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SAFETY EXCAVATION IN SALT ROCK USED FOR UNDERGROUND STORAGE IN ROMANIA

Susana Arad & Victor Arad
Professor at University of Petrosani,
332006 Petrosani, Universitatii str. 20, Romania
arad@dec.com.ro; varad@upet.ro

Joel Veres & Olimpiu Stoicuta
Assoc. Professor at University of Petrosani
Lecturer at University of Petrosani
veresioel@yahoo.com

ABSTRACT

The use of underground excavation in salt-rock formations for waste storage imposes the precise analysis of properties of salt rock and a stress analysis. One of the main mechanisms responsible for a degradation of isolation ability of the rock salt is the generation and development of cracks under influence of mining processes. Various aspects of cracking in salt rocks are studied – both in situ and in laboratory tests – for rocks of the Targu Ocna Salt Mine. The aim of this paper is to describe the time behavior of rock-salt around underground mining excavations and in situ stress monitoring system of rock mass was proposed.

KEYWORDS

Salt, underground excavation, stress, numerical analyze

1. GENERAL ASPECTS

Romania is rich in natural deposits of salt, some of them forming massive salt domes which appear as a result of pressure, which pushes the salt up through the rocks from great depths. Such domes, mainly encountered in the sub-Carpathian region have been worked since ancient times and now host a multitude of active as well as in conservation salt mines, the last one representing the ideal location for underground storage.

A lot of cavities and underground excavations were obtained from salt mining. Underground storage is a safety way to store large quantities of wastes or food. National research facilities are also being developed in rock caverns and tunnels for major particle physics experiments or underground laboratory.

Stress analysis plays an important role in design of many different mechanical and electrical components. Generally the quantities of interest in stress analysis are displacements, strains and different components of stresses.

The task of determining rock mass properties is not usually an end in itself. It is carried out in order to provide input for numerical analysis programs, which require material properties in order to perform a stability or stress analysis. With regard to the behavior of a salt cavern on experimental tests and numerical modeling of the salt rock massif for using of caves as underground storage has been done.

2. MATHEMATICAL MODELING. FUNDAMENTALS

One of the most important investigation methods of the geo-mechanical phenomenon around the underground mining excavation is the mathematical modeling method. It allows the correlation of theoretical models with both the laboratory data and the field measurements.

Generally, in the mathematical models based on the constitutive equations used today one is making several simplifying assumptions which could yield to some discrepancies when the results are compared with the measurements "in situ". Thus, mathematical models, which would describe more accurately the mechanical properties exhibited by rock-salt are needed.

The displacement field is assumed to be completely defined by the two components of the displacement vector δ in each point for plane problems. Only three components of strain and stress tensors are independent in both plane stress and plane strain cases. The strain-displacement relationship is defined as:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial \delta_x}{\partial x} \\ \dfrac{\partial \delta_y}{\partial y} \\ \dfrac{\partial \delta_x}{\partial x} + \dfrac{\partial \delta_y}{\partial y} \end{Bmatrix} \qquad (1)$$

The corresponding stress components:

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \qquad (2)$$

The equilibrium equations for the plane problems are:

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{xy}}{\partial y} = -f_x \\ \dfrac{\partial \tau_{xy}}{\partial x} + \dfrac{\partial \sigma_y}{\partial y} = -f_y \end{cases} \qquad (3)$$

For linear elasticity, the stresses are related to the strains using relationship of the form $\{\sigma\} = [D](\{\varepsilon\}-\{\varepsilon_0\})$, where D is a matrix of elastic constants, and ε_0 is the initial thermal strain. The specific form of the matrix depends on a particular problem formulation.

For plane stress and isotropic material the matrix D is defined:

$$[D] = \frac{E}{1+\nu} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \dfrac{1+\nu}{2} \end{bmatrix} \qquad (4)$$

In all these equations E denotes Young's modulus of the isotropic material and ν is a Poisson's ratio for isotropic material; G_{xy} and G_{zr} are the shear moduli.

In order to describe the slow deforming in time rock salt, taking into account the volumetric dilatancy and/or compressibility, it’s mechanical properties will be modelled using an elasto-viscoplastic constitutive equation [1].

Based on the experimental data, let us formulate some constitutive assumptions [2].

- The rock salt is homogeneus and isotropic;
- The strain rates are additive:

$$\dot{\varepsilon} = \dot{\varepsilon}^E + \dot{\varepsilon}^I \qquad (5)$$

where ε is the deformation tensor, ε^E is the elastic component of the deformation tensor, ε^I is the ireversible component of the deformation tensor, σ is the stress tensor.

The development of the rock salt damage through microcracks or fractures, is judged by separate criteria for shear and tensile fracture and by the dilation criterion:

- Shear stress criterion for compression [3]:

$$t_f \geq b|s_m|^p$$

where t_f is the predicted shear stress at failure, s_m the mean stress and b, p are fitting parameters. A safety factor is defined as: FS = toct / tf with toct the actual octahedral shear stress. Under compression loads, failure will occur if FS > 1.

Tension-induced failure is assumed if the maximum principal stress exceeds a tension limit of 1 MPa.

- Compression-dilation boundary [4]:

$$t_{oct} \geq f_1\sigma_m^2 + f_2\sigma_m = 0$$

where f_1 and f_2 are fitting parameters.

Salt is a viscoplastic substance and slow creep tends to dissipate shear stresses over times of several hundred years, hence the initial and final stress states in salt are isotropic ($\sigma_V = \sigma_H$ min = σ_H max; where σ_V and σ_H are the vertical and horizontal stresses, respectively) [5]. Steady-state salt creep is assumed to be a power function of the shear stress σ of the form [6]:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(\frac{\sigma}{\sigma_0} \right)^n \quad (6)$$

where $\sigma = \sigma_V - \sigma_H$ is the shear stress, σ_0 is a reference stress, $\dot{\varepsilon}$ the shear strain rate, and $\dot{\varepsilon}_0$ is the shear strain rate at σ_0.

3. NUMERICAL STRESS ANALYSIS

One of the major obstacles which is encountered in the field of numerical modeling for rock mechanics, is the problem of data input for rock mass properties. The usefulness of elaborate constitutive models, and powerful numerical analysis programs, is greatly limited, if the analyst does not have reliable input data for rock mass properties.

In order to simulate the behaviour of the salt rock-mass from Targu Ocna Salt Mine, besides the direct laboratory testing methods, we used the rock mass strength analysis based on the Hoek-Brown failure criterion with RocLab program, Figure 1.

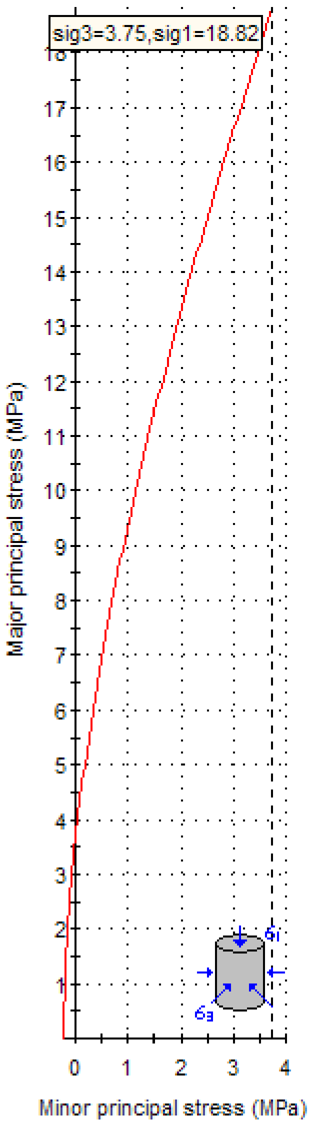

Figure 1 Analysis of Rock Strength from Targu Ocna Salt Mine

The engineering practice allows us to choose a GSI (Geological Strength Index) taking into account the geological structure, GSI = 77. That means a well interlocked undisturbed rock mass consisting of cubical block formed by tree intersecting discontinuity sets. The RQD coefficient value, similarly to GSI, is 78 to 85 for the Targu Ocna Salt Mine, indicating a good quality and the fact that the excavation is stabile for this case study [6]. The values for major principal stress and minor principal stress (σ_1 = 18.82, σ_3= 3.75), the parameters of Hoek Brown Criterion, the Mohr-Coulomb Fit and the rock mass parameters are automate obtained and analysis of rock strength was done.

Knowing the geo-morphological characteristics of the salt rocks at Targu Ocna, the values of the constant *m*i into the range (10 ± 2), according to the recommendations from literature was chose. The salt in the deposit of Targu Ocna, Salt Mine, was analyzed from the point of view of the geo-mechanical characteristics and it can be said that it has a viscoplastic behavior, with a slow creep. So, it suffers important deformation before breaking.

The rock mass strength based on Hoek-Brown criterion was obtained also in stress analysis in a geotechnical context with Examine2D program used. We examined the Strength Factor SF in each case when applied a gravitational in-situ field stress and a constant one using Examine2D program and in the first case good results there were obtained, shown in Figure 2. The SF represents the ratio of material strength to induced stress, at a given point. The SF obtained is greater than 1, this indicates that the material strength is greater than the induced stress and the underground excavation is safety. The model represents a vertical cross-section in the room of salt mining methods.

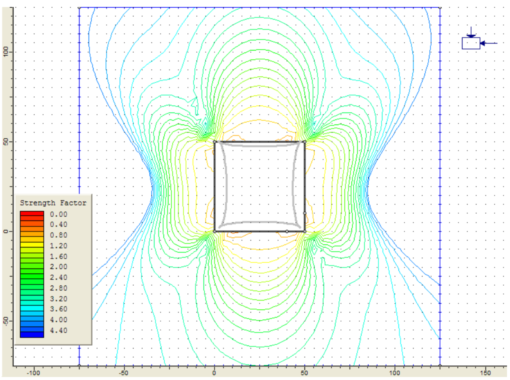

Figure 2 Strength Factor in gravitational field

A two-dimensional finite element model was also described in stress analysis, assuming plane strain conditions. Aiming to perform a quantitative stress analyse over the above studied application, we set up a very simple excavation model with specific geometrical data from Targu Ocna Salt Mine and the material properties determined by experimental tests. Within QuickField software we obtained the stress analysis by stress field simulation, in assumtion the plane stress with isotropic materials. The plane stress model is suitable for analyzing structures that are thin in the out-of-plane direction, e.g., thin plates subject to in-plate loading. Out-of-plane direct stress and shear stresses are assumed to be negligible. The plane strain model is formulated by assuming that out-of-plane strains are negligible. This model is suitable for structures that are thick in the out-of-plane direction.

The rooms and pillars exploitation method is applied at Targu Ocna Mine, at a depth towards the surface between 80-280 m. The rooms have 12-16 m width and 8 m height, the pillars have between 15 and 18 m and 8 m height. The thickness of the roof is of 75 meters.

We select the geometry class of our model. Our excavation geometric model is in plane – parallel model class, with formulation of the plane stress.

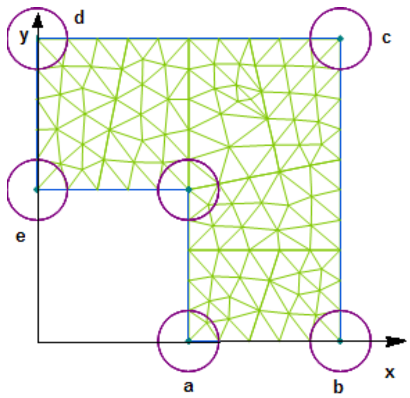

Figure 3 Geometric model of excavation with the mesh

The model represents a vertical cross-section at the mid-plane. The plane of analysing for cavern is in the xoy plane, where we have geometric model like in the Figure 3, with the dimensions x = 12 m, y = 10 m and z = 200 meters lenght.

We assumed for stress analysis: the isotropic material properties and the loading sources are body forces f_x= f_y.= 19500 N/m^3.

The boundary conditions are defined through displacements prescribed. We prescribed that in x direction there is no horizontal displacement (ab) and also is no vertical displacemenet in y direction., Figure 3.

After postprocessing the obtained results are displacements, stress components, principal stresses, von Mises stress, Tresca, Mohr-Coulomb and Drucker-Prager criteria. The numerical results from the finite element analysis by QuickField software are shown through the maximum and the minimum value of displacement, principal strain and Mohr stress, shown in Table 1.

Table 1 Results of stress analysis

Parametres	*Minimum value*	*Maximum value*
Displacement [mm]	0.103	0.153
Principal Strain [%]x10^{-3}	0.004	0.448
Mohr Strees [MPa]	0.135	11.6

Stress on failure criteria has the maximum values on the corner in the top of excavation and the stress tensor with deformed boundary and desplacement vectors are presented in Figure 4. The results of the simulation show that there is tendency of pushing the resistance pillar and also of the ceiling inflation, which means the superior room floor.

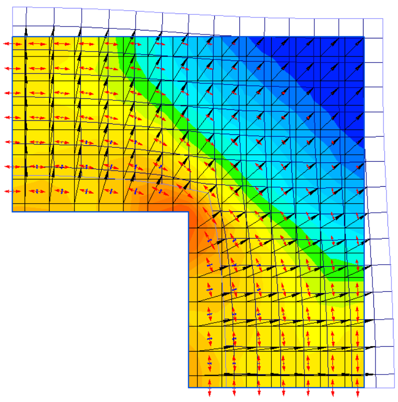

Figure 4 Mohr stress with deformed boundary and desplacement vectors

4. MAIN RESULTS AND DISCUSSION

For the long-term performance of such underground repositories in rock salt the evolution of the Excavation Disturbed Zone and of the geo-mechanical properties in this zone represent an important issue with respect to the integrity of the geological and technical aspects.

The geo-mechanical and rheological characteristics of salt rocks were assessed through laboratory test in Rock Mechanical Lab from University of Petrosani and the average results it shown in Table 2 and Table 3.

Table 2 Elastic and rheological parameters of salt rock from Targu Ocna

Parameter	*UM*	*Average*
Young's Modulus, Em	[MPa]	21.34
Poisson's ratio μ	–	0,290
Elasticity limit, σ_e	[MPa]	3.29
Strain at failure for compression stress, ε_{rc}	[%]	7.05
Strain at failure for weigh down, $\varepsilon_{rî}$	[%]	5.89
Strain at failure on tensile strength, ε_{rt}	[%]	6.57
Rheological elasticity modulus, E_∞	[MPa]	408.5

This parameter indicates the minimal value of stress at which the first cracks appears in the rock salt massif (pillars, floors) and when disturbed mass appears.

Table 3 Mechaanical and phisical charactersistics of rock

Parameter	*UM*	*Average*
Uniaxial compressive strength, σ_{rc}	[MPa]	24.25
Tensile strength, σ_{rt}	[MPa]	1.33
Cohesion, C	[MPa]	2.83
Friction Angle, Φ	[º]	63.77
Bulk gravity $\gamma_a.10^4$	N/m^3	1.947
Porosity n	%	7.21
Humidity W	%	2.70

It is well known that rock salt is a rock type that has typical behaviour of rheology, i.e., the deformation is connected with time. the creep characteristics are emphasising that the salt from targu ocna, salt mine alters his resistance characteristics in time.

5. MONITORING SYSTEM

The stability of underground excavations has to be monitored through the surface subsidence measurement, rock convercence of the excavation. The monitoring system of automated data acquisition was completed by analog and digital devices for in situ measurements, electronic interface, comunication system (RS232 or RS485), data base for storage and internet transmision on PC server. We have to do the monitoring of rock displacement in points where there is maximum stress and also the monitoring of vibration, humidity, and temperature in the rock mass. A geographic information system (GIS) is employed to acquire and analyze spatial data and generate the optimum earthmoving plan using the mass haul diagram. The model automatically generates digital terrain models. It accepts several input formats and provides graphical and tabular reports.

Traditional investigations (partly with specially designed equipment) are accomplished by the testing methods of rock failure for determination of critical values of stress intensity factors.

Computerized monitoring system has been designed for stability assessment of excavation and it must be implemented at Targu Ocna salt mine to perform the following functions:

- data acquisition from analogue and digital devices (displacements, load, temperature, humidity, etc) in some points on the contour of excavation and rock mass;
- measuring of surface subsidence;
- storage of data in Data Base;
- analysis of rock strength, stress and Strength Factor;
- Communication with local office room, PS server via display, network, radio and cable (RS232 or RS485).

The model is implemented in prototype software that operates in Microsoft Windows environment.

6. CONCLUSIONS

In this paper the numerical modelling was developed and the evolution of the excavation disturbed zone in the near field of the excavation or cavities has been investigated. The scope of this analysis is the simulation of the excavation disturbed zone under different conditions experiment in the Targu Ocna Mine, and around an emplacement drift in a planned repository.

It has been investigated for a long period the behavior of a salt cavern and underground excavation from Targu Ocna salt mines for environmental protection, on one hand, and to several new projects in which caverns are used for disposal of industrial wastes, or carbon dioxide on the other hand.

The salt in the deposit of Targu Ocna, Salt Mine, was analyzed from the point of view of the geo-mechanical characteristics and it can be said that it has a viscoplastic behavior, with a slow creep, so, it suffers important deformation before breaking.

The Strength Factor for the excavation analysed was determined and indicates that the material strength is greater than the induced stress and the underground excavation is safety in present conditions.

Tensile stress appeared in the cavity top is the main reason of making the cavities' failure and collapse. The thickness of the "floor", or the vertical distance between the cavity top and the overlying rock (mud-conglomerate), and the cavity diameter are the main factors of influencing the tensile stress values. With the decrease of the "floor" thickness and increase of the diameter, the values of tensile stresses increase rapidly.

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