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Editor's Note

In preparation for this issue of our newsletter, we have introduced a new strategy to attract articles of interest to our readership. Members of ARMA Publications Committee were asked to personally solicit articles from leading rock mechanics specialists on the newest theoretical, numerical, and applied research. For this first issue of the newsletter in which this plan is implemented, we have received one article by Haiying Huang, a member of our Committee, reporting results of her research in advanced modeling. We also received four other articles from rock mechanics specialists on new advances in their field of study. Because of space limitations, we decided to publish three of the articles in this issue, and the other two in the following one.

In this issue you will find a comprehensive report by Erik Eberhardt, University of British Columbia, on new approaches to copper mining -- in order to access deeper resources -- by transitioning from current open pits to underground mass block and panel caving mining. Applied rock mechanics questions like the extent of surface subsidence and the effectiveness of caving and fragmenting in view of stronger rock masses at great depth are considered in the article. Yang, Westman, and Sun report on a laboratory demonstration of passive seismic tomography imaging changes; they describe the results of imaging stress-induced velocity changes within a granitic sample undergoing a four-point bending test in the laboratory. Finally, Haiying Huang discusses the advantages and limitations the discrete element method (DEM) poses in modeling failure related to engineering problems.

*—Bezalel Haimson, Chair
ARMA Publications Committee*

Transitioning from Open Pit to Underground Mass Mining: A Review of the Rock Engineering Challenges and Progress in Deep Caving

Submitted by Erik Eberhardt, University of British Columbia, Vancouver, Canada

Introduction

Recent numbers from the International Copper Study Group (ICSG 2017) show that the global demand and production of copper has more than tripled in the last 50 years. This has been in response to increasing populations and economic growth. Demand is expected to increase even further in response to the shift towards electric cars and renewable energy sources, which are heavily reliant on copper. However, the ICSG (2017) also identified several constraints on copper supply, one of which includes declining ore grades -- especially as near surface resources are exhausted and mining seeks deeper supplies.

This has seen the transition from several large open pits to underground mass mining operations in order to access deeper resources. Mass mining methods such as block and panel caving are favored due to the tonnages and economic benefits achievable when dealing with lower grade ore. These methods involve developing an extraction level beneath the ore, followed by undercutting to initiate caving. As the broken rock is mined from different drawpoints on the extraction level, the cave propagates upwards through the orebody to provide a constant feed of broken ore to be mined. This methodology is attractive because of its safety merits, tonnages produced, and low production costs that can often compete with those of open pit operations.

Projections suggest that global copper production from underground caving operations will double by 2030, with volumes approaching that from large open pits. This increase in production will require a step change for the industry (Moss, 2011). This will entail a series of "super caves" that will be an order of magnitude greater in size than current underground norms and will require the construction of more than 1000 km of development tunnels, at least 10 production and ventilation shafts, and upwards of 12,000 drawpoints (Moss, 2014). Data compiled by Woo et al. (2013) show that the next generation of block cave mines will see unprecedented block heights being caved and increased mining depths (Figure 1). This will present a number of significant engineering challenges and technical risks compared to other block cave operations, with Brown (2012) identifying several key rock mechanics related issues, including:

- Can we predict the nature and extent of surface subsidence and its impact on natural surface features and surface infrastructure for the block heights and mining depths involved?
- Will the cave propagate as planned and at an acceptable rate relative to the presence of different geological lithologies and structures for the block heights planned?
- Will the orebody cave and fragment satisfactorily, given the expectation of encountering stronger rock masses at greater depths?
- Will the undercut and extraction level excavations remain stable given the depths involved and the expectation of stress-induced spalling and strain-bursting?

These challenges expose limitations in existing empirical and analytical design tools, which have largely been developed based on experiences with poorer quality rock masses and lower stress environments. The call for step change (Moss, 2011) has led to several large collaborative research initiatives, including the Mass Mining Technology consortium (and its predecessor, the International Caving Study), and the Rio Tinto Centre for Underground Mine Construction (RTC-UMC). These were tasked with establishing the research networks required to develop the knowledge base, innovation, and next generation of design tools and best-practice guidelines needed to safely manage the uncertainty and complex rock mass responses expected for the scale and mining depths involved. This review will summarize some of the progress made toward the key issues identified above, highlighting research outcomes from several recent university-industry research collaborations.

Caving-Induced Subsidence

As a mass mining method, block caving results in significant ground collapse above the mine footprint and extensive surface subsidence. If not properly accounted for, the resulting differential surface displacements may threaten the integrity and safety of overlying mine and civil infrastructure. A common means for assessing the zone of caving disturbance on surface is through the use of empirical design charts that use as input the rock mass quality and block height to be caved (e.g., Laubscher, 2000). The resulting prediction assumes symmetry; i.e., the zone

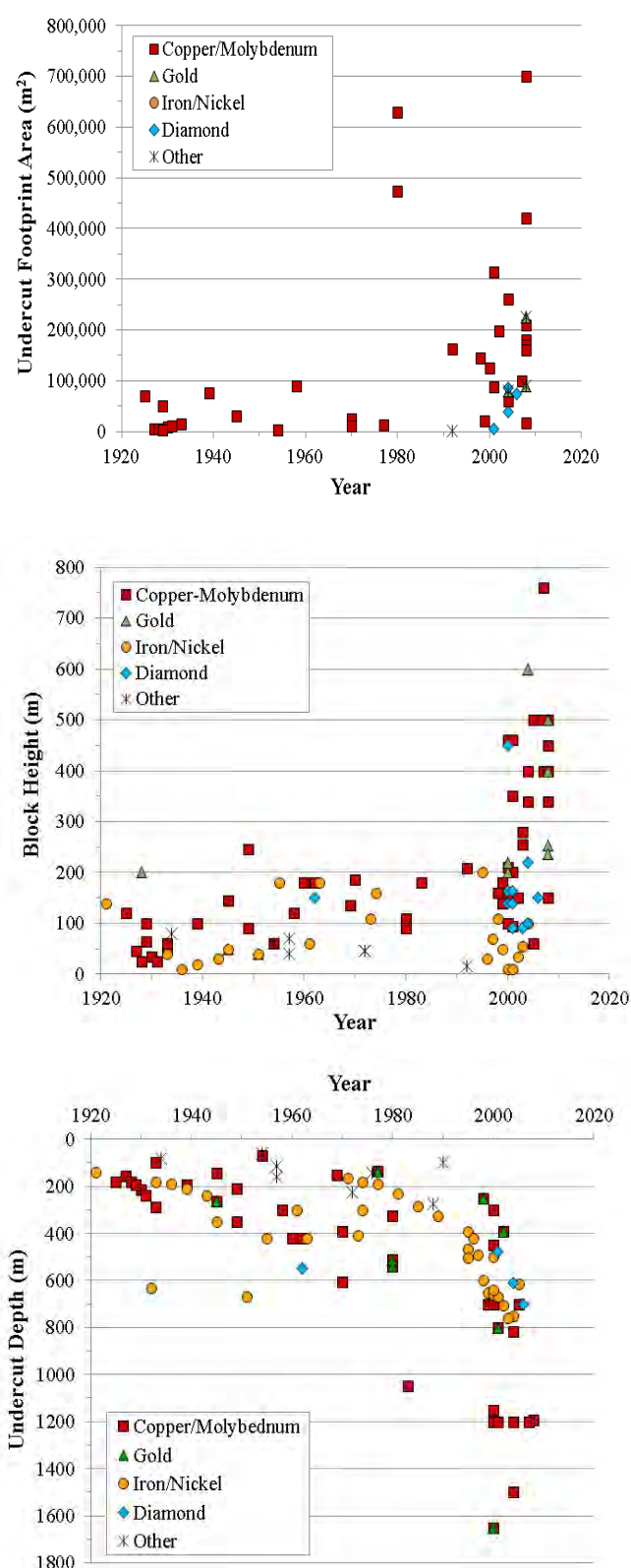


Figure 1. Historic block cave mining data showing sharp increases in footprint area, block height, and undercut depths over the last 20 years (data compiled by Woo et al., 2013).

of surface disturbance is equally projected from all points around the mine footprint at depth.

Woo et al. (2013) analyzed 47 caving-induced subsidence observations to determine the influence of

faults, geological heterogeneity, and topography in promoting asymmetric surface deformations. These results clearly showed that asymmetry is a prevalent attribute and that a single caving angle produced by using existing design charts would either over- or under-predict the extent of ground deformations for some portion of the zone of caving at surface. The application of these caving charts, therefore, requires sound engineering judgment and a full consideration of the geological and geotechnical setting in which they are being applied. Their analysis also showed that the empirical data is largely restricted to visible indicators of tension cracks and collapse features that develop immediately above the cave. They do not include data of smaller-strain subsidence.

Figure 2 shows results from a series of hybrid FEM-DEM numerical models incorporating brittle fracture capabilities, using the commercial code ELFEN (Rockfield, 2009). The models and input properties are described in detail in Woo et al. (2013). The models indicate the extent of the larger collapse features that develop in response to the simulated caving, which in this case are partially constrained by the presence of sub-vertical faults. However, the colored contours also show that the smaller-strain subsidence extends significantly beyond this. The differential displacements involved are still significant enough to threaten the integrity of surface structures.

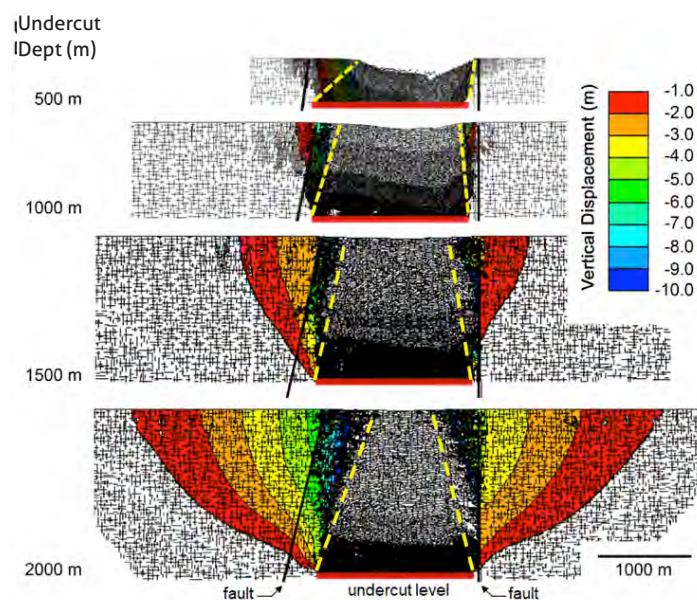


Figure 2. Hybrid FEM-DEM brittle fracture modeling results using ELFEN showing the extent of caving-induced ground collapse (yellow dashed lines) and corresponding subsidence (coloured contours) as a function of mining depth (i.e., undercut depth). The continuous black lines to the left and right of the undercut are bounding faults, and the red line at the bottom indicates the undercut level. (after Woo et al. 2013).

The model results in Figure 2 also show the influence of mining depth. As evident in the figure, for a given block height (i.e., extraction volume), the extent of the collapse zone that develops on the surface decreases as the depth of mining (i.e., undercut depth) increases. This is because the increasing depth results in a decreasing extraction ratio; i.e., for a constant block height, the ratio of mined volume to total volume decreases. However, this does not apply to the smaller-strain subsidence, which shows its extent increases as a function of undercut depth. These caution against relying on empirical design charts for estimating caving-induced subsidence where small-strain subsidence is of concern and show a clear need for advanced numerical modeling to better understand the influence of adverse cave-surface interactions.

This may be seen in the 800m high pit wall failure at the Palabora mine in South Africa in 2004, which occurred three years after the initiation of caving and shortly after breakthrough of the cave into the bottom of the pit. The failure extended 300 m beyond the outer perimeter of the pit, affecting access and haul roads, tailings, water and power lines, water reservoirs and a railway line (Moss et al., 2006). Fortunately, other critical mine infrastructure was not affected.

Moss et al. (2006) remarked that the failure at Palabora revealed deficiencies in our understanding of cave-pit interactions. Subsequently, a number of studies were carried out applying sophisticated numerical modeling to retrospectively analyze the Palabora failure (Brummer et al., 2004; Sainsbury et al., 2008; Vyazmensky et al., 2010). These analyses made significant contributions to the understanding of the pit slope failure mechanism at Palabora and the cave-pit interactions that developed. However, Moss et al. (2006) also stressed that given the level of up-front capital investment in a block cave, it is extremely important to develop reliable predictive tools for forward modeling.

Woo et al. (2012) investigated the use of high-resolution InSAR data as a means to calibrate and validate advanced 3-D numerical models of cave-pit interactions for the Palabora mine using FLAC3D (Itasca, 2009). InSAR technology is capable of detecting displacements on the scale of centimeters to millimeters for a surface area resolution of several square meters, providing a means to monitor caving-induced differential strains, including small strain subsidence across an irregular surface topography. The FLAC3D model (Figure 3a) integrated the mine geology, projected cave geometries for differ-

ent time intervals, in situ stress conditions, and rock mass properties for each geological unit. Analysis of the 2004 failure was used to constrain different strain softening thresholds at which strength degradation through brittle fracturing would begin. The calibrated "best fit" set of input properties was subsequently used for forward modeling of the expected caving-induced subsidence for the period 2009 to 2010 (Figure 3b). These were then compared to RADARSAT-2 InSAR data collected for the same period. The close fit, including the displacement-time trend for a point located near the main access and production shafts (Figure 3c), demonstrated the value of the calibrated model to better support decision makers in protecting key mine infrastructure and managing risk and safety related to caving-induced subsidence hazards (Woo et al., 2012).

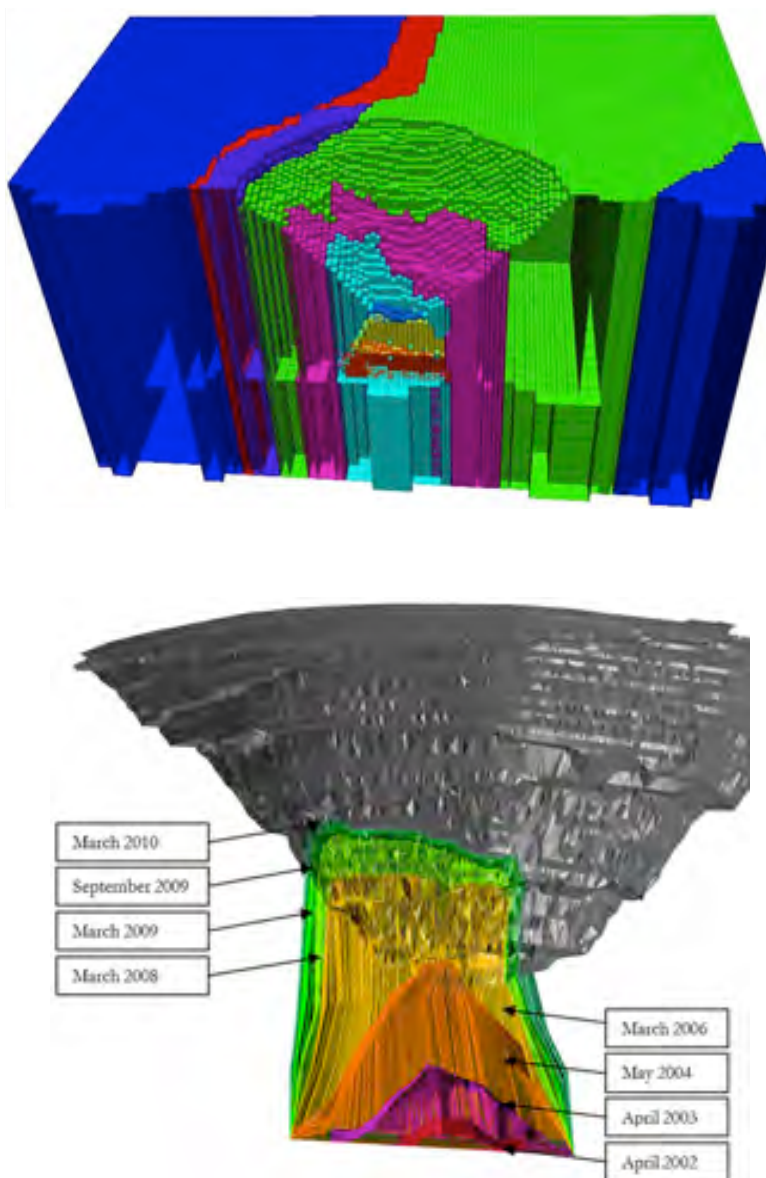


Figure 3a. FLAC3D model with the Palabora mine geology and projected cave geometries for different time intervals;

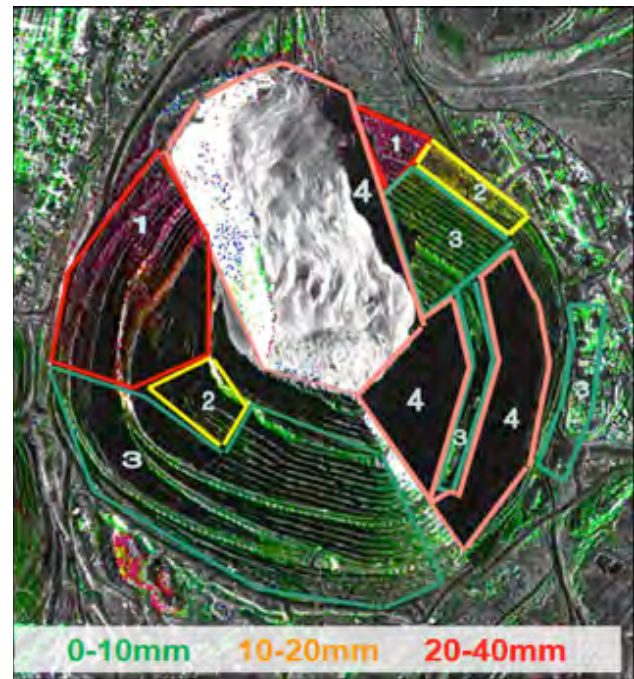
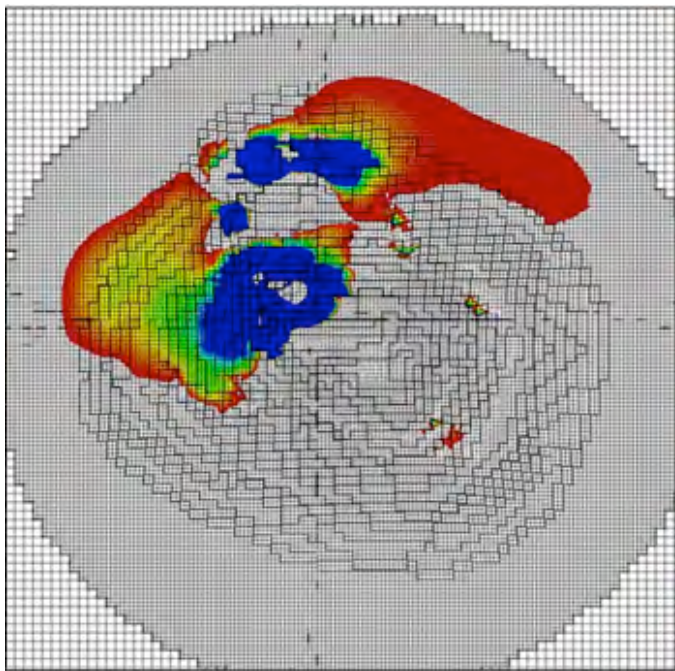


Figure 3b. Results of forward modeling of predicted caving-induced vertical displacements (in meters) for a one-year period with comparison to subsequent InSAR data for the same period.

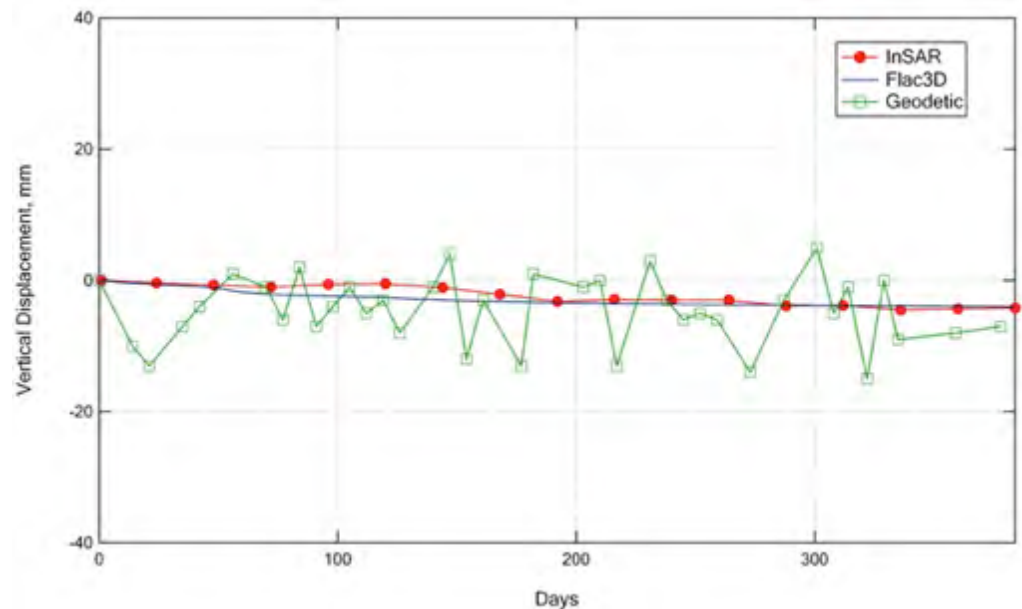
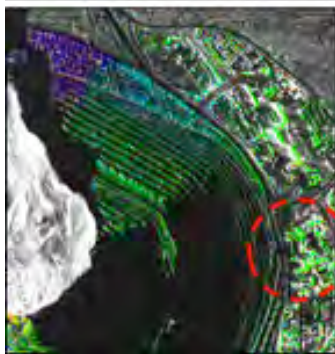
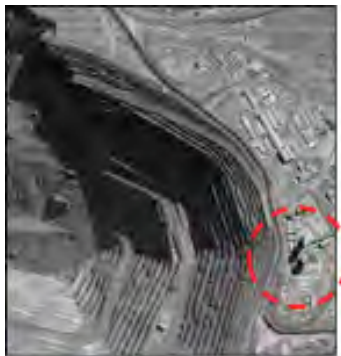


Figure 3c. Comparison for a point located near the main access and production shafts. (after Woo et al., 2012).

Caving Propagation and Induced Fragmentation

Numerical methods vary widely in their representation of the rock mass, from continuum to discontinuum treatments, and deliver contrasting advantages and disadvantages in modeling block caving processes and cave propagation (Elmo et al., 2013; Woo et al., 2014). For practical purposes, a balance must be struck between the appropriate level of detail and the computing time that will be required to

perform a large number of simulations. However, as a minimum, Elmo et al. (2013) show that models need to explicitly account for the presence of faults and rock mass fabric to produce realistic caving results. The best practices they promote include the integration of Discrete Fracture Network (DFN) models with hybrid FEM-DEM brittle fracture models. DFN modeling involves the stochastic generation of a representative network of fracture orientation, size and inten-

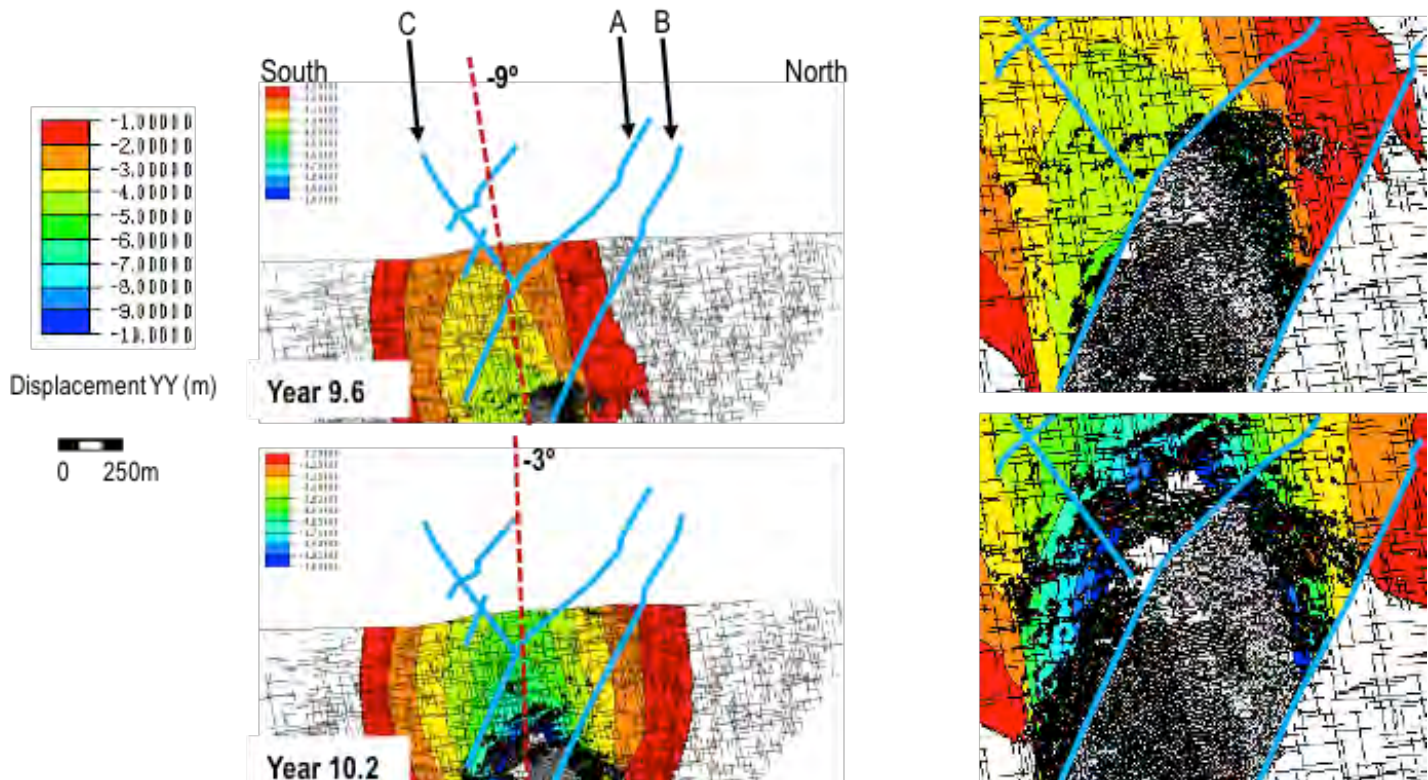


Figure 4. Integrated DFN-FEMDEM numerical modeling results showing the simulated influence of major geological faults (blue lines) and jointing on cave propagation and surface subsidence for the Cadia East panel cave. (after Elmo et al. 2013).

sity distributions (Dershowitz et al., 1998); FEM-DEM incorporates the numerical modeling of brittle fracture mechanics and contact interaction principles (Owens et al., 2004). Together, they allow the realistic simulation of caving fragmentation with full consideration of the anisotropic and heterogeneous effects of natural jointing and rock mass fabric on the failure kinematics.

Figure 4 demonstrates how the integrated DFN-FEM-DEM approach effectively captures key caving mechanisms, including preferential rock fragmentation within the ore column and the controlling role of rock mass fabric and geological structures on cave propagation and surface subsidence (Elmo et al., 2013). The results indicate that jointing and major geological faults will have a significant impact on cave shape and cave propagation direction. The range of vertical displacements produced in these simulations for the Cadia East panel cave mine in Australia highlights the generation of asymmetric caving-induced deformations. A cross-over occurs when the cave front reaches a point along an overlying dipping fault (Fault A in Figure 4) showing that cave development is also clearly asymmetric.

The dynamics of cave propagation also impact the fragmentation and gravitational flow of the ore being mined. These are discussed in detail by Pierce (2010). Block caving designs must consider the spac-

ing of the drawpoints where the ore will be extracted from to ensure proper flow of the caved rock, together with the draw schedule to achieve uniform downward movement of the caved rock and thus proper caving behavior. This requires a full understanding of the mechanisms governing the size, shape, advance, overlap, and interaction of movement zones above each drawpoint (Pierce, 2010). Pierce (2010) used a combination of numerical techniques including REBOP (Rapid Emulator Based On PFC; Cundall et al., 2000) to model the development and interaction of multiple movement zones and internal velocity profiles that develop within them (Figure 5). These calculations showed that the degree of interactive flow between movement zones, controlled by the design of the drawpoint spacing and relation between stresses and rock strengths, must sufficiently overlap to ensure uniform drawdown to avoid leaving large volumes of immobile ore behind and to avoid isolated rapid flow paths that encourage early entry of low grade ore lying above the ore column (i.e., dilution).

Fragmentation also plays a key factor in determining mine productivity (Laubscher, 2000). If the fragmentation is too coarse, large blocks will severely impact operations by impeding material handling and cause costly delays to clear hang-ups at the draw points. If fragmentation is too fine, narrower draw columns might develop, limiting the interactive flow between movement zones

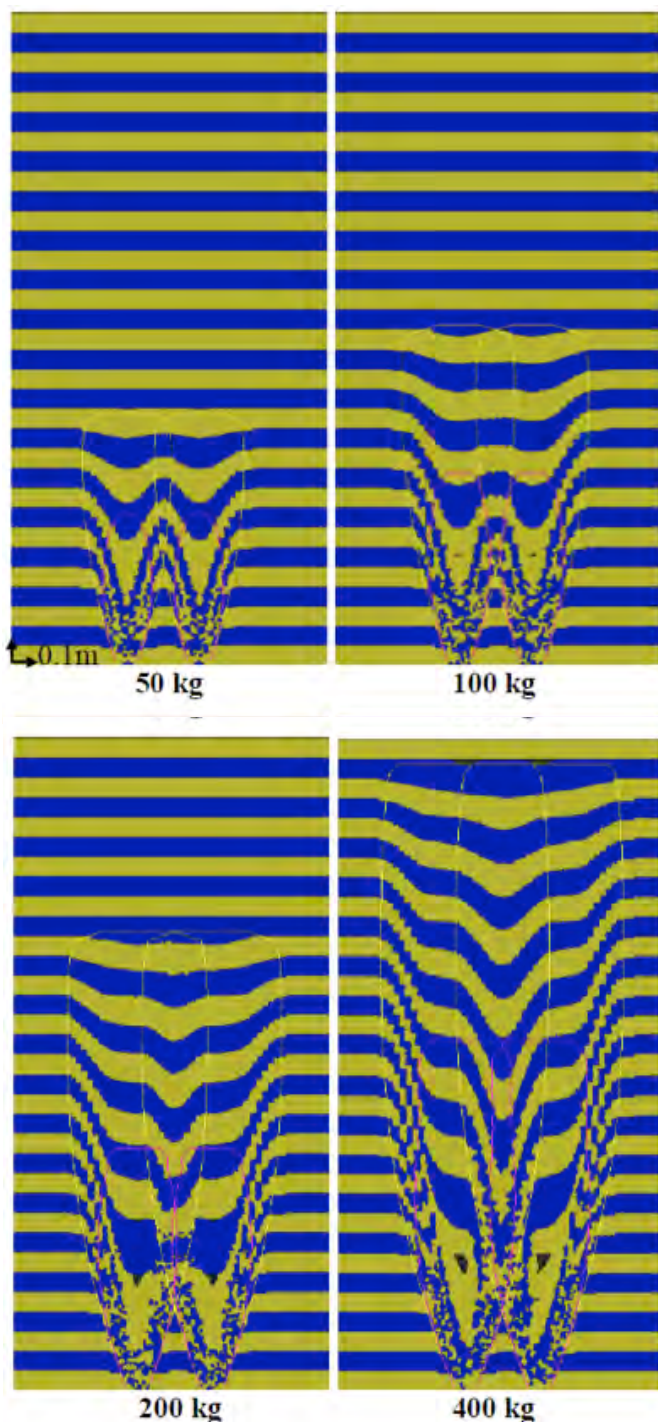


Figure 5. REBOP simulation for two drawpoints, showing the drawdown profile and development of overlapping interactive mobilization zones, after Pierce (2010). The REBOP logic and models were calibrated against physical experiments by Castro (2006). The masses indicate the amount drawn per drawpoint in the physical experiments.

(Pierce, 2010). Brown (2012) cautions that historically, block caving was targeted to relatively shallow, weak orebodies, providing a finer fragmentation. However, with the move towards deep and stronger orebodies, it can be expected that these will produce coarser fragmentation, enabling more widely-spaced drawpoints (reducing development costs), but increased the risk that

the fragmentation may be too coarse or that caving may become stalled in stronger rock units.

Best practices for rock mass characterization have seen several recent research studies investigating the influence of mineral veining (Figure 6a) -- commonly encountered in the porphyry copper deposits targeted by block caving -- on fragmentation and rock mass strength. Conventional rock mass characterization and analysis methods (e.g., Q, RMR, GSI, etc.) generally only consider the intact rock properties and presence of discrete fractures, with veining seen as being a seamless component of the intact rock and having a negligible effect on fragmentation (Day, 2016).

However, veining has been observed in deeper mines with higher stresses to have a significant influence on rock mass behavior and fragmentation. In this case, Day (2016) developed a composite GSI rock mass characterization tool and validated it against data collected at the El Teniente caving operation in Chile. This work includes important laboratory testing protocols for testing veined rock and determining input parameters for numerical models with explicit structure. Dorador (2016) used physical experiments to simulate secondary fragmentation for rock fragments with and without veining, and showed the importance of the loading magnitudes imposed as the draw column height grows and the influence of compressional versus shear loading relative to Pierce's (2010) isolated movement zone model. Turichshev & Hadjigeorgiou (2017) developed the first application of Synthetic Rock Mass (SRM) and Bonded Block Models (BBM) for modeling the behavior of intact veined rock. Their numerical simulations successfully reproduced key experimental behaviors of intact veined rock in compression (Figure 6b), thus helping to build confidence in the approach as a means to realistically simulate fracturing of veined rock in support of larger scale fragmentation and excavation stability studies for high stress environments.

Stress-Induced Failure

As caving operations progress to greater depths, encountering both better quality rock and higher stresses, stress-induced spalling and associated strain bursting can lead to significant safety hazards and costly development and production delays through required repairs to installed support systems. The Oyu Tolgoi block cave mine in Mongolia and DMLZ block cave at the Grasberg mine in Indonesia will be mined at depths of 1300 and 1500 m, respectively, and the proposed Resolution project in Arizona involves a deposit at between 1500 and 2100 m deep. Designs for these operations must consider the full



Figure 6a. Characterization of hydrothermal quartz veins commonly encountered in block caving of porphyry copper deposits (after Day, 2016).

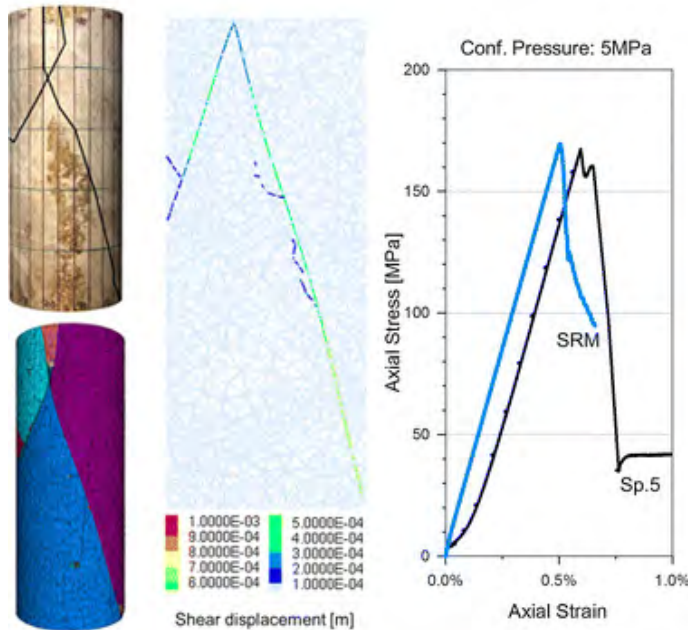


Figure 6b. Synthetic rock mass and bonded block modeling (SRM-BBM) of veined rock with validation against laboratory test results for veined andesite from the El Teniente panel cave (after Turichshev & Hadjigeorgiou, 2017).

stress path pillars will be subjected to, from their initial excavation to the high abutment stresses that will pass over them as the undercut is advanced. In response, a thorough understanding of pillar behavior is required, ranging from brittle failure and bulking near the unconfined pillar boundary, to the ultimate load bearing capacity of the confined pillar core (Kaiser et al., 2011).

Although the mechanisms of spalling and strain bursting are generally well understood, commonly used empirical and analytical design tools have been

developed based on experience in lower stress environments and for shear-based failure mechanisms. However, it is recognized that spalling and brittle failure are driven by extensional fracturing. This has required designers to “trick” conventional shear-based criteria to mimic the dual behavior of rock involving spalling under low confinement near the excavation boundary, then transitioning to shear failure under high confinement within the pillar core (as represented by the well-known “S-shaped curve”; e.g., Diederichs et al. 2004). Experiences in higher stress environments have proven that existing predictive tools are insufficient for robust prediction and displacement-based support design when brittle failure mechanisms like spalling and strain bursting are encountered -- impacting safety and reliable planning.

Research in progress at the University of British Columbia, in collaboration with the Rio Tinto Centre for Underground Mine Construction, has been directed towards developing new predictive tools for simulating rock behavior and support performance in high stress environments that correctly capture the mechanism of spalling and brittle failure. The first study involves the work of Masoud Rahjoo who has developed a first-of-its-kind 3-D confinement-dependent spalling and post-peak dilation model for brittle rock. Spalling involves the initiation and propagation of brittle fractures sub-parallel to the maximum principal stress, with opening and dilation perpendicular to this. Therefore, dilatancy and bulking have a directional attribute, which is accounted for in the new UBC model, whereas conventional models treat dilation as a volumetric attribute. The UBC model has been developed to allow it to be implemented in commonly-used software like FLAC3D to take advantage of the efficiencies of 3-D continuum-based numerical methods. In this case the finite difference method enables predictive modeling of depth of spalling failure (Figure 7) and corresponding pillar bulking potential across an extraction level footprint (Rahjoo et al., 2016). This can then be used for support design optimization for drawpoints being brought into operation and preventative support maintenance for those already active.

The second UBC study involves the work of Thierry Lavoie, who has developed a new bonded block modeling approach applicable at the drawpoint/pillar scale, using 3DEC (Itasca, 2016; referred to here as 3DEC-BBM). This work recognizes that with spalling and brittle fracture damage, rock mass bulking in severe cases includes buckling and dilation due

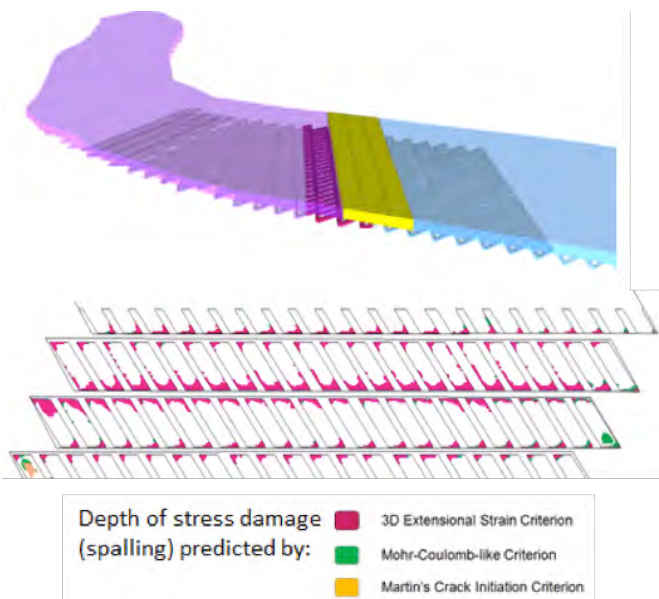


Figure 7. Simulated block cave footprint and undercut, with modeled spalling hazard map comparing UBC 3-D extensional strain criterion with commonly used shear-based criteria (Rahjoo et al., 2016).

to geometric incompatibilities when broken rock fragments move relative to each other as they are squeezed into the excavation. This geometric dilation, when it arises, is the largest contributor to rock mass bulking (Kaiser et al., 2000). Lavoie et al. (2018) have utilized the discontinuum capabilities of 3DEC-BBM to explicitly model spalling, geometric dilation/

bulking, and ground support performance. This addresses several significant challenges with respect to 3-D geometric controls on pillar performance at extraction draw point intersections, correct handling of the directional bulking associated with spalling, and careful consideration of the highly localized straining of support elements at discrete fractures that are both opening and shearing. The model is capable of tracking the full mining stress path, from pillar excavation to the loading and unloading as the abutment stresses/shadows pass over the pillar; this allows modeling progressive development and evolution of rock mass bulking (Figure 8). Findings from this work demonstrate that it is crucial to install appropriate support before the undercut passes over the extraction level pillars. The depth of damage and amount of bulking can increase significantly during pillar unloading following passing of the undercut. This effect is mostly attributable to the reduction of stresses and confinement in the pillar that enable irreversible slip along the generated fracture surfaces. Subsequent loading, during production for example, can exacerbate the bulking experienced. Extra confinement applied to the failed pillar skin allows it to carry more load and thus provide more confinement to the pillar core, helping to limit further damage and bulking (Lavoie et al., 2018).

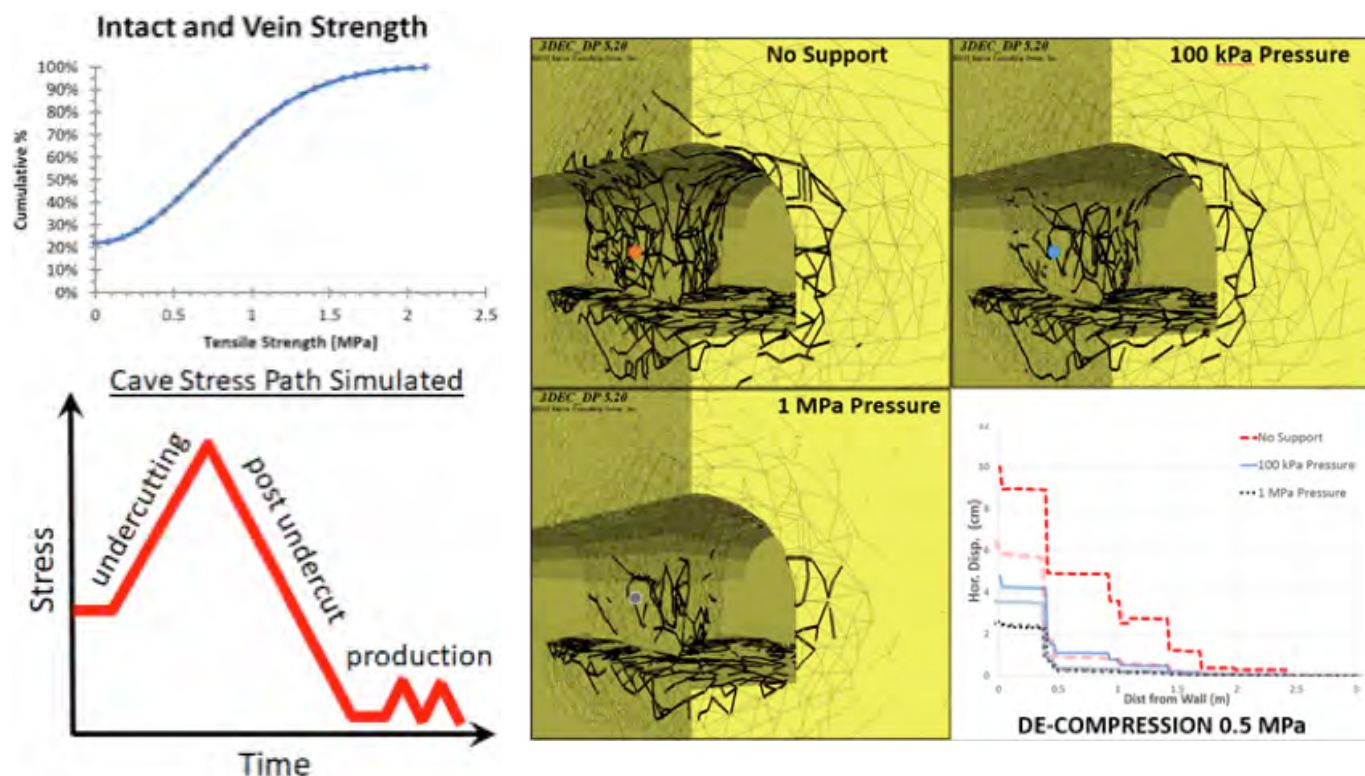


Figure 8. 3DEC-BBM modeling of pillar-scale spalling and support performance, comparing stress-induced brittle fracture damage and bulking for 0, 100 kPa and 1 MPa support pressure scenarios at the end of the cave mining stress path simulated. The displacements corresponding to the undercut abutment stress and maximum pillar compression are included as fainter traces. (after Lavoie et al. 2018)).

Conclusions

As block and panel cave designs evolve to consider deeper and larger undercuts, the influence of geology and in-situ stresses on cave development becomes more pronounced and interactions between the cave and surface environment become more complex and far reaching, challenging our current design abilities and experience. This requires that both geological uncertainty and model uncertainty (related to the applicability of conventional tools developed for shallower mining conditions) be fully accounted for and managed.

Results from several recently completed research studies focused on addressing limitations in design practices associated with the transitioning from open pit to underground mass mining clearly show the need for the development of new tools in the form of state-of-the-art numerical modeling techniques, constrained by retrospective analyses and use of high-resolution data (spatial and temporal) monitoring data (e.g., InSAR in the case of caving-induced surface subsidence) to better support decision makers in managing risk, safety and optimization related to deep caving.

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Tomographic Imaging of Stress Redistribution Prior to Failure in a Four-Point Bending Test

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Introduction and Background

Passive seismic tomography has increasingly been used to image changes within a rock mass (Vatcher et al., 2018). The ultimate goal of these studies is to improve the ability to monitor a rock mass so that safety and efficiency can be optimized. The objective of the study described in this article was to provide a laboratory demonstration of passive tomography imaging changes within a sample.

Previous studies have demonstrated the relationship between induced stress within a rock sample and the p-wave velocity of an elastic wave traveling through the sample (Scott et al, 1993). Because the velocity of an elastic wave generally increases with an increasing stress level, there is the possibility of using seismic tomography to infer the locations of stress concentrations within a rock sample. This has been demonstrated previously in underground mines. For example, Kormendi et al. (1986) used explosives to generate seismic energy in an underground coal mine and mapped the forward abutment loading of a longwall panel over several days. Young and Maxwell (1992) subsequently used explosives to conduct an active seismic tomography survey to locate highly-stressed zones in an underground hardrock mine. Later, Luxbacher et al. (2008) used the mining-induced seismicity to conduct a passive seismic tomography experiment, imaging the change of the stresses associated with the forward abutment zone at a longwall coal mine.

However, in spite of the demonstrated use of this method at field sites, there has been only a limited number of laboratory demonstrations of the use of seismic tomography to analyze stress redistribution (Scott et al, 1993). This article briefly describes the results of three-dimensional passive tomography over time for imaging stress-induced velocity changes within a granite sample undergoing a four-point bending test in the laboratory.

Lab Setup and Data Collected

A sample of Mt Airy granite, with dimensions of 100 by 50 by 200mm, was used for the four-point bending test. Thirteen acoustic emission sensors were attached to the sample (Figure 1, top) and over a pe-

riod of 170 minutes the sample was loaded to failure (Figure 1, bottom). A total of 350 acoustic emission events were located based on the p-wave arrival. These events were divided into three intervals, including background loading (25 events), pre-peak loading (70 events), and peak loading (255 events) (Figure 2). Each event was recorded by up to 13 sensors resulting in 321, 890, and 3,161 raypaths for each of the respective loading intervals. The average velocity of the elastic waves traveling through the granite sample was approximately 5,000 m/s.

The locations of these events for each loading interval are shown in Figure 3, where it is shown that most of the events occur in the upper portion of the sample.

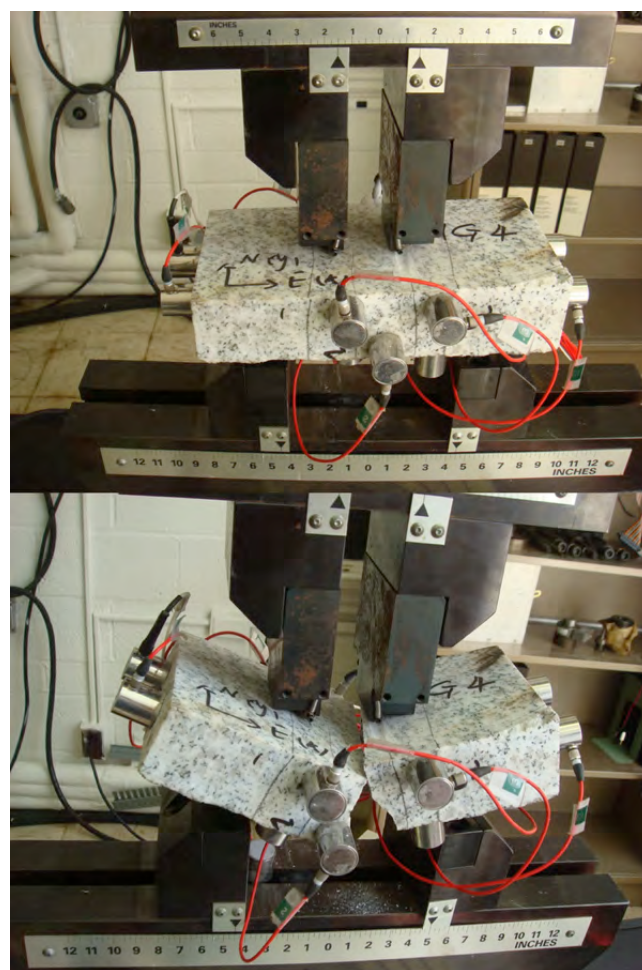


Figure 1. Photographs of the granite sample and acoustic emission sensors both before (top) and after (bottom) the four-point bending test.

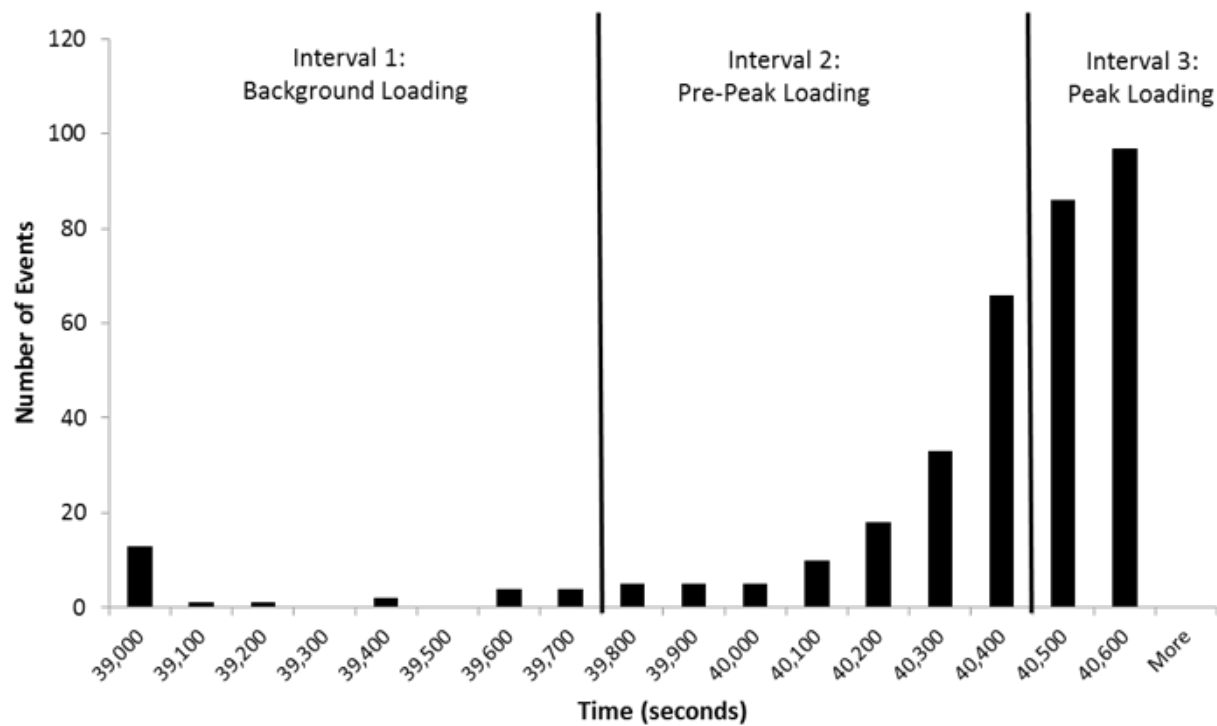


Figure 2. Distribution of recorded acoustic emission events versus time for the four-point bending test. Event series is divided into three intervals: background loading, pre-peak loading, and peak loading.

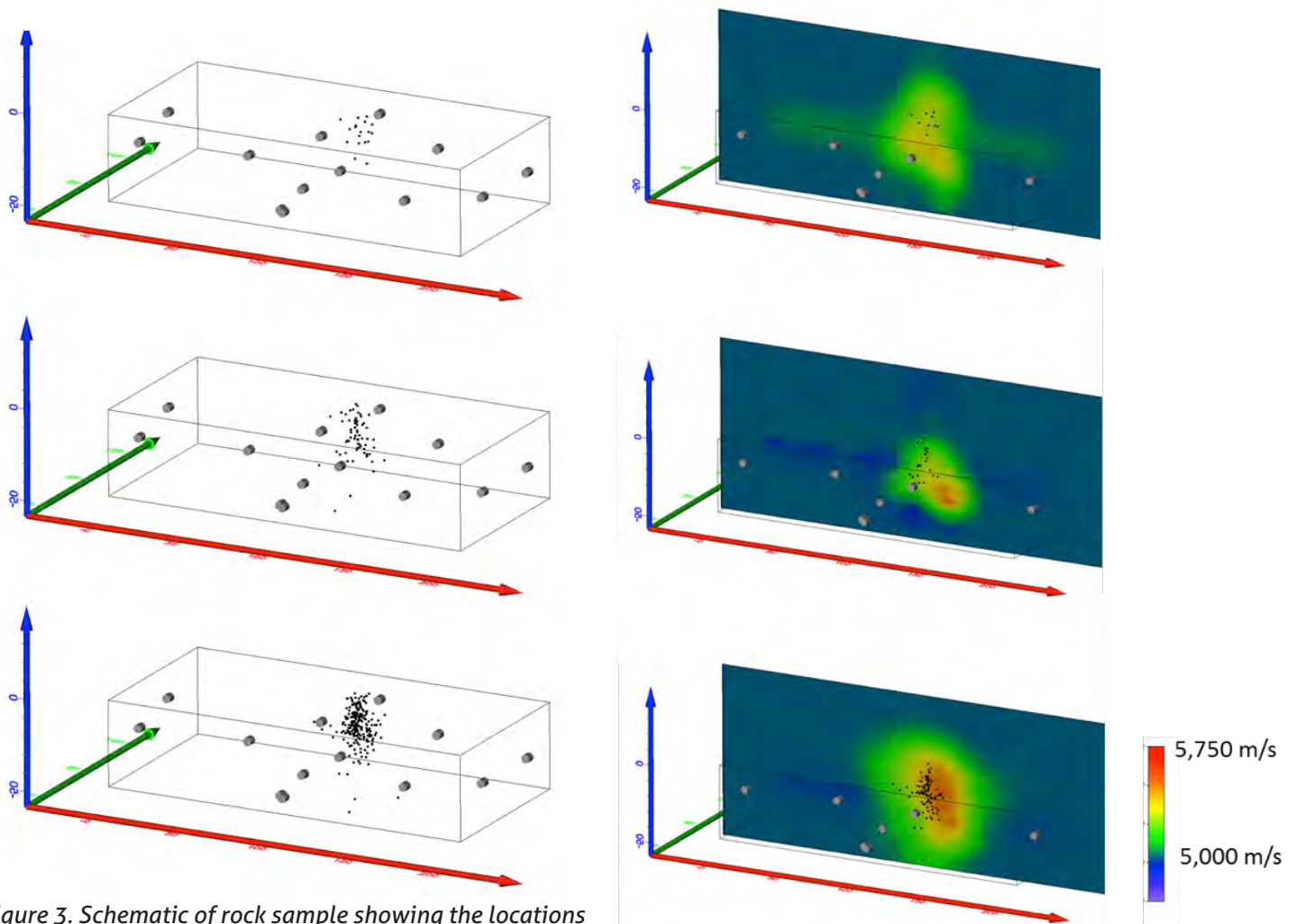


Figure 3. Schematic of rock sample showing the locations of the acoustic emission events in the background loading (top), pre-peak loading (middle), and peak loading (bottom) intervals.

Figure 4. Velocity distribution through middle of rock sample in the background loading (top), pre-peak loading (middle), and peak loading (bottom) intervals.

Results and Discussion

Separate tomograms were generated for each of the three different loading intervals. Figure 4 shows the vertical cross section for each of the loading intervals along the central axis of the longest cross-sectional dimension of the sample. It can be seen that as the load increases toward failure the velocity also increases within the middle of sample where failure eventually occurs.

In the initial loading interval, including the limited amount of data due to the small number of events during the background loading, the high velocity zone is about 5,250 m/s or about 5% higher than the background velocity. This higher velocity zone is laterally concentrated beneath the two loading platens on the top of the sample and uniformly distributed from the top of the sample to the bottom.

During the second loading interval, comprised of a 500-second time period that concludes 250 seconds before failure, the highest observed velocity increases to about 5,500 m/s (about a 10% increase from the background velocity). This highest velocity zone is located toward the bottom of the sample but still between the loading platens. A zone of increased velocity (of approximately 5% above the background velocity) extends to the top of the sample and contains the volume where most of the located acoustic emission events occurred.

In the 250-second interval prior to failure, the high-velocity zone is clearly defined as a vertically-oriented volume in the middle of the sample with a velocity of approximately 5,500 m/s. Although the magnitude of the velocity in this zone is no higher than that of the preceding interval, the distribution of the high-velocity region is much more widespread. During this interval preceding failure, the locations of the recorded acoustic emission events are very clearly shown to be in the high-velocity volume. This indicates that although the sample ultimately fails in tension the majority of the recorded events are not tensile. There is the possibility that the acoustic emission events due to tensile failure within the sample were not of a high enough amplitude to be recorded by the monitoring system.

One result that is notable is that no low-velocity zone of dilation is imaged where the ultimate tensile failure occurs. This may be due to the dilation zone only developing shortly prior to ultimate failure and that the 250-second interval used in this experiment is too coarse to observe it.

Summary and Conclusions

This brief article has demonstrated that velocity distribution, indicative of stress distribution, within a laboratory rock sample undergoing a bending test can be imaged. A total of 350 acoustic emission events were collected and the location and p-wave arrival times were used to develop velocity tomograms in three separate loading intervals. Results showed that velocity continued to increase in the central portion of the sample prior to failure, indicating an increase in stress level. Additionally, no velocity decrease was observed which, if it had been present, could have indicated the location of dilation within the sample prior to failure.

This study provides a demonstration of the time-lapse passive tomography method which is being increasingly used for field monitoring. Rock mass monitoring with passive seismic tomography provides an additional tool, along with direct observation, point-location measurements, and numerical modeling, for engineers to optimize the safety and efficiency of an operation.

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Displacement Softening as an Ingredient to Increase the Strength Ratio for DEM Modeling

Submitted by Haiying Huang, School of Civil and Environmental Engineering, Georgia Institute of Technology

Introduction

Failure in many engineering problems involves more than one mechanism. For example, in landslides, shear slip may occur after development of tensile cracks in the crest of a slope; in drilling or mechanical excavation, damage induced immediately underneath the tool bits, combined with rock chipping and fragmentation, contributes to the total volume removal; in borehole stability, breakout as well as induced fracturing are both possible scenarios.

Discrete element method (DEM) has a unique advantage over continuum mechanics-based numerical methods in modeling this class of engineering problems. In DEM, both brittle fracture and plastic flow can be modeled within the same constitutive framework defined by contact laws at the micro-scale. The macro-scale failure behavior emerges as a result of interaction and failure at the micro-scale. No continuum scale constitutive model is required as direct input for the numerical model. The obvious drawback is that calibration of the material properties between the micro- and macro-scale becomes a prerequisite for DEM modeling.

For DEM based on bonded spherical particles (Potyondy and Cundall, 2004), a well-known issue is that the maximum ratio of compressive over tensile strength (UCS/UTS) that a particle assembly can attain is only about ~ 3 -5 (Huang, 1999), if the interactions between particles are limited to short-range, elasto-perfectly brittle and frictional. In comparison, the strength ratio for quasi-brittle materials such as rocks and concretes is in the range of 10-30 (Hoek and Bieniawski, 1965; Hoek and Martin, 2014). Furthermore, the failure envelope for the particle assembly generally fails to capture the high nonlinearity in the confined extension range.

The strength ratio, which can be considered a measure of material brittleness, directly affects the failure mechanisms and the transition between the failure modes if the problem of interest involves both the ductile and brittle mode of failure. In general, a low UCS/UTS means that the material in a confined extension stress state is more likely to fail in shear, while a high UCS/UTS means that brittle tensile failure is more likely to occur. As has been shown for the

Brazilian tensile test (Fairhurst, 1964; Ma and Huang, 2018c), a low UCS/UTS could result in plastic shear failure near the loading platens with the development of the center crack being suppressed.

Numerical strategies such as clumping/clustering particles (Cho et al, 2007), increasing the particle interaction range (Scholtès and Donzé, 2012) or using multiscale representation of the grain structure and rock fabric (Pierce et al, 2007; Potyondy, 2012), have been suggested in the literature to address the aforementioned issues. Nevertheless, DEM modeling for spherical particles having only short-range interactions has its appeal in its computational efficiency.

Here we show that a realistic strength ratio and the associated nonlinear failure envelope in the confined extension range can in fact be achieved by incorporating displacement softening in the contact law for conventional spherical particle DEM (Cundall and Strack, 1979). Formulation of a displacement softening contact model is first introduced and effects of the contact parameters on the strength ratio are then discussed. Importance of calibrating the strength ratio for problems involving both brittle and ductile mode of failure is illustrated through the Brazilian test. Calibration of the DEM model against Berea sandstone is given as an example.

Contact Model Formulation

The displacement softening contact model is developed based on the parallel bond option in PFC2D/3D (Potyondy and Cundall, 2004; Itasca, 2015). The parallel bond model has two contact components, a particle-particle point contact and an area contact through the bond in between the particles. The contact forces are superimposed from the two components. Moments can be transmitted through the area contact. The point contact is elastic and frictional, while the area contact is elasto-perfectly brittle.

The modification is restricted to the normal bond component only in this study. Displacement softening is introduced to the force-displacement law in the normal bond component (see Figure 1, where compression and stretch of the bond are taken as positive). For a bond in stretch, onset of softening occurs if the normal bond force reaches its maximum

$\bar{F}_{n\max} = \bar{\sigma}_c A$, where $A = \pi \bar{R}^2$ is the cross sectional area of the bond of radius $\bar{R}$. The softening path is defined by the softening coefficient β , a ratio between the normal stiffnesses along the softening and elastic loading paths, $\beta = \bar{k}_u/\bar{k}_\ell$. The parallel bond model is recovered if $\beta \rightarrow \infty$.

The bond fails if one of the criteria below is met at the contact,

$$\bar{\delta}_n + \bar{R}|\bar{\theta}| \geq \bar{\delta}_c \quad (1)$$

$$\frac{|\bar{F}_s|}{A} + \frac{|\bar{M}^n|\bar{R}}{J} \geq \bar{\tau}_c \quad (2)$$

where $\bar{F}_s$ is the shear bond force; $|\bar{M}^n|$ is the twisting moment; J is the polar moment of inertia of the bond; $\bar{\tau}_c$ is the shear bond strength; $\bar{\delta}_n$ is the normal bond stretch; $\bar{\theta}$ is the relative angle of rotation between the particles; and $\bar{\delta}_c$ is the critical stretch defined according to.

$$\bar{\delta}_c = \frac{\bar{\sigma}_c A}{\bar{k}_\ell} \left(\frac{\beta}{1 + \beta} \right) \quad (3)$$

If we make an analogy between the bond and a beam cross section, the failure criterion for the normal component, Eq. (1), is essentially equivalent to state that a bond breaks when the stretch at the outer edge of the bond reaches a critical value. Once a failure condition is reached, the contact forces in the bond are immediately reduced to zero and the contact is active only through the point contact component. Bond breakage is termed here a micro-crack event, in tension according to Eq. (1) and in shear according to Eq. (2).

Numerical Results

It follows from dimensional analysis that the primary factors influencing UCS/UTS in this model are the bond strength ratio $\bar{\tau}_c/\bar{\sigma}_c$ and the softening coefficient β . Uniaxial compression and direct tension tests

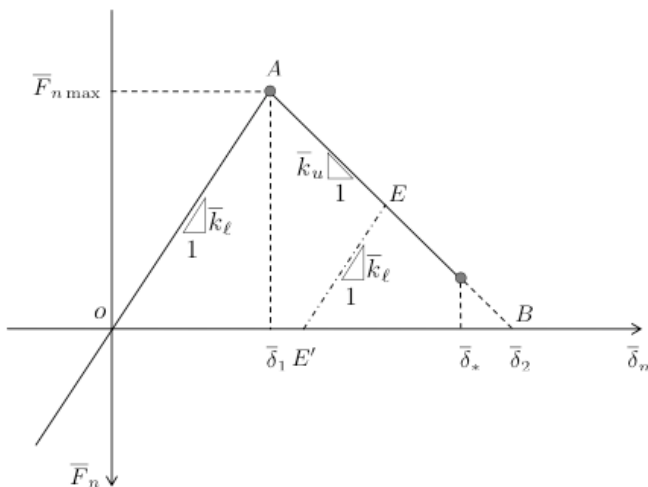


Figure 1. Force-displacement law for the normal bond.

are performed in both 2D and 3D to illustrate the effects of these two parameters. A rectangular sample of $W \times H = 60 \times 120$ mm and a cylindrical sample of $D \times H = 40 \times 80$ mm are generated with the following set of micro-scale parameters: particle and bond radii $\bar{R} = 0.8 - 1.66$ mm in uniform distribution, density $\rho = 2630$ kg/m³; stiffness ratio $K_n/K_s = 4.0$, friction coefficient $\mu = 0.5$, and bond stiffness ratio $\bar{k}_n/\bar{k}_s = 4.0$.

• Effect of bond strength ratio

For a given β , the bond strength ratio $\bar{\tau}_c/\bar{\sigma}_c$ basically controls the relative percentage of shear vs. tensile micro-cracks. When $\bar{\tau}_c/\bar{\sigma}_c \leq 0.5$, all bonds fail in shear; the corresponding UCS/UTS remains constant. When $\bar{\tau}_c/\bar{\sigma}_c \geq 10$, all bonds fail in tension; UCS/UTS reaches another plateau. UCS/UTS increases with $\bar{\tau}_c/\bar{\sigma}_c$ in the transition from the shear micro-crack dominant regime to the tensile micro-crack dominant regime. The two plateau values corresponding to small and large $\bar{\tau}_c/\bar{\sigma}_c$ depend on the softening coefficient β . Variation of UCS/UTS with the bond strength ratio is shown in Figure 2. The results are obtained with the following additional parameters: point and area contact moduli $\bar{E}_c = E_c = 20$ GPa, normal bond strength $\bar{\sigma}_c = 15 \pm 1.5$ MPa following the Gaussian distribution and $\beta = 0.15$. The largest strength ratio is UCS/UTS = 12.63.

In this set of simulations, the macro-scale failure mechanism in the form of shear localization remains similar in all the uniaxial compression tests. However, there are notable differences in the morphology of the failure plane in direct tension. At large $\bar{\tau}_c/\bar{\sigma}_c$, coalescence of the micro-cracks can be interpreted to form a mode I tensile crack. As $\bar{\tau}_c/\bar{\sigma}_c$ decreases, the failure plane become much more tortuous. The failure plane forms a spiral-like feature at $\bar{\tau}_c/\bar{\sigma}_c = 0.3$ (see Figure 3). Observations about the effect of $\bar{\tau}_c/\bar{\sigma}_c$ here are consistent with that from the perfectly brittle contact bond model in PFC (Huang and Detournay, 2008).

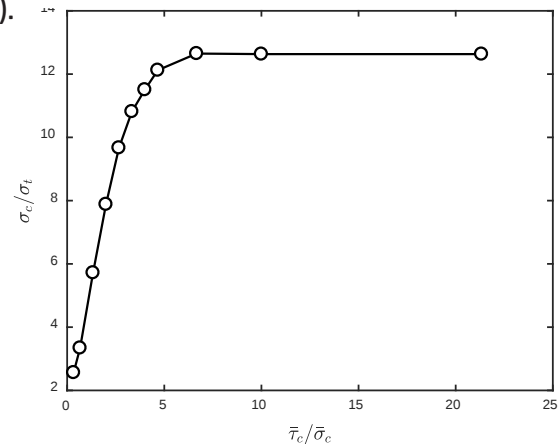


Figure 2. Variation of the compressive over tensile strength ratio with the bond strength ratio (Ma and Huang, 2018a).

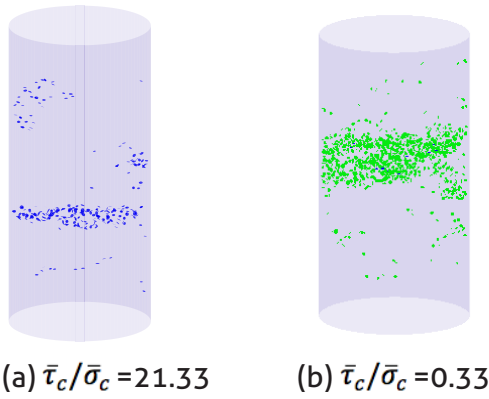


Figure 3. Distribution of the micro-cracks in the post peak at 80% of the peak load from direct tension test; blue for tensile micro-cracks and green for shear (Ma and Huang, 2018a).

• Effect of the softening coefficient

In order to explore the maximum range of UCS/UTS for the displacement softening contact model, $\bar{\tau}_c/\bar{\sigma}_c > 20$ is set in this series of simulations to investigate the effect of the softening coefficient β . As a result, the uniaxial strengths are mainly affected by the softening coefficient β and the normal bond strength $\bar{\sigma}_c$. Primarily for the reason of saving computational time, instead of β and $\bar{\sigma}_c$, we choose to parametrize the simulations with the normal bond strength $\bar{\sigma}_c$ and the nominal bond energy loss density $\bar{U}_b$, which characterizes the area underneath the force-displacement curve in Figure 1. The simulations are conducted with $\bar{U}_b$ being fixed while the normal bond strength $\bar{\sigma}_c$ varies to reflect the change in β . $\bar{\sigma}_c = 50$ MPa is first chosen for the perfectly brittle case ($\beta \rightarrow \infty$) and $\bar{\sigma}_c = 50\sqrt{\beta/(1+\beta)}$ in the other cases. The point and area contact moduli are set to be $\bar{E}_c = E_c = 50$ GPa in this series of simulations.

Variation of the uniaxial strength ratio with β is shown in Figure 4. It can be seen that the softening model is ineffective when $\beta \gtrsim 3.5$. This can be explained by the fact that unloading of the system, consisting of the bond plus the particles around it, is basically controlled by the softer one between the two components. The neighborhood around the broken bond controls the unloading when the bond softening path is stiff.

It is most interesting to note that as β decreases, UCS/UTS increases to as high as ~ 30 . To understand the reason for such an increase, we consider three particular cases with $\beta = 0.015, 0.1$ and ∞ from the 3D simulations. The corresponding normal bond strength is $\bar{\sigma}_c \approx 6, 15$ and 50 MPa. While the uniaxial tensile strength increases with the bond strength, UTS = 6.82, 7.53, 15.57 MPa, the uniaxial compressive strength in fact decreases with $\bar{\sigma}_c$, UCS = 222.68, 111.02, 61.62

MPa. The strength ratios for three cases are: UCS/UTS = 32.60, 14.70, 4.18. In these uniaxial tests, the macro-scale failure mechanisms, i.e., a mode I tensile crack in direct tension and shear localization in uniaxial compression, remain unchanged. There are very few micro-cracks prior to the peak during the tensile test. But there are a large number of micro-cracks prior to the peak in the compression test and the number of micro-cracks at the peak increases substantially as β decreases. We may therefore conclude that while UTS is primarily affected by $\bar{\sigma}_c$, UCS depends strongly on $N\bar{U}_b$, a nominal measure of the energy loss due to breakage of N number of bonds. As a result, the strength ratio UCS/UTS increases significantly as β decreases.

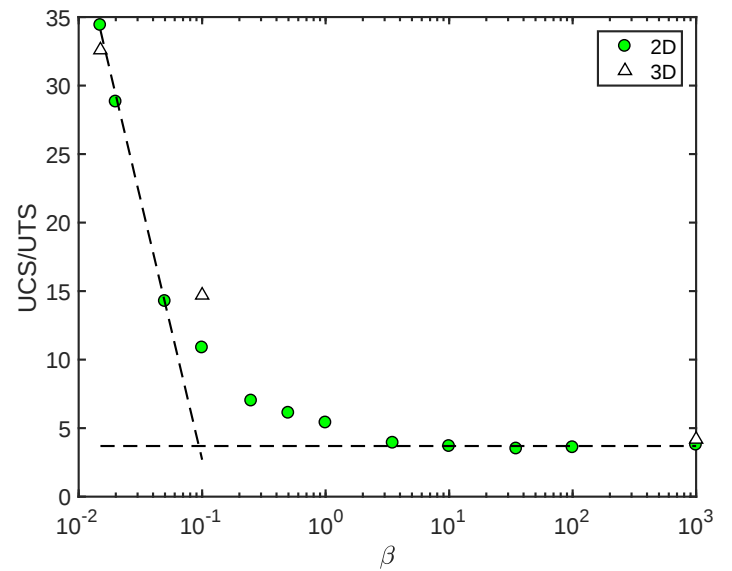


Figure 4. Variation of the strength ratio with the softening coefficient β (Ma and Huang, 2018b).

The Brazilian test is a robust laboratory experiment that has been commonly used for indirectly measuring the tensile strength. The diametric splitting strength is considered a good measure of the tensile strength with the premise that tensile failure initiates from the center of the specimen and propagates unstably towards the two loading platens. Nevertheless, existence of two distinct types of failure scenarios, namely, tensile failure from a center crack and the indentation-type of failure, has been verified through a variety of experimental techniques (see Ref. in Ma and Huang, 2018(c)).

For a DEM model with an elasto-perfectly brittle contact model ($\beta \rightarrow \infty$), since the strength ratio is rather low (UCS/UTS ~ 4), only the indentation-type of failure can be reproduced (see Figure 5a). The center crack scenario can however be reproduced if the displacement-softening contact model is used (see Figure 5b) with $\beta = 0.015$ (UCS/UTS = 32.60). These tests

are conducted with a sample diameter $D=40$ mm and thickness $t=10$ mm. The out-of-plane displacement is constrained on both the front and back faces. It should be noted that the tensile strength is in fact overestimated by the splitting strength in $\beta=0.015$, but underestimated in $\beta \rightarrow \infty$. This means that as far as material property calibration is concerned, it is important to calibrate the tensile strength of the particle assembly using direct tension instead of the indirect Brazilian test (Ma and Huang, 2017).

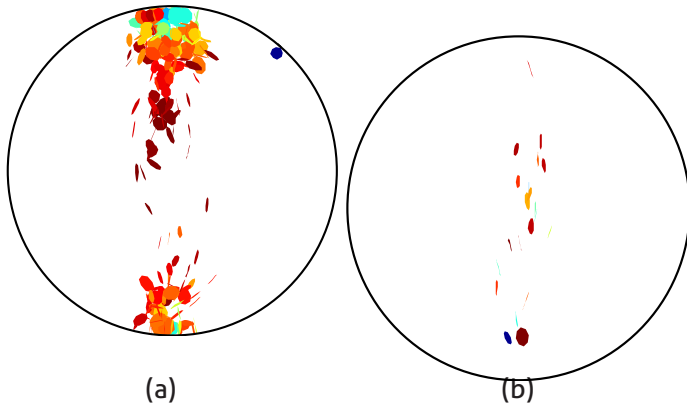


Figure 5. DEM simulations of the Brazilian test showing that the ratio of compressive over tensile strength ratio (UCS/UTS) affects the failure scenarios: (a) indentation-type of failure with $\beta \rightarrow \infty$; (b) failure from a center tensile crack with $\beta = 0.015$, colored circles represent micro-cracks; blue for early time and brown for late time micro-crack events (Ma and Huang, 2018c)

• Calibration for Berea Sandstone

Triaxial extension and compression tests on a 3D cylindrical sample with $\bar{E}_c = E_c = 20$ GPa, normal bond strength $\bar{\sigma}_c = 15 \pm 1.5$ MPa, $\bar{\tau}_c/\bar{\sigma}_c = 21.33$ and $\beta=0.15$ yield an excellent match up to $\sigma_3 \sim 100$ MPa with the failure envelope from the experiments with Berea sandstone in Bobich (2005) (see Figure 6). These tests are performed following the stress path of the conventional triaxial experiment. The numerically obtained failure envelope also offers an interesting insight. While the overall failure envelopes can be very well fitted by the Hoek-Brown criteria, the tensile strength remains nearly constant if the magnitude of the compressive principal stress is limited to a few times of uniaxial tensile strength. This means that the use of a tension cutoff in conjunction with a failure criterion for shear is indeed justified.

Other mechanical properties of the particle assembly are: Young's modulus $E=17.98$ GPa, UCS = 108.35 MPa, UTS = 6.80 MPa and UCS/UTS = 15.88, which agree very well with those of Berea sandstone (Bo-

bich, 2005): $E=8-24$ GPa, UCS = 79 MPa and UTS = 4.9-7.3 MPa (UCS/UTS = 10-16). The tensile strength from the experiment is determined from a direct tension test. Note UCS/UTS here is slightly different from the results in the previous section since the samples are two different statistical realizations.

As far as the failure mechanisms are concerned, failure planes in the triaxial tests show rather complex morphology as the confinement increases. Failure in direct tension is still strongly localized on a horizontal plane. However, in the confined extensions tests, the failure planes appear to become wavy and

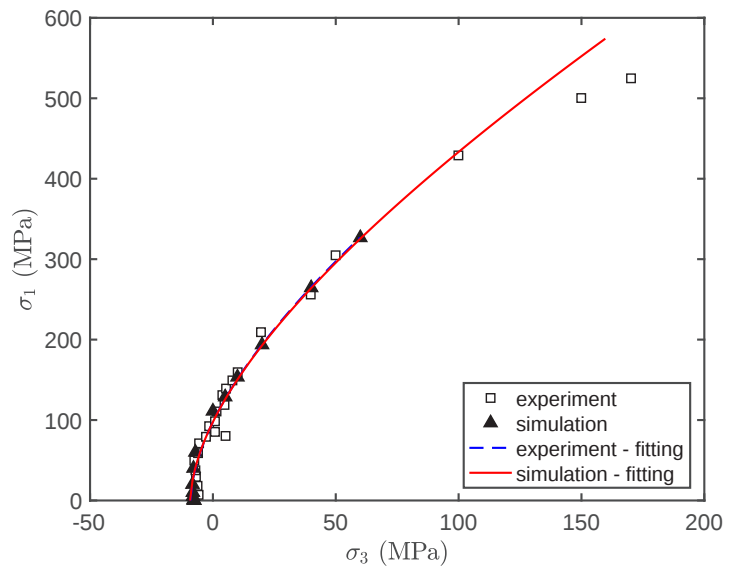


Figure 6. Comparison of the failure envelopes between the simulations and the experiments of Berea sandstone (Bobich, 2005); fitted by Hoek-Brown criteria; the dashed blue line coincides with the red solid line (Ma and Huang, 2018b).

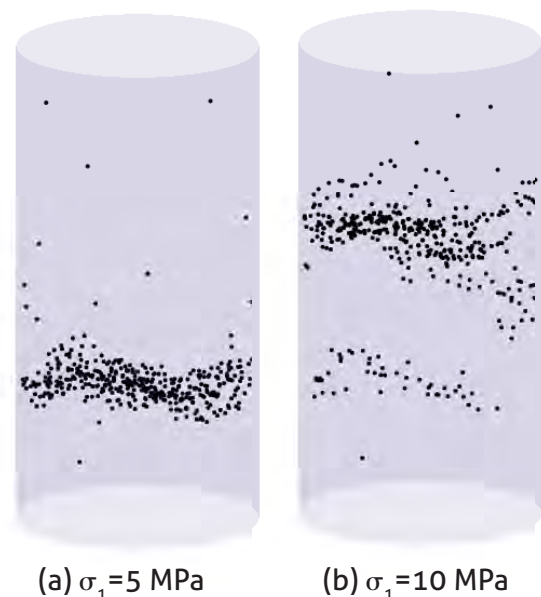


Figure 7. Distribution of the micro-cracks at 90% post-peak in the confined extension tests for modeling Berea sandstone (Ma and Huang, 2018b).

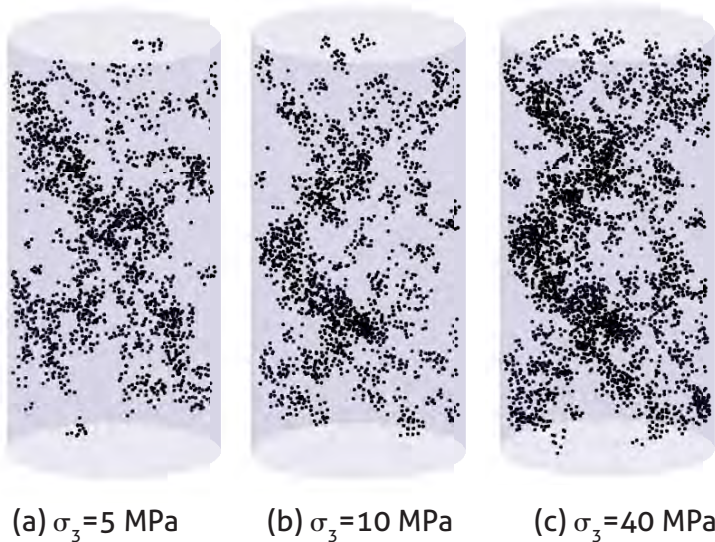


Figure 8. Distribution of the micro-cracks at peak in the triaxial compression tests for modeling Berea sandstone (Ma and Huang, 2018b).

inclined (see Figure 7). Meanwhile, rather intricate shear band structures are obtained from the triaxial compression tests (see Figure 8). As the confining stress increases, the conjugated shear bands seem to become connected to form spirals.

Concluding Remarks

Displacement softening in the contact laws has shown to be an effective ingredient in increasing the strength ratio and capturing the nonlinearity in the failure envelope in the confined extension range for DEM modeling. However, with the bond strength ratio and the softening coefficient both affecting the uniaxial strength ratio, conventional material property calibration using only elastic constants and the uniaxial strengths become insufficient. Future work is needed to examine the additional aspects of material behaviors at both the micro- and macro-scale so that a DEM particle assembly can model more effectively the behaviors of quasi-brittle materials such as rocks.

Acknowledgments

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ARMA Student Chapters: A Vital Contribution

Submitted by John McLennan, Department of Civil and Environmental Engineering, University of Utah and ARMA Fellow

Overview

As part of the charter of the American Rock Mechanics Association (ARMA), it is necessary not only to share technical and scientific information relating to rock mechanics and geo-engineering, but to try to expand its core knowledge, to develop the profession and to contribute to its related industries. This necessitates that ARMA as a professional and scientific organization finds means for continual innovation and sustained development to attain the social, economic, and scientific undertakings and accomplishments that ARMA aspires to.

In support of this, a recent phenomenon is the establishment of student chapters of ARMA at a number of universities. These chapters serve important functions. They encourage student participation in

a professional and scientific society, and they create opportunity for academic and professional integration. They also provide platforms for future leadership that will contribute to succeeding generations of ARMA membership, ensuring progressive advancement of rock mechanics/geo-engineering.

This article summarizes the current status of chapters at four universities. All have made significant contributions to their schools and their engineering departments, to ARMA as an organization, and most importantly, to the active involvement of those training in rock mechanics/geo-mechanics.

The summary characteristics of the featured chapters are presented in the following table, with highlights from each reporting chapter to follow.

Table 1. Chapters at a Glance

Chapter	Year established	Members	Correspondent	Contact
Colorado School of Mines	2011	26	Olawale Adekunle (President)	oadekunl@mymail.mines.edu
Missouri University of Science & Technology	2015	15 (14 grad, 1 u-grad)	Weicheng Zhang (President)	wz9qd@mst.edu
Texas Tech	2015	78 (20 grad, 58 u-grad)	Marshal Wigwe (Treasurer)	Marshal.Wigwe@tu.edu
Virginia Tech	2017	40 (5 grad, 35 u-grad)	Juan J. Monsalve (Co-founder)	jjmv94@vt.edu

Colorado School of Mines (CSM)

Since its establishment in 2011 as the first student chapter of ARMA, the CSM chapter activities have grown significantly, serving the CSM geomechanics community and providing students, faculty and research staff with numerous learning and networking opportunities. They have organized a distinguished speaker series, often in conjunction with the Unconventional Natural Gas and Oil Institute (UNGI), the Society of Petroleum Engineers (SPE), the International Association

of Drilling Contractors (IADC), and others. They also have organized periodic field trips and group events. There has been special focus on professional development with software training, use of specialized equipment, presentation skills, and career management. The CSM chapter has its own website: www.armorocks.org/membership/student-chapters. (Note: others may find the link to their bylaws useful if they are planning on organizing a chapter.)

One unique feature that helps build membership is periodic participation as a group in civic and charitable and community events. Rock mechanics can do good works, particularly if done as a chapter.



Figure 1. Natural Fractures Field Trip Fall 2017 (Colorado School of Mines)

Missouri University of Science and Technology



Figure 2. Chapter picture. (Missouri University of Science and Technology)

This chapter holds monthly meetings, has frequently invited guest speakers, and plans future technical workshops. They often will encourage topics and presentations on interdisciplinary studies and topics. One valuable function is using chapter members for a rehearsal and acting as a sounding board for those attending and making presentations at the annual ARMA symposia.

Texas Tech

The ARMA chapter at Texas Tech aims to recruit members with civil engineering and geosciences background and interests. In their history (and common to other chapters) they have successfully managed to add members each year in spite of the inevitable attrition that occurs with graduations. After a recent down-sizing and loss of the founding members, their efforts to recruit candidates have been successful in rebuilding the number of members.

They coordinate monthly technical events and seminars, with interdisciplinary speakers from academia and industry. Two recent events were in January, 2018 with the organization of a symposium on "Optimize the Unconventional" and in February hosting a town hall meeting on "Entrepreneurship for Young Engineers."

The chapter publishes an e-magazine ("Armazine") for its members, with potential readership beyond the chapter and the university.



Figure 3. Members pick up food and ARMA t-shirts, new members registration. (Texas Tech)

Virginia Tech

While this chapter was only recently formed (December, 2017) it has shown dramatic progress in a short time. They have had three recruiting meetings, making in-class presentations. They also convened their initial chapter meeting, where the fundamentals of organization were addressed with the election of officers. The chapter has developed an annual agenda, and adopted policies and procedures. Planned member activities include research discussions, field trips, guest speakers, and webinars. And they pay attention to social life, with a "meet and greet" cookout in February; chapters can have fun as well.

Combined ARMA and DFNE Symposium: Invitation to Seattle, Washington

The American Rock Mechanics Association invites you to its 52nd US Rock Mechanics/Geomechanics Symposium to be held in Seattle, Washington, USA on 17-20 June 2018. This year, the symposium will be followed by the 2nd International Discrete Fracture Network Engineering (DFNE) Conference on 20-22 June 2018.

The symposium program will focus on new and exciting advances in all areas of rock mechanics and geomechanics. Two short courses and one workshop will be held immediately prior to the symposium.

Seattle is one of the country's fastest growing and exciting cities. Home to some of the world's most innovative companies (including Microsoft, Amazon and Starbucks), Seattle is known for its beautiful mountains and waterfront, its world-class restaurants, and its sophisticated cultural institutions.

Technical tours and field trips are scheduled. Sightseeing tours will include various city landmarks, markets, and other attractions. For further information or to register, see website: <http://armasyposium.org/>



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