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WHEN CRACKS LOOK DIFFERENT

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Abstract. In this work, by means of numerical experiments based on Los Alamos National Laboratory's combined finite discrete element method (FDEM) software package MUNROU, it is demonstrated that fracture patterns do not only depend on the solid properties, but that the presence of a fluid medium plays a key role in driving both the dynamic fracture propagation and stress state in solid. The "dry" and "wet" fracture patterns obtained in this work look very different, thus emphasizing the critical importance of capturing all of the "first principle physics" involved in order to model all the phases of a given fracturing medium.

1 INTRODUCTION

Fracture mechanics has been an important topic since the pioneering work of its founders [1]-[4]. Interestingly enough, pioneering developments have been mostly motivated by considerations of design components not failing. It has long been recognized that cracking, fracturing, and fragmenting solids is at the core of many modern industrial processes, the naming of which would probably go over a few pages. For this reason, very early on, it was recognized that numerical methods of computational mechanics of discontinua provide a valuable set of tools that have the potential for addressing the problem with some degree of accuracy. First, discrete element methods were employed [5]-[14], [25]-[32] and later on the combined finite discrete element method (FDEM) was introduced [15]-[24]. The fracture patterns obtained using the combined finite discrete element method have independently been benchmarked and validated for a number of problems starting with rock, concrete, glass, and more recently anisotropic solids. Agreements between numerical and experimental results in terms of fracture patterns and residual strengths have exceeded the expectations of even the most enthusiastic development teams around the world.

Many industrial processes critically depend on cracking, fracture and fragmentation. Oil and gas exploration based on fracking is one of these processes. Fracking, in the U.S, is a an approach for exploiting oil and gas reserves to the extent it should be able to bolster the energy resources of the country for the next couple of centuries through the exploitation of its reserves alone. Nevertheless, the whole process is still poorly understood and often based on qualitative predictions similar to trial and error simply because the field does not possess an adequate quantitative predictive capability.

As the process is associated with some very serious environmental risks such as water pollution, this is not satisfactory and better predictive capabilities based on first principle physics and "state of the art" computational simulations are urgently needed to both better understand the processes involved and to provide better quantitative predictive capabilities that are able to optimize the exploration process, while at the same time providing a margin of safety against a major environmental disaster. A major environmental disaster associated with the process could set the exploration momentum back by a number of years and will possibly cost hundreds of billions in lost profits, compensation claims, higher oil and gas prices, etc. It is therefore of major importance that resources are put into related research and development.

At Los Alamos National Laboratory (LANL) a comprehensive simulation platform based on the combined continua-discontinua approach with an integrated fluid capability has been adopted in order to address the problem. The resulting platform is called the Hydrofrac Optimization Software Suite (HOSS). HOSS incorporates LANL's MUNROU software package which contains the next generation of FDEM solvers, an extensive material model library, grand scale parallelization, modern software design practices and proprietary fluid solvers, Figure 1. In this work, using HOSS-MUNROU, we will demonstrate the critical role fluid plays in fracture development.

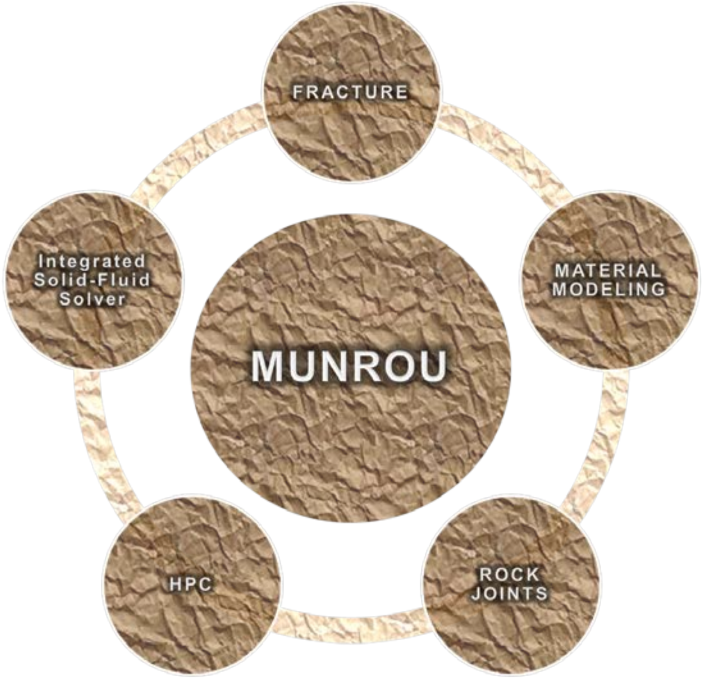

Figure 1: HOSS-MUNROU: FDEM software package.

2 COMPUTATION FRACTURE MECHANICS CHALLENGES

Fracture and fragmentation of brittle rock material has long been a challenging endeavor for the field of computational mechanics. For decades researchers have strived to achieve some semblance of fidelity as they have examined a myriad of industrial challenges from block caving, deep mining techniques, rock blasting, seismic waves, packing problems, rock crushing problems, etc. The pros and cons of whether to utilize a continuum approach versus a discontinuum technique in their analysis usually came to the blunt reality that discontinua approaches, although unique, were either limited in their material handling capability or were just too computationally expensive to utilize.

As a result, practitioners of the art moved mountains to develop continuum fracture techniques that could best describe the expected material damage. For example purposes, we display here a novel continuum fracture approach that was developed by LANL researchers, see Figure 2. For its purposes we would contend that few other continuum model approaches could capture the rate sensitivity and damage effects that this model is capable of achieving.

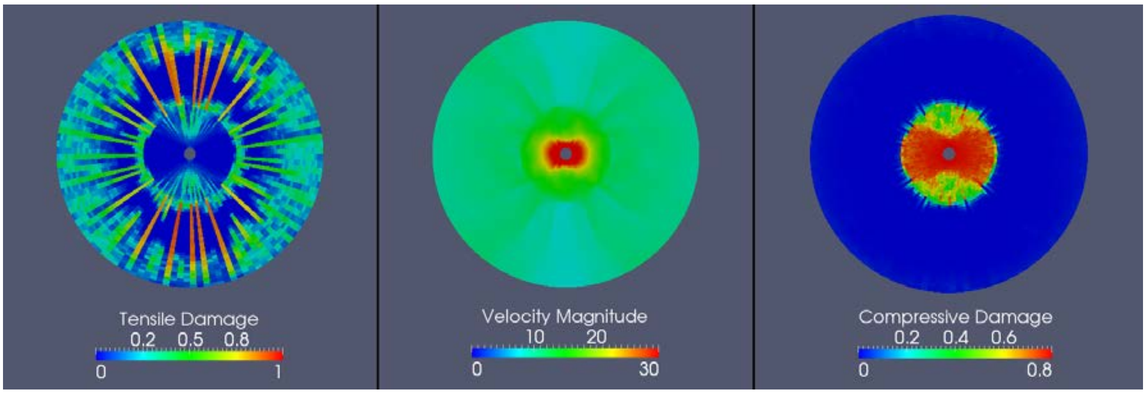

Figure 2: Example of a novel continuum fracture model with anisotropic stochastic strength behavior results. The evolution of the sample after 5.0 ms is shown. In this case the effect of the anisotropic nature of the material is apparent as noted by the elliptical shape of the wave front.

That stated, one must recognize that for this simple borehole example the prescribed continuum approach appears to have effectively captured the essential energy dissipation mechanisms as well as the mandated inertia effects. But, do objects break in this manner or in a manner as seen in Figure 3.

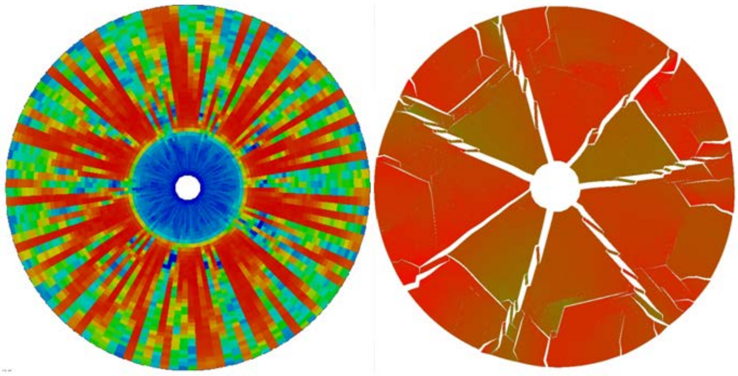

Figure 3: Example of continuum model fracture compared to FDEM fracture result.

Aesthetics aside, describing the well-known differences of the two approaches is beyond the scope of this paper. Rather, if discontinua approaches are to become a more mainstream technique it is imperative that practitioners are convinced that the selected software's approach is viable given its degree of accuracy on "tried and true" experimental results.

3 HOSS-MUNROU BENCHMARKING: COMBINED CONTINUUM DISCONTINUUM FRACTURE PATTERN

Within the past six months LANL researchers have conducted a full scale 3D analysis of a Split Hopkinson Pressure Bar experiment on granite material utilizing the FDEM capabilities in HOSS-MUNROU. Extensive details on this verification and validation exercise will be forthcoming in a soon to be published journal article. Here, rather than focus on the simulation's intricate details we want to focus on the comparison of some of HOSS-MUNROU's numerical results to the experimental results.

For this particular experiment, the sample's diameter and thickness for the numerical model were fixed at 50.8 mm and 25.4 mm respectively. The 3D mesh for the granite sample had an element size that ranged between 0.6 mm to 1.5 mm. As such, the total number of elements employed was around 90,000. The mesh for the incident and the transmission bars comprised of 6,600 elements each. The numerical experiment was run on a parallel computer, utilizing 208 processors. In Figure 4 the final fracture pattern obtained in the experiment and by 3D simulation are shown side by side. As can be seen, there is a remarkable resemblance in the fracture pattern obtained by the 3D HOSS-MUNROU simulation when compared to the final state of the real sample.

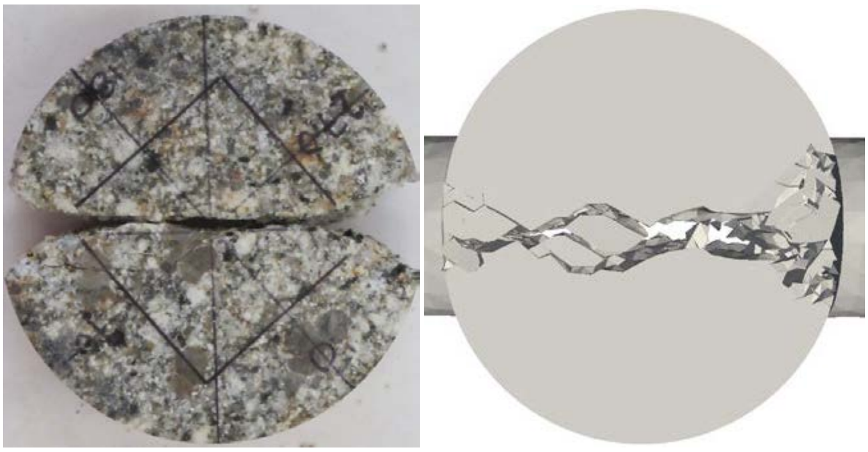

Figure 4: Split Hopkinson Pressure Bar virtual experiment. Comparison of sample condition with actual experiment.

When coupled with results for the equivalent tensile stress (Figure 5) the combined results give confidence in robustness and accuracy of the 3D FDEM capability in HOSS-MUNROU.

As noted earlier, confidence in experimental agreement is needed but not necessarily indicative that the software approach will be viable for industrial application spaces such as "fracking." One must be convinced that the approach can effectively replicate fracture and fragmentation processes as would be seen in field types of environments.

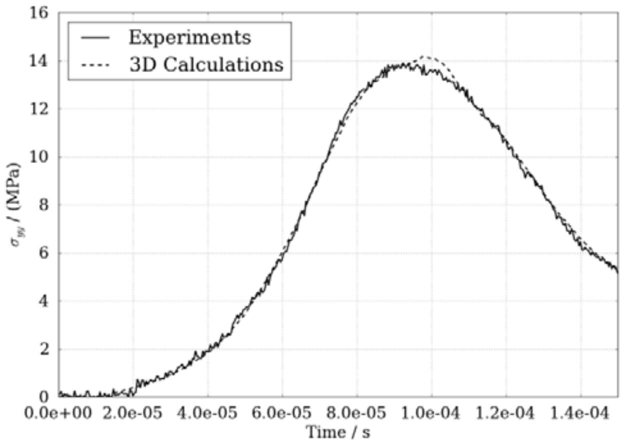

Figure 5: Split Hopkinson Pressure Bar virtual experiment results.

4 HOSS-MUNROU: FLUID DRIVEN ROCK DEFORMATION EFFECTS

One of the more challenging aspects of “fracking” in the field environment is known as wellbore stability. To investigate the fracturing phenomena associated with collapsing wellbores this study utilized a somewhat industry accepted model used for 2D analysis efforts, see Figure 6.

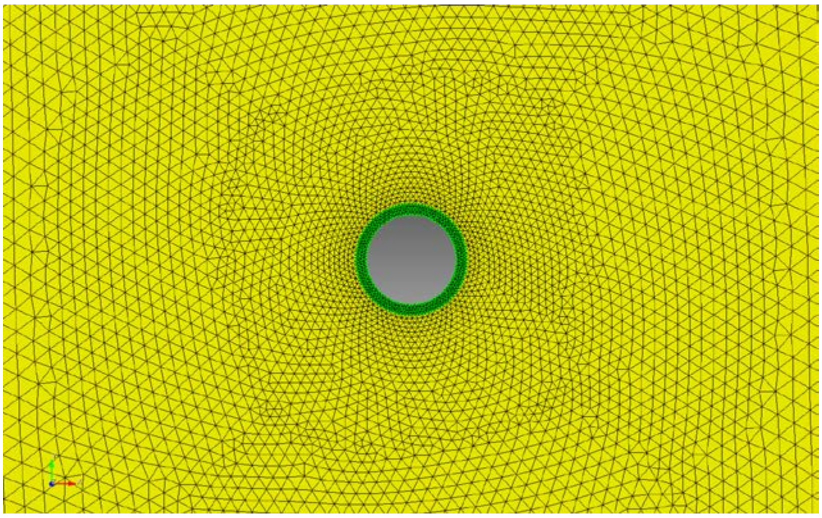

Figure 6: 2D borehole with cemented annulus.

The simulation was set-up with a inner concrete annulus surrounded by shale-like material. A pressure pulse of 60 MPa was driven outward against the interior concrete surface. For analysis purposes it was assumed horizontal and vertical stresses were equal. Four snapshots of the resultant dry rock fracture pattern are seen in Figure 7.

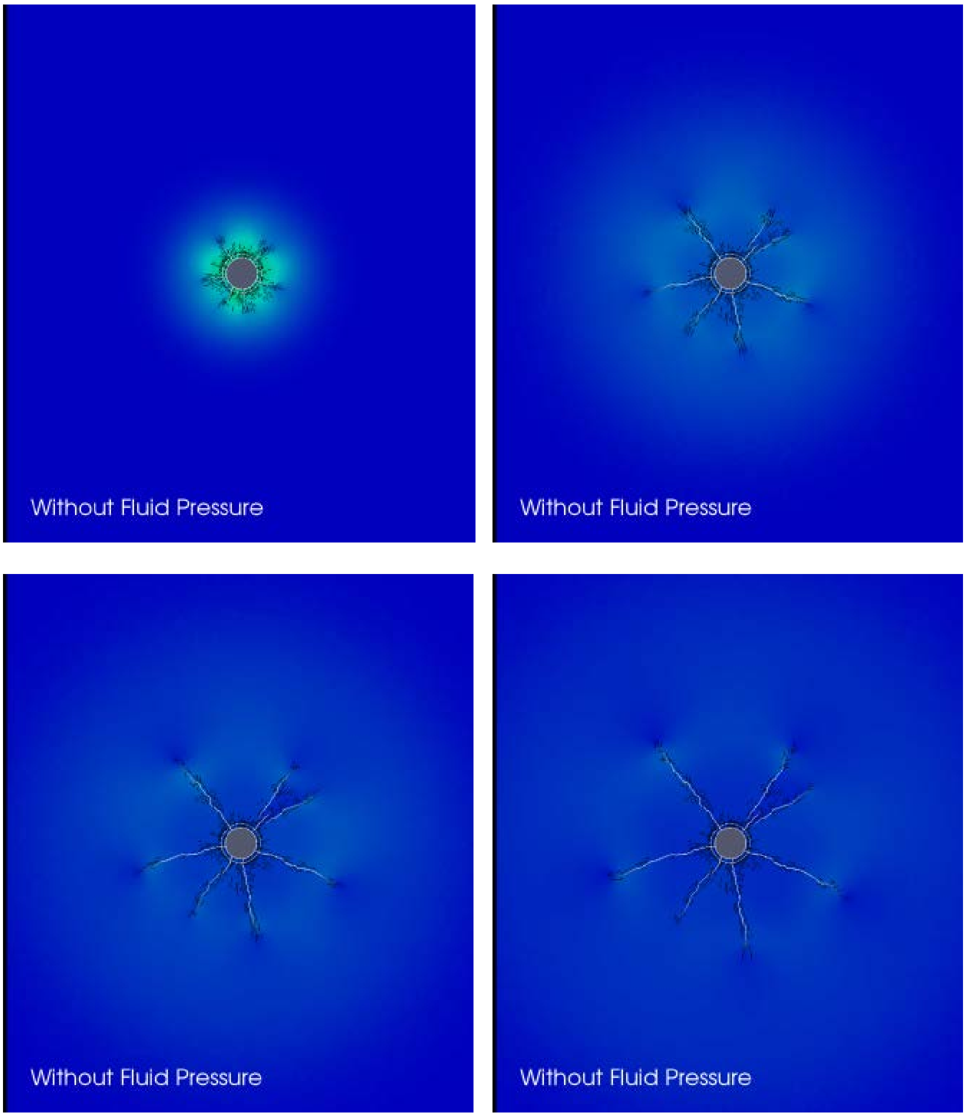

Figure 7: Borehole stability – 60 MPa, no fluid pressure.

As can be seen, the FDEM produces a quite satisfactory fracture network for dry material. Interestingly, when fluid pressure is accounted for there is a profound difference in the realized fracture network, see Figure 8.

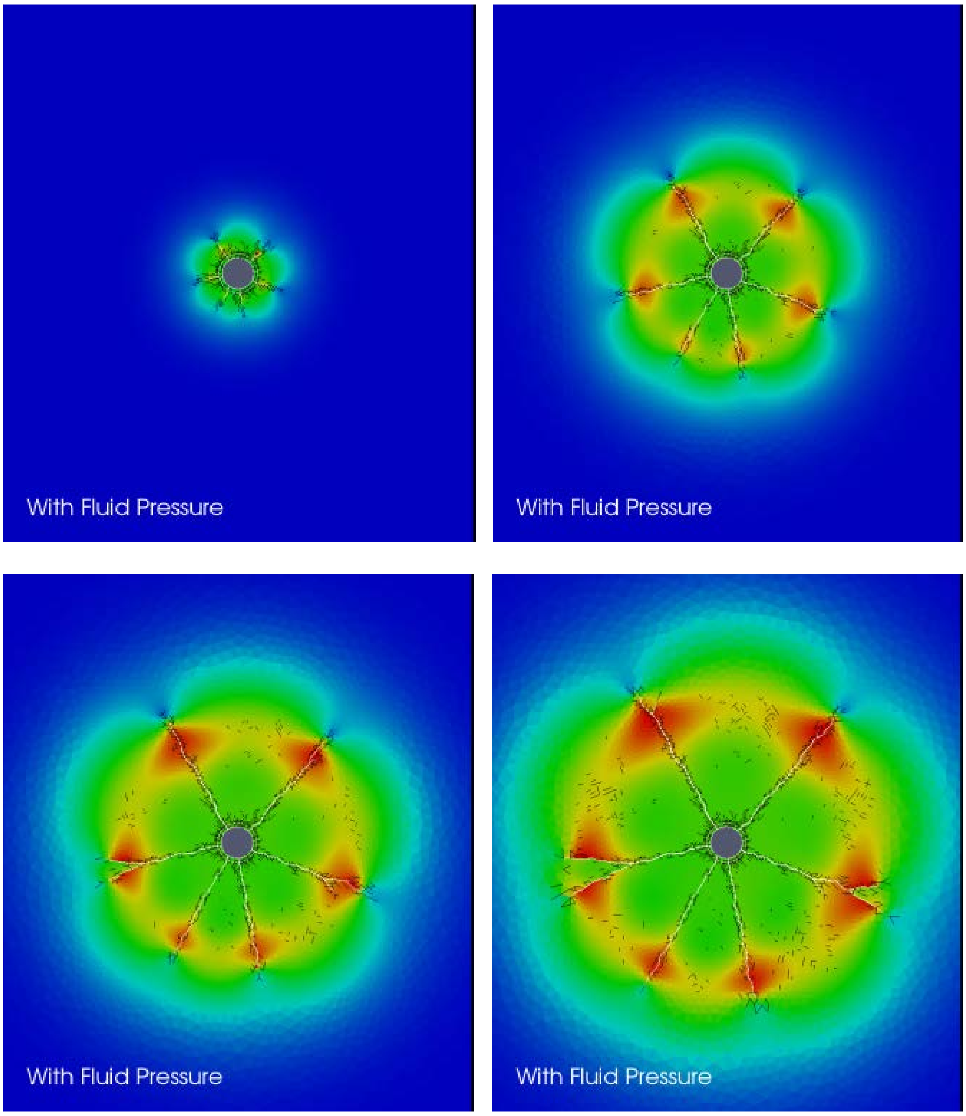

Figure 8: Borehole stability – 60 MPa, with fluid pressure.

Intuitively, one would expect differences however as seen in Figure 9, the phenomenological differences are astounding. For example:

- When it comes to the fluid driven fracture, the fluid plays the key role in formation of fracture pattern.
- The dry and wet fracture patterns look quite different.
- As a consequence of the results, it is evident that the fluid side of the FDEM (or any other) fluid driven fracture model has to be taken seriously.

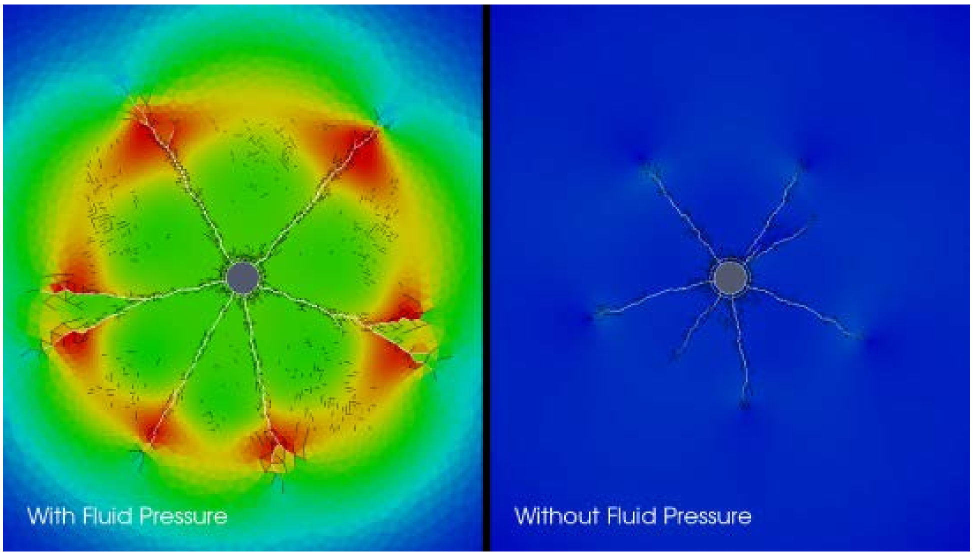

Figure 9: Comparison of final fracture pattern, with and without fluid pressure, at 60 MPa Borehole pressure.

5 CONCLUSIONS

A benchmark type of experiment shown in this work is a relatively simple 2D example of fracture propagation under pressure inside a borehole. Nevertheless, the results shown clearly demonstrate that fluid plays a major role in driving the cracks to such an extent that fracture patterns for dry and wet cracks are completely different. In other words, the presence of fluid affects both the extent of crack propagation and the bifurcation mechanisms leading to the formation of the fracture patterns, such as forking.

In real life problems with non-homogeneous anisotropic rock the difference between dry and wet crack propagation mechanisms is expected to be even greater due to the presence of initial cracks, joints and weaknesses in the rock matrix. Obviously, investigations into these mechanisms are mandated if we are to gain more insight into the industrial arena of "fracking." This work took some initial steps, by testing the hypothesis that fluid driven cracks can be heavily influenced by the presence of the fluid in the cracks. The obtained results clearly demonstrate the importance of the fluid effects even in the simplest of cases.

REFERENCES

[1] Griffith, A.A. The phenomena of rupture and flow in solids, *Philosophical Transactions of the Royal Society of London, A* **221:** 163–198, (1921).

[2] Inglis, C.E. Stresses in a plate due to the presence of cracks and sharp corners, *Trans. Instn. Naval Archit.* **55:** 219, (1913).

[3] Westergaard, H.M. Bearing pressures and cracks, *J. Appl. Mech.* **10:** 77, (1939).

[4] Rice, J.R. A path independent integral and the approximate analysis of strain concentration by notches and cracks, *Journal of Applied Mechanics* **35:** 379–386, (1968).

[5] Cundall P.A. Distinct element models of rock and soil structure. *Analytical and computational methods in engineering rock mechanics,* E. T. Brown Ed. London: Alien and Unwin,(1987).

[6] Cundall P.A. Formulation of Three-dimensional Distinct Element Model-Part 1. A Scheme to Detect and Represent Contacts in System Composed of Many Polyhedral Blocks. *Int., J. Rock Mech. Min. Sci. 8 Geomech. Abstr.* **25(3):** 107-116, (1988).

[7] Cundall, P.A. A discontinuous future for numerical modelling in geomechanics? *Proc. Inst. Civ. Eng - Geotech. Eng.,* **149(1):** 41-47, (2001).

[8] Hocking, G., Mustoe, G.G.W. and Williams, J.R. Dynamic analysis for generalized three dimensional contact and fracturing of multiple bodies, *INTERA Technologies, Inc.* (1988).

[9] Hocking, G., Mustoe, G.G.W. and Williams, J.R. Two and Three Dimensional Contact and Fracturing of Multiple Bodies. *NUMETA '87 Numerical Methods in Engineering, Theory and Application*, A.A. Balkema, Rotterdam, (1987).

[10] Hocking, G., Mustoe, G.G.W. and Williams, J.R., Validation of the CICE Discrete Element Code for Ice Ride-Up and Ice Ridge Cone Interaction, *ASCE Speciality Conference, ARCTIC '85,* San Francisco, (1985).

[11] Mustoe, G.G.W., Williams, J.R., Hocking, G. and Worgan, K.J. Penetration and Fracturing of Brittle Plates Under Dynamic Impact' NUMETA '87, Swansea, UK, 1987

[12] Mustoe, G.G.W., Williams, J.R. and Hocking, G. The discrete element method in geotechnical engineering. *In Developments in soil mechanics and foundation engineering*, Banerjee, P.K. and Butterfield, R. (eds), 233-263. London and New York: Elsevier Applied Science, (1987).

[13] Mustoe, G.G.W., Williams, J.R. and Hocking, G. The Discrete Element Method in Geotechnical Engineering. *Ch. 7 of Developments in Soil Mechanics and Foundation Engineering,* Elsevier, Barking, U.K., (1977).

[14] Cook, B., Noble, D., Preece, D. and Williams, J.R. Direct simulation of particle-laden fluids. *Pacific Rocks 2000.* Ed. Girard, Liebman, Breeds, and Doe. Balkema, Rotterdam, 279-286, (2000).

[15] Munjiza, A. and Andrews, K.R.F. NBS contact detection algorithm for bodies of similar size. *Int. J. Numer. Meth. Eng.,* **43:**131-149, (1998).

[16] Munjiza, A. and Andrews, K.R.F. Penalty function method for in combined finite-discrete element systems comprising large number of separate. *Int. J. Num. Methods Eng.,* **49:** 1377-96, (2000).

[17] Munjiza, A., Andrews, K.R.F. and White, J.R. Discretized Contact Solution for combined finite-discrete Method, *5th ACME Conf. London* UK, 96-100, (1997).

[18] Munjiza, A., Bicanic, N., Owen, D.R.J., Ren, Z. The central difference time integration scheme in contact impact problems, *Proceedings NEC-91, Intl. Conf. on Nonlinear Engineering Computations,* Eds. Bicanic et al, 569 - 576, Pineridge Press, (1991).

[19] Munjiza, A., Discrete Elements in Transient Dynamics of Fractured Media, Ph.D. thesis, Civ. Eng. Dept. Swansea, (1992).

[20] Munjiza, A. and Latham, J.P., Computational Challenge of Large Scale Discontinua Analysis, *Proc. 3rd Int. Conf. on Discrete Element Methods,* Santa Fe, NM, (2003).

[21] Munjiza, A., Owen, D.R.J., Bicanic, N. and Xian, L. A concept of contact element in the discrete element method. *Proceedings NEC-91, Intl. Conf. on Nonlinear Engineering Computations,* Eds Bicanic et al, Sept 1991, 435 - 448, (1991).

[22] Munjiza, A., Owen, D.R.J., and Bicanic, N. A combined finite-discrete element method in transient dynamics of fracturing solids, *Int. J. of Engineering Computation,* **12:** 145-174,

(1995).

[23] Munjiza, A., RG computer code, (2D explicit discrete element code for transient dynamics of fractured media), Civ. Eng. Dept., Swansea, (1992).

[24] Munjiza, A. and John, N.W.M. Towards one billion particle system. *The 3rd MIT conference on computational fluid and solid mechanics,* June 14-17, USA, (2000).

[25] Preece, D.S. The Influence of Damping on Computer Simulations of Rock Motion. *In Proceedings of the 25th Annual Oil Shale Symposium,* Colorado School of Mines, Golden, CO, (1992).

[26] Preece, D.S. and Chung, S.H. Rock Blasting 3-D Discrete Element Heave Predictions for Surface Coal Mines and Rock Quarries, *in Proceedings of NARMS-TAC 2002,* Toronto, Ontario, (2002).

[27] Preece, D.S., Burchell, S.L. and Scovira, D.S. Coupled Explosive Gas Flow and Rock Motion Modeling With Comparison to Bench Blast Field Data, *in Proceedings of the Fourth International Symposium on Rock Fragmentation by Blasting,* Technical University, Vienna, Austria, (1993).

[28] Preece, D., Jensen, R., Perkins, E. and Williams J.R. Sand Production Modeling using Superquadric Discrete Elements and Coupling of Fluid Flow and Particle Motion. *Proceedings of the 37th U.S. Rock Mechanics Symposium.* Ed. Amadei, Kranz, Scott, and Smeallie. Balkema, Amsterdam, (1999).

[29] Preece, D.S. and Taylor L.M. Complete Computer Simulation of Crater Blasting Including Fragmentation and Rock Motion, *Proceedings of Research Symposium,* Society of Explosive Engineers Spring Meeting, (1989).

[30] Preece, D.S. and Taylor, L.M. Spherical Element Bulking Mechanisms for Modeling Blasting Induced Rock Motion, *Proceedings of the Third International Symposium on Rock Fragmentation by Blasting,* Brisbane, Queensland, Australia, (1990).

[31] Preece, D.S. and Knudsen, S.D. Computer Modeling of Gas Flow and Gas Loading of Rock in a Bench Blasting Environment, *Proceedings of the 33rd U.S. Symposium on Rock Mechanics,* Santa Fe, New Mexico, (1992).

[32] Preece, D.S. Rock Motion Simulation of Confined Volume Blasting, *Proceedings of the 31st U.S. Symposium on Rock Mechanics,* Colorado School of Mines, Golden, Colorado, (1990).

[33] Munjiza, A. *The combined finite-discrete element method.* 1st ed. Chichester: John Wiley & Sons, (2004).

[34] Munjiza, A., Knight, E.E. and Rougier, E. *Computational Mechanics of Discontinua*. John Wiley & Sons, (2011).