AFFECTING PROCESS OF EXPLOSION IN ROCK MASS BY CYLINDRICAL CHARGE①

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ABSTRACT

The explosion effects and physical process in rock mass by cylindrical charges are discussed. The maximum explosion cavity radius and the coefficient of effective explosion work are found through mechanical model and numerical method. The dependance of explosion parameters on time is got. The results show that the maximum explosion cavity radius produced by cylindrical charge of ammonium trinitro-toluene No.2 explosive in limestone and diabase is 1.50 and 1.26 times respectively as much as that of blasthole; and the coefficient of effective explosion work is 0.71 and 0.54 respectively as much as that of the blasthole.

Key words: explosion cavity blasting in rock mass explosion effect

1 INTRODUCTION

The affecting process between cylindrical charge and rock mass, which is the main part of rock blasting mechanism, is a complicated project and is studied through the mechanical model and numerical method in this paper. Here, three prerequisites are supposed which are: (1) the cylindrical charge is in infinite rock mass; (2) the cylindrical charge is detonated axially symmetry; and (3) the charge is coupled.

2 EXPLOSION AFFECTING MODEL

2.1 *The Initial Parameters of Explosion Affecting on Holewall*

The explosion instantaneous moment is considered as initial time and its corresponding affecting parameters are called initial parameters.

The shock impedances of industry explosives are frequently smaller than those of the rocks, so that the shock wave in the rock is produced at the explosion moment and the reflected shockwave is produced in the explosion gas. At that time, the shock pressure p_x on the holewall is larger than that p_H on the C−J side of the detonating wave. The reflected wave makes the particle velocity u_H of the explosion gas reduce to the moving velocity u_x of the holewall. If the detonating wave acts with the holewall at a right angle, the basic equation is[3]

$$u_x = \frac{D}{\gamma+1}\left[1+\frac{(\bar{p}-1)\sqrt{2\gamma}}{\sqrt{(\gamma+1)\bar{p}+(\gamma-1)}}\right] \quad (1)$$

where $\bar{p}=p_x/p_H$; D is detonating speed; γ is the isentropic index of the expolsion gas.

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From the conservation law of momentum and the conservation law of matter, for the shock wave in rock mass there exists

$$u_x = \sqrt{p_x(\rho_{ro}^{-1} - \rho_{rx}^{-1})} \quad (2)$$

where ρ_{ro} and ρ_{rx} are respectively the initial rock density and the rock density on wave front. The state equation of the rock[4] is

$$p_x = B(\bar{i}_{rx}^{4} - 1) \quad (3)$$

where $B = 1/4c_0^2\rho_{ro}$; c_o is the velocity of the longitudinal wave; $\bar{i}_{rx}$ is the compression ratio and $\bar{i}_{rx} = \rho_{rx}/\rho_{ro}$. From equations (1)~(3) p_x, u_x and $\bar{i}_{rx}$ can be calculated. And then from the conservation law in rock mass we get

$$c_p\rho_{ro} = (c_p - u_x)\rho_{rx} \quad (4)$$

where c_p is the velocity of shock wave. And from equation (3) the shock wave velocity on holewall can be calculated as

$$\rho_{rx} = \rho_{ro}(p_x/B+1)^{1/4}$$

From the equation mentioned above just now and equation (2),there is

$$u_x = \sqrt{\frac{p_x}{\rho_{ro}}[1 - (p_x/B+1)^{-0.25}]} \quad (5)$$

From equations (1) and (5), p_x can be found; then from (5), u_x can be found; from (3), $\bar{i}_{rx}$ can be found and from (4), c_p can be found.

2.2 *The Parameters During the Expanding of Holewall*

After getting initial parameters, the holewall begins to expand. During the reforming of holewall, a scattered wave is transmitted into the detonation gas, and the pressure of explosion gas is supposed as $p_1(t)$, where t is the time from the initial moment. The isentropic equation of the explosion gas is

$$p_1(t) = A\rho^{\gamma} \quad (6)$$

where A is a constant. According to equation (6), there is

$$p_1(t) = p_x(t-\triangle t)[\frac{R(t-\triangle t)}{R(t)}]^{2\gamma} \quad (7)$$

where $\triangle t$ is a time increment, $R(t-\triangle t)$ and $R(t)$ are the cavity radii at the time of $t-\triangle t$ and t respectively. If $\triangle t$ is small enough, the expanding velocity $u_1(t)$ of the gas at the moment of t can be considered as the reforming velocty $u_x(t-\triangle t)$ of holewall at the moment of $t-\triangle t$. At the moment of t, because the scattered wave has trasmitted into the explosion gas, the expanding veolcity $u_1(t)$ of the gas increases to $u_x(t)$ and the pressure of the explosion gas changes from $p_1(t)$ to $p_x(t)$. Therefore, during the reforming of holewall, for the gas there is

$$u_x(t) = u_1(t) + \int_{p_x(t)}^{p_1(t)} \frac{dp}{\rho c} \quad (8)$$

where c is the velocity of sound in explosion gas, which can be defined as $c = (dp/d\rho)^{1/2}$.

From c and the isentropic equation of explosion gas, we can get $c/c_1 = (\rho/\rho_1)^{(\gamma-1)/2}$, $\rho/\rho_1 = (p/p_1)^{1/\gamma}$, $c_1^2 = \gamma p_1/\rho_1$, and $c_I(t) = c_1(t-\triangle t)[p_x(t-\triangle t)/p_1(t)]^{\frac{\gamma-1}{2\gamma}}$ where $c_1(t)$ and $c_1(t-\triangle t)$ are the velocity of sound in the gas respectively at the moment of t and $(t-\triangle t)$. Substituting the four equations above into equation (8),we get

$$u_x(t) = u_1(t) + \frac{2c_1(t)}{\gamma-1}[1 - (\frac{p_x(t)}{p_1(t)})^{\frac{\gamma-1}{2\gamma}}] \quad (9)$$

On the front of shock wave in the rock, there are:

(1) the coversation of momentum $p_2(t) = \rho_{ro}c_pu_2$;

(2) the coversation of matter $(c_p - u_2)\rho_r = c_p \cdot \rho_{ro}$;

(3) the state equation $p_2(t) = B(\bar{i}_r^{4} - 1)$

where $p_2(t)$ is the front pressure; u_2 is the particle velocity; $i_r = \rho_r/\rho_{ro}$; ρ_{ro} and ρ_r are respectively the rock density before and after the front. According to the three equations above, there is

$$u_2^2(t)=\frac{p_2(t)}{\rho_{ro}}[1-(\frac{p_2(t)}{B}+1)^{-0.25}] \quad (10)$$

The continuous equation of the shock wave after the front is

$$\frac{\partial \rho_r}{\partial t}+\frac{\partial(\rho_r u_2)}{\partial r}+\frac{\rho_r u_2}{r}=0$$

where r is the radius of shockwave. The rock mass after the wave front can be considered as imcompressible medium, that is ρ_r = constant. The equation above after the intergral is changed into

$$u_2(t)=u_x(t)R(t)/r \quad (11)$$

where $R(t)$ is the instantaneous explosive cavity radius. Under the action of explosion load, the rock arround the blasthole is broken and the medium after the wave front is umcompressed, so that there is

$$p_2(t)=p_x(t)\frac{R(t)}{r} \quad (12)$$

where $p_x(t)$ is the pressure on the holewall at the moment of t. The explosion cavity radius $R(t)$ and the shock wave radius r can be calculated by numerical integrating as

$$R(t)\approx R_o+\sum_{i=1}^{N}\triangle t\cdot u_x(t_i) \quad (N=t/\triangle t)$$

$$r=R_o+\sum_{i=1}^{N}\triangle t\cdot c_p \quad (N=t/\triangle t)$$

where R_o is the initial radius of the hole or the radius of the cylindrical charge

2.3 *The Coefficient of Effective Explosion Work*

The energy of cylindrical charge in a unit length is

$$E=\pi R_o^2\rho_o Q \quad (13)$$

where ρ_o is the density of charge; Q is the detonation heat of the charge.The work acted on the rock by the explosion of charge in unit length is

$$E_1=2\pi\int_{R_o}^{R_{max}}R(t)p_x(t)\mathrm{d}R$$

where $R_{\max}$ is the maximum explosion cavity radius. Since $\mathrm{d}R=u_x(t)\mathrm{d}t$, therefore, the equation is changed into

$$E_1=2\pi\int_{o}^{t_{max}}R(t)p_x(t)u_x(t)\mathrm{d}t \quad (14)$$

where $t_{\max}$ is the time corresponding to $R_{\max}$. According to definition, the coefficient of effective explosion work can be calculated through equations (13) and (14)

$$\eta=\frac{2\int_{o}^{t_{max}}R(t)p_x(t)u_x(t)\mathrm{d}t}{R_o^2\rho_o Q}.$$

Let $\overline{R}=R(t)/R_o$, $\overline{t}=t/(R_o/c_o)$, the equation above can be rewritten into

$$\eta=\frac{2\int_{o}^{\overline{t}_{max}}\overline{R}(\overline{t})P_x(\overline{t})u_x(\overline{t})\mathrm{d}\overline{t}}{\rho_o Q C_o} \quad (15)$$

3 THE NUMERICAL METHOD AND RESULTS

The isentropic index γ of the explosion gas chooses its values as

$\gamma=3$ when $p_1(t)>200$ MPa

$\gamma=1.4$ when $p_1(t)\leqslant 200$ MPa

For example, two kinds of representative explosives are chosen: (1) ammonium trinitrotoluene No.2 explosive, $\rho=1{,}000$ kg/m^3, $D=3{,}600$ m/s, $Q=3{,}761{,}870$ J/kg; (2) ammonite explosive, $\rho_o=1000$kg/m^3, $D=3{,}600$ m/s, $Q=4{,}435{,}676$ J/kg. And two kinds of representative rocks are chosen: (1) Limestone, $\rho_{ro}=2{,}420$ kg/m^3, $C_o=3{,}430$ m/s; (2) Diabase, $\rho_{ro}=2{,}870$ kg/m^3, $C_o=6{,}430$ m/s. The step length of time $\triangle t=0.2R_o/c_o$. The results are shown in the table 1~4.

Table 1 The affecting parameters in limestone by Ammonium trinitro-toluene No.2 explosive

$t/(2R_o/C_o)$	P_x/MPa	u_x/ms^{-1}	R	η
0	4,911	500	1.00	0.00
1	2,130	242	1.20	0.41
2	1,623	154	1.31	0.54
3	1,101	137	1.39	0.61
4	876	100	1.45	0.63
5	613	73	1.50	0.69

Table 2 The affecting parameters in limestone by Ammonium trinitro-toluene No.2 explosive

$t/(2R_o/C_o)$	P_x/MPa	u_x/ms^{-1}	R	η
0	5,900	306	1.00	0.00
1	4,063	216	1.08	0.23
2	3,070	165	1.14	0.35
3	2,469	133	1.19	0.44
4	2,067	112	1.23	0.49
5	1,780	98	1.26	0.54

Table 3 The affecting parameters in Limestone by ammonite explosive

$t/(2R_o/C_o)$	P_x/MPa	u_x/ms^{-1}	R	η
0	7,257	695	1.00	0.00
1	2,545	287	1.25	0.62
2	1,477	174	1.38	0.78
3	1,045	126	1.47	0.85
4	812	99	1.54	0.89
5	666	83	1.59	0.92

Table 4 The affecting parameters in Diabase by ammonite explosive

$t/(2R_o/C_o)$	P_x/MPa	u_x/ms^{-1}	R	η
0	8,802	445	1.00	0.00
1	5,343	282	1.11	0.38
2	3,779	203	1.19	0.56
3	2,927	195	1.24	0.67
4	2,393	131	1.29	0.74
5	2,027	112	1.32	0.79
6	1,761	97	1.36	0.82

4 THE CRITERION OF THE MAXIMUM EXPLOSION CAVITY RADIUS

Because the medium after the wave front in the rock is considered as uncompressed, after the pressure p_2 on the wave front is smaller than the dynamic strength of the rock, the hole-wall reforming becomes only elastic. At this time $p_2=\sigma_s$. The corresponding cavity radius is maximum and effective for the work on the rock, so that the effective work on the rock by the explosion energy reaches maximum. When the loading rate is $10\sim10^3$ MPa / s, the dynamic strength of the rock is $1.16\sim1.43$ times as much as the static strength

$$\sigma_s=(1.16\sim1.43)[\sigma_s]$$

where $[\sigma_s]$ is the static compression strength in the uniaxis. The larger the loading rate is, the higher the value of the soft rock is. For limestone, $[\sigma_s]=45$ MPa and we choose $\sigma_s=1.43[\sigma_s]$. For Diabase,$[\sigma_s]=158$ MPa and we choose $\sigma_s=1.16[\sigma_s]$. The results are shown in Table 5, η_{max} in the table is the maximum explosion work coefficient.

Table 5 The computeration results of $\bar{R}_{max}$ and η_{max}

Explosive–rock	$\bar{R}_{max}$	η_{max}
Ammonium trinitro-toluene No.2–Limestone	1.50	0.69
Ammonium trinitro-toluene No.2–Diabase	1.26	0.53
Ammonite–Limestone	1.59	0.92
Ammonite–Diabase	1.36	0.80

5 SUMMERY

(1) The calculated affecting proeess between Limestone / Diabase and ammonium trinitro-toluene No.2 explosive agrees with the experienced values. The reason why the explosion work coeffocent is higher than the reality has three points: (a) the supposes of that the cylindrical charge is detonated axially symmetry and the detonation wave acts the holewall at a right angle are not completely in agreement with the practice: (b) when the work coefficient during $\triangle t=t_i-t_{i-1}$ was calculated by numerical method, $p_x(t_i)$ was considered as the average pressure on the holewall; (c) the present experiment information can not be

obtained in infinite medium, so that the moving of the stem, of the blasthole will certainly make energy loss;

(2) The higher the detonation velocity of the explosive is, the more the energy ratio owned by skock wave is;

(3) The closer the sound impendances between the rock and the explosive are, the higher the explosion work coefficient is;

(4) The explosion work coefficient of ammonium trinitro-toluene No.2 explosive is 0.69 on limstone, and 0.54 on diabase, the corresponding explosion cavity radii are respectively 1.50 and 1.26 times as much as that of the blasthole;

(5) The change laws of explosion affecting parameters on the blasthole wall with the time provide the method and basis determining the boundary condition for the calculation of the explosion stress distribution in the rock.

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(*Continued form page* 16)

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