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SENSITIVITY TO EXPECTED RANGES OF ROCK STRENGTHS AND STRESS FIELDS, OF STRESS ANALYSES OF UNDERGROUND CAVERNS

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A method of assessing the stability of underground caverns over a range of rock strengths and primary stress fields is presented. The technique is based on the use of the finite element method and on the assumption that rock mass strength can, in general, be adequately represented as a percentage of rock substance strength. The preliminary design of an underground power station is presented to illustrate the procedure.

On présente une méthode d'évaluation de la stabilité de cavernes souterraines pour une gamme des résistances de rochers et de champs de contraintes insitu. La technique se base sur la méthode d'éléments finis et sur la supposition que la résistance de massifs rocheux peut, en général, être suffisamment representée comme pourcentage de la résistance du matériel rocheux. On donne un premier schéma d'un centrale souterraine pour illustrer la méthode.

Vorgelegt wird hiermit eine Methode, die die Stabilität von unterirdischen Höhlen innerhalb eines Bereichs von Felsenstärken und primären Spannungs- bzw. Druckfeldern misst. Das Verfahren beruht auf der Anwendung der "begrenzten Element-Methode" und auf der Annahme, dass im allgemeinen die Stärke der Felsenmasse angemessen dargestellt werden kann als Prozentsatz der Widerstandsfähigkeit der Felsenmasse. Der vorläufige Entwurf eines Untergrundkraftwerks wird vorgelegt, um das Verfahren zu illustrieren.

Introduction

When an opening is excavated in a rock mass, part of the existing structural support is removed. The resulting redistribution of stresses in the vicinity of the opening may create less stable conditions in the surrounding rock mass. The stability of an opening of a given shape and orientation is governed by the nature and properties of the rock mass and by the primary stress field existing in the rock prior to disturbance by excavation. By performing a stress analysis of the proposed opening shape acted upon by the primary stress field, stress concentrations around the opening can be defined and compared with the rock mass strength to assess stability.

The actual strength and deformability of the rock mass, and the magnitude and orientation of the primary stress field acting on the rock mass, can seldom be truly known prior to excavation of the opening. The rock mass strength and deformability may be estimated, from the results of laboratory tests on exploratory bore cores and surveys of the nature, spacing and orientation of discontinuities. The primary stress field may be estimated by analogy with what is known of the stress fields acting in comparable rock masses.

In preliminary design studies for a proposed excavation, estimated rock mass strengths and stress fields can be utilized, provided that in replicate design calculations, the values of these variables cover the full expected range. This type of study is called a sensitivity analysis. In this way, the sensitivity of the proposed excavation to particular rock properties or stress field orientations can be analysed. Preliminary insitu testing can be designed to specifically investigate the presence or otherwise of any ranges of strengths or stresses which the sensitivity analyses indicate would lead to unfavourable excavation conditions. It may not be feasible to conduct this preliminary insitu testing in the exact location where the prototype excavation is to be constructed, due to its depth below surface, or other difficulty of access. The results of such testing will represent a refinement of the initial estimates, but there may still be a range of uncertainty, and sensitivity analyses covering the entire range of probable conditions are still desirable at this stage of the design.

Primary stress determinations, and monitoring of rock deformations and support loads, conducted in the first access tunnels into the actual excavation zone, can be checked for any unfavourable conditions indicated by the second series of sensitivity analyses.

Examples of sensitivity analyses, conducted for a proposed pumped-storage power cavern in the State of Victoria, in Australia, are discussed in this paper.

Rock Mass Strength

The strength of a rock mass is predominantly controlled by the rock substance strength and the nature and frequency of discontinuities present. For numerical evaluation of the stability of an underground opening, it is convenient to define the rock mass strength in terms of an algebraic formula. In the absence of any major discontinuities, rock mass strength can be taken as a percentage of rock substance strength.

Rock substance strength can be expressed in terms of octahedral stresses

$$\tau_{oct} = a + b\sigma_{oct} \quad \text{.............. Equation (1)}$$

where $\sigma_{oct} = (\sigma_1 + \sigma_2 + \sigma_3)/2$, the applied stress condition, and τ_{oct} is the octahedral shear strength of the rock =

$$\tfrac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

The relationship determined for a particular fine-grained granite was

$$\tau_{oct} = 8.0 + 1.15\sigma_{oct} \text{(Megapascals)} \quad \text{... Equation (2)}$$

Primary Stress Fields

All subsurface rock is subject to some primary stress fields. A vertical stress field is imposed by gravitational loading. Elastic equilibrium requires that the principal stresses at a free surface must be parallel or perpendicular to the surface, so in areas with rugged topography, the direction of the primary principal stresses may be significantly influenced by surface topography. The stresses should approach a horizontal/vertical orientation at considerable depths below the surface. A geostatic stress field acting below the surface of a horizontal half-space will produce uniform horizontal stress

$$\sigma_h = \frac{\nu}{(1 - \nu)} \cdot \sigma_v \quad \text{........... Equation (3)}$$

where $\sigma_v = \rho g D$, and D = depth below the surface

Hast (1967) observed that measured horizontal stresses are often much greater than the geostatic horizontal or vertical stresses, and postulated a linear relationship between the sum of the horizontal principal stresses and the depth below the surface —

$$\sigma_{H1} + \sigma_{H2} = 18.7 + 0.097D \text{ (Megapascals)} \quad \text{Equation (4)}$$

where D is the depth, in metres

Over the past decade, many other authors, such as Ranalli & Chandler (1975), and Bamford (1976), have confirmed Hast's observations, extended them to other geographical and geological regions, and postulated that the stresses may be linked to the processes of plate tectonics. As these processes are of global application, it appears reasonable that high horizontal stresses may be expected to occur in almost any strong, well-consolidated pre-Tertiary rock formations, unless stress determinations have proved otherwise.

Stress Analysis

A model underground power station for a proposed hydro-electric power scheme was analysed using the finite element method. The model scheme consisted of two significant underground caverns — the machine-hall measuring 20m wide, 35m high, 65m long and an adjacent transformer gallery 12m wide, 12m high and 58m long. The caverns are 10m apart. The expected depth of the caverns is 300m.

In the preliminary stage of design, the caverns were simulated by a plane strain finite element model (Figure 1). The finite element model was analysed by the computer program Static SAP, a computer program developed by the Department of Civil Engineering, University of California (1972). The program is designed to perform linear elastic analyses of large three dimensional systems.

Stress analyses were performed for the following assumed primary stress fields at 300m depth :

σ_V	σ_H	σ_H/σ_V	Theory
8.0MPa	2.0MPa	0.25	Geostatic (ν = 0.2)
8.0MPa	25.0MPa	3.1	Hast

The ground surface above the proposed site slopes significantly and the stress field applied to the top of the finite element grid was proportioned appropriately. The stresses noted above are those that would be acting at the centre of the finite element grid prior to excavation of the caverns.

After analysing the model under the assumed loading conditions, and obtaining the resultant stress distributions, it was found convenient to plot diagrams indicating the relative safety of the rock mass. The stress conditions in each finite element were compared with the strength criterion discussed earlier. The relative safety was then defined by Equation (5) :

$$S = \frac{(\text{Strength} - \text{Stress})}{\text{Strength}} \times 100 \quad \text{... Equation (5)}$$

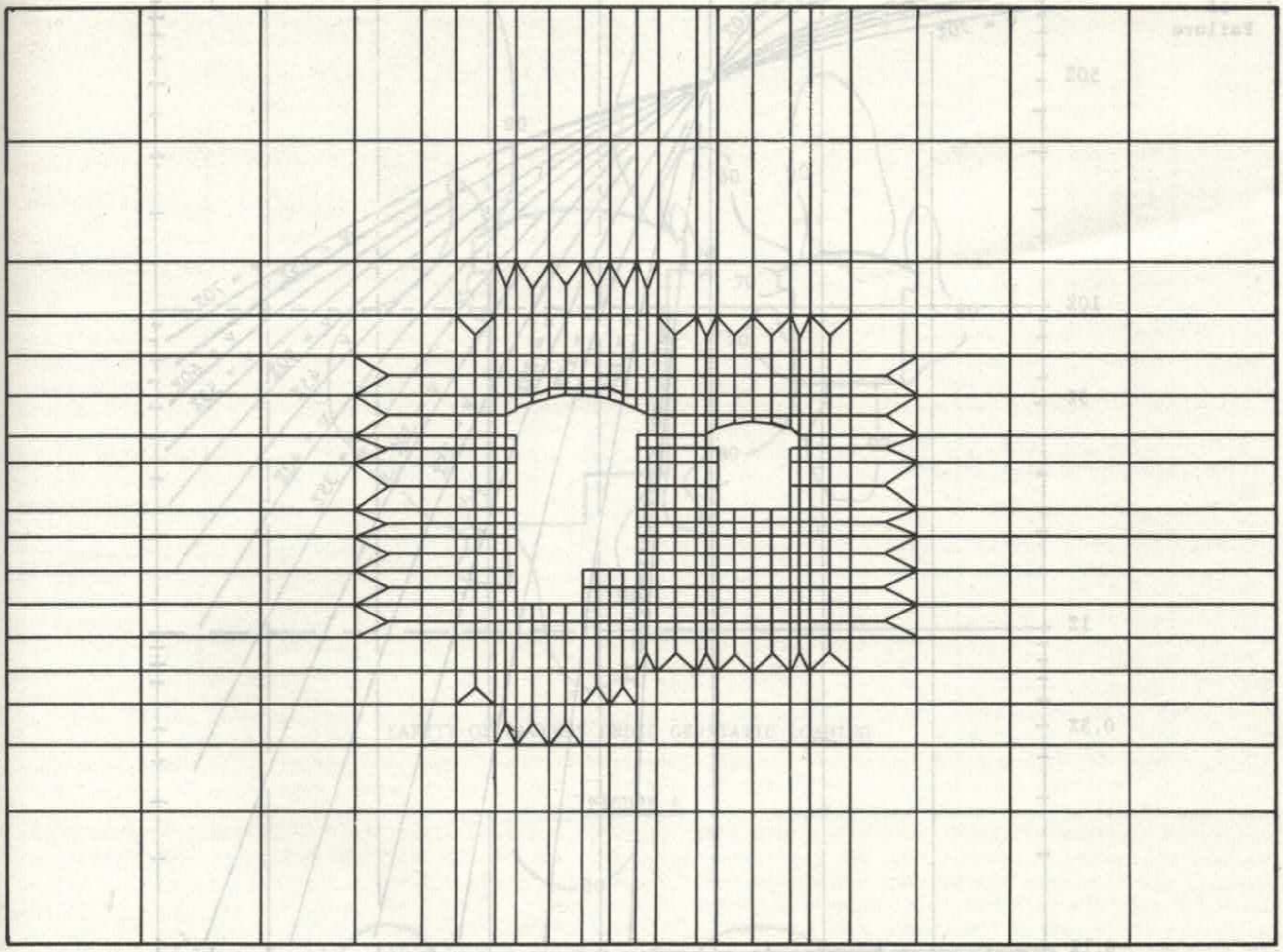
where Stress = Octahedral Shear Stress within a particular element

Strength = Octahedral Shear Strength, for the octahedral normal stress within the same element

A value of S less than or equal to zero indicates a high probability of imminent failure. A positive value indicates safe conditions, with the relative safety being proportional to the magnitude of S.

Equation (5) was used rather than the common "factor of safety" (strength/stress), as it permits simple interpretation in terms of a probability of failure. For example, if the rock strengths have a coefficient of variation (standard deviation/mean) of 10%, then a value for S of +10 represents a situation where the octahedral shear stress is one standard deviation below the mean octahedral shear strength. If the value of S is +12.8, the probability of failure is 10%, while if S equals -12.8 the probability of failure is 90%. If S

FIGURE 1



UNDERGROUND POWER STATION FINITE ELEMENT GRID

equals +23.3, the probability of failure is 1%, while if S equals -23.3, the probability of failure is 99%.

Figure 2 further illustrates such relationships, with the probability of failure being plotted versus S, as a series of lines corresponding to different values of coefficient of variation. Table 1 also allows the probability of failure resulting from a particular combination of S and coefficient of variation to be read off.

When considering a failure criterion based upon rock substance strengths measured in the laboratory, it is convenient to be able to consider reduced values of this strength as an estimate of rock mass strength. For example, if the rock mass strength is 50% of the rock substance strength determined from laboratory tests, then stress conditions resulting in a value of S of 50 when rock substance strength is used in equation (5) would represent a 50% probability of failure in the rock mass. Thus, with this system, the influence of different rock mass strengths on a cavern's behaviour can be conveniently evaluated.

In Table 2 we tabulate the probabilities of failure resulting from various combinations of the insitu strength/laboratory strength ratios, S values, and the coefficients of variation, found in the compressive strength tests (11%) and punch shear tests (34%).

Contour lines representing values of S for the above caverns under geostatic and 'Hast' loading conditions have been plotted in Figures 2 and 3 respectively. These values of S have been based on rock material strength determined by laboratory testing of fresh granite.

Under geostatic loading, where the vertical stress dominates, the probability of failure of the sidewalls of the caverns is higher than that in the arch and floor. For there to be a 50% probability of compressive failure occurring, the rock mass strength would have to be only 30% of that of the rock substance.

FIGURE 2

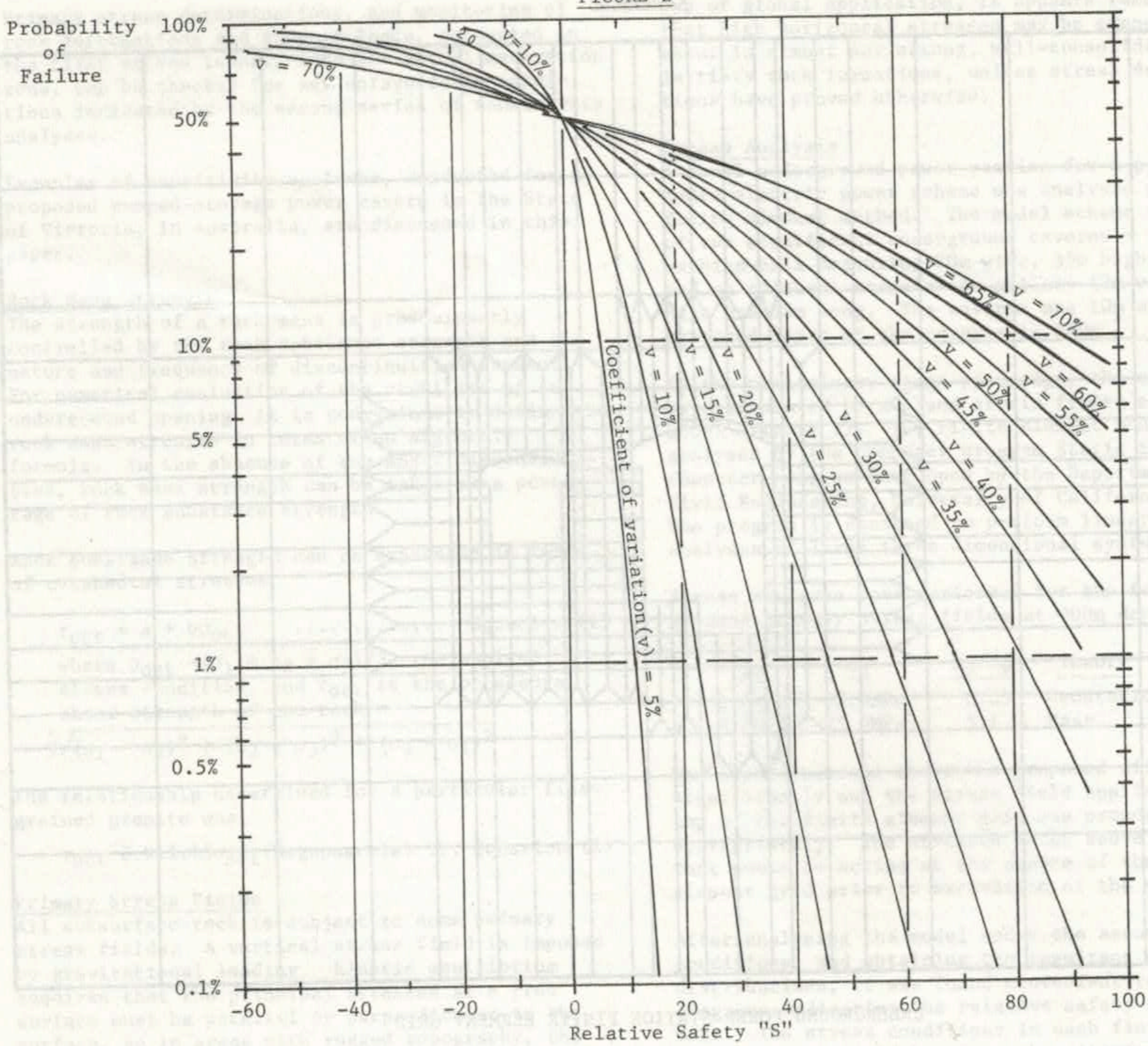
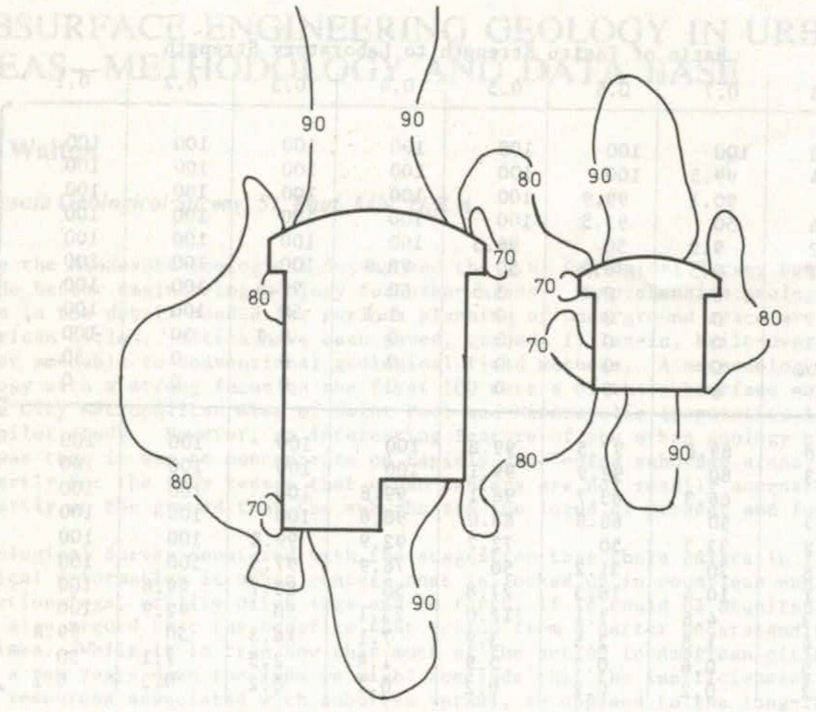


TABLE 1

Relative Safety "S"	Coefficients of Variation 5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
-50	100	100	100	99.4	97.7	95.2	92.3	89.4	86.7	84.1	81.8	79.8	77.9	76.2	74.8	73.4
-40	100	100	99.6	97.7	94.5	90.9	87.4	84.1	81.3	78.8	76.6	74.8	73.1	71.6	70.3	69.2
-30	100	99.9	97.7	93.3	88.5	84.1	80.4	77.3	74.8	72.6	70.7	69.2	67.8	66.6	65.5	64.6
-20	100	97.7	90.9	84.1	78.8	74.8	71.6	69.2	67.2	65.5	64.2	63.1	62.1	61.2	60.5	59.9
-10	97.7	84.1	74.8	69.2	65.5	63.1	61.2	59.5	58.8	57.9	57.2	56.6	56.1	55.7	55.3	55.0
0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
10	2.3	15.9	25.2	30.8	34.5	36.9	38.8	40.5	41.2	42.1	42.8	43.4	43.9	44.3	44.7	45.0
20	0	2.3	9.1	15.9	21.2	25.2	28.4	30.8	32.8	34.5	35.8	36.9	37.9	38.8	39.5	40.1
30	0	0	2.3	6.7	11.5	15.9	19.6	22.7	25.2	27.4	29.3	30.8	32.2	33.4	34.5	35.4
40	0	0	0.4	2.3	5.5	9.1	12.6	15.9	18.7	21.2	23.4	25.2	26.9	28.4	29.7	30.8
50	0	0	0	0.6	2.3	4.8	7.7	10.6	13.3	15.9	18.2	20.2	22.1	23.8	25.2	26.6
60	0	0	0	0	0.8	2.3	4.3	6.7	9.1	11.5	13.8	15.9	17.8	19.6	21.2	22.7
70	0	0	0	0	0.3	1.0	2.3	4.0	6.0	8.1	10.2	12.2	14.1	15.9	17.6	19.1
80	0	0	0	0	0.1	0.4	1.1	2.3	3.8	5.5	7.3	9.1	10.9	12.7	14.3	15.9
90	0	0	0	0	0	0.1	0.5	1.2	2.3	3.6	5.1	6.7	8.3	9.9	11.5	13.0
100	0	0	0	0	0	0	0.2	0.7	1.3	2.3	3.4	4.8	6.2	7.7	9.1	10.6

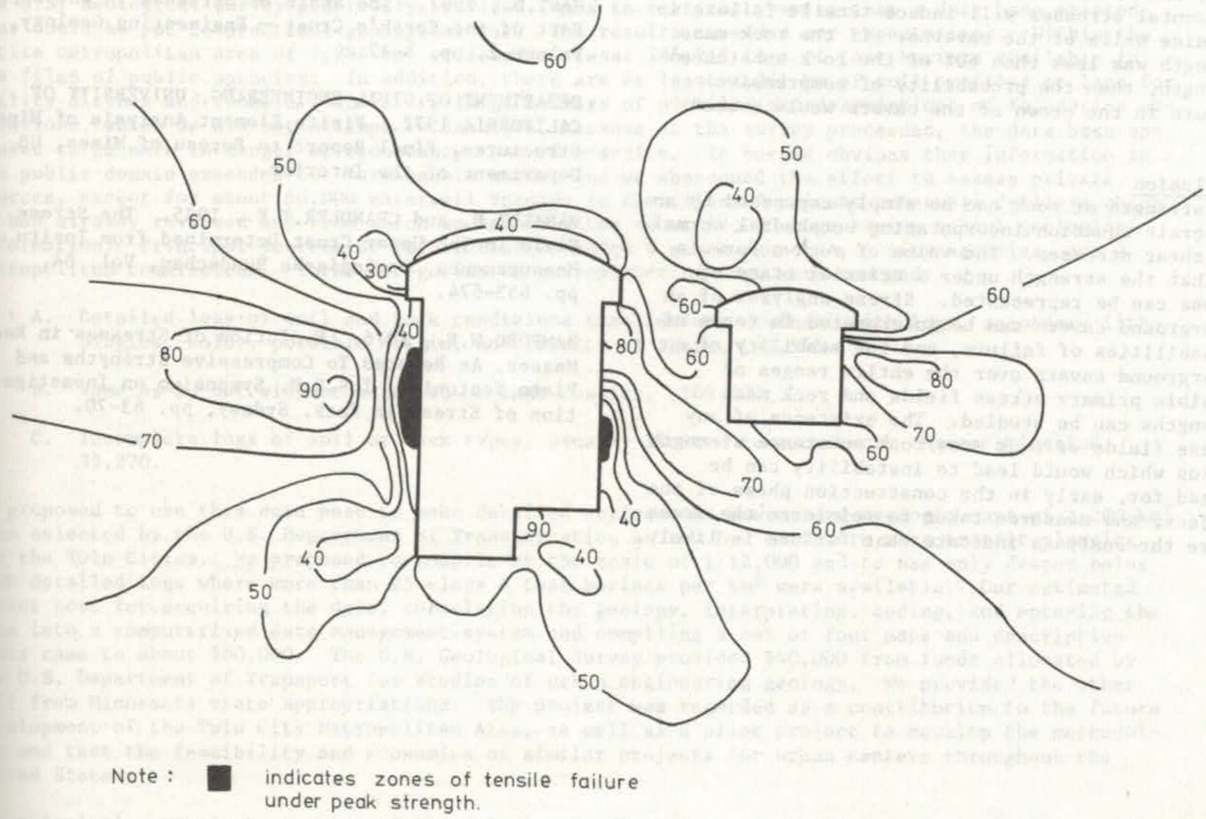
Probabilities of Failure (%)

FIGURE 3



SAFETY OF CAVERNS UNDER GEOSTATIC LOADING

FIGURE 4



SAFETY OF CAVERNS UNDER "HAST" LOADING

TABLE 2

Relative Safety "S"	Ratio of Insitu Strength to Laboratory Strength 0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	
0	84.4	98.8	100	100	100	100	100	100	100	
10	50	91.4	99.5	100	100	100	100	100	100	
20	15.6	50	90.1	99.9	100	100	100	100	100	
30	2.2	8.6	50	93.5	100	100	100	100	100	Coefficient of variation = 11%
40	0.1	1.2	9.9	50	96.5	100	100	100	100	
50	0	0	0.5	6.5	50	98.9	100	100	100	
60	0	0	0	0.1	3.5	50	99.9	100	100	
70	0	0	0	0	0	1.1	50	100	100	
80	0	0	0	0	0	0	0.1	50	100	
90	0	0	0	0	0	0	0	0	50	
100	0	0	0	0	0	0	0	0	0	
0	62.8	76.8	89.6	97.5	99.8	100	100	100	100	
10	50	64.3	80	92.9	99.1	100	100	100	100	
20	37.2	50	66.3	83.7	96.1	99.8	100	100	100	
30	25.7	35.7	50	68.8	88.0	98.6	100	100	100	Coefficient of variation = 34%
40	16.3	23.2	33.7	50	72.2	92.9	99.8	100	100	
50	9.6	15.8	20	31.2	50	76.9	97.5	100	100	
60	5.1	7.1	10.4	16.3	27.8	50	83.7	99.8	100	
70	2.5	3.3	4.6	7.1	12.0	23.1	50	92.9	100	
80	1.1	1.4	1.8	2.5	3.9	7.1	16.3	50	99.8	
90	0.4	0.5	0.6	0.7	0.9	1.4	2.5	7.1	50	
100	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	

Probabilities of Failure %

Under the 'Hast' stress field, the dominant horizontal stresses will induce tensile failure in the side walls of the caverns. If the rock mass strength was less than 60% of the rock substance strength, then the probability of compressive failure in the crown of the cavern would exceed 50%.

Conclusion

The strength of rock can be simply expressed by an algebraic equation incorporating octahedral normal and shear stresses. The value of such a formula is that the strength under a triaxial state of stress can be represented. Stress analyses of an underground cavern can be interpreted in terms of probabilities of failure, and the stability of an underground cavern over the entire ranges of possible primary stress fields and rock mass strengths can be studied. The existence of any stress fields or rock mass/rock substance strength ratios which would lead to instability can be tested for, early in the construction phase of the project, and measures taken to reinforce the areas where the analyses indicate that failure is likely.

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