Rock Mechanics Approach for the Recovery of the Zone G Crown Pillar at the Raglan Katinniq Mine

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ABSTRACT: The recovery of the Zone G crown pillar, located between the bottom of the open pit and the top of the underground workings at the Raglan Katinniq Mine in Nunavik, started in the summer of 2008 and should be completed by the end of 2009. This article describes the rock mechanics-based approach implemented to design the recovery of this valuable block of ore. The stereophotography-based ShapeMetriX3D technique was first used to provide a comprehensive assessment of the various joint sets that comprised the pillar. Then, the statistical distributions obtained for the dip, dip direction, spacing and persistence of these sets were used in conjunction with the geometry of the large-scale faults present in the area to build and run a series of explicit rigid numerical models. Each of these models had a slightly different jointing geometry, randomly constructed from these statistical distributions. Incorporating in a properly formulated numerical model the variability of some of the input parameters has allowed the engineering team to assess in a rational and reliable manner the likelihood of success of the proposed mining method and sequence.

1 INTRODUCTION AND BACKGROUND

The Xstrata Nickel Raglan Mine (Raglan) is located 1,850 km north of Montreal in the Nunavik region at the northern limit of the Province of Quebec, in Eastern Canada. The site, situated well north of the 60th parallel, lies in permafrost, which extends to a depth of about 500m below surface. The operation, currently comprised of three distinct mines (Katinniq, Mine 2 and Mine 3), has an average grade of 2.53% nickel, and also produces copper, cobalt and platinum group metals.

By March 2008 the extraction of Zone G at the Katinniq mine had evolved to the point where the recovery of the crown pillar between the open pit and underground workings had to be planned. Itasca Consulting Canada, Inc. (Itasca Canada) assisted the Raglan engineering team by numerically investigating various geomechanics aspects of the recovery of this crown pillar, planned with blastholes drilled from the bottom of the pit. In particular, the following issues were to be examined : 1) the response of the crown pillar to successive blasts fired in it, as well as that of the back of Cut 1525 from where mucking was to be carried-out underground, and including the behaviour of the successive brows created by consecutive blasts in the crown pillar ; 2) the behaviour of the rock mass around the main draw point on the east side of Cut 1525 ; and, 3) the stability of the hanging wall that was going to be created and progressively enlarged with mining.

The numerical analyses were completed with the *3DEC*™ inelastic code (which stands for “3-dimensional Discrete Element Code”) – an advanced inelastic package for the simulation of stresses, deformations and failure in solids –, and the *ItasCAD*™ platform for results visualisation and interpretation purposes. The *3DEC* code is based on the distinct element method, which is a discontinuum analysis technique (Itasca, 2003). It treats the system to be analysed as an assembly of discrete bodies with interfaces between them, which can be either considered as such, or turned into a continuum by "gluing" these blocks together. Rather than building a global stiffness matrix and converging towards a solution, as is generally done with boundary element and finite element methods, *3DEC* uses an explicit time-marching algorithm to solve the equations of motion directly, with equilibrium being reached when the unbalanced force in the model is reduced to zero.

Two types of numerical analyses were conducted for the Zone G crown pillar project. Firstly, zoned analyses were completed, whereby the rock mass was considered continuous. This approach, in which the cablebolts installed in Cut 1525 were explicitly included, focused on the behaviour of the rock matrix in response to the stress changes and deformations caused by mining. Figure 1 shows a view looking north and from above of the zoned *3DEC* model constructed for this project – note the three large-scale faults (shown in green) included in the model, which were expected to affect stability. Cut 1525, from where mucking was to be carried out, is also visible in the figure, directly underneath the crown pillar (shown in pink).

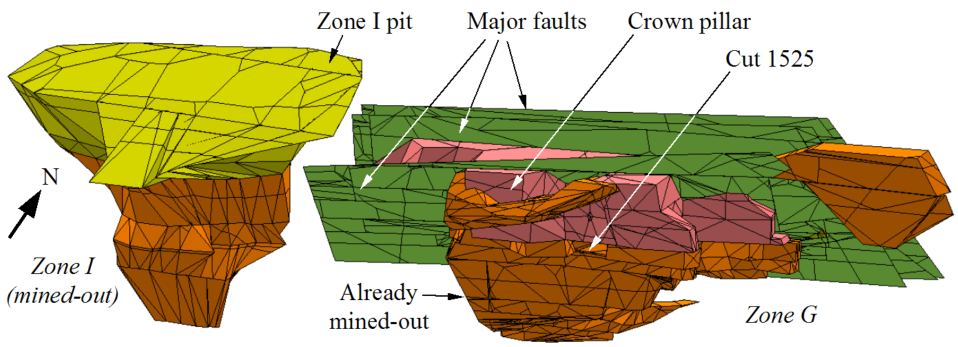


Figure 1. Isometric *ItasCAD* view of the zoned *3DEC* model looking north and from above. The separate (and already mined-out) Zone I is on the left of the figure, Zone G is on the right hand side. The encasing rock mass and the pit above Zone G have been hidden from view for clarity.

The zoned analyses did not highlight any major problem, based on the rock mass properties that Itasca Canada had previously used successfully at Raglan, the excavation geometry examined, the three faults considered and various zones of low RQD material incorporated in the model. In other words, no excessive deformation and/or stress changes that would have caused failure around the voids were identified with the mining approach, extraction sequence and ground support system proposed for the recovery of the crown pillar above Zone G.

Following these zoned analyses, a series of discrete/jointed/un-zoned simulations were then completed, whereby the discrete blocks created by the various joint sets were allowed to move along, or rotate around, their interfaces, as well as detach and free-fall into the voids. These kinematic analyses focused on the potential for the rock mass to unravel along the joint sets and major faults when large spans are developed in it. This unravelling was expected to be the most likely mode of failure in the case at hand given the low confining stresses acting upon the near-surface rock mass. Since the likelihood of this failure mechanism was confirmed by this second round of simulations, subsequent work focused on trying to *quantify* the chance of it materialising. The remainder of this paper describes this particular aspect of the work.

2 DISCRETE KINEMATIC ANALYSES

Two series of discrete models were constructed and used for this aspect of the project : one for the analysis of the crown pillar (and particularly the back above Cut 1525 and the brows of the excavation), and another for the analysis of the hanging wall. Both considered only limited spans along with simplified geometries, and, as mentioned, were meant to investigate the potential for kinematic structurally-controlled gravity-driven unravelling to occur with the joint set configuration associated with each exposed surface. The limited spans and simplified geometries were needed to keep the model run times reasonable. Note that each rigid model also incorporated the three major faults previously considered in the zoned analyses, but accounted for no ground support elements. The remainder of this paper focuses mainly on the crown pillar analyses – note however that the exact same methodology was applied to the hanging wall analyses.

2.1 *Determination of the joint sets characteristics*

The first step of the process was to derive the geometrical characteristics of the various joint sets (including their variability) in the areas of interest, i.e., in the ore material for the crown pillar model, and in the encasing Peridotite waste for the hanging wall model. This was done in a number of stages. Firstly, stereographic pairs of photographs were taken underground in both horizons in Zone G along various orientations. Detailed line mapping was then done "virtually" in the office with the ShapeMetriX3D™ package on 17 photographic pairs, which provided values of dip, dip direction, spacing and length for 244 joints (74 in the ore and 170 in the Peridotite). The determination of the joint sets (in terms of dip and dip direction) was then completed with the DIPS™ programme, from the geometrical joint data obtained with ShapeMetriX3D. Figure 2 shows the results of these analyses in the case of the ore material.

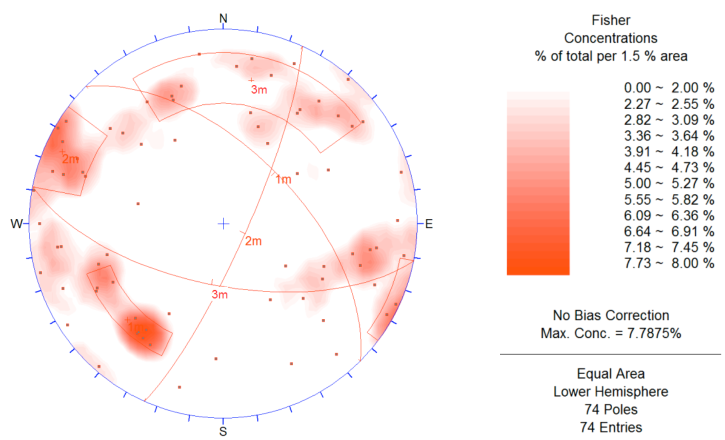


Figure 2. Results of the DIPS analyses performed on the line mapping data obtained "virtually" with the ShapeMetriX3D package from stereographic photographs taken in the ore in Zone G.

The standard deviation values around the average geometrical characteristics of the joint sets were then derived with Excel™. Table 1 summarises the results of these statistical analyses, again for the ore material.

Table 1. Results of the statistical analyses performed on the mapping data obtained with ShapeMetriX3D for the ore material in Zone G.

Joint set	Dip		Dip direction		Spacing		Length	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1	59°	12.9°	045°	16.6°	0.56m	0.68m	0.86m	0.80m
2	80°	14.6°	114°	10.8°	0.58m	0.70m	0.83m	0.70m
3	64°	13.3°	191°	28.2°	0.45m	0.40m	0.97m	0.64m

In this work, joint spacing and joint length were assumed to follow normal distributions. This, given the high standard deviation values shown for these parameters in Table 1, can result in them taking on negative values, which is obviously not realistic. As will be discussed in Section 2.2, this was however not an issue given the logic used to generate the joint sets in the discrete models.

2.2 *Explicit representation of the joint sets in a simplified* 3DEC *model*

For each series of analyses (for the crown pillar and hanging wall simulations), a succession of unique models were created by randomly generating explicit joint patterns, based upon the average and standard deviation values of the dip, dip direction, spacing and persistence of the various sets in each geological horizon. Because standard deviations were considered, a slightly different jointing pattern was effectively constructed each time a model was run, the exact same jointing pattern never being obtained twice. This variability allowed the creation of random block geometries that are much more realistic and less prone to artificial uncontrolled unravelling than when regularly-shaped blocks are generated, as is the case when only average (i.e., constant) values of dip, dip direction and spacing are considered. The variability of the persistence of each set was also taken into account, which resulted in the creation of realistic intact rock bridges throughout the rock mass.

The actual algorithm used to generate the joint sets consisted of several successive passes in which joints were cut in the volume of interest with an increasingly tight spacing and small persistence. The general form of one cutting pass was as follows :

```
jset dip 59 12.9 dd 045 16.6 ori x y z num 1000 pers 1 spac 4.0 0.5 id 10001  (for set 1)
jset dip 80 14.6 dd 114 10.8 ori x y z num 1000 pers 1 spac 4.0 0.5 id 10002  (for set 2)
jset dip 64 13.3 dd 191 28.2 ori x y z num 1000 pers 1 spac 4.0 0.5 id 10003  (for set 3)
```

Those familiar with *3DEC* will recognise the *jset* command with its characteristic *dip*, *dd* (for “dip direction”) and *ori* (for “origin”) components. One will however notice the presence of the corresponding standard deviation values immediately following the dip and dip direction averages, for each joint set (these values are defaulted to zero if not specified). Let us consider the first command line (the one for set #1) : it will create 1,000 cuts in the volume of interest, centred around point (x,y,z), the dip and dip direction of each cut being randomly selected based upon normal distributions centred around 59° and 045°, respectively, and as per the specified standard deviations of 12.9° and 16.6°, respectively. Note that this volume of interest is controlled by hiding blocks that are not part of it – in other words, regions in the model that are not to be affected by this *jset* command must be previously hidden. The lateral spacing between successive cuts will also be randomly selected based upon a normal distribution centred around 4m and with a standard deviation of 0.5m. Since spacing is set cumulatively from the (x,y,z) starting point, it does not matter if a negative value is selected by the random process – in this case, the new joint will simply lie *before* the previously cut joint, i.e., closer to the starting point. Note that the number of cuts (1,000 in this case) is purposely made high in order to ensure that the cutting process will cover the entire volume of interest. Although it is clear that this many joints cannot fit in the volume of interest, this is not a problem – as mentioned, no joints will be created outside the zone of interest if its neighbouring regions are hidden. The *pers 1* command means that the cuts will affect the entire volume, from end to end, and, hence, result in joints with a 100% persistence in that volume.

The final jointing pattern, along with the intact rock bridges that are required in order to obtain a realistic kinematic behaviour, is created in the volume of interest by repeating this set of commands with incrementally tighter spacings and lower persistence values. Continuing with the same example as before, the second pass was as follows :

```
jset dip 59 12.9 dd 045 16.6 ori x y z num 1000 pers 0.8 spac 2.5 0.5 id 10001   (for set 1)
jset dip 80 14.6 dd 114 10.8 ori x y z num 1000 pers 0.8 spac 2.5 0.5 id 10002   (for set 2)
jset dip 64 13.3 dd 191 28.2 ori x y z num 1000 pers 0.8 spac 2.5 0.5 id 10003   (for set 3)
```

Notice the *pers 0.8* command, which results in an 80% probability that any given block lying in the path of a joint will be cut – this constitutes the basic logic with which the intact rock bridges between joints are maintained. Notice also the tighter 2.5m spacing that will result from the *spac 2.5* command. One will notice that the standard deviation associated with the spacing is maintained at 0.5m in successive cuts in all cases. This value is close to the average of the standard deviations shown in column 7 of Table 1 – this level of precision is quite sufficient for the purpose at hand.

It is clear that each time these sets of command lines are launched, a slightly different *3DEC* model will be constructed. Because of this variability in the input file, a number of simulations must be completed for each set of analyses (for the crown pillar and the hanging wall), in order to capture the range of possible behaviours. Ideally, a large number of runs (30, or more) should be completed to derive some statistical confidence in the results, as is done with Monte Carlo simulations, for example. In this particular case, this was not feasible. Indeed, the completion of 60 runs (30 for the crown pillar and 30 for the hanging wall) would have been prohibitive time-wise. Instead, only three (3) runs were completed for each surface of interest, to broadly assess the variability of the results and whether or not more runs were subsequently needed.

Another aspect to mention is that the volume in which the joint sets were constructed was smaller than the actual crown pillar itself, again for the sake of speeding-up the generation of results. Figure 3 illustrates this aspect. Note how the volume examined was maintained as small as possible, while still being wide enough to allow for the unravelling of the rock mass in the case of an unstable discontinuity pattern.

Location of the jointed crown pillar model (approximation of the actual geometry)

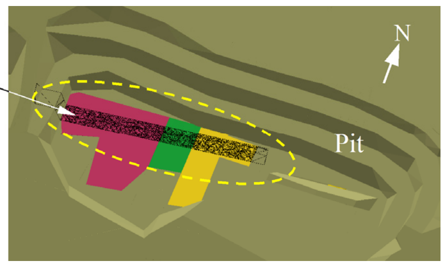


Figure 3. Isometric view looking approximately north–north-west and down at the pit, showing the location and extent of the jointed crown pillar model.

Figure 4 shows longitudinal sections looking north, cut through the centre of two models prior to any mining taking place. The zone of interest in the crown pillar is clearly visible, in the form of the much denser jointing pattern – both models, although very similar at first glance, are in fact slightly different and, as will be shown later, produced significantly different results.

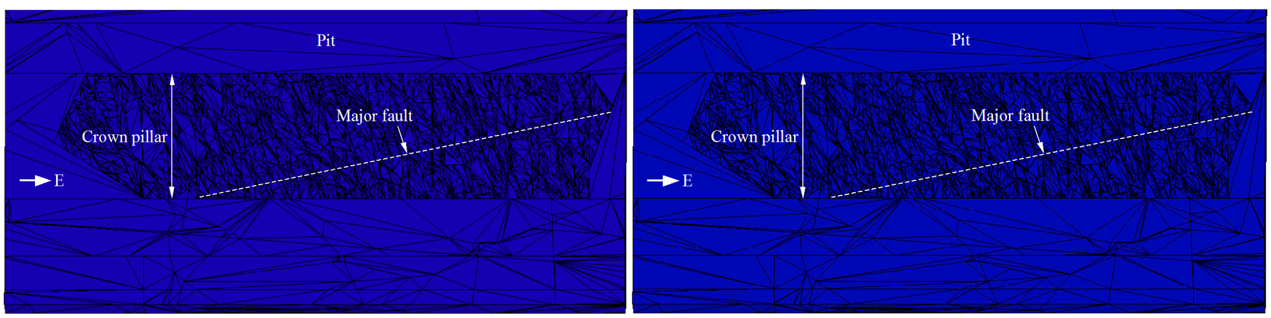


Figure 4. Elevation sections looking north cut through the centre of two explicit discrete models of the crown pillar, prior to any mining (i.e., with the pit and underground workings not yet extracted). The zone of interest is the crown pillar, indicated by the denser jointing. Both models, although similar at first glance, are effectively slightly different.

2.3 *Mechanical properties, stress field and constitutive behaviour*

The mechanical properties used for the various joint sets and major faults considered in the jointed models were the same as those retained in a previous project, which focused on the 3B-3F regional pillar at Mine 3. These, in turn, were originally derived in 2003 (Andrieux & Zhu, 2004) for the crown pillar above Stope 3B, also at Mine 3 – these properties ended-up providing a very good match with the field results eventually observed after the recovery of the 3B crown pillar. The mechanical properties of the joint sets and major faults modelled in the discrete analyses are summarised in Table 2.

Table 2. Mechanical properties of the various geological discontinuities in the jointed *3DEC* models.

Structure	Normal stiffness (GPa/m)	Shear stiffness (GPa/m)	Friction angle (degrees)	Cohesion (kPa)	Tensile strength (kPa)
Major faults	19.2	11.4	28	0	0
Joint sets	1.0	1.0	28	300	0

All the geological discontinuities were modelled using the "area contact elastic/plastic with Coulomb slip failure" joint constitutive model, whereby failure in shear or tension results in frictional only behaviour following failure. With this approach, any initial cohesion and tensile strength is brought to zero at failure, with the friction angle value being maintained.

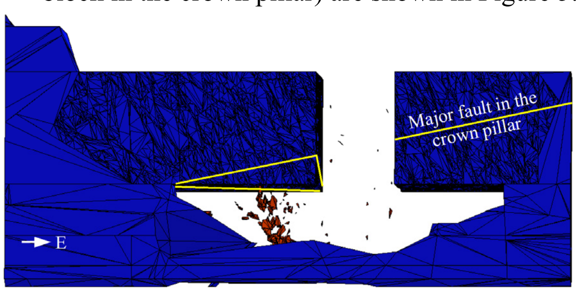
The *in situ* (or pre-mining) stress field considered in these analyses was the same as the one used in earlier modelling projects – it is summarised in Table 3 below. Note that this stress field was only meant to provide some low magnitude (given the shallow depth of the crown pillar) confinement to the discrete blocks – the blocks themselves being rigid (i.e., not zoned), they were unable to deform, accumulate stress internally and fail.

Table 3. *In situ* stress field used in the numerical analyses.

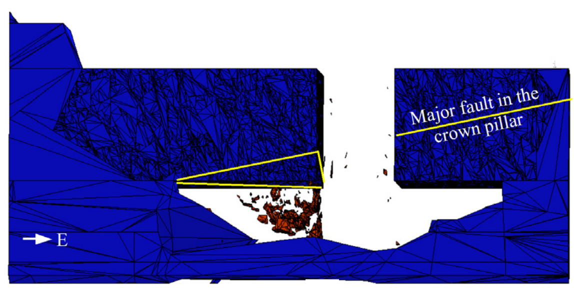
Principal stress component	Orientation	Gradient (MPa/m of depth)
Major (σ_1)	Horizontal, North-South	0.0513, k_1 = 1.9
Intermediate (σ_2)	Horizontal, East-West	0.0378, k_2 = 1.4
Minor (σ_3)	Vertical	0.0270

2.4 *Results of the kinematic analyses*

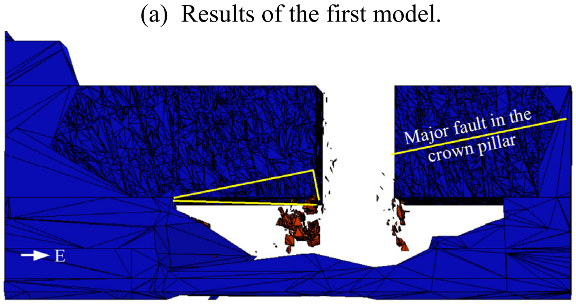
The results of these analyses are best shown in the form of block displacement contours. The unstable blocks that have detached from the surface of interest and are free-falling in the open void are clearly visible in these plots. As mentioned, and due to time constraints, only three models were run for the crown pillar situation – their results (after the extraction of the first block in the crown pillar) are shown in Figure 5.



(a) Results of the first model.



(b) Results of the second model.



(c) Results of the third model.

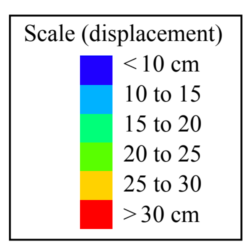


Figure 5. Results of the explicit kinetic analyses completed with the three jointed *3DEC* crown pillar models. (Elevation sections looking north cut through the centre of the models.)

Note that these models were not cycled to equilibrium – they were in fact stopped long before this state was attained. Reaching equilibrium would have required running the models until all the detached blocks landed on the floor of the open stope below and stabilised there, which would have taken very long while providing little additional relevant information.

In all three models, most of the unstable blocks that detached from the back and free-fell into the stope below came from the west side and from a zone delimited by one of the major faults. Only one of the models (the third one, shown in Figure 5c) indicated a relatively large-scale failure on the east side, from where mucking was going to take place. This failure was however at the brow of the first blast, and a reasonable distance from the main draw point located at the far east side of Cut 1525, and it was not deemed a safety problem. The same procedure was applied to the hanging wall, with a separate series of models. These analyses also did not indicate major stability problems on this surface.

3 RECOVERY OF THE CROWN PILLAR

The extraction of the crown pillar started in the summer of 2008 and should be completed by the end of 2009. At the time this paper was written, the behaviour of the rock mass had, so far, been close to what the models have predicted. Figure 6, for example, compares the results of the jointed simulations for the west brow (in terms of displacement contours, and after mining the central portion of the crown) with this actual brow – the depth of failure was close to that predicted. Figure 7 is the same comparison, but for the east brow.

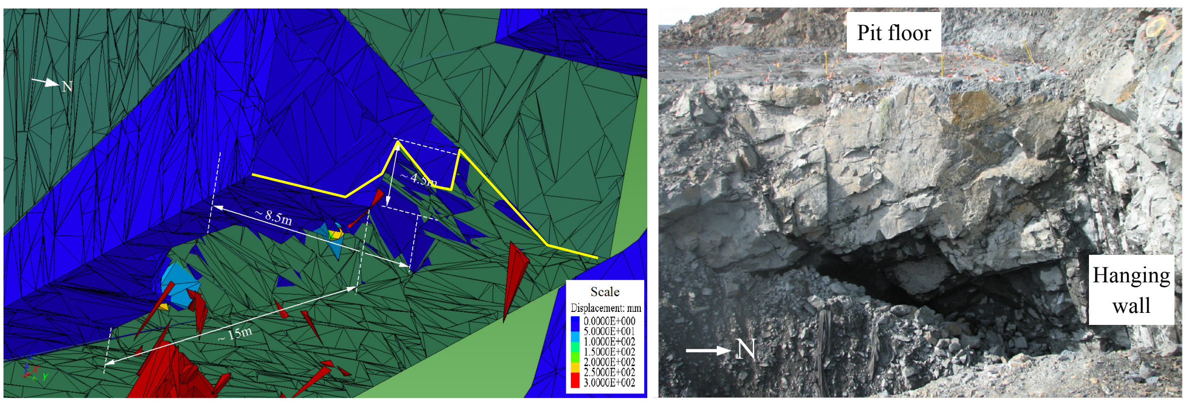


Figure 6. Left : isometric view looking north-west and upwards showing the failure predicted in the west brow by the third jointed *3DEC* model, following the removal of the crown pillar central portion. Right : photograph looking west at this brow.

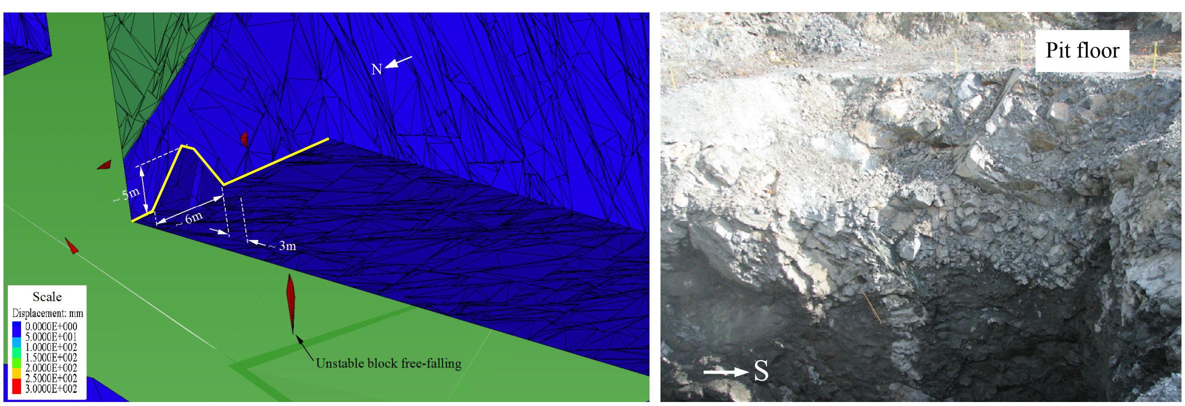


Figure 7. Left : isometric view looking north-east and upwards showing the failure predicted in the east brow by the third jointed *3DEC* model, following the removal of the crown pillar central portion. Right : photograph looking east at this brow.

As can be seen is Figure 7, there is generally good agreement between the modelling predictions and the actual results on the east side as well.

4 CONCLUDING REMARKS AND RISK-BASED DESIGN

As predicted by the numerical modelling work, the stability of the excavations created by the extraction of successive ore blocks in the Zone G crown pillar at Raglan has been primarily controlled by unravelling along the local joint sets and large-scale faults, as opposed to stress-induced failure within the rock mass matrix. When this is the case, jointed analyses with rigid blocks are well-suited to examine, in a stochastic manner, the likelihood of failure of various surfaces, as well as the possible extent of such failure. This is done by first establishing the dip, dip direction, spacing and persistence of the various relevant joint sets, in terms of average values and standard deviations. Stereophotographic techniques, such as ShapeMetriX3D, are well suited to this purpose. The statistical distributions obtained for the various joint sets can then be used to build and run a series of explicit rigid numerical models, each one with a slightly different jointing geometry, as randomly constructed from these statistical distributions. This approach, whereby a properly formulated numerical model incorporates the variability of some of the input parameters, allows one to assess in a more rational and reliable manner the likelihood of success of a proposed mining method and sequence. Note that the variability associated with other input parameters, such as the mechanical properties of the joint sets, for example, can be introduced as well, if available. In the case of the Zone G crown pillar, no ground support was considered in the jointed kinematic analyses, to keep them conservative. The ground support, in the form of primary support, cablebolts, shotcrete posts and rock posts, simply further increased the factor of safety associated with the design.

It would have been ultimately possible to estimate the *probability of occurrence* of problematic ground falls in various areas. For this purpose, additional runs would have been required – probably at least thirty – in order to perform statistical Monte Carlo analyses on the results.

Since modelling also provides the type and extent of failure to expect, should it materialise, it generally makes it possible to estimate the *cost* of such failures, which is generally in the form of production delays (or losses) and rehabilitation work (which, besides direct expenses, also causes additional delays). Multiplying this cost by the probability of failure estimated with the model would give the *risk* associated with the mining approach being considered. Risk is indeed best quantified in terms of dollars, in the form of a cost to be subtracted from the base case financial performance. If the risk associated with a particular mining approach is deemed too high, one option is to assess the effect on stability of additional ground support and weigh it against the cost of its implementation, to evaluate if it improves the expected risk-factored financial performance of the design. This methodology allows engineers to present risk in a manner that can be used by management in the decision making process.

5 REFERENCES

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Itasca, 2003. *3DEC – Theory and Background*. Published by the Itasca Consulting Group. 218 pp. Minneapolis, MN, USA.

Notes :

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