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ENVIRONMENTAL PROTECTION AND CAVERN STABILITY IN THE MAARDU GRANITE DEPOSIT

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Mining and processing of the mineral resources of Estonia may sharply disturb the environment. The underground mining of the Maardu granite deposit may have a significant impact on the groundwater resources if the resultant caverns are unstable. On the positive side, it is possible to use the caverns for storage of crude oil, gas and petroleum products, for storage of radioactive waste or the waste products of Tallinn. This process is safe and does not harm the environment. The shape and the dimension criteria were evaluated by numerical modelling.

This paper presents the results of a study based on a two-dimensional explicit finite difference modelling (FLAC) of the rock mass. Since little field information was available, the rock mass parameters are estimated from geological data, using Bieniawski's rock mass rating (RMR).

All the calculations are performed for single and multiple caverns. The resulting rock mass responses are presented in terms of induced deformation and stresses.

The results indicate that for the single and multiple caverns, even with different cavern shapes, there are no significant differences in the stability situation. A continuous rock mass approach does not seem to give adequate results and it is recommended that a discontinuous rock mass approach be used in future analyses.

Introduction

The mineral wealth of Estonia is located in a densely populated and rich farming district. Mining and processing of different resources may sharply disturb the environment, both the lithosphere and hydrosphere. For instance, the underground mining of the Maardu granite deposit may also have significant impact on local and regional groundwater resources as a result of denaturing in the active mining area. This case exemplifies the need for considering cavern stability in the granite formation.

In addition, it would be possible to use the caverns resulting from granite mining as storage or as sites for various technical projects. Using the caverns for the crude oil, petroleum product, chemical and gas storage is safe and does not harm the environment. The caverns are practically invisible; the landscape above remains untouched, and the risk of explosions is minimal.

Another alternate is to use the caverns to store radioactive wastes, and other waste products from Tallinn.

Calculation Method

For a feasibility study, stability problems were investigated. The shape and the dimension criteria were evaluated by numerical modelling. All computer runs reported in this paper were performed using the Fast Lagrangian Analysis of Continua (FLAC). All the calculations were made in the Rock Mechanics Laboratory at the Helsinki University of Technology.

FLAC is a two-dimensional explicit finite difference code that simulates the behaviour of structures built in continuous rock materials [1]. In differential methods, the problem domain is divided into a set of elements (grid) and the solutions' procedure is based on numerical approximations of the governing equations. Using the “Lagrangian” calculation scheme - the grid can deform and move with the material. It is suited to modelling large distortions. The explicit, time-marching solution method enables effective modelling of the continuous rock mass.

Since matrices are never formed, and the memory requirement is minimal, the computational effort per timestep is small. It is possible to follow a physically reasonable path from initial conditions to solution.

Modelling of discontinuities is possible, but the amount of work required for data preparation increases rapidly with the number of intersecting discontinuities. The FLAC is especially suitable in modelling nonlinear, large strain and physically instable continuous system [1].

Geology

The Neeme granite pluton is located in the northern part of Estonia, at the eastern boundary of the city of Tallinn. Field investigations were carried out by means of wide-scale boring program over an area of about 100 km^2. The worked-out Maardu phosphorite open-pit mine, the new transit port at Muuga, and the Iru power station are all located in the vicinity of the pluton. The overburden of the Maardu granite deposit is represented by three layers: fine-grained sandstone, claystone and sandstone (Fig. 1). The surface over the deposit is covered by waste piles from the worked-out phosphorite open-pit mine. On average, the density of the overburden rocks is 2,200 kg/m^3.

There are two water-bearing strata in the overburden. The second water-bearing stratum (II) is the water source for Tallinn. The body of the porphyraceous granite lies at a depth of 160-180 m. The top of the granite body is overlaid by weathered granite having a thickness of 1.2-11.4 m. The fracture system of the granite body is characterised by three types of joints: two sub-vertical (70-80°) and one horizontal. The spacings between adjacent joints are from 3 to 10 m. The surfaces of the joints are slightly rough but are rarely weathered and seldom contain fill materials.

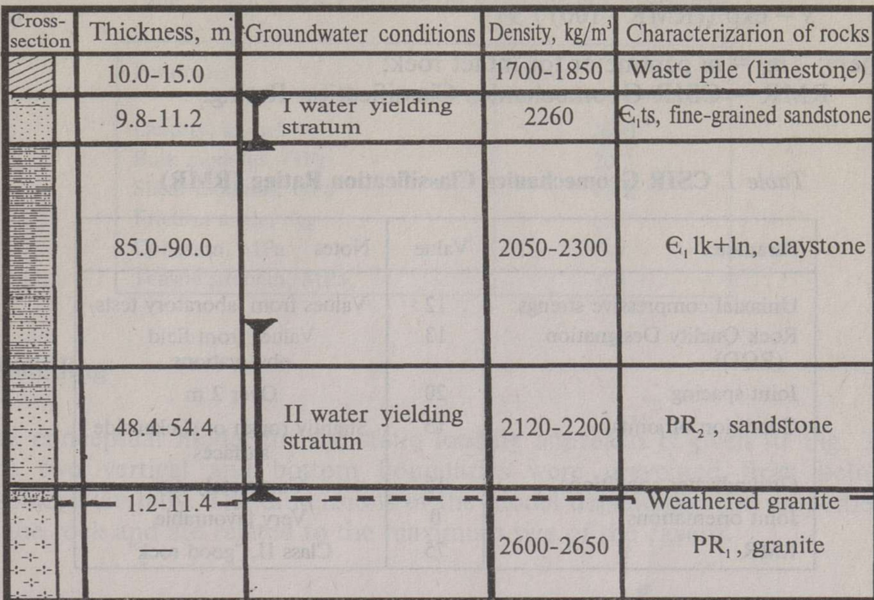

Figure 1. Overburden cross-section of the Maardu granite deposit

Calculation of Parameters

During the early stage of the project, while relatively little field information is available, it is reasonable to estimate the rock mass properties from geological data. The selection of all rock mass properties was based on Bieniawski's rock mass rating (RMR) [2]. By combining the field observations, laboratory tests and RMR-system, a good approximation for rock mass properties can be constructed.

The rock quality at the site was estimated to be class II ("good rock") according to the RMR-system (Table 1).

The in-situ modulus of deformation E is related to Bieniawski's RMR by the following equation [3]:

$$E = 10^{\frac{RMR - 10}{40}} \tag{1}$$

This was applied for calculation of the bulk and shear modulus of rock mass.

In the model, the Mohr-Coulomb failure criterion was used for rock mass. The estimation of the tensile strength, internal friction angle and cohesion was made by the method presented by Hoek [4]. The values of material constants m and s are calculated for undisturbed rock mass as follows [5]:

$$m = m_i \exp((RMR - 100) / 28); \quad (2)$$

$$s = \exp((RMR - 100) / 9) \quad (3)$$

where: m_i = m parameter for intact rock;
RMR = CSIR Geomechanics Classification Rating.

Table 1. **CSIR Geomechanics Classification Rating (RMR)**

Parameter	Value	Notes
Uniaxial compressive strengs	12	Values from laboratory tests
Rock Quality Designation (RQD)	13	Values from field observations
Joint spacing	20	Over 2 m
Condition of joints	15	Slightly rough or slickenside surfaces
Groundwater conditions	15	Completely dry
Joint orientations	0	Very favourable
RMR	75	Class II, "good rock"

The value of the parameter m_i for intact rock was estimated according to the rock type [4].

The uniaxial tensile strength of the rock mass is presented by the following equation [5]:

$$\sigma T = (\sigma c / 2)\,(m - \sqrt{m^2 - 4s}) \quad (4)$$

where: σT = uniaxial tensile strength of the rock mass;
σc = uniaxial compressive strength of the intact rock.
The cohesion c and internal friction angle Φ can be calculated as follows [4]:

$$\sigma n = 2s(\sigma c / 4\sqrt{s} + m);$$

$$\tau = \sigma n \sqrt{1 + m / (2\sqrt{s})};$$

$$\Phi = 90 - \arcsin\,(2\tau / (\sqrt{s}\,\sigma c) \quad (5)$$

$$c = \tau - \sigma n \tan \Phi \quad (6)$$

Here all joints were included in the calculation of the strength and elasticity parameters for the rock mass, and are presented in Table 2.

World-wide experience shows that vertical stresses in an undisturbed rock mass are in fair agreement with the present calculation method, but the horizontal stresses are significantly greater than the vertical ones [6].

Taking this into consideration, it is reasonable for the modelling to use a value of 0.6 to 2.0 for the ratio of the average horizontal stress to vertical stress.

Table 2. **Rock Mass Properties Used for the Modelling**

Parameter	Value
Density, kg/m^3	2600
Bulk modulus, GPa	20.7
Shear modulus, GPa	18.2
Friction angle, deg	65.7
Cohesion, MPa	3.5
Tensile strength, MPa	0.8

Modelling

The conceptual model for the static loading approach is given in Fig. 2. The two vertical and bottom boundaries were prevented from being displaced laterally. The dimensions of the model depend on the properties of the rock and are related to the maximum size of the cavern.

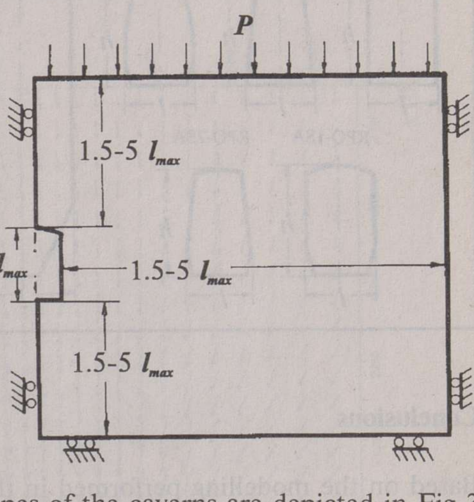

Figure 2. Conceptual model for static loading approach. l_{max} - maximum dimension of the cavern

The vertical, cross-sectional shapes of the caverns are depicted in Fig 3. Cavern shapes RPQ-1C was formed from the actual mining of the granite and the other shapes were for storage or as sites for various technical projects.

Another important task in engineering design is to determine dimensions for the cavern cross-sections. The dimensions must be suited to the mechanics of the bedrock, to the blasting methods, to the excavation equipment used, and to other cost factors. Using world wide experience, the dimensions for cavern RPQ-1C set the height h equal to 150 m, the widths l equal to 60 m, and the angles of the inclined sidewall

A equal to 60°. In the other caverns, the height and width are 30 m and 20 m, respectively.

The calculation sequence is as follows:

Step 1 - establishing equilibrium under in-situ stresses;
Step 2 - modeling excavation of the cavern or caverns;
Step 3 - determining equilibrium stresses under mined-out conditions.

Between calculation steps 1 and 3, all displacements were reset. This does not affect the calculations, but makes it possible to evaluate the incremental deformation response from each step. Since this study focuses on the rock mass and the cavern stability response to the stress and displacement, only results from Step 3 are presented here.

The resulting rock mass responses are presented in terms of induced deformation and stresses. Figures 4 to 9 show the displacement and principal stress vectors in the vicinity of the single and multiple caverns. The vertical axis represents the depth from the surface and horizontal - the width from the axis of symmetry. In this case, the ratio of the average horizontal stress to vertical stress ranges from 0.6 to 2.0. The Figures suggest that all the caverns are stable and the stress-concentrating effect depends upon the values of the in-situ stresses and the number of caverns.

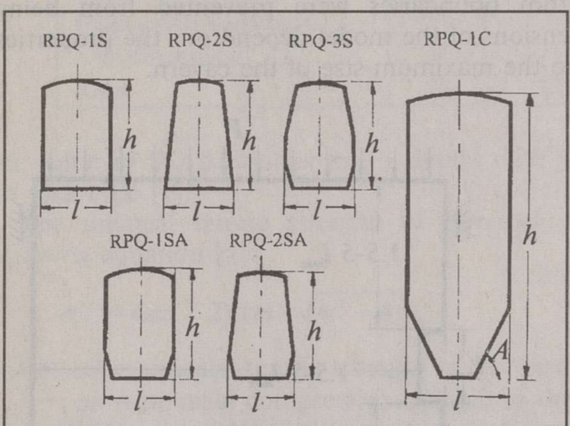

Figure 3. Shapes of the caverns:
l - the width of the cavern;
h - the height of the cavern;
A - the angle of the inclined sidewall

Conclusions

Based on the modelling performed in this study, the following conclusions and recommendations can be made.

1. The preliminary calculations shows that all the caverns are stable and do not impact on local and regional groundwater resources, and the surface landscape remains unchanged.

2. The stress-concentrating effect of the single and multiple excavations dies away fairly rapidly. The ratio of induced- to applied-stress is very close to unity (l=1.0-2.5 l_{max}). The stress-concentrating effect depends on the properties of the rock, in-situ state of stresses and the imparted

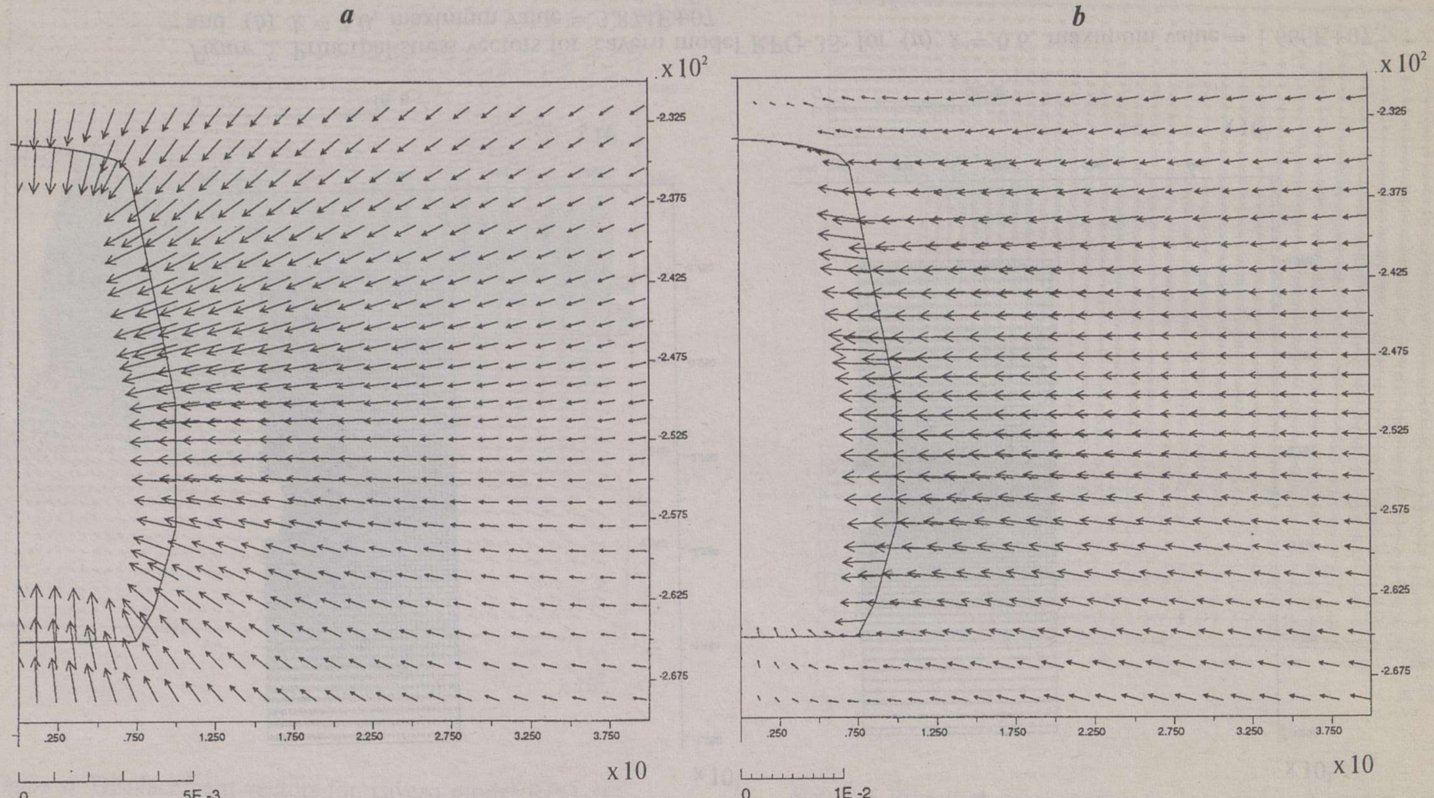

Figure 4. Displacement vectors for cavern model RPQ-3S: for (*a*) the ratio of the average horizontal stress to vertical stress $k = 0.6$, maximum vector = 1.645E-03, and (*b*) k=2.0, maximum vector = 5.654E-03

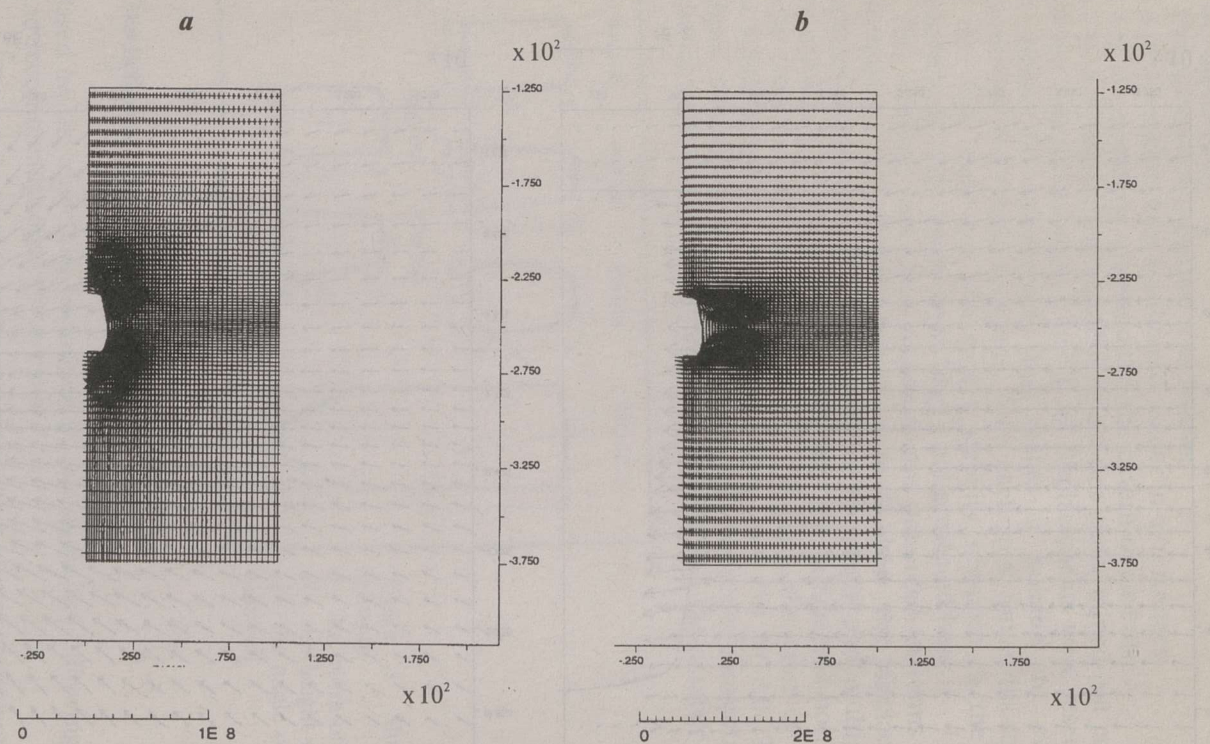

Figure 5. Principal stress vectors for cavern model RPQ-3S: for (*a*) $k = 0.6$, maximum value = 1.666E+07, and (*b*) $k = 2.0$, maximum value = 3.874E+07

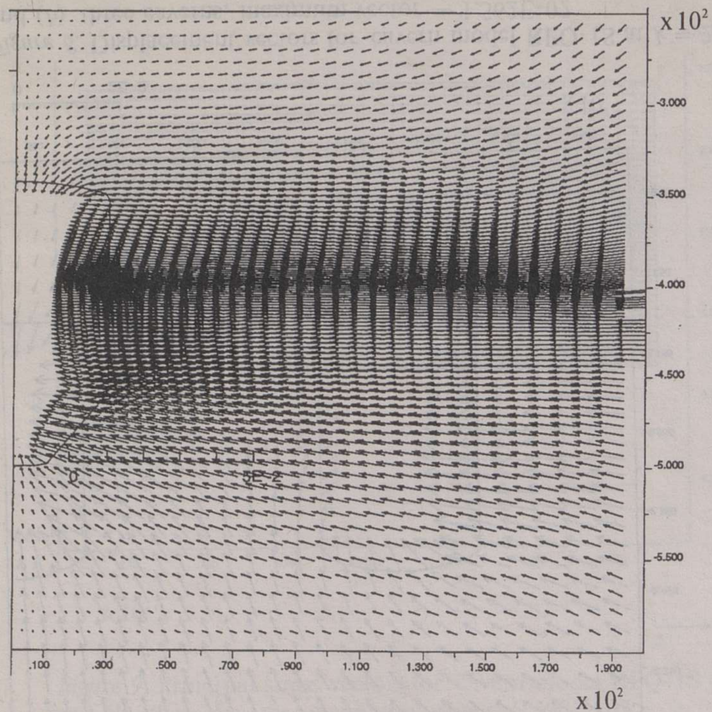

Figure 6. Displacement vectors for cavern model RPQ-1C: $k = 0.6$, maximum vector = 1.537E-02

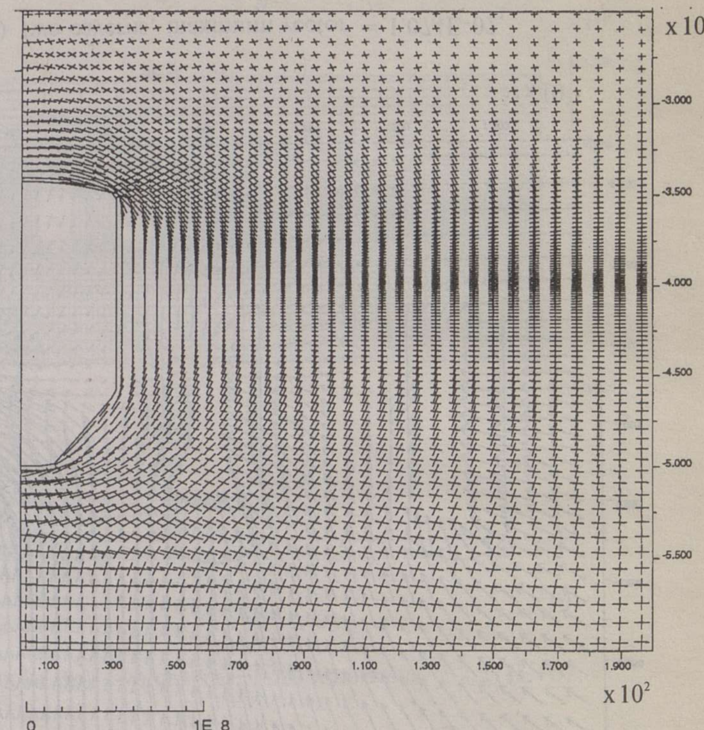

Figure 7. Principal stress vectors for cavern model RPQ-1C; $k = 0.6$, maximum value = 3.131E+07

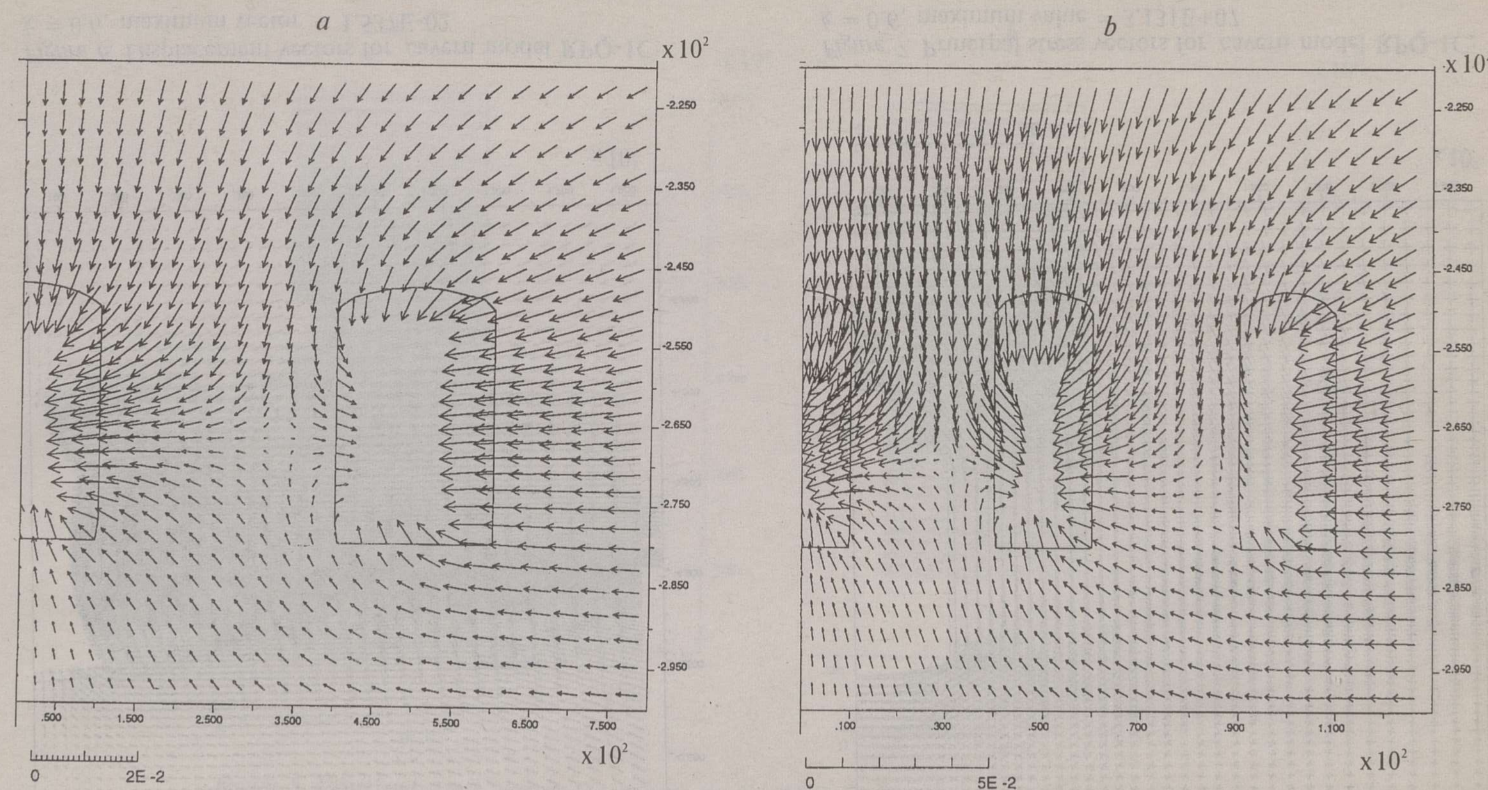

Figure 8. Displacement vectors for cavern model RPQ-1S at $k = 2.0$: for (*a*) two caverns, maximum vector = 1.074E-02, and (*b*) three caverns, maximum vector = 1.562E-02

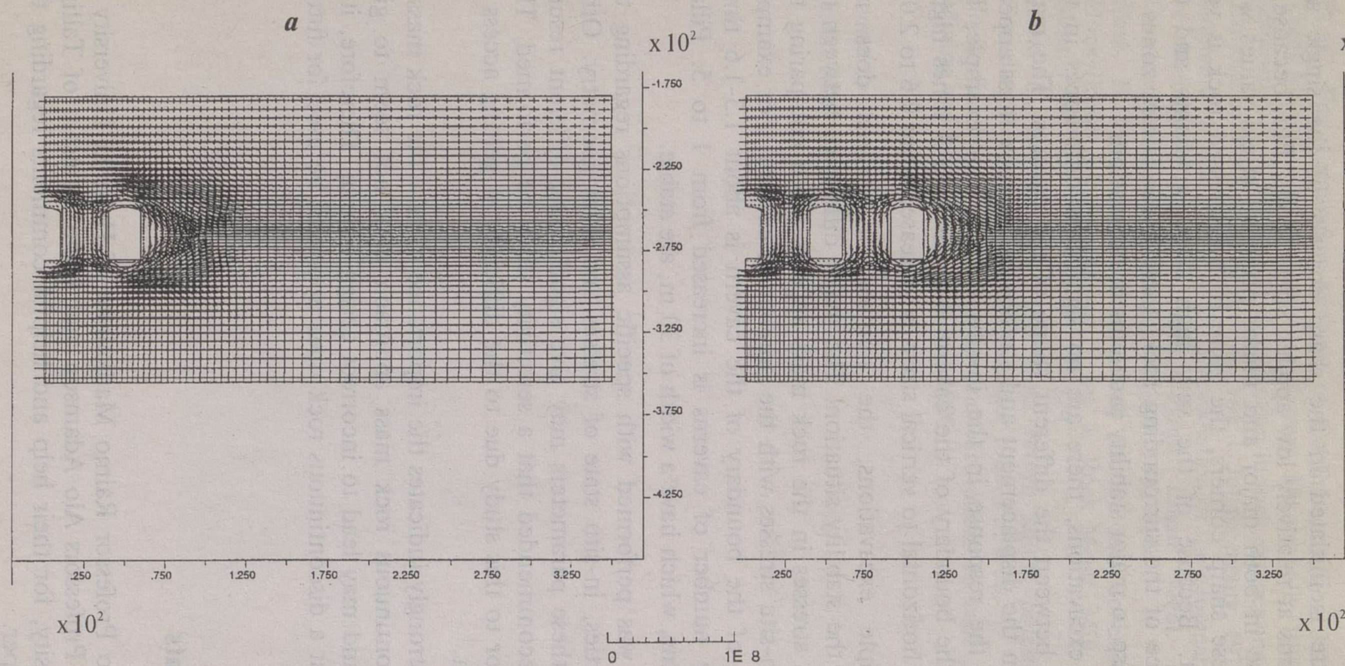

Figure 9. Principal stress vectors for cavern model RPQ-1S at $k = 2.0$: for (*a*) two caverns, maximum value = 2.511E+07, and (*b*) three caverns, maximum value = 2.590E+07

direction. In this case, the minimum size of the model should be 2.0 times the maximum dimension of the excavation in the model.

3. Shear failure is initiated in the sharp corners of the single and multiple excavations at relatively low applied stress levels. But, because of the rapid decrease in both major and minor principal stress values with distance from these sharp corners, the zone of overstressed rock is very limited in extent. Because of the very high stress gradients and the confining influence of the surrounding rock, these shear failure zones do not usually give rise to major stability problems in excavations.

4. For single excavations, there are no significant differences in the stability situation between the different shape of the caverns. The major difference between the displacement and stresses in the rock mass appears when comparing the response in the in-situ stresses. For example, the displacement of the boundary of the cavern is about 2 to 3 times higher when the ratio of horizontal to vertical stress is increased from 0.6 to 2.0.

5. For multiple excavations, the number of caverns does not significantly alter the stability situation. The major difference between the displacement and stresses in the rock mass appears when comparing the response in the in-situ stresses with the number of caverns. For example, the displacement of the boundary of the cavern is about 1.3-1.6 times higher, when the number of caverns is increased from 1 to 5. Pillars between the caverns, which have a width of 30 m, are stable.

6. This study was performed with specific assumptions regarding the rock mass properties, in-situ state of stresses and joint geometry. Other combinations of these parameters may give significantly different results. Therefore, it is recommended that a sensitivity study be performed. This was not done prior to this study due to the difficulty in getting access to the granite deposit.

7. This study strongly indicates the importance of how the rock mass is represented. A continuous rock mass approach does not seem to give adequate results and may lead to incorrect design criteria. Therefore, it is recommended that a discontinuous rock mass approach be used for future analyses.

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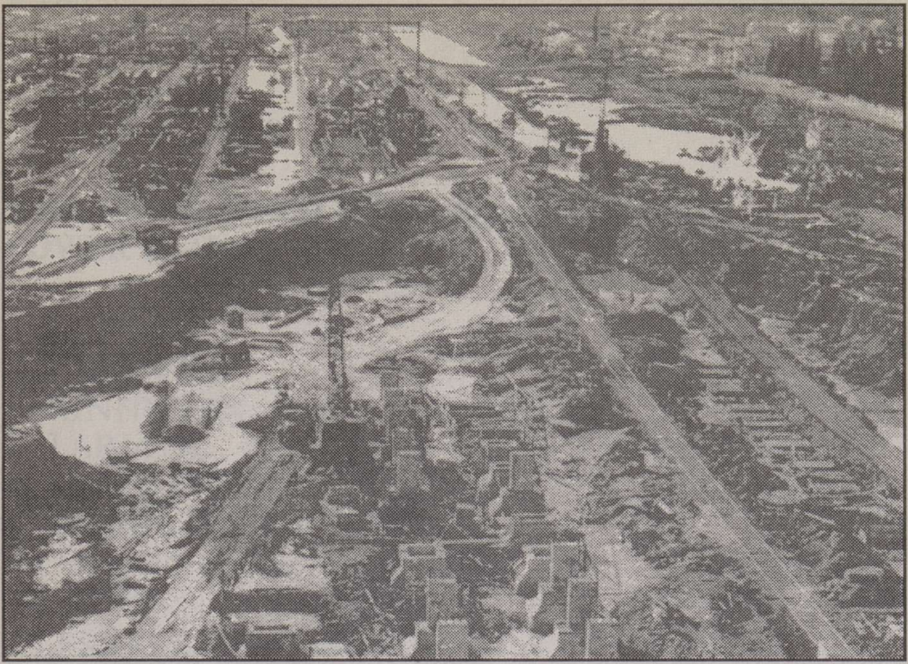

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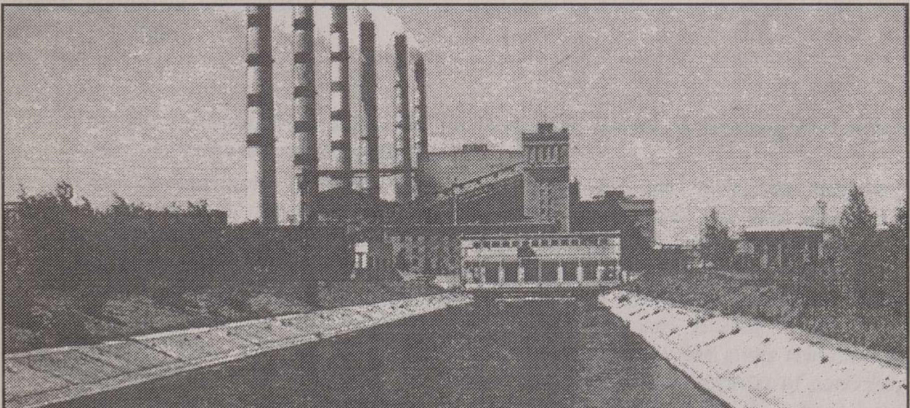

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