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Transition from Surface to Underground Mining — Understanding Complex Rock Mass Interactions Through the Integration of Mapping, Monitoring and Numerical Modelling Data

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Abstract

Numerous mining operations are considering the move from surface to underground mining in order to economically mine deeper resources particularly where open pit mine lives are nearing an end. However, the body of practical knowledge related to the impacts of underground mining on the surface environment in terms of induced differential strains, surface subsidence and slope stability is limited, imposing both economic risks to the mine and safety risks to mine personnel. This paper describes the framework of a large collaborative research initiative between the University of British Columbia (UBC), Simon Fraser University (SFU), Rio Tinto plc and Diavik Diamond Mines. The main objective of this work is to develop a methodology to characterise and better understand the complex rock mass interactions between underground mass mining operations and strain-sensitive surface structures through the integration of advanced numerical modelling methods, rock mass characterisation and deformation monitoring.

1 Introduction

With ever-increasing global demand for mineral resources, numerous mines are moving towards developing deeper, more complex and lower grade ore bodies. Recent years have seen the transition from surface to underground mass mining operations at several major mines worldwide in order to access deeper resources. Canadian examples include the Porcupine Joint Venture gold mines (Timmins, Ontario), Lac des Iles palladium mine (Thunder Bay, Ontario) and the QR gold mine (Quesnel, British Columbia), with the Diavik diamond mine (Northwest Territories), Highland Valley copper mine (Kamloops, British Columbia) and Afton copper-gold mine (Kamloops, British Columbia) considering similar moves.

The rock engineering interactions involved with such plans are complex and challenging. On surface, pit wall slopes are exceeding heights of several hundred metres for which the potential for deep-seated, stress-controlled rock slope failures is becoming more of an issue than bench-scale, structurally-controlled wedge failures. Underground, mass mining methods such as block caving are being promoted due to the favourable economics such mining methods afford when dealing with lower grade ore. Block caving by its very design results in a near-immediate response of the rock mass leading to deformation and surface subsidence. This effect may be localised to the surface area directly above the footprint of the cave, often observed as concentric lines of surface fractures stepping outwards from a central glory hole, or extend even further as tilting/sliding blocks and small strain subsidence over a significantly larger area (e.g. Figure 1).

Within the caved zone, obvious geotechnical hazards may arise from unexpected propagation of a stope back or cave breaking through to surface; e.g. the hangingwall wedge failure at the Kidd Creek mine in Canada (Board et al., 2000), the 800 m high pit wall failure at Palabora in South Africa (Brummer et al., 2006), or the fatal air blast caused by sudden caving at the Northparkes mine in Australia (Hebblewhite, 2003). The consequences of unexpected or underestimated differential strains outside the caved and fractured zones (Figure 1), however, may also have a negative impact on the integrity of strain-sensitive surface structures. Recent studies by Benko and Stead (1998), Hajiabdolmajid and Kaiser (2002) and Eberhardt et al. (2004) highlight the relevance of small strains (<1 %) on the destabilisation of open pit, engineered and natural slopes.

Given the ecological sensitivity of the northern regions of Canada, sustainable mining practices are a key priority – i.e. maximising mining of the resources, while reducing adverse effects. Diamond mines in the Northwest Territories (NWT) are facing such questions, primarily the effects that new underground developments may have on the stability of protective earth dikes, open pit mine slopes and other strain-sensitive surface structures. Owing to problems of scale, geological uncertainty and data quality, a fundamental understanding of the complex rock mass response in underground mass mining settings remains limited. Few reliable methods for subsidence prediction are available, as traditionally, little consideration has been given to surface impacts, even though underground mining operations induce considerable changes over vast areas (Laubscher, 1994).

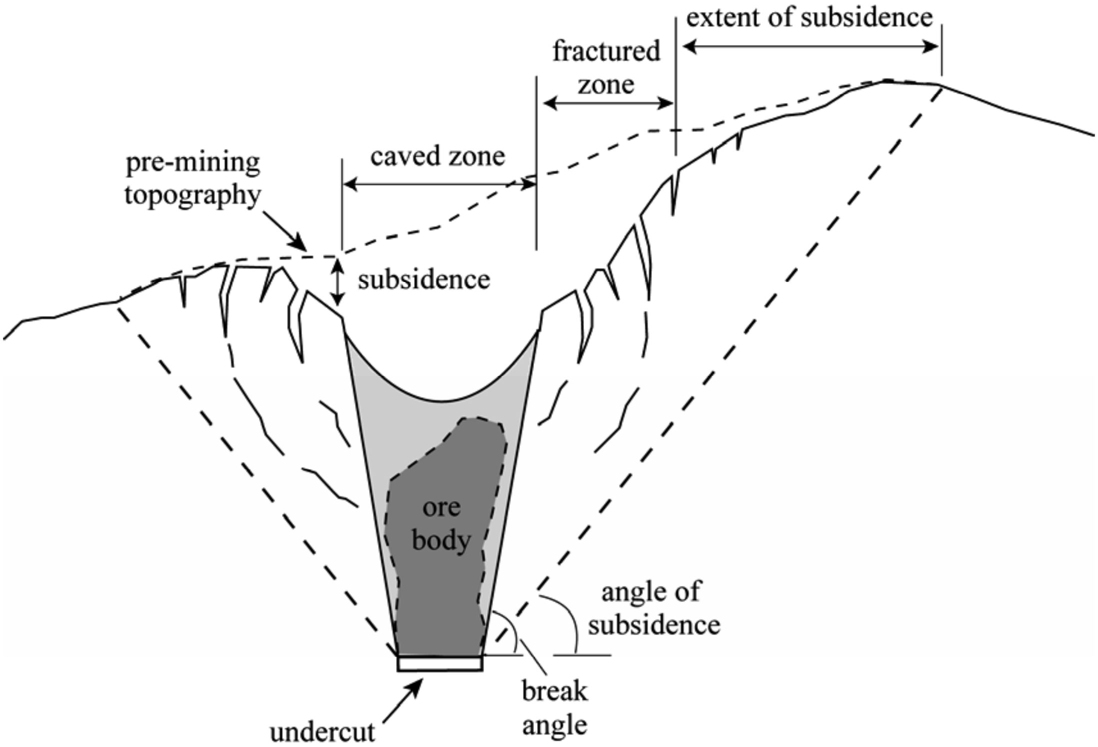


Figure 1 Surface subsidence associated with block cave mining (modified after van As, 2003 and Gilbride et al., 2005)

This paper presents an overview of a large collaborative research programme, the Canadian Block Caving Subsidence study, between the University of British Columbia (UBC), Simon Fraser University (SFU), Rio Tinto plc, Diavik Diamond mines and the Natural Sciences and Engineering Research Council of Canada (NSERC). The framework is focussed on examining the rock mass response between surface and underground mining operations and the impacts of differential strains on the destabilisation of open pit mine slopes by integrating advanced numerical modelling methods, state-of-the-art deformation monitoring systems and rock mass characterisation databases.

2 Subsidence prediction in block cave mining

Current practice in predicting the effects of underground mining on surface displacements is largely founded on empirical estimates. Much of this work has been directed towards longwall mining and continuous subsidence, for which empirical procedures and guidelines are relatively well established (Whittaker and Reddish, 1989). In block cave mining, relationships have been developed that correlate the mining rock mass rating (MRMR), height of caved rock and mine geometry to the break angle (Laubscher, 1990). Typical values of break angle (see Figure 1) are reported by Laubscher as ranging from 75 to 90°. This approach, however, does not account for the effects of major geological structures which may influence cave propagation and the symmetry and continuity of the resulting subsidence; estimates need to be adjusted for local geological conditions requiring sound engineering judgment and experience in similar geotechnical settings (Elmo et al., 2007a).

The influence of such factors as geological heterogeneity and surface topography (e.g. where a steep natural or open pit slope may be present) has led to a need for numerical methods, which are more ideally suited for treating problems involving complex geometries and material behaviour. Several techniques have been applied to the analysis of block caving subsidence (see review by Elmo et al., 2007a), ranging from those that treat the problem domain as a continuum (or equivalent continuum in the case of fractured rock) to those where key discontinuity sets and their influence on the caving and subsidence process can be modelled explicitly. Recent developments have seen the extension of these techniques to allow for the modelling of the transition from continuum to discontinuum through fragmentation during the caving process based either on brittle fracture constitutive relationships and discrete crack insertion algorithms (e.g. Elmo et al., 2007b; Vyazmensky et al., 2007; Stead et al., 2007) or through the rupturing of particle bonds (e.g. Gilbride et al., 2005; Pierce et al., 2007).

One of the primary objectives of the Canadian Block Caving Subsidence study is to develop guidelines related to the use and integration of advanced numerical modelling methods to characterise complex rock mass behaviour above block cave mines. Emphasis will be placed on answering questions related to both parameter and model uncertainty in order to gain a deeper understanding of the roles geological structure and brittle fracture play in the development and distribution of surface subsidence and how best to incorporate their influence in predictive models.

2.1 Parameter uncertainty

The numerical method chosen (continuum, discontinuum, etc.) depends on the varying strengths and limitations inherent in each of the different methodologies relative to the data available and the key objectives of the analysis. Models can be simple, focussing on specific questions to gain a basic understanding of the contributing subsidence mechanisms, and then increase in complexity to improve confidence in subsidence predictions. Figure 2 shows the progressive failure of a 45° pit slope wall during the upward advancement of a block cave mine using the finite difference continuum code FLAC (Itasca, 2005). The model is relatively simple and only includes the effects of volume loss at depth on the stability of the slope assuming a Mohr-Coulomb yield criterion. The model shows that with increasing cave height the amount of vertical displacement at surface increases and that the stability state of the slope is sensitive to small strains.

This sensitivity is a function of the elasto-plastic shear strength yield properties chosen for the rock mass, in this case, cohesion = 1.25 MPa and bulk friction = 40° assuming an elastic-perfectly plastic constitutive model. The nature of the continuum model requires that the rock mass properties reflect those of an equivalent continuum that treats any discontinuities or planes of weakness in the material implicitly. Lower strength properties will result in the slope failing sooner with a reduced cave height (the cave height shown in Figure 2e is 400 m with a crown pillar thickness of 400 m), and higher strength properties will result in a stable slope or require the cave to daylight in the pit floor bottom for slope failure to occur. Sensitivity analyses are common practice when performing a numerical analysis, providing an improved understanding of the influence of uncertainty in the material input parameters on the model results (e.g. Figure 3).

The modelling process becomes an incremental and iterative process, with other key factors being added to the model to increase its complexity and to approach a better representation of the in situ conditions. This enables an evaluation of the confidence in the model, assessing the uncertainties associated with the modelling process and the influence of various factors on the predictive outcome (e.g. geological heterogeneity, in situ stress, role of bulking factors, influence of pore pressures, undercut sequencing, etc.).

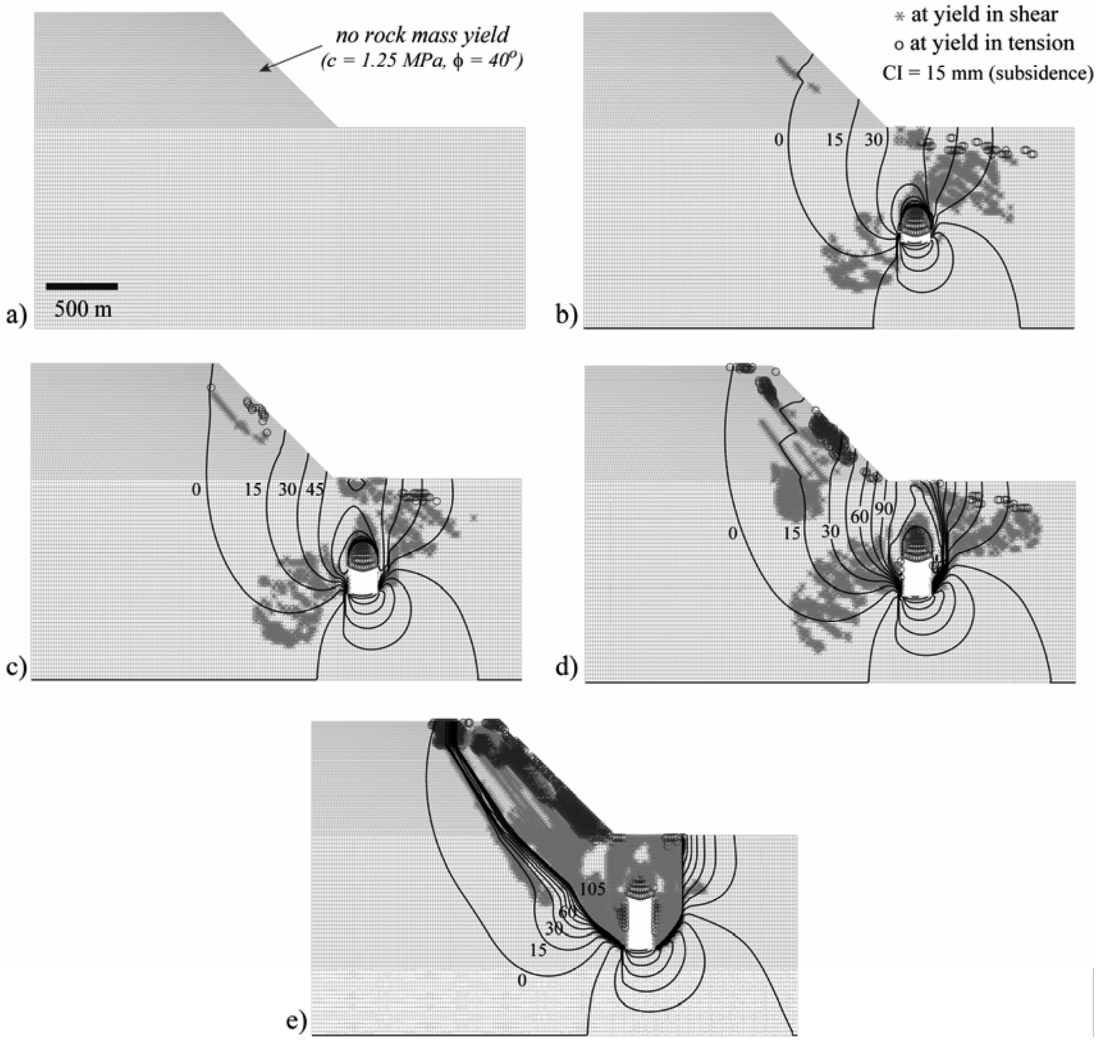


Figure 2 FLAC continuum model of a developing rock slope failure due to small strains associated with block cave mining: a) pre-caving, b-e) cave heights of 100, 200, 300 and 400 m, respectively. Assumed equivalent continuum rock mass properties are c = 1.25 MPa and ϕ = 40°

2.2 Model uncertainty

The modelled interaction between an advancing block cave and open pit slope can be viewed from a number of perspectives: the influence of the caving process on the stability state of the pit slope, as well as the influence of the pit slope on the stresses in the crown pillar and their influence on the caving process. Thus the modelling method and required degree of complexity typically relate to the specific objectives for which the analysis is being carried out. The degree of model complexity is also constrained through a balance between computational efficiency and solution runtimes. Mine-scale models in 3-D generally necessitate simplifying assumptions such as treating the rock mass as an equivalent continuum (e.g. Elmo et al., 2007a).

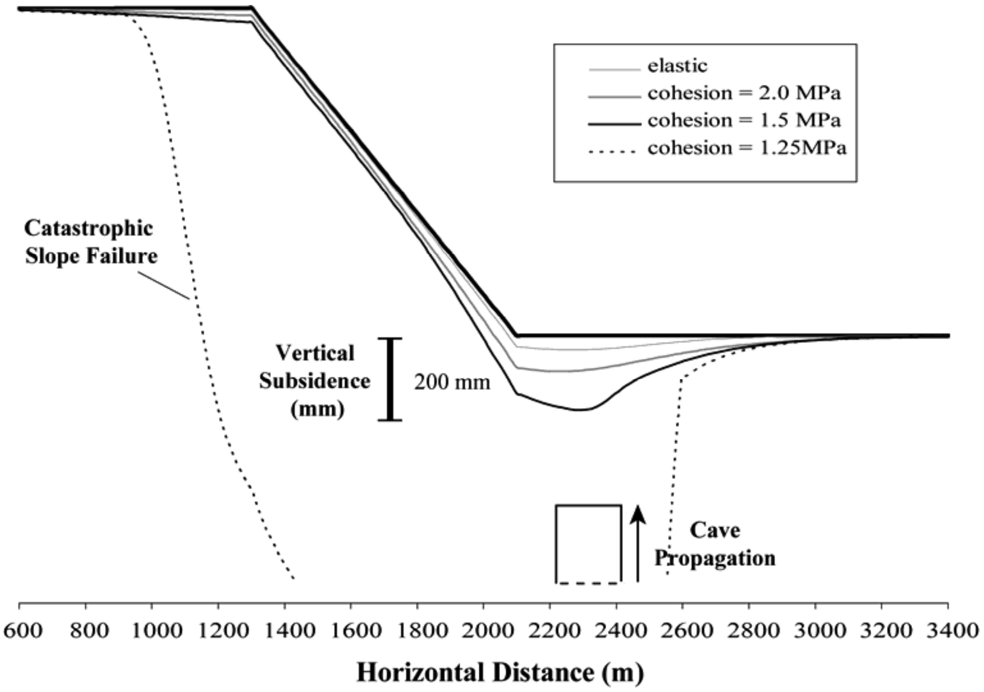


Figure 3 Sensitivity analysis of pit wall stability as a function of rock mass cohesion based on the continuum analysis shown in Figure 2 (bulk friction = 40°, cave height = 400 m, crown pillar thickness = 400 m, slope angle = 45°). Note that catastrophic failure of the slope occurs for a cohesion value of 1.25 MPa

This raises the question of model uncertainty; are we employing the correct numerical techniques or constitutive models to properly represent the physics and behaviour of the rock mass system (e.g. Stead et al., 2007)? In block cave mining, the heterogeneous and discontinuous nature of the rock where fractures open, slip, propagate and shear, often dominates and controls its behaviour. Brown (2003) summarises the current state of practice for discontinuous subsidence related to hard rock mining and block caving in fractured rock. In both cases, established methods are predominantly based on continuum mechanics and assumptions of geological homogeneity for which the subsidence profile calculated is largely symmetric. In accounting for the effects of rock mass heterogeneity and discontinuities, the procedural steps outlined by Brown (2003) state that the break angle should be "modified" accordingly. The vagueness of such guidelines and brief treatment of "subsidence prediction in practice" in the International Caving Study monograph (Brown 2003) underscore the need for further research.

The interaction between discontinuous mining-induced subsidence and the ground surface/open pit slopes has defied empirical attempts of characterisation. Continuum-based finite-element/finite-difference analyses are equally deficient. Eberhardt et al. (2007) demonstrated for the case of consolidation subsidence over a deep hard-rock tunnel that although the maximum subsidence could be predicted using a finite-element solution, the fit to the overall shape of the subsidence trough was poor, and for the most part, the magnitudes of vertical displacements were under predicted. A better fit of the width and asymmetry of the subsidence profile was instead achieved through a discontinuum-based distinct-element analysis where mapped geological structures within and above the tunnel could be explicitly included.

Figure 4 shows a similar comparison for the block cave/open pit interaction example previously described. Continuum-based surface subsidence profiles along a 45° pit slope above an advancing block cave (cave height = 400 m, crown pillar thickness = 400 m) are compared to those from a discontinuum-based analysis using the distinct-element code UDEC (Itasca, 2004). The discontinuum models differ based on the dip and shape of the blocks formed by a series of persistent joints cross-cut by a series of orthogonal joints. The same Mohr-Coulomb shear strength properties, corresponding to the stable slope condition determined in Figure 3 (c = 1.5 MPa, $\phi = 40°$), are used for the equivalent continuum rock mass blocks in the different models. The discontinuities in the discontinuum models are assumed to be cohesionless with a joint friction angle of 40°.

The results shown in Figure 4 demonstrate that both the magnitude and shape of the subsidence profile modelled can vary as a function of modelling approach (continuum vs. discontinuum), constitutive model (elastic vs. elasto-plastic), and geometry of the discontinuity network. Figure 5 shows the distribution of shear and tensile plasticity indicators for several different discontinuity network configurations if the block cohesion value is lowered to that which resulted in catastrophic failure for the continuum-based models (Figure 3, c = 1.25 MPa). The explicit inclusion of discontinuities in the UDEC models result in deformations that are irregular, asymmetric and discontinuous owing to their changing influence on the kinematics of the slope. By discounting the influence of geological structure in promoting asymmetry in the shape of the subsidence profile, the magnitudes and reach of displacements affecting the pit slope may be under predicted.

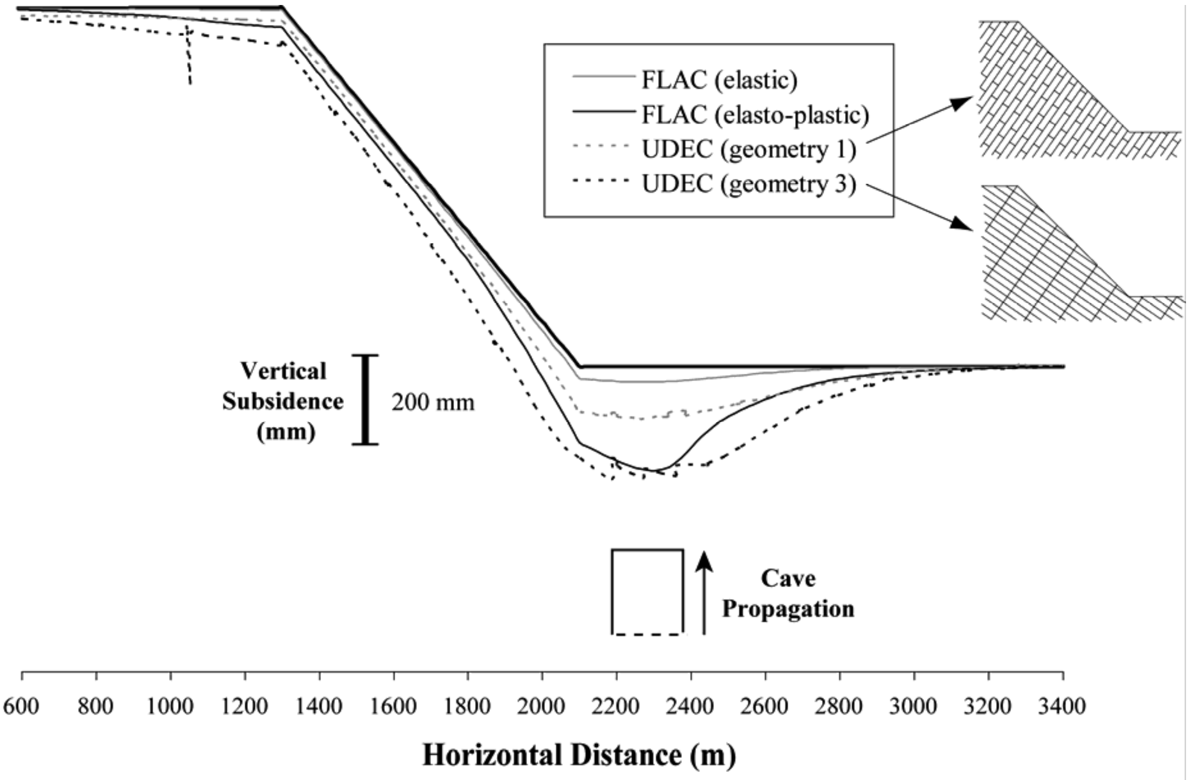
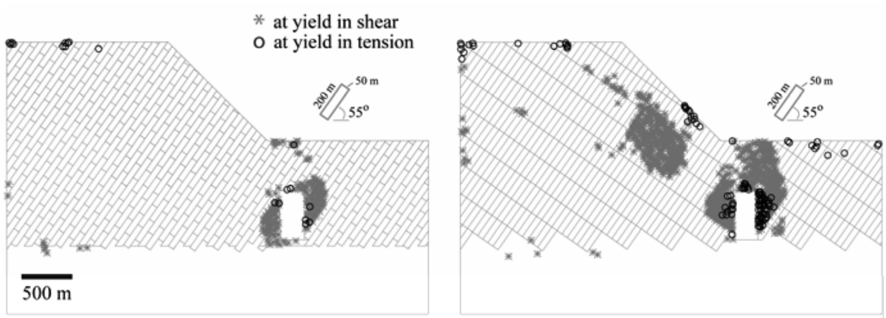


Figure 4 Comparison of continuum and discontinuum derived subsidence profiles (slope angle = 45°). The dip angles of the joints in the two UDEC models are 55 and 145°, counter-clockwise from horizontal, with varying joint persistence and spacings (see Figure 5)

2.3 Brittle fracture modelling

The results in Figure 5 emphasise the role of intact rock fracture/continuity in induced slope failure. One significant limitation of conventional continuum and discontinuum numerical analyses is their inability to explicitly account for brittle fracture processes, and their subsequent role in underground-surface mine interactions. The caving process from which the complex combination of discontinuous/continuous ground relaxation occurs, is largely controlled by the initiation and propagation of brittle fractures through intact rock bridges separating non-persistent discontinuities (see also Elmo et al., 2007c). Following an undercut and initiation of the caving process, the cave will propagate upwards and will continue to do so as long as shear and/or tensile yield in the cave back is sufficient to prevent the formation of a stable arch. The rock mass interactions involved thus comprise global failure of the rock mass in both tension and compression, along existing discontinuities and through intact rock bridges.



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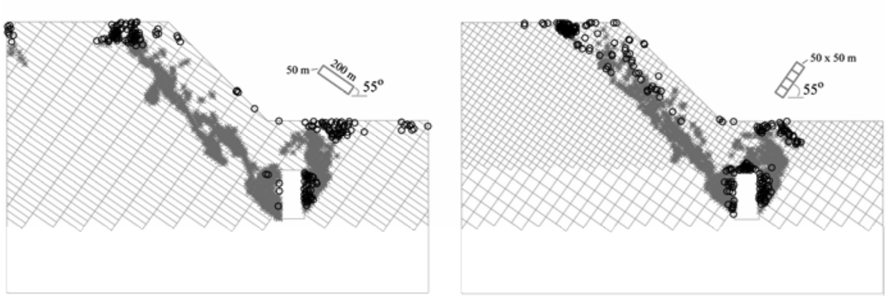

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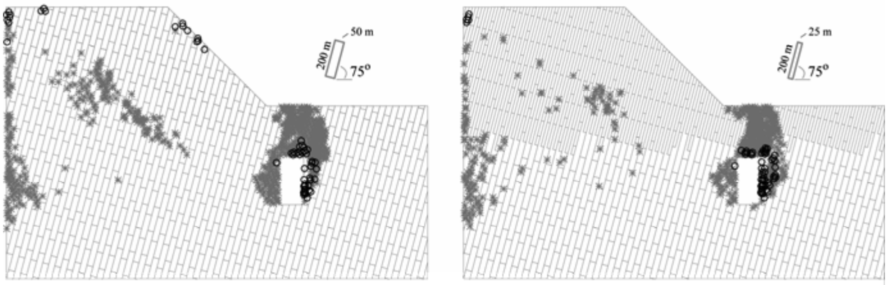

Geometry 5 Geometry 6

Figure 5 Distribution of shear (*) and tensile (o) plasticity indicators for several different discontinuity network configurations (slope angle = 45°)

Within the scope of the Canadian Block Caving Subsidence study, work in the Resource Geotechnics group at Simon Fraser University is concentrating on the applicability of state-of-the-art hybrid finite-/discrete-element brittle fracture codes in modelling complex subsurface-surface mine interactions. For this, the commercial code ELFEN (Rockfield, 2004) is being used, which combines the advantages of both continuum and discontinuum techniques to model intact rock behaviour, interactions along existing discontinuities and the initiation and propagation of new stress-induced fractures based on fracture mechanics principles (Figure 6; Elmo et al., 2007b). Brittle fracture and fragmentation in these models is enabled through an adaptive remeshing procedure coupled with contact search algorithms. A detailed description of the method can be found in Owen et al. (2004, 2007), and is summarised below.

The rock mass in ELFEN can be represented using a variety of constitutive criteria including a Rankine rotating crack model, which uses tensile strain-softening to represent material degradation. For tension/compression stress states, the Rankine model is combined with a capped Mohr-Coulomb criterion in which the softening response is coupled to the tensile model (Klerck et al., 2004; Owen et al., 2004). After initial yield, the constitutive model introduces damage by degrading the elastic modulus in the direction of the principal stress invariant. This leads to localisation in individual elements followed by insertion of a discrete crack once the elastic modulus within the localisation zone has degraded to zero. The fracture is inserted together with additional nodes into the domain and an adaptive remeshing procedure is used to update the necessary elemental connectivities and refine the mesh. Contact interaction laws are implemented and the solution moves to the next time step.

This combined finite-/discrete-element approach thus allows an initial continuum to be gradually degraded into discrete blocks as fractures are inserted. Fracture propagation and coalescence occurs in the directions that attempt to maximise the subsequent energy release rate and minimise the strain energy density; i.e. the optimum propagation path maintains an orientation normal to the maximum extension strains (Owen et al., 2004).

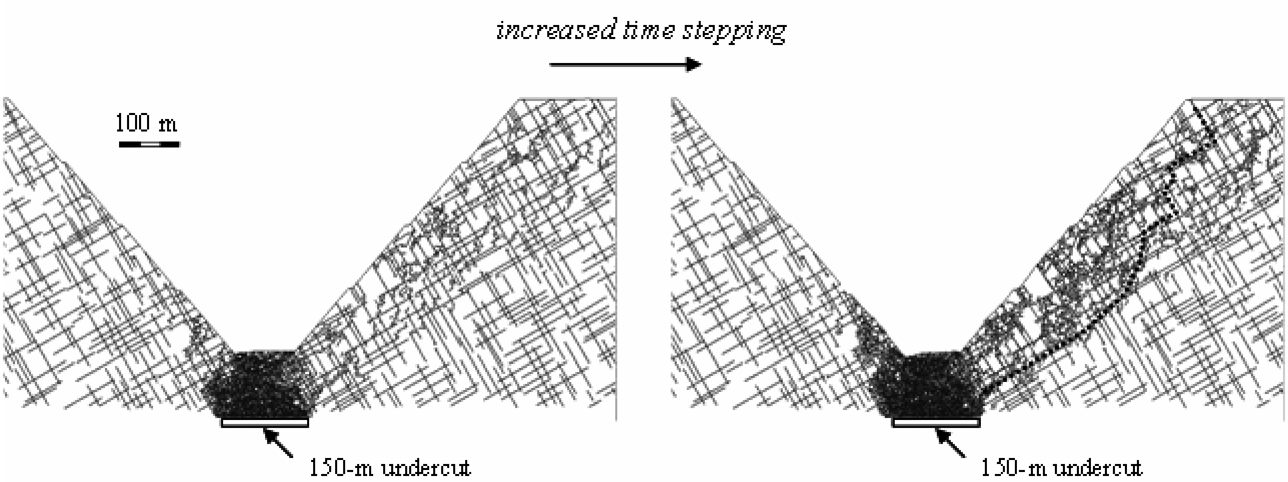

Figure 6 Hybrid finite-/discrete-element modelling of a pit wall slope failure above a block cave mine (after Elmo et al., 2007b). The two figures show progressive stages in fracture development following a 150 m undercut 100 m below the pit floor

For the model run shown in Figure 6, horizontal and vertical displacements of the pit walls were analysed as a function of the undercut sequence (taken in 30 m stages and terminating at a width of 150 m). Input for the geometry of the joint network was generated using the Discrete Fracture Network program FracMan (as reported in Elmo et al., 2007b, and discussed below and in detail in Stead et al., 2007). The results of the model clearly show that progressive block caving results in an increased inward horizontal movement of the pit wall slope with time, ultimately resulting in a relatively large slope failure characterised by a combined sliding-toppling mechanism. The dashed line in Figure 5 represents the failure surface which formed as a result of extension of pre-existing fractures and step-path fracture through intact rock material.

The initial 2-D conceptual models of the interaction between open-pit and block-caving mining shown in the work of Elmo et al. (2007b) and Vyazmensky et al. (2007) constitute a required and important precursor to more complex and larger-scale simulations (i.e. with extended model boundaries and more details related to undercut sequencing, cave propagation, etc.). Future work within the context of this study will focus on calibrating the model parameters to ensure that simulated caving behaviour corresponds to the trends observed in situ and to develop a correlation between rock mass properties and specific fracture patterns.

3 Integration of discrete fracture networks and monitoring discontinuous subsidence

The increasing complexity of these numerical techniques necessitates the need for balance with the quantity and quality of the engineering geological field data collected to help minimise geological uncertainty. There have been considerable developments in the characterisation of rock slopes using remote sensing techniques such as laser scanning and digital photogrammetry. As such, the broader framework of the Canadian Block Caving Subsidence study will focus not only on the integration of different modelling techniques, but also their integration with rock mass characterisation tools and deformation monitoring systems (Figure 7).

Characterisation efforts will examine the use of laser scanning and digital photogrammetry in determining: digital structural domains; kinematic admissibility of rock slope failure mechanisms; discontinuity spacing, persistence, offset and block size volume distributions; “step-path” and intact rock bridge characteristics; digital rock mass quality measures; and integration of data with discrete fracture network codes (DFN). DFN codes like FracMan (Golder, 2006) provide a powerful means with which to synthesise realistic fracture network models from digitally and conventionally mapped data, and several studies have begun to explore their applicability to a range of problems related to block cave mining (e.g. Rogers et al., 2007).

Figure 8 provides an example of the combined use of FracMan together with a block theory analysis (using the FracMan module RockBlock; Golder, 2006). Through collaboration with Golder Associates, FracMan will be used to quantify the effects of discontinuity connectivity, persistence and intact rock bridges on caving mechanisms, and to link rock mass characterisation data sets with correlations between cave propagation and subsidence (see Elmo et al., 2007c). This work continues that by Elmo (2006) to develop fracture trace maps based on regularly defined joint sets to import into ELFEN to study the effects of varying fracture orientation and intensity on stress-induced fracture propagation (as demonstrated in Figure 6 with respect to rock slope interactions with block cave mines; see also Stead et al., 2007).

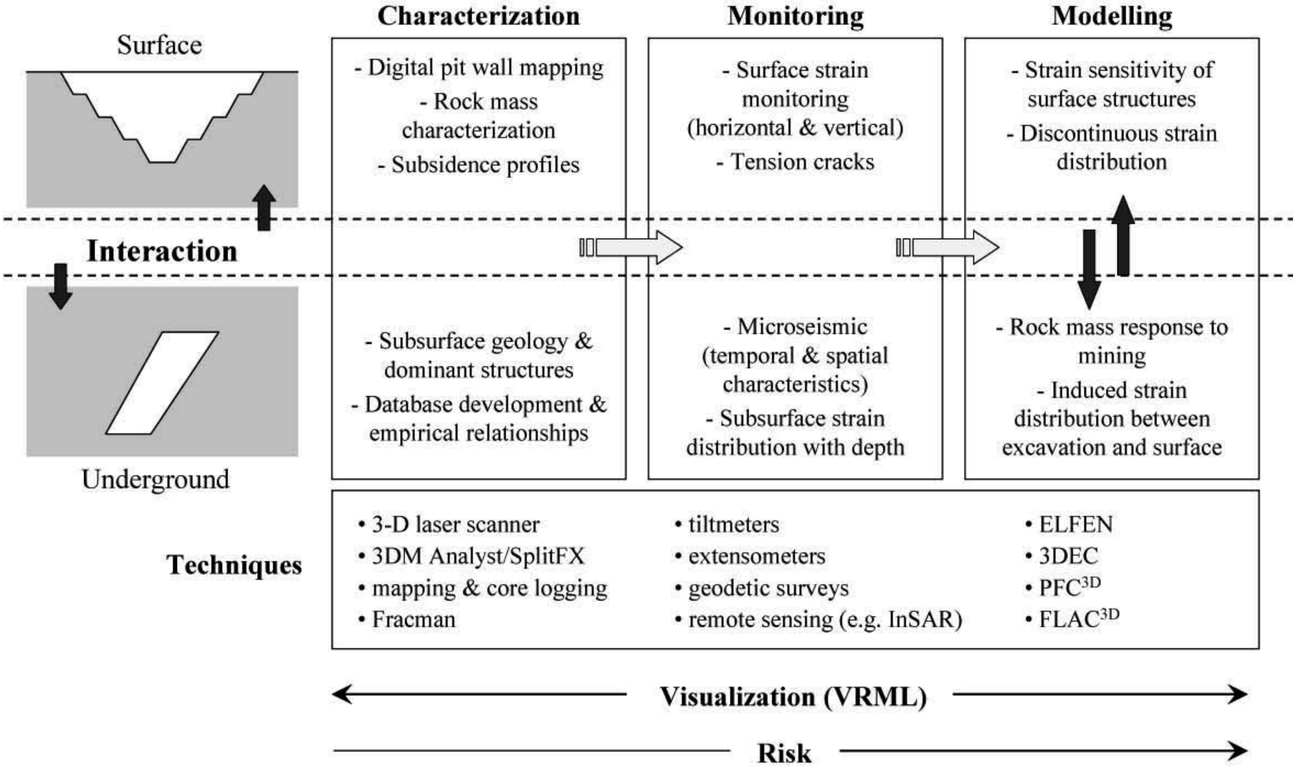

Figure 7 **Integration of study components to investigate complex rock mass interactions between underground and surface mining excavations**

To complement the rock mass characterisation studies, remote sensing data, geodetic measurements and high-resolution tiltmeters and crackmeters will be used to measure and characterise the effects of geological heterogeneity on underground-surface mine interactions and surface subsidence. Existing data from several operating mine sites will be used together with new data sources to provide the necessary resolution and spatial/temporal coverage required. Satellite imagery and air photos will be used to characterise macro-deformations where ground collapse has occurred and surface tiltmeters, crackmeters and geodetic measurements will be used to analyse small strain microdeformations and surface subsidence profiles.

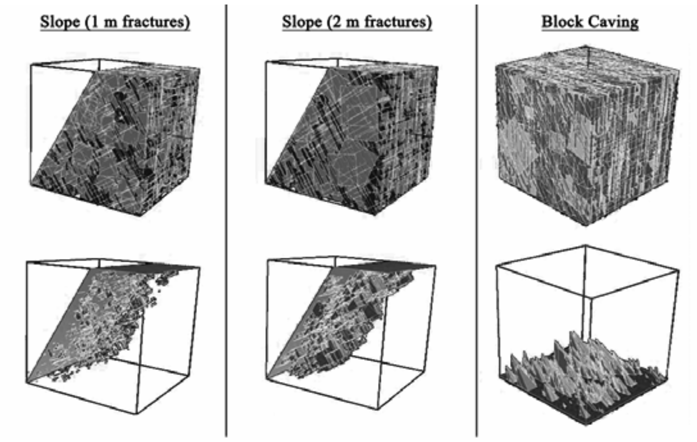

Figure 8 FracMan Discrete Fracture Network (DFN) model integrated with a block theory analysis to characterise block shape/volume for pit slope and block caving applications (after Elmo et al., 2007c)

Figure 9 provides an example of a Differential Interferometric Synthetic Aperture Radar (DInSAR) trial assessment performed at the Palabora block cave operations in South Africa (AMEC, 2005). Deformation maps were prepared for several consecutive time periods and compared to weekly ground survey data. The general trend and magnitude of deformations indicated by the ground survey data correlated well with the DInSAR data. One of the major studies to be carried out as part of the deformation characterisation work will be to integrate and compare DInSAR datasets with surface-based geodetic measurements. Further applications of DInSAR to the measurement of subsidence will be explored and undertaken, integrating further data from surface tilt meters, GPS and microseismic arrays.

Existing microseismic data, including event frequency (temporal control), source location (spatial control) and source characteristic data, will further be integrated into the combined data set. A detailed review paper on microseismic monitoring of open pit slopes is given by Lynch and Malovichko (2006). Comparisons will be made between seismic and aseismic zones, and their rock mass characteristics to gain insights into the role of geological and structural controls as a function of the induced/disturbed stresses. Source characteristics will be analysed to delineate tensile and shear activity and sources within the seismogenic zone (i.e. separating brittle fracture events from those related to slip along existing joints or newly formed fracture planes. Further correlations will be made with the layout and progress of mine operations and measured surface displacements.

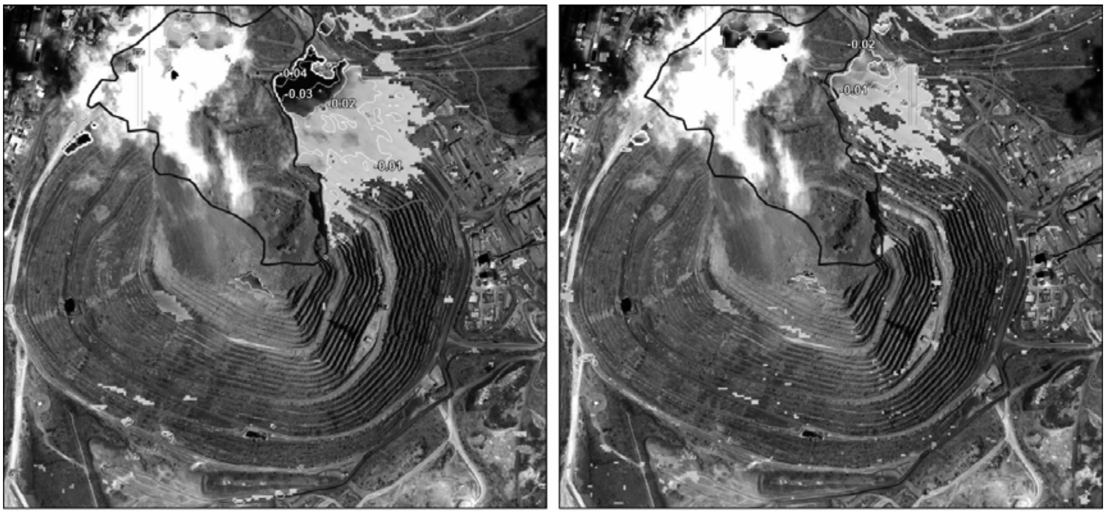

Figure 9 Comparison of two months of pit wall movement in 2004 due to block cave mining at the Palabora mine in South Africa (AMEC, 2005). July 22 to August 15 (left) and August 15 to September 8 (right)

The large number of data sets involved in this project, ranging from numerical to satellite imagery to ground-based measurements, will require that they be stored and interpreted in an efficient manner. For this, state-of-the-art computer visualisation techniques will be adopted using Virtual Reality (VR) technology. The ELFEN software already allows data visualisation in Virtual Reality Modelling Language (VRML) and it is intended to extend these capabilities through this project. VR facilities combine large format spherical stereoscopic projection with advanced earth modelling software that enable the mapping of numerous data sets to a single, world coordinate system (Kaiser et al., 2002). Kaiser et al. (2002) note that this “fusion” of data when viewed in the VR setting enables the identification of hidden relationships, discovery and explanation of complex data interdependencies, and means to compare and resolve differing interpretations.

4 Conclusions and future work

Owing to problems of scale and lack of access, a fundamental understanding of the complex rock mass response in block caving settings remains limited. Issues related to geological complexity and both parameter and model uncertainty represent a significant obstacle to better predicting the spatial and temporal evolution of catastrophic rock slope failures. This paper describes the framework and initial results from a large collaborative research initiative whose main objectives are to better understand and characterise the complex rock mass interactions leading to surface subsidence above block cave mines and their impact on strain-sensitive surface structures. The use of state-of-the-art continuum, discontinuum and hybrid finite-/discrete-element techniques forms a fundamental part of the ongoing research.

The framework presented in this paper emphasises the need to better integrate the various data sets collected through both field-based investigations and analytical/numerical modelling studies in order to overcome the challenges of geological complexity and uncertainty and bring better understanding of the controlling slope destabilising mechanisms into the engineering decision-making process.

References

AMEC (2005) Earth observation market development program land subsidence pre-commercial trial Palabora mine, South Africa. AMEC Report VM00344, 82 pp.

Benko, B. and Stead, D. (1998) The Frank slide: A re-examination of the failure mechanism. Canadian Geotechnical Journal 35, pp. 299-311.

Board, M., Seldon, S., Brummer, R. and Pakalnis, R. (2000) Analysis of the failure of a large hangingwall wedge: Kidd Mine Division, Falconbridge, Ltd. CIM Bulletin 93(1043), pp. 89-97.

Brown, E.T. (2003) Block caving geomechanics. JKMRC, University of Queensland, 516 pp.

Brummer, R.K., Li, H. and Moss, A. (2006) The transition from open pit to underground mining: an unusual slope failure mechanism at Palabora. Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations, S.A.I.M.M., Johannesburg, pp. 411-420.

Eberhardt, E., Stead, D. and Coggan, J.S. (2004) Numerical analysis of initiation and progressive failure in natural rock slopes – the 1991 Randa rockslide. International Journal of Rock Mechanics and Mining Sciences 41(1), pp. 69-87.

Eberhardt, E., Zangerl, C. and Loew, S. (2007) Subsidence over hard rock tunnels. Tunnels & Tunnelling International 39(3), pp. 50-53.

Elmo, D. (2006) Evaluation of a hybrid FEM/DEM approach for determination of rock mass strength using a combination of discontinuity mapping and fracture mechanics modelling, with particular emphasis on modelling of jointed pillars. PhD Thesis, Camborne School of Mines, University of Exeter, U.K.

Elmo, D., O'Connor, C., Vyazmensky, A., Stead, D., Dunbar, S., Eberhardt, E., Scoble, M.J. and Moss, A. (2007a) Integrated modelling of subsidence mechanisms and impacts due to mine caving. 109th CIM Annual General Meeting, Montreal.

Elmo, D., Vyazmensky, A., Stead, D. and Rance, J.R. (2007b) A hybrid FEM/DEM approach to model the interaction between open-pit and underground block-caving mining. 1st Canada-US Rock Mechanics Symposium, Vancouver. Taylor & Francis, London, Vol. 2, pp. 1287-1294.

Elmo, D. Yan, M., Stead D. and Rogers, S.F. (2007c) The importance of intact rock bridges in the stability of high rock slopes: Towards a quantitative investigation using an integrated numerical modelling - discrete fracture network approach. Proceedings of the International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Perth.

Gilbride, L.J., Free, K.S. and Kehrman, R. (2005) Modelling block cave subsidence at the Molycorp, Inc., Questa Mine - A case study. 40th U.S. Symposium on Rock Mechanics, Anchorage, Alaska. ARMA/USRMS 05-881.

Golder Associates (2006) FracMan software suite. FracMan Technology Group (www.fracman.com).

Hajiabdolmajid, V. and Kaiser, P.K. (2002) Slope stability assessment in strain-sensitive rocks. EUROCK 2002, Madeira. Sociedade Portuguesa de Geotecnia, Lisboa, pp. 237-244.

Hebblewhite, B.K. (2003) Northparkes findings – The implications for geotechnical professionals in the mining industry. 1st Australasian Ground Control in Mining Conference, UNSW Press, Sydney, pp. 3-10.

Itasca (2004) UDEC version 4.0. Itasca Consulting Group, Inc., Minneapolis.

Itasca (2005) FLAC version 5.0. Itasca Consulting Group, Inc., Minneapolis.

Kaiser, P.K., Henning, J.G., Cotesta, L. and Dasys, A. (2002) Innovations in mine planning and design utilizing collaborative virtual reality (CIRV). 104th CIM Annual General Meeting, Vancouver.

Klerck, P.A., Sellers, E.J. and Owen, D.R.J. (2004) Discrete fracture in quasi-brittle materials under compressive and tensile stress states. Computer Methods in Applied Mechanics and Engineering 193, pp. 3035-3056.

Laubscher, D.H. (1990) A geomechanics classification system for the rating of rock mass in mine design. The Journal of the South African Institute of Mining and Metallurgy 90(10), pp. 257-273.

Laubscher, D.H. (1994) Cave mining – the state of the art. The Journal of the South African Institute of Mining and Metallurgy 94(10), pp. 279-293.

Lynch, R.A. and Malovichko, D.A. (2006) Seismology and slope stability in open pit mines. Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations, Johannesburg. S.A.I.M.M., pp. 375-390.

Owen, D.R.J., Feng, Y.T., de Souza Neto, E.A., Cottrell, M.G., Wang, F., Andrade Pires, F.M. and Yu, J. (2004) The modelling of multi-fracturing solids and particulate media. International Journal for Numerical Methods in Engineering 60(1), pp. 317-339.

Owen, D.R.J., Feng, Y.T., Laboa, M., Leonardi, C.R., Zhao, S.Y. and Yu, J. (2007) Simulation of multi-fracturing rock media including fluid/structure coupling. 1st Canada-US Rock Mechanics Symposium, Vancouver. Taylor & Francis, London, Vol. 1, pp. 457-465.

Pierce, M., Cundall, P., Potyondy, D. and Mas Ivars, D. (2007) A synthetic rock mass model for jointed rock. 1st Canada-US Rock Mechanics Symposium, Vancouver. Taylor & Francis, London, Vol. 1, pp. 341-349.

Rockfield (2007) ELFEN Version 3.8.9. Rockfield Software Ltd., Swansea, UK.

Rogers, S.F., Kennard, D.K., Dershowitz, W.S. and van As, A. (2007) Characterising the in situ fragmentation of a fractured rock mass using a discrete fracture network approach. 1st Canada-US Rock Mechanics Symposium, Vancouver. Taylor & Francis, London, Vol. 1, pp. 137-142.

Stead, D., Elmo, D., Yan, M. and Coggan, J.S. (2007) Modelling brittle fracture in rock slopes: experience gained and lessons learned. Proceedings of the International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Perth.

Van As, A. (2003) Subsidence definitions for block caving mines. Technical report, Rio Tinto.

Vyazmensky, A., Elmo, D., Stead, D. and Rance, J.R. (2007) Combined finite-/discrete-element modelling of surface subsidence associated with block caving mining. 1st Canada-US Rock Mechanics Symposium, Vancouver. Taylor & Francis, London, Vol. 1, pp. 467-475.

Whittaker, B.N. and Reddish, D.J. (1989) Subsidence - Occurrence, Prediction and Control. Elsevier, 528 pp.