STUDY OF THE STABILITY OF CAVERNS IN ROCK SALT CREATED BY SOLUTION MINING PROPOSAL FOR A NEW DESIGN CRITERION

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ABSTRACT

It is intended to convert several fuel storage cavities at MANOSQUE into natural gas storages. For this purpose, the stability conditions of the gas caverns as well as the possibility to increase their volume need to be assessed in vieww of the new planned operating conditions. To study this problem, a new set of mechanical tests were performed on MANOSQUE rock salt and their results are presented in this paper. The results made it possible to fit a rheological model which has been used in F.E.M. numerical modelling.

1. - INTRODUCTION

1.1. - Presentation of the site

The Manosque site was chosen in 1967 for the development of an underground hydrocarbons storage (Clerc-Renaud 1978). The reasons for this choice were both geographical (figure 1.a) and geological (figure 1.b.). Storage operations began in 1969 and since then, more than 33.10^6 m^3 of hydrocarbons have passed through the site.

The Manosque salt deposit dates from the Oligocene and its present structure is a result of the Alpine orogeny at the end of the Miocene. The salt extends along an east–west anticline. Tectonic movements subsequently deformed the evaporites, causing local thickening of the salt layers, depending on their initial position. The layers of insoluble materials, mainly anhydrite, were crushed to form fragments often of decimetric size. The formation thus has the aspect of a diapir, though there are no traces of piercing through the upper layers. The proportion of insolubles is around 12 %.

The caverns, with a height of up to 400 meters, were leached by solution mining at depths of between 400 and 1500 meters. The current capacity of the caverns is $6.3.10^6$ m^3 of petroleum products (crude oil, fuel oil, naphtha, etc.).

1.2. – Conversion

In view of the increasing demand for natural gas in France and the lack of gas storage facilities in the south–east of France, Gaz de France and the Geostock company decided to create the GEOMETHANE joint venture to construct and operate a natural gas storage site at Manosque.

The natural gas conversion of storage caverns initially intended to receive liquid hydrocarbons raised a certain number of problems, including the geotechnical issue discussed in this paper.

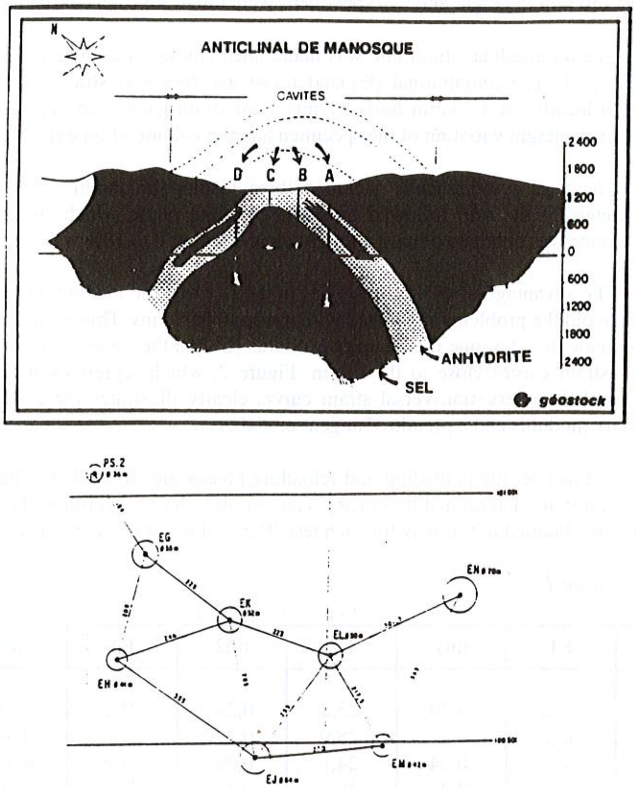
Seven existing caverns were selected for conversion, on the basis of the following criteria :

- depth,
- potential for increasing storage volume,
- geographical isolation with respect to the other caverns.

1.3. – Geotechnical problem

Liquid hydrocarbons are stored at a practically constant pressure (more than 12 MPa at a depth of 1000 meters), whereas gas storages are operated at pressures of between 6 MPa and 18 MPa. It was therefore necessary to revise the design criteria in accordance with the results of new laboratory and numerical simulation techniques.

Figure 1 : Geology and position of caverns



2. – MECHANICAL BEHAVIOR OF SALT

Mechanical behavior was studied on the basis of laboratory tests on cylindrical specimens :

- at the C.G.E.S. (Centre de géotechnique et d'exploitation du sous–sol) for cyclical and creep tests,
- at the L.M.S. (Laboratoire de mécanique des solides) for strain–hardening tests.

2.1. – Determining elastic characteristics

A series of simple and triaxial compression tests was performed in the Manosque salt, with confining pressures (P) of 0, 1, 5, 10, 20 and 30 MPa. The specimens measured 65 mm in diameter and 130 mm in height and two specimens were tested for each confinement.

The longitudinal strain rate was maintained constant throughout the test, at a value of around $2.10^{-6}.s^{-1}$. The longitudinal ($\in_1$)and transverse ($\in_2=\in_3$) strains of the specimen were measured both locally on a 20 mm basis by means of strain gauges and globally using induction sensors measuring height variation of the specimen and the volume of oil expelled from the cell.

The tests systematically included three loading–unloading cycles to determine the elastic parameters of the salt, followed by a final loading phase which continued either until a residual resistance was obtained or until a longitudinal strain of 8 to 10% was observed.

The advantage of cyclical tests lies in the fact that the loading–unloading phase makes it possible to avoid the problems associated with irreversible strains. This is far from being true when attempts are made to determine the Young's Modulus (E) and the Poisson's ratio (ν) from the slope of the stress–strain curves close to the origin. Figure 2, which represents the stress–longitudinal strain curve and the stress–transversal strain curve, clearly illustrates the difference between the actual elasticity modulus and a pseudo "Tangent modulus".

In practice, the unloading and reloading phases are isolated and the Young's modulus and Poisson's ratio are determined by linear regression in order to determine the elastic parameters. Three values are obtained in this way for each test. The results obtained are shown in table 1 below.

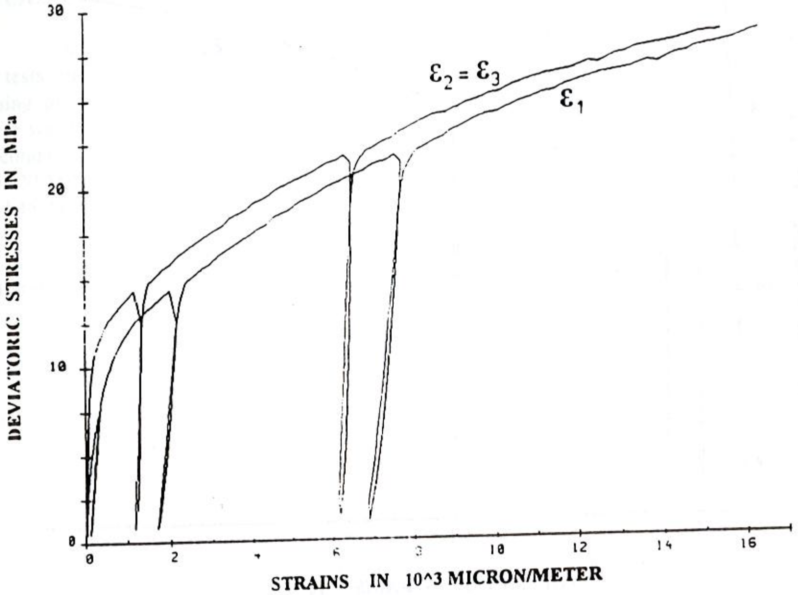
Table 1

P	**E1**	**nu1**	**E2**	**nu2**	**E3**	**nu3**	**(σ1 – P)d**
0	29,2	0,20	25,2	0,24	21,1	0,23	11
0	32,7	–	28,9	0,27	24,6	0,31	11
1	28	0,24	24,1	0,29	21,8	0,33	11,5
1	32,1	0,23	26,3	0,33	22,1	0,40	10
5	30,7	0,25	29	0,32	27,1	0,30	16
5	34,7	0,23	31,6	0,23	28,2	0,25	32
10	47,1	–	42,9	–	40,7	–	–
10	36,9	0,21	36,9	0,29	37,2	0,29	18
20	39	0,33	38,4	0,31	35,3	0,31	17,5
20	–	–	–	–	22,5	0,36	< 17
30	40,9	0,23	37,7	0,29	36,8	0,27	16
30	40,6	0,32	37,8	0,30	34,2	0,32	18

Stresses are in MPa and the Young's moduli in GPa.

Figure 2 : $(\sigma_1 - P) = f(\epsilon_1, \epsilon_2 = \epsilon_3)$

MANOSQUE SALT - TRIAXIAL COMPRESSION TEST - CONFINING PRESSURE= 1 MPa



This table gives rise to the following remarks :

- The values of the Young's moduli are between 20 and 40 GPa, whereas the "tangent modulus" used to plot the curves may give values which are four to five times lower.

- The Young's modulus increases with confining pressure and decreases with each successive cycle.

2.2. – *Revealing salt damage*

Through an appropriate combination of strain measurements, it is also possible to plot a deviatoric stress curve as a function of volumetric strain ($\epsilon_v = \epsilon_1 + 2\epsilon_2$), (figure 3). In all cases, the existence of a limit stress is observed, beyond which the salt is no longer contractile but dilatant. This result was obtained both with the C.G.E.S. cyclical tests and the L.M.S. tests performed for different confining pressures (between 0 and 25 MPa) and with two loading rates.

. *Figure 3* : $(\sigma_1 - P) = g(\sigma_v)$

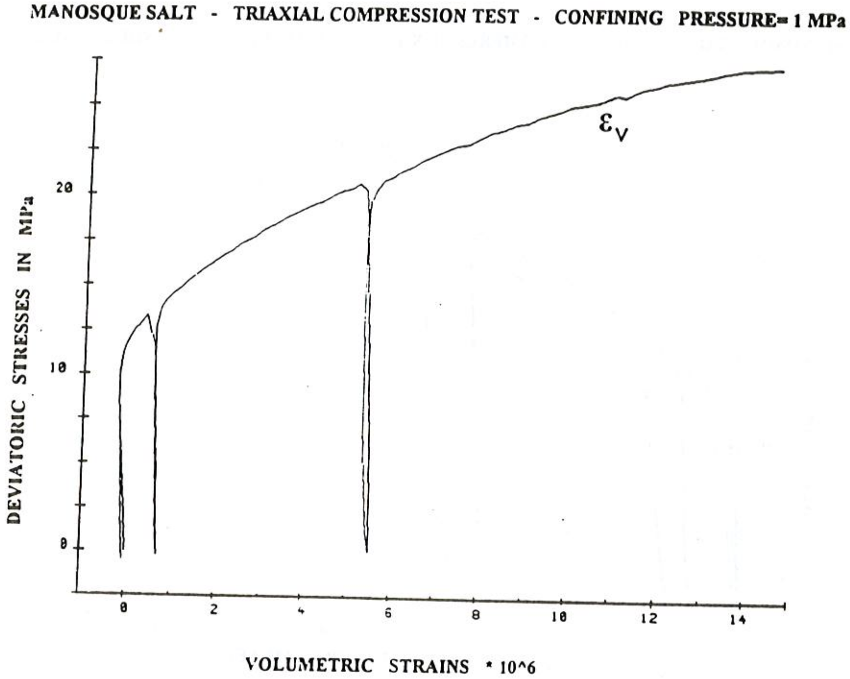


Table 1 shows the limit stress $(\sigma_1 - P)_d$, beyond which the salt starts to become dilatant. We note that it increases substantially with confining pressure between 0 and 5 MPa and then stabilizes at around 17 MPa. For the rateş used, the strain–hardening tests revealed that this dilatancy threshold was independent of the loading rate.

Table 2 gives a number of additional measurements of longitudinal wave velocities V_l performed after loading in the two main directions of the specimen (parallel V_{pa} and perpendicular V_{pr} to the directions of the deviatoric load).

Table 2

P (MPa)	V_l	$\in \times 10^{-3}$	V_{pa}	V_{pr}
0	4425	3,5	4112	1792
2,5	4630	12	2744	900
25	3910	> 25	3800	3100

The drop in wave velocities indicates damage due to loading, a result that can be observed in table 1 relating to the elastic moduli. The difference in wave velocities in the two main loading directions also reveals the anisotropy of damage. We also note the influence of confinement, which tends to reduce the effect of this anisotropy.

2.3. – Creep characteristics

In order to identify the rheological behavior of the Manosque salt, two series of three creep tests under triaxial compression were performed. For the first series, the temperature and confining pressure were maintained constant, respectively at 50°C and 20 MPa, and the axial pressure was successively raised to 24, 28, 32 and 36 MPa, each stage lasting around 45 days. For the second test series, axial pressure and confining pressure were maintained constant at respectively 32 and 20 MPa and temperature was raised successively to 30, 40, 50 and 60°C, each stage lasting around 45 days.

The rheological parameters are identified by comparing experimental strain and the response of J. Lemaître's theoretical model to the same load history (J. Lemâitre 1970).

For this model, in the case of the triaxial test with constant confinement, the response in terms of axial strain is described by the equations below :

Where :

$\in$: total strain.
$\in_e$: elastic strain.
$\in_{th}$: thermal strain.
D : physical deviatoric stress $(\sigma_1 - \sigma_3)$.
E' : instantaneous deformability modulus.
λ : coefficient of dilation per unit length.
ΔT : temperature variation with respect to initial state.
$K(T_0), \alpha, \beta$: parameters of the Lemaître model.
T_0 : arbitrarily chosen temperature reference, equal to 300 °K.
R : constant of perfect gases.
Q : activation energy.
T : current temperature in °.K.

ξ is an internal variable which remains continuous throughout the test. If the variation of D and T over time is known, it is possible to calculate the evolution of ξ by integration and thereby to deduce the evolution of $\in_{vp}$. The evolution of $\in_{th}$ and $\in_e$ is evident and the response of the model is obtained by summation in the form of an explicit function of time and of the parameters $\alpha, \beta, K(T_0)$, Q/R, E' and λ. By minimizing the quadratic difference between the measured difference and the response of the model by means of a specifically designed program (DTFLU, Achiq et al 1993), we can deduce the set of parameters $\alpha, \beta, K(T_0)$, Q/R, E' and λ, which best take account of experimental results.

It should be noted that the E' modulus determined in this way is significantly lower than the Young's modulus E deduced from the loading–unloading cycles : we find the same difference as between the first loading modulus and the elasticity modulus indicated in paragraph 2.1. In our calculations, we used the modulus deduced from the cyclical tests.

Figure 4 : Creep at increasing load stages

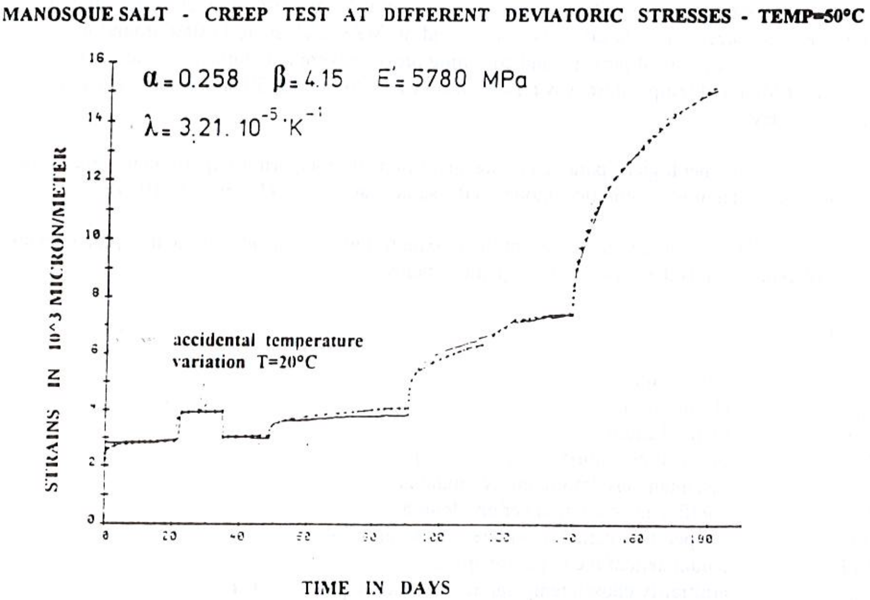


Figure 4 gives an example of experimental results of creep at increasing load stages (small crosses) and the adjustment made by the model (continuous line). We note that the model is able to take account of the effect of an accidental temperature variation as well as the planned variation in stresses.

Figure 5 : Creep at increasing temperature stages

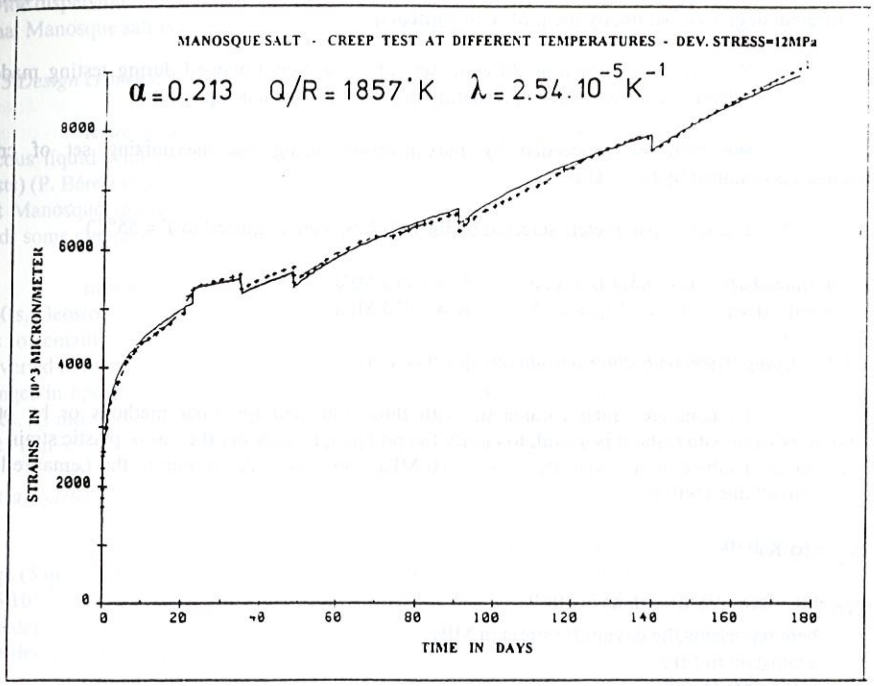


Figure 5 displays a creep test at increasing temperature stages and in this case too, illustrates the quality of the model adjustments.

The creep tests were performed under compression rather than tension, since our experience of these tests enabled us to conclude that the same rheological laws are applicable to both types of test. The early failures observed in tension indicate, in our view, that in this situation the specimen is in unstable equilibrium since the thinning of the central part causes a reduction in axial stress which, in turn, amplifies this thinning to the point where the specimen is under tensile load and is destroyed by britte failure.

2.4. – Synthesis of tests, rheological behavior

2.4.1. – Constitutive law

We consider that the Lemaître law recommended by the C.G.E.S. is able to take account of most of the tests conducted both in the laboratory and on site.

. Our approach was therefore to perform numerical modelling calculations using this constitutive law and to compare the predicted stress and strain states with those resulting in failures or substantial damage during laboratory tests. It was thus possible to take account of results obtained at different degrees of strain, by the L.M.S. in particular.

However, the numerous different sets of parameters obtained during testing made it impossible to determine a single law representing the behavior of Manosque salt.

We therefore proceeded by maximization, using the maximizing set of creep parameters obtained by the C.G.E.S.

The set of parameters selected by the C.G.E.S. were (adjusted to T = 55°C)

- maximized set : $\alpha = 0.326$ $\beta = 3.63$ K = 1.115 MPa
- minimized set : $\alpha = 0.213$ $\beta = 2.55$ K = 1.075 MPa

2.4.2. - Comparison with other parameters or other salts

To compare creep parameters with those obtained by other methods or by other laboratory or in-situ tests, it is useful, to clarify the problem, to consider the visco-plastic strain e_{vp} of a specimen subject to a deviatoric stress of 10 MPa over 1 year. According to the Lemaître law, the strain obtained will be :

$$\in_{vp} = (\sigma/K)^{\beta}.t^{\alpha}$$

$\in_{vp}$ the visco-plastic strains in 10^{-6}
σ here represents the deviatoric stress in MPa
K a constant in MPa
t is the time in days

This approach produces the following results :

Manosque salt

Maximized set :

$\alpha = 0.326$ $\beta = 3.63$ K = 1.115 MPa $e_{vp} = 1.96\%$

Minimized set :

$\alpha = 0.213$ $\beta = 2.55$ K = 1.075 MPa $e_{vp} = 0.10\%$

Lower Etrez salt

$\alpha = 0.440$ $\beta = 3.90$ K = 1.950 MPa $e_{vp} = 0.79\%$

Tersanne salt

$\alpha = 0.500$ $\beta = 3.63$ K = 0.89 MPa $e_{vp} = 14.70\%$

Analysis of these results shows :

- wide dispersion
- that Manosque salt is not subject to significant creep, particularly as compared to Tersanne salt.

2.4.3 Design criterion

If we assume that the behavior of salt, as indicated by the Lemaître law, is that of a viscous liquid with positive strain–hardening (or with a relatively low plasticity threshold, if it exists) (P. Bérest et al 1981, G. Vouille et al 1983), then the first approach, used for the design of the first Manosque storage caverns, though sufficient for caverns dedicated to hydrocarbons storage, needs some complementary approach for a gas storage when the cavern is subject to lower pressure.

Indeed, for the design of the Manosque hydrocarbon storage caverns developed in the 1960's, Geostock used a criterion based on the existence of an inter–cavern pillar whose behavior was to remain elastic with a certain margin of safety. The design of hydrocarbon caverns to be converted to natural gas should be reexamined in the light of this approach and taking account of the changes in operating conditions. The new concept no longer considers any purely elastic behavior zones. At most, like metallurgists, we are able to determine that behavior is close to elastic behavior when non–elastic strains are small and when the stresses created do not embrittle the massif.

– Strain criteria

In order to define such a criterion, we first considered that within the relevant pressure range (5 to 30 MPa), the various laboratory tests show that maximum strains are between 9.10^{-2} and $12.5.10^{-2}$, a small share of which corresponds to elastic strains ($0.5.10^{-2}$). We can therefore consider that minimum irreversible strains are around 7.10^{-2} to 8.10^{-2}, with a behavior that can be considered as essentially ductile–non–brittle.

To our knowledge, there is no universally recognized criterion on salt rupture and the excessively strict notion of the safety coefficient is, in our view, meaningless. However, we consider that salt is a sufficiently ductile material to withstand irreversible strains, in the order of a few percent, without excessive damage.

– Stress criterion

The volume strain analyses performed by the two laboratories are highly interesting and quite new as regards the notion of damage. Despite the relative scattering of results, a number of phenomena were observed.

During the first loading cycles, the tendency to increase in volume (swell) only appears when deviatoric stress values are equal to or greater than 11 MPa, and this value tends to increase with confinement and successive cycles. Despite this real damage, which is apparent on the volumetric strain curves, the sound velocity and cyclical moduli measurements, this damage is largely masked in overall behavior by visco–plasticity phenomena.

In other words, specimen embrittlement by damage is moderate, with respect to the hardening caused by visco–plastic strain. Strain–hardening thus remains clearly positive under the test conditions. Overall, damage remains relative.

As our understanding of the phenomena now stands, we consider that the value of 11 MPa for the deviatoric stresses should not be exceeded in the case of Manosque, except perhaps in the immediate vicinity of the caverns.

2.4.4. Failure criterion

We did not use a failure criterion. The damage criteria that we envisage, in terms of stress and strain around the storage (in the salt) can be easily plotted on the various test curves and it is clear that these criteria are much more conservative than the observed rupture envelopes (we compare deviatoric stresses of around 10 MPa to tests often reaching 12.5% strain and deviatoric stress of 25 to 40 MPa without producing failure).

3. - INDUSTRIAL PROBLEM

3.1. - Geometry of the system

As in all cavern fields, the real geometry of the system is purely three-dimensional. We therefore "meshed" various revolution geometries in order to make up for the limited possibilities of simulation.

First of all, as shown in table 3 below, we note that the releached caverns are not very different from each other and that the spacing measured between neighbouring caverns are all of the same order of magnitude. It is for this reason that we chose to consider both the behavior of a standard cavern (roof at 1150 m, bottom at 1450 m, diameter 64 m, spacing 260 m) located within the cavern field and that of an isolated extreme cavern. Two meshes were used, corresponding to the case of the single cavern and the cavern located in an infinite field, in order to analyze more fully the qualitative influence of other caverns in close proximity.

Table 3

CAVERN	DATE OF ACQUIRED GEOMETRY	DIAMETER AFTER LEACHING (Din m)	DEPTH OF ROOF (m)	DEPTH OF BOTTOM (m)	DISTANCES TO CENTER OF ADJACENT CAVERNS (m)				VOLUMES AFTER RE-LEACHING (m^3)
					D 1	D 2	D 3	Ratio D1/D	
EG 24	1976	55	1150	1445	208,7 (EH)	229,0 (EK)		3,79	348
EH 26	1979	41	985	1371	208,7 (EG)	246,0 (EK)		5,09	360
EJ 30	1978	64	1263	1555	255,3 (EL)	270,3 (EH)		3,99	500
EK 28	1976	52	1090	1400	223,2 (EL)	279,0 (EG)	246,0 (EM)	4,29	385
EL 32	1978	50	1074	1263	217,5 (EM)	223,2 (EK)	255,3 (EJ)	4,35	250
EM 27	1976	42	1165	1421	267,5 (EL)	270,3 (EJ)		5,18	217
EH 35	1978	70	1130	1482	301,5 (EL)	342,9 (EM)		4,3	500

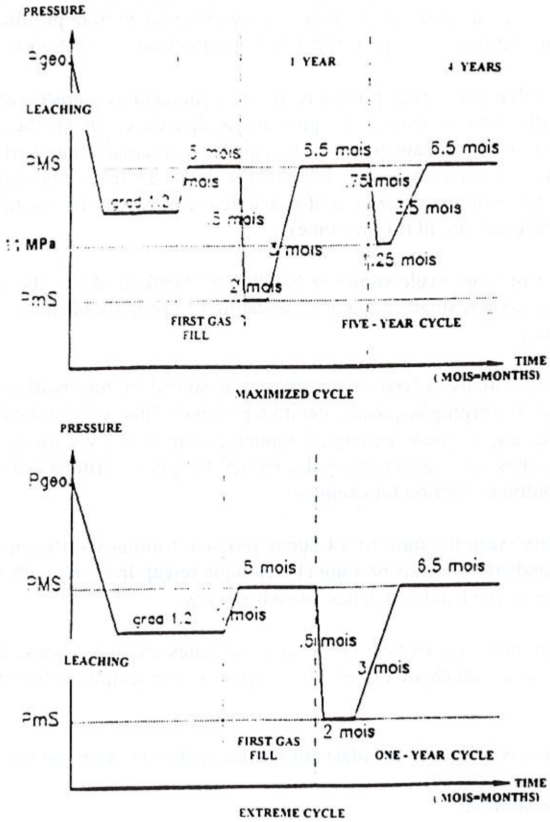
We also examined the case of the isolated cavern (called type I). This case appears to be representative of a cavern located at the edge of a cavern field. In this case, only the limestone roof was modelled above the salt.

Lastly, in order to maximize results, we use the conditions of symmetry existing in an infinite cavern field (zero horizontal displacement at the center of the pillar) to obtain a possible maximization of volume losses due to cavern creep. The mesh is called "C", standing for "champ", the French word for field.

3.2. – Predicted history of pressures. Operating conditions

One of the main problems facing the designer is that of establishing reliable data on future operating conditions or obtaining such data from the operator. As we will see, the history of pressures certainly represents one of the fundamental parameters in simulation results. This is to be related to the fact that an exponent "β" of around 3 is assigned to stress in the rheological law.

Figure 6 : Predicted history of stresses



We were thus able to define two types of pressure history, represented in figure 6, one considered to be sufficiently penalizing to serve as a basis for our simulations (with pressure dropping to minimum service pressure of 6 MPa for a two month period every five years), the other considered as extreme, with pressure dropping to minimum for two months each year.

4. – NUMERICAL SIMULATION

4.1. – Description of the calculation code

Calculations were performed using the finite elements method with the VIPLEF program developed at the Ecole des Mines in Paris (S.M. Tijani, 1979).

VIPLEF is a numerical code for the calculation of displacements, elastic and non–elastic strains and stresses in two–dimensional mechanical structures subject to initial stresses, external forces, temperature fields and pore pressures. Under the influence of these loads, which may be a function of time, the structure is subject to movement which may present plastic, viscoplastic or other irreversibilities. Calculations can be performed for both small and large strains.

In order to solve non–linear problems, the real problem is adjusted at all times to a problem of elasticity with initial stresses. The problem is discretized using the finite elements method, taking advantage of all modern techniques available : internal renumbering of nodes to reduce memory size and computation time, skyline storage, linear system resolution in blocks via temporary working files for optimum utilization of available memory, etc. In addition, the stiffness matrix is triangularized once and for all (to save time).

The problem of large–scale strains is handled by breaking down the real path into a succession of phases, processed as small strains with updating of geometry (standard technique) and stresses (original technique).

To deal with plasticity, a fixed point problem is solved by means of a simple "spiral" method (construction of a converging sequence, iterative process). This is a standard technique, but in VIPLEF, before introducing any new rheological model, constitutive laws are analyzed to avoid any linearization process, thus leading to increased accuracy for plastic criteria with discontinuous derivative, such as the Coulomb criterion for example.

Viscoplasticity takes the form of a Cauchy problem (ordinary differential system with initial values) which is handled by means of a novel technique (creep in stages) which is similar to the semi–implicit Eulerian method and which has two advantages :

- though the rheological laws are expressed in terms of rates in most cases, parameters are identified by laboratory tests which are essentially creep tests. The technique therefore involves a return to source,

- this technique makes it very simple to calculate automatically the optimum integration step.

4.2. – Meshing and limit conditions

The results presented here correspond to a "standard cavern", 64 meters in diameter, with its roof at 1150 m and its bottom at 1450 m and with a spacing of 260 meters.

In addition to the condition of axisymmetry, we impose conditions of vertical "non-displacement" at the base of the model and conditions of constant pressure to simulate the top of the model. On the edge of the model, we use either constant pressure conditions (infinite conditions) or horizontal blockage conditions to simulate symmetries (cavern field).

By means of these simulations we have thus evaluated the stress and strain conditions after 20 years of utilization for gas storage.

4.3. – Results

4.3.1. Synthesis

As a synthesis of these simulations, we established table 4, giving penalizing estimations for the areas around the caverns after 20 years of "maximizing" or "extreme" operation (T. You, P. Colin, 1990).

Table 4

RESULTS	CENTRAL CAVERN (maximized cycle)	CENTRAL CAVERN (extreme cycle)	ISOLATED CAVERN (maximized cycle)	ISOLATED CAVERN (extreme cycle)
ϵ_{vp} at wall (%)	18	30	7	9
ϵ_{vp} at 130 m (%)	2	4	0,5	0,6
σ at wall (MPa)	16	20	11,5	14
σ' at 130 m (MPa)	9	12	5	6,5
Volume loss (%)	21	30	9	16

We note from this table that although the pressure history has no fundamental consequences for isolated cavities, this is not the case for the simulation of the cavern "field". The geometrical conditions of the caverns converted to gas storage are therefore not neutral with respect to future operating conditions. However, the study shows that this geometry is fully compatible with the planned oprating conditions.

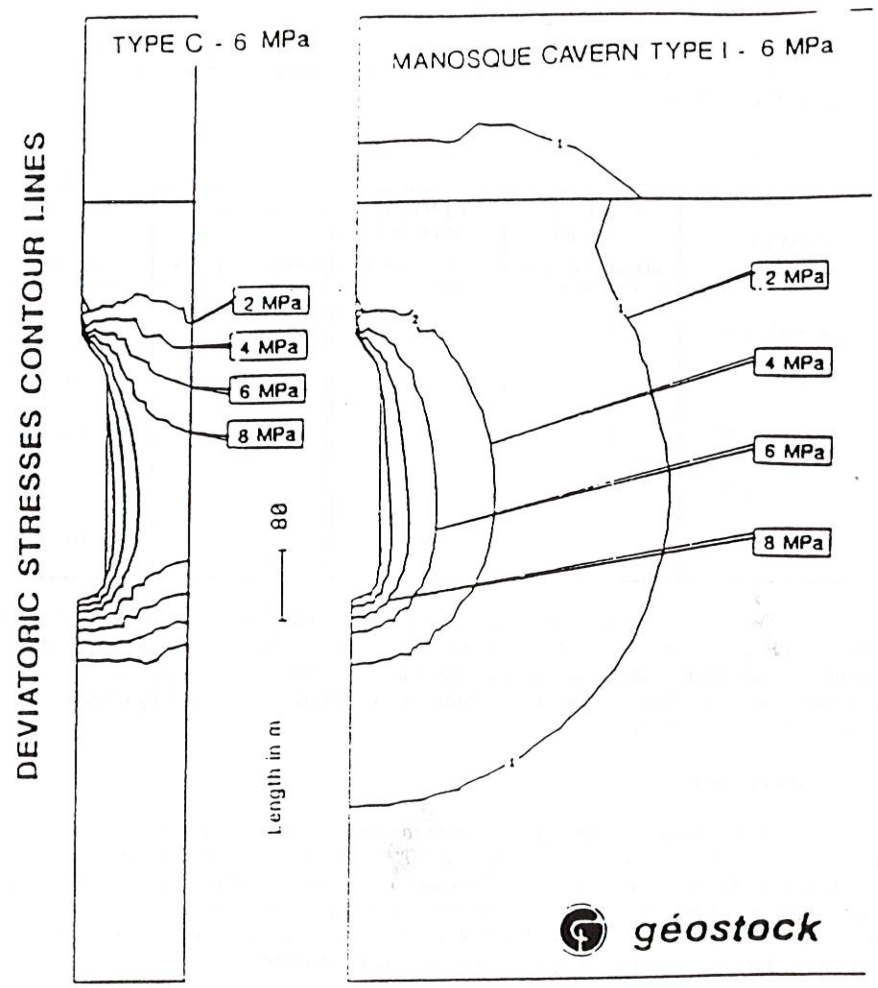
4.3.2 – Strain criteria

The simplified numerical modelling results give estimations of wall strains after 20 years of gas storage operation of around 10.10^{-2} and strains in the core of the massif of around 1.10^{-2}. Moreover, it would appear that only the inter-cavern pillars and the immediate wall exceed 2.10^{-2} of non-elastic strain, without any significant propagation of this "damage", either laterally or in the roof. It is clear therefore that the irreversible strains liable to occur are of a very reasonable order of magnitude with respect to overall storage stability.

4.3.3. – Stress criteria

These results, presented in figures 7a (type "C") and 7b (type "I") illustrate the existence of a significant pillar whose state of stress indicates that it has not reached the minimum damage "threshold". At most, this threshold is reached in the case of the "extreme", excessively penalizing cycle, though even here, more detailed examination of confinement pressures (see 2.4.3.) would doubtless make it possible to raise the design criterion.

Figure 7 : Numerical calculation. Stress contours.



5. - CONCLUSIONS

The Geomethane project has made it possible to define a new methodology for analyzing the stability of natural gas storage caverns leached out of salt. This approach, which has only recently been applied to rock salt, opens up new perspectives for research in the understanding and modelling of the behavior of salt massifs.

Having brought to light the damage phenomena which affect salt without modifying its apparent integrity, research could concentrate on the notion of recrystallization, fatigue and on the influence of loading rates.

From an industrial point of view, this progress opens new possibilities for the use of salt for the construction of underground structures.

N.B. : This study was performed between 1989 and 1990 and funded by Geomethane. Since that date, the caverns have been enlarged by leaching and the first gas filling operations should start shortly.

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