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STIFTELSEN BERGTEKNISK FORSKNING
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REPRESENTING SPALLING IN ROCK EXCAVATIONS WITH BBM

Representation av spänningsinducerade brott i tunnlar och bergrum med BBM

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PREFACE

Spalling occurs in many different types of projects in rock masses in Scandinavia, including projects in the mining, infrastructure, and storage sectors. Spalling can be problematic for these projects as it may change the profiles of the excavations and transmissivity of the surrounding rock mass. However, numerical modelling of spalling is complex. Typically, continuum models are used with strain softening constitutive models, but they are only a proxy for spalling. They are unable to capture the mechanisms underlying spalling, and they therefore work best as back analysis.

This project studies the suitability of a new modelling technique to represent spalling in Scandinavia. The technique is called "Bonded Block Modelling" (BBM) and represents the rock mass as a conglomerate of blocks. Rock mass damage is represented by breakage of the contacts between blocks. The focus of this study is to give advice to practitioners who wish to use BBM in the future, through a literature review and an application of BBM to laboratory tests and *in situ* spalling of an actual case from LKAB's Malmberget Mine. The report concludes with a discussion, recommendations, and suggestions for future work to provide practitioners and researchers alike a path forward.

The project group included Jonny Sjöberg and Jessa Vatcher (both with Itasca Consultants AB). The reference group included Axel Bolin (Trafikverket), Diego Mas Ivars (SKB), Beatrice Lindström (formerly Trafikverket), Marie von Matérn (WSP), Thomas Wettainen (LKAB), and Per Tengborg (Rock Engineering Research Foundation - BeFo).

It is our hope that this report is one of many steps towards the common use of BBM techniques. This project was financed by BeFo, Rock Engineering Research Foundation, and Itasca Consultants AB contributed in-kind.

Stockholm, 2021

Per Tengborg

FÖRORD

Spjälkning sker i många olika bergprojekt i Skandinavien, inkluderande gruvor, infrastrukturtunnlar och berganläggningar för förvaring. Spjälkning kan vara problematiskt i dessa miljöer eftersom den kan orsaka ändringar i uttagsprofilen och bergmassans transmissivitet. Att modellera spjälkning är dock komplext. Det är vanligt att man använder kontinuum-modeller med en töjningsmjuknande konstitutiv modell, men det är bara en proxy för spjälkning. Denna teknik fångar inte upp de underliggande mekanismerna och funkar därför bäst som tillbakaräkning.

Detta projekt är en förstudie som utforskar lämpligheten av en ny modelleringsteknik för att representera spjälkning i Skandinavien. Modelleringstekniken heter 'Bonded Block Modelling' (BBM) och representerar bergmassan som ett konglomerat av block. Skador i bergmassan representeras av brott längs kontakter mellan block. Fokus på förstudien är att ge råd till de som vill tillämpa BBM i framtiden, framtagna via en litteraturstudie och en applicering av BBM på laboratorietester och *in situ* spjälkning av ett aktuellt fall från LKAB:s gruva i Malmberget. Rapporten avslutats med en diskussion, rekommendationer och förslag på framtida arbete för tillämpning av BBM.

I projektgruppen ingick Jonny Sjöberg och Jessa Vatcher (båda vid Itasca Consultants AB). Projektets referensgrupp har bestått av Axel Bolin (Trafikverket), Diego Mas Ivars (SKB), Beatrice Lindström (tidigare Trafikverket), Marie von Matérn (WSP), Thomas Wettainen (LKAB) och Per Tengborg (Stiftelsen Bergteknisk Forskning - BeFo).

Det är vår förhoppning att föreliggande rapport är ett av många steg mot en mer regelbunden användning av BBM-tekniken. Projektet har finansierats av BeFo, Stiftelsen Bergteknisk Forskning, och Itasca Consultants AB bidrog med naturainsats.

Stockholm, 2021

Per Tengborg

SUMMARY

Bonded block modelling (BBM) is a relatively new numerical modelling technique that attempts to capture rock mass damage through the interaction and breakage of contacts between "blocks" (volumes) of rock. Its suitability for modelling spalling cases in Scandinavia is evaluated in this report. The intended outcome of this work is to provide up-to-date information, guidance, and insights on how BBM can be applied and used by practitioners.

While steadily increasing in quantity, the small number of published works on BBM show promising qualities for modelling rock mass damage. A gap in the literature exists, however, concerning many choices those modelling BBM must make. Additionally, the examples found in the literature typically use block sizes which are significantly larger than those that would be required to represent the spalling phenomenon, as spalling occurs at the inter- and intra-grain level.

A well-documented spalling case was selected for analysis: Malmberget Mine's Öde E8 ventilation shaft. The depth of spalling was approximately 10 cm. A BBM material with very small blocks (near grain size) was created. The rock in the shaft was represented by this BBM material through a careful calibration process. This process included models of UCS and Brazilian tests. It was demonstrated that the configuration of the blocks effects the results. *In situ* quasi-3D models were created with a BBM region in the expected area of spalling. Results were obtained for the calibrated BBM material calibrated to the laboratory test results, as well as a BBM material where the UCS was reduced to that of the laboratory crack initiation value. Spalling was present in both models; however, the position and form did not match that of the actual case. The reduced strength models had more spalling, but still did not achieve the spalling depth of the actual case. Signs exist that the stiffnesses between and in the continuum portion of the model and the discontinuum portion of the model are resulting in some boundary effects. It is one of the challenges of these models.

The research presented in this report, both the literature review and practical application, is one of many steps towards the regular use of BBM techniques by practitioners. While BBM is a promising step forward towards a better understanding and modelling capability of rock mass damage, the application of BBM for spalling behaviour in *3DEC* is currently challenging due to the requirement of small block sizes and the limitations of current computing power. Modelling depth of spalling damage is possible with BBM, provided one does not need to capture the entirety of the underlying mechanism.

Specific recommendations to practitioners concerning modelling of spalling using BBM include:

- Suitable spalling cases to be modelled using BBM techniques are those which have good data concerning laboratory testing and can be run in quasi-2D.

- Attempting to model the exact process of spalling using BBM is currently difficult due to computational limitations restricting minimum block size. It is suggested that for practical cases block size should currently be selected to achieve at least six blocks across the damage (notch) depth and width, similarly to common practice in continuum modelling. Care should be taken to check that this block resolution is appropriate for each specific modelling case, by examining the results from a critical perspective.
- Adequate time for the calibration process is important, as it is not always straightforward.
- Block configuration during the calibration process is important.
- Contact shear and normal stiffnesses are less significant than the other properties, such as cohesion and tension in models of laboratory tests.
- The use of a ratio between tension and cohesion is appropriate until proven otherwise.
- A distribution of the tensile strength (and therefore cohesion) across all contacts may help better represent the variance of UCS tests. Correlated random fields should be considered.
- Start *in situ* modelling with simplistic models (continuum) to check model behaviour and identify exactly where in the model the BBM region should be built.
- Contact stiffnesses in *in situ* modelling between the BBM region and the continuum should likely be based on zone size, not the values from calibration. These stiffnesses may result in problems with the stresses in the model, and time and effort may be required to find values that work.
- It is inconclusive if a reduction of the BBM material strength is required when the block sizes are near grain size. However, it is still postulated that this strength reduction is required for larger blocks. It is proposed that this is due to a combination of 1) rock mass strength being less than intact strength, 2) the lack of strength heterogeneity of the material, and 3) the lack of damage build-up possibly caused by the stress path.

Keywords: numerical modelling, BBM, spalling, damage

SAMMANFATTNING

Bonded block modelling (BBM) är en relativt ny teknik inom numerisk modellering som försöker fånga upp bergmassans beteende genom samspelet och brott längs kontakter mellan "block" (volymer) av berg. I denna rapport utvärderas lämpligheten av BBM för modellering av spjälkning i Skandinavien. Syftet med detta arbete är att ge aktuell information, vägledning och insikter om hur BBM kan tillämpas och användas.

Även med en stadigt ökande mängd litteratur i ämnet, så visar det förhållandevis lilla antalet publicerade verk på BBM på en del lovande resultat för modellering av bergmassans beteende. Det finns dock en kunskapslucka beträffande många av de modelleringsval som krävs för BBM-tillämpningar. Dessutom är de blockstorlekar som vanligen beskrivs i litteraturen signifikant större än de som skulle krävas för att representera spjälkning, eftersom spjälkning sker på mineralkorns-nivå.

Ett väldokumenterat fall av spjälkning valdes ut för analys: ventilationsschaktet Öde E8 i LKAB:s gruva i Malmberget. Observerat spjälkningsdjup var ungefär 10 cm. Ett BBM-material med mycket små block (nära mineralkornsstorlek) skapades i beräkningsmodellen. Berget runt schaktet representerades av detta BBM-material genom en noggrann kalibreringsprocess. Denna process inkluderade modeller av enaxiella trycktester och indirekta dragtester ("Brasilien"-tester). Analyserna visade att blockkonfigurationen påverkade resultaten. *In situ* pseudo-3D-modeller av schaktet skapades med en BBM-region i det förväntade spjälkningsområdet, med BBM-materialet från modeller av labtester samt med ett BBM-material med hållfasthet minskat till sprickinitieringsnivå. Båda materialen uppvisade spjälkning, men motsvarande inte helt observerad position eller form av spjälkning i Öde E8. Modellerna med minskat hållfasthet hade ett större spjälkningsdjup, dock nådde de inte de observerade 10 cm djup. Resultaten visade att styvheten både inom kontinuum-regionen och mellan denna och BBM-regionen resulterade i randeffekter. Detta är en av utmaningarna med dessa modeller.

Forskningen som presenteras i denna rapport, både litteraturöversikten och den praktiska tillämpningen, är ett av många steg mot en mer regelbunden användning av BBM-tekniken. Tekniken är ett lovande steg framåt mot en bättre förståelse och modelleringsförmåga för bergmassans beteende, men tillämpningen av BBM för spjälkning i *3DEC* är för närvarande utmanande på grund av kravet på små blockstorlekar och nuvarande begränsningar av datorkraft. Att modellera formen av spjälkning är troligtvis möjligt med BBM (genom att använda större block), förutsatt att man inte behöver fånga hela den underliggande mekanismen. Med de väldigt små block som användes i denna studie var det dock inte möjligt att helt matcha den faktiska spjälkningsformen eller djupet. Indikationer finns att styvheten mellan kontinuum- och diskontinuum-områdena i modellen påverkar resultaten i BBM-området.

Specifika rekommendationer för modellering av spjälkning med BBM inkluderar:

- Lämpliga spjälkningsfall som ska modelleras med BBM-tekniken är de där det finns bra data på laboratorietester och som kan analyseras med en pseudo-2D geometrisk modell.
- Att modellera den exakta processen för spjälkning med BBM är för närvarande svårt på grund av tillgänglig datorkraft, vilket begränsar minsta möjligt användbara blockstorlek. Det föreslås att för praktiska fall bör blockstorlek väljas så att man uppnår minst sex block över spjälkningens djup och bredd, på samma sätt som vanlig praxis vid kontinuum-modellering. Försiktighet bör iakttas för att kontrollera att denna blockupplösning är lämplig för varje specifikt modelleringsfall genom att undersöka resultaten ur ett kritiskt perspektiv.
- Det är viktigt att avsätta tillräckligt med tid för kalibreringsprocessen eftersom den inte alltid är enkel och rättfram.
- Blockkonfiguration under kalibreringsprocessen är viktigt att beakta.
- Skjuv- och normalstyvhet för kontakter mellan block är mindre signifikanta än de andra egenskaperna, såsom kontaktkohesion och kontaktdraghållfasthet i modeller av laboratorietester.
- Användningen av ett förhållande mellan kontaktkohesion och kontaktdraghållfasthet är lämpligt tills annat bevisats.
- En fördelning av kontaktdraghållfasthet (och därmed kontaktkohesion) över alla kontakter kan hjälpa till att bättre representera variationen i enaxiella trycktester.
- För *in situ*-modellering är det viktigt att börja med förenklade kontinuummodeller för att kontrollera modellbeteende och identifiera exakt var i modellen BBM-regionen ska byggas.
- Kontaktstyvheter mellan BBM-regionen och kontinuumet för *in situ*-modellering bör troligtvis baseras på zonstorlek, inte värdena från kalibreringen. Dessa styvheter kan vara problematiska för spänningar i modellen och därmed kräva tid att modellera korrekt.
- Det kan inte fastställas om en minskning av hållfastheten för BBM-materialet var viktigt för att uppnå spjälkning i *in situ*-modellerna. Det är emellertid fortfarande antaget att en sådan hållfasthetsminskning krävs för större block. Detta kan bero på att: 1) bergmassans hållfasthet är lägre än intakt hållfasthet, 2) heterogenitet i hållfasthet inte beaktats och/eller 3) brist på uppkomst av skador i bergmassan till följd av applicerad spänningsväg.

Nyckelord: numerisk modellering, BBM, spjälkning, bergskador

CONTENTS

1. INTRODUCTION

The purpose of this project is to explore and evaluate the relatively new Bonded Block Model (BBM) numerical modelling technique to represent spalling for cases in Scandinavia. The intended outcome of this work is to provide up-to-date information, guidance, and insights on how BBM can be applied and used by practitioners.

Spalling is the progressive, onionskin-like flaking of rock (*in situ* examples shown in Figure 1). It occurs in brittle environments and is a tensile cracking phenomenon that is believed to occur between mineral grains with some intragrain breakage. When a volume on the excavation boundary is highly stressed, tensile cracks form along the direction of loading. These tensile cracks form between and through grains, eventually aligning, resulting in thin slabs of rock broken off from the main rock mass. The resulting shape of the damage when it has stabilized is typically a notch. In Scandinavia, the mining, infrastructure, and spent nuclear fuel repository industries often deal with brittle ground, which can exhibit spalling behaviour. Spalling can be an issue in each of these industries as it causes unexpected overbreak, which can result in 1) no longer meeting design acceptance criteria, and/or 2) larger scale stability problems. Prediction of spalling location and depth is important to many types of rock excavations.

Figure 1. Examples of in situ spalling, where a) is a shaft in Garpenberg Mine (Edelbro, 2008), b) is a shaft exposed to thermal load to create spalling (Andersson, 2007), and c) is a close up of a cross-section of spalling in the tunnel in the Mine-by-Experiment (Martin, 1997).

Although spalling is a well-known phenomenon, the understanding of the physical process and modelling thereof is less complete. Standard spalling analysis consists of using simple numerical models to get the approximate stress tensor combined with empirical criteria such as crack initiation limit. Numerical representation of the spalling process has been difficult and modelling inter- and intragrain breakage is not straightforward. Modelling techniques which can spontaneously recreate the spalling process would enable a deeper understanding and ability to forecast spalling locations and depths. This is where the BBM technique offers promise, although since it is not an established method, groundwork needs to be done to understand if this technique can be useful for cases in Scandinavia.

BBM represents the rock mass as bonded blocks, where the breakage of the contact between blocks represents new fracturing in the rock mass. This study evaluates the use of BBM for a well-documented example of spalling in Sweden to better understand the use and applicability of BBM. The case selected was a ventilation raise (Öde E8) in LKAB's Malmberget Mine due to the excellent documentation, good underlying data, and previous modelling work. Since there is relatively little published on BBM, a scientific and first principles approach was taken in this work to help guide practitioners.

This study is limited to evaluating spalling in only one rock type. Some fundamental questions remain unexplored in this study, although all attempts have been made to identify these aspects for future researchers.

This document begins with an introduction to spalling and BBM. A section on the experimental setup follows, which includes much of the lessons learned during this project about how the BBM modelling process should take place. Results from the modelling work of spalling in the Malmberget Mine ventilation raise Öde E8 are then presented. The report concludes with a discussion of the lessons learned and applicability of BBM.

2. LITERATURE REVIEW OF BBM

BBM is a discontinuous numerical modelling technique that is relatively new. The technique represents the rock mass as bonded blocks (Figure 2). These blocks may be rigid or deformable and are decided by the zone constitutive model and associated properties. All block contacts are provided a constitutive law and associated contact properties, which are sometimes referred to as microproperties. Spontaneous rock mass fragmentation is exhibited by the models as breakage of the contacts, making fragments. This makes BBM a tool of interest in representation of spalling, since the current methods using continuum model results and empirical relationships miss the mechanisms, even if some constitutive models in the continuum can be well calibrated to damage extent and form.

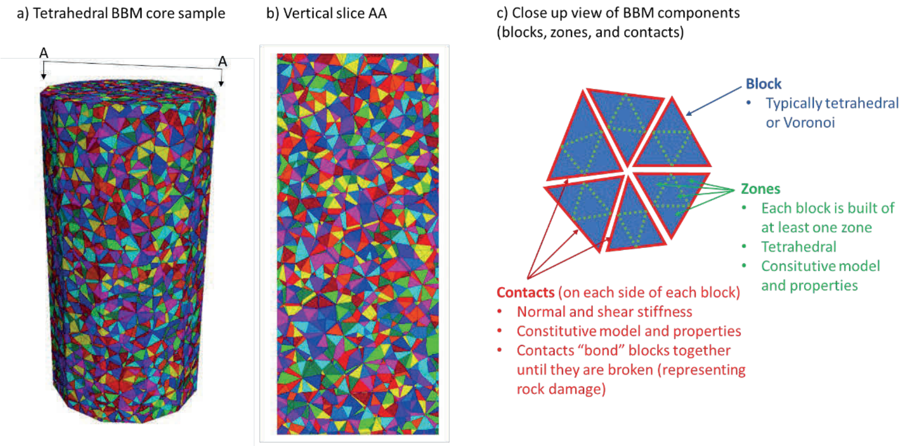

Figure 2. BBM model construction in 3DEC, where a) is a tetrahedral BBM core sample ready for UCS testing (blocks are coloured), b) is a vertical slice through that core sample (blocks are coloured), and c) is a close up depiction of the three components of BBM models. The components are blocks (blue), zones (edges shown in green), and contacts between blocks (red).

Some published work using BBM exists (Garza-Cruz *et al.*, 2014; Ghazvinian *et al.*, 2014; Turichshev, 2016; Azocar, 2017; Turichshev and Hadjigeorgiou, 2017; Gao *et al.*, 2019; Gong *et al.*, 2019; Li *et al.*, 2019; Sinha and Walton, 2019; Walton and Sinha, 2020). Published works show that BBM offers much promise in representing rock behaviour and damage. Some of the more applicable works concerning spalling are summarised in the following paragraphs.

Walton and Sinha (2020) provide an overarching summary of advances in BBM, focusing on what phenomena can be reproduced, if BBM can reproduce field behaviour (including deformation and dilation), and if BBM can reproduce rockbolt-rock mass interaction.

While spalling is not the focus of this paper and is not significantly addressed, many aspects of the paper describe large steps forward in BBM technique research.

Garza-Cruz *et al.* (2014) provides a published example of the use of BBM in *3DEC* (Itasca Consulting Group, Inc., 2019a) to represent spalling around a tunnel at depth. Model response showed rock mass damage due to high stresses, including fracturing and bulking of massive rock. The extent of damage was larger than in corresponding continuum models, although difficulties exist in validation due to lack of field data on rock damage. This paper discusses spalling; however, it is important to note that the block size, and therefore the smallest possible fragment size as a result of spalling, is relatively large (0.25 m).

Since BBM is relatively new, gaps exist in the literature providing much opportunity for researchers and practitioners alike. To date, definitive published information is not yet available concerning the influence of the following on the model behaviour, although many authors have started exploration of these topics:

- Block size

  Potyondy and Cundall (2004) have clearly shown that in bonded particle modelling (BPM) particle size has a strong influence over material fracture toughness. Although BPM is not exactly the same as BBM in as the numerical formulation is different, there are enough similarities to identify that block size may affect results. With consideration to computational power, it is tempting to calibrate models of laboratory tests with a small block size and use the results of this calibration on *in situ* models with a larger block size. It is postulated that this change in block size will affect material behaviour, however.

- Block shape

  Ghazvinian *et al.* (2014) illustrated in 2D that the use of triangular grains encourages smooth pathways for cracking and shear sliding, whereas Voronoi grains have rougher cracking pathways which act like asperities (Figure 3). Further evidence of differing behaviours due to grain shape can be found in Potyondy *et al.* (2020). Although these models were in completed in *PFC3D*, the grain shape significantly affected material laboratory behaviour and spalling. An important conclusion of this work was that the tetrahedral shapes were most appropriate to model rock. It is unclear if this conclusion can be extended to *3DEC*, due to their significantly different numerical formulation.

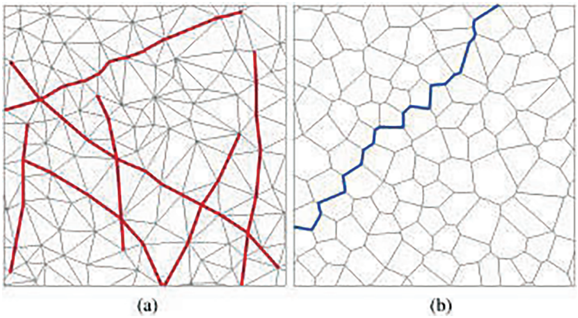

Figure 3. Cracking pathways from a) triangular grains and b) Voronoi grains. Notice that the Voronoi grain cracking pathways have many more asperities. (Ghazvinian *et al.*, 2014).

- Block configuration

  A gap in the literature exists concerning block configuration in BBM. It is postulated that model stiffness is affected by the alignment of BBM blocks to vessel edges (such as UCS core sample edges or tunnel edges).

- Block internal properties and constitutive model

  Walton and Sinha (2020) are one of the pieces of literature that have methodologically addressed this topic at the laboratory scale. They identified that incorporating grain internal stiffness heterogeneity was important for accurate simulation of damage initiation and propagation. An inelastic constitutive model was required to simulate the transition between extensile fracturing and shear fracturing. Specific to the stress conditions where spalling tends to occur (low confinement, high major principal stress), all macroscopic attributes aside from post-peak behaviour were, however, achieved with homogeneous properties and an elastic material model.

- Distribution of contact properties

  A gap in the literature exists concerning the effect of using a distribution for contact properties. Many authors have used a distribution of contact properties; however no information has been found of the necessity nor effect thereof. An important aspect of contact property distribution is also how the distribution is spatially correlated. For example, smooth gradients between high and low values rather than sharp contrasts may result in different behaviour. This is further discussed in Le Goc *et al.* (2015).

- Relationship of contact tensile strength (also referred to as micro tension) to contact cohesive strength (also referred to as micro cohesion)

  Current standard procedure is to use a constant relationship between these contact properties, where the contact cohesive strength is 2.5 times greater than the contact tensile strength. (Garza-Cruz *et al.*, 2014) However an in-depth exploration of effect of this assumption on model results is not available in current literature.

- 2D versus 3D modelling

  BBM exist in 2D, quasi-3D (where there are multiple BBM particles across the small depth of a 3D model representing a plane-strain or plane-stress problem), and true 3D. While it is clear that rock damage and failure processes are a 3D phenomenon, a gap exists in the literature comparing the results and techniques between the two modelling forms, specifically if 2D BBM models produce the same behaviour as their quasi-3D and 3D counterparts.

- Best calibration process

  All BBM models rely upon a calibration process, where the behaviour of the rock in laboratory tests is replicated in models by adjusting the contact properties. This step is essential to ensuring that the behaviour of the rock in the models corresponds to the actual behaviour of the rock. A relatively standardized calibration approach exists based on work in BPM, as is outlined by both Mas Ivars (2010) and Turichshev (2016). This calibration approach is as follows:

  1. Calibrate contact normal and shear stiffness in elastic UCS tests to reproduce correct Young's moduli and Poisson's ratios.
  2. Calibrate the contact tensile strength, and therefore contact cohesive strength, of the samples to reproduce the direct tension of the sample. This value is often equated to the indirect tensile tests (Brazilian tests) by an analytical relationship.
  3. Return to the UCS tests with the calibrated properties from 2. Check that the behaviour is correct and adjust the contact tensile strength (and cohesion) as needed.

While it is clear from the literature that BBM has the potential to represent failure processes in ways we have not previously been able to explore, additional research is required. This need for research makes it difficult for practitioners to apply BBM in their daily work. It is because of this difficulty that this report focuses on the process of BBM modelling work, with identifications of common pitfalls and important considerations as identified through the case study.

3. EXPERIMENTAL SETUP

Since BBM is a relatively new technique that clearly has many unaddressed aspects in the literature, this project approaches the problem from a research perspective. Fundamental assumptions are studied in the most rigorous manner allowed for within the constraints of the project. This section explains the experimental setup of the entire project, and includes lessons learned along the way that shaped this setup. In that way, this section is a part of the project results and includes insights into how this method can be applied to other problems. Special attention is therefore given in this section to identifying aspects of BBM that this experimental setup did not address.

The analysis code *3DEC* (Itasca Consulting Group, Inc., 2019a, 2020a) was selected to complete this evaluation. *3DEC* is a discontinuum numerical stress analysis software, which enables complete separation and rotation of blocks. At the time of project conception and commencement, *3DEC* was the natural choice for BBM models. BBM models are a subset of the Discrete Element Method (DEM), where finite displacements and rotations of bodies are possible and new contact detection is automatic (particularly important for BBM). Commercially available codes which are capable of this are few. It should be noted that now, however, recent adaptations in the computer program *PFC* (Itasca Consulting Group, Inc., 2019b) have enabled rigid block BBM. This creates new possibilities for BBM models in the future, as the alternate formulation that exists in *PFC* makes it more appropriate to deal with many blocks as well as ease of use due to recent significant program updates.

This exploration of spalling consists of two phases:

1. Material calibration
2. *In situ* models using the calibrated material to see if spontaneous spalling can be captured in the models.

Initially, multiple *in situ* spalling cases were selected, and multiple hypothetical cases covering infrastructure, energy, and mining sectors were planned as a part of this project. However, more attention was instead given to further understanding basic research questions. Therefore, after material calibration, *in situ* models of a single selected spalling case of the Öde E8 ventilation raise in Malmberget Mine were completed.

This section begins by discussing the important modelling considerations to enable scientific validity, followed by a more in-depth discussion of the two phases of the case study.

3.1 Important modelling considerations

The setup of this study was deliberate to avoid excessive unknown variables that would cloud cause and effect. This section discusses these specific decisions made during the modelling and should be important to directing future work in BBM.

Based upon the work of numerous authors in BBM and particle modelling as discussed in Section 0 as well as lessons learned through the modelling of this case study, BBM are potentially affected by:

- Block size
- Block shape
- Block configuration
- Block internal properties and constitutive models
- Distribution of contact properties
- Relationship of contact tensile strength (also referred to as micro tension) to contact cohesive strength (also referred to as micro cohesion)
- Modelling technique, such as thickness in the in-and-out of plane direction of the pseudo-3D models (see below for a detailed explanation)

This study is limited to identifying these parameters and the preliminary study of the effect of only some of these variables. The effect of block configuration, the distribution of contact properties and modelling technique have been addressed to some level in this study. However, the effect of block size, block shape, block internal properties and constitutive models, and the relationship of contact tensile strength have not been explored. In order to limit the effect of these potential variables, block size and block shape were restricted in this study. Tetrahedral blocks, created using the pre-processor *Griddle* (Itasca Consulting Group, Inc., 2020b), where the only shape of block used.

The block size had an average edge length of 0.42 mm, approaching grain size (0.03 to 1 mm, (Debras, 2010)), see Figure 4 for examples of the models with this block size. This block size was maintained for all models, those of laboratory tests and *in situ*. Such a small block size results in an extreme number of blocks, in particular for the larger *in situ* models. Due to computational limitations, the BBM regions of the *in situ* models was limited.

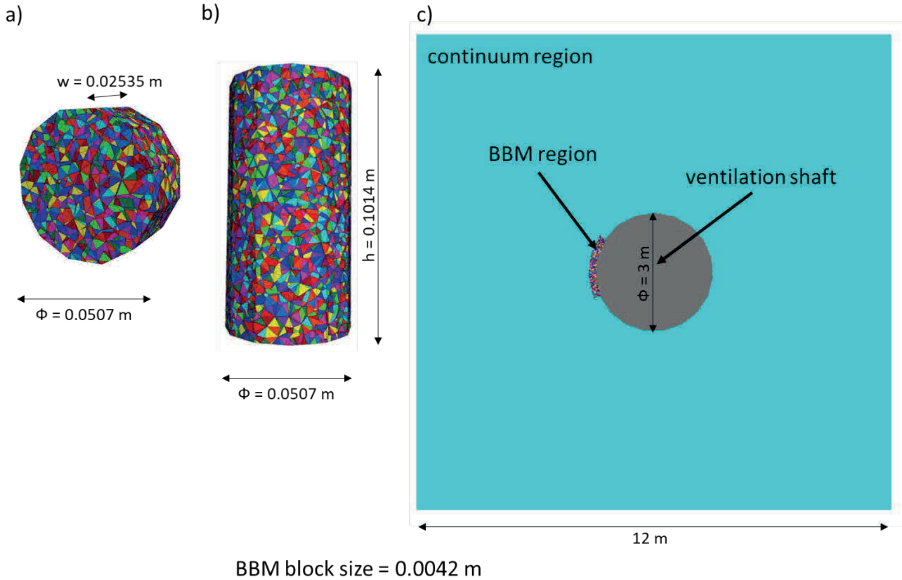

Figure 4. Example BBM models with 0.42 mm blocks, a) Brazilian test, b) UCS test, c) Malmberget Öde E8 ventilation raise.

Block configuration may significantly affect rock mass behaviour. If blocks conform to a given shape, for example the core sample for the UCS test, the response may be very different than if the blocks are randomly arranged. To test this postulate, where possible, volumes containing BBM blocks were carved out at of a much larger cube of BBM blocks. Specifically in this case, the blocks on the edges of the cube were aligned with the cube boundaries. Visual inspection showed that the outermost four blocks were aligned with the edges; these were avoided during laboratory sample selection. A more qualitative technique to evaluate this would be useful for future work. An example of this selection process is shown in Figure 5. This approach was used for models of laboratory tests but was too computationally intensive for the *in situ* models.

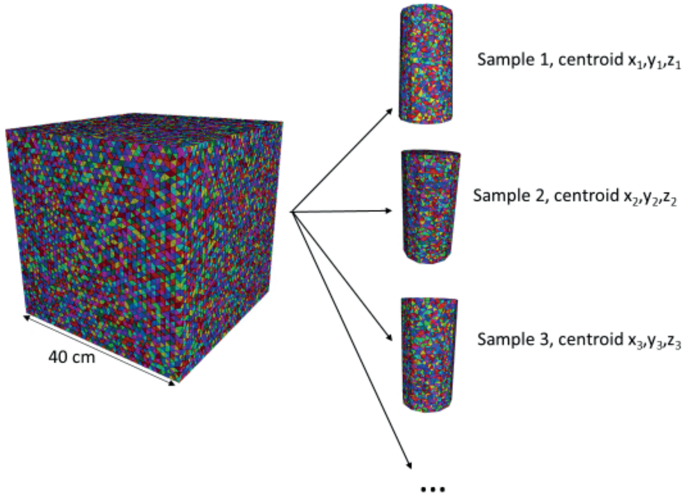

Figure 5. Carving out random samples from a larger block, resulting in random configurations of blocks in each unique sample.

In this study, constant contact properties are used to better understand the influence of other variables, such as block configuration. It should also be noted that in some previous BBM models "gaps" are introduced, for example by Garza-Cruz *et al.* (2014). These are bonds between blocks that are never bonded, representing grain segments that are not fully bonded to their neighbours (pre-existing fractures). This variable is not addressed in this study. Moreover, this study does not address the relationship of contact tensile strength to contact cohesive strength.

Due to computational limitations, BBM is currently limited to problems that are 1) small, or 2) suited to plane strain or plane stress conditions (in other words, 2D problems). However, the configuration of the blocks in 3D is important to developing realistic and spontaneous rock mass behaviour. Therefore, pseudo-3D models (occasionally referred to in other literature as "2.5D models") are typically used in BBM approaches when model size becomes too large. Pseudo-3D models are essentially a 2D model with a small thickness in the out of plane direction (Figure 6). This enables interlocking of blocks in all dimensions while reducing computational time. Models are evaluated along a 2D plane in the central portion of the model. 3D models were used for analysis of the laboratory tests since available computational power was sufficient. Pseudo-3D models were used for the *in situ* models in this analysis.

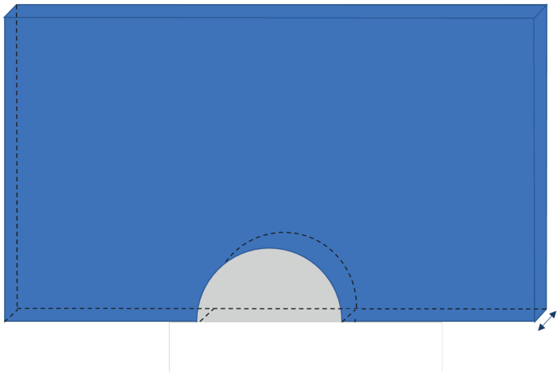

Figure 6. Example of a pseudo-3D model, which is really a plane-strain problem that enables some small 3D features to be included (in this case blocks).

3.2 Phase 1: Material Calibration

The use of an actual spalling case is critical to the success of this project. The presence of spalling is dependent upon both rock properties and stress conditions. Much like all particle modelling techniques, BBM relies on calibration of model properties to represent the target behaviour.

Malmberget Mine's Öde E8 ventilation raise was selected as the case for this project because it is a well documented example of spalling in Scandinavia, with a relatively large amount of laboratory testing data. The stress conditions leading to spalling are also relatively well studied and in addition, continuum 2D modelling work has been completed by Sjöberg *et al.* (2015). Rock mass properties in the model were adjusted so that the yielding pattern would match the location and extent of spalling. These plastic continuum models showed a good correlation between the shape and extent of the yielded volume and *in situ* spalling, provided the cohesion-weaking friction-strengthening constitutive model was used. However, since they are continuum models the spalling process is not explicitly represented. The use of plasticity as a proxy for spalling limits our ability to understand the spalling process and therefore makes it difficult to predict the extent of spalling in advance of the behaviour.

Extensive UCS and Brazilian test data were available from LKAB for the rock types mapped at the position of the ventilation raise. Table 1 summaries the laboratory testing data provided by LKAB for the three rock types mapped at the location of the Öde E8 ventilation raise (red-gray leptite (RGL), granite (GRA), and red leptite (RLE)). Detailed mapping of exactly where the rock types are in relation to the ventilation raise is not available, however it is known that the raise is predominantly in RGL with some GRA and RLE. Therefore, for calibration purposes target properties were calculated based on the laboratory statistics using 90% RGL with 5% GRA and 5% RLE (Table 2). In Table 1, E and E_{std} is the mean and standard deviation of Young's modulus, ν and ν_{std} is the mean and standard deviation of the Poisson's ratio, UCS, UCS_{std} and UCS_n is the mean, standard deviation, and number of tests of the UCS, and ITS, ITS_{std} and ITS_n is the mean, standard deviation, and number of tests of the indirect tensile strength (Brazilian tests).

Table 1. Summary of laboratory data of the rock types at the location of the ventilation raise.

Rock type	**E** [GPa]	**E_{std}** [GPa]	**ν** UCS tangent	**$ν_{std}$** UCS tangent	**UCS** [MPa]	**UCS_{std}** [MPa]	**UCS_n**	**ITS** [MPa]	**ITS_{std}** [MPa]	**ITS_n**
RGL	69.6	22.2	0.30	0.02	195.5	75.3	5	14.3	4.9	12
GRA	56.2	32	0.33	0.03	247.5	39.7	7	9.9	2.3	10
RLE	55.8	15.2	0.30	0.04	208.8	88.9	7	14.9	5.2	12

Table 2. Target properties for calibration (90% RGL, 5% GRA, 5% RLE).

E [GPa]	**E_{std}** [GPa]	**ν** UCS tangent	**$ν_{std}$** UCS tangent	**UCS** [MPa]	**UCS_{std}** [MPa]	**UCS_n**	**ITS** [MPa]	**ITS_{std}** [MPa]	**ITS_n**
68.24	22.5	0.302	0.022	198.8	74.8	19	14.1	4.8	34

The calibration process attempted to match the behaviour of the models with behaviour of the actual rock in laboratory tests by adjusting the material properties in the models. The process is summarised in Figure 7. A large sampling volume was first created. Young's modulus and Poisson's ratio in the models were matched to lab test results by adjusting the contact shear and normal stiffness in models of UCS tests. Adjustment of the contact tensile strength and contact cohesive strength was completed until the models of the Brazilian test results matched the material values. The peak UCS was then calibrated by further adjusting the contact tensile strength and contact cohesive strength.

It is apparent that calibration should be done with consideration of the statistical distribution of the laboratory tests. These BBM models attempt to accommodate all fracturing between blocks, as fracturing through blocks is not computationally possible with *3DEC*. That means that the blocks are represented as stiff, elastic entities, while adjustment of the plastic properties for the calibration process is completed on the contacts between blocks. In this study, the contact properties adjusted during the calibration include shear stiffness, normal stiffness, and tensile strength. The contact cohesive strength was adjusted indirectly as it remained a constant ratio of 2.5 times the tensile strength, alike the strategy used by Garza-Cruz *et al.* (2014). This was done as it is a realistic value and it helps to limit the number of unknown variables.

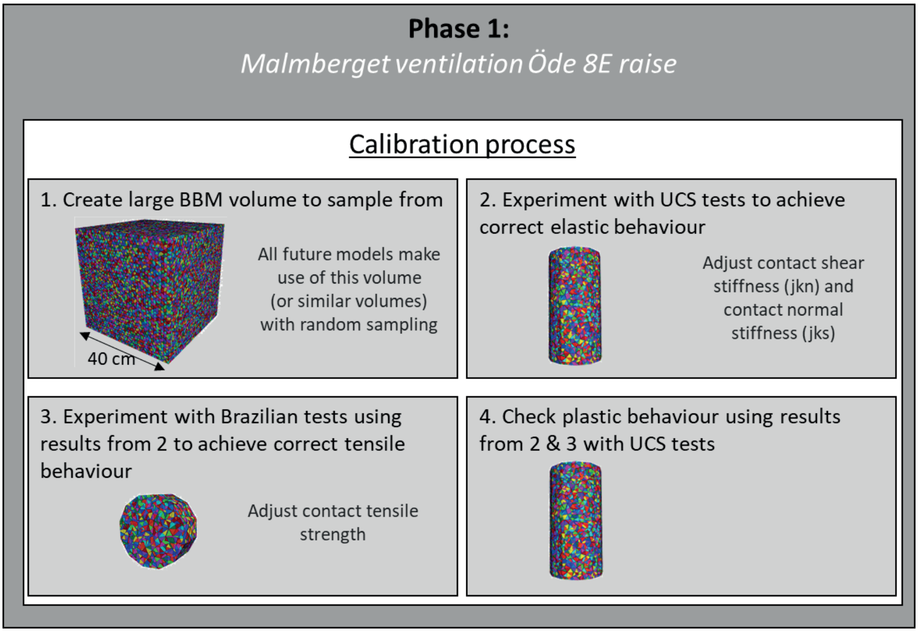

Figure 7. Visual explanation of the stages in Phase 1, calibration to laboratory testing results.

UCS and Brazilian tests were modelled during the calibration process. To reduce model run times, UCS tests were loaded using the full strain technique presented by Mas Ivars (2010), adapted for *3DEC*. This technique loads the sample by applying a graduated velocity to each block, mimicking sample loading while the sample boundary conditions are released, creating unbalanced forces. The sample boundaries are then locked, and the sample is run to equilibrium to allow for the stress state as a result of the loading conditions to develop in the sample. The Brazilian tests were much smaller models and therefore used a classical loading technique, where the sample was loaded with a constant velocity from above. The loading was checked to be in the quasi-static via decreasing the load in successive tests until the indirect tensile strength stabilised. Loading is quasi-static when the test results do no longer are dependent upon loading speed.

3.3 Phase 2: *In situ* models using the calibrated material

The second phase of this study consisted of *in situ* models of Malmberget's ventilation raise. With current computational power and numerical formulation of *3DEC*, it is of utmost importance to minimize the volume of BBM as much as possible when using such a small block size (a necessity to represent spalling). Reduction techniques can include smart modelling decisions using symmetry and limitation of the BBM volume to where one expects fracturing. In this project, both strategies were used. A line of symmetry perpendicular to the shaft axis was used (making a quasi-3D model) and the BBM volume was limited to a little larger than the expected spalling volume. The thickness of the model out of plane was selected to have 5 blocks across the width. This is likely sufficient as a minimum number of blocks to have discontinuum behaviour (Mas Ivars, 2010).

Figure 8 provides an image of the general BBM model geometry used in *3DEC* (Itasca Consulting Group, Inc., 2020a). Note that for the *in situ* models, *3DEC* version 7.0 was used (whereas 5.2 was used in the laboratory calibration process). A fortuitously timed version release provided the opportunity for increased computation speeds and an improved method for geometry building (described in more depth below). While the previous results showed the importance of block configuration to sample behaviour, computation limitations eliminated the use of the sampling technique for the *in situ* models. Instead, the BBM region of the model conforms to the boundaries. Roller boundaries were used out of plane, and stress boundaries were used along the edges representing the stress state when spalling occurred ($\sigma_x = 19.84\,MPa,\ \sigma_y = 21.15\,MPa, \sigma_x = 44.05\,MPa, \sigma_{xz} = 3.22\,MPa,$ from Sánchez Juncal and Mas Ivars (2014)) in model coordinates, where y is aligned with the axis of the ventilation shaft). Multiple *in situ* models were run with a variety of contact and rock (block) properties. The properties used are further discussed in the results section, as the selection of them was an iterative and exploratory process.

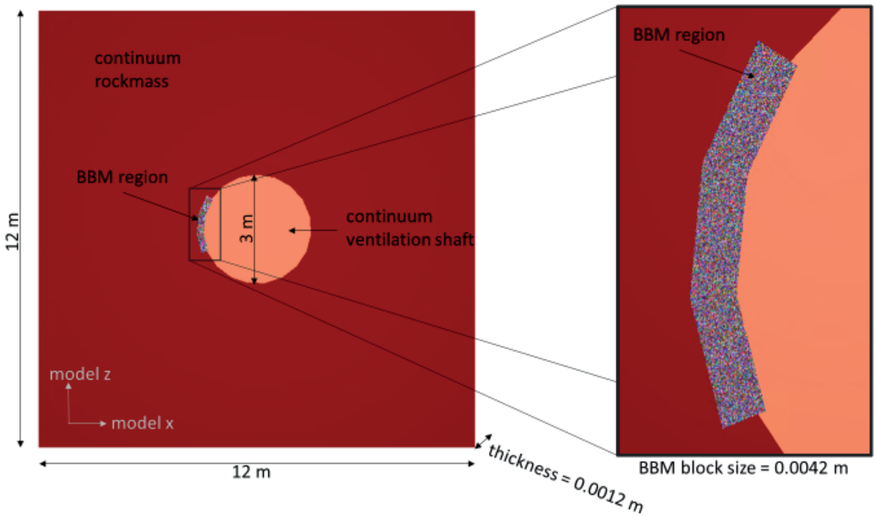

Figure 8. Illustration of *in situ* model of the Öde E8 ventilation raise.

As is typical with numerical modelling, one should start simple and add complexity successively. Otherwise, in particular with complex models, confirming correct behaviour and understanding the more complicated mechanisms becomes convoluted. The modelling strategy was as follows:

1. Simplified continuum model in *3DEC* (with relatively large zone sizes of 0.5 m) to identify where the maximum tangential stress occurs along the ventilation raise boundary (Figure 9 a). In this case, this could also have been accomplished by analytical solutions due to the circular nature of the ventilation raise, but modelling was part of the model behaviour verification process. The latest version of *Griddle* is well suited to this task; one can reduce the number of blocks in the model to two using the "deformable blocks" option (one for the continuum region, and one for the region that will be BBM in subsequent models).

   To create continuum models in *3DEC*, one must assign contact properties between the blocks that allow for smooth stress/displacement transfer, but do not yield. This was accomplished by using a high value for cohesion and tension (1e20 Pa) and using calculated values for contact normal and shear stiffness. Contact stiffnesses should be calculated based on material stiffnesses and minimum zone size, according to the following equation:

   $$k_{zi} = \frac{K+\frac{4}{3}G}{z_{min}},$$

   where k_{zi} is the contact stiffness, K is the minimum shear modulus of the material(s), G is the minimum bulk modulus of the material(s), and z_{min} is the minimum zone size.

2. Create a new continuum model in *3DEC* where the zone sizes are the same as what is to be used for blocks (Figure 9 b, 0.0042 m). Run this model to ensure that the resulting stresses are as expected, indicating that zoning is appropriate. Contact stiffnesses should be calculated based on material stiffnesses and minimum zone size.

3. Create the discontinuum model in *3DEC* with individual blocks in the BBM region (Figure 9 c). In the latest version of *3DEC*, an appropriate way to do this is to use the continuum model created in 2), remove the continuum region that will be the BBM region, and then use *Griddle* to create a rigid block volume using the previously developed mesh of the BBM region. It is this model that is used for BBM.

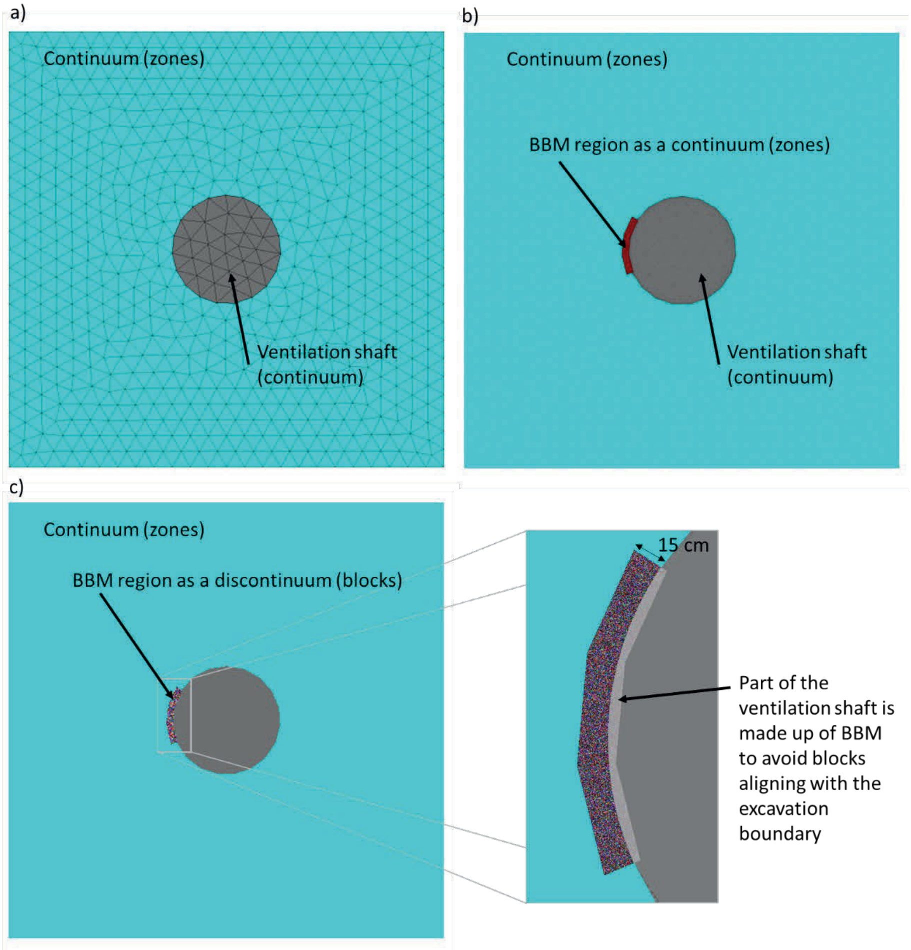

Figure 9. Depictions of the different types of *in situ* models, a) simplified continuum, b) continuum with zones where the BBM blocks will be, and c) discontinuum with blocks in the BBM region.

4. RESULTS

4.1 Need for calibration

Calibration is a necessary process. To illustrate this clearly, a test model was run with a small BBM region where the contact properties were the same as rock mass properties from Sjöberg *et al.* (2015). As shown in Figure 10 this resulted in *in situ* stress irregularities in the test model. This result clearly shows a need for calibrating the BBM portion of the models so an accurate behaviour can be recreated.

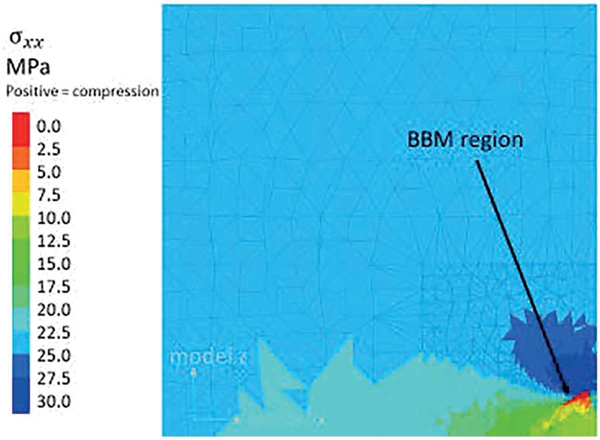

Figure 10. Stress irregularities due to non-calibrated BBM material.

4.2 Calibration acceptance criterion

During the calibration process, acceptance criteria must exist. Since laboratory test results provide a distribution of properties due to the nature of rock masses as well as sampling procedures, this study uses an acceptance criterion based on the statistical distribution of the laboratory testing results. A modelling result is accepted as valid if the result is within one standard deviation of the mean of the laboratory tests.

4.3 Young's moduli and Poisson's ratio

Contact normal- and shear stiffnesses (*jkn* and *jks* respectively) were adjusted until sets of properties were found that resulted in acceptable Young's moduli (E) and Poisson's ratios (v). Contact tensile strength and contact cohesive strength were set as artificially high to ensure elastic behaviour. An example UCS model and resulting stress-strain curve is shown in Figure 11. 125 unique models of UCS tests were run and evaluated to determine E and v, where the results are summarised in Table 3.

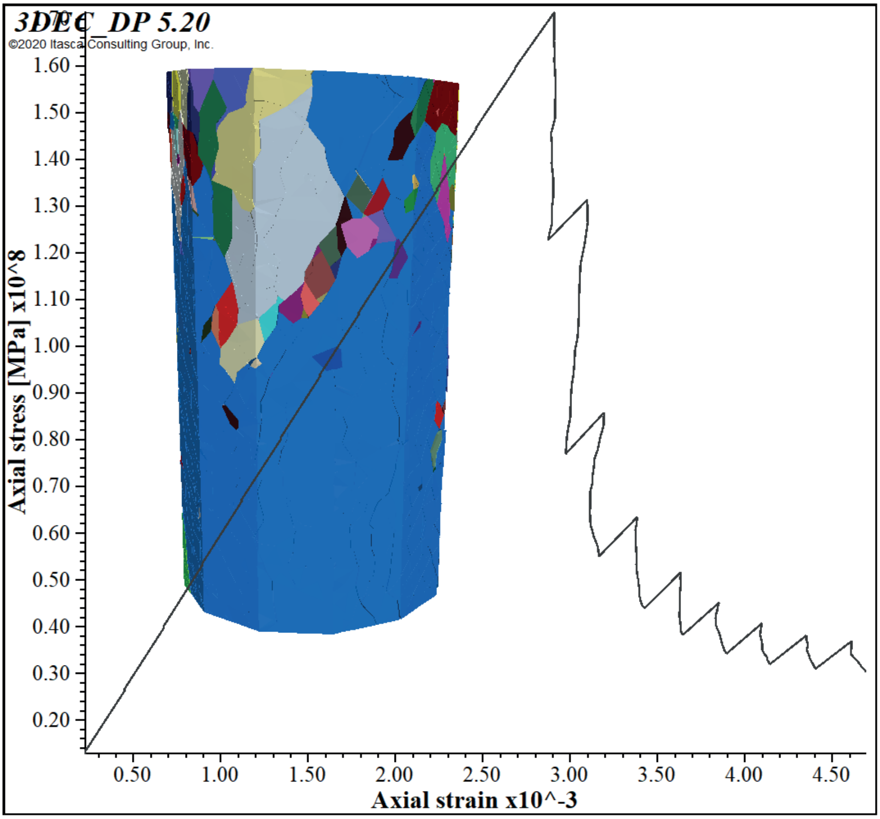

Figure 11. Example UCS model test. Individual fragments (separated blocks) are coloured. Stress-strain curve overlaid.

Table 3. Calibration of elastic properties via UCS test results.

	Number of accepted jkn and jks sets (% of 125)
Young's modulus within one standard deviation of the target properties	87 (69.6%)
Poisson's ratio within one standard deviation of target properties	27 (21.6%)
Young's modulus AND Poisson's ratio both within one standard deviation of target properties (see Figure 12)	25 (20.0%)

It is immediately evident that there were significantly more sets of *jkn* and *jks* that had acceptable Young's moduli than Poisson's ratio. A linear relationship between *jkn*, *jks*, *jkn*/*jks*, and *E*, or between *jkn*, *jks*, *jkn*/*jks*, and *v* is not evident in the results of this study. As can be seen in Figure 12, some rejected model results had very similar *jkn* and *jks* values to accepted results. This was mostly a result of Poisson's ratio not converging, rather than Young's modulus. The only difference between these models is the configuration of blocks, since each modelled test is randomly sampled from the larger volume full of tetrahedral blocks. Moving forward, a constant value of *jkn* and *jks* was used in all models.

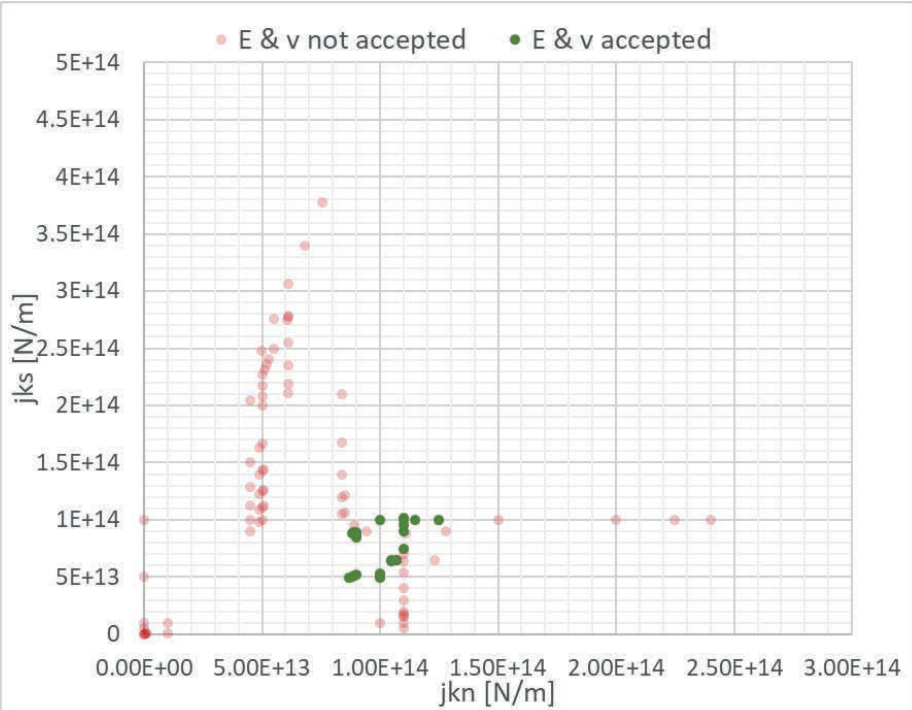

Figure 12. All 125 sets of *jkn* and *jks*, where the green data points represent *E* and *v* within one standard deviation of the target values (accepted results) and the red represent results where *E* and/or *v* were outside of one standard deviation of the target values (not accepted results).

4.4 Indirect tension tests (Brazilian tests)

A total of 58 unique models of Brazilian tests were created and analysed. As previously mentioned, the contact tensile strength was altered while the contact cohesive strength was a factor of 2.5 the contact tensile strength. An example of the Brazilian models before and after loading to failure is shown in Figure 13. The results show a relatively linear relationship between contact tensile strength and the indirect macro tensile strength of the sample, particularly in the acceptance range (Figure 14). The only difference between the models that have shared contact tensile strengths is the configuration of blocks due to the random sampling. Therefore, these results illustrate that block configuration significantly influences the variation in the test results.

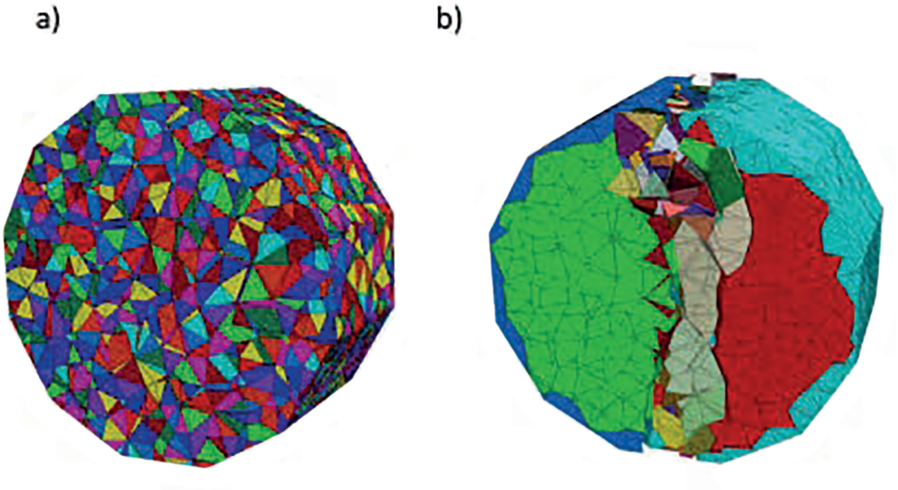

Figure 13. Brazilian test model example, a) before loading where individual colours represent individual blocks, and b) after failure, where individual fragments created during testing are uniquely coloured.

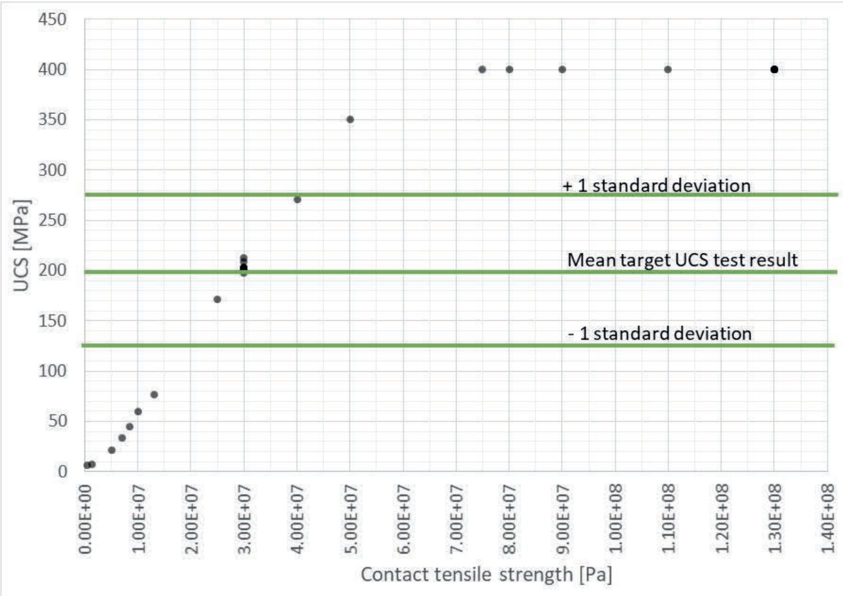

Figure 14. Brazilian test model results from all 58 unique Brazilian test models using different contact tensile strengths (and therefore contact cohesive strengths), with the mean and standard deviation results from the target laboratory tests overlaid.

4.5 UCS tests

Interestingly, the results are not as expected when using the calibrated contact properties discovered during the Brazilian tests. Despite nine unique model attempts, UCS values were extremely high (well beyond the acceptance criteria). This may be indicative that the failure mode in the models of the Brazilian tests was not equivalent to the failure mode in the laboratory Brazilian tests.

The UCS test results are deemed to be more important to spalling behaviour than Brazilian test results since spalling occurs essentially under the same conditions as a UCS test; high stress, low confinement. Due to this, additional calibration was required during the UCS tests. The contact tensile strength (and therefore the contact cohesive strength) was adjusted to complete this calibration. A total of 35 unique models of UCS tests were created and analysed to determine appropriate properties to recreate target peak strength. The contact tensile strength and UCS result are shown in Figure 15. It should be immediately noted that UCS results reported at 400 MPa actually indicate a higher UCS; models were stopped at 400 MPa when it became evident that they were well over the acceptance criterion. The remaining data points indicate near linear behaviour, with the exception of the UCS results less than 20 MPa. A total of 12 tests were accepted. These tests consisted of 3 different property sets, and the results are summarized in Table 4.

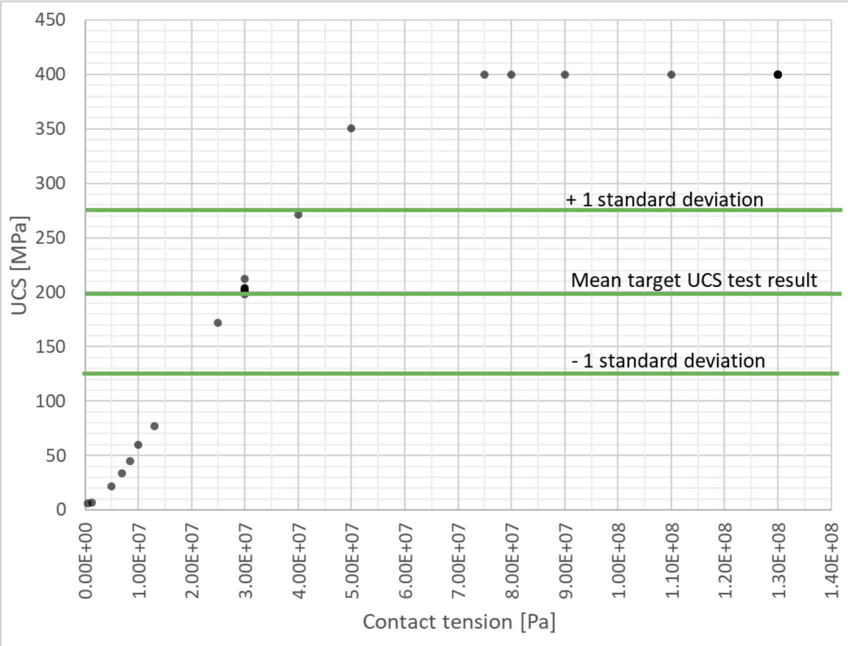

Figure 15. UCS test model results from all 35 unique UCS test models using different contact tensile strengths (and therefore contact cohesive strengths), with the mean and standard deviation results from the target laboratory tests overlaid. Note that results at 400 MPa do not represent failure of the sample, rather that these samples were stopped when it was clear that they were to be rejected.

Table 4. Summary of the UCS results from the models with accepted parameter sets.

Contact tensile strength [Pa]	**Contact cohesive strength [Pa]**	**Number of unique UCS models with these parameters**	**Mean UCS [MPa]**	**Standard deviation UCS [MPa]**
2.5e7	6.25e7	1	171.7	-
4.0e7	1.0e8	1	271.3	-
3.0e7	7.5e7	10	201.75	1.32

The models' mean UCS (201.75 MPa) using a contact tensile strength of 3.0e7 Pa is a good match to the target test results' mean UCS (198.8 MPa) (Table 4). However, the standard deviation of the UCS models' results (1.32 MPa) is significantly lower than the standard deviation of the target test results (74.8 MPa).

4.6 *In situ* tests

As described in Section 3.3, three different types of *in situ* modelling were completed: 1) simplified continuum with large zones and few blocks (no BBM region), 2) continuum with zones where the BBM blocks will be, and 3) discontinuum models with blocks in the BBM region.

The first two types of models, the continuum models, used the same block and contact properties throughout. Contact stiffnesses were calculated based on zone size (see Section 3.3, 1000e11 N/m), the contact friction angle was that used during calibration (45°), and the contact cohesive and tensile strength were both set to 1e20 Pa. The stiffness of the zones in the continuum material was set to be equivalent to the resulting stiffness of the UCS tests in *3DEC* (37e9 Pa), to avoid stiffness differentials between the continuum material and discontinuum material in the final type of models. Zone density and Poisson's ratio were set to those of the rock mass (2700 kg/m^3 and 0.22 respectively).

The two continuum models resulted in similar stresses, as expected. Examples of the major principal stresses from the continuum models (simplified continuum and continuum with BBM as zones) are shown in Figure 16. The location of the maximum major principal stresses in the simplified continuum model was used to identify where the BBM region should be included.

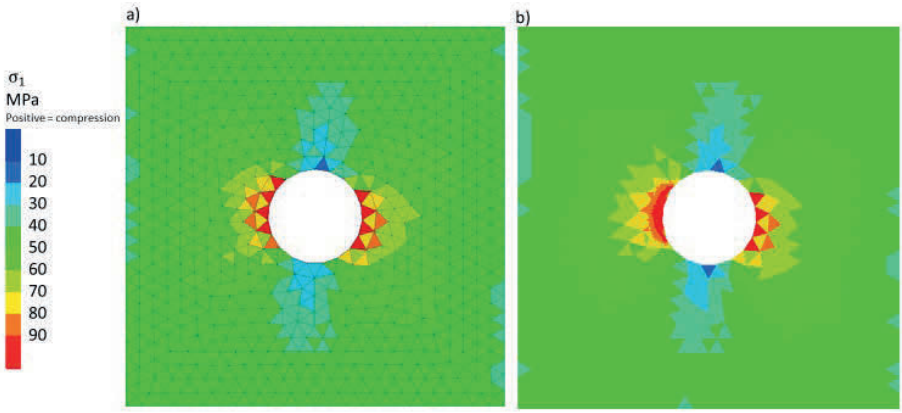

Figure 16. Major principal stresses from a) simplified continuum with large zones and few blocks (no BBM region) and b) continuum with zones where the BBM blocks will be. Note that both of these models are continuum models (there are no discontinuum regions).

The discontinuum models were first tested with the contact properties determined in the calibration phase between the blocks in the BBM region, including the contact normal and shear stiffness for all contacts in the model. This resulted in an incorrect concentration of stresses surrounding the BBM region. Using the calculated contact stiffness based on zone size (see Section 3.3) between the BBM region and the continuum region (BBM calibrated stiffnesses inside of the BBM region) improved the stress distribution around the opening. However, the stresses around the tunnel were not as well distributed as in the continuum models shown. This aspect, connecting the continuum to the discontinuum in *3DEC* was challenging with this model setup. It is postulated that the extremely small block size in these models, combined with their high stiffness and few zones inside of each block increases the difficulty of finding appropriate stiffness values to connect the continuum to the discontinuum.

Stress and damage (broken contacts) results with the calibrated BBM strength and actual stress are shown in Figure 17. It is immediately evident that the stress field in the BBM region is imperfect (Figure 17 a). The stress contours inside of the BBM region do not line up well with the contours in the continuum region (shaded in Figure 17 a). This is the manifestation of the previously described connection problems between the continuum and discontinuum regions.

Figure 17 b shows the damage in the form of broken contacts. This is taken as a proxy for spalling in this analysis. Promisingly, most of the contacts have failed in tension, as expected during spalling failure. The form, depth, and width of the spalling damage does not, however, match the 10 cm deep notch seen *in situ.* It is postulated that this is because of a combination of 1) the incorrect stress state due to the coupling issues, and 2) that the BBM region’s strength (intact strength from calibration to laboratory testing) needs to be downgraded to *in situ* strength, 3) lack of ability to model intragrain breakage, 4) lack of strength heterogeneity of the material, and 5) lack of true stress path in the models. The material calibrated was representative of material tested in the laboratory, whereas the *in situ* material is likely weaker due to geological features and processes in addition to mining activities. This limitation may have been overcome if the blocks modelled were small enough to enable the correct intragrain breakage that occurs during spalling. Additionally, the true stress path during both shaft boring and the induced stress field caused by production may have weakened the material. Strength heterogeneity may have enabled spalling to occur in the correct place due to predefined weaknesses. None of these factors were represented in these models.

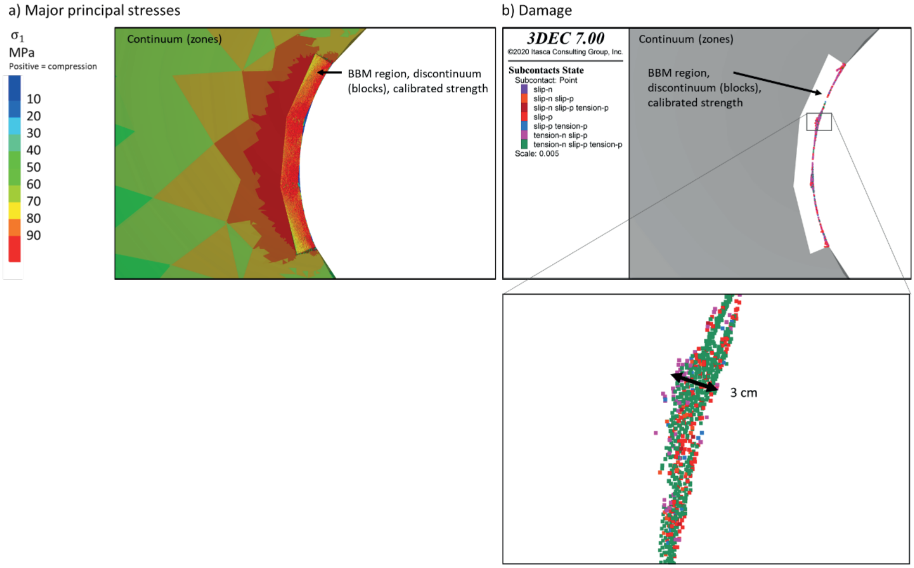

Figure 17. a) Major principal stress, and b) damage (broken contacts) in the quasi-3D *in situ* models. Laboratory calibrated properties in the BBM region.

To test the hypothesis that the BBM region was too strong to result in spalling, two numerical modelling techniques are available: 1) reduce the strength of the materials while maintaining the correct laboratory behaviour, and 2) increase the magnitudes of the stresses. Since data exists from the extensive calibration efforts presented earlier, reducing the strength of the materials in this case is relatively straightforward. The crack initiation strength from laboratory testing of the predominant rock type (RGL) at Öde E8 is 52% of the UCS (Nygård, 2020). According to the lab testing data used for calibration, the crack initiation strength for this case is therefore 103.4 MPa. Using the model calibration results shown in Figure 15, the contact tensile strength (and therefore contact cohesive strength) that produces a model UCS of 103.4 MPa can be approximated. Models were run with a contact tensile strength of 16 MPa to represent material calibrated to break at the laboratory tested crack initiation strength. These properties are referred to as rock mass properties in this report.

Results from the quasi-3D *in situ* models with the rock mass properties in the BBM region are shown in Figure 18. In comparison with the laboratory calibrated properties, the stress field in the BBM region with the rock mass properties is improved (Figure 18a). This indicates that these models are sensitive to the stiffnesses between the continuum and discontinuum regions. Spalling was evident in these models (Figure 18b). The maximum depth of damage in the model is approximately 11 cm, but the maximum spalling depth (concentrated damage) is 4 cm. However, the form and width of the *in situ* spalling is not matched by the models. The damage seen in Figure 18b shows clear boundary effects from the coupling between the continuum and discontinuum regions (the damage is focused where there are sharp bends and corners).

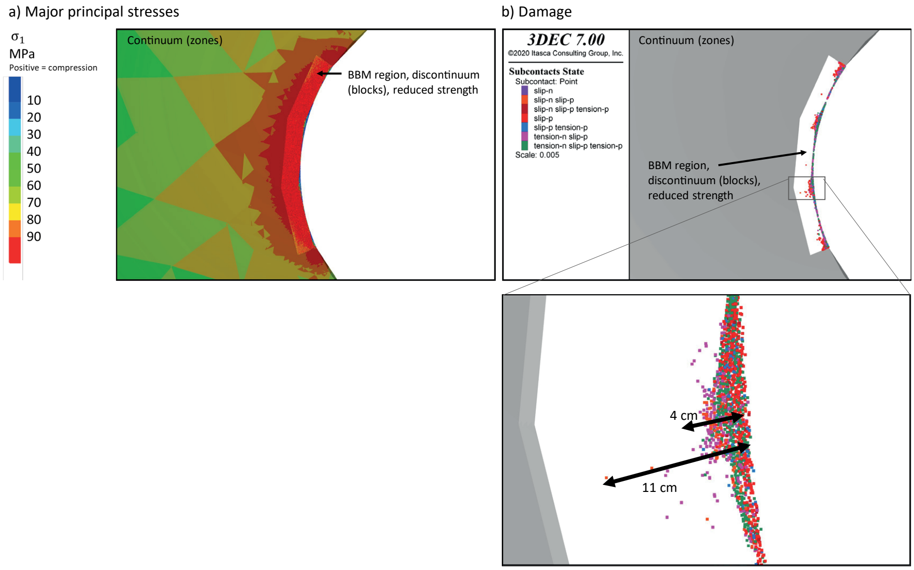

Figure 18. a) Major principal stress, and b) damage (broken contacts) in the quasi-3D *in situ* models. Rock mass properties in the BBM region.

5. DISCUSSION

With the currently available computational power, this project was ambitious. While for research purposes, this small of a block size was important to see if the true mechanisms of spalling could be represented, for practical purposes a less computationally intensive block size is recommended. Despite this significant challenge, there is much potential for BBM techniques to aid in the understanding of rock mass damage. With *a priori* estimation of damage depth, it is postulated that appropriate block sizes can be selected so that there are still at least six blocks across the width of the damage, hopefully resulting in fewer blocks than were used in this study. A minimum of six blocks was suggested as it should provide enough resolution for an accurate stress state.

An interesting aspect of BBM becomes evident during analysis of results. Clearly, the objective is to have a pattern and extent of damage in the models similar to that *in situ*. However, it is worth considering that although it is commonly the “notch” formed during spalling that is called damage, the surrounding rock mass may also have experienced damage in the sense that its initial strength is reduced. This is seldom evaluated *in situ* due to practical difficulties. Damage can also be represented in the BBM model in different ways, for example as distinct fragments or as yielded contacts. These aspects should be clearly defined before the calibration process.

The calibration process was a lengthy one. This was in part due to the need for an individual to check the results and adjust the next run in a meaningful way. Opportunities exist in the future to improve the speed of this process. A possible solution is to remove the human component of the calibration process. Techniques such as artificial intelligence and machine learning can make decisions based on input variables and learn how to optimize the problem. The variables accepted during the calibration process may not necessarily be unique. That is to say other sets of variables may have also produced reasonable results. This is a challenge for optimization.

It is unclear why in this project the Brazilian test result calibration did not produce acceptable results in the UCS tests. It may be a function of the model, the measurement, or the failure mechanism in the test itself. Direct tensile tests in BBM should also be used in the future, as is common in BPM methods.

The process of starting with simpler models and adding complexity progressively was integral to the *in situ* models. For example, the challenges with contact stiffness between the continuum and discontinuum regions of the model would have otherwise been difficult to identify.

Based on the *in situ* model results, there were significant challenges connecting the BBM material to the continuum material. It is believed that this problem occurred because of stiffness differentials between the two materials, and possibly due to having so few zones in each BBM block. Unfortunately, due to computational power and small block size, having a continuum region was a requirement. In a perfect world, it would have been possible to run the model with only BBM, thereby eliminating the need for this connection in *3DEC*. This problem in the future may be avoided by 1) having more zones in each BBM block, 2) having a larger block size, 3) evaluating the possibility of gradation in block size (if block size does not affect behaviour), and 4) the use of the coupling logic between *PFC3D* and *FLAC3D* instead of *3DEC*.

It is difficult to speculate how the use of pseudo-3D *in situ* models instead of 3D models may have affected the results. One potentially important aspect that is not captured due to the use of pseudo-3D is the effect of the true stress path on the rock mass ahead of the excavation. That stress and deformation changes occur ahead of the face are well-known phenomena. It is also known that with laboratory testing, materials are damaged with increased load, well before maximum load is reached.

The scaling of intact properties to the *in situ* rock mass is a seemingly constant challenge in rock mechanics. Interestingly, the original hypothesis that grain-scale blocks calibrated to laboratory tests would recreate spalling behaviour was partially true—while damage was observed that was of a spalling nature (tensile), the form and position were not matched to the actual case. It may be that the desired spalling characteristics were not achieved due to the difficulties with the coupling of the continuum and discontinuum regions of the model, for example. The reduction of the strength of the BBM region did, however, improve the match somewhat. It is inconclusive if a strength reduction is required when the blocks are at the grain scale. The requirement for strength reduction may have to do with scale issues, such as the limitations of these models not allowing for intragrain cracking, the lack of heterogeneity of the rock properties, and/or it may have to do with damage in the rock mass before the spalling occurred not being represented. It is currently standard to reduce the unconfined compressive strength of the BBM rock mass material to laboratory crack initiation (in particular for models with block sizes that are not representative of grain size). Crack initiation is often considered to be the long-term strength of material (as rocks do exhibit time dependent failure), and this may be why this scaling seems to work so well in BBM.

6. CONCLUSIONS AND RECOMMENDATIONS TO PRACTIONERS

The research presented in this report, both the literature review and practical application, is one of many steps towards the regular use of BBM techniques by practitioners. While BBM is a promising step forward towards a better understanding and modelling capability of rock mass damage, the application of BBM for spalling behaviour in *3DEC* is currently challenging. Spalling is a process that involves inter- and intra-grain breakage; meaning that it involves very small particles. Computational limitations mean that the applications of BBM to model the mechanisms underlying spalling is currently limited. However, literature shows that it is possible to model depth of spalling damage using BBM with a block size that related to the damage depth, rather than grain size. The described thought and modelling process in this report should offer guidance to practitioners who are interested in accomplishing similar and further work.

Specific recommendations to practitioners concerning modelling of spalling using BBM include:

- Suitable spalling cases to be modelled using BBM techniques are those which have good data concerning laboratory testing and can be run in quasi-2D.
- Attempting to model the exact process of spalling using BBM is currently difficult due to computational limitations restricting minimum block size. It is suggested that for practical cases block size should currently be selected to achieve at least six blocks across the damage (notch) depth and width, similarly to common practice in continuum modelling. Care should be taken to check that this block resolution is appropriate for each specific modelling case, by examining the results from a critical perspective.
- Adequate time for the calibration process is important, as it is not always straightforward.
- Block configuration during the calibration process is important.
- Contact shear and normal stiffnesses are less significant than the other properties, such as cohesion and tension in models of laboratory tests.
- The use of a ratio between tension and cohesion is appropriate until proven otherwise.
- A distribution of the tensile strength (and therefore cohesion) across all contacts may help better represent the variance of UCS tests. Correlated random fields should be considered.

- Start *in situ* modelling with simplistic models (continuum) to check model behaviour and identify exactly where in the model the BBM region should be built.
- Contact stiffnesses in *in situ* modelling between the BBM region and the continuum should likely be based on zone size, not the values from calibration. These stiffnesses may result in problems with the stresses in the model, and time and effort may be required to find values that work.
- It is inconclusive if a reduction of the BBM material strength is required when the block sizes are near grain size. However, it is still postulated that this strength reduction is required for larger blocks. It is proposed that this is due to a combination of 1) rock mass strength being less than intact strength, 2) the lack of strength heterogeneity of the material, and 3) the lack of damage build-up possibly caused by the stress path.

7. FUTURE WORK

Suggestions for future work include:

- Improvement of the calibration process through automation. This would greatly enhance the speed and practical use of BBM.
- In-depth testing of the ratio of contact tensile and cohesive strengths.
- In-depth analysis of the effect of using a distribution to populate the contact tensile and cohesive strengths. Correlated random fields should be considered.
- In-depth analysis of the effect of block size.
- In-depth analysis of the use of blocks with different constitutive models. Perhaps intragrain breakage could be represented by plastic shear strain concentrations.
- Comparison of suitability of *PFC* and *3DEC* for BBM.
- Interaction of the BBM represented rock mass with support elements.

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8. REFERENCES

Andersson, J. C. (2007) *Rock Mass Response to Coupled Mechanical Thermal Loading : Äspö Pillar Stability Experiment, Sweden*. PhD Thesis. Byggvetenskap. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-4287 (Accessed: 6 November 2020).

Azocar, K. (2017) *Investigating the mesh dependency and upscaling of 3D grain-based models for the simulation of brittle fracture processes in low-porosity crystalline rock*. PhD Thesis. Available at: https://qspace.library.queensu.ca/handle/1974/15317 (Accessed: 5 January 2018).

Debras, C. (2010) *Petrology, geochemistry and structure of the host rock for the Printzsköld ore body in the Malmberget deposit*. Master's thesis (2010:052).

Edelbro, C. (2008) *Strength, fallouts and numerical modelling of hard rock masses*. PhD Thesis. Luleå University of Technology. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-17781 (Accessed: 6 November 2020).

Gao, F., Kaiser, P. K., Stead, D., Eberhardt, E. and Elmo, D. (2019) 'Strainburst phenomena and numerical simulation of self-initiated brittle rock failure', *International Journal of Rock Mechanics and Mining Sciences*, 116, pp. 52–63. doi: 10/gf88gt.

Garza-Cruz, T. V., Pierce, M. and Kaiser, P. K. (2014) 'Use of 3DEC to study spalling and deformation associated with tunnelling at depth', in *Proceedings of the Seventh International Conference on Deep and High Stress Mining*. *Deep Mining 2014*, Sudbury, Canada: Australian Centre for Geomechanics, pp. 421–434. Available at: https://papers.acg.uwa.edu.au/p/1410_28_Garza-Cruz/ (Accessed: 2 October 2019).

Ghazvinian, E., Diederichs, M. S. and Quey, R. (2014) '3D random Voronoi grain-based models for simulation of brittle rock damage and fabric-guided micro-fracturing', *Journal of Rock Mechanics and Geotechnical Engineering*, 6(6), pp. 506–521. doi: 10.1016/j.jrmge.2014.09.001.

Gong, F., Wuxing Wu, Tianbin Li and Xuefeng Si (2019) 'Experimental simulation and investigation of spalling failure of rectangular tunnel under different three-dimensional stress states', *International Journal of Rock Mechanics and Mining Sciences*, 122, p. 104081. doi: 10/gf88gv.

Itasca Consulting Group, Inc. (2019a) *3DEC*. Minneapolis, Minnesota: Itasca International Inc.

Itasca Consulting Group, Inc. (2019b) *PFC*. Minneapolis, Minnesota: Itasca International Inc.

Itasca Consulting Group, Inc. (2020a) *3DEC*. Minneapolis, Minnesota: Itasca International Inc.

Itasca Consulting Group, Inc. (2020b) *Griddle*. Minneapolis, Minnesota: Itasca Consulting Group.

Le Goc, R., Bouzeran, L., Darcel, C. and Ivars, D. M. (2015) 'Using Correlated Random Fields for Modeling the Spatial Heterogeneity of Rock', in. *ISRM Regional Symposium - EUROCK 2015*, International Society for Rock Mechanics and Rock Engineering. Available at: https://www.onepetro.org/conference-paper/ISRM-EUROCK-2015-096.

Li, Q., Zhao, G.-F. and Lian, J. (2019) 'A Fundamental Investigation of the Tensile Failure of Rock Using the Three-Dimensional Lattice Spring Model', *Rock Mechanics and Rock Engineering*, 52(7), pp. 2319–2334. doi: 10.1007/s00603-018-1702-z.

Martin, D. (1997) 'The effect of cohesion loss and stress path on brittle rock strength', in *Canadian Geotechnical Journal - CAN GEOTECH J. Seventeenth Canadian Geotechnical Colloquium*, pp. 698–725. doi: 10/ctsrfg.

Mas Ivars, D. (2010) *Bonded Particle Model for Jointed Rock Mass*. PhD Thesis. KTH. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-12055 (Accessed: 4 January 2018).

Nygård, D. (2020) *Laboratorietester för framtagande av materialegenskaper för spröd materialmodell för huvudbergarterna i Malmberget och Kiruna*. Master's thesis. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-79049 (Accessed: 3 June 2020).

Potyondy, D. O. and Cundall, P. A. (2004) 'A bonded-particle model for rock', *International Journal of Rock Mechanics and Mining Sciences*. (Rock Mechanics Results from the Underground Research Laboratory, Canada), 41(8), pp. 1329–1364. doi: 10/bfzp5k.

Potyondy, D., Vatcher, J. and Emam, S. (2020) *Modeling of Spalling with PFC3D: A Quantitative Assessment*. 2-5732–02:20R50. Minneapolis, Minnesota: Itasca Consulting Group, p. 106.

Sánchez Juncal, A. and Mas Ivars, D. (2014) *Fallouts in Ore Passes and Ventilation Shafts in Malmberget -- Numerical Modeling and Comparison with Observations*. Version 1.1. Itasca Consultants AB.

Sinha, S. and Walton, G. (2019) 'Understanding continuum and discontinuum models of rock-support interaction for excavations undergoing stress-induced spalling', *International Journal of Rock Mechanics and Mining Sciences*, 123, p. 104089. doi: 10/gf88gs.

Sjöberg, J., Bolin, A, Juncal, A. S., Wettainen, T., Ivars, D. M. and Perman, F. (2015) 'Input to ore pass design — a numerical modelling study', in Potvin, Y. (ed.) *Proceedings of International Seminar on Design Methods in Underground Mining*. *of International Seminar on Design Methods in Underground Mining*, Perth, pp. 571–584. Available at: https://papers.acg.uwa.edu.au/p/1511_36_Sjoberg/.

Sjöberg, J., Bolin, A., Sánchez Juncal, A., Wettainen, T., Mas Ivars, D. and Perman, F. (2015) *Input to orepass design — a numerical modelling study*. Australian Centre for Geomechanics, pp. 571–584. Available at: https://papers.acg.uwa.edu.au/p/1511_36_Sjoberg/ (Accessed: 20 August 2018).

Turichshev, A. (2016) *Experimental and Numerical Investigations of the Behaviour of Intact Veined Andesite*. University of Toronto.

Turichshev, A. and Hadjigeorgiou, J. (2017) 'Development of Synthetic Rock Mass Bonded Block Models to Simulate the Behaviour of Intact Veined Rock', *Geotechnical and Geological Engineering*, 35(1), pp. 313–335. doi: 10/gf86gp.

Walton, G. and Sinha, S. (2020) 'Advances in Bonded Block Modeling', in. *Bergmekanikdagen*, Stockholm, Sweden.

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