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A CASE STUDY OF SURFACE CROWN PILLARS: THE NIOBEC MINE

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A CASE STUDY OF SURFACE CROWN PILLARS: THE NIOBEC MINE

by

M.C. Bétournay*, Y.S. Yu**, S. Thivierge+

ABSTRACT

The Niobec surface crown pillars are composed mainly of massive horizontal, unjointed limestone, and span underground openings located in zones of niobium enrichment of a carbonatite intrusive. The pillars/abutments supporting the surface crown pillars are competent with excellent rock mass quality characteristics. The openings will be enlarged in the future and left opened.

The methods applied in analysing the stability of present and planned openings are: elastic theory, "voussoir solutions" and 3-D finite element analysis. Using these, the existing surface crown pillars and related openings are stable, confirmed by visual surveys. In particular, numerical modelling of the largest primary opening, 23 m $\times$ 72 m in plan, 90 m high, yields low compressive and tensile stress concentrations. Without support pillars, localized, progressive failure of carbonatite and limestone may result. Application of cable bolting may prove necessary. Critical stable opening spans are calculated.

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key words

limestone, carbonatite intrusive, surface crown pillars, large open stopes, joints, bolting, pillar stability, elastic theory, voussoir solution, finite element modelling, failure mechanisms.

UNE ÉTUDE DE CAS DE PILIERS DE SURFACE: LA MINE NIOBEC

par

M.C. Bétournay*, Y.S. Yu **, S. Thivierge+

RÉSUMÉ

Les piliers de surface de la mine Niobec sont composés essentiellement de calcaire massif, avec litage horizontal, sans démontrés de diaclases. Ils couvrent des ouvertures souterraines situées en zones de haute teneur de Niobium d'un intrusif de carbonatite. Les piliers/côtés de massifs qui supportent les piliers de surface sont compétents avec d'excellentes caractéristiques de massif rocheux. Les ouvertures seront aggrandies dans quelques années et resteront ouvertes.

Les méthodes utilisées à l'analyse de la stabilité des ouvertures actuelles et celles planifiées sont: la théorie élastique, les solutions "voussoir" et la modélisation numérique en 3-D. En appliquant ceux-ci, on calcule que les piliers de surface et les ouvertures connexes sont stables, ce qui est confirmé par des études de terrains. En particulier, la modélisation numérique de la plus grande ouverture, 23 m × 72 m en plan, 90 m de haut, démontre de basses concentrations de contraintes compressives et tractives. Sans les piliers de support, une rupture localisée et progressive de la carbonatite et de calcaire est possible. L'application de cable d'ancrage donc pourrait être nécessaire. Les dimensions de stabilité critiques sont également calculées.

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mots clés
calcaire, intrusif de carbonatite, piliers de surface, larges chantiers ouverts, diaclases, boulonage, stabilité de pilier, théorie élastique, solution voussoir, modélisation par éléments finis, mécanismes de ruptures.

INTRODUCTION

In 1984, at the request of the Niobec Mine, Québec Canada, a mine stability evaluation program was started by governmental agencies. In particular, geomechanical analysis of the rock mass, laboratory determination of strength/deformation parameters and analytical and numerical formulation were performed. This paper deals with the aspects related to the mine's surface crown pillars.

A surface crown pillar is a mine structure of variable geometry, situated between an uppermost stope of a mine and surface. Surveys of surface crown pillars in Canadian underground hard rock mines [1][2] have shown that, contrary to the Niobec setting, deposits dip steeply and are generally either single or multiple veins. Considerable overburden usually caps the deposits. The rock mass is often altered and intersected by major discontinuities.

MINING ASPECTS

The mining activity takes place in a carbonatite pluton located in the Pre-Cambrian Shield. The carbonatite and satellite rocks are capped by flat lying Paleozoic limestone [3]. The carbonatite, a rock rich in carbonate minerals, contains small vertical zones of niobium enrichment. Mining pattern follows irregularly distributed ore concentrations, thereby creating numerous openings and overlying surface crown pillars, generally 60 m thick. When the limestone is less than 60 m, the difference is made up by carbonatite. The mine uses large diameter blasthole stoping with no backfill.

The plan dimensions of the stopes vary from $20\,m \times 20\,m$ to $30\,m \times 100\,m$. Some areas group several stopes, separated by support pillars $15\,m \times 20\,m$ to $30\,m \times 50\,m$ in plan. These vertical pillars are expected to be mined once primary stoping is completed. The open stopes could then reach considerable dimensions, table 1.

Mining activity takes place on two tiers, each 90 m high. The upper tier begins with the surface crown pillar. The second is separated from the first by a 30 m sill pillar. The lower stopes follow the same ore zones of the upper stopes. The mine has almost finished its primary stoping in the upper tier and is poised to begin mining the support pillars. The lower tier has seen limited primary stoping.

STABILITY CONSIDERATIONS

There are two structural geology features in the carbonatite. The first consists of large extension joints, created by stressing/destressing activity of the intrusive with sub-horizontal (85%) and vertical (15%) orientations. The second is composed of joints ($< 50\,cm$) oriented similarly to the large joints, but created by the cooling of the intrusive. The large sub-horizontal joints predominate at deeper reaches; the large sub-verticals occur at random. The intersection of the large joints form "T" or "⊥" patterns. No faulting has been revealed. The joints are generally planar with large scale undulations.

For two main reasons few instability problems have occurred. Firstly, the mine is operating at shallow depths. There is limited influence from in situ stresses. At 290 m, the ground stress has a maximum value of 22 MPa, in a horizontal direction. Secondly, the upper tier of the mass is favorably jointed, the joints are less than 50 cm and rarely intersect. These observations are well corroborated by the high RQD values ($> 80\%$) and NGI rock mass rating from 3 to 99 (usually > 14). The drifts are excavated to $3\,m \times 4\,m$ using pre-split drill and blast. Drift walls are unsupported, the backs are supported according to need. Instability problems have either been minor or located at depths below the first mining tier.

The limestone, composed of calcareous units with alternating shale bands, is even, regularly bedded, dense and of uniform composition. Examination of accessible stopes indicates that they are all stable. The pillars/abutments supporting the limestone possess the stated high quality mass characteristics. They are not bolted.

The stopes with a limestone roof provide the first indication that this unit is massive and unjointed. No joints have been seen in this rock. There is also no past instance of roof fall. Whether this is due to the efficient use of support as soon as the opening was made, or not is not certain. 1.2 m resin grouted bolts were emplaced soon after standard 2.2 m mechanical bolts were installed for development. Evidence from other exposures of limestone would also suggest that this unit has high self-supportive capabilities. The limestone exposed in raises, drifts and along the mine ramp also shows a lack of jointing and even parting of shale layers. Parting along shale layers, but no jointing, occurs in BQ core from numerous drill holes. RQD values are usually $> 90\%$.

ANALYSIS OF PILLAR STABILITY

Surface crown pillar design benefits from an integrated approach. A series of analyses will form a broad view of design and expectation of behaviour. Elastic theory, "voussoir" solutions and 3-D finite element analysis have been applied in analysing the stability of present and planned opening sizes shown in table 1. All are used to analyse the surface crown pillars. The supporting pillars are analysed by numerical modelling.

Basic data required for the elastic and voussoir analyses were obtained from tests on limestone [4]. Large size beam tests have yielded a tensile strength value of 5.8±2.6 MPa. Compressive strength tests produced σ_c=91.5±22.5 MPa and E=35.8±9.9GPa. Though consideration of large scale rock structures by the elastic theory is simplistic and of preliminary use in considering jointed rock masses, the nature of the massive surface crown pillars justified an elastic beam/plate analysis. This analysis assumes that tensile stresses may develop in the limestone; when the stresses reach the lab tensile strength, the structure is expected to fail in tension followed by complete degradation. This is the limiting equilibrium condition, Factor of safety F_s=1. Obviously, the mine must operate under a larger F_s, even though there are no overlying surface installations or bodies of water. Figure 1 portrays design curves for critical spans with F_s=1 to 2.5. The contribution of rock bolts and effect of water are not considered. The carbonatite is taken as a no-tension material, limestone dimensions are used.

With two short edges fixed, the surface crown pillar is separated in a series of 1 m wide beams, each with induced stresses of:

$$\sigma_{induced} = \frac{qL^2}{2h^2}$$

where L, h, q are , respectively, length, thickness and pillar distributed load.

Using plate analysis with four sides fixed, factors (β) are used to relate length to breadth b [5]:

$$\sigma_{induced} = \frac{\beta q b^2}{h^2}$$

Table 1 shows that under this analysis, existing surface crown pillars fall at F_s levels >2.5, more so with four sided support. Only one of the four largest future openings will meet the required F_s > 1.0, considering two edged support; the F_s will increase under four sided support. The limit spans for surface crown pillars, representing the range of limestone thickness, 37.5 m to 67.2 m, are: 128-160 m for two sided support consideration, 256-330 m for 2b=L plates and 333-418 m for b=L plates. The mine can use the same curves for higher F_s to evaluate the stability of future openings (using F_s=2.5 reduces the spans by 25%).

The voussoir arching principle, Fig. 2, is also a limit equilibrium analysis, where a detached layer carries its weight by arching [6]. Table 1 outlines the minimum arching layer thickness in present stable openings and that required for future openings. Since the pillars are intact, the 4.7 m voussoir thickness obtained for the widest existing span is conservative. Bolting could add tensile resistance, but this is minor compared to the 4.7 m limit equilibrium thickness. Two other reasons can explain this stable state: the failure mechanism put forward is not reasonable for this unjointed rock, or the beds will not part on a large scale. Shear failure of the bolted beds requires critical spans several times more than voussoir action, even more than planned opening spans. Based on the voussoir principle, two of the four future openings can meet limit equilibrium. The same curves can be used to evaluate the stability of 2b=L and b=L dimensions, figure 3. In situ E is used, based on lab results.

Stope 102-23, figure 4, is being excavated to span 73 m; future removal of surrounding support pillars will create a 24 m wide opening spanning 274 m. To assess the structural stability of the present and future stope dimensions, a 3-D finite-element model was constructed. The dimensions are outlined in an isometric view of the model, figure 5. All stopes are separated by 24.38 m wide pillars. The surface crown pillar is made of 22.5 m of carbonatite under 37.5 m of limestone.

Planes of symmetry were used for simulating only one quarter of the structure, thereby simplifying the model. The mirror image of 102-23 is modelled instead of the existing two small stopes separated by a pillar. The effects of the yet to be excavated small stopes below will be modelled in the future. The approximations in terms of the actual mine geometry should provide a conservative estimate of its state in terms of stresses or failure conditions. The model is divided into nine sections of varying thickness, and yields a total of 3344 8-nodes elements and 4140 nodes.

The computer program was written in Fortran IV for a Cyber 730 computer. The theory on which it is based and the derivation of formulation have been described in detail elsewhere [7,8]. The program performs static, and linear elastic analysis. Material properties are assumed to be isotropic. It is capable of handling gravity and distributed surface loads. Initial residual stresses, if known, can also be used as input. Mesh generation is also incorporated [9].

Two loading cases were examined [10,11]. Loading case A, far field stresses due to gravity loading only:

$$\textit{Loading Case A}: \quad \sigma_z = \gamma Z$$
$$\sigma_x = \sigma_y = \frac{\nu}{(1-\nu)}\sigma_z$$

Based on field stress measurements at the mine, the following far field stress conditions were adopted:

$$\begin{aligned} \textit{Loading Case B}: \quad \sigma_z &= \gamma Z \\ \sigma_y &= 1.5\sigma_z \\ \sigma_x &= 2.0\sigma_z \end{aligned}$$

Where σ_z is the vertical stress at a depth Z; σ_x and σ_y are the horizontal stresses in the EW and NS directions respectively; γ is the unit weight of rock; ν is Poisson's ratio.

As expected, the simulated mining of C-102-23 stope under Loading Case B induced higher compressive stresses around the lower portion of the stope. These compressive stresses, however, were not high enough to create any ground failure problem. Tensile stress zones occur in stope walls, back, floors, and along pillars. Tensions are particularly noticeable in the stope back. Here is a summary of the modelling results:

(a) Under existing stresses, ground stability conditions around stope C-102-23 are better than those under gravitational loading. The largest compressive stresses occur near the stope corners, with a magnitude of about 15 MPa. These are not sufficient to cause stability problems. Figure 6 shows a typical stress contour representing the average stresses in the central section of the stope under loading case B.

(b) Tensions developed along the walls of C-102-23 stope (T-102-21 pillar) are relatively small, ranging from 0.5 to 1.0 MPa for both loading cases. The tensile strength of carbonatite is estimated at 5 - 10 MPa [12]. With favorable joint orientation, wall stability should not be a problem.

(c) Small tensions (less than 0.5 MPa) occur along most of the T-102-19 pillar height. Since it is only 24 m wide, care should be taken to ensure its integrity, such as protection against blast damage.

(d) The tensile zone, developed under gravity loading in the central portion of the roof, is reduced by approximately 50% considering tectonic stresses. Here the tensile zone in the centre of the roof at the stope centre line is limited to a depth of 5m and extends 5m towards both the stope walls. The largest tension (less than 1 MPa) is at the quarter span and diminishes gradually toward the walls. The stope roof is in carbonatite. Even under such low tensile conditions, ground conditions around C-102-23 stope should be regularly observed as mining progresses. If adverse ground conditions develop, additional support should be considered.

Local factors of safety in terms of the Drucker/Prager yield function have also been calculated. Figure 7 shows a typical plot of the local factor of safety, under Loading Case B, for the center section. No yield zones are indicated ($F_s \geq 1.0$). The C and ϕ values used in the study, 2 MPa and 40° respectively, can be considered conservative. Therefore, shear failure in the roof or pillars is not likely to occur under either loading conditions. If failure occurs, it would be localized tension failure rather than shear failure.

The average pillar stresses for T-102-21 and T-102-19, 2.92 and 2.51 MPa respectively, were evaluated based on the vertical stresses acting at the middle height of each pillar. The average stresses in the transverse direction are 7.76 MPa and 6.46 MPa, respectively. The weakest compressive strength of the carbonatite is 90 MPa [12]. The pillar stresses are below the compressive strength of altered carbonatite; therefore, the pillars are stable and no imminent shear failure is anticipated.

CONCLUSIONS

The analyses presented have touched on a number of stability elements of surface crown pillars and related stopes. Though the failure mode advocated for elastic beam/plate analysis is unlikely, the massive nature of the limestone can reach strength levels comparable to that determined from laboratory tests. The numerical modelling under gravity loading provides tensile values similar to the ones obtained with elastic beam analyses, more conservative than elastic plate considerations. In reality, a major tensile failure in this structure will not render it unserviceable because of the large thickness. Poor parting of limestone beds and the positive effect of resin grouted bolts have rendered voussoir analysis too conservative, but still the most plausible failure mechanism is voussoir action. Progressive failures of layers in an opening that is too wide may work itself into a stable dome shape before the surface is reached. Finally, the 3-D numerical modelling provides an in-depth view of the small stress and strain distributions produced, and prediction of localized failure based on the Drucker/Prager yield function. However, it fails to address the effect of joints in terms of the overall stability.

The stability analyses indicate that the surface crown pillars, supporting pillars and stopes of the upper level of the Niobec Mine are stable, and consistent with field surveys, and therefore no imminent failure is anticipated under present mining configurations. However, it is likely that when support pillars are removed, localized failure in carbonatite and limestone may result. Application of cable bolting to abutments and roof may prove to be a necessity.

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Table 1. Elastic and voussoir analysis of pillar stability

Stope	Limestone Dimension (m) h	b	L	Two sided support Lab strength/induced tension	Four sided support Lab strength/induced tension	Required voussoir layer thickness (m)
Largest Existing Openings						
102-23	37.5	24.4	73.2	5.8/1.91 = 3.0	5.8/0.35 = 16.8	3.3
102-17	48.4	26.5	48.8	5.8/0.64 = 9.2	5.8/0.28 = 21.0	2.0
203-27	50.0	32.0	34.1	5.8/0.31 = 19.0	5.8/0.19 = 30.3	0.7
203-23,25	50.0	25.9	54.9	5.8/0.80 = 7.3	5.8/0.21 = 26.8	2.8
206, 202-14	40.8	27.4	73.2	5.8/2.11 = 2.8	5.8/0.28 = 20.9	3.5
203-13,15	64.0	15.2	91.4	5.8/1.74 = 3.4	5.8/0.05 = 106.7	4.7
Largest Future Openings						
102-25´ 102-15	37.5	24.4	274.3	5.8/26.8 = 0.2	5.8/1.00 = 5.8	20.6
T203-29´T203-13	50.0	22.9	160.0	5.8/ 7.1 = 0.8	5.8/0.16 = 37.6	10.4
202-16´ 202-14	43.4	21.3	91.4	5.8/ 2.7 = 2.2	5.8/0.11 = 53.4	4.7
201-13´ 203-09	67.2	60.0	100.0	5.8/ 2.0 = 2.9	5.8/0.54 = 10.9	5.4

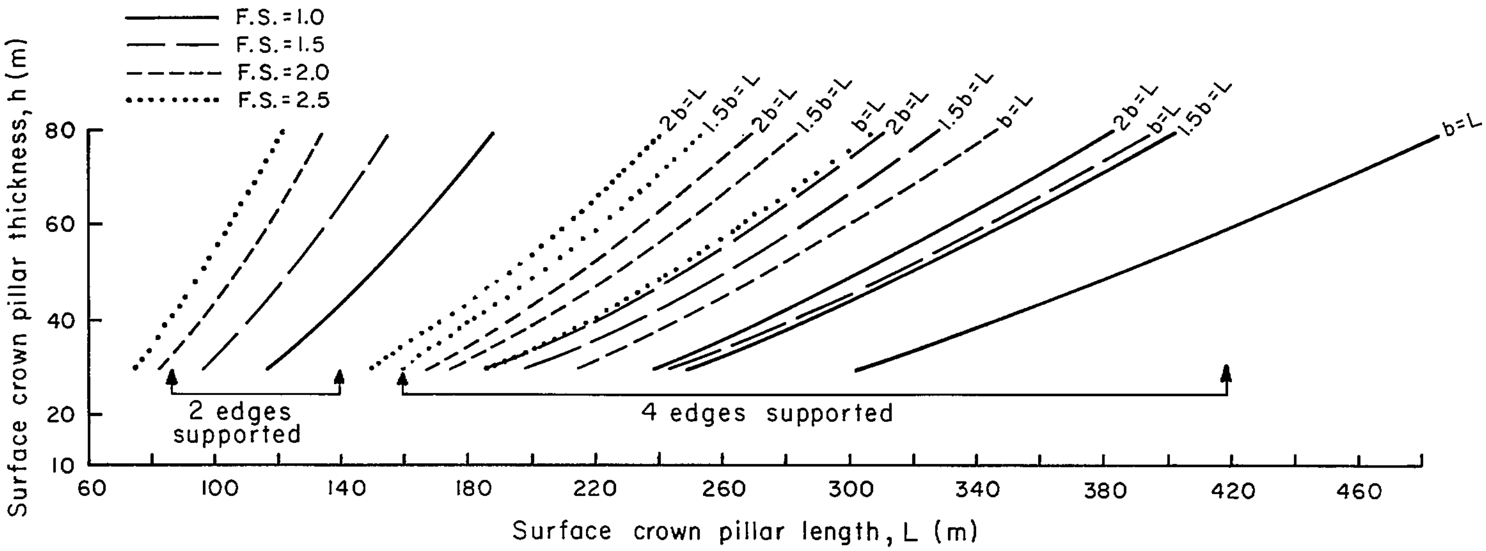


Figure 1. Design curves for surface crown pillars, elastic analysis. b = breadth L = length

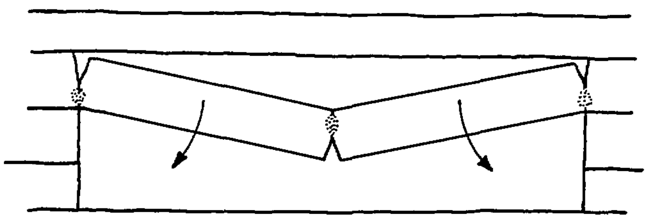


Figure 2. Voussoir action.

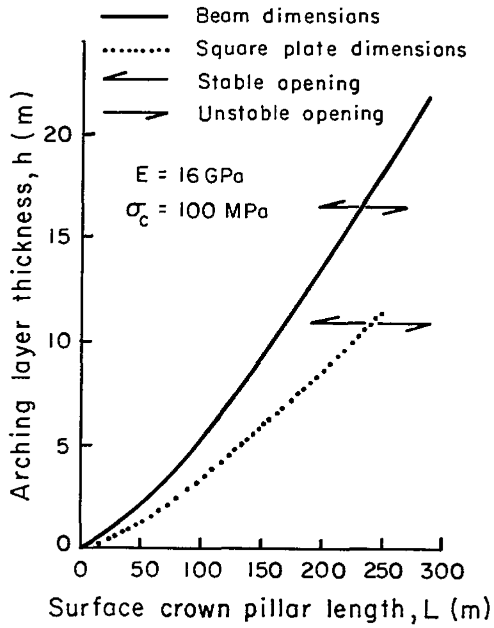


Figure 3. Design curves for surface crown pillars, Voussoir solution.

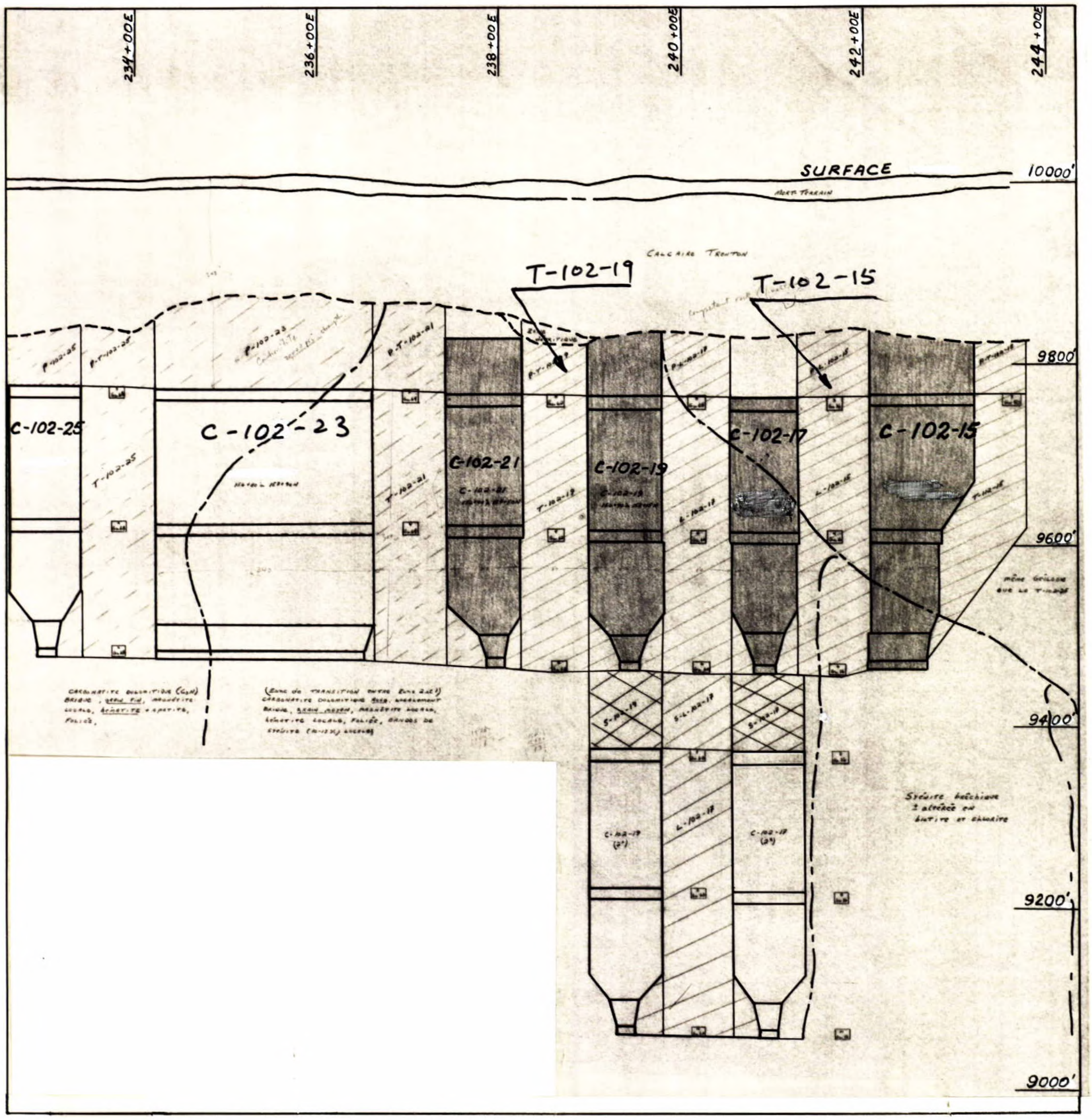


Figure 4. Stope C-102-23 and surrounding mine workings. Mined out stopes in gray.

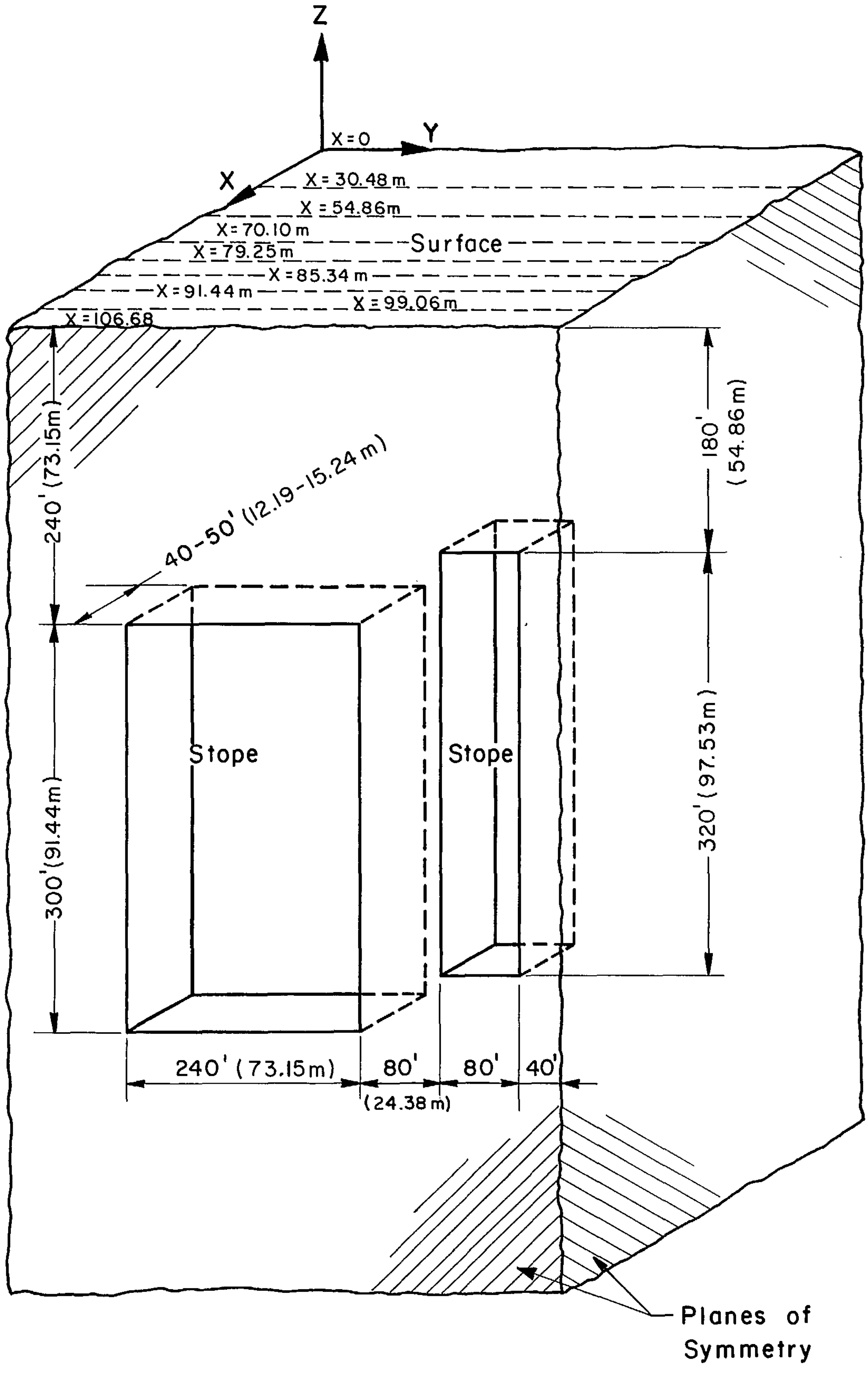
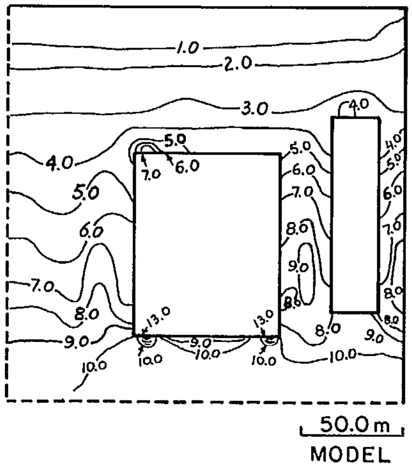
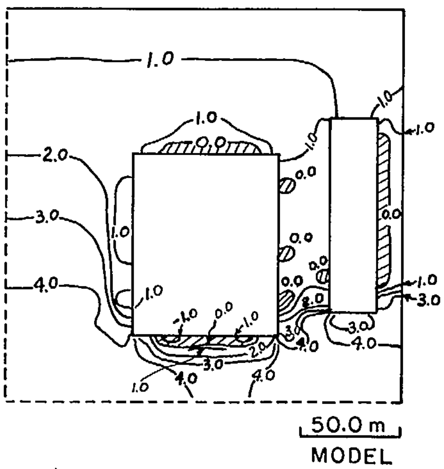


Figure 5. Isometric view of the mine model (quarter of the structure).



(a)



(b)

Figure 6. Average stresses in the central section of C-102-23 loading case B. (a) major principal stresses, (b) minor principal stresses, in MPa. Tensile values are negative.

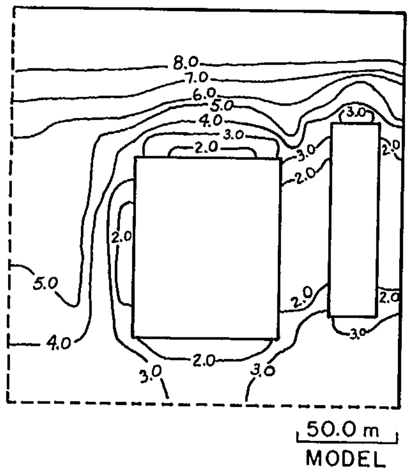


Figure 7. Local factors of safety, centre section stope C-102-23, loading case B.

Table 1. Elastic and voussoir analysis of pillar stability

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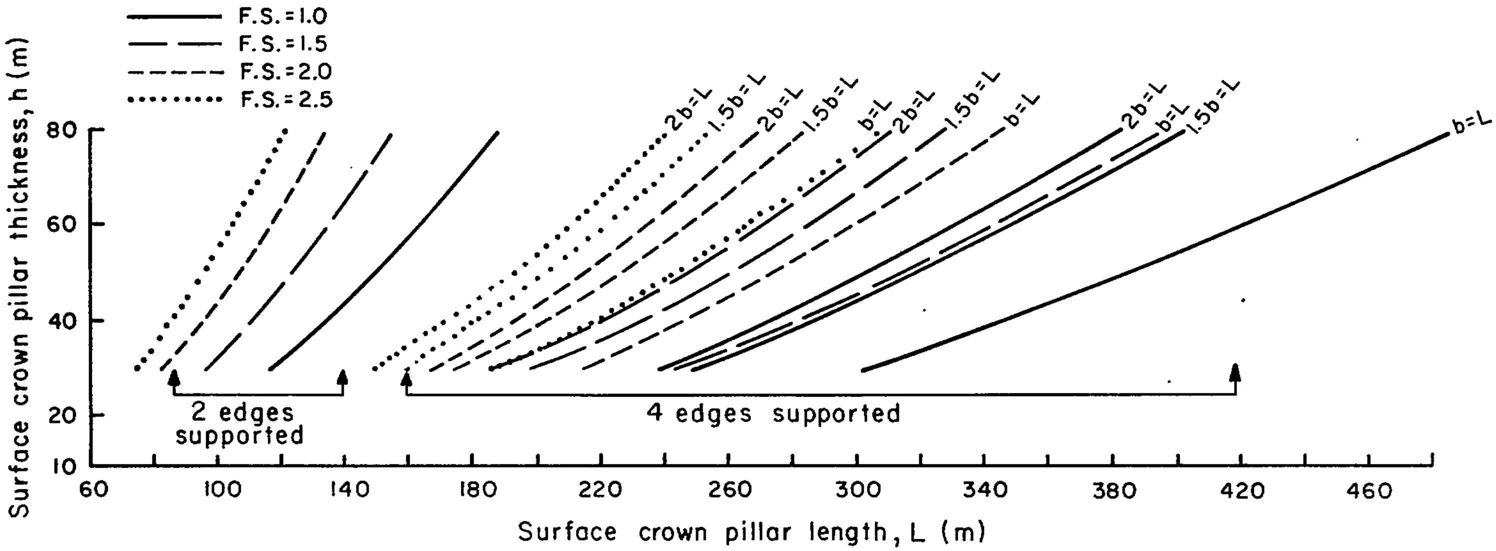

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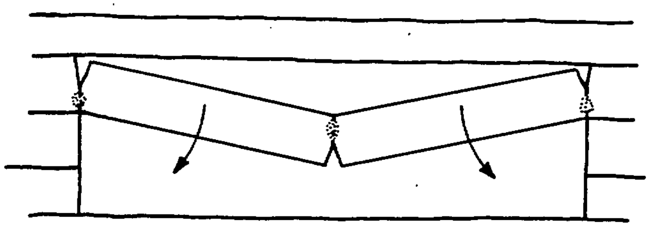

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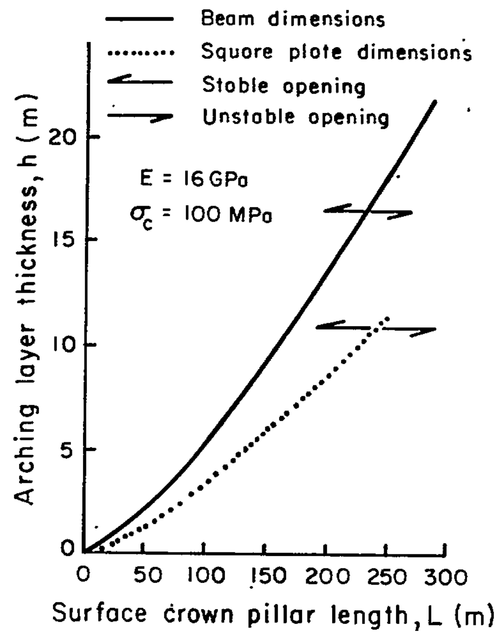
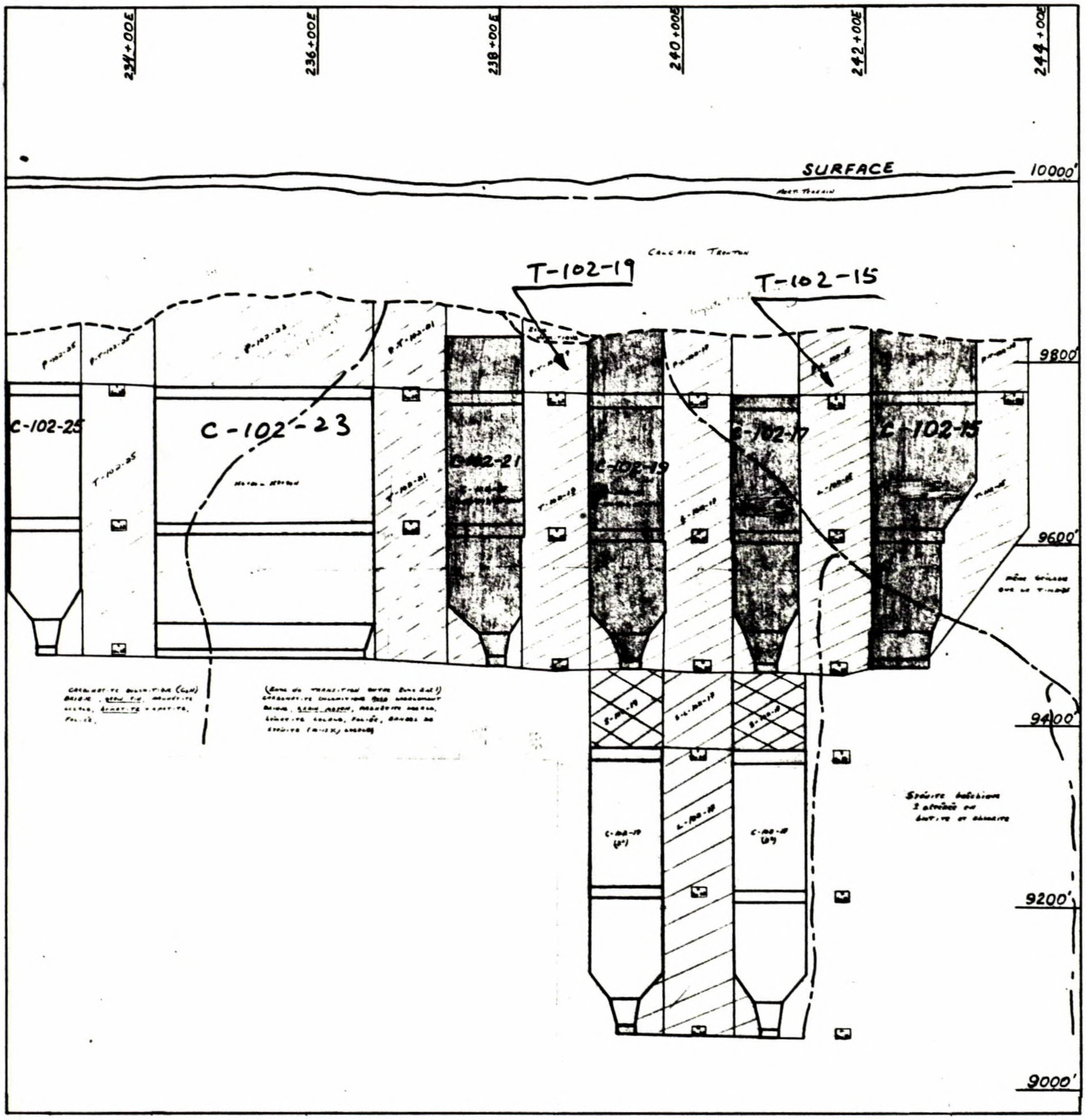


Figure 3. Design curves for surface crown pillars, Voussoir solution.



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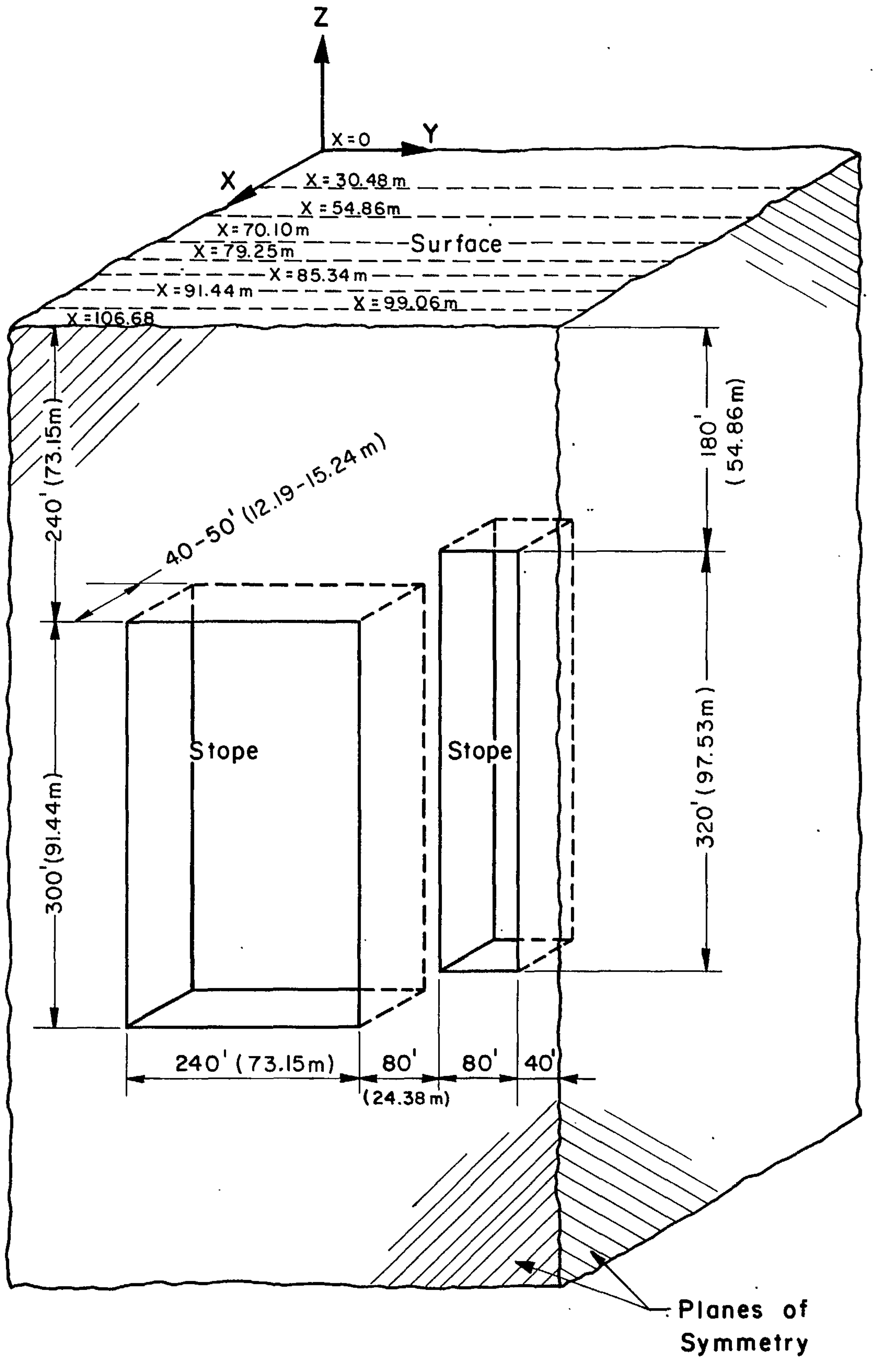

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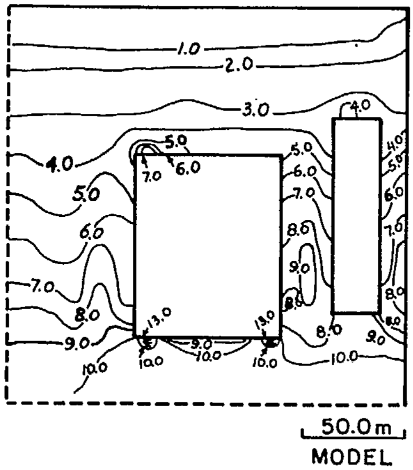
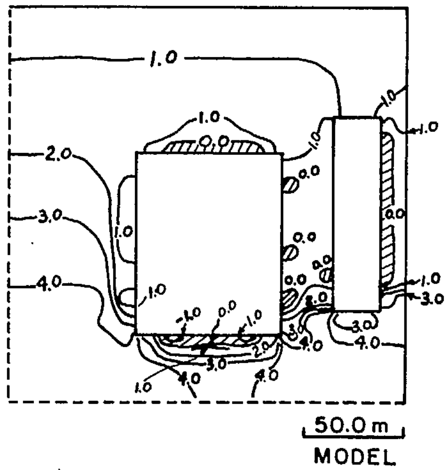


(a)



(b)

Figure 6. Average stresses in the central section of C-102-23 loading case B. (a) major principal stresses, (b) minor principal stresses, in MPa. Tensile values are negative.

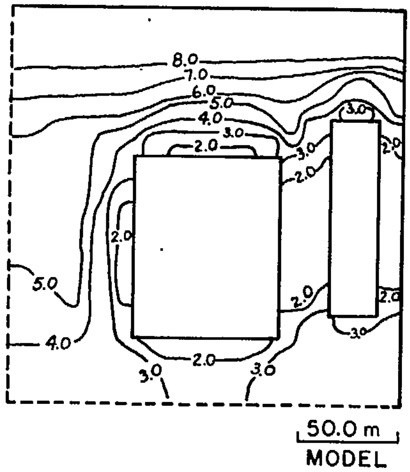


Figure 7. Local factors of safety, centre section stope C-102-23, loading case B.