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Mining the Remaining portion of the ross shaft pillar

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ABSTRACT: Past finite element analysis of pillar mining effects on the Ross Shaft at the Homestake Mine in Lead, SD, indicated stability of the shaft during mining on both sides of a central pillar that was defined within a much larger original shaft pillar. Experience with pillar mining that began in 1988 verified the earlier forecast of stability. Mining of the remaining central portion of the original pillar began in early 1995. A "cave" occurred in 1996 that led to a temporary cessation of pillar mining; pillar mining began anew in 1997 and continued for a short period. A relatively small portion of the central pillar remains. Previous pillar mining on north and south sides of the central pillar and mining between the central pillar and the Ross Shaft as well as top and bottom sill development have isolated the ore remaining. Thus, one intuitively expects little effect of final mining on the Ross Shaft. Results of the present study confirm this expectation and show very little change in shaft stability as a consequence of mining the ore remaining in the central portion of the original shaft pillar. Comparisons of three-dimensional finite element model displacements with borehole extensometer measurements that began in June, 1944, reinforce this conclusion.

1 BACKGROUND

The Spokane Research Laboratory, Homestake Mining Company and the University of Utah have been engaged in cooperative rock mechanics research for many years with the goal of improving safety, stability and efficiency. Studies include pillar analyses in vertical crater retreat mining, comparisons of conventional and "bird-cage" cable bolting and shaft pillar mechanics. Laboratory testing for rock properties, determinations of stress *in situ*, finite element simulations of mining sequences and numerous borehole extensometer measurements of rock mass displacements were done in each study.

As in previous shaft pillar analyses (Pariseau and others, 1995, 1996), the main rock types considered are the Poorman, Homestake and Ellison formations. Each is considered anisotropic (orthotropic) and has nine elastic moduli (three Young's moduli, three shear moduli, three Poisson's ratios) and nine strengths (three unconfined compressive, three tensile and three shear strengths). Principal material directions are down foliation dip, parallel to strike and perpendicular to foliation. These properties were originally determined in an extensive suite of laboratory tests. Subsequent comparisons between finite element model displacements with mine extensometer measurements led to scale factors of 0.25 and 0.50 for elastic moduli and strengths, respectively. The present study uses elastic moduli and strengths that are also 0.25 and 0.50.

The present study differs from past analyses (c.a. 1990) in two ways. First, the computer code UTAH3 was modified to produce a more accurate anisotropic factor of safety and to execute faster. UTAH3 is an elastic-plastic finite element program that uses associated flow rules; Drucker-Prager and anisotropic quadratic yield criteria are available. Hydro-mechanical coupling and viscoplastic versions exist, but the mine is dry and no time-dependency was considered in this study. Equation solving is by line iteration using a tangent stiffness that is updated after each load increment. Second, the mining sequence was modified to more accurately reflect actual pillar mining. This latter modification was done following discussions with Homestake personnel in May, 2000. Earlier forecasts of shaft pillar stability were based, in part, on assumed pillar mining plans.

The starting state of stress was determined from a number of stress measurements in the mine that were done by several groups at various times on different mine levels. In this regard, the stress state is "normal" in the sense that the greatest premining compression is vertical; the least premining compression is parallel to strike, while the intermediate principal premining stress is normal to

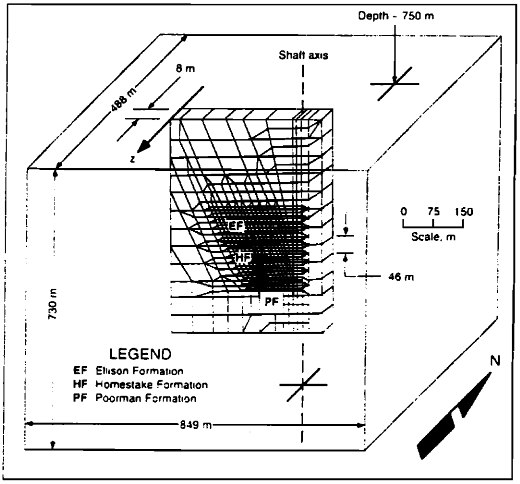

Figure 1. Schematic of the three-dimensional "coarse" mesh used in the analysis.

strike. Thus S_v=28.3d, S_H=14,320+12.0d, S_h=834+12.4d where d is depth in meters v=up-down (vertical), H=east-west, h=north-south and the stresses are in kPa. Shaft pillar mining occurs at about 1000 m (3600 Level); the mine extends below 2340 m (7800 ft).

Figure 1 shows a schematic of the overall three-dimensional finite element mesh. Mining follows the north-south trend of the ore in the plunging folds of the Homestake formation that lies between the Poorman and Ellison formations. The original shaft pillar extended about 33 m north and south of a vertical plane extending east and west through the shaft centerline. Mining within the shaft pillar has been restricted by a 60 m (200 ft) stop line from the shaft center, although there is ore closer to the shaft. The mesh extends vertically from about the 2800 Level (feet below surface) to about the 4800 Level. Level interval is about 46 m (150 ft). Most of the pillar mining has occurred between the 3350 and 3800 Levels and within the original 30 m north and 30 m south of the shaft centerline. This mesh is relatively coarse and was not intended to produce detailed stress concentration data in the vicinity of the production stopes. However, there are more than 34,000 nodes (and elements) in the mesh.

The finite element analysis goal was to determine the effects of stoping on the shaft. Specifically, the objective was to assess the potential for large-scale or catastrophic failure of the rock mass about the shaft. A simple criterion for large-scale failure was whether the rock mass near the shaft remained elastic. Some local yielding could be accommodated, but the appearance of an extensive yielding zone that would engulf the shaft would indicate a high probability of large-scale and possibly catastrophic failure.

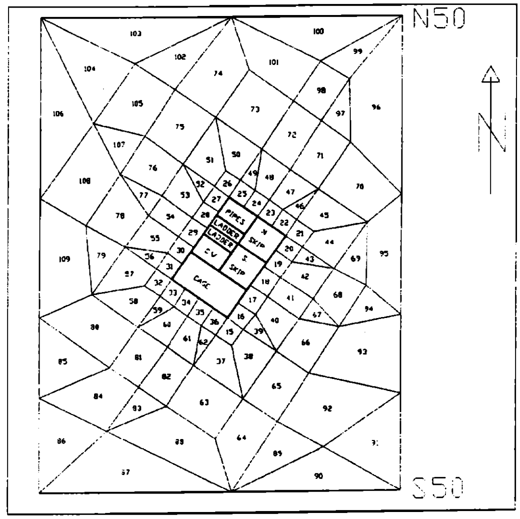

Figure 2. Plan view of the three-dimensional "fine" shaft mesh with element numbers.

Detection of stress concentration and possible yielding near the shaft walls required a more refined mesh. A plan view of this "fine" mesh is shown in Fig. 2; vertical extent of this mesh is the same as the coarse mesh. The shaft outline is about 4.5x6.3 m (15x21 ft); at the shaft wall elements are about 1 m square. No extraordinary support is needed to control the skin of the shaft to 1 m (3 ft). This mesh is not highly refined, but serves the purpose of stability assessment.

The entire mining sequence consists of 26 interleaved coarse mesh - fine mesh analyses. Displacements from a coarse mesh computer run are prescribed outer boundary displacements for the companion fine mesh run. The sequence starts with excavation of the Ross Shaft, proceeds with historical mining that led to definition of the original shaft pillar, continues with pillar mining to the present state (October, 2000) and ends with a forecast of effects from mining the remaining portion of the central pillar. This last mining is expected to be completed before the end of 2001.

2 UTAH3 FEM Model Results

The finite element model produces a great deal of output data, stresses, strains, displacements and so forth. Results that are most useful for stability and safety evaluation are the distributions of element safety factors and node displacements.

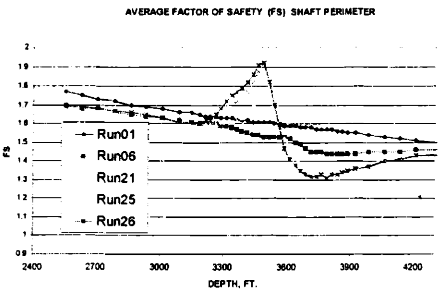

Figure 3. Average shaft wall element factor of safety as a function of depth and mining.

Figure 3 shows that on average the Ross Shaft wall safety factor decreases with depth after excavation of the shaft (Run01). The same trend is evident at the completion of historical mining (Run06) which generally lowers the average shaft wall safety factor at all depths but especially below 3650 Level. Pillar

2.1 *Shaft Wall Element Safety Factors*

Figure 3 shows the variation of average shaft wall factor of safety (FS) with depth between the 2450 and 4250 Levels in the Ross Shaft. Factor of safety in this context is a ratio of stress to strength such that for FS>1, an element in the shaft wall is in the elastic range of stress and deformation. If FS=1, then the element is at the elastic limit. As deformation proceeds, yielding occurs that relieves any tendency to accumulate stress; the factor of safety remains at one. Safety factors less than one are physically impossible. The legend of run numbers in Figure 3 is:

Run01=Excavation of the Ross Shaft
Run06=End of historical mining
Run21=Pillar mining outside central pillar region
Run25=End of central pillar mining, present state
Run26=End of mining remaining portion of the central pillar

mining increases the average safety factor above 3500 Level but decreases the average safety factor below (Run21). Mining in the central pillar accentuates this trend (Run25); mining the remainder of the central pillar shows little additional change (Run26). The lowest value of the average shaft wall safety factor is about 1.3 which occurs at about the 3800 Level after completion of pillar mining.

Some elements at the shaft wall have safety factors less than the average, of course. Indeed, some elements reach the elastic limit and yield below the 3350 Level, for example element number 27. This particular element (ELM 27) is near the pipe compartment. Evolution of the safety factor of ELM 27 from the shaft cut to completion of pillar mining is shown in Figure 4. The greatest reduction in safety factor for ELM 27 occurs in response to historical

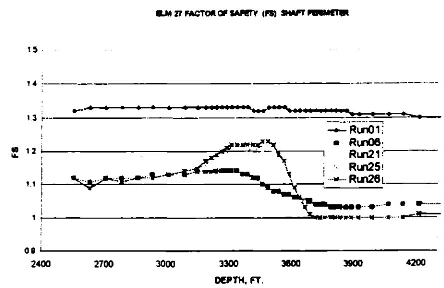

Figure 4. Shaft wall ELM 27 safety factor as a function of depth and mining.

excavation (Run01). Historic mining (Run06) causes a westward displacement towards the region of mining of about 2.0 cm (0.8 inches). Pillar mining (Run21) induces an additional 1.0 cm (0.4 inches). Central pillar mining (Run25,26) causes about 0.5 cm (0.2 inches) additional corner node displacement.

2.2 *Shaft Wall Node Displacements*

Figure 5 shows a horizontal component of displacement at a corner node (node 6). A negative displacement is westward, towards pillar mining. This displacement component is important to deformation of shaft steel. Model results show a small westerly displacement in response to shaft mining (Run06). Pillar mining causes an increase in safety factor above 3500 Level and a decrease to the point of yielding below 3650 Level. The effect of pillar mining is explained by redistribution of stress about the shaft wall in response to mining. Ultimately, yielding at the shaft wall is slight and limited to a single element thickness, about 1 m. At most, yielding occurs in nine of the 22 shaft wall elements. At no time does yielding extend completely around the shaft. The small amount of yielding indicated by the model and verified by experience poses no danger of catastrophic shaft failure. In essence, the shaft is contained by elastic ground and is stable.

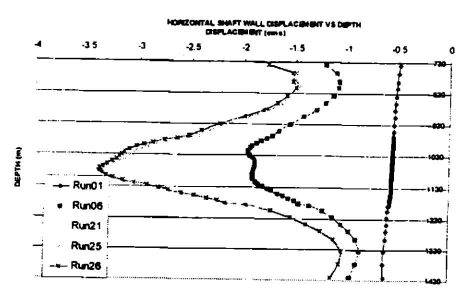

Figure 5. Horizontal displacement of shaft corner node 6. Negative is west.

Displacement of a node at the middle of the long side of the shaft is somewhat greater and totals about 3.5 cm (1.4 inches). Displacement is greatest near the 3650 Level, but diminishes above and below, as expected in consideration of stope location relative to the shaft. *Relative* displacement between shaft walls is slight; the shaft tends to "float" towards the region of active mining. This is an important consideration because it is relative displacement that causes deformation of shaft framing steel.

3 BOREHOLE EXTENSOMETERS

Figure 6 shows the layout of the borehole extensometer array; all holes are down holes. Eleven extensometers with four anchors every 9 m (30 ft) to 36 m (120 ft) were in the original plan. Nine were grouted in holes and read electronically with periodic manual check readings. Two were secured with hydraulic anchors for comparison (Hole 3B and Hole 14) and were also read manually. No extensometer was installed in Hole 3. The extensometer in Hole 3C was lost during installation; extensometers in Hole 3 and 3A were lost after about 17 months of service. The hydraulic anchor extensometers proved difficult to read manually because of corrosion and were abandoned. After more than six years of service, six extensometers (Hole 2, 4, 5, 6, 8 and 12) were still being read.

Figure 7 illustrates the nature of the extensometer data from the central pillar. These data indicate a complicated history of displacement change with some sections extending and some compressing along the hole axis. The data also show a time-dependency in the form of rounded stair-steps after each mining advance.

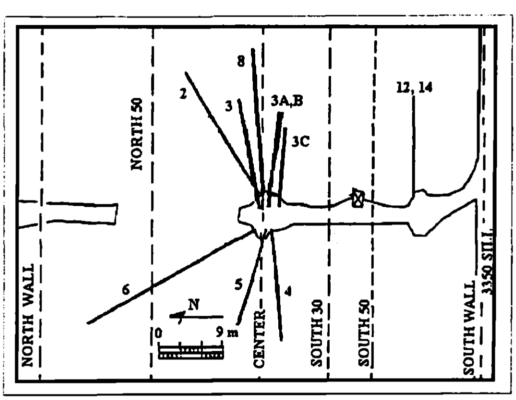

Figure 6. Schematic of borehole extensometer layout on the 3350 Level (plan view).

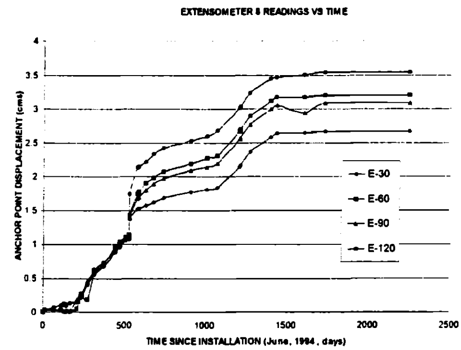

Figure 7. Extensometer data from Hole 8 from June, 1994.

4 CALCULATED vs MEASURED READINGS

Calculated and measured displacements from the surviving six extensometers are plotted in Fig. 8. This one-to-one comparison of finite element results with mine measurements provides a simple, direct and rigorous test of model reliability. Inspection of Fig. 8 indicates two data populations are present, one where model displacements are noticeably higher than measurements and one where model displacements are noticeably lower. These two populations correspond to extensometer Holes 4. 5 and 6 that point to the West, and Holes 2, 8 and 12 that point to the East in Fig. 6. Regression analyses of these two clusters of data (West and East) give correlation coefficients of 0.720 and 0.815, respectively. (Regression analysis of each of the six extensometer data sets produce correlation coefficients up to 0.897.) Thus, a simple linear model explains over half the variance of each of the two data sets, which contain 60 and 50 points, respectively. Ideally, the slopes of any regression line should be 1.0. However, the West data regression line has a slope of 1.69, while the East

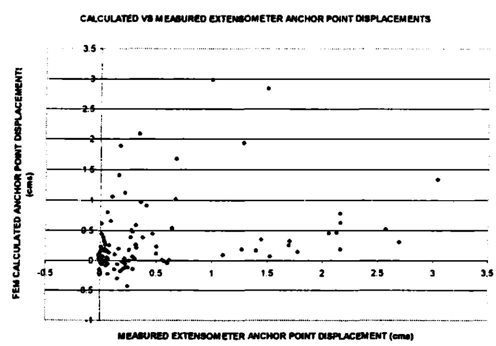

Figure 8. Calculated versus measured extensometer displacements.

data regression line slope is just 0.24. The average of these two slopes is 0.96. This result reinforces confidence in model reliability and also suggests that model adjustment of the mining sequence would simultaneously reduce the over predicted displacements and increase the under predicted displacements. In fact, an omission of mined elements on the shaft side of the extensometers, after correction, had such an effect. However, other than checking for major errors in data definition and entry, no attempt was made to fine tune the model in the interest of improving appearances.

5 CONCLUSION

Three-dimensional finite element modeling of shaft pillar mining shows that mining the remaining portion of the central segment of the shaft pillar has little effect on shaft stability. The main reason is that the this remaining portion of the original ore reserve has been isolated from the shaft by previous mining. When mine measurements are within model expectation, as they have been, confidence is gained in the safety and stability of mining plans. Indeed, the difference between the time when it was necessary to define the original pillar (1950's) and the present 1990's) is our ability to apply quantitatively rock mechanics principles to mine engineering problems. Results of this latest cooperative study coupled with past mining experience in the Ross Shaft pillar adds further support to these conclusions.

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