This article presents means to address potential failures associated with large scale mining and demonstrates the effects of regional hard rock mining in several case studies of shallow stope cave-in failures. Applicable numerical modeling methods indicate that destressing of the rock mass is in effect under such extensive mining, which facilitates the occurrence of block caving, raveling and plug failures in effectively fissured rockmasses.

1. Introduction

Shallow stopes of metal mines, abandoned as well as active, can be subject to several gravity-driven failure mechanisms [1] (Figure 1), originating within a variety of geological terrains and controlled by a range of rock mass quality and disposition of discontinuities.

The rock mass elements controlling stability are listed in Table 1.

Table 1. Summary of instability elements for failures of shallow stopes of metal mines.

<table>
<thead>
<tr>
<th>Type of Failure</th>
<th>Mobilized Rock Mass</th>
<th>Lack of Ground Stress Clamping</th>
<th>Controlling Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock fracturing</td>
<td>FW, CR, or HW</td>
<td>No</td>
<td>Stress loading (gravity induced)</td>
</tr>
<tr>
<td>Plug failure</td>
<td>CR</td>
<td>Yes</td>
<td>Near-vertical continuous discontinuities; low friction surface conditions</td>
</tr>
<tr>
<td>Ravelling</td>
<td>CR, HW, FW</td>
<td>Yes</td>
<td>Blocky rock mass</td>
</tr>
<tr>
<td>Strata failure</td>
<td>CR, HW</td>
<td>No</td>
<td>Stratification, stope span</td>
</tr>
<tr>
<td>Chimneying disintegration</td>
<td>CR, HW</td>
<td>No (rock mass can be overstressed)</td>
<td>Material of low cohesion; dominance of small scale rock components</td>
</tr>
<tr>
<td>Block caving</td>
<td>CR, HW</td>
<td>Yes</td>
<td>Well-developed jointing and blocks; stope span; similar-sized blocks</td>
</tr>
</tbody>
</table>

FW footwall  HW hangingwall  CR surface crown pillar

In the case of block failures (ravelling – periphery block by block failure, block caving – rock mass break-up and gravity flow towards and into an underground opening, and plug failures – sudden fall of the surface crown pillar as a unit), there is normally sufficient natural ground stress to maintain confinement of the rock mass to prevent rock mass gravity failures into shallow workings. Natural tectonic ground stress values typical for the Canadian Shield, where most metal mining has been carried out in Canada, and some in the United States, show that major principal stress acts horizontally and for shallow depths exist at a value of about three
Figure 1. Common failure mechanisms of shallow stopes of hard rock mines: (a) rupture, (b) plug [4], (c) ravelling [14], (d) delamination [4], (e) strata failure, (f) alteration disintegration, (g) chimneying disintegration, (h) block caving [1].
times the vertical rock load [2]. In other areas in North America, tectonic ground stresses may not be as significant.

Horizontal stress normally gets reoriented, and reduced or amplified, depending on the impact of the shallow stope on the stress field. Basic block failure analysis [3] has shown that very low confinement (of the order of 0.5 MPa) will be sufficient to prevent extensive block failures from the periphery of the shallow stope to surface.

There are a number of mining areas in the world where intense regional metal mining activity, whether from one large mine, or from several adjoining mines has occurred, such as the lead-zinc deposits occupying portions of Missouri, Oklahoma and Kansas, the Timmins mining camp, Ontario, and the Sullivan Mine, British Columbia. The effect has been to remove or seriously reduce confining stresses and facilitate the occurrence of block failures.

In these areas, infrastructure located above or near surface will be subjected to subsidence, progressive or sudden, depending on the type of failure mechanism and the overlying soil. Study of failed cases has indicated that there is little subsidence associated with failures of shallow stopes until the failure front comes close to the top of bedrock. There is an exception in the case of block caving where subsidence or outright cave-in occurs with the displacement of the rock mass, depending on the geometry of the flow movement envelope and its depth from surface [1].

Because the controlling elements in these failures relate to the existence of blocks, the intensity of jointing and the shear resistance of block surfaces, it becomes important to identify all structural aspects of the rock mass and their distribution aspects.

A comprehensive study of discontinuities (sets and properties, zones of variations, etc.) through a quantitative survey should be carried out in the rock mass over the shallow stopes to capture the variability and dominant structures that can initiate and control failure. The survey should:
- Map the orientation and extent of major joint sets, faults, shear zones
- Obtain sufficient measurements to reflect general and locally different conditions, as well as variations between geological units
- Map variations

The survey data should include:
- Engineering aspects (roughness, infilling, persistence, spacing, orientation)
- Intersection aspects of jointing
- Geological fabric

If access to upper portions of the bedrock is not possible or insufficient exposure of the rock mass exists, rock core evaluation is required.

The rock mass data is essential as input into evaluation of failure behaviour. Analysis techniques to evaluate a-priori potential areas of subsidence must adequately represent failure behaviour (mechanism, extent). Available techniques are classified as analytical, empirical and numerical methods.
Analytical methods have been developed for all the common failure mechanisms [1] (except for block caving) and consist of limit equilibrium factor of safety equations which in the case of raveling and plug failures relate the block surface shear resistance (provided be confining stress) against the force of gravity. One empirical approach based on a large number of case studies [4] is designed to provide maximum span before block failures will occur. The Janelid and Kvapil studies [5] can be used to provide subsidence or cave-in of the surface depending on the size of the underground opening, its span and the depth to the stope [1]. Block type failures require distinct element numerical modeling which specifies interaction between blocks and determines their displacements; indications of failure path to surface is obtainable, but not factors of safety.

2. Case Studies

Three case studies of large or regional mining operations are used to highlight failure occurrences of raveling, block caving, and plug failures, and the controlling factors.

Hollinger Mine, Ontario

The area under, and adjoining, the city of Timmins (located in northern Ontario 670 km north of Toronto) represents a striking example of intense undermining of infrastructure and dwellings. Seven mines operated in this immediate area in which gold was primarily recovered. Of note, is the very large extent of the number of underground stopes of the Hollinger Mine (Figure 2), (from surface to 1,800 m deep). The shallow stopes cover an area 1.6 km x 1 km. Historically, the area has also been subject to numerous and widespread rock mass, and fill failures from shallow stopes to surface. The Hollinger Mine has been the focus of considerable site remediation to reduce the impact to population safety and to infrastructure.

The mines in the Timmins area are situated in terrains dominated by basalt and dacite lava flows. Imposition of folding brought about faulting and shearing of these units and created open fracture conditions generally conducive for intrusions and formation of vein systems. Figure 3 provides a view of the geology in the mine area. Their widths normally ranged from 0.3 m to 22 m and averaged ~3 m. The host Precambrian lava flows are schistose and altered. Major jointing patterns for this area have not been reported. Some investigative work [6,7] indicates normally up to three jointing families occurring in shallow drill core samples: two families oriented NE-SW, one dipping South 45–55°, the other dipping North 45–55°, and a third, vertical, occurring with less regularity. Added to these families are occasional discontinuities related to the geological units themselves. Lava formations vary from massive, to brecciated where blocks occur 0.1 m to 1 m in width. Sharp and gradational contacts exist between flow units. Schistocity is in close proximity or hosts to the fractured-filled deposits. It occurs variably and gradationally. These discontinuities have effectively created a blocky rockmass.

The closest in situ stress measurements carried out at mines 6 km and 90 km away [8, 9] show values horizontal stress to vertical rock load values typical for the Canadian Shield $k \geq 2.75$ near surface ($\leq 300$ m) [2]. In both cases the major principal stress was oriented at 235° (roughly parallel to the strike of the Hollinger orebody and schistocity) with shallow dip, and the minor
Figure 2. Location of shallow Hollinger Mine stopes reaching surface (grey). 3D finite element area application (larger ellipse), block code application (smaller ellipse).

Figure 3. Geological cross-section of Hollinger Mine [15].
principal stress was near vertical. The intermediate principal stress was roughly orthogonal to these directions and twice the value of the minor principal stress.

Mining on the lower levels was done by cut-and-fill using sandy gravel backfill. From 150 or 180 m to near-surface, mining was carried out using shrinkage stoping where after the ore was broken and removed, some stopes were filled back with gravel through openings on surface. The fill material would thus tend to form cones at the material angle of repose thereby leaving considerable void space. Some stopes were mined and filled to surface. Subsidence from slump of the dumped fill has occurred, which amounts to $\geq 4$ cm in the denser mined out areas, during the life of the mine, due to readjustments with post-extraction mine flooding, collapse of unfilled cavities and sill failures. Subsidence of the order of 10-18 m due to piping, run-out or pillar collapse has been registered at other adjoining minesites, such as the Moneta Mine involving a major collapse causing 3 empty buses to fall in the cave-in (Figure 4).

Numerical modeling was applied to this case study to approximate the effects of large-scale mining of the Hollinger Mine on the ground stress field. Numerical modeling was also applied to measure the long-term propensity of the rock mass to fail according to the dominant rock mass controlling elements, in this case well-defined blocks and the ground support offered by the stope filling.

Modeling such a large mine is complex and difficult. CANMET’s large 3D finite element code, ROCK3D [10] was used to model the entire upper stopes of the mine in order to obtain the impact on the existing stress field. The model was 6,600 m long and 3,300 m wide, containing at its centre the stope area. The model mesh was refined in the ore zone, brick element size was about 2 m. The model has 1,246,560 3D brick elements. Figure 2 provides the location of the shallow stopes modelled, most of which have been mined to surface. Figures 5 and 6 show the results of the modeling using the input parameters of Table 2. The effect of having a high density of underground stopes over a wide area is to reduce the compressive stress that would
Table 2. Rock mass properties used in the ROCK3D finite element modeling [11].

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Rock Mass Modulus of Elasticity (GPa)</th>
<th>Poisson’s ratio</th>
<th>Rock Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porphyry (footwall)</td>
<td>8.0</td>
<td>0.24</td>
<td>2.68</td>
</tr>
<tr>
<td>Ore zone (mineralized veins and basalt)</td>
<td>12.0</td>
<td>0.20</td>
<td>2.68</td>
</tr>
<tr>
<td>Faulted basalt (hangingwall)</td>
<td>7.0</td>
<td>0.28</td>
<td>2.68</td>
</tr>
<tr>
<td>Ground stresses</td>
<td>$\sigma_1$</td>
<td>$\sigma_2$</td>
<td>$\sigma_3$</td>
</tr>
<tr>
<td></td>
<td>235$^0$</td>
<td>190$^0$</td>
<td>0.66 $\sigma_1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical</td>
<td>0.33 $\sigma_1$</td>
</tr>
</tbody>
</table>

Figure 5. ROCK3D result cross-section, minor principal stress distribution (tension positive) [11].

Figure 6. Plan view of central Hollinger Mine stopes, 14 m below surface, ROCK3D model results, minor principal stress distribution (tension positive) [11].
normally be present around just a few stopes. Specifically, zero or tensile confining stresses are present to much deeper levels around the shallow stope peripheries as well as near-surface in and surrounding the surface crown pillars of central and many peripheral stopes. CANMET’s BSM3D block code [11] was used to measure the representative deformation of the rock mass which has well-developed blocks and could indicate the location of progressive block movement and major rock mass displacements. In this case, since the rock mass is essentially de-stressed as shown by the application of ROCK3D, a gravity-based stress distribution was adopted to evaluate such rock mass movements. The area modeled (Figures 2, 7) has been subjected to numerous cave-ins. The area was subdivided into two models that were executed with variations in fill height (to the top/15 m below the top of underground stopes). Model A was 500 m deep, 600 m long and 600 m wide and contained 106,900 blocks. Model B was 500 m deep, 600 m long and 600 m wide containing 112,000 blocks. The mesh density was increased towards the stope periphery.

Table 3. Rock mass parameters used in BSM3D discontinuous models [11].

<table>
<thead>
<tr>
<th>Site</th>
<th>Joint Density</th>
<th>Model Joint Spacing</th>
<th>Surface Properties</th>
<th>Model Joint Properties (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf course area</td>
<td>&lt;5 cm to 3 m</td>
<td>1 m</td>
<td>smooth planar to slickensided undulating, no infilling, surface staining to slightly altered</td>
<td>( \phi = 30^\circ ) ( c=0 ) orientations: N45E 45 SE N45E 45 NW N45W 90</td>
</tr>
</tbody>
</table>

*estimated using the NGI Empirical Rock Mass Quality Evaluation System [17].

Figure 7. Perspective view of the southwest region modeled showing location of BSM3D models A and B [11].

It was also increased around the surface crown pillars, from 12 m, to 6 m, 3 m, and 1 m. Joint properties, obtained from various Hollinger site evaluation reports are shown in Table 3. Joint surface properties are fairly consistent but joint density and RQD varies considerably, most often in the 1 m spacing range. The water table is normally 0 to 8 m below surface, which was taken into account in the models.
The Model A results (Figure 8) show that the loose fill emplaced in all the breakthrough stopes still allows for 3-8 cm displacement of the peripheries. More displacements are registered when no fill is present, within the top of the hangingwall and the surface crown pillar into the shallow stope, forcing local lowering of the bedrock surface. More serious movements occur when stopes are close. Model B results (Figure 9) reflect Model A results with respect to hangingwall and surface crown pillar movements as well as underground stope proximity effects. Rock displacements into unfilled stopes will allow fill to follow this displacement and subside on surface. Block raveling from unfilled stopes is put forward as the rock mass displacement to surface.

**Figure 8.** BSM3D Model A results, underground shallow stope empty, cross-section, exaggerated deformed mass (displacements in meters) [11].

**Figure 9.** BSM3D Model B results, underground shallow stope empty, zoom-in cross-section, exaggerated deformed rock mass (displacements in meters) [11].

**Gaspé Copper Mine, Quebec**

The mine, in operation from 1955 to 2001, extracted copper ore from several horizons formed from porphyritic emplacement (Figure 10). The ore occurs within a skarn zone and is
considerably faulted and fractured. At the Needle Mountain deposit, wall rocks are well-bedded argillaceous limestone or calcareous shales and siliceous limestones that have been altered.

Figure 10. Gaspé Copper Mine geology [18].

Figure 11. Gaspé Copper Mine, Needle Mountain Zone B collapse areas [4]. Scale: 1 cm = 50 m.
Extraction was carried out by a room and post pillar method with stopes dipping from 0° to about 35°. Final pillar sizes of 18 m x 12 m were created from rib pillars 18 m wide. It is during the creation of the post pillars that a major failure occurred in 1981 at the Needle Mountain extraction area, in Zone B. This zone alone extended 600 m x 150 m and was 10 m high, with other zones laterally and vertically offset from this one. It is suspected that a plug failure of some 60 m wide and over 250 m high dropped about 1.5 m, crushing the pillars below (Figure 11) [4]. The walls of the plug were defined by extensive joint surfaces. The area was known to be closely jointed. Bétournay [2] has shown that very low confining stresses and well-developed extensive near-vertical discontinuities must be present for such failures to develop. The absence of these pillars to bear the overlying load overstressed neighbouring areas and failure of adjacent pillars advanced progressively over a time period of three to six months. No other rock mass failure was reported to surface.

Sullivan Mine, B.C.

The Sullivan Mine extracted lead-zinc ore from a very large, gently dipping, orebody of Precambrian age of volcanogenic origin from 1896 to 1997. It was the largest lead-zinc mine in the North American Cordillera measuring 1.6 km longitudinally and 1 km down dip (Figure 12). The footwall is composed of sediments, with some conglomerates, the hanging wall quartzites. Steep north trending normal faults occur, associated with a well-developed jointing family. The central part of the ore zone consists of a mass of pyrite and a mass of pyrrhotite. At the time of hangingwall rock mass instabilities, the mine only extracted remnant pillars organized in a retreat front (Figure 13).

Figure 12. Plan view of Sullivan orebody with affected pillar area [12]. Scale: 1 cm = 150 m.
Ground conditions became increasingly deteriorated, with the mine deciding to leave broken masses of ore as buffer pillars [12] that could add roof support for the pillars being produced. This stored ore became oxidized creating temperature and SO2 emissions forcing the mine to accelerate its removal resulting in a block cave to surface, some 160 m height over a two-week period (Figure 14).

The lack of confinement from such a large extraction and local over-spanning were probably the initial conditions which allowed the rock mass to mobilize. Ground control conditions continued to worsen.

Block caving also occurred in another area in a highly faulted and fractured zone at the edge of the retreat front. The block cave had begun affecting the surface some 210 m above. Full caving to surface took at least 13 months to develop.

Plug failures of surface crown pillars have also been reported [13], further indicating a lack of confinement.

3. Conclusions

The case studies have clearly indicated the de-stressing that is imposed to large-scale regional mining. The gravity-driven failures, raveling, block caving and plug failures, that have occurred at these mines, can be attributed to a lack of confinement and effectively dissected rock masses, which led to cave-ins to surface. Furthermore, rock mass movements can effect the deformation of fill in stopes resulting in surface subsidence.

Various tools to a-priori evaluate potential failure areas related to these conditions have been successfully applied.
4. References


