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Subsidence above rock-salt cavities – Numerical and explicit evaluations

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ABSTRACT: Subsidence is always a long-term effect from the exploration of natural gas storage cavities. The internal pressure being less than in situ pressure leads to cavity convergence with has economical consequences as well as possible outcomes on the surface. After reviewing the subsidence phenomenology, by identifying what can be observed at the surface, and its environmental and structural consequences, some empirical and analytical means of estimating its deformation values are referred. With more detail, a numerical application is presented which uses coupled boundary and finite elements for subsidence evaluation due to deep storage cavities. This last characteristic gives rise to large extensions of deformed zones towards the surface. A real case of a storage cavity field with subsidence measurements made for more than ten years is taken as example and some predictions are made on future subsidence and horizontal displacement.

1 INTRODUCTION

Storage cavities in rock salt are often created with a dissolution process where fresh water is injected through the well and salt water recovered. After this leaching technique being carried out during several months, a huge cavity in salt can be used for liquid or gaseous hydrocarbon strategic reserves. This process of void creation disturbs the initial equilibrium of the rock salt leading to cavity convergence because internal pressure will always be less than geostatic pressure. This will cause a volume decrease, with the inevitable economic consequences, and also give rise to surface deformations made up of subsidence and horizontal displacements.

The use of analytical models to interpret the thermomechanical behavior of these storage cavities is essential to predict future evolution of the underground structures as well as its repercussions on the surface like for instance subsidence. Explicit analytical solutions are limited to very simple cases of cavities and are more used with parametric studies than with real structures.

The numerical analysis of a storage cavity group is a three-dimensional problem leading to calculations difficult to perform. If certain conditions regarding field geometry are satisfied the solution can be approximated by a superposition of several calculations of single cavities in infinite medium. The need of an accurate calculation of the subsidence due to one cavity is therefore needed as

this phenomenon extends to a large distance on the surface. This is not easy with classical numerical methods, given the small dimensions of the cavity compared to its depth. For this purpose, one uses a recently developed mixed finite and boundary elements model, which is specially adapted to the problem (Menezes, 1996).

In contrast with storage cavities, the dissolution induced mine subsidence is more significant as cavity internal pressures are hydrostatic type or even null. Van Sambeek (1996) gives a demonstrative example in a very elaborate report. In addition many of the storage cavities in rock salt formations are filled with salt water after its final closure to exploration.

2 ETREZ STORAGE CAVITY FIELD

The surface subsidence observations performed by Gaz de France on the Etrez gas storage field were done with the same purposes as those performed in the Tersanne field, which were object of several former reports and publications (Durup, 1990, 1991; Nguyen-Minh et al., 1994). It has been shown that rock salt played a major role in the subsidence phenomenon, while the cover strata behavior, which characteristics are not well known, was of secondary significance.

Etrez storage field has its cavities arranged as shown in Figure 1. There is a regular hexagonal centered pattern with spacing between cavities of

about 600 m. The former cavities are surrounded by more recent ones. This strategy of cavity distribution contributes to a low measured and computed subsidence as will be presented later. In Figure 2 the distribution in time of the cavities first year operation is shown. Table 1 summarizes the main geometric characteristics of the cavities.

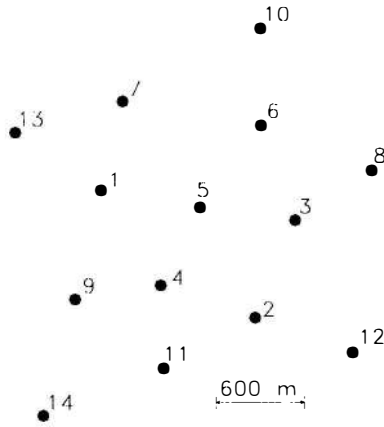


Figure 1. Surface distribution of storage cavities from Etrez.

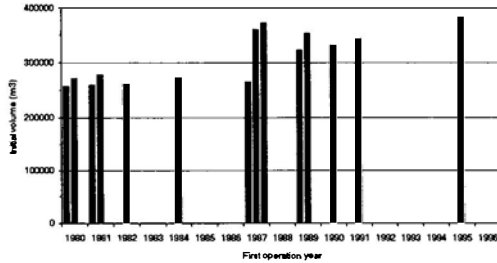


Figure 2. Time distribution of first year operation.

Table 1. Etrez cavity field.

Cavity N.	Year	Volume	Depth
		m ³	m
1	1980	257600	1441
2	1980	272500	1443
3	1981	260500	1448
4	1981	278400	1457
5	1982	261600	1442
6	1984	272100	1441
7	1987	264700	1440
8	1987	361000	1380
9	1987	373100	1500
10	1989	322600	1390
11	1989	354500	1390
12	1990	332300	1450
13	1991	343800	1380
14	1995	383600	1450

3 NUMERICAL MODEL FOR SUBSIDENCE EVALUATION

The subsidence analysis of a cavity field is a three-dimensional problem. However, simplified analysis using a superposition procedure with the calculation of a single cavity in infinite medium can be used. This procedure was validated in previous studies on Tersanne site (Nguyen Minh et al, 1994). Theoretically, the superposition should not be valid according to the non-linear nature of the problem. But validity of this method holds for the specific conditions of the problem, involving linear elastic cover strata and largely spaced cavities (typically 600 m).

The viscoplastic law representing the salt rheology corresponds to Norton-Hoff or Lemaitre-Menzel-Schreiner depending on its parameters values (Equation 1):

$$\epsilon_{vp} = 10^{-6} \left(\frac{\sigma}{K} \right)^{\beta} t^{\alpha} \quad (1)$$

where t = time in days; ϵ_{vp} = viscous deformations.

The viscoplastic behavior law can be expressed in a more general form as Equation 2:

$$\dot{\epsilon}_{ij}^{vp} = -10^{-6} \frac{3}{2} \frac{\sigma'_{ij}}{\sqrt{3J_2}} \frac{d}{dt} \left(\xi^{\alpha} \right); \xi = \left(\frac{\sqrt{3J_2}}{K} \right)^{\beta \alpha} \quad (2)$$

If one considers a spherical cavity, submitted to an interior constant pressure, located in a homogeneous and isotropic infinite domain, volume variation rate is given by Equation 3:

$$\frac{dV}{V dt} = -10^{-6} \alpha \left(\frac{P_{\infty} - P_i}{A} \right)^{\beta} t^{\alpha-1}; A = \left(\frac{2}{3} \right)^{\beta} K \beta \quad (3)$$

where P_i = internal pressure; P_{∞} = geostatic pressure.

The N-H rheological parameters used in the numeric calculations were identified in order to obtain an equivalent behavior after 10 years for a spherical cavity located at 1500 m depth, in a viscoplastic domain. Internal pressure P_i was determined in such a way that the volume loss of one spherical cavity would be the same as one real cavity with a real pressure history at Etrez. This pressure would be 16.5 MPa with the L-M-S model.

Constitutive laws for rock salt validated over short time periods are more uncertain for a 100 years forecast. Therefore bounds must be proposed to subsidence by choosing two alternative laws, with one admitting a stationary creep (N-H). The rheological parameters used in the numerical calculations, identified according to observation periods of ten years average, are the following:

-Superior Etrez salt at the in situ temperature of 50 °C

$\alpha = 0.36$ $\beta = 2.98$ $K = 1.1$ L-M-S

$\alpha = 1.00$ $\beta = 3.0$ $K = 6.34$ N-H

-Inferior Etrez salt at the in situ temperature of 55 °C

$\alpha = 0.44$ $\beta = 3.93$ $K = 1.95$ L-M-S

Each basic computation involves a single spherical cavity with the volume and depth indicated in Table 1, located inside the inferior salt layer and where intermediate cover strata is located 110 m above the roof of the spherical cavity, as shown in Figure 3.

The new numerical model used for the basic computation presents the novelty of using the integral equation and boundary element method, associated with the finite element method. Besides, one introduces infinite elements in order to simulate infinite remote boundaries. The surface discretization reaches a much larger distance than at the level of cavity strata in order to obtain a precise solution of field displacements on the surface. As cover elastic strata are discretized with boundary elements such distance does not constitute an excessive weight for computer memory. In this way one obtains a mixed mesh which develops following a greatly bigger distance in reaching the soil surface.

When salt cavities are not axisymmetrical and it is not possible to rely on superposition procedures one must use three-dimensional numerical models. These are beginning to have a more generalised use as numerical and graphical processing grow in efficiency. You et al. (1996) present one such code and try some simulations of several case studies. Hilbert et al. (1998) also present a 3D model although with different applications. They have good correlation between measured and computed subsidence.

A logical future development of the mixed numerical model presented above is its extension to three-dimensional problems. This is already in progress and soon other type of cavities and storage fields will be analysed with its true geometry.

As an example of an explicit method for prediction of subsidence above salt cavities, the method of Schober (1987) should be referred. It assumes that cavity convergence is essentially horizontal and gives expressions to compute its value. However the viscoplasticity characteristic of rock salt is not taken into consideration as time has no influence on the computed values.

4 SUBSIDENCE CHARACTERISTICS IN ETRÉZ

Mining engineering, especially from coal extraction industries, has a vast amount of experience about the movement processes above

mined cavities. However, these theories refer to the collapse of roof layers and so they are not suitable to the case of storage cavity fields in rock salt formations.

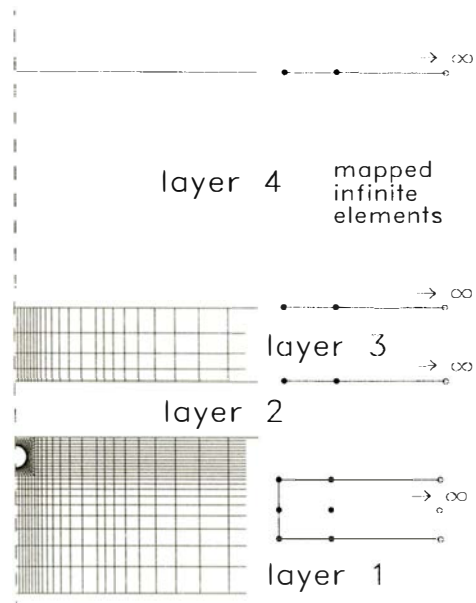


Figure 3. Mixed discretization of a cavity domain at Etrez.

National regulations in some countries make reference to the effects of subsidence over the environment. The European Norm EN 1918- 3:1998 (NF EN, 1998) reminds that the subsidence eventuality must be considered as a consequence of an underground storage project. Therefore one must make provisions of future surface deformations and, if needed or imposed by regulations, establish an observation program.

The cumulated information of more than ten years from surface subsidence observations at the Etrez gas storage field, in France, can be used as a validation example of a numerical model. For a single cavity, the maximum subsidence must lie on the vertical of the void centre, although in some cases the cavity bubble migration towards the surface might produce some negative subsidence. The horizontal displacements increase from zero at the centre to a maximum somewhere above the limits of the cavity field. A compression zone is then delimited, surrounded by a traction zone.

The effects of surface subsidence depend on several factors as the problem geometry, the geologic nature of the rock mass, the excavation process and the pressure history of the cavities. It is quite difficult to include all these variables in a

theoretical analysis, so several methods do exist to give an approximate function of the vertical movements.

Subsidence or vertical displacements can give rise to trough formation at the surface. Horizontal displacements can have serious consequences on existing surface structures. Usual empirical methods are incomplete for some situations as they only estimate subsidence values and not dangerous horizontal movements.

Other alternative is to estimate the convergence rate from the subsidence data. Some predictions can be made assuming that convergence rates remains constant if operating conditions does not change significantly (Reitze & Von Tryller, 1996).

In Figure 4 measured subsidence values, obtained during the period of 1985-1995, are compared with the subsidence curves calculated for 5, 10 years, and the difference between these two.

5 SUBSIDENCE LONG TERM PREDICTIONS

For long calculation time (100 years) displacements may become too large to still admitting the hypothesis of the small deformations. So, for each cavity a variable geometry numerical analysis was performed by reassembling a global rigidity structure each time there was a new topology to consider.

All cavities were discretized with their real volume and depth in the superposition procedure. The true surface coordinates were also considered as the date of starting operation year. So the cumulated volume losses, calculated for the 15 cavities, are all different.

The fact of counting with the geometric modifications avoids some quite important numerical errors, otherwise, after a certain period of time lost volume in surface would become superior to the lost volume in the cavity.

After performing the superposition of the displacement fields for the 15 cavities arranged as indicated on the Figure 1, one obtains the subsidence curves represented in Figure 5. The inflection points are represented and they practically define the compression and traction zones.

The horizontal movement previsions are shown in Figure 6. Positive values are considered as being from West to East just for a graphical convenience. Positive and negative signs show the extension of traction and compression zones and not the displacement direction. It seems that their size does not change significantly with time.

Around an isolated cavity horizontal movements are zero at the centre and maximum at a certain distance from the axisymmetrical axis. This point

coincides practically with the inflection point of the subsidence curve.

Above the cavity field, after 50 or 100 year time, the curve geometry is practically the same. The compression zone above the storage field does not enlarge significantly with 50 years more. The traction zone combined with important differential settlements should be the most critical one for the structural stability of existing buildings and its foundations.

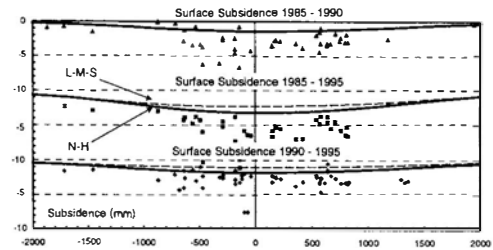


Figure 4. Comparison between measured subsidence at Etrez and calculated values.

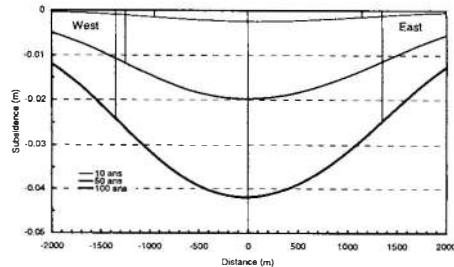


Figure 5. Subsidence predictions at Etrez.

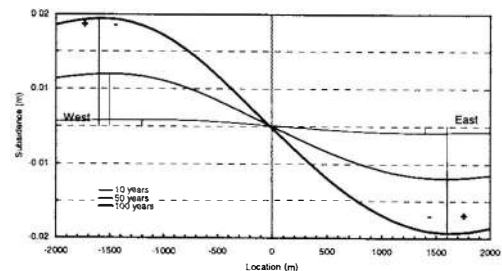


Figure 6. Horizontal displacement predictions at Etrez.

6 CONCLUSIONS

Although some refinement is still necessary, the numerical model presented seems capable of simulating satisfactorily the behavior of storage caverns in rock salt formations. The elastic cover parameters are somehow arbitrary but that is not the main reason why there is some poor agreement between the numerical model results and the observed subsidence. The Etrez salt is less viscous than the one corresponding to the parameters determined after the observation of the structure evolution until present time. This means that the prediction for 100 years by the numerical model with stationary creep (Norton-Hoff) is a reasonable superior limit. Its parameters are equivalent with a previous Lemaitre-Menzel-Schreiner model.

In the superposition procedure there must be no significant superposition of plastic zones around each cavity. Its application is restricted to cases where spacing between cavities and its depth have some minimum values. This validity was demonstrated and used in a global way.

The numerical model presented can be taken as a specific tool of subsidence analysis, especially with the improvements brought with the utilization of boundary and infinite elements for the semi-infinite elastic layers modelization, where it is essential a good precision necessary to the surface subsidence evaluation. This model is quite appropriate for the case where there are several rock salt layers intercalated with non-viscous strata.

The use of boundary elements becomes particularly useful in subsidence computations. This because one is able to compute surface displacements over a very large extension without losing precision and avoiding expensive costs concerning the time necessary memory for calculations.

New solutions for the hydrocarbon storage demand that numerical models support its complexity. The three-dimensional characteristic of many new cavities does impose 3D computations. The generalization of the mixed code referred above to non axisymmetrical space calculations will soon be tested with some real case studies calculations.

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