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Numerical study on rock fracture and vibration due to blasting

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Abstract: Fracture and ground vibration of rock subjected to different decoupling decked charges are investigated based on the numerical simulation. The dynamic pressure value is studied, which demonstrates that simulation of fracture zone is feasible. Attenuation index of dynamic pressure is 2.06, 2.05 and 1.93 for air, water and sand intervals respectively. The small attenuation of sand interval results in the large ground vibration. The predicted vertical vibration waveform and peak particle velocities (PPV) in far-field are in agreement with the monitoring results. The results show that the air and water decked charges can improve the effect of rock fracture in near-field and reduce ground vibration in far-field.

Key words: rock blasting; finite element; numerical simulation; vibration effect; fracture
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Study of fracture and vibration effect is important in the area of rock blasting. Rock blasting by explosive is complex due to the rock properties of unhomogeneity and anisotropy. Because of the large number of complex variables involved, numerical simulation has become a usefull tool. To perform numerical studies on the fragmentation process of rock, new computer hydrocodes, such as LS-DYNA, MSC/DYTRAN and ABAQUS, have been developed.

Some researchers have applied experimental and numerical methods to investigate the behavior of rock subjected to blasting [1-3]. Because the LS-DYNA models can model most types of rock, this paper presents an analysis of rock blasting with this model. The model include two steps the simulation of fracture zone and the simulation of ground vibration far away from the borehole. The predicted waveform is used to demonstrate the feasibility of simulation.

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1 Experiment and simulation method

In the experiment, the diameter and the depth of the explosive column are 0.2 m and 14.0 m respectively. The geometry is shown in Fig. 1. The No. 2 rock explosive is used, and its weight is 175 kg. The explosive is distributed in three layers with a ratio of 4 : 2 : 1. Rocks are Grabbro. The decked stemming includes air, water and sand. The length of decked stemming is 1.5 m at the bottom and 2.0 m at the upper. The vibration monitoring points are at 40 m away from charges.

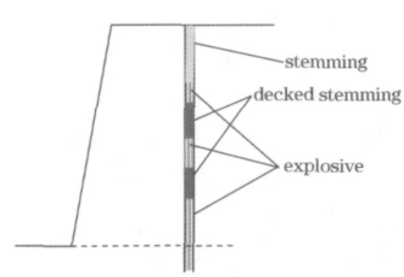

Fig. 1 Configuration of experiment

Simulations of the charge detonation, the size and shape of the broken rock and the propagation of stress wave are theoretically possible. However, factors, such as the characteristic of medium, the difference of time step and the restriction of computer resources, make it difficult to numerically simulate the process from charge detonation to stress wave propagation [4-5]. In this paper, the simulation is carried out in two stages on the basis of the different fields: ① Around the borehole (near-field or fracture field), the high stress level, large deformation and even fluid state are produced in rock media. Therefore, the ALE method is used to simulate fluid-solid coupled problem, and the stress data are obtained on elastic-plastic boundary. ② Far away from the borehole (far-field or vibration field), elastic vibration is produced with the attenuation of shock waves. The Lagrangian method is used to simulate the ground vibration and get the peak particle velocity. Based on equivalent theory, the stress data obtained in this near-field boundary are used as loading condition to simulate the elastic stress wave propagation.

2 Simulation of near-field

2.1 Finite element and material model

Fig. 2 shows the geometry and the local enlarged finite element model. The radius and depth of the cylinder are 3 m and 16 m respectively. Three-dimension mesh of the model is produced using ANSYS. Due to geometrical symmetry an axisymmetric computational model is constructed. The meshes of explosive, air, water and soil are modeled as Eulerian meshes and the mesh of rock is modeled as Lagrangian mesh. The materials of explosive, air, water and soil are specified as multi material. The node transitional displacement normal to the symmetry planes is constrained, the upper plane of z is free surface, and others are dealt with non-reflective boundary. The model is divided into mesh using different step means, including 76 284 nodes and 67 080 elements.

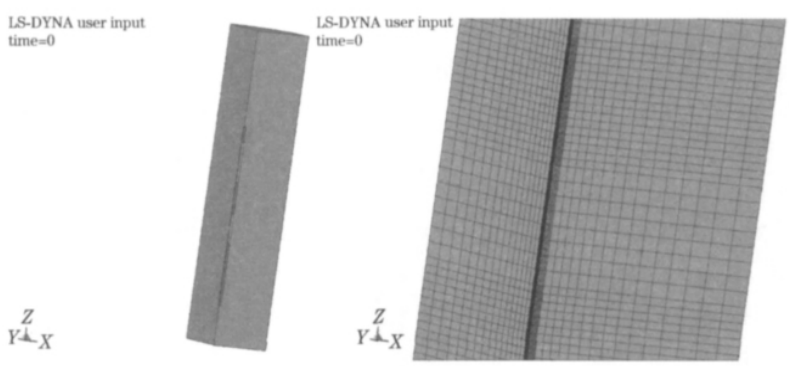

Fig. 2 Geometry of the model and finite element mesh of local enlarged

One of the most widely used EOS for modeling explosive materials is by Jones, Wilkins, and Lee known as the JWL EOS [6]. The following equation provides the basic form of the JWL EOS, which defines pressure (P) as a function of internal energy per initial volume (E) and the current relative volume (V).

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)\exp(-R_1 V) + B\left(1 - \frac{\omega}{R_2 V}\right)\exp(-R_2 V) + \frac{\omega E}{V},$$

where A, B, R_1, R_2, ω are JWL parameters.

Null material model has been adopted by LS-DYNA to model the fluid-like materials. In this work, air and water was modeled as a null hydrodynamic material. This model allows consider equation of state to avoid deviatoric stress calculations. The Gruneisen EOS and linear polynomial EOS are used for the water and air material respectively. An elastoplastic type rock is modeled, with sand being regarded as a part of rock to simplify the simulation. The maximum principal stresses failure criteria is added to rock material by using * MAT_ADD_EROSION. The material properties and parameters of EOS[7] are listed in Tab. 1 and Tab. 2.

Tab. 1 Material parameters of explosive

ρ/(g·cm^{-3})	V/(m·s^{-1})	C/GPa	A/GPa	B/GPa	R_1	R_2	ω	E_0/GPa
1.00	4 500	5.06	178	0.311	4.75	1.05	0.18	2.25

Tab. 2 Parameters of rock

ρ/(g·cm^{-3})	E/GPa	ν	σ_b/GPa	σ_{bc}/GPa
2.89	55.8	0.21	0.004 8	0.126

2.2 Results and discussion

Fig. 3 shows curves of pressure in different locations in rock at the condition of air, water and sand intervals. At a distance of $1R$ (R is the radius of the explosive charge) from the borehole, the pressure peak is 1.914 GPa, 2.016 GPa and 2.245 GPa, at a distance of $5R$, the pressure peak is 138 MPa, 140 MPa and 144 MPa, while at a distance of $15R$, the pressure peak is 110 MPa, 100 MPa, and 120 MPa. The peak value of stress wave reduces rapidly near the borehole, while slowly far from the borehole. As shown in these

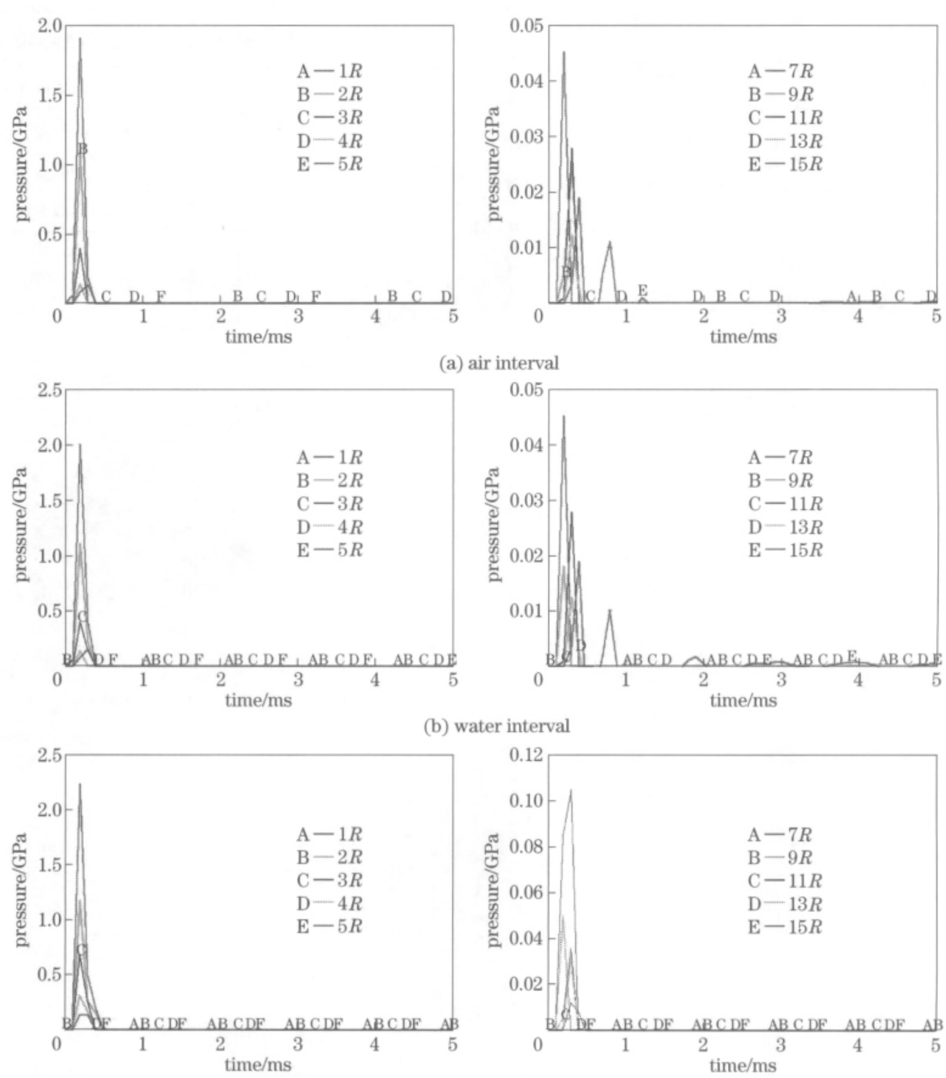

Fig. 3 Pressure vs. time

curves, the propagation of pressure wave in sand decked charge is similar with that in the air and water decked charge, while the value of pressure wave is bigger. This might be a reason of large volume of rock breakage in sand decked charge.

The measure of pressure around a borehole is usually difficult because of the extremely high pressure and temperature generated by detonation gas. Thus, empirical formulas are useful to estimate the magnitude of pressure and the rate of pressure decay. According to Hino [8], based on a dimensionless scaling approach, this empirical equation can be expressed as: $P = P_0(R'/R)^{-\alpha}$, where P is the pressure at distance R' from the centre of a borehole, P_0 is the maximum pressure at the borehole wall, R is the borehole radius, and α is the pressure decay. Tab. 3 summarizes the pressure value obtained from numerical simulation. The respective fitting equation is given in Tab. 4. The α values are 2.06, 2.05 and 1.93 for air, water and sand intervals. The little attenuation of sand interval will result in the following large ground vibration.

Tab. 3 Pressure value of different distance ratios (R'/R)

R'/R	P/GPa		
	air	water	sand
1	1.914	2.016	2.245
2	1.084	1.118	1.176
3	0.400	0.400	0.684
4	0.141	0.142	0.311
5	0.138	0.160	0.144
7	0.045	0.045	0.105
9	0.028	0.028	0.050
11	0.026	0.025	0.036
13	0.012	0.013	0.032
15	0.010	0.011	0.012

Tab. 4 Fitting equations for different intervals

interval	fitting equation
air	$P = 2.94(R'/R)^{-2.06}$
water	$P = 3.02(R'/R)^{-2.05}$
sand	$P = 3.68(R'/R)^{-1.93}$

3 Simulation of far-field

3.1 Model of finite element

The finite element is shown in Fig. 4. The rock model has a radius of 103 m and a depth of 16 m. One fourth of the rock is analyzed assuming symmetry on the plane XOZ and YOZ. The upper plane of z coordinate is free face and other faces are set to non-reflective boundary. The total number of elements used in the model is 37 638. The elastic model is used with the parameters shown in Tab. 1.

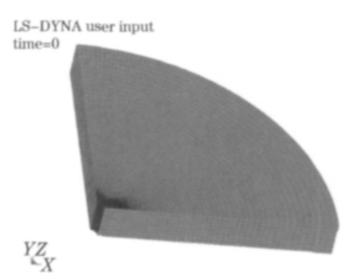

Fig. 4 Finite element meshes

3.2 Results and discussions

Figs. 5 – 7 show the measured and predicted

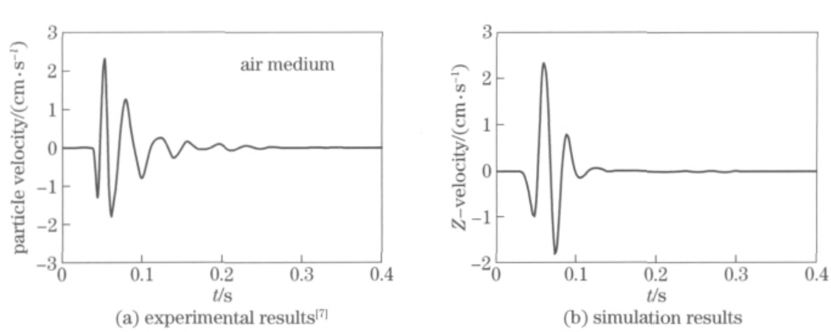

Fig. 5 Measured and predicted vertical vibration waveform at 40 m (air medium)

vertical vibration waveforms at 40 m in different decked charges. The results of calculation are in good agreement with the monitoring results. The measured and predicted PPV values are listed in Tab. 5. For air, water and sand interval, the measured values are 2.21, 2.45 and 2.48, while the predicted values are 2.35, 2.49 and 2.59. The predicted values are higher than the measured values. These results show that, the vibration effect of sand decked charge is a little larger than that of air and water decked charge, but the difference is not obvious.

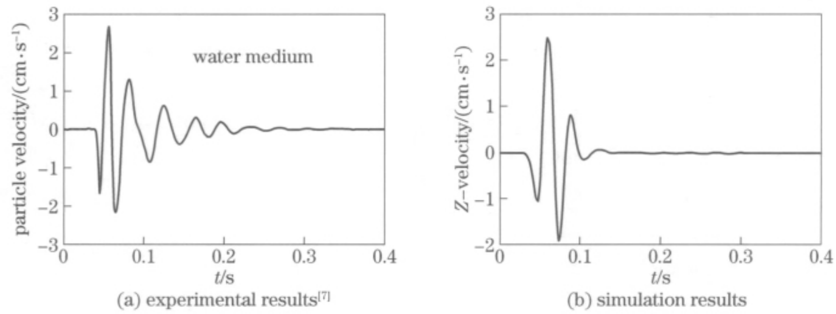

Fig. 6 Measured and predicted vertical vibration waveform at 40 m (water medium)

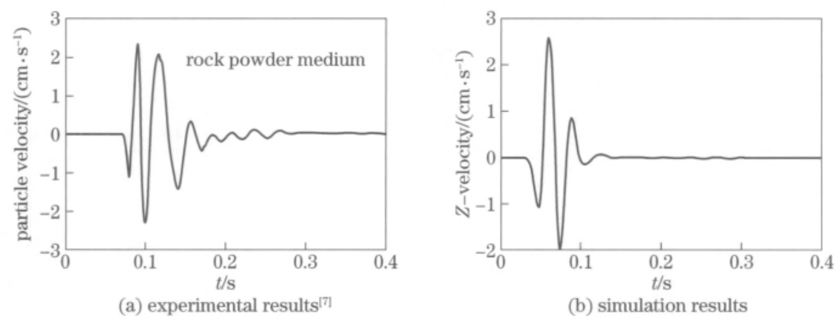

Fig. 7 Measured and predicted vertical vibration waveform at 40 m (rock powder medium)

Tab. 5 Measured and predicted value of PPV

interval	PPV/($cm \cdot s^{-1}$)	
	measured	predicted
air	2.21	2.35
water	2.45	2.49
sand	2.48	2.59

4 Conclusion

To perform numerical studies on the fracture and blasting vibration of rock, 3D ALE and Lagrangian approach are applied in two stages respectively. The results show the similar characteristics in the propagation of stress wave and the formation of fracture zone. However, breakage in the sand decked charge is severer than the breakage in the air and water decked charge, which agreed with the experiment observations. Attenuation index of dynamic pressure is 2.06, 2.05 and 1.93 for air, water and sand intervals. The small attenuation of sand interval results in the following large ground vibration. From monitoring data, the predicted vertical vibration waveform and PPV are in good agreement with the monitoring results. The vibration effect of sand decked charge is the strongest, while that of air decked charge is the weakest. The results demonstrate that the air and water decked charges can improve the effect of rock fracture in near-field and reduce vibration in far-field.

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