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Investigation of shaft stability and anisotropic deformation in a deep shaft in Idaho, United States

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ABSTRACT

During construction of a deep shaft at Hecla's Lucky Friday Mine, excessive anisotropic ground deformation led to significant damage to the shaft liner. This necessitated a major design change during construction, with the excavated shape of the shaft being changed from a circular to an approximately elliptical geometry. This study utilizes extensometer data collected during construction as well as a three-dimensional finite-difference model of stress redistribution around the shaft and a calibrated two-dimensional discontinuum numerical model to develop an understanding of the factors affecting the relative stability of both shaft geometries. Although the focus of the work is the deformation behavior of the foliated rock surrounding the shaft, the role of liner installation in suppressing ground displacements is also considered. The change in shaft geometry was found to be highly effective in improving stability of the shaft, with the maximum time-dependent displacement around the shaft decreasing by approximately an order of magnitude. Additionally, finite-difference models confirmed that increased stress concentrations around the shaft caused by adjacent level developments played a significant role in exacerbating ground deformation in the circular portion of the shaft.

1. Introduction

Mine shafts provide efficient access to underground ore bodies, and become increasingly economical in comparison to other mine access options (e.g. declines, ramps) at great depths.[1] With respect to global experience in deep shaft sinking, a limited number of shafts have been constructed below 2 km to date, including Creighton Mine's #9 Shaft in Sudbury, Canada,[2] an internal shaft at the Kidd Creek Mine, Timmins, Canada,[3] the Resolution Copper #10 Shaft in Superior, Arizona, the #10 Shaft at the Val Reefs mine in South Africa, and the South Shaft at the Mponeng Mine in South Africa. This study is concerned with geomechanical aspects of the recent sinking of the #4 Shaft at the Lucky Friday Mine in Mullan, Idaho.

The #4 Shaft is a 5.5 m finished diameter internal shaft, or winze, extending from the mine's 4760 level, 1743 m below surface to the 8620 level, 2923 m below the surface, making it the deepest shaft in North America. The #4 Shaft provides access to the deep, high-grade zones of the Gold Hunter vein system, which is currently being mined between the 6300 and 6400 levels, approximately 2200–2230 m below surface. In addition to the shaft itself, the shaft construction project involved the excavation of several horizontal levels (the 6500, 6580, 7500, 7580, 8300, and 8380 levels). Design of the shaft began in 2006, with construction starting in the fourth quarter of 2009.[4]

During construction, the geological conditions of the shaft led to stability issues which ultimately necessitated design modifications. During and following the design modification process, extensometers were installed to monitor ground deformation. This study presents an analysis of the data collected, as well as numerical modeling results which illustrate the nature of geomechanical issues encountered.

2. Geotechnical characteristics of #4 shaft

Conventional shaft design often accounts for the potential for wedge formation in jointed rock and accounts for stress-induced liner loading through the use of analytical calculations. These calculations typically assume an isotropic in-situ stress condition and an isotropic, elastic rockmass.[5] In the case of the #4 Shaft, these assumptions are not valid.

The #4 Shaft was excavated through the thinly bedded argillites of the pre-Cambrian Wallace Formation (see Fig. 1). Due to the presence and persistence of bedding in this unit, its mechanical behavior is highly anisotropic; the bedding orientation is near vertical with a roughly east-west strike, and experience has shown that significantly more damage and deformation is observed in drifts driven parallel to strike than in those driven perpendicular to strike. The argillite

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Fig. 1. Photo from the Lucky Friday mine showing the argillite unit through which the #4 shaft was excavated; the kinking of the beds shown in this photo is present in some locations, but is not ubiquitous throughout the unit.

rockmass also does not behave elastically at depth, as the bedding planes are relatively weak due to the presence of soft mineral coatings; small-scale tilt tests performed underground found the joint friction angle to be approximately 25°. The in-situ stress condition is also anisotropic, with the major and minor horizontal principal stresses estimated to be approximately 1.5 times and 1.25 times the vertical stress, respectively.[4]

Based on previous observations made at the Lucky Friday mine, the primary mode of yielding in the argillites was predicted to be time-dependent buckling of the individual laminations at their point of tangency to the shaft; similar behavior had previously been observed in bored raises excavated in the argillite (see Fig. 2).

During the initial phase of shaft sinking, 2.4 m long 22 mm passive grouted rebar bolts installed with 1.2 m spacing and welded wire mesh were used to maintain stability of the shaft surface prior to liner installation. The initial liner design consisted of a 300 mm thick annulus of unreinforced concrete to be installed within approximately two diameters of the advancing shaft face. In practice, due to over-excavation, the actual liner thickness was estimated to range between 460 mm and 640 mm based on poured concrete volumes. Following the successful excavation of the first 450 m of the shaft with minimal observed rockmass deformation, the bolts used for primary support were changed to 1.8 m long split sets installed with 1.5 m spacing.

Liner stability issues were first noticed during shaft excavation below the 6500 station level. A large horizontal crack was noted above the brow of the 6500 level shortly after its excavation. As a result of this observation, the primary support design was modified to include 6 m long 18 mm diameter grouted bulbed cables spaced at 1.5 m vertically and 1.2 m horizontally. The additional ground support was only implemented along the North and South sides of the excavation where the opening is tangent to the bedding and buckling was expected. Believing the adverse rockmass behavior to be associated with increased stress concentrations caused by the presence of lateral developments off the shaft, the requirement for cable bolt installation was removed once the shaft passed 12 m (approximately two excavated shaft diameters) below the 6580 level. No rockmass or liner stability issues were observed between this point and the approach to the 7500 level.

Fig. 2. Example of stress-induced argillite buckling in a raise at the Lucky Friday mine (after[4]).

At a distance of 12 m from the 7500 level, cable bolts were added back into the primary support requirements for the shaft. During excavation of the shaft between the 7500 and 7580 levels, damage to the concrete liner above the brow of the 7500 level prompted a further increase in primary support. The cable bolt spacing was reduced to 1.2 m in the vertical direction and 3.6 m long grouted rebars were installed between the cable bolts (see Fig. 3).

Shortly thereafter, the damage to the liner became more pronounced with concrete spalling noted between the 7500 and 7580. This prompted an initial installation of several extensometers in this area to monitor rockmass movements behind the liner. Damage to the liner continued and expanded over several months (see Fig. 4), ultimately necessitating the rehabilitation of approximately 75 m length of concrete liner, including the demolition and re-pouring of the entire liner section between the 7500 and 7580 levels. During this timeframe, a decision was made to modify the shaft shape to an ellipse with its long axis perpendicular to bedding strike (this geometry is referred to as elliptical, although in reality, it is somewhat closer to a notched circle as shown in Fig. 3b). This decision, driven by the results of preliminary numerical models, was based on the concept that removing the unstable, highly dilatant portion of the rockmass should result in lower rockmass displacements. This is analogous to findings from studies in overstressed brittle rockmasses which have found that such rockmasses tend to self-stabilize once stress-induced damage has re-shaped circular excavations into notched or pseudo-elliptical geometries.[6,7]

The change to an elliptical cross section was made approximately 25 m below the 7580 level. At this point, extensometers were periodically incorporated into the excavation sequence to proactively detect potential liner instability. The primary support pattern was unchanged at the North and South sides of the shaft, although 1.8 m length split sets installed on a 1.2 m × 1.2 m were incorporated on the East and West sides of the shaft (see Fig. 3). The shaft liner was modified such that the lined cross section would remain circular. This corresponds to a nominal liner thickness of 300 mm on the East and West walls of the shaft and a maximum nominal thickness of 1500 mm at the North and South sides of the shaft. Based on the concrete volumes poured, the actual North and South side thicknesses are estimated to range between 1050 mm and 1550 mm, corresponding to a typical excavation profile which is slightly less elongated perpendicular to bedding than mandated by the revised design due to limitations of the shaft sinking equipment.

Following completion of the shaft construction, no evidence of liner damage has been observed in the elliptical portion of the shaft, and all extensometers installed in this portion of the shaft show little to no rockmass movement with time indicating a stable rockmass condition. Ultimately, several questions were left unanswered prior to the completion of shaft sinking, including the following: How significant were three-dimensional stress re-distribution effects in contributing to the shaft instability observed near the 6500, 6580, 7500, and 7580 levels? What was the effect of the change in shaft shape on rockmass displacement trends from a quantitative perspective? What effect did liner installation have on suppressing rockmass displacements, and in the case of the elliptical shaft, was the increased liner thickness in the areas of greatest instability a major contributor to shaft stability?

In this study, we attempt to answer these questions through a numerical analysis of stress redistribution in the vicinity of horizontal