Proc. Estonian Acad. Sci. Engin., 1995, 1, 1, 20–31
https://doi.org/10.3176/eng.1995.1.02

PRELIMINARY ANALYSIS OF THE CAVERN STABILITY IN THE MAARDU GRANITE DEPOSIT

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Presented by H. Käär

Received 10 November 1994, accepted 1 June 1995

Abstract. This paper analyses the cavern stability in the granite mass. Also, feasibility of using a cavern fuel storage is discussed. The shape and the dimension criteria were evaluated by numerical modelling, using the two-dimensional distinct element code UDEC. Rock properties were estimated from geological data by Bieniawski's rock mass rating. Though potentially unstable wedges appeared, with the unreinforcement models, cable reinforcement ensured stabilization of the rock wedges.

Key words: rock mass rating, joint stability, reinforcement, cavern, joint system, wedge, grout annulus, cable bolt, scaling factor, *in situ* stress.

1. INTRODUCTION

Located in the northern part of Estonia, the Maardu granite deposit borders the capital city of Tallinn in the east. Close to that location are: a worked-out phosphorite open-pit, a new transit port, and a power station. Because the body of the granite lies at a relatively small depth, the cavern from mining could be used as a storage or as a basis for various technical projects. For instance, it could store crude oil, petroleum products, chemicals and gas, which are safe and environmentally harmless. Alternatively, the cavern could hold radioactive waste and the waste produced in Tallinn. Such use of the cavern would cut granite mining costs.

For the feasibility study, stability problems were investigated. The shape and the dimension criteria were evaluated by numerical modelling. For the evaluation, the two-dimensional Universal Distinct Element Code (UDEC) version 2.00 was used [1]. UDEC is a two-dimensional (2D) explicit distinct element code which simulates the behaviour of the structures built into discontinuous rock materials. This code utilizes an explicit time stepping algorithm which allows large displacement, rotations and non-linear constitutive behaviour for both the rock blocks and the joints.

The calculations for the stability studies were made in the Laboratory of Rock Engineering of the Helsinki University of Technology.

2. GEOLOGY

Commonly, the overburden of the Maardu granite deposit has three layers: fine-grained sandstone, claystone, and sandstone (Fig. 1). The waste pile of the worked-out phosphorite open-pit lies on the surface. The overburden contains two water yielding strata. Stratum II is the water source for Tallinn. The body of the porphyraceous granite is embedded at the depth of 160–180 m. The surface of the granite body is represented by 1.2–11.4 m thick weathered granite. The joint system of the granite body has three sets of joints: two are subvertical (70–80°) and one is horizontal. The angle of the intersection between the two subvertical joints is about 60–85°. Joints spaced at 3 to 10 m have a slightly rough surface, rarely weathered or filled with materials. Sometimes, the fracture zones are found in the granite body.

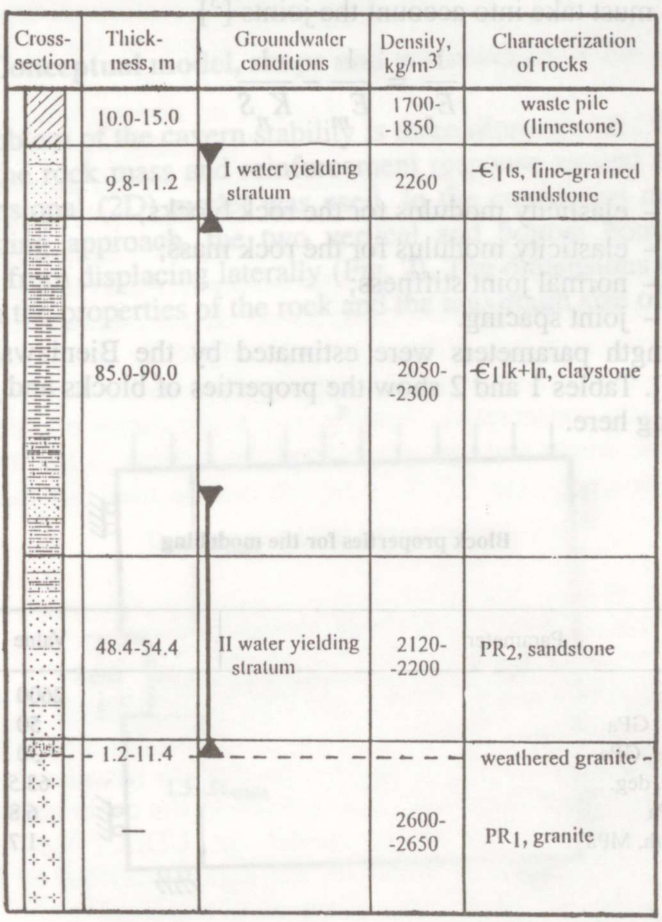


Fig. 1. Cross-section of the overburden of the Maardu granite deposit.

3. MODEL DESCRIPTION

3.1. Model properties

At first, little field information was available to estimate the rock mass properties. For this estimation, geological data were used. The rock mass properties were selected, based on Bieniawski's rock mass rating (RMR) [2]. By combining the field observations, laboratory tests and the RMR-system, a good approximation for rock mass properties was constructed. Rock quality at the site was estimated as class II ("good rock").

The blocks were assumed to behave like an elastoplastic material with a Mohr–Coulomb yield criterion. The behaviour of the joints was assumed to be elastoplastic with a Coulomb slip criterion. The elasticity modulus for the rock mass was calculated by the following formula [3]

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

However, the model is discontinuous, and the elasticity modulus for the rock blocks must take into account the joints [3]

$$\frac{1}{E_r} = \frac{1}{E_m} - \frac{1}{K_n S} \tag{2}$$

where

E_r – elasticity modulus for the rock blocks;
E_m – elasticity modulus for the rock mass;
K_n – normal joint stiffness;
S – joint spacing.

The strength parameters were estimated by the Bieniawski's RMR-system [4, 5]. Tables 1 and 2 show the properties of blocks and joints used for modelling here.

Table 1

Block properties for the modelling

Parameter	Value
Density, kg/m^3	2600
Bulk modulus, GPa	50
Shear modulus, GPa	30
Friction angle, deg.	63.5
Cohesion, MPa	6.8
Tensile strength, MPa	1.7

Table 2

Joint properties for the modelling

Parameter	Value
Normal stiffness, GPa/m	23
Shear stiffness, GPa/m	6
Cohesion, KPa	120
Friction angle, deg.	30
Tensile strength, MPa	0

3.2. *In situ* stresses

The world experience shows that vertical stresses in an undisturbed rock mass are in good agreement with the calculation method, but the horizontal stresses significantly exceed those of the vertical ones [6]. Thus, for this modelling, the ratio of the average horizontal stress to the vertical stress 0.6 and 2.0 was used.

3.3. Conceptual model, shape and orientations of the caverns

The problem of the cavern stability is three-dimensional (3D). With the focus on the rock mass and reinforcement response around the cavern, a two-dimensional (2D) model was used. In the conceptual model for the static loading approach, the two vertical and bottom boundaries were prevented from displacing laterally (Fig. 2). The dimensions of the model depend on the properties of the rock and the maximum size of the cavern.

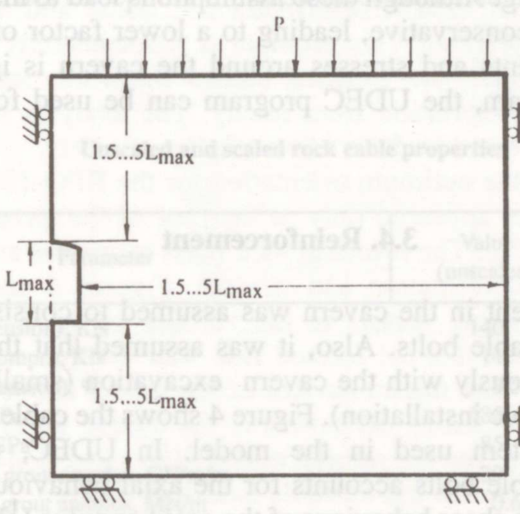


Fig. 2. Conceptual model. L_{max}, maximum dimension of the model.

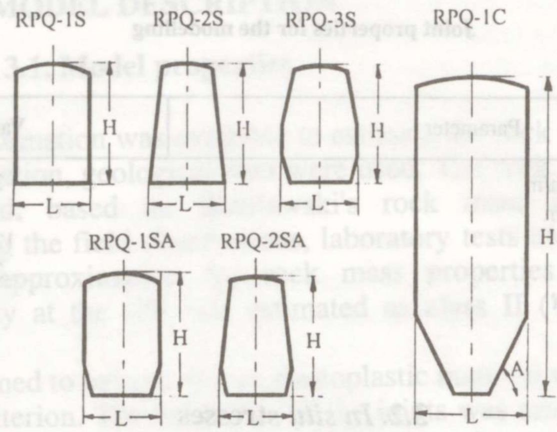


Fig. 3. Cavern shape. L, cavern width; H, cavern height; A, the angle of the inclined side-wall.

Figure 3 illustrates the shape of the caverns, where the vertical axis is the only axis of symmetry, which will enable us to simplify modelling. Our analysis of the cavern stability in the rock mass showed that at the sharp corners of the excavations, the concentrating effect of the stress did not cause a major stability problem [6]. For this reason, the RPQ-1SA and RPQ-2SA caverns are not treated in this study.

The optimum orientation and the shape of an underground excavation in a jointed rock gave the smallest volume of potentially unstable wedges. It may be necessary to analyse potential failures for a range of possible excavation orientation by the program UNWEDGE [7]. UNWEDGE is a tool for analysing the geometry and the stability of underground wedges defined by intersecting structural discontinuities in the rock mass surrounding an underground excavation. It is assumed that the discontinuity surfaces are plane and the wedges are subjected only to gravitational loading. Although these assumptions lead to inaccuracies, the error is generally conservative, leading to a lower factor of safety. If the property of the joints and stresses around the cavern is ignored by the UNWEDGE program, the UDEC program can be used for the stability analysis.

3.4. Reinforcement

The reinforcement in the cavern was assumed to consist of 5 m long 15 mm diameter cable bolts. Also, it was assumed that the cables were installed simultaneously with the cavern excavation (small deformations occurred before cable installation). Figure 4 shows the cable bolt geometry and the joint system used in the model. In UDEC, the numerical formulation for cable bolts accounts for the axial behaviour of the cable material and for the shear behaviour of the grout annulus [1].

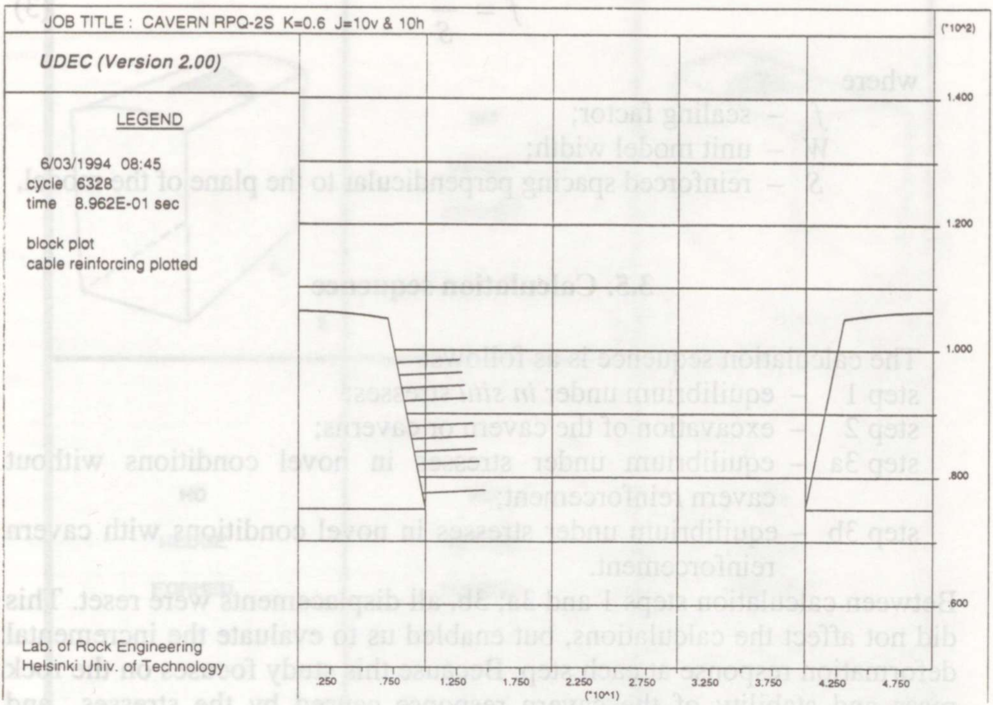


Fig. 4. Cable bolt geometry and joint pattern.

Reduction of 3D problems with regularly spaced reinforcement to 2D problems involves averaging the reinforcement effects in three dimensions over a distance between the cables. The linear scaling of material properties is a simple and convenient way of distributing the discrete effect of reinforcement over the distance between the cables in a regularly spaced pattern [8] (Table 3). Here, a scaling factor is used to scale all material properties except the dimensionless parameter.

Table 3

Unscaled and scaled rock cable properties

Parameter	Value (unscaled)	Value (scaled)
Yield capacity (tension), KN	140	70
Yield capacity (compr.), KN	14	7
Strain capacity (tension), %	3.5	3.5
Bulk modulus, GPa	180	90
Shear modulus, GPa	85	42.5
Bond stiffness of grout annulus, GN/m/m	39	19.5
Bond strength of grout annulus, MN/m	0.6	0.3

$$f = \frac{W}{S} \quad (3)$$

where

f – scaling factor;
W – unit model width;
S – reinforced spacing perpendicular to the plane of the model.

3.5. Calculation sequence

The calculation sequence is as follows:

step 1 – equilibrium under *in situ* stresses;
step 2 – excavation of the cavern or caverns;
step 3a – equilibrium under stresses in novel conditions without cavern reinforcement;
step 3b – equilibrium under stresses in novel conditions with cavern reinforcement.

Between calculation steps 1 and 3a; 3b, all displacements were reset. This did not affect the calculations, but enabled us to evaluate the incremental deformation response at each step. Because this study focuses on the rock mass and stability of the cavern response caused by the stresses and displacement, only results of step 3a and 3b are presented here.

4. RESULTS

Because of difficult access to the granite deposit, the rock properties were estimated from geological data, and the *in situ* stresses were determined theoretically, using the world experience. These preliminary data may lead to an error in the stability calculations and have to be further elaborated. The joint system determines the shape and volume of the blocks in the granite mass. This problem is fundamentally 3D in nature, but with a 2D model, the inclined blocks transform into a rectangle (Fig. 4), which is a deviation from reality. The analysis shows that the error is conservative and leads to a lower factor of safety.

Figure 5 shows the optimum orientation for the RPQ-1S cavern. Here, the unstable wedges appeared only in the roof of the cavern and all the side-walls were stable. The resulting rock mass responses are presented in terms of induced deformation and stresses. Figures 6 and 7 show the displacement and stress vectors in the vicinity of the RPQ-2S cavern. These figures suggest that the formed side-wall wedges are unstable and destressed (Fig. 7). The minimum size of the model should be 2.0 times the maximum dimension of the cavern in the model. Figure 8 shows the displacement vectors for the reinforcement. The modelled reinforcement was sufficient to stabilize the unstable side-wall wedges. Figures 9*A* and 9*B* demonstrate that very small cable forces and strains appeared.

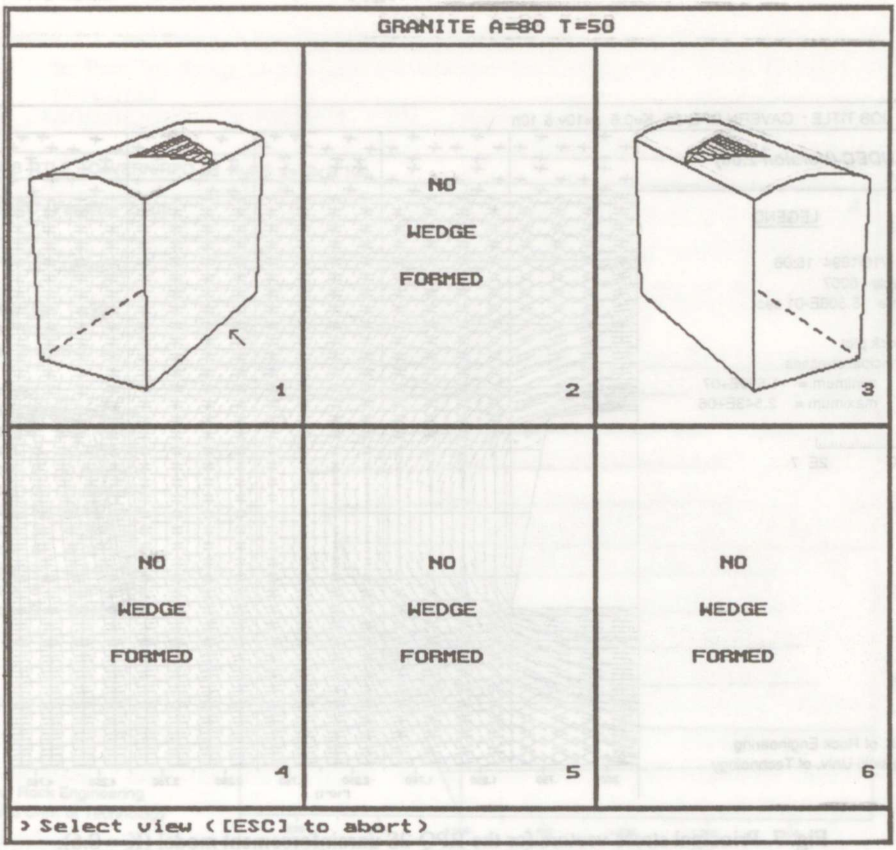


Fig. 5. Optimum orientation for the RPQ-1S cavern in the granite mass.

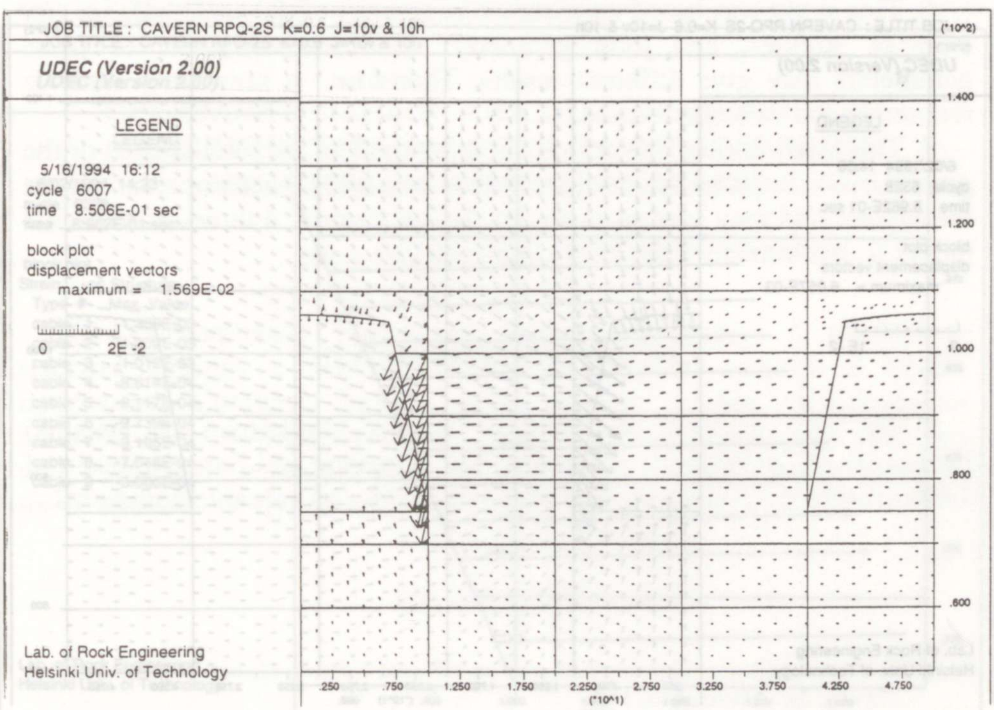


Fig. 6. Displacement vectors for the RPQ-2S unreinforcement model (the ratio of the average horizontal stress to vertical stress K = 0.6).

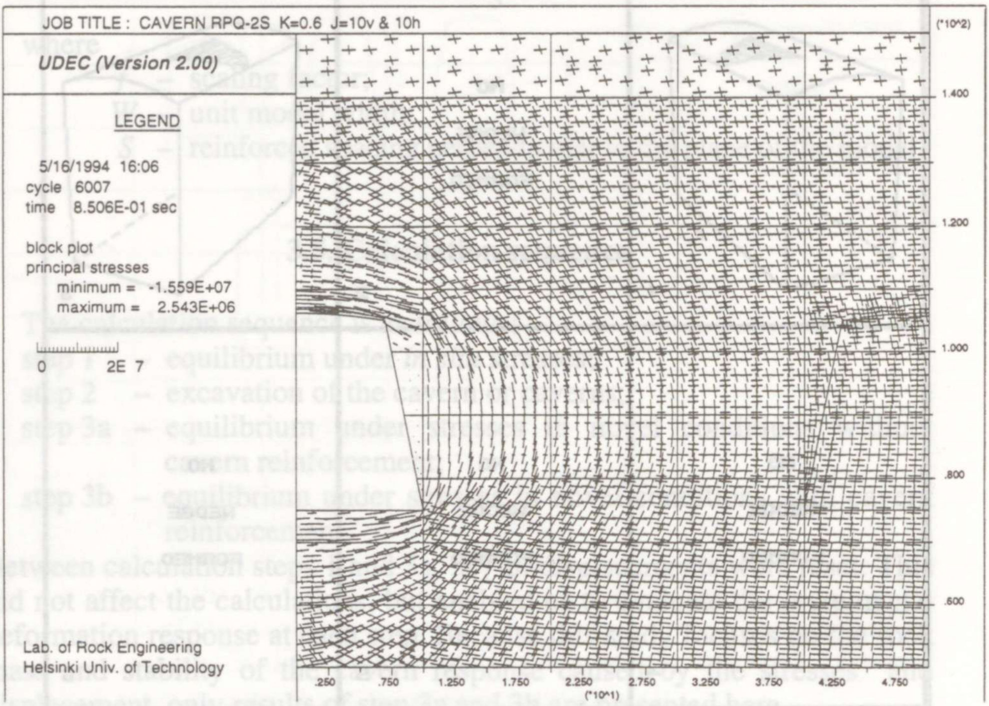


Fig. 7. Principal stress vectors for the RPQ-2S unreinforcement model (K = 0.6).

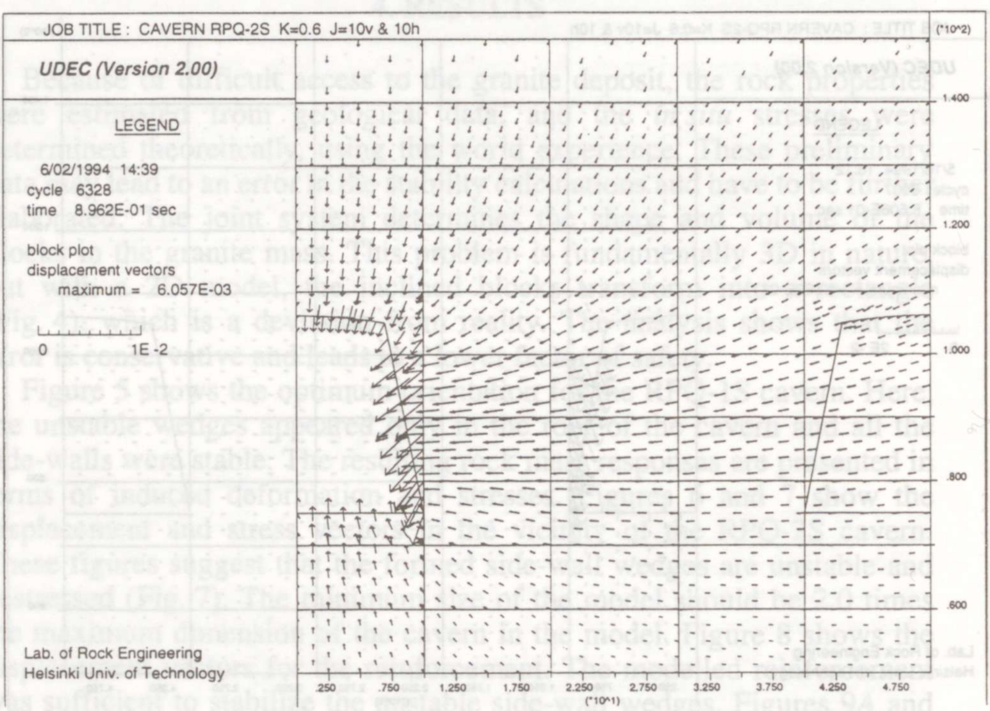
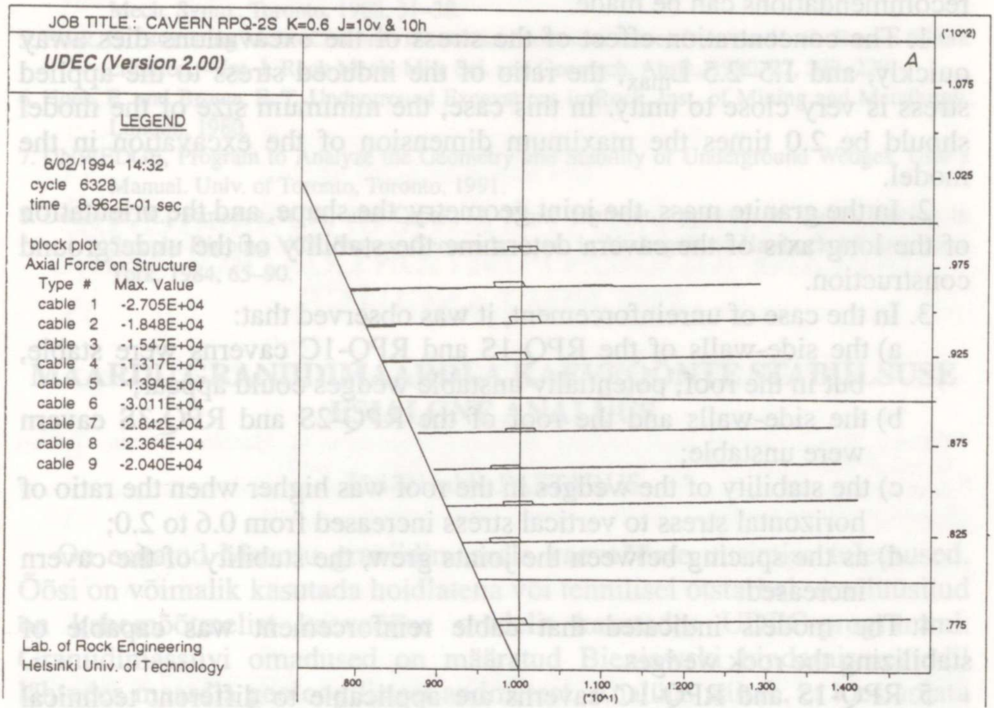


Fig. 8. Displacement vectors for the RPQ-2S reinforcement model (K = 0.6).



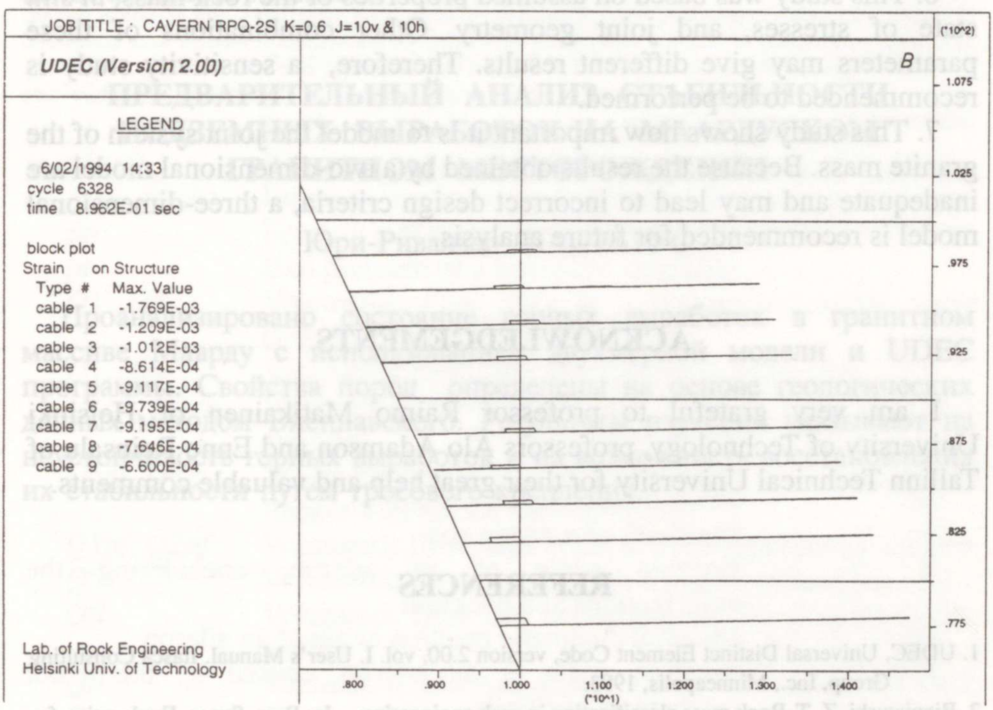


Fig. 9. Cable forces (*A*) and strains (*B*) for the RPQ-2S model.

5. CONCLUSIONS

As a result of this study, the following conclusions and recommendations can be made.

1. The concentration effect of the stress of the excavations dies away quickly, and 1.5–2.5 L_{max}, the ratio of the induced stress to the applied stress is very close to unity. In this case, the minimum size of the model should be 2.0 times the maximum dimension of the excavation in the model.

2. In the granite mass, the joint geometry, the shape, and the orientation of the long axis of the cavern determine the stability of the underground construction.

3. In the case of unreinforcement, it was observed that:
   a) the side-walls of the RPQ-1S and RPQ-1C caverns were stable, but in the roof, potentially unstable wedges could appear;
   b) the side-walls and the roof of the RPQ-2S and RPQ-3S cavern were unstable;
   c) the stability of the wedges in the roof was higher when the ratio of horizontal stress to vertical stress increased from 0.6 to 2.0;
   d) as the spacing between the joints grew, the stability of the cavern increased.

4. The models indicated that cable reinforcement was capable of stabilizing the rock wedges.

5. RPQ-1S and RPQ-1C caverns are applicable to different technical projects when the amount of reinforcement is minimum.

6. This study was based on assumed properties of the rock mass, *in situ* state of stresses, and joint geometry. Other combinations of these parameters may give different results. Therefore, a sensitivity study is recommended to be performed.

7. This study shows how important it is to model the joint system of the granite mass. Because the results obtained by a two-dimensional model are inadequate and may lead to incorrect design criteria, a three-dimensional model is recommended for future analysis.

ACKNOWLEDGEMENTS

I am very grateful to professor Raimo Matikainen of Helsinki University of Technology, professors Alo Adamson and Enno Reinsalu of Tallinn Technical University for their great help and valuable comments.

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MAARDU GRANIIDIMAARDLA KAEVEÕÕNTE STABIILSUSE ESIALGNE ANALÜÜS

Jüri-Rivaldo PASTARUS

On esitatud Maardu graniidimaardla kaeveõõnte uurimise tulemused. Õõsi on võimalik kasutada hoidlatena või tehnilisel otstarbel. Analüüsitud on kahemõõtmelist kaeveõõne mudelit kasutades UDEC-programmi. Graniidimassiivi omadused on määratud Bieniawski hindamismeetodil lähtudes maardla geoloogilistest andmetest. Analüüs näitab, et toestamata kaeveõõntes võivad tekkida varingud, kuid trosstoestiku kasutamine tagab nende küllaldase stabiilsuse.

ПРЕДВАРИТЕЛЬНЫЙ АНАЛИЗ СТАБИЛЬНОСТИ ПОДЗЕМНЫХ ВЫРАБОТОК НА МААРДУСКОМ ГРАНИТНОМ МЕСТОРОЖДЕНИИ

Юри-Ривальдо ПАСТАРУС

Проанализировано состояние горных выработок в гранитном массиве Маарду с использованием двухмерной модели и UDEC программы. Свойства пород определены на основе геологических данных методом Биениавского. Результаты изучения указывают на неустойчивость горных выработок и на возможность восстановления их стабильности путем тросового крепления.