gradually decreases until $k=3.0$, and it reaches its minimum and then raise again. The total length of fracture when $k=5.0$ is longer than that when $k=1.0$ because more explosive energy is used in oversmash on hole when $k=1.0$. It means that water coupling blasting, which can adjust the distribution of the explosive energy, reduces effectively the smash area and increases the number of fractures and the total length of fractures. The relationship between the number and the total length of fracture and k value coincides well with the theoretic calculation and the experiment of explosive fragmentation mentioned above in water coupling blasting.

With increasing k, the number and the total length of fractures reduce and the splitting time of fracture and the stagnant time of the hole splitting increase. It means that the effect of

Table 2 Experiment results of fracture development

Type	Diameter/mm	k	Fracture number	Fracture length/mm	Split time /μs	Stagnant time/μs	Description
Coupling	3.5	1	4.75	1 027	39.3	1.2	Broken hole wall, visible small fractures
Water coupling	7	2.0	4.82	934	47.1	11.5	Broken hole wall, visible small fractures
	10.5	3.0	4.5	918	47.2	14.2	Destroyed hole wall, part wall remaining, visible smaller fractures
	14	4.0	4.6	933	48.2	17.6	No broken hole wall, no fractures
	17.5	5.0	5.0	1 017	50.7	22.6	Visible fractures, whole hole wall
Air coupling	7.0	2.0	3.8	790	54.3	18.7	Slightly broken hole wall, no fractures
	10.5	3.0	2.3	460	60.6	27.5	Whole hole wall, no fractures
		14.0	4.0				Whole model unbroken

limited boundary of the mould has little influence to the fracturing of the blasting mould.

6 CONCLUSIONS

(1) According to the theoretical calculation of equivalent wave impedance method, there are two phases about the two coefficients of stress and energy(T_σ and T_e) in water coupling blasting. The two coefficients T_σ and T_e reduce with k increasing when $k < 3.5$, increase when $k > 3.5$, and reach their minimium when $k = 3.5$. The theoretical result is verified by the experiments of blasting fragmentation and fracture development law in water coupling blasting.

(2) The theoretical calculation and the result of experiments show that k should be reduced to less than 1.5 in order to use water coupling blasting in control blasting because of the higher coefficient of the stress transmitting within hard rock. It bespeaks that the water coupling blasting is suitable for the shaking fracture and making rift on the hard rock. But there is a good broken effect in soft rock because of the higher coefficient (T_e) of energy transfer.

(3) Water coupling blasting can adjust the discontribution of the explosive energy and reduce effectively the area of smash. It can increase the number and the length of fractures when $k = 2.0$ or 5.0 in the experiments. This advantage could be used in the presplittling and smooth blasting.

(4) The experiment and the theoretical calculation show that the two coefficients have the minimum when $k = 3.5$, decrease when $k < 3.5$ and increase when $k > 3.5$ again. The fracture development experiment bespeak that the hole wall is destroyed when $k < 3.5$ but not when $k > 3.5$. Based on this result, the value k can be changed according to the project situation. When $k < 3.5$, the diameter of hole can be small and the expense is cheap. Otherwise, when $k > 3.5$, big hole is needed, and the expense is expensive, but the hole wall is protected in the process. In a word, the changing of two coefficients when $k < 3.5$ can be repeated when $k > 3.5$ but the effects on the wall of hole is different.

(5) From the results of the two imitating experiments, it is concluded that the changing of k and the diameter of holes has little effect on the result of experiment, so the effect of limited boundary has little influence on the coupling patterns of media.

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