Typology of strata movement related to old solution mining of salt at Sarralbe (Lorraine, France)

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TYPOLOGY OF STRATA MOVEMENT RELATED TO OLD SOLUTION MINING OF SALT AT SARRALBE (LORRAINE, FRANCE)

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RESUME : Dans l'objectif de la fermeture des cavités de dissolution de sel situées près de Nancy (Est de la France) appartenant à la Société Solvay, l'INERIS a entrepris d'importantes investigations sur le site ainsi que divers forages. Elles ont été complétées par des essais de laboratoire et des travaux de modélisation numérique et d'une analyse des mouvements de terrain. Ces travaux complémentaires ont permis d'étudier le comportement à long terme des cavités au regard du risque de rupture du recouvrement. Les résultats ont abouti à conclure que, du fait de la présence des terrains déformables au sein du gisement de Sarralbe, les grandes cavités sont déjà effondrées et, pour l'essentiel, totalement fermées, tandis que des petits chenaux de dissolution ont pu demeurer ouverts sans donner lieu à un fluage significatif du sel du fait de la faible profondeur (de l'ordre de 250 m). Au-delà de l'objectif de cette étude, les investigations réalisées et leurs conclusions présentent un intérêt méthodologique dans le contexte de l'abandon d'exploitations de sel, d'un point de vue de l'évaluation à long terme de leur impact sur la sécurité des personnes et des biens et sur la protection de l'Environnement.

MOTS-CLEFS : affaissements, dissolution, sel, stabilité, long terme, mesures topographiques.

ABSTRACT: In the view of closure of solution-mining cavities in salt near Nancy (East of France) belonging to Solvay Company, INERIS undertook different investigations on the site as well as several boreholes. They were completed by laboratory tests and modelling as well as the analysis of strata movement. These complementary works allowed to study long term behaviour of cavities regarding the risk of collapse of the overburden. The results came to the conclusion that because of presence of deformable strata in Sarralbe deposit, large cavities have already collapsed and now mostly closed. Meanwhile, small dissolution channels might have remained open without any significant salt creep due to their rather small depth (almost 250 m). Beyond the objective of the performed study, the investigations and their conclusions are of a methodological interest for the propose of salt mines closure with respect to the evaluation of their long term impact on the safety of people and properties as well as Environment protection.

KEY-WORDS : subsidence, dissolution, salt, stability, long term, topographic measurements

1 Introduction

After a long period of exploitation, France as some other industrial countries is dealing with mine closure. Long term impacts of cavities on public safety, properties and the Environment bring to undertake specific investigations. They are of major importance for the cavities created by salt mines and solution mining, due to the high solubility of salt in water and the continuous creep of this material.

As a matter of fact, hydrogeological context, overburden characteristics, geometry and dimensions of cavities, their depth and the exploitation method have to be analysed in detail. This requires to collect all the data available and to complete them by field measurements, laboratory tests and modelling. Such investigations have been performed prior to the definitive closure of Sarralbe solution-mining cavities situated near Nancy (East of France).

2 Context and characteristics of Sarralbe deposit

Many investigations were undertaken during the period 1999-2001 in order to evaluate residual risks related to the solution-mining of salt by Solvay company in Sarralbe near Nancy and to establish the administrative abandonment procedure. At the request of SOLVAY, INERIS was in charge of this work. It was based on the data provided by Solvay (salt production, topography monitoring, etc.), prospection works on the boreholes, characterisation of mechanical behaviour of rocks (LAEGO), hydrogeological studies (ANTEA) and numerical modelling of long term behaviour of the site (The Ecole Polytechnique).

2.1 Location

In Sarralbe region, Solvay Company has got licence for 37 zones (concessions) located at the border of Lorraine and Alsace (Departments of Moselle and Bas-Rhin). Ten of them have been mined out by solution-mining. The location of the dissolution area is shown in figure 1.

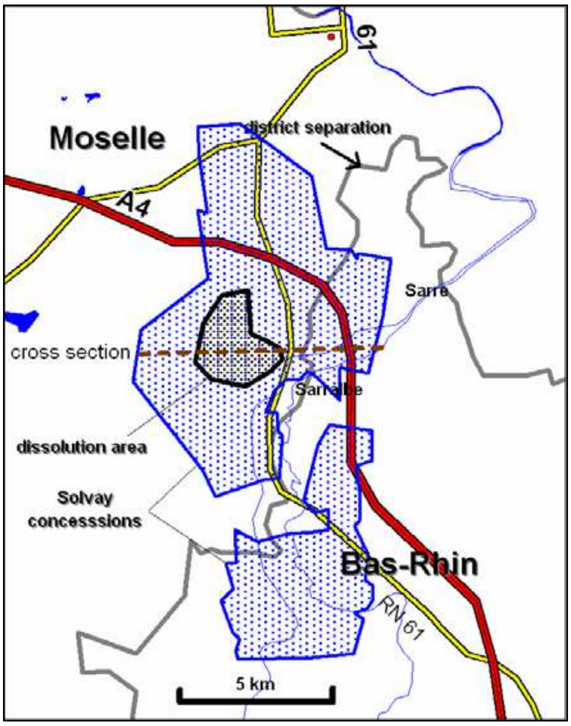

Figure 1. Location of concessions and solution mining in Sarralbe

2.2 Geology

Salt has been mined out in Lorraine from Sarralbe region (NE) to Nancy (SW). Halite is present at two levels :

- the most recent formation, in Keuper marls forming upper triassic. This is the case of the salt mines of Varangeville, Einville, Vic and Dieuze and solution mines of Haraucourt plateau (Nancy region).
- the oldest formation in the grey layers of middle Muschelkalk, at Sarralbe, situated at North-East extremity of Sarreguemines Synclinal, the area considered in this paper.

Figure 2 shows two lithological deposits present in Sarralbe and Nancy. The difference between these two regions basically depends on thickness of the salt deposit : 20 m at Sarralbe compared to 80 m at Nancy. The difference is also due to the presence or absence of the stiff dolomite layer of Beaumont which is found only in Nancy area but not in Sarralbe.

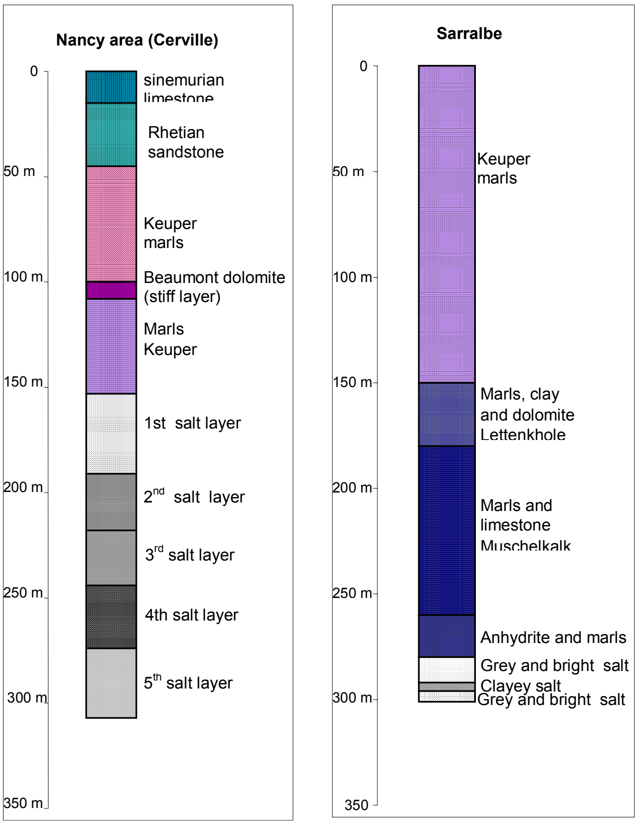

Figure 2 : Lithological series of triasic salt deposit and overburden in Lorraine (France).

The geological context of Sarralbe region is known thanks to many boreholes drilled for the purpose of exploration and exploitation of the deposit. The strata form a synclinal with the axis oriented in NNE-SSE (see cross-section in figure 3 and its location in figure 1).

In the mining area, salt deposit is found between 220 and 290 m of depth. Its thickness changes from 20 to 22 m in average, including irregular beds of marl and anhydrite with a cumulated thickness of 3 m.

The overlying strata are constituted by marl limestones and limestones of Muschelkalk and Lettenkohle besides a thick deposit of keuper marl (150 m in the mined out area).

The analysis of geological data, in particular those provided by the boreholes drilled during the year 2000 allowed a qualitative knowledge of the over-all mechanical behaviour of the strata forming the overburden : except for a few stiff layers of a few meters thick that are found in Muschelkalk limestone, the overburden strata are of poor mechanical properties that can be qualified as “globally deformable”. There is no stiff layer which the mechanical properties could have allowed large cavities to remain open in time.

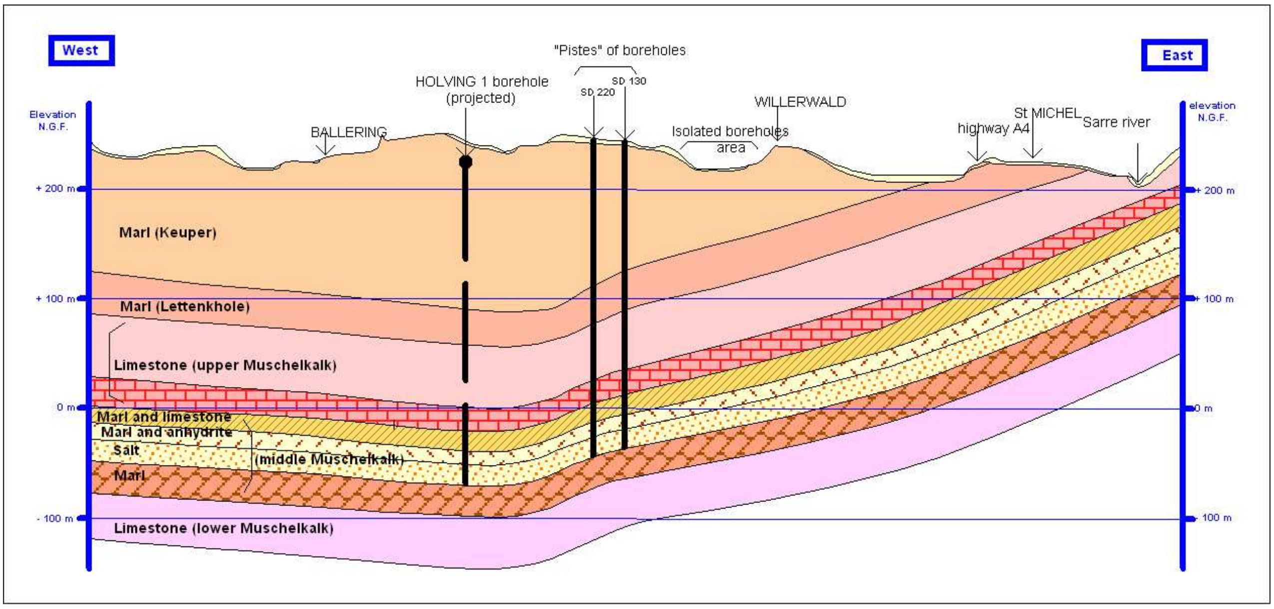

Figure 3. cross section of salt deposit and overburden in Sarralbe

3 Mining method

The main industrial solution-mining was done using different techniques : first through isolated boreholes drilled at deposit roof, then using the technique of group of boreholes (1884-1947) and finally by means of the so-called technique of “piste” of boreholes (1943-1983).

3.1 Isolated boreholes and group of boreholes

The first boreholes drilled at Sarralbe, called isolated boreholes have always been constituted by two holes with the maximum distance of 20 m. The cavities created at salt roof by introducing fresh water finished to be in communication (figure 4). One of the two boreholes was used to introduce fresh water, the other one for the brine extraction. This method was not optimised and did not allow an efficient dissolution of the deposit in all its thickness. It leaded too an out of control of lateral extension of dissolution.

By early XX^{th}, groups of 10 to 20 boreholes were drilled (figure 4). After the communication between different boreholes was established, a part of them became fresh water in-flow boreholes where as the other part was used for the brine extraction. This corresponds to the initiation of whatever became later on the method of solution mining by “pistes” and boreholes.

The dissolution was always done to achieved a better control of the extension of the dissolved zones and a more efficient exploitation of the deposit thickeness. This became possible thank to the deeper boreholes and their optimal distribution in space. Figure 5 shows the groups of boreholes. Note that the different dissolution techniques performed at the salt roof allowed extracting of $5,4.10^6$ tonnes of salt between 1884 and 1947.

3.2 *Pistes of boreholes*

In the following, the terme « piste » of boreholes is defined as a set of aligned boreholes. By the years 1930, the dissolution method of “piste” and boreholes was under operation at Sarralbe. This method is specific to Solvay Company. It is still under operation in other deposits, especially for the thick salt deposit of Cerville (Meurthe-et-Moselle). The method has been subjected to a favourable evolution leading to a rationalisation of mining that has begun with the group of boreholes in the first half of XXth century. The basic evolution feature of this method is related to the two following aspects :

- the dissolution is done from the floor to the roof of deposit ;
- it is oriented in the direction of boreholes line.

A piste is formed with boreholes drilled up to the basis of the salt deposit. The distance beetwen the boreholes is 50 m. They are placed in the direction of the highest slope line. First, all the boreholes are put in communication by creating dissolution channels using an air blanket. After achievement of channels formation, the piste can be mined out. Fresh water is introduced in the boreholes located in front of the piste and the brine is extracted through the backward boreholes.

The method allows salt mining with a maximum extraction ratio from floor to roof with an appropriate control of the dissolved zones.

At Sarralbe, two pistes roughly parallel with a distance of 200 m were mined out. The « piste 100 » compromises 52 boreholes and the « piste 200 », 40 boreholes. They resulted in the extraction of 8.64 millions of tonnes of salt. It has to be noticed that while mining was stopped at 1983, half of the « piste 200 » was not yet mined out. Only the dissolution channel, a few meters high, was already formed.

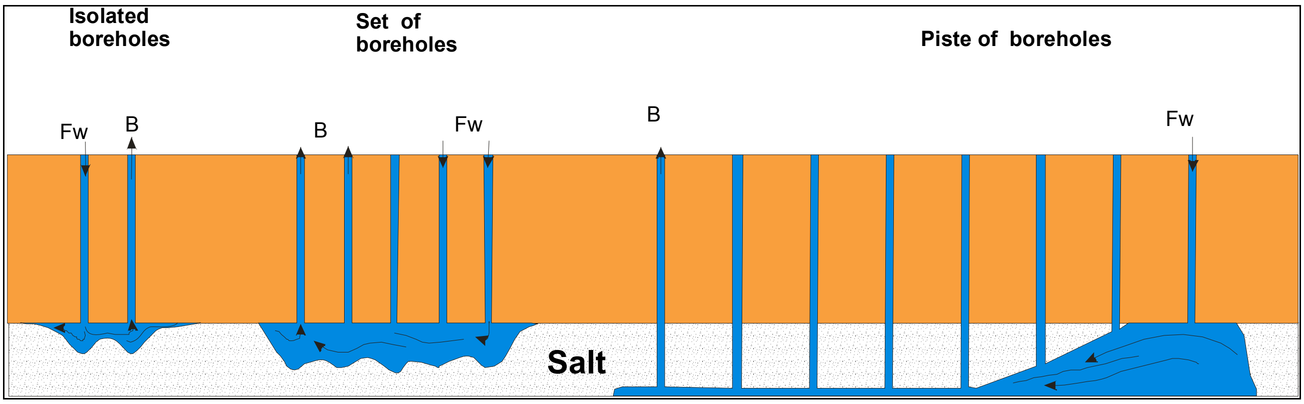

Figure 4 : cross section showing different solution mining techniques used at Sarralbe
(B : brine, Fw : fresh water)

The data available on the exploitation Sarrable pistes (extracted salt, Sonar, other investigations) allow to give some indications on the dimension and the extensions of the void spaces created by dissolution : dissolution channels were formed with a maximum height of 4 to 6 m and a lateral extension of 50 to 60 m. The solution-mining led to mine out the whole thickness of the salt layer, about 20 m in average. Moreover, the cavities were extended 40 to 50 m around the piste axis.

4 Strata movement induced by solution mining in Sarralbe

It has to be underlined that the different techniques of solution-mining used in Sarralbe have not resulted in any malor collapse. Only subsidence has occurred.

4.1 Features and rates of subsidence

Strata movement induced by dissolution could be analysed in detail thanks to the measurements provided by the topographic survey carried out from the beginning of mining period at the end of XIX th century.

Topographic measurements were taken systematically for the first boreholes (double boreholes or group of boreholes). Further more, an extended topographic network was set up for the exploitation. A few plots have been kept and followed by measurement until 2000. As a matter of fact, data are available almost 20 years after the mining was stopped.

4.1.1 Subsidence amplitude and extension

Mining at salt roof

For isolated boreholes formed by double ones, the measured subsidence is about 1 m (table 1). For the two groups of boreholes, that of “spond” and “brook”area, the maximum amplitude of basin subsidence reaches 3.9 and 5.6 m respectively. The number of mined out boreholes appears to be proportional to the maximum amplitude of subsidence. This denotes the fact that the group of boreholes were subject to communication. Therefore, the residual width/depth ratio was developped and resulted in the increase of soil subsidence amplitude.

Figure 5 shows the subsidence extension within the area of basic group of boreholes. The values of subsidence were extrapolated from the values of total subsidence for each borehole head measured in 1938.

Pistes of boreholes

In the area of mined pistes, the average value on subsidence is 3 m where and the maximum reaches 4.4 m. Above the area that has not been exploited, that is to say where there is only dissolution channel, no sensitive soil displacement has been registred neither during mining nor since the mining has been stopped in 1983.

By measuring the cavities dimensions using ultrasonic technique, the value of subsidence influence angle was estimated to be 37° where the limits of dissolution zone are known

Table 1. subsidence magnitude in Sarralbe

	Maximum subsidence in meters	Average subsidence in meters	Exploited boreholes
Isolated boreholes I, IV and V	1.09	0.96	2
Isolated boreholes II	2.4	2.4	4
Isolated boreholes III	3.7	3.7	6
Set of boreholes – “spond” area	3.9	3.2	10
Set of boreholes – “doerenbach brook” area	5.6	3.7	23
« Pistes » of Boreholes	4.4	3	50

4.1.2 Subsidence ratio

For each solution-mining technique, boreholes pistes and set of boreholes, the values of subsidence ratio (volume of subsidence over cavities volume) are relatively small. They change between 0.2 and 0.4 respectively for the exploitation by « boreholes pistes » and « set of boreholes ».

The results of numerical modelling (see paragraph 5), the mechanical properties of the strata and the subsidence amplitude agree on the fact that the small values of subsidence ratio are explained by the following factors :

- the small width of voids compared to the depth (sub-critical exploitation). This is the case specially for the pistes where the ratio cavity width over its depth is less that 0.5 ;
- the residual voids. Basically, the void spaces which have not been filled with the bulking of the collapsed strata are concerned ;
- the results of the different investigations indicate that most of the cavities has already collapsed. Only small cavities might be still open (not fully collapsed). This is particularly the case of the dissolution channels.

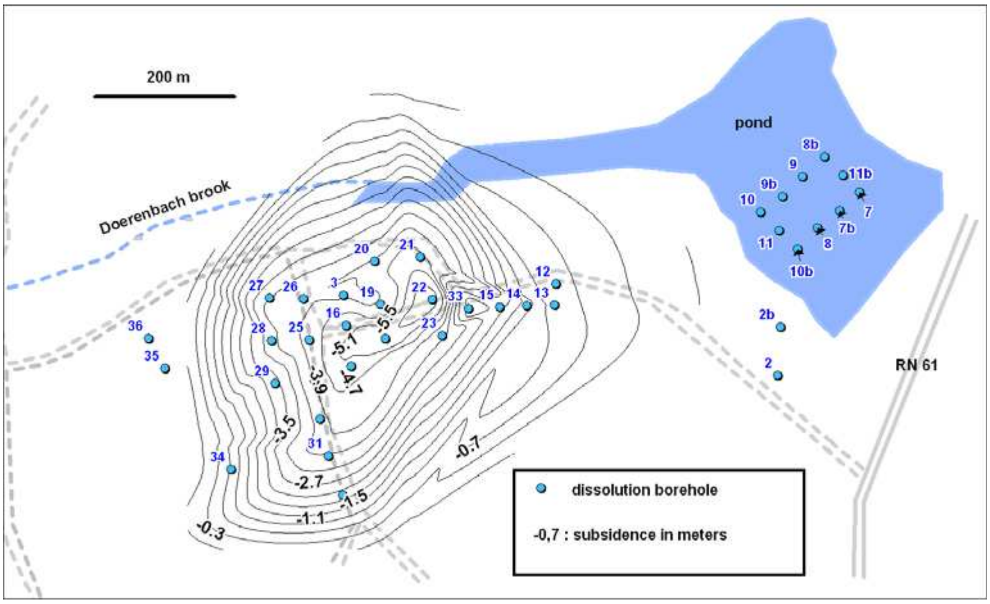

Figure 5 : subsidence extension at the aera of basic group of boreholes (cumulative values to 1938)

4.2 Subsidence evolution in time

Subsidence has been measured in time for the basic group of boreholes (Daerenbach brook area) and for the pistes. The main features of the time-dependent behavior of subsidence are as follows (see figures 7 and 8 for the basic group of boreholes).

The subsidence has basically occurred during the mining period. It is well correlated with brine extraction without any significant delay (figure 7). No jump has been observed for the subsidence plots. This clearly shows that the overburden has never failed since there is not any stiff layer in the overburden able to keep a large cavity open in time.

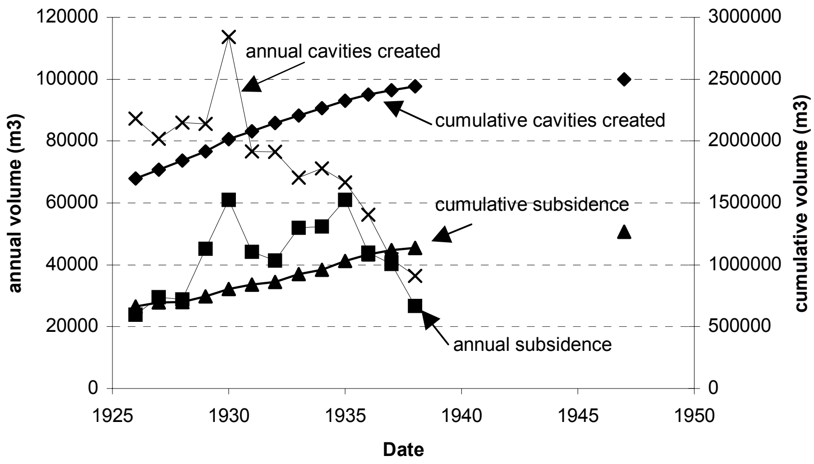

Figure 7 : Basic group of boreholes (Daerenbach brook area). Comparison between cavities and subsidence volumes (cavities assumed to be full of brine)

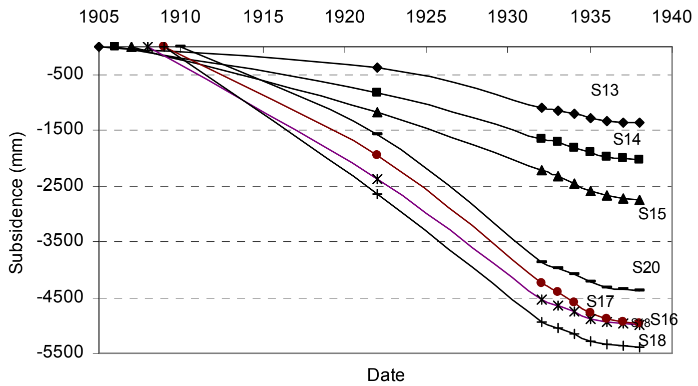

Figure 8 : subsidence evolution of basic group of boreholes (Daerenbach brook area).

The residual subsidence rate is negligible (less than mm/year) a few years after the end of mining (and so today). This result shows that salt (thin layer fully mined out) does not play any significant role on the overall behavior of the strata and upon the long term displacement of the surface. Figure 8 shows the subsidence evolution until 1938 for a part of boreholes belonging to the basic group. These boreholes have not been under operation for several years. For the exploitation by pistes, the topographic measurements taken at several occasions during the last 10 years and their comparison with the measurements made during the mining period show up that at present, there is no measurable displacement that can be measured on surface. The latest measurements (of the order of 1 cm) have been made locally in 1998. One can wander whether they are not related to the natural "breathing" of the soil rather than to a real subsidence.

5 Modelling

Evaluation of long term evolution of cavities and its impact on the soil surface and possible future structures and population required to model different kinds of cavities according to the solution mining methods.

In order to take into account, as far as needed, cavities, layers, their constitutive models and their properties, Finite Element computations were made. A special attention was paid to the modelling of the failure of various layers in the overburden. The results provided by the laboratory tests performed on the cores taken from a borehole (especially drilled for the purpose of this study) guided to select the appropriate constitutive models : brittle elastic for limestone, Cam Clay elasto-plastic model for clays and marls, elasto-viscoplastic model for salt (Norton law).

Using the values of mechanical properties obtained by laboratory tests, as reference values, a series of calculations was systematically made in the view of a sensitivity study. A wide range of the parameters values as well as the cavities dimensions were introduced in the model in order to evaluate in a satisfactory way, the effects of various data on the model results and conclusions. This priority required many modellings with iterative time-consuming computations (non linear and time-dependent behavior of rocks). In this condition, only 2D computations were feasible. They were done both in plane strain condition (for the pistes) and using axisymetric assumption (for the group of boreholes, on the basis of circular iso-subsidence curves, as shown in figure 5).

We emphasise on the fact that in spite of the fantastic progress of computers and modelling in the latest decades, accurate computation of the subsidence induced by a cavity collapse cannot be described precisely by any existing model (discrets elements, distinct elements, finite elements, etc). In fact, the bulking factor can easily reach a high value close to 0.3 (30 % of additional volume created by the void spaces among the blocs of rock) where as the models cannot take amount of this factor. Consequently, the calculated values of the subsidence amplitude and extension are usually exagerated in comparison with the reality. This is the reason why in this study, we preferred to calibrate the parameters of the model using the topographic measurements. This required systematically a very significant reduction of the mechanical properties of the overburden indicating that the overburden is globally very deformable.

The model being calibrated, long term stability of the caverns and the overburden was then investigated in different cases : group of boreholes, pistes, channels.

This evaluation was based on the concept of limit load theorem which is very common in soil mechanics (e.g. slope stability calculation). The idea is that for given values of mechanical properties, collapse takes place when a critical load value is reached.

In a numerical computation, this method requires a step by step decrease of the mechanical properties (e.g. strength, cohesion …). A sudden jump of displacements (for example, the cavity convergence) indicates that the limit load is reached and the cavity can no longer remain stable (overburden failure). In practice, for given values of overburden load and cavity width, different computations are made by decreasing continuously the mechanical strength of the overburden. The cavity closure and the soil subsidence (computation results) are then increased. This is shown in figure 9 for different values of cavity width. On can observe that the strength limit is increasing with the cavity width; that is to say under a given load, a small cavity is more stable than a large one (a large cavity needs a stronger overburden in order to remain stable, in comparison with a small one).

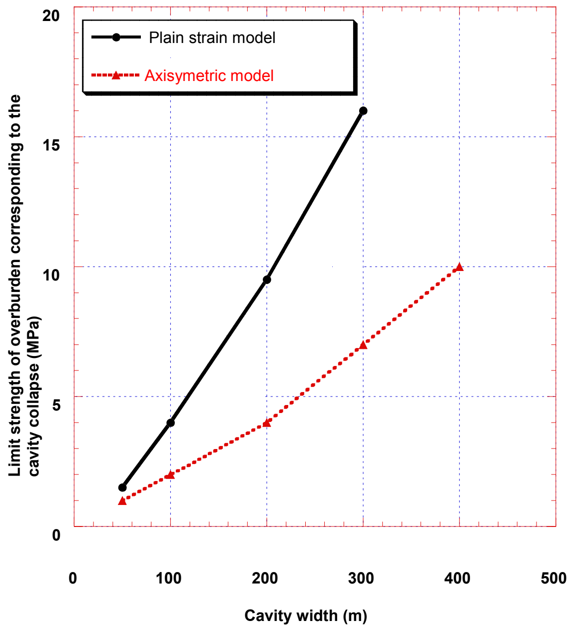

Figure 9 : Evolution of the limit load as a function of the cavity width

The following basic results came out of various computations :

1. there is clearly a mechanical (and hydraulic indeed) interaction between neighbouring cavities. Consequently the overall behaviour of the group of boreholes can be assimilated to that of a large cavity containing individual cavities. This is conform to the topographic data. Also, the computed values of subsidence are very close to the measured ones (figure 10) ;
2. the measured values of subsidence amplitude (a few meters) cannot be explained unless the roof fall and the cavities collapse are considered. This result denotes that most of the cavities has already collapsed ;
3. in spite of the fact explained above, the value of subsidence coefficient (subsidence volume over caverns volume) is almost small, between 0.2 to 0.5 depending on the exploitation context. This result fits well the measurements. Nevertheless, the calculated values of angle of influence (related to the lateral extension of subsidence) are higher than the measured values. This is due to the continuous feature of the model (in fact any significant subsidence does induce an overburden fracturing where as the model remains continuous anyhow) ;
4. the behaviour of dissolution channels is governed by salt properties : good strength and rather small creep at a depth of 200 –300 m.

The results of the calculations indicate that many channels remain probably still open. Their creep rate is very small and does not lead to any measurable effect on the soil surface (figure 11). On the whole, the results of modelling allow to conclude that the overburden has clearly a “soft” behaviour with poor mechanical properties. Cavities were already closing during the solution mining period and the most subsidence has already occurred at short term. Moreover the residual subsidence due to the open cavities and the channels is negligible and cannot result in any disorder of the overlying structures. Nevertheless, in case any heavy structure is planned in future, special investigations and operations have to undertaken prior to any construction of this type.

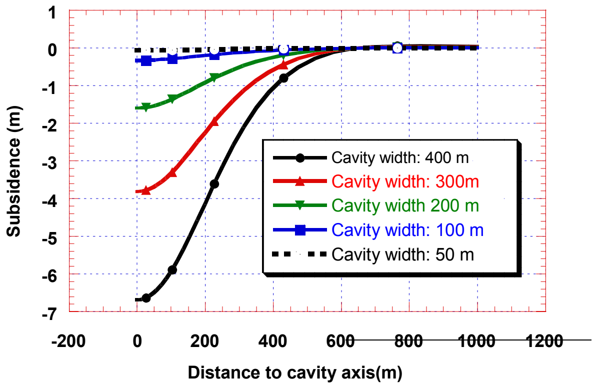

Figure 10 : Soil subsidence calculated for different widths of an axisymetric model of cavity

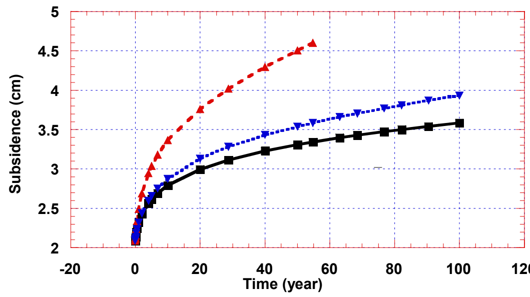

Figure 11 : Time dependent evolution of the soil subsidence above a channel modelled in axisymetric representation (calculation with 3 sets of model parameters)

6 General conclusions with respect to closing of salt mines.

The main interest of this study is due to the fact that mining has systematically been accompanied with a topographic monitoring from the beginning of the industrial solution-mining period. The investigations show up clearly that the geological context of Sarralbe site can be distinguished from that of the salt deposit in Nancy area (figure 12) :

- within the Nancy area, the Beaumont dolomite layer, very stiff and resistant, can potentially fail and generate large collapse. In fact, presence of a stiff layer in the overburden makes it possible to create large caverns. When the cavity becomes larger than a critical value (see the case of Gelloncournt cavity and the pistes reference) deflection of the dolomite layer leads to its failure resulting in the collapse of the overlying strata presenting poor mechanical properties. One has to notice that in Nancy region, the deposit thickness is nearly 80 m and the so-called "intensive" technique allows creation of few ten meters high cavities.
- Beaumont dolomite stiff layer does not exist in Sarralbe overburden which is globally "soft" with poor mechanical properties. In addition, the thickness of the salt layer (about 20 m) and, as a matter of fact, the cavities height are much smaller in Sarralbe in comparison with Nancy. Void spaces created by dissolution are easily filled because of the roof fall (bulking). The overlying strata are deformed smoothly leading to surface subsidence. The topographic measurements discussed in this paper showed up that the amplitude of the surface subsidence can reach a few meters. The subsidence is almost stabilised a few years after the brine extraction has been stopped.
- an intermediate case of the overburden behaviour and the induced effects at surface has been analysed by Wassemann (1980) and Bekendam (1997) in Twenth (Netherlands). It deals with a salt deposit, about 50 m thick, mined out by isolated boreholes and groups of boreholes. This mine induced a significant surface subsidence of a few meters, a few years after the exploitation was stopped. Like within Nancy area, the cavity formed by dissolution is characterised by an upward evolution in consolidated layers. But there is no stiff layer able to keep open the cavity for a long time. When the cavity reaches the basis of unconsolidated clays, these layers are subjected to a deflexion above the cavity leading to their failure and fall. The material fill the available volume and result in a significant surface subsidence. It has to be underlined that the subsidence rate was a few mm/year while the cavity was located at lower layers with rather good mechanical properties. Later on, as the cavity reaches the soft clay base, it is collapsing and generates subsidence of few m/year.

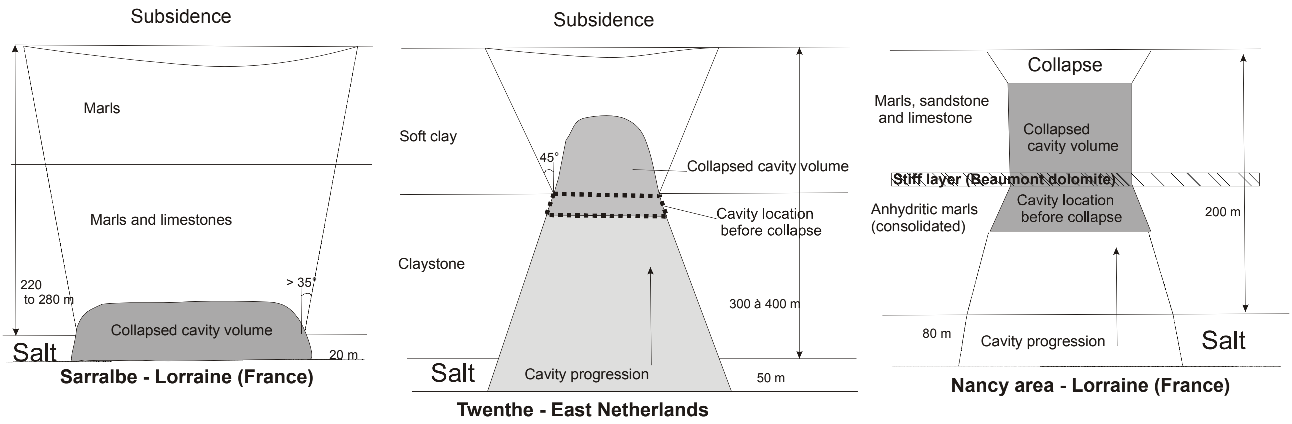

Figure 12 : schematic representation of the cavity evolution for different bedded salt contexts and induced soil movements.

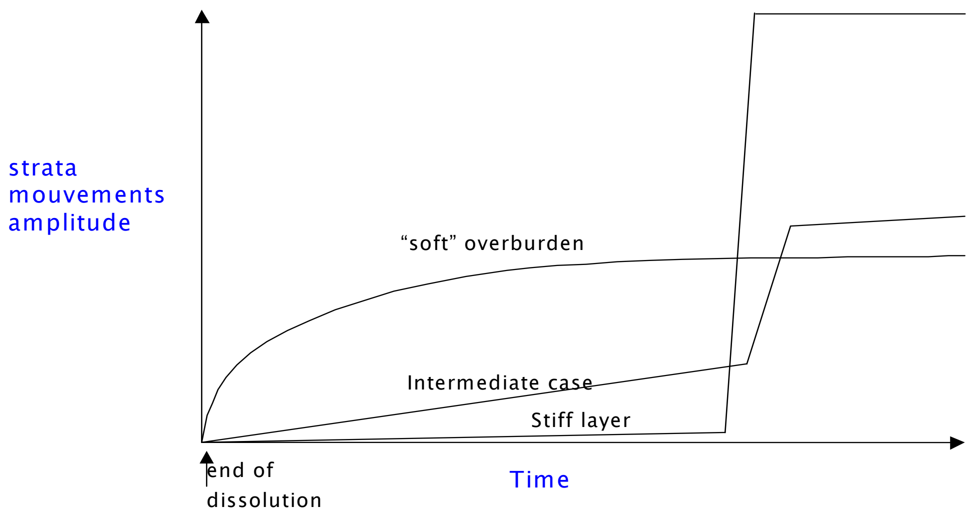

Figure 13 : schematic representation of the strata movement amplitude evolution for different bedded salt contexts

The analysis of the surface effects induced by mining in Sarralbe compared to the Nancy case and to that of Twenth highlights the important role of geological context especially the nature and the mechanical properties of the overburden. This role is decisional on the mechanisms of evolution of the cavities and on the surface effects. In particular, evolution in time of the effects are different as it is shown in figure 13. Theses differences are of a great importance for the long term management of salt mines regarding the impact on the future urbanism development and also with respect to an efficient monitoring system.

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