INITIAL STABILITY STUDY OF LARGE OPENINGS FOR THE NATIONAL UNDERGROUND SCIENCE LABORATORY AT THE HOMESTAKE MINE, LEAD, SD

Doug Tesarik, Jeff Johnson, and Karl Zipf, Jr.
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA USA

Kenneth Lande
University of Pennsylvania, Philadelphia, PA USA

ABSTRACT: The study of neutrinos—particles infinitesimally smaller than atoms—would be significantly advanced if a deep underground facility were available that would filter out unwanted cosmic radiation. Encouraging progress has been made in satisfying the criteria for such a facility with the selection of the Homestake Mine in Lead, SD, by the National Underground Laboratory Committee as the recommended site for a National Underground Science Laboratory (NUSL). The Homestake Mine is America's oldest and deepest underground mine, and its well-maintained infrastructure to depths of 2438 m below the surface makes the mine an excellent site for such a laboratory. The investigation reported here is an initial study of the stability of the first of the proposed chambers. A cylindrical room with a dome-shaped roof and floor was analyzed in three dimensions using the finite-difference program FLAC3D. The results were compared to recommended support requirements based on Barton's Tunneling Quality Index, Q. Based on model results and observations from previous mining studies, large rooms with 50-m roof spans can be constructed and will remain stable at 2141 m below the surface in the Poorman Formation when the rock is reinforced with cable bolts. Construction may be possible at lower levels in the Yates Formation if more extensive laboratory strength tests confirm initial results.

1. INTRODUCTION

Observation of solar neutrinos began in 1965, when Raymond Davis installed a 600-ton detector at the 4850 level of the Homestake Mine in Lead, SD [1]. From that beginning, neutrino astrophysics has grown into a worldwide research effort. There are large underground laboratories at Gran Sasso in Italy, Baksan in Russia, Kamioka in Japan, and Sudbury in Canada. Although there are U.S. participants in these experiments, until now, U.S. scientists have not been able to follow up on the original work by Davis at a U.S.-based facility. The end of gold mining at the Homestake Mine in December 2001 has provided a unique opportunity for the creation of what would be the deepest and largest underground laboratory in the world. The great thickness of overburden would filter unwanted cosmic radiation, allowing neutrinos to to be "captured" for study.

The primary reason for this growing interest in neutrinos is that understanding their properties is important to answering many cosmological and astrological problems, such as why the neutrino flux emitted by the Sun as a result of nuclear fusion is less than expected, the processes involved during the collapse of a massive star into a neutron star and associated supernova emissions, proton decay, and dark matter.

Among the proposals for a National Underground Science Laboratory (NUSL) is one for a one-million-ton water Cerenkov detector that would be about 20 times the size of the largest present detector, SuperKamiokande in Japan. The proposed Cerenkov detector would consist of 10 cylindrical modules each 50 m in diameter and 50 m high located between the 6950 and 7100 levels of the Homestake Mine in the Yates Formation. (Most mining has been in the Poorman and Homestake formations.) The investigation reported here is an initial study of the stability of the first of 10 proposed chambers and the first step in ensuring the safety of miners during excavation. A cylindrical room with a dome-shaped roof and floor was analyzed in three dimensions using the finite-difference program FLAC3D [2]. The results were compared to recommended support requirements based on Barton's Tunneling Quality Index, Q [3, 4].

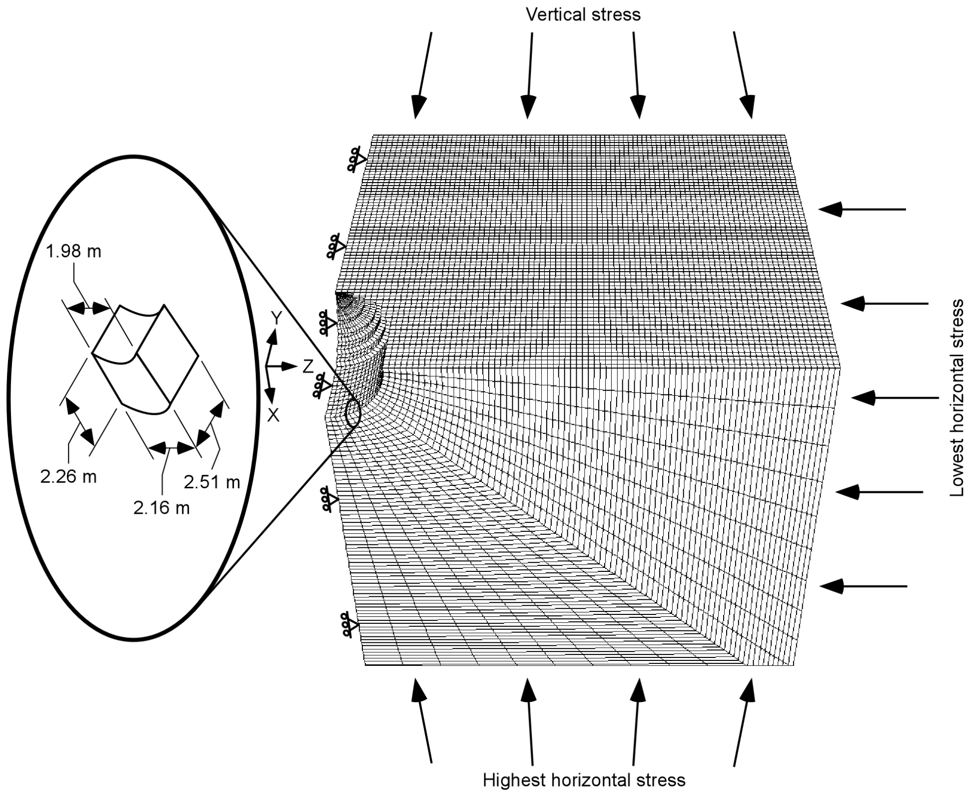

Figure 1.—Finite-difference mesh with excavation in one-eighth symmetry.

2. COMPUTER MODEL AND PREDICTED RESPONSE

The modeled room was a 50-m-high cylinder with 50-m-diameter hemispheres representing the mine roof and floor and a volume of 163,624 m^3. One-eighth symmetry was used to reduce the size of the finite-difference mesh, which consisted of 140,800 zones shaped like extruded annulus sectors having a 2.3-m radial thickness and an extruded length of 2.5 m (fig. 1). Sector dimensions were reduced to approximately 1.5 m for one computer run to confirm that the mesh size was small enough to estimate the depth of failure into the rock mass. The initial in situ state of stress used in these analyses was based on stress measurements made in the 1970's through 1980's at the Homestake Mine. Measurements between 930 and 2256 m in the mine resulted in a linear stress formula (Eq. 1) dependent on depth below the mine surface [5]. The initial stress state in the model was achieved by applying the three orthogonal stresses at the finite-difference mesh boundary seven radii from the rib of the cylindrical room and iterating to equilibrium.

$$\sigma_v = 28.28\ h,$$
$$\sigma_{h1} = 14{,}327.8 + 11.99\ h,$$
and $$\sigma_{h2} = 834.3 + 12.44\ h, \qquad \text{(Eq. 1)}$$

where h = depth in meters,
σ_v = vertical stress in kilopascals (kPa),
and σ_{h1} and σ_{h2} = horizontal stresses in kPa.

The room was assumed to be excavated in a homogenous, isotropic rock mass constructed between existing levels below 2118 m. The average depth between levels was used for parameter h (Eq. 1) to calculate initial stresses. A Mohr-Coulomb failure criterion defined by cohesion and angle of internal friction was used to limit the elastic behavior of the material or the strength of the rock mass. Because there was a limited amount of material property information on the Yates Formation, three values for cohesion were used—12.2, 18.3, and 24.4 MPa. These values represent 50%, 75%, and 100% of average strengths calculated from unconfined compressive strength test results conducted on specimens from the Poorman Formation and a value of 30° for the angle of internal friction. The field-scale unconfined compressive and tensile strengths in the Poorman Formation (42.3 and 6.58 MPa, respectively) were 50% of the average laboratory values. They were obtained by monitoring the loss of borehole extensometer anchors during mining of large vertical crater retreat stopes between 2118 and 2164 m at the Homestake Mine [6]. These extensometers were also used to calibrate a three-dimensional, finite-element program, resulting in a field-scale modulus of deformation equal to

23,615 MPa, or 25% of average laboratory values. This value was used in the finite-difference analyses.

Two specimens were prepared for unconfined compression tests and five specimens were prepared for Brazilian tensile tests from a grab sample of rock from the Yates Formation measuring approximately 1 by 0.5 m. The average tensile strength of these specimens was about the same as the average tensile strength of rock from the Poorman Formation, but the unconfined compressive strength was more than two times the values for the Poorman Formation. This implies that 24.4 MPa is about half the cohesion value for the Yates Formation and, based on these tests, is a reasonable estimate of the field, or rock mass, value of cohesion. It is important to emphasize that these specimens may not represent the entire Yates Formation. A thorough site investigation is essential to characterizing the rock more accurately. The high strength of the laboratory specimens combined with their elastic-brittle behavior when loaded to failure indicate that Yates rock may be prone to bursting.

Results from the finite-difference model indicate that the maximum depth of failure into the rock around the cavity is 10 m and occurs in the lower roof (fig. 2*S*). The maximum yield width in the room's rib is 6.8 m. Yield zones in the y-z plane through the origin are similar in shape, but not as extensive as yield zones in the x-y plane. If the centroid of the chamber is located 2141 m below the surface in rock equal in strength to that of the Poorman Formation, the model calculates yield zones in both the lower roof and ribs (fig. 2*A*). Previous mining experience confirms that a stope 24 m wide, 30 m long, and 46 m high excavated with the vertical crater retreat method at 2141 m suffered some caving, but remained open when the roof was supported with cable bolts [6]. Conversations with mine personnel indicated that large structures (45.7 m high, wide, and long) have been excavated, but are unstable at depths of 2416 m. These observations, combined with the finite-difference results, imply that 2141 m may be the deepest opening that can exist in the Poorman or Homestake formations without encountering stability problems (figs. 2*A*, *S*). However, if the rock strength of the Yates Formation is approximately twice that of the Poorman Formation, as initial laboratory tests indicate, then failure will be limited around the room constructed in Yates rock even at 2416 m underground (fig. 2*U*). Results could differ if the Yates rock has anisotropic material properties.

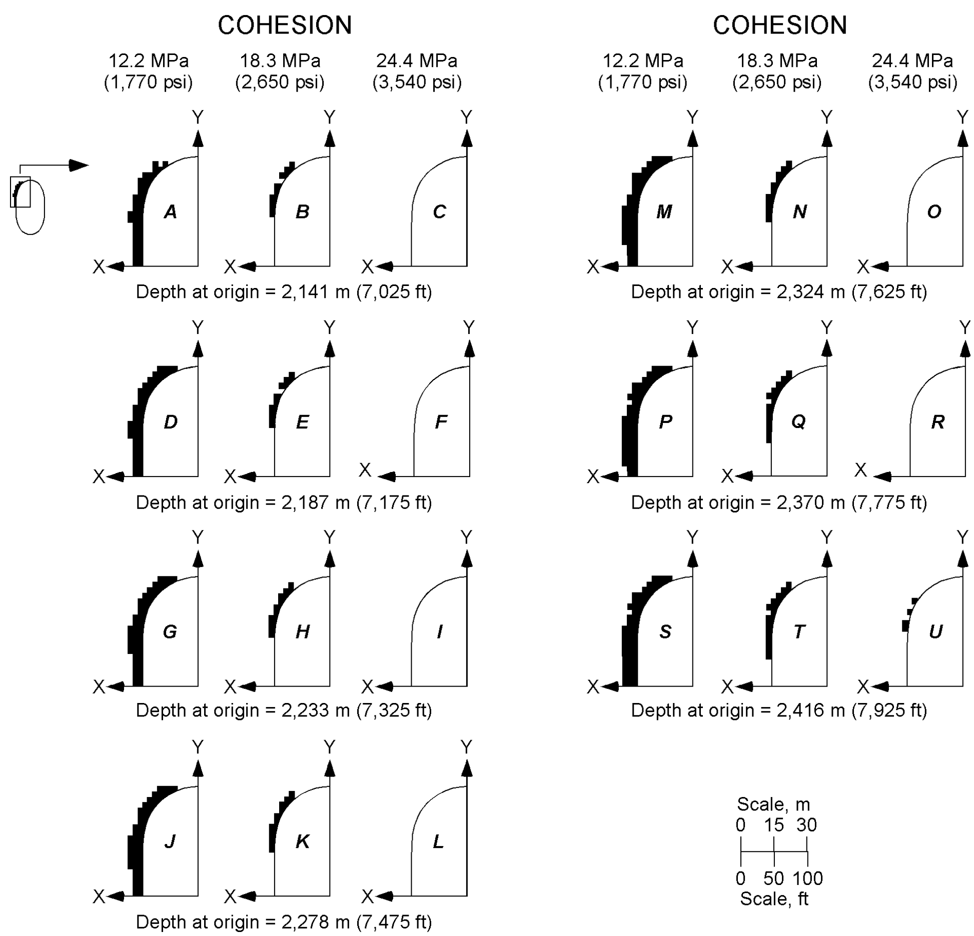

Figure 2.—Failure zones in x-y plane through the origin.

Failure zones were initiated where redistributed stresses became concentrated near the lower roof of the chamber and propagated into the ribs as mining depth increased. The thickness of the failure zone diminished to zero near the apex of the hemispherical roof because the arched opening eliminated a wedge of material of a type that often fails and requires support.

3. ROCK MASS CLASSIFICATION

A comparative rock mass characterization using Q (Eq. 2) was performed with data obtained from three locations at the Homestake Mine to determine if the support recommendations from this system could be reasonably applied to the large chamber proposed in the Yates Formation. Geomechanics data were collected at three different sites.

$$Q = RQD/J_n \times J_r/J_a \times J_w/SRF \qquad \text{(Eq. 2)}$$

where Q = tunneling quality index,
RQD = rock quality designation,
J_n = joint set number,
J_r = joint roughness number,
J_a = joint alteration number,
J_w = joint water reduction factor,
and SRF = stress reduction factor.

Site 1 is located 2118 m underground in rock primarily of the Homestake Formation, although a small amount of Poorman rock is present. Some areas are fractured, presumably from high stress caused by nearby stoping. Steeply dipping bedding planes are the major discontinuity at this site. The bedding planes are tightly healed; however, in highly stressed areas, the spacings between open bedding planes is 5 to 10 cm. These bedding planes are discontinuous, and most of them can not be traced more than 1 m. Occasionally, joints with random orientations were observed. These joints are tight and smooth, contain no filling material, and can be traced for 3 to 6 m. The estimated number of bedding planes, joints, and fractures per cubic meter was 16.

Site 2 is located 2141 m below the surface in the Homestake and Poorman formations. The area is heavily jointed. Steeply dipping bedding planes are spaced 15 to 30 cm apart and, similar to rock at site 1, stress redistributed from nearby stopes has opened up discontinuities that were otherwise tightly healed. One poorly developed joint set was observed that had a spacing of about 30 cm and a continuity of 3 to 6 m. These fractures are tight and rough, and contain a hard filling. The estimated number of bedding planes, joints, and fractures per cubic meter was 12.

Site 3 is 1508 m deep in the Yates Formation, the proposed host rock for the NUSL. Site 3 rock is massive with no or few joints. The estimated number of bedding planes, joints, and fractures per cubic meter was less than 4.

The RQD of the rock at these sites was estimated from the number of joints per cubic meter. All sites were dry. Laboratory unconfined compressive strengths of the intact rock used to calculate the stress reduction factor were 84.6 MPa for sites 1 and 2, and 186 MPa for site 3. Vertical stress (Eq. 1) was used as the major principal stress because three out of four in situ stress measurements at the mine indicated that the major principal stress direction aligned with the vertical [5].

On the basis of empirical charts developed by Barton et al. [3] (fig. 3) and Grimstad and Barton [4] (fig.4), the recommended support for all three sites agreed well with the support used at these sites (table 1), indicating that it is reasonable to apply these charts to the large chamber proposed at the Homestake Mine (table 2).

The Grimstad and Barton chart recommends systematic bolting with 40 to 50 mm of unreinforced shotcrete for 25- and 50-m spans. The Barton chart recommends tensioned bolts with 2- to 3-m spacings for these spans. There are no support recommendations for spans exceeding 70 m because the plotted data exceed the range of the charts.

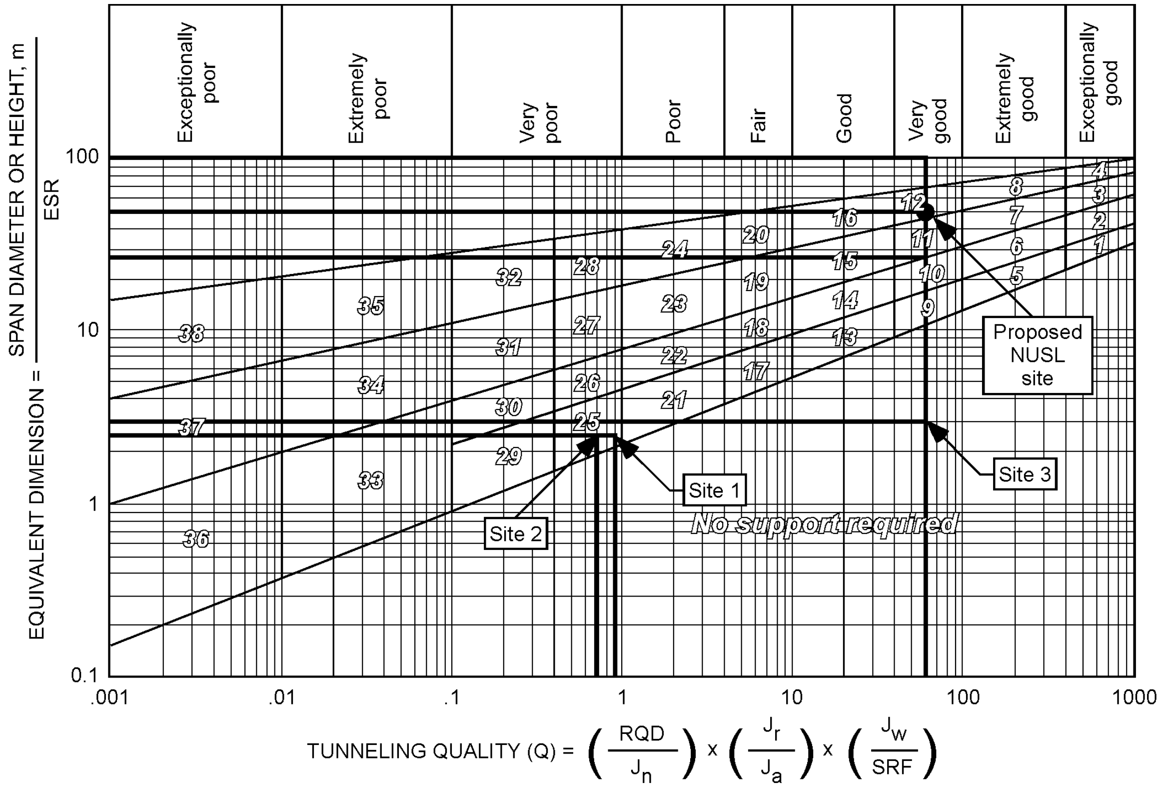

Figure 3.—Recommended support as a function of tunneling quality index and equivalent dimension (after [3])

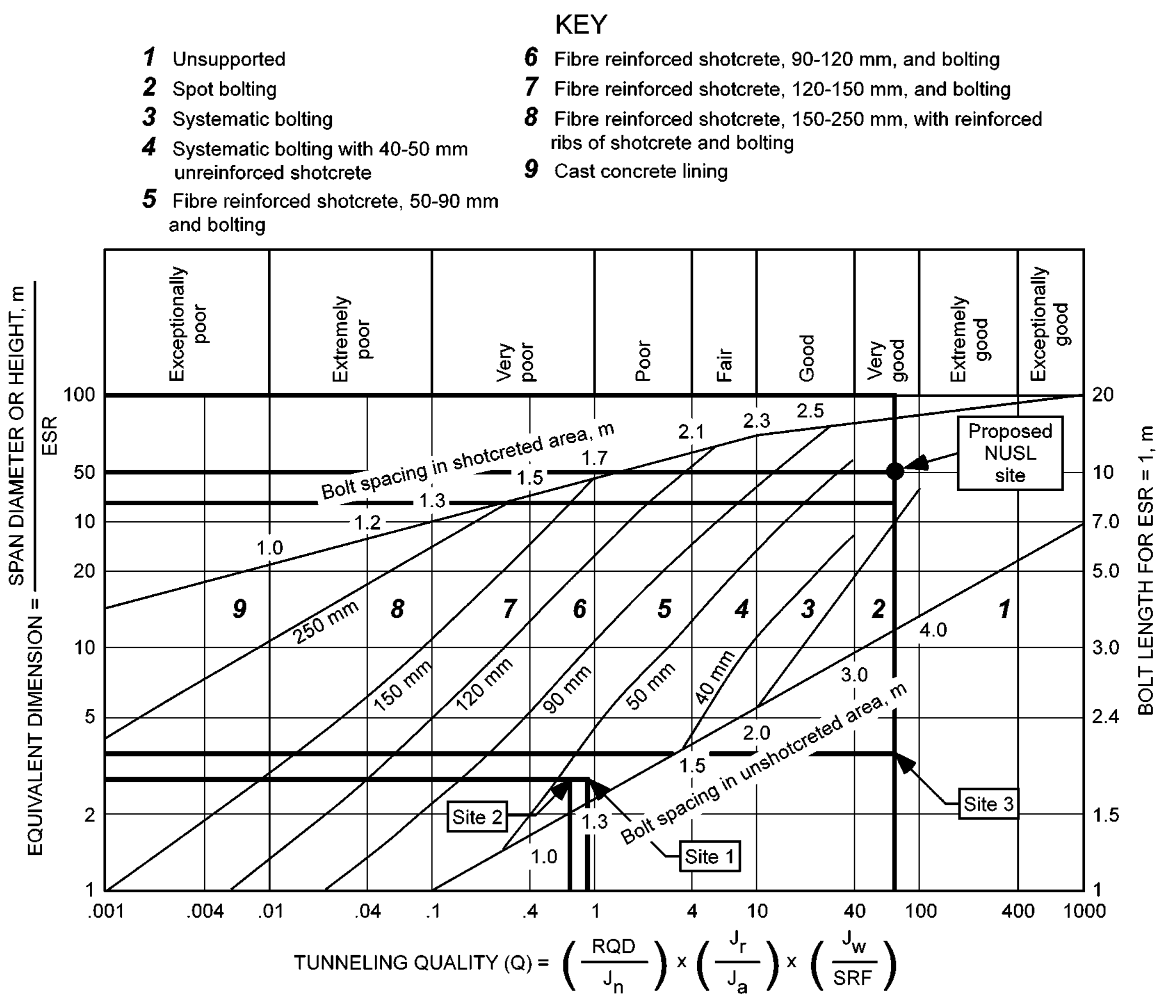

Figure 4.—Recommended support as a function of tunneling quality index and equivalent dimension (after [4])

Table 1.—Support recommendations based on Q compared to actual support used at three sites at the Homestake Mine.

Parameter	Site 1	Site 2	Site 3
Joints/m^3, J_v	16 (13 bedding planes + 3 joint sets)	12 (7 bedding planes + 5 joint sets)	<4
RQD = 115 - 3.3 J_v	60	75	85 (reduced from 100 for unknown joints)
Joint set number, J_N	3 (one joint set + random joints)	4 (2 joint sets)	0.75 (massive, no or few joints)
Joint roughness number, J_R	1 (smooth, planar)	1 (smooth, planar)	4 (discontinuous joints)
Joint alteration number, J_A	1 (unaltered joint walls)	1 (unaltered joint walls)	0.75 (tightly healed joints)
Joint water reduction number, J_w	1 (dry)	1 (dry)	1 (dry)
Stress reduction factor, SRF	20 (σ_c / σ_1[1] = 0.7)	20 (σ_c / σ_1 = 1.2)	10 (σ_c / σ_1 = 4.4)
Tunneling quality index, Q	1.0	0.9	60
Excavation support ratio	1.6 (permanent mine opening)	1.6 (permanent mine opening)	1.6 (permanent mine opening)
Span, m	4	4	5
Equivalent span, m	2.5	2.5	3.1
Recommended support [4]	Category 4 Rock bolts at 1.3-m spacing, 50-mm shotcrete	Category 4 Rock bolts at 1.3-m spacing, 50-mm shotcrete	No support required
Recommended support [3]	Category 25 Untensioned bolts at 1-m spacing, chain link mesh	Category 25 Untensioned bolts at 1-m spacing, chain link mesh	No support required
Actual support used	Friction bolts at 1-m spacing, chain link mesh	Friction bolts at 1-m spacing, chain link mesh	Spot bolting with mechanical-anchor bolts, friction bolts at 1.5-m spacing, chain link mesh

[1]σ_c = rock unconfined compressive strength. σ_1 = major principal stress.

Table 2.—Support recommendations for three roof spans where Q = 60.

Parameter	Span = 25 m (82 ft)	Span = 50 m (164 ft)	Span = 100 m (328 ft)
Excavation support ratio, ESR	1 (large civil cavern)	1 (large civil cavern)	1 (large civil cavern)
Equivalent span, m (ft)	25 (82)	25 (82)	100 m (328 ft)
Required support [4]	Category 4 Systematic bolting 40-50-mm shotcrete	Category 4 Systematic bolting 40-50-mm shotcrete	No recommendations
Required support [3]	Category 11 Tensioned bolts 2-3-m spacing	Category 12 Tensioned bolts 2-3-m spacing	No recommendations

5. CONCLUSIONS

The stability of a mine opening spanning 50 m with a volume of 163,624 m^3 was analyzed at depths from 2141 to 2416 m using the three-dimensional, finite-difference numerical model FLAC3D and empirical rock characterization techniques. Material properties and in situ stresses from a previously calibrated finite-element model applied to vertical crater retreat stopes in the Poorman and Homestake formations were used. The model calculated zones of plasticity around the mine opening at all mining depths below 2141 m. The maximum extent of failure into the rock was 10 m and would occur in the lower roof at all mining depths modeled. However, the thickness of the failure zone diminished to zero near the apex of the hemispherical roof. The maximum yield width in the room's rib was 6.8 m.

These results, combined with observations of instability of rooms by mine personnel at 2438 m underground, suggest that 2141 m may be the deepest level that a room spanning 50 m can be mined and maintained in rock with strengths equal to those of the Poorman and Homestake formations. If the rock strength obtained from the specimens of Yates Formation rock are representative of the entire formation, then construction of large rooms may be possible at levels below 2141 m in this host rock, but may raise rock bursting concerns. A thorough site investigation in the Yates Formation, including joint mapping and directional drilling to obtain core for laboratory tests, is essential for a more accurate stability assessment.

Rock support requirements were validated at three existing sites using empirical design methods, indicating that it is reasonable to apply these methods to the large chamber proposed at the Homestake Mine. The recommended spacing between bolts for a 50-m span constructed in rock believed to be characteristic of the Yates Formation is 2 to 3 m. A 50-mm-layer of shotcrete is also advised.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mark Laurenti, chief mine engineer; Mike Stahl, mine production engineer; and Kathy Hart, chief geologist, Homestake Mining Co., for providing access to underground workings and providing historic stability information on large excavations at the Homestake Mine. Modeling suggestions made by John D. Osnes, manager of Geomechanics, RESPEC, Rapid City, SD, are also much appreciated.

REFERENCES

1. Davis, Rachel, ed. 2001. Underground lab to mine secrets of the universe. *Engineering Times*, Aug./Sep.

2. Itasca Consulting Group, Minneapolis, MN. 1998. FLAC - Fast Lagrangian analysis of continua, version 3.4. 1485 pp.

3. Barton, N.R., R. Lien, and J. Lunde. 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mech*. 6(4):189-239.

4. Grimstad, E., and N. Barton. 1993. Updating the Q-system for NMT. In *Proceedings of the International Symposium on Sprayed Concrete: Modern Use of Wet Mix Sprayed Concrete for Underground Support*. Oslo: Norwegian Concrete Assn.

5. Pariseau, William G. 1985. Research study on pillar design for vertical crater retreat (VCR) mining. Bureau of Mines Contract Report J0215043, Oct.

6. Pariseau, William, F. Duan, and C.S. Schmuck. 1987. Stability analysis of the VCR stope at the Homestake Mine. *Gold Mining 87*, pp. 199-213.