THE TRANSITION FROM OPEN PIT TO UNDERGROUND MINING: AN UNUSUAL SLOPE FAILURE MECHANISM AT PALABORA

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ABSTRACT

At the Palabora Mine, the transition to caving 400 m below the bottom of the 800 m deep pit resulted in a slope failure of the North wall that began in 2003, and is still mobile. This failure can be explained by the daylighting into the cave zone of a prominent joint set. The failure was modelled by the 3-dimensional code 3DEC, which is capable of modelling the nonlinear behaviour of discontinuum materials with large displacement.

1. INTRODUCTION

Palabora mine is one of the steepest and deepest large open pits in the world, with a radius of about 1.5 km, and a depth of about 800 m. The geology of the mine (a volcanic plug) is extremely complex. Besides various rock types (up to ten types at the mine) with different properties, there are four main faults crossing the pit and 3 dominant joint sets ubiquitous in the mine. Ground water is also present.

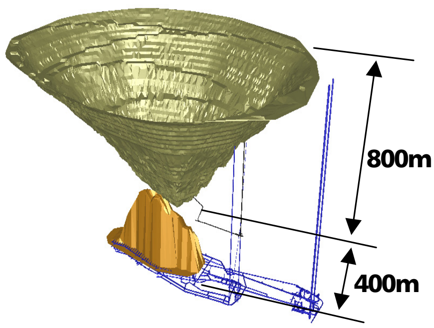

Figure 1 Birds-eye view of Palabora Mine and 3D model of pit and cave

After completion of the open pit mining, a cave was initiated about 400 m below the pit floor, as shown in Figure 1. Contemporaneous with the cave breakthrough into the pit floor in late 2003 and early 2004, anomalous movements become apparent, and it was clear that portions of the north wall were failing.

2. CHRONOLOGY OF FAILURE

In June 2004, displacements of the north and west walls and the pit rim indicated that movement was taking place into the pit. Cracks occurred along portions of the pit rim, particularly on the north of the pit (Figure 3). Because of the presence of major infrastructure around the pit rim (a Zirconium plant to the north west, an exploration/ventilation shaft and production and service shafts to the east, as well as haul roads, rail lines, a power line, water line and water tanks) it was necessary to investigate the mechanism of wall failure.

At the request of Palabora Mining Company Limited (PMC), Itasca Consulting Canada Inc. (ICCI) undertook a programme of 3DEC numerical modelling of the Palabora open pit walls and floor. The purpose of the work was to investigate mechanisms of slope deformation and failure of the pit walls, and the possible relationship between apparent pit wall instability, and the block cave mining taking place beneath the base of the pit. A further requirement was to investigate and report on any potential long-term instability of the pit walls, and in particular the rock around the active shafts in the east wall and on the east rim.

3. ON-SITE OBSERVATIONS

On-site observations revealed the following:

- The limits or boundaries of the surface cracking and the main zone of movement were defined by June 2004. While these boundaries have essentially not changed, movement within the boundaries has continued.

- Within the main zone of movement on the north wall, most of the visible deterioration of the rock mass has been along the western and eastern boundaries, with the central portion of the rock mass appearing to remain relatively “intact”.

- No cracking that can be attributed with certainty to the slope movement has been observed on the east wall.

- There were no combinations of major structures that would delineate a slope failure with a dip or plunge flatter than about 66°, with most structural combinations having a dip or plunge of at least 75°. There are no combinations of major structures that dip or plunge to the south.

- Some joint sets did however create wedges that dip towards the South and daylight into the caved zone – this is discussed later.

- During a two-day maintenance shutdown of the underground mining on October 6 and 7 2004, it was noted that the visibility in the pit cleared up (i.e., the dust settled). This is interpreted to indicate that the movement and deterioration of the north wall is directly related to the pulling of the block cave. This observation was also corroborated by the daily prism readings for the period that bounded the production interruption window, since the movements seemed to slow down during this interruption. However, because the production interruption was relatively short, the movement slowdown was noticeable, but not striking (see Figure 2).

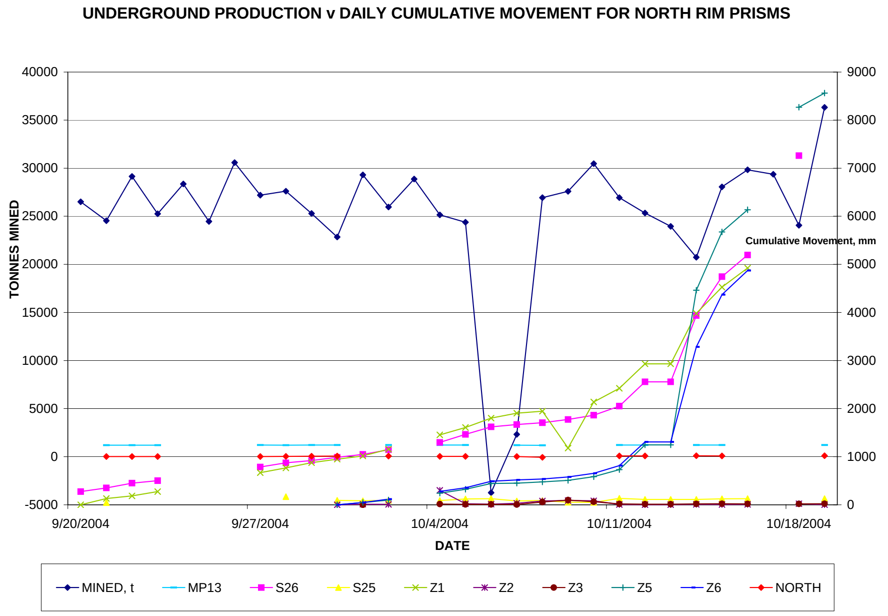

Figure 2 Underground production and cumulative prism movements of North Wall Prisms for period Sep 20 to Oct 21, 2004.

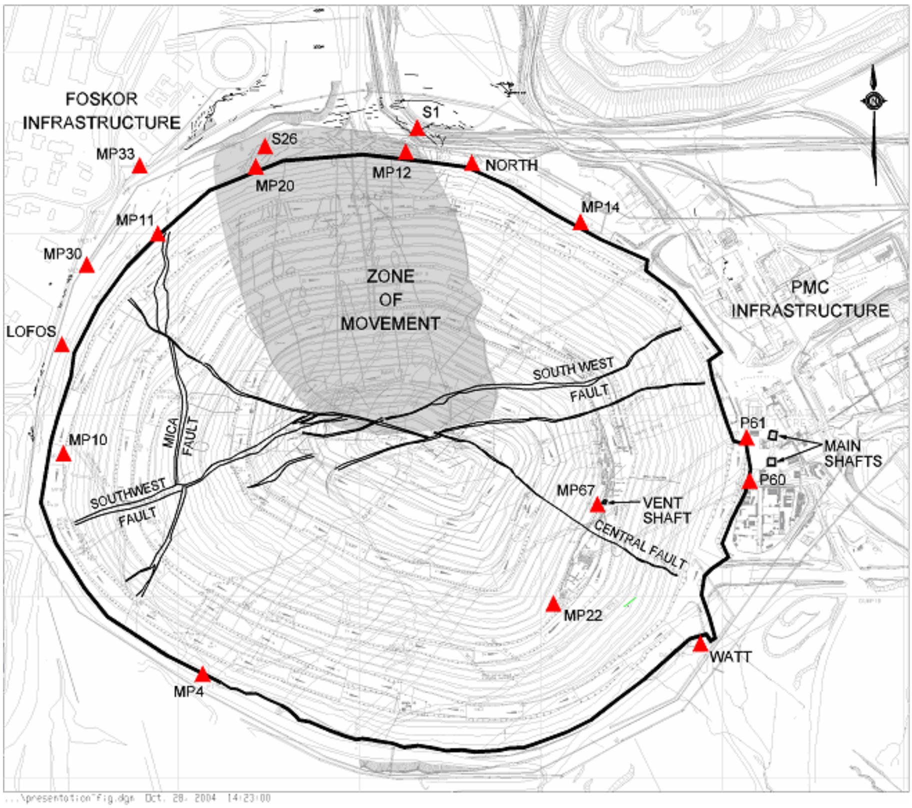

Figure 3. Plan of Palabora Pit showing locations of monitoring points and the initial tension cracks observed on site. The "zone of movement" is the zone of displacements significantly greater than long-term trends observed around the pit.

4. NUMERICAL MODELLING

ICCI developed 7 different 3DEC models, progressing from the relatively simple to the complex. Each model became progressively more sophisticated and incorporated more characteristics of the open pit (geology, dykes, joint sets, failure mechanisms, water pressures, modes of deformation, strength properties).

These models took into account the main factors having an impact on slope stability, including groundwater, faults and dominating joint sets. The models were based on PMC's geological model, and measurements and observations of the failure mechanism being measured while the models were being built. This enabled real-time feedback to be provided to PMC, and also for ICCI to obtain current knowledge of the failure and use this information to refine and calibrate the models being built. This calibration phase made it possible to use the models to make long-term predictions on future pit wall stability. The last of these models is described here, since it was the model that best matched the observed behaviour of the Pit.

4.1. Construction of Model

Model #7 incorporated the main geological units, 4 joint sets, all major faults and the water table, and the caved region (modelled as loose rock). This is shown in Figure 4.

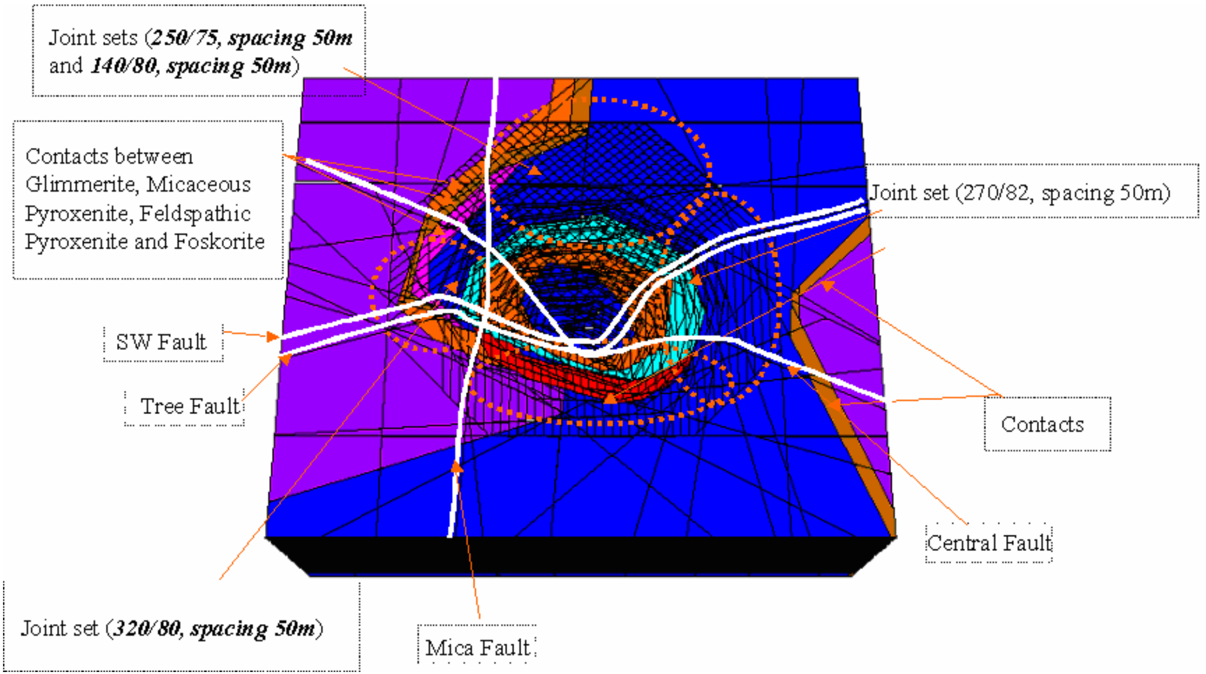

Figure 4. Geometry of Model #7, showing the pit excavation, geological units, major faults, and joint sets in the walls.

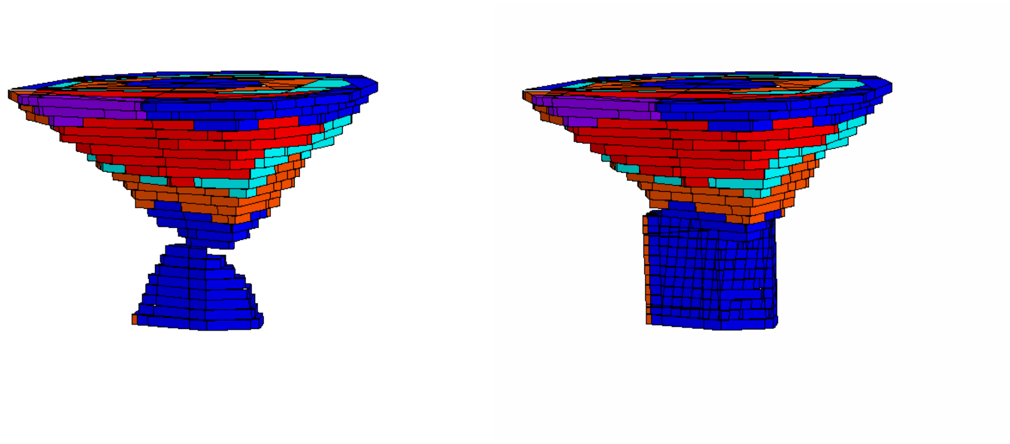

Figure 5. 3DEC model view of pit and cave. The left figure shows estimated final cave; right figure shows assumed final vertical cave.

Properties of geological structures and materials in this model are summarised in Table 1 and Table 2.

Table 1 Properties of rock mass used in Model #7.

Rock Type	Moduli(Gpa)			Mohr-Coulomb Strength	
	Young's (E_m)	Bulk (K)	Shear (G)	Cohesion (Mpa)	Friction Angle (deg.)
Carbonatite	14.1	9.4	5.7	2.9(3.8*)	36(46*)
Foskorite	9.9	6.6	4.0	2.3(3.0*)	31(41*)
Macaceous Pyroxenite	8.4	5.6	3.4	2.2(2.9*)	31(41*)
Weathered Macaceous Pyroxenite	3.1	2.1	1.3	1.6(2.1*)	23(33*)
Dolerite	13.3	8.9	5.3	4.2(5.6*)	44(54*)
Fenite	10.0	6.7	4.0	3.1(4.1*)	38(48*)
Glimmerite	6.1	4.1	2.4	1.7(2.3*)	24(34*)
Massive Pyroxenite	22.0	14.7	8.8	2.9(3.9*)	35(45*)
Feldspathic Pyroxenite	8.4	5.6	3.4	2.2(2.9*)	31(41*)
Granite gneiss	31.6	21.1	12.6	6.2(8.3*)	51(61*)
waste rock	0.5	0.42	0.19	0	35

Note: * denotes value adopted in model #1 ~ model #4

Table 2. Properties of discontinuities

Location	Dip (deg.)	Dip Direction (deg.)	Spacing (m)	Normal Stiff. (GPa/m)	Shear Stiff. (GPa/m)	Cohesion (Mpa)	Friction Angle (deg.)
East Wall	82	270	50	100	8	0	25
South Wall	82	270	50	100	8	0	25
West Wall	80	320	50(100*)	100	8	0	25
North Wall (joint set 1)	80	140	50(100*)	100	8	0	25
North Wall (joint set 2)	80	225	50	100	8	0	25
Tree Fault	90	344	-	10	4	0(0.05*)	25(35*)
SW Fault	90	344	-	10	4	0(0.05*)	25(35*)
Central Fault	89	24	-	10	4	0(0.05*)	25(35*)
Mica Fault	82	93	-	10	4	0(0.05*)	25(35*)
Contacts	-	-	-	100	8	0	25

Note: * denotes value adopted in Model #2

4.2. Model Behaviour

Incremental displacement, failure zones and velocity vectors of the pit walls are shown in Figure 6 to Figure 11.

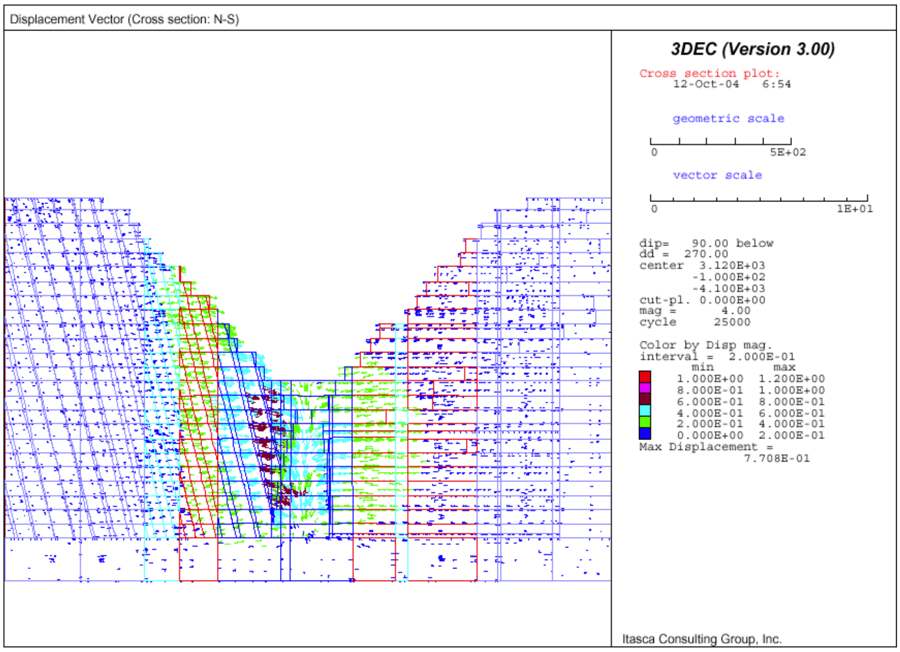

Figure 6 Cross section looking towards the East, showing incremental displacements of the North and South Walls (half completed cave, with broken waste rock in cave void)

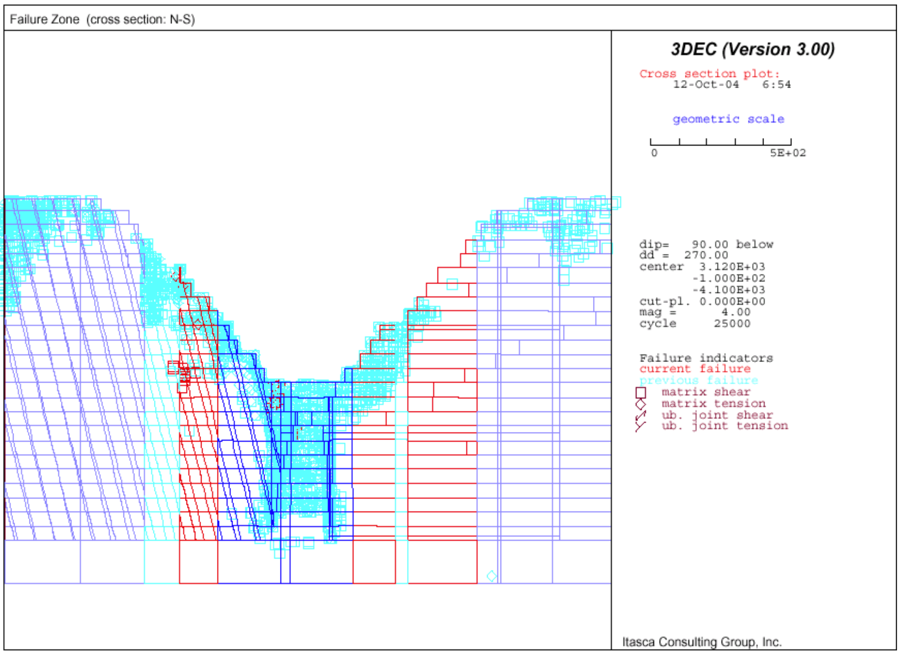

Figure 7. Cross section looking towards the East, showing failure indicators within the North and South Walls (fully formed cave profile with broken rock in cave void)

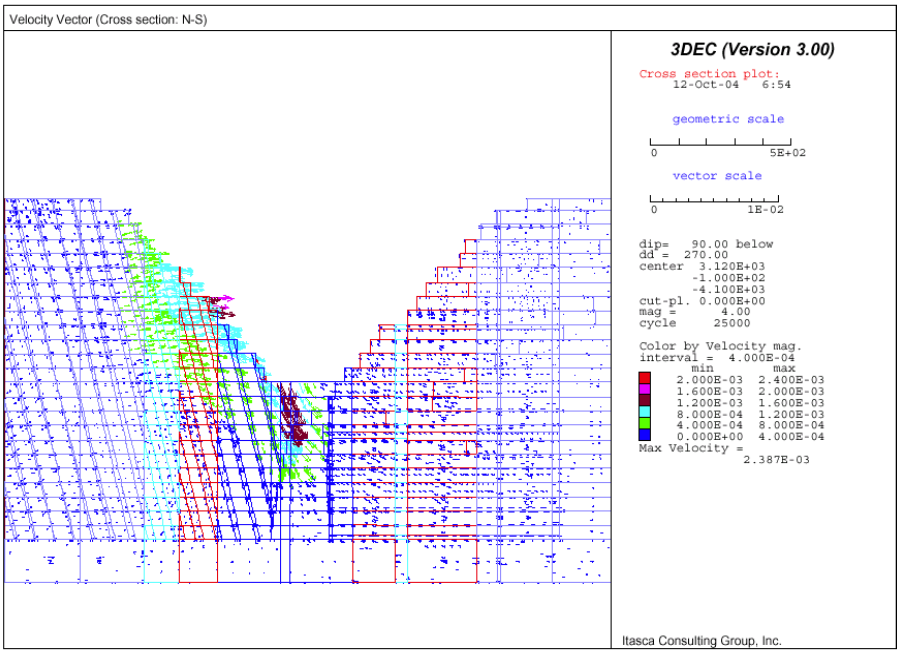

Figure 8. Cross section looking towards the East, showing velocity vectors of the North and South Walls (Long-term cave shape – all ore above undercut is removed, but replaced with caved loose rock). In this plot, the North Wall still has a small velocity of 0.0024m/s (at this model step), but this is decreasing and both the North and South walls are stable due to buttressing from the broken rock in the cave void.

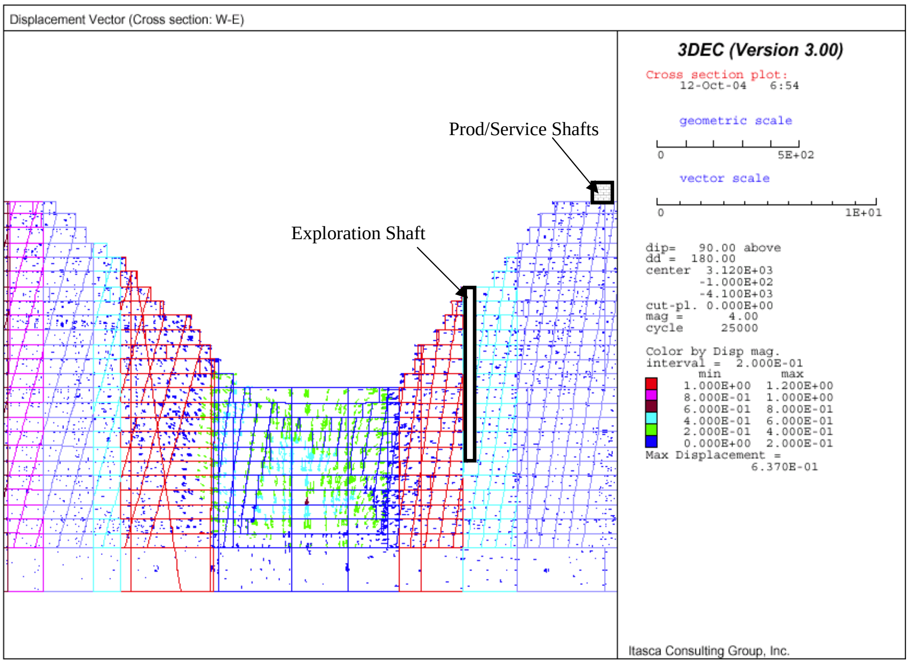

Figure 9. Cross section looking towards the North, showing incremental displacements of the West wall (left) and East Wall (right). In this model all ore above undercut is removed, but loose rock is left in place. This model is stable at this geometry and stage.

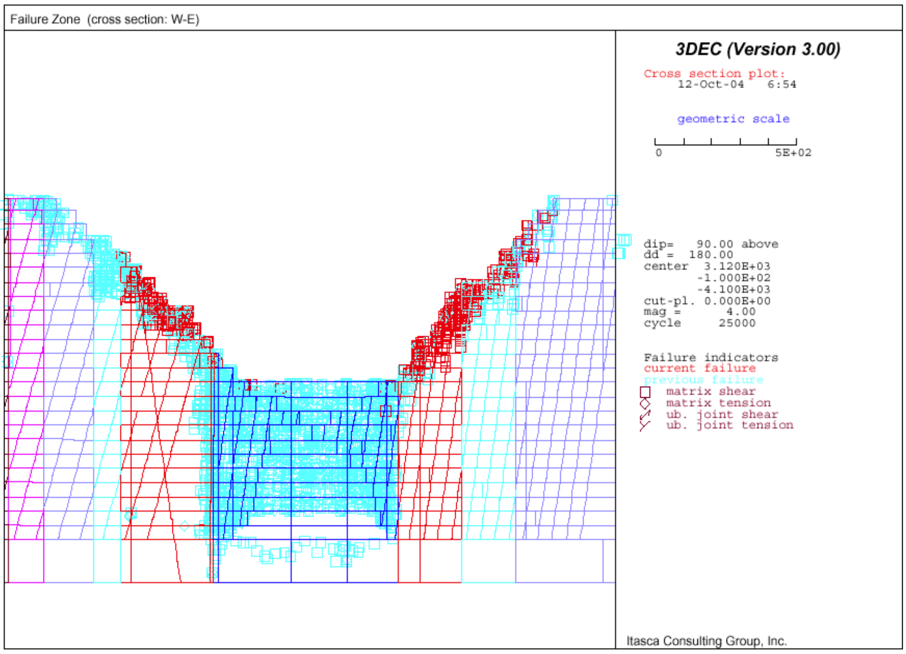

Figure 10 Cross section looking towards the North, showing failure states of the West wall (left) and East Wall (right). All ore above undercut is removed, but loose rock is left in place. This model is stable at this geometry and stage, though some failure of the immediate surface of the pit walls is evident.

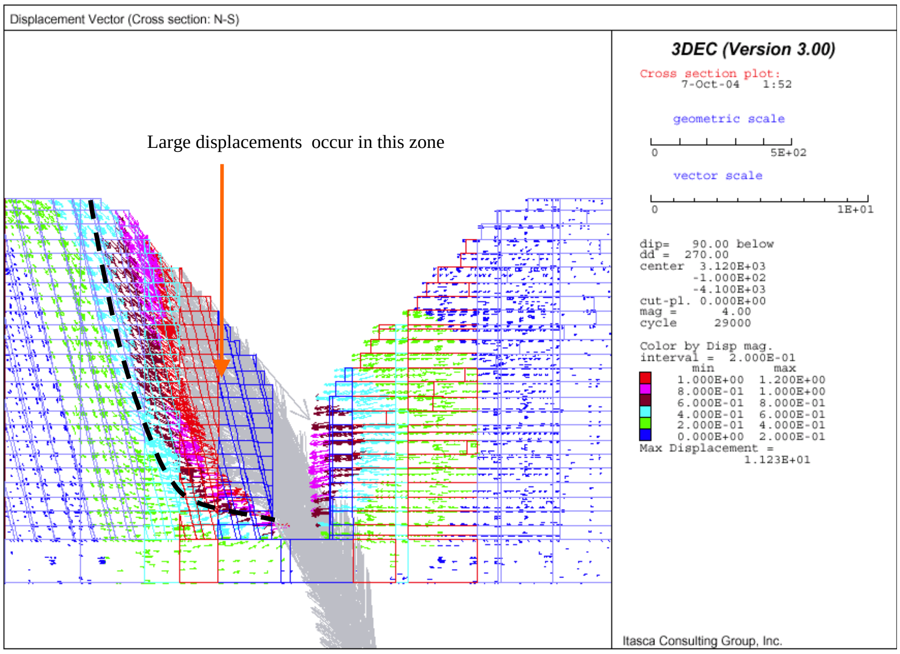

Figure 11. Cross section looking towards the East, showing incremental displacements of the North and South Walls (long-term cave shape – all ore above undercut is removed.) This state is unstable, and the North Wall continues to move into the void created by the cave. Note that failure occurs by a combination of sliding on joints (upper slope), as well as failure through intact material (below pit bottom).

Figure 6 to Figure 11 and Figure 11 show that the loose material in the cave zone controls the movements of the North Wall. The North wall is likely to keep moving into the pit as the ore is caved and removed from the production level. The East, South and West walls appear to be stable in the long term.

5. CONCLUSIONS – PREDICTION OF LONG-TERM BEHAVIOUR

The 3DEC models showed that the instability of portions of the north wall is most likely caused by the fact that pervasive joint sets in the north wall form wedges that daylight into the cave region below the pit. The single on-site estimated joint set of 75/250 (dip/dip direction) produces a failure mode that matches the failure zone. A more detailed model based on the two mapped sets 80/140 and 80/225 also matches the failed zone.

The draw of the ore into the cave zone undermines the north wall, and appears to have a direct control on the movement of the north wall. The 3DEC models incorporating groundwater, faults and joint sets, indicate that deep sliding failure of the north wall is possible if the ore could be removed from the region between the pit floor and the production level. Since the long term plan of the mine is in fact to remove this ore (via the caving process), the stability of the north wall appears to be directly controlled by the caving. The observed behaviour of the north wall during production interruptions supports this conclusion. Since the north wall appears to move in response to the caving operations, this also implies that the north wall is in a state of limit equilibrium, and is unlikely to fail suddenly. However, a sudden influx of water into the marginally stable joint system during a heavy downpour may promote a more rapid failure, though this is conjectural at this stage.

The south wall is more stable than the north wall because the major joint sets present in this wall do not form wedges that daylight into the cave. The production level is also asymmetrically located with respect to the pit, undercutting the north wall more than the south, and this makes the south wall more stable than the north.

The east and west walls are also more stable than the north wall, because of the jointing directions in the wall rocks, and because the smaller radius of curvature of the east and west walls results in higher hoop stresses that act to confine these walls. The east wall is the most stable wall because the production level is located "west of centre" and away from the east wall. In the long term, the exploration shaft located on bench 30 in the middle of the East wall may deteriorate since the upper 100m or 150 m of the shaft is located in rock that is in a state of low stress failure in the 3DEC model. However, deformations associated with this mode of failure are small, and do not continue as the cave ore is extracted. Some local failure on the lower surface of the East wall, especially near the cave may also be expected.

The production and service shafts are far enough away from the pit that they appear to be beyond the region of influence of the cave, even if the caved material was completely drawn from the pit.

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