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Surface Subsidence Over Deep Solution Mined Storage Cavern Field

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Surface Subsidence Over Deep Solution Mined Storage Cavern Field

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SYNOPSIS Ten years observation by GDF on Tersanne solution-mined gas storage field, offers the opportunity for a mechanical interpretation of the surface subsidence.
According to the geological context, the rockmass was modellised by a two-layered medium with highly contrasted mechanical behavior : a soft elastic clay cover, and a viscous salt mass. Given the field uncertainties, mostly related to the cover layer, and the three-dimensional nature of the problem, indirect methods were used to obtain bounds for the surface subsidence evolution and a parametric study was performed. Comparison with data of the field allows to determine likely rock mass parameters, put forward some typical mechanical response, and give some insight on the trends of the subsidence phenomena.

INTRODUCTION

Interest on subsidence above salt caverns has grown up with new environmental protection concerns, and may appear in the future to be a dimensioning factor for cavern arrangement and operating. Subsidence caused by human activity arises whenever large underground openings are created. It may result from mining involving roof breakdowns, or simply from openings' closure, as for leached caverns for hydrocarbon storage. For classical mining, more than one century observations have brought engineers to a heuristic understanding. But few measurements have been undertaken over deep leached salt cavern fields, exhibiting smaller subsidence but delayed phenomena, such as the AZKO brine production field in Netherlands (Wassmann, 1992), or the Tersanne hydrocarbon storage of Gaz de France (G.D.F.) in France (Durup, 1990, 1991)... This latter field will be considered herein. It involves the largest cavity closures due to natural gas storage, and appears to be of particular interest.

Up to now, analyses mainly focused on the near field aspect (Boucly, 1981, Berest & Nguyen-Minh, 1984, Hugout, 1988, Durup, 1989,..) ; extensive laboratory tests and in situ model calibration by G.D.F., led to a fair understanding of salt behavior, and its inference on the cavities' closure, although some undetermination remains concerning long term behavior. But the continuous growing surface troughs evidenced by surface observations raise up new questions on the inference of cavity operating dates and cover layers' properties on the long term evolution of subsidence, and the effects of this subsidence on the well cementations.

Taking advantage of the available field data, we try to answer such questions by a mechanical approach. The problem involves the study of long term phenomena of three-dimensional nature. Uncertainties on the overlying clay cover layers, together with the highly non linear behavior of salt rock are other new specific difficulties of the analysis. This paper presents some new developments of a study partly presented in (Nguyen-Minh & al, 1992). The reader is also invited to refer to another analysis of the AKSO site by Wallner (1992), with a little different approach for leached cavity field in a domal formation (Wassmann, 1992).

TERSANNE FIELD DATA

The Tersanne field lay in a horizontaly layered sedimentary medium, with a cover layer, including basically clay with other soft rocks, a thick 1000 m bedded salt layer, and a rigid sandstone base. Cavities lay 1500 m depth, in salt layer, 150 m beneath the clay cover. With the last cavity in operation since 1983, the fourteen hexagonally arranged cavities and 600 m spaced, 40 m equivalent radius each, are displayed over an area of 3 km^2 offering a storage capacity of 440 million cubic meters (Figure 1). More than ten years field observation by G.D.F. included continuous monitoring of altimetric measurements by a network of surface survey benchmark, covering an area of 15 km^2, as well as underground cavities' closure survey (Durup, 1990).

The observed subsidence trough is is roughly axisymmetric, with the maximum in the central zone ; surface subsidence evolution was converted by careful integration,

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into subsidence volume loss V^s and related to the total volume losses of the caverns V^c. The following noteworthy data will be kept in mind as reference for the mechanical analysis (Figure 2) :

- The maximum subsidence rate is about 1cm/year
- The ratio V^s / V^c is about 60%

This latter data raises the question of a dilatant behavior inside the rock mass.

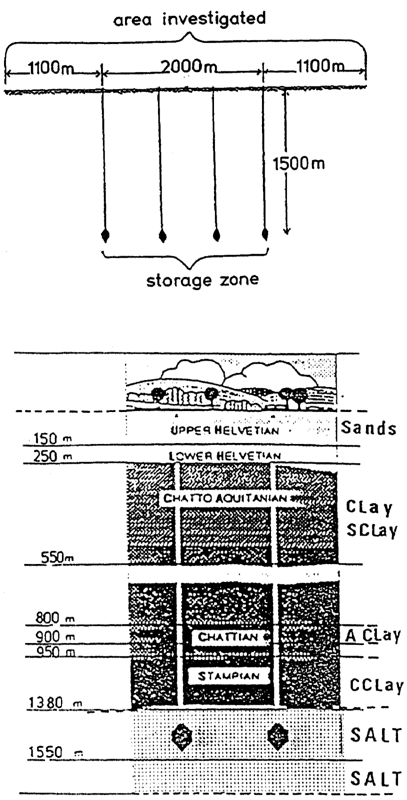

Figure 1 - The Tersanne geology and cavity array

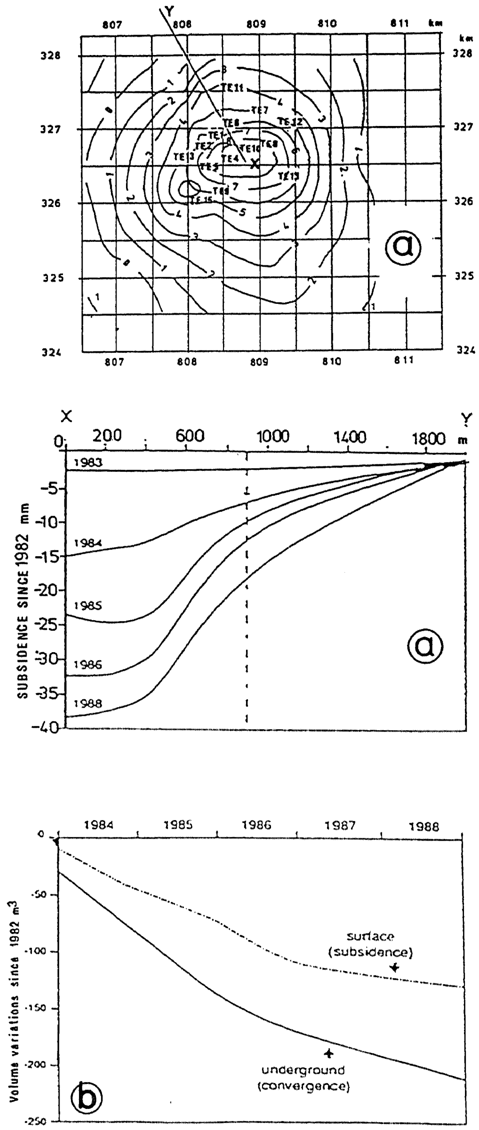

Figure 2 - Subsidence data

MODELISATION

The model includes a geometrical simplification, with spherical cavities standing for the caverns, and a loading history schematization.

1. Two-layered rock mass model : salt rock is much more creeping than the clay cover, and exhibits a stiffer instantaneous response. Besides the uncertainties, this highly contrasted behavior seems to play a key role in the mechanical response of the system. Thus, we modelized the rock mass as a two horizontaly layered medium, with interfaces perfectly bonded, given the small strains involved. Using subscript $()_1$ and $()_2$ for parameters of each medium (Figure 3) :

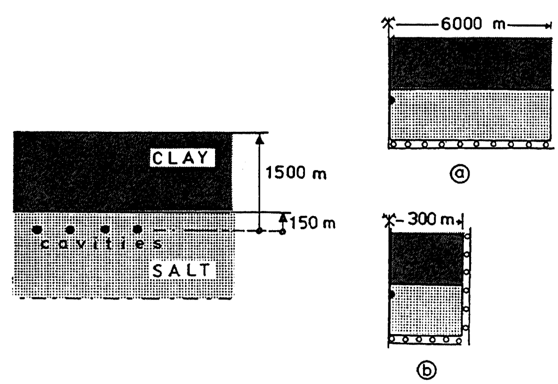

Figure 3 - simplified two layered medium
a - single cavity b-unit cell for an infinite cavity array

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- The thick viscous salt rock layer ranging from 1350 m to 2100 m depth. Its instantaneous linear elastic response is defined by the usual salt constants :

$$E_2 = 25000 \text{ MPa} \quad ; \nu_2 = 0.25$$

For practical reasons, the time dependent response will be described by a classical Norton-Hoff's law (N-H). Dilatancy is ignored, as leaching processes and operational loading history are chosen to induce enough slow strain rates to avoid damage of the material. Let recall the (N-H) constitutive law :

$$\dot{\epsilon} = \dot{\epsilon}^{el} + \dot{\epsilon}^{vp} \qquad \dot{\epsilon}^{el} = \text{elastic strain rate}$$
$$\dot{\epsilon}^{vp} = \text{viscoplastic strain rate}$$

$$(1) \qquad \dot{\epsilon}^{vp} = 3/2 \; a \; (\sigma_e/\sigma_0)^n \; \frac{s}{\sqrt{\sigma_e}} \quad ; \quad \sigma_e = \sqrt{3J_2}$$

and $\sigma_0 = 1$ MPa a reference stress.
$a = 5.68 \; 10^{-8} \text{ day}^{-1} \qquad n = 3$

Temperature dependent parameter "a" is a mean value at the depth of the storage, as the geothermal gradient has been neglected. The former set of parameters have been chosen to obtain equivalent (N-H)'s law to Gaz de France's currently used Lemaitre-Menzel-Schreiner's law (L-M-S) :

$$(2) \qquad \begin{array}{lll} \epsilon_{vp} = a' \; (\sigma/\sigma_0)^n \; t^\alpha & \text{uniaxial creep law} & \\ a' = 1.795 \; 10^{-6} \text{ day}^{-\alpha} & n = 3.6 & \alpha = 0.5 \\ E_2 = 20000 \text{ MPa} & \nu_2 = 0.25 & \end{array}$$

Equivalence was set on the basis of getting a volume closure of some 20% in ten years, as observed on the field, for a cavity in an infinite medium subject to a same equivalent constant differential pressure.

- The overlaying clay cover will be modellized by an homogeneous isotropic equivalent elastic layer, with high deformability. The following typical elastic constants were choosen for the cover, and will be subject to variations according to the parametric study :

$$(3) \qquad E_1 = 6000 \text{ MPa} \quad ; \nu_1 = 0.4$$

2. initial stresses and loading history : initial gravity stresses result from unit weight $\gamma_1 = 0.023$ MN/m^3 for clay and $\gamma_2 = 0.022$ MN/m^3 for salt rock. The ratio K of the horizontal stress σ_{xx} to the vertical one σ_{zz} is :

(4) $K = \nu_1/(1 - \nu_1)$ for clay (elastic equilibium)
$K = 1$ for salt (viscoplastic equilibrium)

Loading history involves a sudden drop of the pressure at the wall of every cavern from its initial geostatic value to a residual constant uniform value (18 MPa). This pressure is equivalent to the differential pressure determined hereabove. As far as long term behavior is concerned, the leaching history and the different timing operation of cavities have been ignored.

STATEMENT OF THE PROBLEM

The three-dimensional problem, involving far field conditions due to the semi-infinite medium, requires a same accuracy for the closure of a 40 m radius cavity and for the displacement on surface 1500 m above. Hence, a three-dimensional finite element calculation would not be realistic at this stage of the study, all the more as parametric studies are needed. Indirect approaches are preferred, with the idea of estimating bounds for the surface subsidence evolution.

Two cases are studied :

1) Superposition of the elementary solution for a single cavity in a semi-infinite medium, for the fourteen Tersanne's cavities, as well as for an infinite array of cavities. The result is correct for the instantaneous elastic response, but is not in the non linear delayed response. In that latter case, the cavities' interaction is neglected, which can be supposed to give a lower bond for subsidence or its rates.

2) The case of an infinite array of cavities, which gives an upper bound for the rates of subsidence.

The analyses are conducted within the frame of a methodology which takes advantage of an adimensional formulation and of the existence of steady stress state field of such kind of problems. Indeed, although no parametric analyses on the viscous coefficients are explicitly displayed in this paper, it is implicitly kept in mind that variations of these parameters can be considered, from the available numerical data ; if n is chosen constant for a given salt rock, the changing of parameter "a" will result into a simple time scale change. Moreover, the calculations obtained herein can be transposed approximately to the (L-M-S) model, by a simple transformation on the time axis (Nguyen-Minh, 1991). The (N-H) parameters chosen herein are then to be considered as typical reference ones. Likeliness of time constants derived from the analysis, as well as comparison with in situ data will serve as guidelines. The numerical calculations were performed with the GEOMEC code from LMS.

Let us define some geometrical parameters related to subsidence (Figure 4). The intermediate level of the clay-salt interface deserves attention. Let note V^s the volume loss by subsidence at the surface, V^i at the interface, and V^c by cavities' closure. The subsidence border is arbitrary defined as the point where 5% of the maximum subsidence

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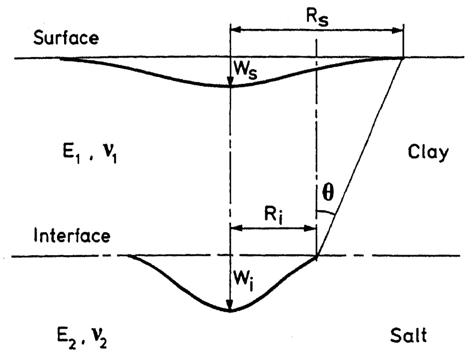

Figure 4 - Subsidence parameters

is attained ; in axisymmetry, this border is a circle of radius R^s on the surface, and R^i on the interface. The transference of subsidence up to the surface is then defined, in a meridian plane, by the "influence angle" θ, between a vertical and a line joining these subsidence borders.

SINGLE CAVITY IN SEMI-INFINITE MEDIUM

The history of loading leads to the following cases :

1. Instantaneous elastic response

The elastic data will serve as a reference for the parametric study, as far as the instantaneous response can influence the delayed behavior. Let first consider the simplified approximate solution of a point sink producing an equivalent loss of ground at certain distance, in an homogeneous medium. The subsidence W for a variation of pressure P inside the cavity of radius R_0 at depth H is then described by a close form solution in cylindrical coordinates (Hetuin & al 1989) :

$$(5) \qquad W = \frac{2 P (1-\nu_2{}^2) R_0{}^3}{E_2} \; \frac{H}{(H^2 + r^2)^{3/2}}$$

For the two-layered medium, a numerical approach is used ; in view of a parametric analysis, initial stresses are still not considered here. Given the great depth of the overburden in the semi-infinite rock mass, and the need for accurate data at the surface, the finite element method was performed in two steps :

In a first step, a global calculation allowed for a good precision within a zone surrouding the cavity, including the interface trough between salt and clay ; the cylindrical model (6000 m outer radius, and a 1500 m deep cavity with radius 40 m), included 1601 nodes and 451 quadratic elements.

In a second step, the displacements of the interface through formerly determined are prescribed on the only elastic cover layer (radius 12000 m, height 1350 m), more finely meshed (2289 nodes and 565 elements).

A good agreement with the closed form solution on the maximum subsidence is obtained for the homogeneous medium. The parametric study on the cover's properties showed that the Young Modulous E_1 is the most influent parameter. When E_1 decreases from 25000 MPa to 2000 MPa, maximum subsidence W^s increases by 90% and the trough radius by 5%. The influence angle θ remains unchanged (55^0). Taken all round, these data show that that cover layer's properties appear to be of secondary importance compared to salt rock's ones, the more as the cover's layer modulous is likely to range in a smaller interval (1000-6000 MPa). The reason rests in the occurence of largest strains in the salt rock host medium.

2. Delayed response

The models considered hereafter include initial geostatic stresses. Typical results for the standard set of parameters for the clay layer (3) are the following (Figures 5, 6, 7) :

- The radius of the interface trough R^i tends to stabilize, while the surface trough diminishes from 3000 m to 2000 m. The dip angle thus decreases from 65^0 to 55^0.

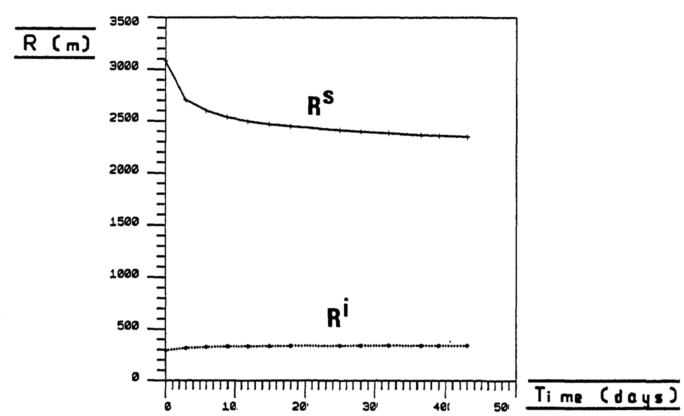

Figure 5 - Evolution of subsidence radii (Single cavity)

- The maximum surface subsidence $W_0{}^s$ still increases, and the subsidence rate $\dot{W}_0$ after 430 days is :

$$(6) \qquad \dot{W}_0 = \quad 1 \text{ mm/year}$$

- No volume losses deficit occurs in the elastic clay layer ($V^s/V^i \simeq 1$).
- Volume losses deficit is mostly localized in the salt layer : ratio V^i/V^c between cavity closure and interface

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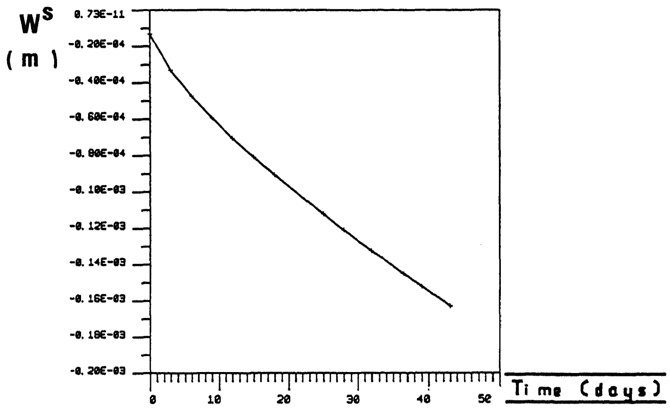

Figure 6 - Evolution maximum surface subsidence (Single cavity)

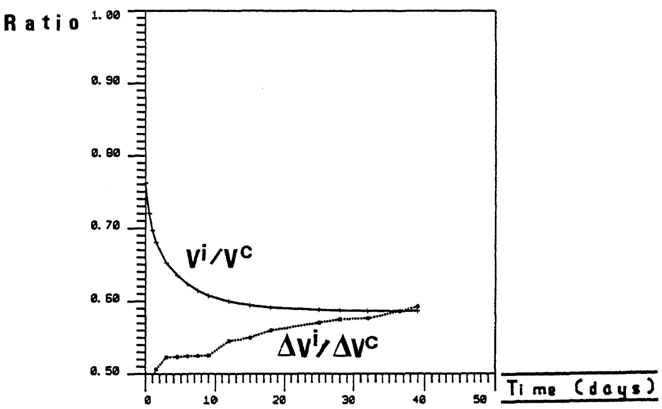

Figure 7 - Evolution of volume losses (Single cavity)

subsidence are only 60%, and will slowly increase with time. This means the salt mass still exhibits an elastic-viscous interaction, and that the asymptotic state, characterized by an incompressible behavior, is not yet attained. The increasing "volume loss rate ratio" $\Delta V^i / \Delta V^c$ allows then to estimate by extrapolation to 1, that 5 years will be necessary to attain that steady state. This asymptotic stress state can be obtained directly by the elastic analog approach (Nguyen-minh, 1990, Blanquer-Fernadez, 1991).

These results remain practically unchanged when E_1 was divided by 2 ($E_1 = 3000$ MPa), excepted the radius of interface trough which decreased by some 5%, and the maximum subsidence rate W_0 which increased by some 16%.

SUPERPOSITION OF ELEMENTARY SOLUTIONS

The superposition was made for the 14 Tersanne's cavity arranged on the Figure 1's pattern and for an infinite array of cavities regularly spaced on concentric circles. For the infinite array, the surface subsidence is flat. For the 14

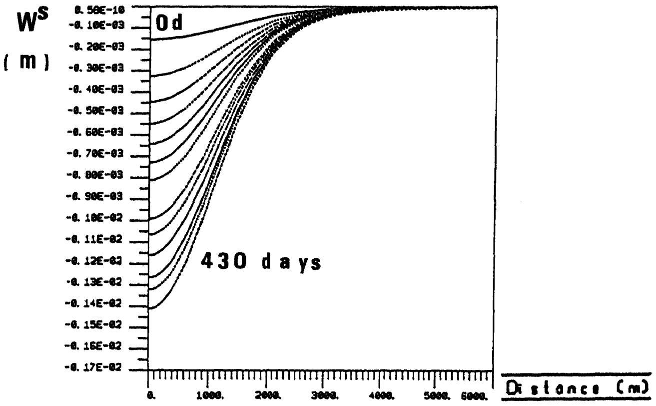

Figure 8 - Evolution of surface subsidence trough (Superposition of 14 cavities)

cavities, the surface subsidence trough is practically axisymmetric with maximum in the center (Figure 8). On the contrary, the interface trough is strongly influenced by the vicinity of the caverns, all the more as creep proceeds ; there results out of center maxima (Figure 9). Let focus our attention on the maximum subsidence, W_0 for a single cavity, W_{14} for the fourteen cavity field and W_∞ for the infinite array.

1. Elastic case : results for an homogeneous medium can be derived analytically from the sink point solution, for the fourteen Tersanne's cavities, and for an infinite array as well ; with $H/R_0 = 37.5$ and a cavity with a differential pressure of 16.5 MPa, we have $W_{14} \simeq 10\ W_0$ and $W_\infty \simeq 40\ W_0$. It can be checked from numerical analyses, that these trends still roughly work for the two-layered medium ; but, taking into account the geostatic stresses will result in some different ratio :

(7) $\quad W_{14} \simeq 11\ W_0$ (instantaneous)
$\quad\quad W_\infty \simeq 28\ W_0$ ....

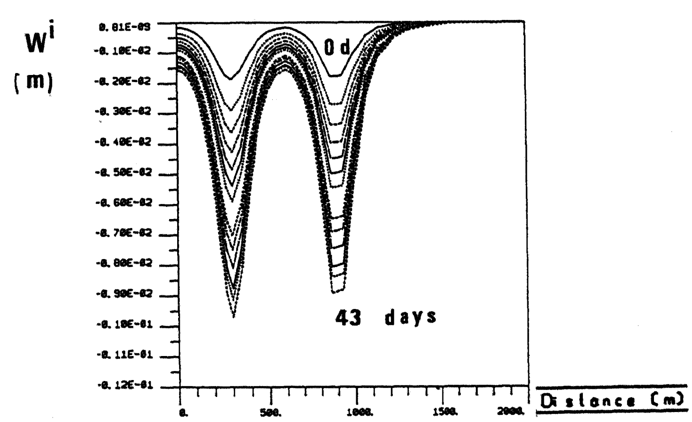

Figure 9 - Evolution of interface subsidence trough (Superposition of 14 cavities)

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These ratio will still change with time as creep will proceed.

2. Delayed behavior : at any time, the solution for the single cavity, is superposed as above, for the fourteen cavities or for the infinite row of cavities. This will result into a same volume loss deficit still localized in the salt layer, around 60% and the time constant to attain steady state around 5 years. The ratios of maximum subsidence to that of the single cavity W_0, which is time dependent, decrease with time :

(8) $W_{14} \simeq 8\ W_0$ (after 43 days)
$W_{\infty} \simeq 16\ W_0$ ....

and for subsidence rates, noted () :

(9) $\dot{W}_{14} \simeq 9\ \dot{W}_0$ (after 43 days)
$\dot{W}_{\infty} \simeq 13\ \dot{W}_0$ ....

This leads, with (6), to 0.9 cm/year subsidence rate for the 14 cavities, which is quite close to the observed data.

INFINITE CAVITY ARRAY

The two-layered medium is modified here by lowering the upper surface of the clay layer to 900 m depth and submitting it to an equivalent uniform pressure due to the weight of the overburden. This was shown not to influence the results and allowed to study a smaller structure. The unit equivalent hexagonal cylindrical cell with a single cavity is replaced by an axisymmetrical problem, with radial displacements fixed (Figure 3). Need of precision, made it necessary to elaborate a fine grid, resulting into a 2609 nodes and 660 quadratic elements model.

1. Displacement field : as thoroughly described in (Nguyen-Minh & al, 1992), a noteworthy result is the rigid descent of the cover some distance above the cavity, including most of the clay cover. Indeed, the mean vertical deformations occur in a stripe of less 300 m height, including the cavity. This implies no influence of the mechanical properties of the cover layers, and a dependence of subsidence on the only salt rock characteristics. The uniform subsidence rate after one month creep is about 8.5 cm/year.

2. Volume loss evolution : Figure 10 shows the evolution of the ratio between the two volume losses V^c/V^s, and between the rates of these volumes $\Delta V^c/\Delta V^s$. For V^c/V^s, one can see that this ratio first decreases from an initial 65% value, and then increases slowly. The ratio $\Delta V^c/\Delta V^s$ continuously increases ; as hereabove, the time to attain steady state can be estimated to $\tau \simeq 1$ year. After that time subsidence will result into a constant rate vertical descent. A parametric analysis has been performed on salt elastic parameters ; it can be remarked that when $\nu_2 = 0.5$, salt would be incompressible, and hence, volume ratio would be 1 at any time, i.e. $\tau = 0$. But these results remain theoretical, since ν_2 is rather well defined and vary in a small range.

DISCUSSIONS AND COMPARISON WITH FIELD DATA

The consistency of the predicted maximum subsidence rate, ranging from 0.9 to 8.5 cm/year, with the 1cm/year observed one, confirms the pertinence of the analysis together with the mechanical parameters. This has however to be tempered by the following remarks.

Compared to the lower bound approach, the actual behavior involves interaction of cavities resulting in a rate increasing ratio. For the 14 cavities, this ratio would range from 1 to 6, the maximum value being determined for the infinite array. Better precision needs further analyses which would imply or not higher cover's modulous E_1.

The upper bound approach is independent from the cover's characteristics. The temporary consistency of predicted 8.5 cm/year demonstrates the preeminence of salt characteristics in the subsidence phenomenon. However, this approach shows some limitation. Indeed, it gives a constant subsidence rate, which is not true, because this rate must finally vanish, as proved as follows:

- The steady stress state implies a rigid descent of the cover, because as $\dot{\sigma} = 0$ everywhere, and specially in the cover, we have, due to elasticity, $\dot{\epsilon} = 0$, including on the interface.

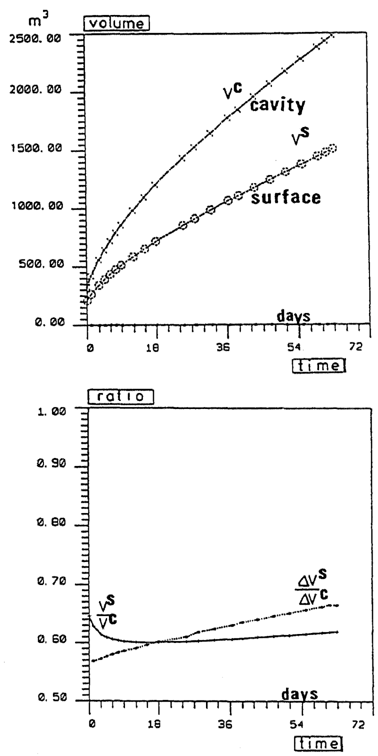

Figure 10 - Evolution of volume losses (infinite array)

- Thus, as the storage field is of finite extent, the finite volume rate of the cavities will result asymptotically, on the infinite interface, in an infinitely small uniformly distributed substance rate. The trough will then finally stabilize. However, this statement has itself to be tempered, because steady state is based on a small perturbation hypothesis. Indeed, the geometry of cavities will change with time, and another larger time scale phenomenon will prevail as the cavities proceed towards total closure (Nguyen-Minh, 1991).

Concerning the volume loss ratios, it is interesting to note that the average 60% observed volume ratio V^c/V^s is readily accounted for from the elastic compressibility of salt, by both approaches. Theoretically, this ratio will attain 100% only after steady state is reached : 5 years for the superposition approach, and 1 year for the infinite array model. The actual time constant would lie in between.

CONCLUSIONS

Although the mechanical response of the cover layer above salt is badly known, this preliminary study has shown that it is possible to draw out some trends and general conclusions on subsidence phenomena thanks to the secondary importance of the cover layer properties compared to those of the salt rock.

The field observed 60% mean ratio V^s/V^c of volume lost by subsidence over that lost cavities' closure, has been mainly explained by the compressibility of the host medium, and on the initial stress state. Then, the risk of dilatancy occuring inside the rock mass had not to be considered.

The analysis has shown that this ratio V^c/V^s first decreases before increasing towards 1. Ultimately, the surface subsidence is believed to stabilize, due to the finite extent of the storage field compared to the infinite interface surface, but more long term phenomena will arise with the complete closure of the cavities.

The cover layer's equivalent elastic modulous should be at least 6000 MPa, and the time constant to reach an asymptotic state would be less than 5 years.

The ongoing analysis will allow us to better take account of the cavities' interaction, define the practical extent of the trough radius, and the time constant of the phenomenon, in order to answer or treat different questions raised hereup.

AKNOWLEDGMENTS

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