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Numerical investigation on fracturing of rock under blast using coupled finite element method and smoothed particle hydrodynamics

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Abstract. This paper aims to provide a coupled finite element method (FEM) and smoothed particle hydrodynamics (SPH) approach capable of reproducing the blast response in rock. In the proposed approach, SPH is used to simulate large deformation and fracture of rock at the near detonation zone, while the FEM is adopted to capture the far field response of the rock. The explosive is modelled explicitly using SPH. The numerical simulations are carried out using LS-DYNA. The interaction of the SPH particles and FEM elements was modelled by the node to surface contact, and for the interactions between explosive and rock SPH parts node to node penalty based contact was used. In the present study, the Johnson and Holmquist constitutive model is used for rock. Jones–Wilkins–Lee model is used for TNT explosive. It is found that the preliminary numerical simulation reproduces some of the well-known phenomena observed experimentally by other researchers. The numerical results indicate that the coupled SPH-FEM approach used in this work can be applied to simulate effectively both compressive and tensile damage of rock subjected to blast loading.

Introduction

Nowadays, drill and blast are still a common excavation technique for rock foundations and underground caverns in the fields of hydropower, transportation and mining because these techniques have good adaptability to different geological conditions [1]. In recent years, with the rapid development of explosion theory and computer technology, numerical simulation has become a promising approach to studying blast and wave propagation [1]. Researchers worldwide have been using different numerical methods to investigate the stress wave propagation in the rock mass. For example, Toraño et al. [2] and Saharan and Mitri [3], employed the finite element method (FEM), to predict blast waves from bench blasting or underground explosion, and evaluated and quantified some factors affecting the blasting vibration to simulate complex waves accurately enough in real blasts. Chen and Zhao [4] applied the discrete element method (DEM) for the study of blast wave propagation in jointed rock masses with the universal distinct element code (UDEC).

Smoothed particle hydrodynamics (SPH) is a mesh-free computational Lagrangian hydrodynamic particle method [5]. Although SPH was originally developed for astrophysics problems [6], it is widely used for solid mechanic problems in which large deformations and fragmentation occur. SPH is mathematically based on interpolation theory by utilising kernel approximation of a function, which is adequately smooth even for higher-order derivatives and provides stable and accurate results. Unlike conventional Lagrangian meshing, SPH is free from mesh tangling and hour glassing effects [5]. As such, SPH particles are used where large deformation or severe material failure occurs in near field domain and FEM meshes are used where intermediate or small deformation is expected in far field domains when a coupled SPH-FEM approach is used. Although SPH is more expensive in terms of computation, the coupled SPH–FEM approach reduces high computational demand. There are methods that allow the coupling interaction between SPH particles and FEM meshes [7]. This paper applies a coupled technique involving SPH and FEM for investigating the blast response of rock. The commercially available non-linear finite element software package LS-DYNA is used in this study. The SPH particles are used to model the explosive and the rock that experience large deformations, while the finite elements are used to model the rest of the rock. Then, based on the obtained results, the response of the rock subjected to blast loading is studied and finally some conclusions are drawn.

Numerical Simulation

The full 3D model of the block of rock with 6 m×6 m×4 m dimensions was used in this work. Fig.1 shows the schematic drawing of half of the simulated rock. In this simulation, a cylindrical bore-hole of 10 cm in diameter and 0.5 m in height was used for the explosive. The borehole was considered in the centre of rock, as shown in Fig. 1, and a cylindrical explosive was modelled using SPH particles. Near borehole rock domain of size of 2 m× 2 m× 2 m, as shown in Fig. 1, subjected to large deformation was modelled with SPH particles, while eight-node solid finite elements were used to model the rest of rock domain experiencing intermediate and small deformations. All SPH particles had approximately equal inter-particle distance of 5 cm. Element size of 5 cm×5 cm× 5 cm was used to model the rock in the FEM region. As reflection of shock waves at the far-field can affect the accuracy of the numerical simulation, non-reflecting boundary conditions (*BOUNDARY_NON_REFLECTING) are placed to allow the shock wave to be transmitted out the rock at the far-field infinite domain without reflection.

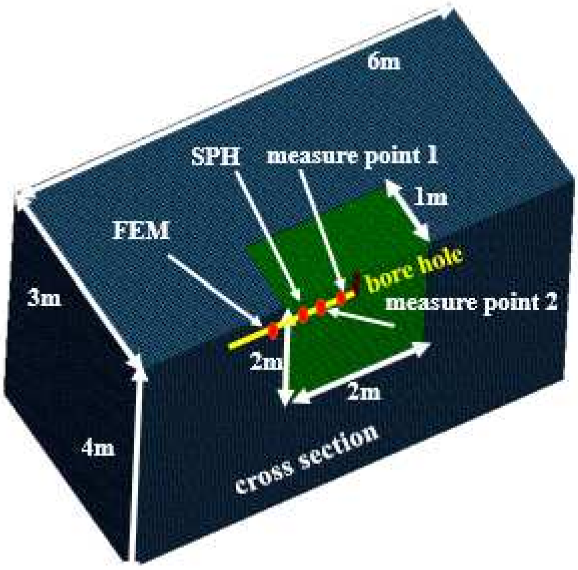

Fig. 1 Schematic drawing of half of the 3D coupled SPH-FEM model.

Material models and equation of state

The explosive was modelled by SPH particles with the Jones–Wilkins–Lee (JWL) Equation of State (EOS) [8]. The JWL EOS defines the pressure P as a function of the relative volume (or the expansion of the explosive) V, and initial energy per volume E in the detonation of explosives as:

$$P=A\,(1-\omega / R_1V)\, e^{-R_1V} + B\,(1-\omega / R_2V)\, e^{-R_2V} + \omega E / V. \tag{1}$$

In the above equation A, B, R_1, R_2 and ω are the empirically derived constants for the explosive. Table 1 shows the material parameters used for TNT (trinitrotoluene) explosive [8]. For the rock constitutive behaviour the Johnson-Holmquist (JH-2) model [1] was used. The model gives the intact and the totally fractured strengths, a polynomial equation of state, and a damage model that represents the material from an intact to a fractured state [1]. A full description of this material model and the model parameters used in our simulations can be found in [1].

Table 1 Material parameters for TNT explosive [8]

Parameters	P [g/cm^3]	v_D [m/s]	PCJ [GPa]	A [GPa]	B [GPa]	R_1	R_2	ω	V	E_0 [kJ/m^3]
TNT	1.630	6930	21	373.77	3.747	4.15	0.90	0.35	1	6.0e+06

Interactions between FEM/SPH and SPH/SPH domains

The contact interface between FEM elements and SPH particles is an essential part of a simulation using the coupling approach. The selection of contact types depend on the interaction phenomenon between the interfaces. For the proposed SPH-FEM coupling method, some preliminary simulations were carried out using *CONTACT_AUTOMATIC_NODES_TO_SURFACE. Although a penalty-based contact does not represent the real interface between SPH and FEM elements, we use this contact type in the rest of the simulations because the differences in pressure at the two points near the FEM and SPH elements are negligible as show in Fig. 2. This approach has also been used to successfully model dynamic behaviour of steel plate under blast load [9]. We will implement *CONTACT_TIED_NODES_ TO_SURFACE option [10] in future work. For the interactions between TNT and rock SPH parts node to node penalty based contact through the keyword DEFINE_SPH_TO_SPH_COUPLING and the interactions between SPH part and solid part, DEFINE_ADAPTIVE_SOLID_TO_SPH were used. When simulating two different materials with SPH particles, it is important to capture interaction effects accurately in order to have realistic simulations. Different interaction approaches can be combined together in one model to reach the best results [9].

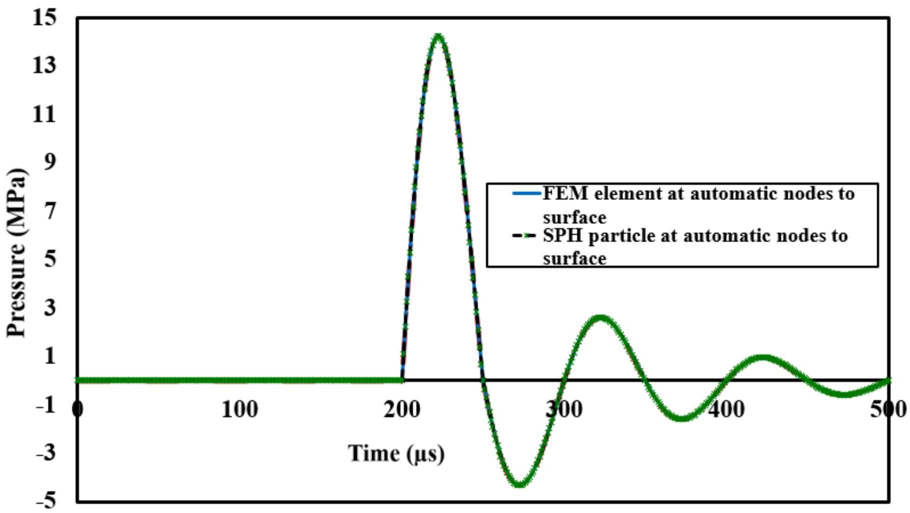

Fig. 2 Comparison of the pressure histories of the two neighboring points at the SPH/FEM interface.

Simulation results

Figure 3 shows the cross section of the effective plastic strain contour at 50 µs, 100 µs, 250 µs, 350 µs and 500 µs after detonation of explosive in the borehole. Effective plastic strain is used as an indicator of damage levels [11]. The zone between the explosive column and the free face are predicted to have the largest damage. This shows that damage pattern due to blasting load by the use of SPH-FEM coupling model can be modelled with our approach. As shown in Fig 3, a columnar damage zone was formed and the degree of damage decreases with the distance to the blast hole. The rock mass close to the blast hole was completely crushed and the damage scalar equals 1.0; then the shock wave changed into a stress wave and the damage degree decreased and ranged between 0.2 and 0.8.

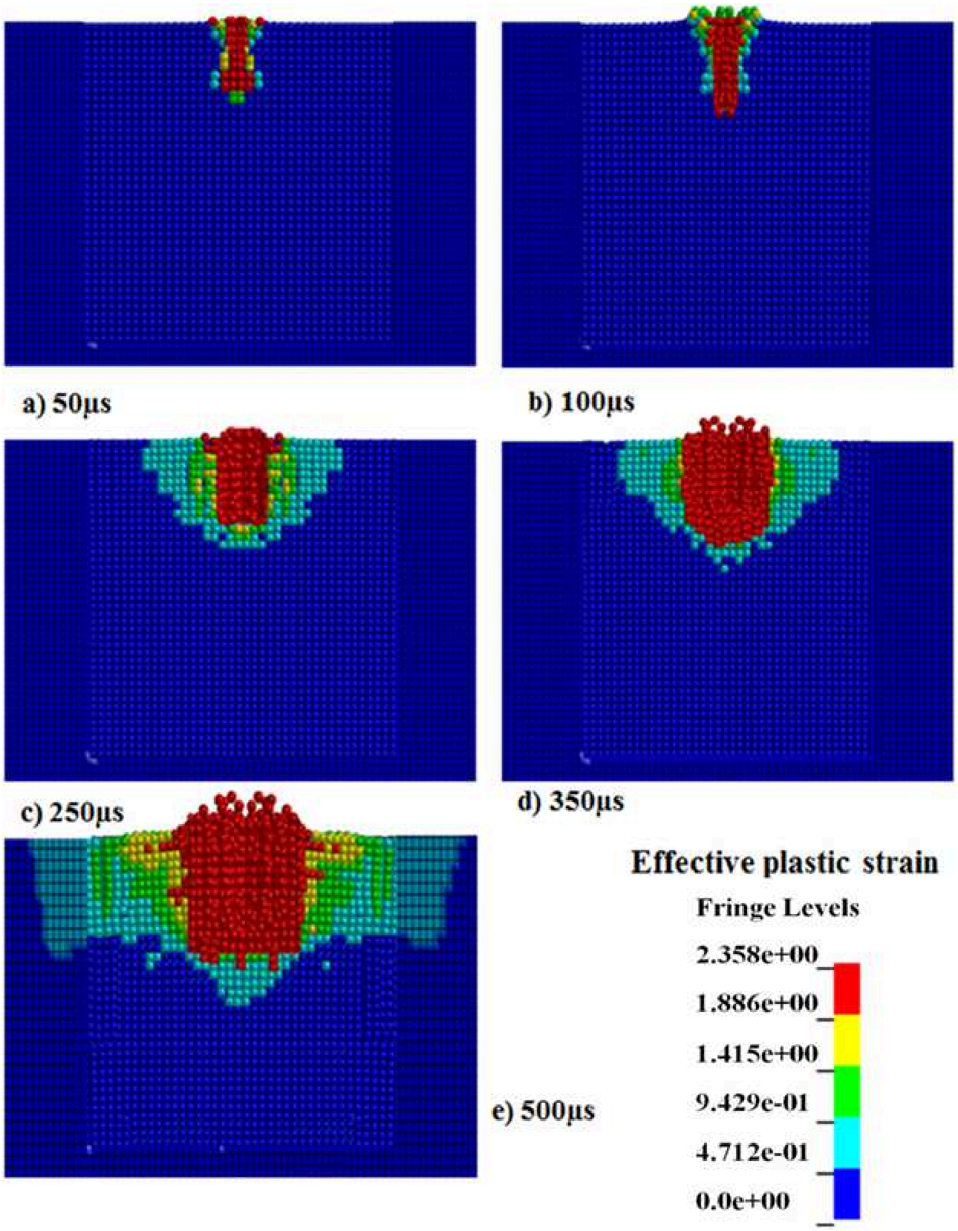

Fig. 3 Cross-section view of the effective plastic strain contour at time (a) 50μs, (b) 100μs, (c) 250μs, (d) 350μs and (e) 500μs.

Measure point 1 shown in Fig. 1, is near the borehole (40 cm from the centre) and in the crushed zone the damage parameter is equal to 1. The histories of the maximun and minimun principal stress at measure point 1 are shown in Fig. 4. These stresses are compressive during the whole simulation. The maximum difference between σ_1 and σ_3 is 441.2 MPa at the time of 98 μs; however, at 151 μs, the difference disappears and σ_1 and σ_3 are identical. Therefore, at the beginning, there is large difference between the maximum and minimum principal stresses (σ_1 and σ_3), resulting in non zero shear stress. The maximum shear stress τ_{max}= (σ_1 - σ_3)/2 is 220.6 MPa, which indicates that the particles at measure point 1 may be largely damaged or have failed based on reported values of dynamic shear strength (30-50 MPa) [12] for this material.. The effective plastic strain history of measure point 1 shown in Fig. 4 indicates that this measure point has been subjected to severe damaged and cannot further sustain any shear stress.

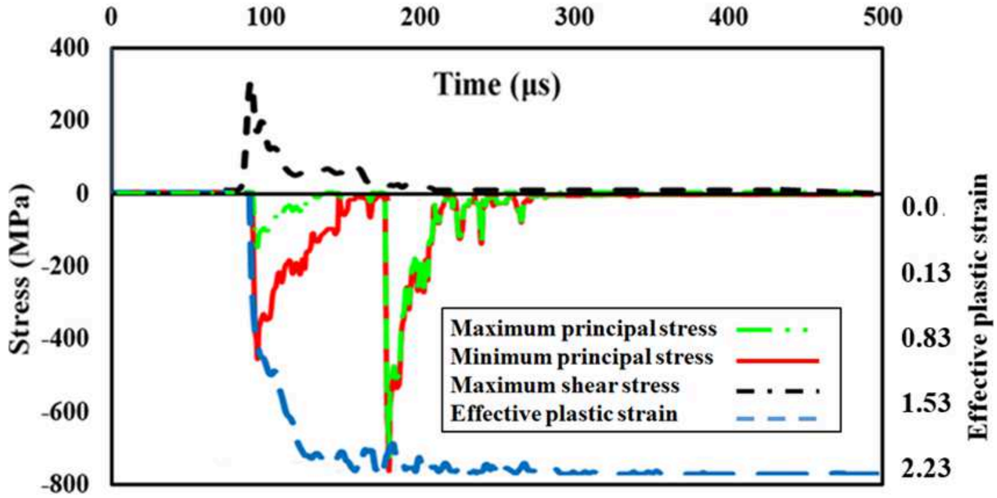

Fig. 4 Relationship of dynamic stresses versus time for the particles in crushed zone.

Measure point 2 shown in Fig. 1 (60 cm from the centre) is in the tensile damage zone. The minimum principle stress at measure point 2 shown in Fig. 5 is always compressive. The maximum principal stress is first compressive and then it changes to tensile and reaches the maximum value of 98.9 MPa at the time of 186 µs, which is larger than the rock dynamic tensile strength (10-30 MPa) [12]. This indicates that the particles in measure point 2 have failed, resulting in a radial crack passing through it. The effective plastic strain history in this point indicates that the severely damaged zone is in tensile.

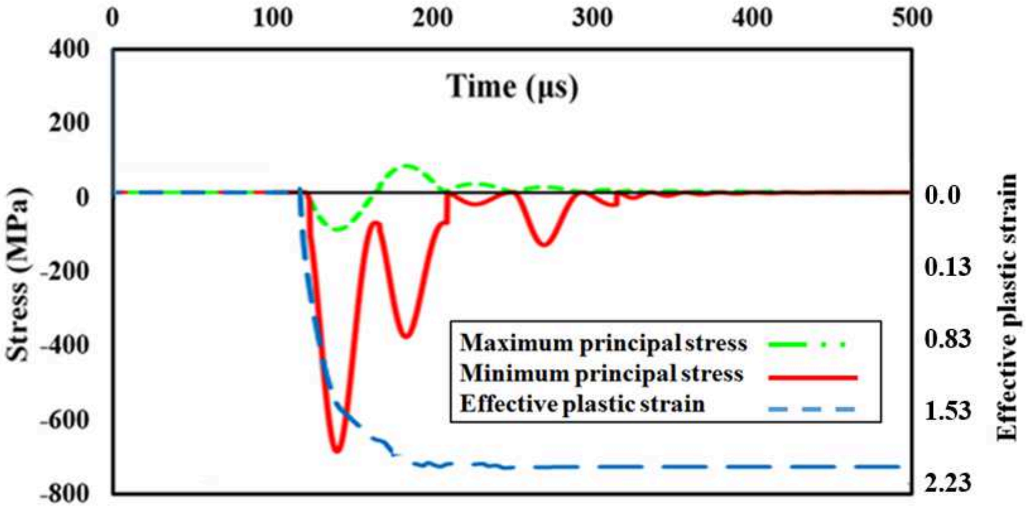

Fig. 5 Relationship of dynamic stresses versus time for the particles in fractured zone.

Discussions and conclusions

Smoothed Particle Hydrodynamics (SPH) method has been used in this paper to model blast of rock material in the proximity of an explosive charge. The preliminary results suggest that proposed coupled FEM-SPH approach could be used as a solution when FEM simulations are prone to large mesh distortion. It is found that our model is capable to capture some of the observed phenomena in rock blasting experiments. As a mesh-free method, SPH can be used to model both explosive and rock mass and the coupled SPH-FEM approach presented in this paper can be applied to treat the problem of blasting-induced crack propagation. The preliminary results show that shear stress (resulting from intense compressive stress) causes the crushed zone in the immediate vicinity of the borehole, and the maximum principal stress causes the radial cracks. This provides confidence in applying the developed techniques to treat the blast response of borehole blasting and the influence of important model and material parameters. It is concluded that our SPH-FEM approach may potentially lead to handling of large deformation problems with low computational cost, however, further numerical research has to be carried out to support the findings in this study.

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References

[1] M.M. Dehghan Banadaki, B. Mohanty, Numerical simulation of stress wave induced fractures in rock, Int. J. Impact Eng. 40-41 (2012) 16-25.

[2] J. Toraño, R. Rodríguez, I. Diego, J.M. Rivas, M.D. Casal, FEM models including randomness and its application to the blasting vibrations prediction, Comput. Geotech. 33 (2006) 15–28.

[3] M.R. Saharan, H.S. Mitri, Numerical procedure for dynamic simulation of discrete fractures due to blasting, Rock Mech. Rock Eng. 41 (2008) 641–670.

[4] S.G. Chen, J. Zhao, A study of UDEC modelling for blast wave propagation in jointed rock masses, Int. J. Rock Mech. Min. Sci. 35 (1998) 93–99.

[5] G.R. Liu, Y.T. Gu, An Introduction to mesh-free methods and their programming. Springer, Dordrecht, (2005) 479.

[6] Z. Wang, Y. Lu, H. Hao, K. Chong, A full coupled numerical analysis approach for buried structures subjected to subsurface blast, Comput. Struct. 83 (2005) 339–356.

[7] T. Rabczuk, S.P. Xiao, M. Sauer, Coupling of mesh-free methods with finite elements: basic concepts and test results, Commun. Numer. Methods Eng. 22 (2006) 1031–1065.

[8] B.M. Dobratz, P.C. Crawford. LLNL Explosives Handbook: Properties of Chemical Explosives and Explosive Simulants. University of California; Lawrence Livermore National Laboratory; Report UCRL-5299; Rev.2 (1985).

[9] LSTC, LS-DYNA keyword user's manual. California: Livermore Software Technology Corporation (2006).

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

[11] E.A. Flores-Johnson, O. Muránsky, C.J. Hamelin, P.J. Bendeich, L. Edwards, Numerical analysis of the effect of weld-induced residual stress and plastic damage on the ballistic performance of welded steel plate, Comput. Mater. Sci. 58 (2012) 131-139.

[12] J. Zhao, Applicability of Mohr–Coulomb and Hoek–Brown strength criteria to the dynamic strength of brittle rock, Int. J. Rock Mech. Min. Sci. 37 (2000) 1115–1121.