Türkiye 14 Madencilik Kongresi / *14th Mining Congress of Turkey,* 1995 , ISBN 975-395-150-7

ESTIMATION OF CAVERN STABILITY IN ROCK SALT

A Komornik
Harry W. Labov and Charlotte Ullman Labov Chair of Geotechnics in Civil Engineering, Technion, Israel Institute of Technology, Haifa, Israel

F. Kirzhner
Department of Geotechnics and Mineral Engineering, Technion, Israel Institute of Technology, Haifa, Israel

ABSTRACT: Cavern stability analysis was carried out, using the FLAC model - a two-dimensional explicit finite-difference code. For the case with unlimited thickness (for example: Dead Sea rock salt group - Sdom Formation) a cylindrical cavem geometry was analyzed. The creep deformation of the rock salt can be approximated by a steady-state model The behavior of rock salt was analyzed by a power law equation. Data for prediction of rock salt fracture in a creep model were obtained

1. INTRODUCTION

Domal and bedded salt has been used for hydrocarbon fuel storage throughout the world for many years, due to its availability and its physical properties. Over the last two decades increasing attention has also focused on utilization of salt caverns for electrical power generation facilities.

Salt caverns have proved highly suitable for compressed-air energy storage for several reasons

- Due to the solution-mining procedure, buildings costs are low.
- Due to the good thermal conductivity of the salt, only slight temperature peaks occur in cases of extreme air rates,- thus having, inter alia, a positive effect on the storage capacity and filling/withdrawal time.
- The salt content in the emergent air is negligible
- The caverns have proved stable, permitting excavation of large cavities without the need of linings
- Because of its very low porosity, rock salt is practically impermeable to gases and liquids over long periods.
- The salt is fairly easily mined and has a very low water content.

It is known that design of underground spaces involves two main questions:

- stability of the host rock surrounding the underground opening;
- prediction of expected rock deformations.

The mechanical behavior of rock salt has been considered by many researchers, and described in numerous practical and scientific publications (Baar, 1977, Dreyer, 1972, Hofer and Thoma, 1968, Le Comte, 1965; Serata, 1960,1964,1974; and more recently by Handin et al., 1986; Hambley et al., 1988) Senseny et al., 1992 described a new approach to the mechanical behavior of rock salt They described the rock salt as a material comprising of four properties, thermal, elastic, viscoplastic and brittle The first- two are well characterized by classical mathematical models with temperature-dependent elastic constants and coefficient of linear thermal expansion The viscoplastic and brittle properties, which produce inelastic, non-recoverable deformation, cannot be characterized by simple models. For their characterization more complex laboratory tests must be performed for obtaining data needed to evaluate these parameters in mechanistically consistent models. Perhaps for this reason many researchers have used finite-element methods with some assumption for estimation of cavern stability in rock salt.

The finite-element method was applied for analyzing solution-mined cavities in rock salt on numerous occasions (Mrugala and Bishop, 1989; Russell, 1979, Serata, 1974; a.o.). It was used in connection with the design of nuclear waste repositories in rock salt (Gnirk et al., 1977; Harrington, 1980), with satisfactory results.

2. RESULTS

For the salt deposits in Israel an analysis was carried out using a two-dimensional explicit finite-difference model which simulates the behavior of structures built of soil, rock or other materials which may undergo plastic flow until reaching their yield limit (FLAC, 1991).

For the case were the thickness of the salt rock formation is a few kilometers thick (for example: Dead Sea rock salt group - Sdom Fm.) a cylindrical cavern geometry was analyzed. The thickness of rock salt in the Sdom Formation exceeds 1000 meters. The thickness of the caprock is about 100 meters.

The problem could be realized as cylindrical openings in a homogeneous mass of rock salt exhibiting isotropic elasto-plastic behavior in an isotropic stress field. For this reason there exists a rather simple analytical solution to the problem. The rock salt is considered as homogeneous and isotropic and assumed to have a lateral pressure coefficient K = 1, i.e. the horizontal primary stresses are equal to their vertical counterparts, corresponding to the overburden pressure. The program can currently analyze two-dimensional plane or axisymmetric shapes, and since real caverns are three-dimensional, some approximation is required.

For the present purpose the following points have been implemented in the FLAC simulation:

i) The material weight of the overlying anhydrite, marl and shale layers have been set equivalent to the weight of rock salt.

ii) An axisymmetric configuration has been implemented, with the axis of symmetry aligned with the center of the cavern. The cylindrical vertical cavem center was taken to be from 850 meters to 1150 meters below the ground surface. The roofs of the cylindrical caverns are from 700 meters to 1000 meters below the ground surface,

iii) The internal pressure in the cavern was changed from 80 to 160 bars (atmospheres).

Elasto-plastic solution

The Mohr-Coulomb strength criteria was used, where the yield shear strength is determined as a function of the applied normal stress as follows

$$\tau_{failure} = c + \sigma \tan\varphi \qquad (1)$$

when σ is less than the threshold normal stress (10 MPa); c = cohesion, (1 MPa); q> = angle of internal friction (22 degrees); and when o is greater than the threshold normal stress: c = 5 MPa; q> ^{m} 0 degrees.

The results of the finite-difference analysis depend greatly on the parameters used to characterize the materials. For analysis of the rock salt cavern field, it was decided to use normal (average) parameters based on the properties published in references (Gnirk et al., 1977; Harrington, 1980; Branstetter and Preece, 1983; Mrugala and Bishop, 1989; a.o.). The following properties of rock salt were taken: shear modulus = 4.3*10 kPa; bulk modulus = 8.8*10^6kPa; Poisson's ratio = 0.5; density = 2.18 T/m^3 ; dilatation angle = 0.

In the worst case, of a cylindrical cavem of radius 15 meters and internal pressure of 40 atmospheres (bar), the maximal displacement of the cavem wall was found to be only 42 centimeters. The results obtained through the analytical solution (Serata and Gloyna, I960) are compared to those of the numerical solution. The comparisons were found to be almost the same with only slight deviations between the two. The volume loss was about 20,000 cubic meters - about 5% of the original cavern volume.

Creep solution - time dependence

The variety and number of creep stress-strain laws which have been published in the literature is an indication of the degree of uncertainty which exists regarding proper description of the material behavior. Different expressions have been used by various researchers to describe the creep behavior of rock salt, frequently indicating very different types and magnitudes of creep strain (Harrington, 1980; Branstetter and Preece, 1983; Mrugala and Bishop, 1989; Handin et al., 1986; a.o.)

For cases where the load on the structure or temperature remain constant or change very slowly, the creep deformation of rock salt can be approximated by a pure steady-state model. The constitutive laws most often used to define the creep behavior of rock salt are based on a power law equation of the following type (Senseny, 1988; Rolnik, 1988)

$$\varepsilon_{creep} = A\,\sigma^{n} \qquad (2)$$

where o = effective stress; e,^„ = steady-state strain rate; A and n = experimentally determined material constant According to the literature, the steady-state stress exponent n vary from 3 to more than 7, but is often found in the laboratory tests to be between to 4-5. The parameter A for various conditions of rock salt, ranges from 2.3*10~M to 9.1*10-*, kPA",sec~'. Calculations with the FLAC model were carried out with a value of A=1.7*10"2' for a temperature of about 326° K (53° C) for the rock salt.

Figure 1 illustrates the magnitude of the maximum deformations which could occur at the cavern walls (cavern volume - 376800 cubic meters, 20 meters radius, internal cavern pressure 80 atmospheres (bars)). The cylindrical cavern center was fixed at the depth of 1000 meters below the ground surface and the creep solutions were run for estimated time of up to 34 years. As should be expected the displacements grew with time, and at a faster rate close zero time The magnitudes of the deformations are seen to be much larger than those developed solely on the basis of the elasto-plastic solution

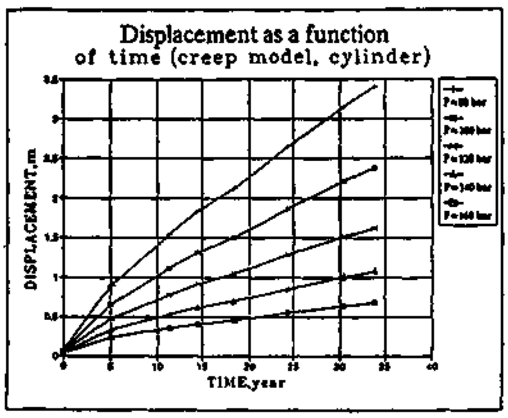


Fig. 1. Development of maximum wall displacement of cavern with radius of 20 m as a function of time.

Figure 2 is an attempt to illustrate the effects of the cavern depth and . internal pressure on the development of deformations around a cylindrical cavern, after 30 years Two important points may be seen in figures 1,2 First, the deformations around the cylindrical cavern increase with decrease of the internal pressure The second point is that the displacements at the depth of the larger cavern are considerably smaller than those of a comparable cavern at lesser depth. For example, after thirty years of cavern exploitation the maximum displacement of the cylindrical cavern, whose center was fixed at 1150 meters below the ground surface with an internal pressure of 80 atmospheres is 316 centimeters, while at the depth of 850 meters it is reduced to 115 centimeters under the same pressure conditions (Figure 2). But with an increasing of the caverns internal pressure from 80 to 160 bars decreasing difference of maximal displacements from 201 centimeters in the case of lower pressure (80 bars) to 49 centimeters in case of higher pressure (160 bars).

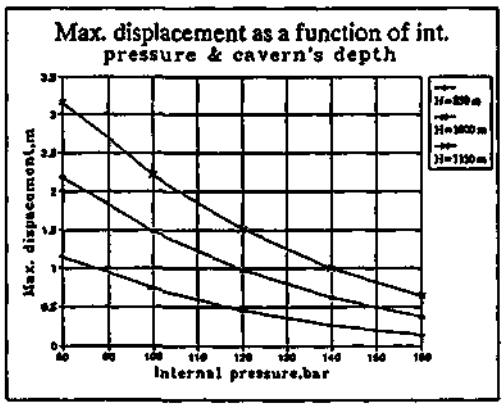


Fig. 2. Development of maximum wall displacements of cavern with radius 20 m as a function of internal pressures.

One difficult question in rock mechanics is prediction of rock salt fracture in a creep model. For estimating the deformation causing rock salt to fracture the model proposed by Miller et. al., 1982, Preece and Foley, 1983; Preece and Wawersik, 1984; was used. The relationship between the confining pressure and effective creep strain is given in the following equations:

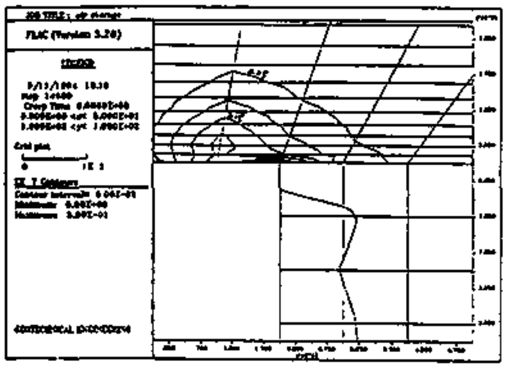
$$\phi' = 150.0\cdot(\varepsilon - 0.023 - f(P)) \qquad (3)$$

$$f(P) = \begin{cases} 0.132 \text{ for } P \geq 1.256\cdot 10^{5} \text{ psf} \\ (2\ 117\cdot 10^{-6})\cdot P - (8\ 45\cdot 10^{12})* \\ *P^{2} \text{ otherwise} \end{cases}$$

where $' = fracture/crush function; 8 = effective creep strain; $P = (a, +a_2 +a_3)/3.0$ = confining pressure; f (P) = function of confining pressure.
When function (3) becomes positive the potential for fracture or crushing of rock salt will exist Equation (3) evolves into the Fish function (a programming language embedded within FLAC) for calculating effective creep strains.

Figures 3 (a, b) illustrate the development of the effective creep strain field at the roof and bottom of a cylindrical cavem after 30 years of exploitation. For our conditions equation (3) becomes positive if e > 0.155 For example rock salt will be crushed at a depth of 17.3 meters from the bottom and 1 6 meters from the roof of the cylindrical cavern

(a)



(b)

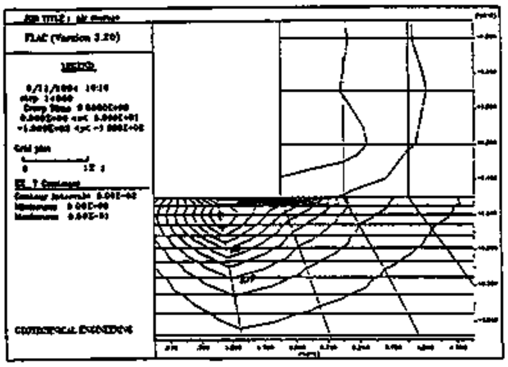


Fig. 3 Development of the effective creep strain field at the roof - (a) and at the bottom - (b) of cavern with radius 20 m at internal pressure of 80 atmospheres

Figure 4 is an attempt to illustrate the effects of the cavern depth and internal pressure on the development of the failure zone at the roof of a cylindrical opening, after 30 years.

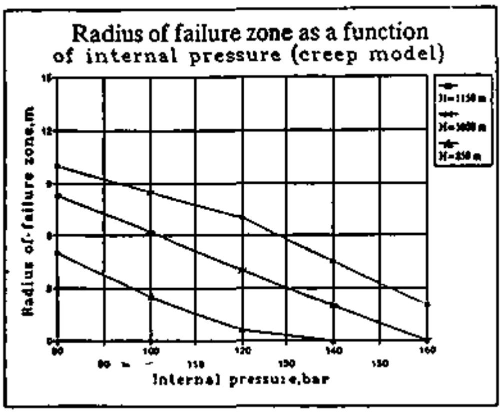


Fig. 4. Development of radius of failure zone of the roof of cavern with radius 20 m as a function of internal pressure

Two important points may be seen in figure 4 The first is that the minimum of the internal pressure in a cylindrical cavern should not be less than 100-120 bars. If the internal pressure is less than 100-120 bars, than fracture around cavern may occur The second point is that with increasing cavern depth the stability of the cavern will be preserved by increasing the internal pressure up to 160-180 bars

CONCLUSION

The maximal displacements of the cavern wall obtained through elasto-plastic solution were found to be only 40-55 centimeters and volume loss about 5% of the original cavern volume It was shown that time dependent deformations are far greater than the elasto-plastic deformation For example, after thirty years of cavern exploitation the maximum displacements of the cylindrical cavern were found to be 115-316 centimeters

The radii of failure zone around cavern wall were determined as relationship a function of the confining pressure and effective creep strain The minimum internal pressure in a cylindrical cavern for condition discussed above, should not be less than 100-120 bars. If the internal pressure is less than 100-120 bars, than fracture around cavern may occur

In relation to this topic, it is pertinent to note that more detailed calculation will be needed, taking into consideration various cavern roof shapes, the effect of the overlying rock salt above the cavern, and the influence of internal pressure reduction on stress concentrations in the rock salt zone surrounding the cavern. For estimation of long-time cavern stability the effect of pressure and temperature loading rates; creep rupture of the rock salt; air penetration to the rock salt and loss of mechanical stability, are highly important.

The obtained data will permit forecasting of the behavior of rock-salt caverns, depending on the exploitation time and on the temperature of the surrounding rock. This is of extreme importance in ensuring future stability and serviceability of the compressed-air storage facility.

Acknowledgments

The research on which this paper is based was sponsored by the Center for Absorption in Science, Ministry of Immigrant Absorption, State of Israel, and by the Wolfson Family Charitable Trust Program.

The authors are indebted to Dr. Mark Talesnick, who supported the research project.

REFERENCES

Baar,C.,1977, *"Applied salt-rock mechanics I - The in situ behavior of rocks"*, Elsevier Scientific Publishing Company.

Branstetter.L., and Preece,D.,1983, "Numerical studies of laboratory triaxial creep tests *Proc. of the 24th USSymp. on Rock Mechanics.*

Dreyer,W.,1972, *"The science of rock mechanics", Trans-Tech.* Publications.

FLAC.1991, *"Fast Lagrangian Analysis of Continua"*, Version 3.0, ITASCA consulting group, INC, Minneapolis, Minnesota.

Gnirk,P., Grams,W., and Zeller,T.,1977, "Analysis of design engineering aspects of radioactive waste isolation in salt", *Proc. of the 1st International Symposium* "Storage in excavated rock cavern", Stockholm.

Hambley,D, Dusseault,M., and Mraz.D.,1988, "Characterization of salt rock creep behavior", *Proc. of the 29 th USSymp. on Rock Mechanics*

Handin,!, Russell,!, and Carter,N.,1986, "Experimental deformation of rock salt", *American Geophysical Union Monogram, Vol.36.*

Harrington,T.,1980, "Time-dependent closure analysis of nuclear waste repository in bedded salt", *Proc. of the 21st USSymp. on Rock Mechanics.*

Hofer,K., and Thoma, K.,1968, "Triaxial tests on salt rocks", *International Journal of Rock Mechanics, Vol.5.*

Le Comte, P ,1965, "Creep in rock salt", *Journal of Geology, Vol. 73, No. 3.*

Miller,!, Stone.C, and Branstetter,L.,1982, "Reference calculations for underground rooms of the WIPP", Sandia National Laboratories, *Project SAND82-II76.*

Mrugala,M., and Bishop,W.,1989, "Performance of two cavern storage system using finite element method", *Proc. of the 30th US Symp. on Rock Mechanics.*

Preece,D, and Foley,!, 1983, "Finite element analysis of salt caverns employed in the strategic petroleum reserve", U.S. Department of Energy, *Project DE-AC04-76DP00789.*

Preece,D, and Wawersik, W., 1984, "Leached salt cavern design using a fracture criterion for rock salt", *Proc. of the 25th US Symp. on Rock Mechanics.*

Rolnik,H ,1988, "High-level waste repository in rock salt suitable rheological forms", *Proc. of the 2nd Conf.Mech. Behavior of Salt.*

Russell, J ,1979, "Finite element models of caverns in salt", Prepared for Solution Mining Research Institute Full Meeting - October 14-16, Toronto, Canada

Senseny,P., Hansen,F., Russell,!, Carter.N., and Handin,!, 1992, "Mechanical behavior of rock salt: phenomenology and micromechanisms", *Int. Journal RockMech. and Min. Set., Vol.29, No.4.*

Senseny,P.,I988, "Creep properties t)f four rock salt", *Proc. of the 2ndConfMechBehavior of Salt.*

Serata,S.,1964, "Principles of stress field in underground formations", National science Foundation, *Projects G-19791 & GP-2646, Progress Report No. 74-0005-SMRI.*

Serata,S.,1974, "Development of research program for detection, prediction and prevention of surface failure over solution cavities by using REM computer technique", Solution Mining Research Institute, *Annual report No. 74-0005-SMRI.*

Serata,S, and Gloyna,E,1960, "Principles of structural stability of underground salt cavities", *Journal of Geophysical Research, Vol.65, No.9.*