The Analysis of Blasting Seismic Wave Passing Through Cavity Based on SPH-FEM Coupling Method

Jianmin Zhou, Xuguang Wang, Huaming An, Mingsheng Zhao, Min Gong

Abstract—**Based on the secondary development of LS-DYNA, smoothed particle hydrodynamics(SPH) method is implemented into the blasting vibration method. A method of SPH used in the near zone and FEM used in the far zone is proposed. Dynamic effect of deep hole bench blasting is simulated with this method based on the Specific engineering example. The results show that SPH-FEM method could simulate the large deformation in the near zone. The comparison between blasting vibration monitoring and numerical results demonstrate that SPH-FEM method could forecast the blasting vibration and dynamic response in far zone. The mode is then used to assess the blasting seismic wave passing through the cavity adjacent to upper bench blasting. The results show that the peak particle velocity of measuring points above the mined-out area have presented the obvious amplification phenomenon, owing to wave reflection from the cavity which is about 5 m underneath the ground surface.**

Index Terms—**numerical simulation, blasting vibration, SPH-FEM coupling, dynamic response, cavity**

I. Introduction

BLASTING is an important method widely used in the tunnel excavation and mining industries. With the increasing need of the construction, the research on the predicting the blasting effect has become necessary[1], [2], [3]. The blasting vibration is one of the hazards in the process of the blasting. So far, many researchers at home and abroad have analyzed the effect of various blast design parameters and the properties of rock mass on the blasting vibration with field experiments and numerical simulations[4], [5], [6]. However, the properties of rock mass rock are complex materials, which lead to the investigation of rock blasting process hard and the field experiments expensive and time-consuming. With the development of computer technology, numerical methods have become an effective way to predict the rock blasting process[7], [8].

The common numerical simulation methods used to predict the rock blasting process are mesh-based methods. S. Mohammadi[9] used Finite Element Method to analyze the explosion in fractured solid media. Ning[10] used the Discontinuous Deformation Analysis to model the rock blasting considering explosion gas penetration. Vyazmensky[11] used the finite element modeling/discrete element modeling (FEM/DEM) to analyze the block caving-induced instability in a large open pit slope. Saiang David[12] analyzed the blast-induced damage zone by continuum and coupled continuum–discontinuum methods. However, the above methods have their disadvantages. Continuum-based methods often fail to simulate blasting fragmentation and large deformation in the near zone in the process of blasting while discontinuous-based methods often fail to obtain the parameters of the rock joints, such as spatial distribution and mechanical properties. The Smoothed Particle Hydrodynamics (SPH) has the ability to simulate the large deformation in the blasting near zone and can forecast the blasting vibration and dynamic response in far zone[13], [14], [15].

SPH method was originally proposed by Lucy and Gingold and Monaghan[16], [17]. Instead of finite difference method and finite element method, SPH method can build the model with the ‘‘particles’’, which interact with each other through an interpolation function. Because of the characteristic of Lagrangian and meshfree, it is well suited to analyze large deformation in the blasting near zone. However, the SPH method requires the uniformly sized particles in the blasting region. Besides, it’s impossible to simulate the entire model with the SPH particles which need a large calculation time. Thus, the SPH-FEM coupling method is proposed which combines the FEM meshes and SPH particles, to combine the advantages of each other.

In the present research, a method of SPH used in the near zone and FEM used in the far zone was realized. Dynamic effect of deep hole bench blasting was simulated by this method based on the specific engineering example. The mode is then used to assess the blasting seismic wave passing through the cavity adjacent to upper bench blasting. Site monitoring and numerical simulation were compared to verify the feasibility and accuracy of this technology.

This work is supported by National Natural Science Foundation of China.
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(Advance online publication: 1 February 2019)

II. The Coupling Method of SPH-FEM

A. The SPH method and basic theory

The SPH method is a mesh-free technique which initially proposed by Lucy and Gingold in the field of astrophysics in early 1977. The core of the SPH method is a kind of interpolation. In this method, the state of a system is represented by arbitrarily distributed particles, which carry all the simulation information including elastic modulus, velocity and mass. Based on the concept of kernel and particle approximation[18], the conservation equations of mass, momentum and energy for the numerical simulation of blasting are given as follows.

The conservation equation of mass:

$$\dot{\rho} = \rho_j \sum_{j=1}^{N} \frac{m_j}{\rho_j} \left(v_i - v_j\right) \bullet \tilde{\nabla} \tilde{W}_{ij} \quad (1)$$

The conservation equation of momentum:

$$\dot{v_i} = \rho_j \sum_{j=1}^{N} \frac{m_j}{\rho_j} \left(\frac{\sigma_i}{\rho_i^2} - \frac{\sigma_j}{\rho_j^2} \right) \bullet \tilde{\nabla} \tilde{W}_{ij} \quad (2)$$

The conservation equation of energy:

$$\dot{e}_i = \frac{\sigma_i}{\rho_i^2} \sum_{j=1}^{N} m_i \left(v_i - v_j\right) \bullet \tilde{\nabla} \tilde{W}_{ij} \quad (3)$$

B. The realization of SPH-FEM coupling method

SPH method can deal with large deformation under the Lagrangian method; the material can meet the need of fracture calculation under high loading rate. Therefore the SPH method is adopted in the blasting near zone, and the FEM method is adopted in the blasting far zone, to establish an applicable SPH-FEM coupled calculation method to describe the blasting process. The core of this method is the applicable to introduce the SPH particles and FEM model in a unit at the same time. The establishments of the SPH particles have two methods. One is established in LS-prepost directly which is fit in the model of rule; another kind of method is based on the ANSYS module to set up the complex geometrical shape numerical model, and using FORTRAN programming converts it to be the format which Ls-dyna can read. This article uses the first method. The calculation of coupling and settings of contact were considered after the model is successfully established, make blasting model import to SPH-coupled FEM algorithm, thus realizing the SPH-FEM coupling calculation.

C. Coupling contact

The problem how to pass the information such as stress, strain from the row of SPH particles which closes to the finite element mesh to FEM smoothly is the key of SPH and FEM coupling method. The more effective way is to make the SPH particles and the finite element mesh bonding together through contact settings, the information of motion equation will be passed from the bonded particles to finite element mesh. SPH and FEM interface coupling schematic diagram is shown in figure 1. The process of calculation will be realized using the *CONTACT_TIED_NODES_TO_SURFACE in the LS-DYNA. The parameters of penalty function, such as exposure settings can be choose for trial which based on the advice in LSTC specification range. By comparing the correction of the stress between SPH particles and unit, obtain the proper contact parameters.

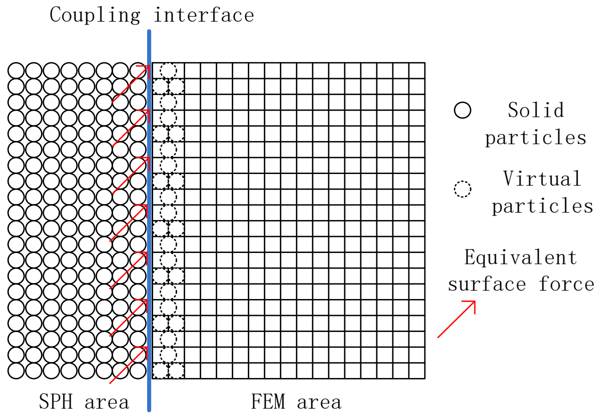


Fig. 1. The schematic diagram of SPH and FEM interface coupling

III. Engineering Verification of SPH-FEM Coupling Algorithm

In order to verify the accuracy of simulation in the process of blasting in near and far zone based on the SPH-FEM coupled analysis method, numerical simulation was carried out with the test of deep hole bench blasting which based on the engineering background of a certain open-pit mine blasting in Guizhou. By comparing the results of monitoring data with the numerical simulation, validate the feasibility of SPH-FEM coupling algorithm.

A. Calculation Model and material parameter

A limestone mine is a hillside open-pit mine in Guizhou province. The rock mass of the open-pit mine contain gray limestone, the geological structure of the mining area is complex, and the joint fracture is relatively developed. Larger scales of mined-out areas exist in Guizhou open-pit mine based on the results of geological radar detection. According to the existence of the mined-out areas in the mine, deep hole blasting construction scheme is proposed. The parameters of blasting are that borehole diameter is 160mm, bench height is 12m, borehole depth is 13m, ultra-depth is 1m, spacing is 5m, row distance is 4m, stemming is 4m. The cavity is about 5 m underneath the ground surface, the cavity height is 10m, and length is 10m.

MAT_PLASTIC_KINEMATIC was used to simulate rock mass[19], the parameters of rock mass are listed in Table I.

TABLE I The Parameters of Rock Mass

ρ/ kg·m⁻³	E /GPa	μ	δ_s /MPa	E_t /GPa
2670	78.36	0.27	106.8	1.48

Where ρ_1 is rock mass density, kg·m^{-3}, E is elastic modulus, GPa, μ is Poisson ratio, δ_s is yield stress, MPa, and E_t is tangent modulus, GPa.

The JWL equation of state was used to simulate the pressure generated by the expansion of the detonation product of the explosive[20].

Where A, B, w, R_1, R_2 are the material parameters, and they are constants when the explosive type is chosen. P is detonation pressure, E_0 is the specific volume inner energy of the explosive, V is the relative volume of explosive. The parameters of JWL equation and explosive are shown in Table II.

$$p = A\left(1-\frac{w}{R_1V}\right)e^{-R_1V} + B\left(1-\frac{w}{R_2V}\right)e^{-R_2V} + \frac{wE_0}{V} \quad (4)$$

TABLE II PARAMETERS OF EXPLOSIVE MATERIALS AND JWL EQUATION

ρ_2 /kg·m^{-3}	D /m·s^{-1}	A/GPa	B/GPa	R_1	R_2	w	E0/GPa
1150	4500	214.4	0.182	4.2	0.9	0.15	4.192

MAT-NULL and EOS-LINEAR-POLYNOMIAL were used to simulate cavity:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (5)$$

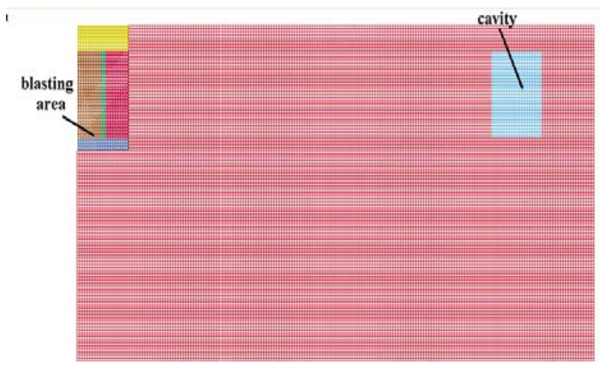
Where $C_0 \sim C_6$ are constants, E is the ratio of the internal energy and the initial volume. The parameters of cavity are shown in Table III.

TABLE III PARAMETERS OF MINED-OUT AREAS AND POLYNOMIAL EQUATION

C_0	C_1	C_2	C_3	C_4	C_5	C_6	E
0	0	0	0	0.4	0.4	0	2.5E+5

The SPH-FEM model of deep hole bench blasting with cavity are shown in figure 2. The explosive and the rock mass which are 2m away from the explosive are modeled with SPH particles, other parts are modeled with the conventional FEM modeling method. The whole SPH particle number is 5600, finite element mesh is 78400.

(a) The simulation mode



(b) The mesh of SPH-FEM model

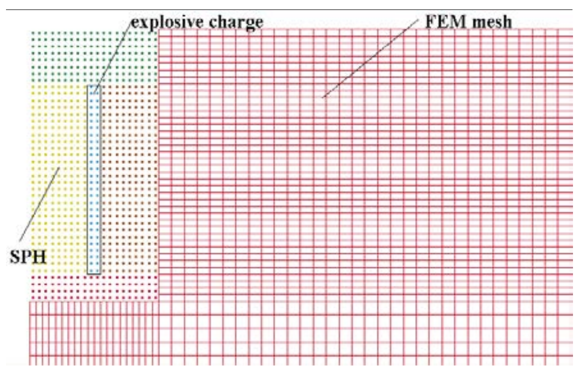


Fig. 2. The SPH-FEM model of deep hole bench blasting with cavity

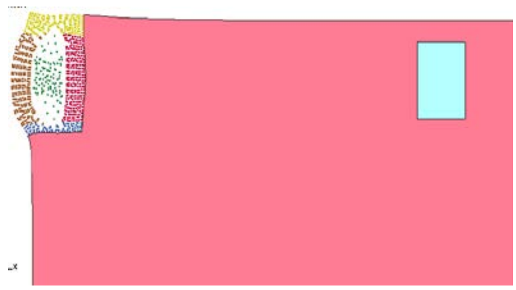
B. Simulation results

The deformations of blasting near zone based on SPH-FEM coupling method are showed in figure 3.

(a)0.1us

(b) 10.5us

(c)136.9us



(d)364.5us

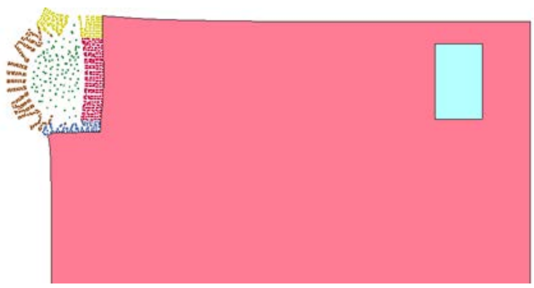


Fig .3. The deformation of near zone under the deep hole bench blasting

The results of figure 3 showed that after the initiation of explosive, the explosion cavity began to swell, the rock near the side of free face began to move outward, the outermost layer of left free face and the stemming segment inclined to obvious cracking. With the explosion cavity continues to expand, the crack continue to expansion, ultimately the rock near the free face and the stemming segment were thrown in the form of a block of rock mass. Meanwhile, the distribution of different density crack was found in the reserved rock mass. The deformation of the rock mass and the actual casting process in the blasting near zone described in figure 3, indicated that the SPH- FEM coupling analysis is validity to simulate the deformation of the rock mass and the blasting process in near zone under the deep hole bench blasting.

In order to check whether the success of SPH coupling or not, using the continuity of the stress nephogram to compare the stress of the SPH particles and FEM meshes. The SPH-FEM stress distribution nephogram during blasting process were showed in figure 4.

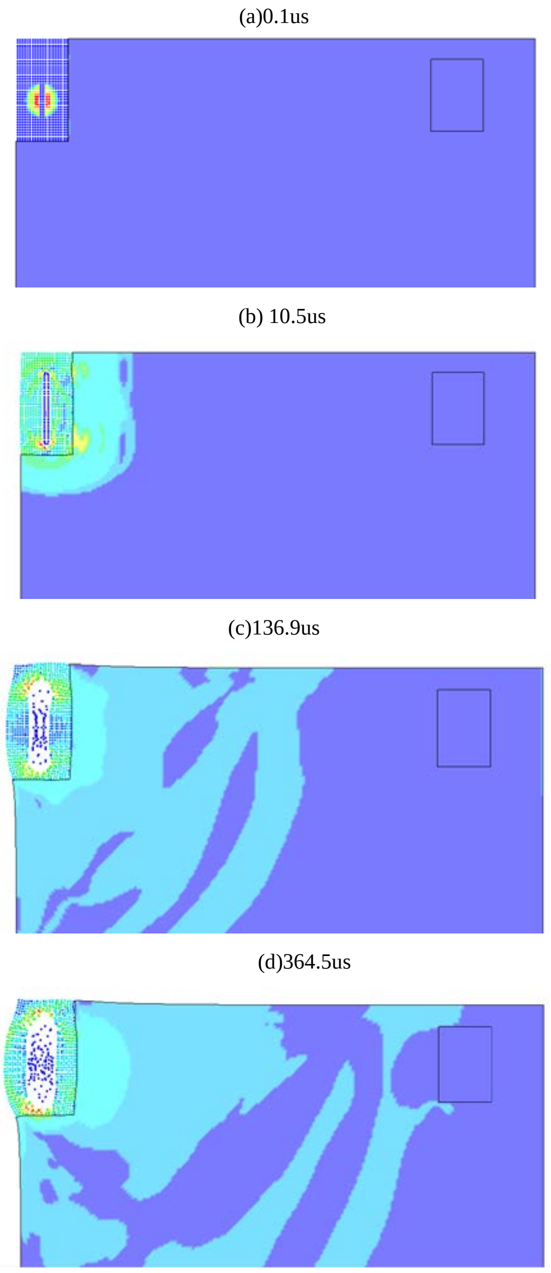


Fig. 4. The SPH–FEM stress distribution nephogram during blasting process

The results of figure 4 showed that the tensile stress was obviously appeared in the rock mass near the side of the free face, the pressure near the blast hole tend to transmit continuously from inside to outside , there was not breakpoints in the transition between the SPH particles and FEM meshes. Figure 5 shows the comparison of the pressure curve between the adjacent SPH particles and FEM meshes.

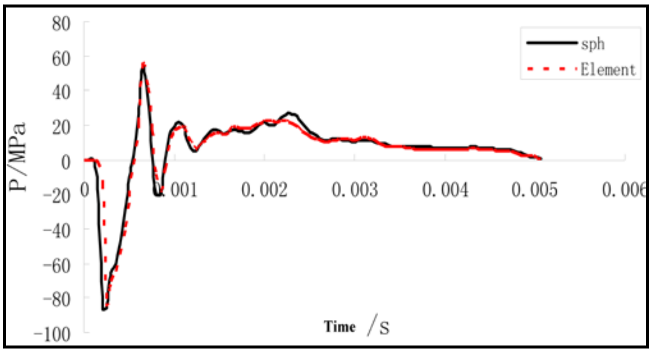


Fig. 5. Comparison of the pressure curve between the adjacent SPH particles and FEM meshes

The results of figure 5 showed that pressure curve between the adjacent SPH particles and FEM meshes were basically matched, the pressure peak of the FEM was slightly smaller than SPH particles. Meanwhile, the pressure fluctuation time was almost overlapping. Because of the calculation method of SPH particles, the obvious oscillation of the pressure curve appeared compare to FEM meshes. In general, the calculation of coupling setting can ensure that the stress, deformation and other information of the SPH particles in the blast near zone can be successfully passed to FEM unit, which confirmed the validity of the SPH-FEM coupling method.

C. The engineering validation

The blasting vibration was tested by TC-4850 vibration tester with three standard velocity sensors to obtain the peak particle velocity of blasting vibration. The testing point 7 was set directly above the centre of the cavity. Alone with the propagation of the blasting seismic wave, testing point 1 to 6 were set left side of the cavity, and testing point 8 to 10 were set on the different sides of the cavity, respectively. All the points were at the same vertical section and on a straight line towards the blasting area center. The layout of testing points is shown in Fig.6.

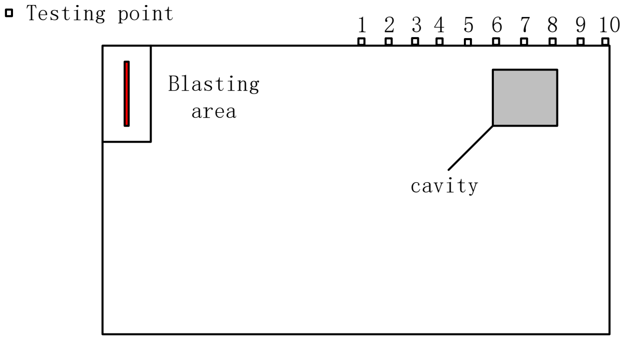


Fig. 6. The layout of testing points

According to distribution of blasting monitoring sites, the comparison between the numerical results and the field test results were shown in Table IV.

TABLE IV THE RESULTS OF BLASTING VIBRATION

Test points	Distance /m	Charge /kg	PPV of horizontal/cm/s		error/%	PPV of vertical/cm/s		error/%
			Testing results	Numerical results		Testing results	Numerical results	
1	35	124	10.72	11.83	10.35	9.86	10.76	9.13
2	40	124	8.65	9.46	9.36	8.12	9.24	13.79
3	45	124	7.08	8.12	14.69	6.54	7.18	9.79
4	50	124	5.89	6.64	12.74	5.37	5.97	11.17
5	55	124	4.96	5.38	8.47	4.45	4.91	10.34
6	60	124	5.23	5.69	8.79	4.72	5.23	10.81
7	65	124	5.43	5.93	9.21	5.16	5.58	8.14
8	70	124	4.57	4.87	6.56	4.18	4.73	13.16
9	75	124	3.45	3.82	10.72	3.29	3.76	14.29
10	80	124	2.56	2.85	11.33	2.35	2.57	9.36

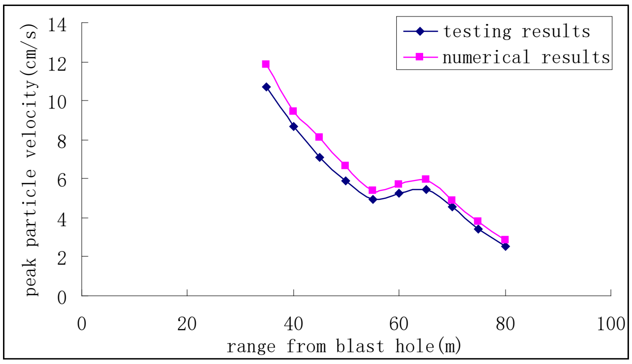


Fig. 7. PPV of horizontal changing with distance from blast hole

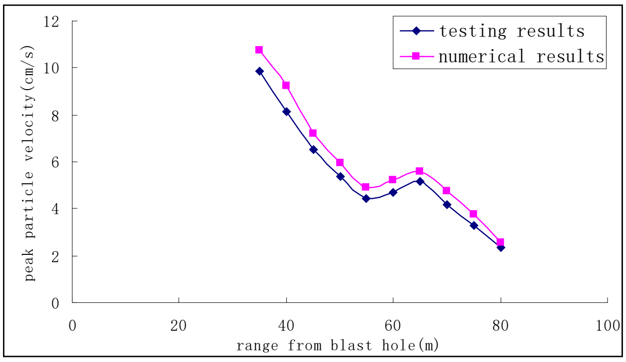


Fig. 8. PPV of vertical changing with distance from blast hole

According to the result of the above figure and table:

The PPV results of simulation and the field test has good consistency, the error is at around 10%.Therefore, it can be concluded that SPH-FEM method can predict and inverse the distribution characteristics of blasting vibration.

With the increased of distance from blast hole, the PPV of blasting vibration tend to attenuate obviously, which decreased from 10.72cm/s to 2.56cm/s under the horizontal direction. In addition, the PPV of vertical direction were smaller than the horizontal direction under the same distance from blast hole.

The propagation of blasting vibration has obvious changed due to the existence of mined-out area, namely the peak particle velocity of measuring points above the mined-out area have presented the obvious amplification phenomenon, owing to wave reflection from the cavity which is about 5 m underneath the ground surface.

IV. CONCLUSION

This paper has presented the numerical simulation of the complete blasting response using the SPH–FEM coupling method. The coupling method of the SPH particles and mesh unit are developed based on the explicit finite element code LS-DYNA, combing with the interface contact technology.

Dynamic effect of deep hole bench blasting is simulated with this method based on the Specific engineering example. The results show that SPH-FEM method could simulate the large deformation in the near zone. The comparison between blasting vibration monitoring and numerical results demonstrate that SPH-FEM method could forecast the blasting vibration and dynamic response in far zone.

The mode is then used to assess the blasting seismic wave passing through the cavity adjacent to upper bench blasting. The results show that the PPV of blasting vibration tend to attenuated obviously, which decreased from 10.72cm/s to 2.56cm/s under the horizontal direction with the increased of distance from blast hole. In addition, the PPV of vertical direction are smaller than the horizontal direction under the same distance from blast hole. The PPV results of the SPH-FEM coupling method and the results obtained from field test has good consistency, the error is at the range of 10%. Therefore, it can be concluded that SPH-FEM method can predict and inverse the distribution characteristics of blasting vibration.

The propagation of blasting vibration has obvious changes due to the existence of mined-out area, namely the peak particle velocity of measuring points above the mined-out area have presented the obvious amplification phenomenon, owing to wave reflection from the cavity which is about 5 m underneath the ground surface.

REFERENCES

[1] A. Fakhimi, M. Lanari, DEM-SPH simulation of rock blasting, Comput. Geotech. 55 (2) (2014) 158–164.

[2] Lu Wenbo, Yang Jianhua, Chen Ming, Zhou Chuangbing, An equivalent method for blasting vibration simulation, Simul. Model. Pract. Theory 19 (9) (2011) 2050–2062.

[3] Hu Y, Lu W, Chen M, et al. Numerical simulation of the complete rock blasting response by SPH–DAM–FEM approach, Simulation Modelling Practice & Theory. 56 (2014) 55-68.

[4] R.D. Ambrosini, B.M. Luccioni, R.F. Danesi, J.D. Riera, M.M. Rocha, Size of craters produced by explosive charges on or above the ground surface, Shock Waves 8 (1) (2002) 3–21.

[5] Fernando G. Bastante, Leandro Alejano, Jose Gonzalez-Cao, Predicting the extent of blast-induced damage in rock masses, Int. J. Rock Mech. Min. 56 (2) (2012) 44–53.

[6] Hu Yingguo, Lu Wenbo, Ming Chen, Peng. Yan, Comparison of blast-induced damage between presplit and smooth blasting of high rock slope, Rock Mech. Rock Eng. 46 (5) (2013) 1–14.

[7] G.W. Ma, X.M. An, Numerical simulation of blasting-induced rock fractures, Int. J. Rock Mech. Min. 45 (2) (2008) 966–975.

[8] W.B. Lu, Y.G. Hu, J.H. Yang, Spatial distribution of excavation induced damage zone of high rock slope, Int. J. Rock Mech. Min. 64 (5) (2013) 181–191.

[9] S. Mohammadi, A. Pooladi, Non-uniform isentropic gas flow analysis of explosion in fractured solid media, Finite Elem. Anal. Des. 43 (2) (2007) 478–493

[10] Y.J. Ning, J. Yang, G.W. Ma, P.W. Chen, Modelling rock blasting considering explosion gas penetration using discontinuous deformation analysis, Rock Mech. Rock Eng. 44 (1) (2011) 483–490.

[11] A. Vyazmensky, D. Stead, D. Elmo, A. Moss, Numerical analysis of block caving induced instability in large open pit slopes: a finite element/discrete element approach, Rock Mech. Rock Eng. 43 (1) (2009) 21–39.

[12] Saiang David, Stability analysis of the blast-induced damage zone by continuum and coupled continuum–discontinuum methods, Eng. Geol. 116 (2009) 1–11.

[13] T. Rabczuk, J. Eibl, Simulation of high velocity concrete fragmentation using SPH/MLSPH, Int. J. Rock Mech. Min. 56 (2003) 1421–1444.

[14] G.W. Ma, X.J. Wang, F. Ren, Numerical simulation of compressive failure of heterogeneous rock-like materials using SPH method, Int. J. Rock Mech. Min.48 (2011) 353–363.

[15] M.B. Liu, G.R. Liu, K.Y. Lam, Z. Zong, Smoothed particle hydrodynamics for numerical simulation of underwater explosion, Comput. Mech. 30 (2) (2003)106–118.

[16] L.B. Lucy, A numerical approach to the testing of the fission hypothesis, Astron. J. 82 (1977) 1013–1024.

[17] R.A. Gingold, J.J. Monaghan, Smoothed particle hydrodynamics-theory and application to non-spherical stars, Mon. Not. Roy. Astron. Soc. 181 (1977)375–389.

[18] Zhongqi Wang, Lu Yong, Chunhua Bai, Numerical simulation of explosion-induced soil liquefaction and its effect on surface structures, Finite Elem.Anal. Des. 47 (2011) 1079–1090.

[19] Zhou Jian-min, Wang Xu-guang, Zhao Ming-sheng, Tao Tie-jun, Wang Yang. The Effects of Rock Structure Planes on the Propagation of Blasting Seismic Wave—A Case Study, Electronic Journal of Geotechnical Engineering. 11 (7) (2016) 4587-4599.

[20] Zhou Jian-min, Wang Xu-guang, Gong Min, Zhao Ming-sheng, Tao Tie-jun. The Superimposed Effect Analysis on the Blasting Seismic WavePass Through Rock Structure Planes, Electronic Journal of Geotechnical Engineering. 23 (21) (2016) 7491-7501.