Research on the setting of maximum pressure in salt caverns intended for CO_2 storage

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Abstract. The caverns are built in the salt massifs, by dissolving the salt at depths from 150 m to 1000÷2000m, and can have a volume between 5000 and 1 000 000 m3. These can provide the storage of large amounts of hydrocarbons, hydrogen or carbon dioxide. Sealing is a fundamental prerequisite for many underground works where it is necessary for the stored product to have minimal leakage. The main factors in the appearance of well leakage are: Fluid pressure distribution, geological environment, well cementing operation and cavern architecture. For a functioning cavern, fracturing the walls is a major risk, which can lead to loss of tightness. Consequently, the pressure of the stored product must be less than the absolute value of the lowest compression effort, even when a margin of safety is being taken. Knowledge of these efforts, their evolution over time and their distribution around the caverns, is the research objective for the authors of this article. For real-scale analysis, a 3D model of finite element analysis was used, using numerical modelling software for geotechnical analysis of rocks.

1 Introduction

The depletion of natural gas deposits in Central Europe as well as the liberalization of gas prices creates the demand for additional gas deposits, especially in salt caverns.

Salt caverns are deep cavities (from 150 m to 1000÷2000m) that are connected to the surface by a cemented well. They are built into the salt massifs by dissolving the salt and can have a volume between 5000 and 1 000 000 m^3.

Worldwide, caverns of this type are used to store various products of hydrogen, natural gas, carbon dioxide, up to crude oil or nuclear waste, which requires caverns to be sealed. Under favorable conditions for the formation of gemstone salt deposits existed in Europe during the Permian, the Mezoic and the Tertiary period. The notable concentration of deposits in gas caverns in Northern Germany is primarily due to geology (Permian age deposits), as well as Germany's central position in Europe (Fig. 1).

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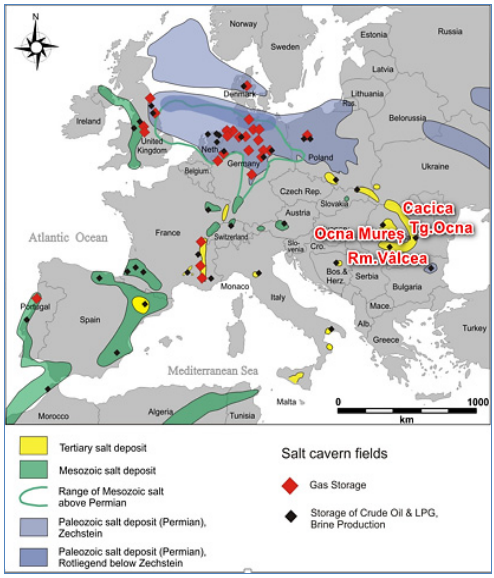

Fig. 1. Salt deposits in Europe and gas storage in caverns [1].

In Romania (tertiary age deposits), the salt exploitation through dissolution is done in Târgu Ocna, Ocnele Mari, Ocna Mureș and Cacica. The salt deposit from Ocna Mureş, located in some areas, the salt thickness exceeds 1000 m and is exploited by wells with a depth between 350 m and 1160 m. At the Cacica salt mine, starting with the year 1959, there were put into production 9 wells located in the mine, with a depth of approx. 100 m and the diameter of the dissolving chamber 25-30 m. In the same year, the exploitation at the Târgu Ocna salt mine began, through 2 probes with a depth of 550 m and the diameter of the dissolution chambers of about 50 m, reaching at present 35 wells (partially in conservation). In Ocnele Mari, in 1960, brine production began in field I, continuing with field II, III, and IV, through 61 wells (partially closed). The thickness of the sterile intercalations varies from 1-2m to 25m, which led to problems in operation and even accidents.

2 Maximum allowable pressure

In the salt caverns used for storage, a maximum allowable pressure should be selected to avoid any loss of the stored product. The pressure in the cavern must be maintained lower than the geostatic pressure or, more precisely, lower than the lowest compression pressure in the wall of the cavern. The redistribution of tensions in the rock mass should be considered, due to the visco-plastic nature of the gemstone salt. There are several known cases where a hydraulic connection has occurred between adjacent caverns, or between a cavern and the edge of the salt dome. These connections came from geological anomalies rather than from the creation of a fracture.

There is a pressure threshold, lower than the geostatic pressure, for which micro-fracturing occurs, followed by an increase in salt permeability, and inevitable product losses, so a safety margin is required when selecting the maximum pressure.

The pressure in a cavern must be determined in accordance with the in situ stresses at that depth, making a fundamental difference between the "initial" or "primary" stress state (that existed before the creation of the cavern) and the "secondary" stress state (resulting from the creation and functioning of the cavern) [2].

2.1 Primary stress state

Determining this measurement is very difficult, because we do not know exactly the boundary conditions, the constitutive law, nor the history of geological formation of the deposit, and most often assumptions are made. The simplest way to assess the vertical in situ (σ v (-), conventionally negative, compression load) is to assume that this demand is the main one, from the surface to the depth considered. This assumption is reasonable, although it is not proven to be generally valid. Most often, the density of the rock, $\rho = \rho(z)$, is measured by density samples on the cores when drilling a well. In this hypothesis, the vertical effort at depth z is provided by an integration, with the mention that this method does not take into account the two main horizontal tension ($\sigma_h = \sigma_H$), unless an isotropic state of tensions is assumed $_v(z) = \sigma_h(z) = \sigma_H(z)$ (Relation 1):

$$\sigma_v^{dens} = -\overline{\rho} gz = -\int_0^z \rho(\zeta) g d\zeta \quad (1)$$

2.2 Secondary stress state

Taking into account the construction of a well with radius ***a***, the pressure difference in the cavern from the outside (pressure of the salt massif at the given depth), $\Delta P = P_\infty - P_I > 0$ and a constitutive power law $\dot{\varepsilon} = A\sigma^n$, 3<n<6, at the equilibrium state the tension distribution is (Relations 2):

$$\sigma_r = -P_\infty + \Delta P \left(\frac{a}{r}\right)^{\frac{2}{n}}$$

$$\sigma_\theta = -P_\infty + \left(1 - \frac{2}{n}\right) \Delta P \left(\frac{a}{r}\right)^{\frac{2}{n}} \quad (2)$$

$$\sigma_z = -P_\infty + \left(1 - \frac{1}{n}\right) \Delta P \left(\frac{a}{r}\right)^{\frac{2}{n}}$$

where σ_r, σ_θ, σ_v, are radial, tangential requests, and vertical respectively.

2.3 Measuring the stress state

It can be done through the so-called “frac test”. A hydraulic or pneumatic fracture test consists of isolating an interval in the well drilling (e.g. by using a packer device). The two ends of the packer are sealed on the rock, and through the middle of the device a pressure is allowed to apply to the salt wall of the isolated range. Hydraulic and pneumatic tests are performed in a salt formation in which the injected fluid is either saturated brine (for hydraulic test) or nitrogen (for pneumatic test). The pressure of the fluid in the packer is rapidly increased until the breaking pressure (fracturing) is reached, (Fig. 2); this is observed when the pressure-volume curve of the injected fluid reaches a maximum followed by a sudden drop in pressure. The injection rate is then controlled so that the pressure of the injected fluid is constant (fracture propagation pressure). Several such "fracturing cycles" are performed.

In general, it is assumed that hydraulic fractures propagate in the direction of the least resistance (weakening plans). According to [3], the weight of the overload can be measured by "determination of density in rock samples, analysis of lithodensity logs, hydraulic fracture tests and gravitational measurements in drilling. The pressure determined by the breaking tests (the so-called 'closing pressure') is considered to be the main effort (the least compression effort).

As a preliminary conclusion, although fractionation tests are useful, the selection of maximum allowable pressures in a cavern based on favorable results of fracking tests is not very safe; it seems reasonable to adopt the authors' conclusion [3] that "density logs have proven to provide data of sufficient quality" for the determination of vertical pressure.

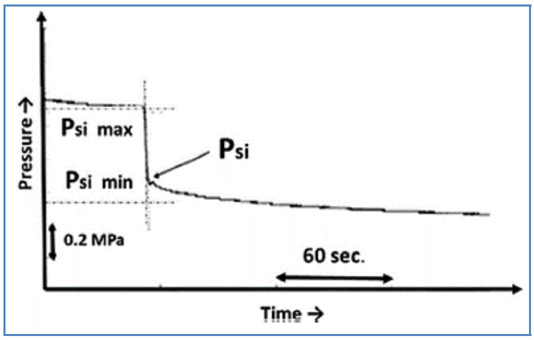

Fig. 2. Schematic procedure for FRAC test [4].

2.4 The pressure of the stored product

The pressure of the stored product it is a place-specific notion and must be established for each warehouse (Fig. 3) [3]. The pressure difference between the stored product and the rock formations is a function decreasing with depth, and is the driving force in the event of the leakage accident of the stored product.

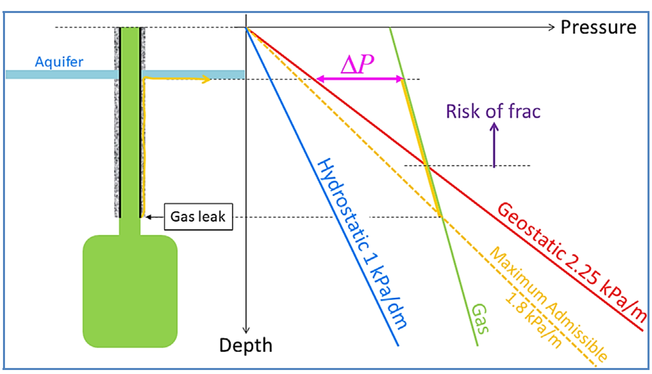

Fig. 3. The pressure gradient depends on the depth of the deposit.

The selection of a maximum operating pressure in the cavern must take into account that the value will remain, throughout the operation period, lower than the lowest compression tension (Fig. 4). Following a pragmatic approach, the evaluation will take into account:

- Estimation of vertical stress at the depth of the cavern using density data from the geological logs following drilling, assuming that this is equal to vertical stress;

laboratory density measurements can also be used, providing a lower limit of the density of the rock in situ.

- selecting a maximum allowable pressure of (80–85%) from the vertical load.

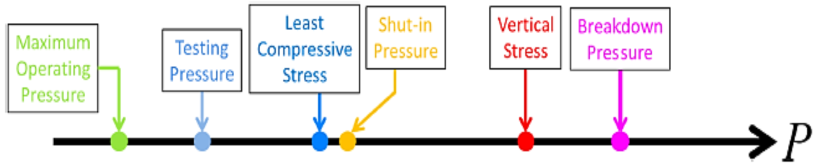

Fig. 4. Selection of maximum operating pressure in a salt cave.

This safety margin of 15-20% takes into account factors such as geological uncertainties, or insufficiently known physical or mechanical processes (secondary tensions).

2.5 The pressure gradient

defined as a depth-based scalar size, is not uniform for all areas, it varies according to specific geo-mineral conditions. In Table 1, some examples of pressure gradients related to areas with storage activity in salt caverns are presented.

Table 1. Pressure gradiants depending on the area.

Gas storage	Depth (m)	Pmax. (MPa)	Maximum gradient (MPa/m)
Aldbrough, England	1800	27	0.015
Carriço, Portugalia	1000	18	0.018
Etzel, Elveția	1150	20	0.017
Holford, England	≈550	10	0.018
Krummhörn, Germany	≈1500	27	0.018
Nütthermos, Germany	≈1000	17	0.017
Teesside, England	≈350	4.5	0.013
Zuidwending, Netherlands	1000	18	0.018
Manosque, France	1000	18	0.018
Stublach, United Kingdom	≈550	10	0.018
Egan, Ethiopia	1125	23	0.0204
Kansas, USA	NA	12	
China	≈2000	17	0.016-0.017
Aldbrough, England	≈1500	27	0.0155
Nütthermos, Germany	≈1020	17	0.017
	≈648	12.2	0.0188
Torup, Sweden			0.0184
Huai'an, China	1493	26.0	0.0175
Jintan, China	937	13.5	0.144
Jintan, China	≈1000	17.0	0.0170
		18.0	0.0180
Jintan, China	900	17.0	0.0188
Qanjiang, China	1980	32.0	0.0160

Selecting a maximum operating pressure higher than those suggested above 80÷85% of the overload pressure increases the risk of a significant leak and therefore can only be accepted when a large amount of information is available.

3 Example of application for an existing cavern within the salt mine Tg.Ocna

We considered the case of a cylindrical cavern, excavated in a layer of salt 200 m thick, at a depth of 265 m, Fig. 5. The salt roof consists of acvitanian deposits consisting of clay sands and sandy clays, with intercalations of sandstones.

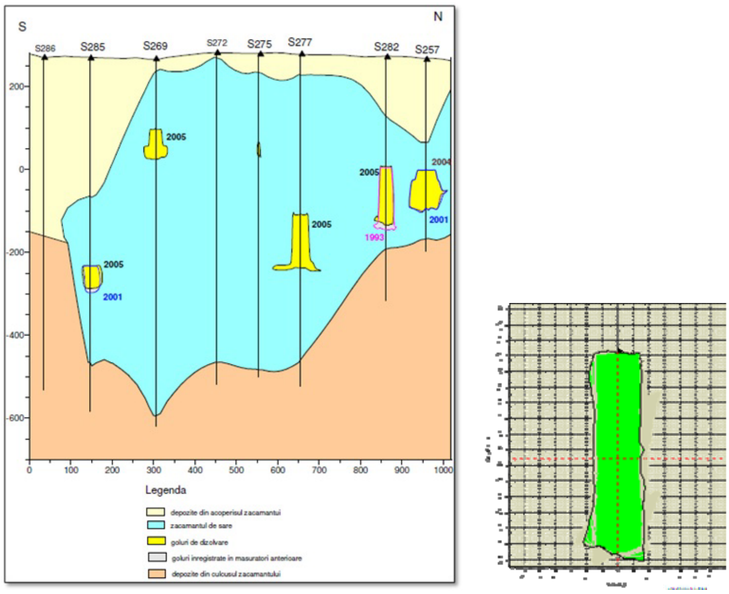

Fig. 5. Vertical sections through salt caverns from the perimeter of the Gura Slamic Tg.Ocna.

The cavern of, Fig. 5 which we will analyse using finite elements of hexahedral volume, has the following constructive and location dimensions [5]:

- depth of 265 m, in a layer of salt of approx. 200 m thick;
- cylindrical cavern, diameter 34 m and height 120 m;
- the roof of the cavern consists of 120 m of salt and a layer of 145m of sterile.

The 3D model under analysis is a representative sample of the size in meters of 200x200 shown a quarter in Fig. 6, due to symmetry conditions.

The physical and elastic characteristics of the salt are those determined in the laboratory of "Geomecanics" of the University of Petroşani (Table 2).

Table 2. Elastic characteristics of the salt from Tg. Ocna.

Sample no.	Static elasticity module [MPa]	Dynamic elasticity module [MPa]	The constant and Poisson's coefficient
1	2545	34850	0.260
2	2430	35400	0.280
3	2550	35250	0.275
4	2610	35900	0.282
5	2150	33800	0.293
6	2240	32950	0.299
Average	2420,83	34691,67	281,5

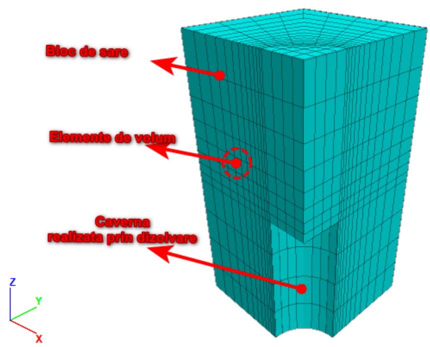

Fig. 6. 3D model and discretization with volume elements.

The average and rheological elastic properties were input data for analysis, considering for salt the creep behavior a law of power with a single component:

$$\dot{\varepsilon} = A \cdot \dot{\sigma}_c^n \quad (3)$$

Table 3. Mechanical and rheological properties of the model.

Elastic properties:	
Young's module [MPa]	2421
The Poisson's coefficient	0,282
Rheological properties:	
A	3.9×10^{-7}[MPa$^{-4.9}$year^{-1}]
n	4.9

Boundary conditions in a numerical model consist of field variable values that are prescribed at the boundary of the numerical grid, instead using a boundary condition command within a finite element calculation, a condition or constraint is imposed that will not change unless specifically modified by the user. The model limits may be real if the dimensions are reasonable, otherwise artificial limits are introduced to reduce the size of the model.

We believe that the model size of 200x200 meters is a limit far enough from the area of interest that the behavior in that area is not very affected (Fig. 7).

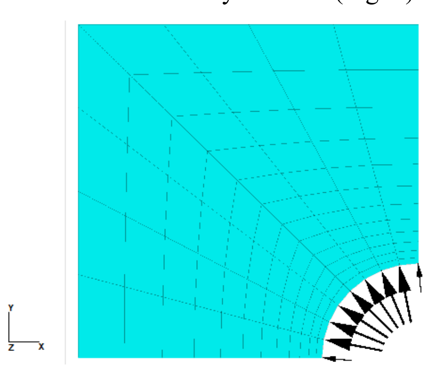

Fig. 7. Limit conditions for the chosen model.

The initial stress state (prior to the execution of the cavern) is loaded into the system, as it will influence the subsequent behavior of the model.

The components of the tensor of the initial tension state with the sign (-) are compression:

$$\sigma_{zz} = \sigma_{xx} = \sigma_{yy} = -3.5 MPa \tag{4}$$

For this axis, a pressure gradient of 0,013 MPa/m is considered, which at the depth of 265m creates an overload of 3,445 MPa, which causes us to choose a pressure of the cavern of maximum 2,928 MPa (max. 85% of vertical load).

The operation of the cavern is determined by the demand for the stored product, which requires a pressure regime in the cavern in the range (1÷0,1) maximum working pressure. The distribution of tensions in the salt massif near the cavern, in the two situations of pressure limitation of 2,928 MPa (29 bar), respectively depressurization at 0,29 MPa (3 bar), are shown in figures Fig. 8 and Fig. 9.

As is apparent from the distribution of the tensions on the contour, the minimum main tension is 2,9463 MPa and therefore the pressure in the cavern should not exceed this value (29 bar).

In the case of the supply of cavern products, it should be taken into account that their depressurization should not be below a critical value. This value is 2,0258 MPa and results from the distribution of the minimum main tension in the hypothetical “zero” depressurization situation.

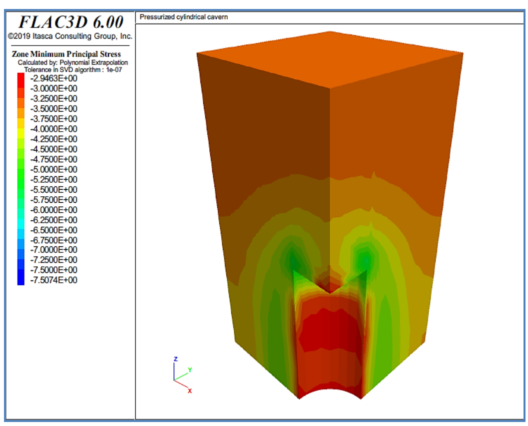

Fig. 8. Distribution of tensions for a pressure of the cavern of P=2.9Mpa.

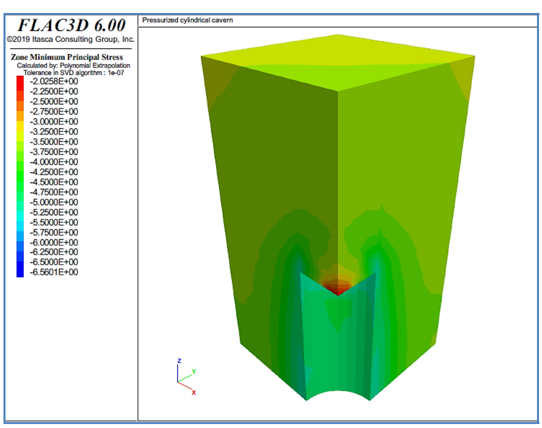

Fig. 9. Distribution of tensions for a pressure of the cavern of P=0 MPa.

4 Conclusions

Setting the maximum allowable pressure at the standard value 80÷85% of the vertical weight is valid and therefore adoptable for the salt mine Tg.Ocna. The excess of this value must be justified by further documentation of the geological conditions specific to the storage site (a layer of salt or plastic clay several hundred meters thick above the roof of the cavern constitutes a favorable situation, whereas a permeable rock at a short distance from the roof of the cavern, on the contrary, is unfavorable).

The selection of the maximum pressure in a gas storage cavern can be based on the assessment of the vertical tension, which can be easily calculated from the density logs. Fracture tests may also be useful, but they provide an upper limit to actual vertical tension.

The maximum operating pressure should be selected to avoid the fracture of the cavern wall, which in principle occurs when the pressure in the cavern is greater than the minimum main stress in the rock mass.

It is recommended to perform numerical calculations and verify that the selected operating mode does not lead to unfavorable redistribution of secondary tensions in the rock mass.

References

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