Confidence Building in Relation to the Optimisation and Extension of the Hvornum Brine Field in Mariager, Denmark

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Abstract

Akzo Nobel Salt b.v. operates the Hvornum brine field in Mariager, Denmark, since 1964. In order to optimise the dimension of the caverns and/or extend the brine field, an overall geomechanical investigation has been performed by IUB in 1998.

Problems arise when specific data / core material is not available. At that point the specific material behaviour of the rock salt can only be determined by reviewing and evaluating all available field data. In case of the Hvornum brine field these specific data are: Sonar surveys of the caverns, surface subsidence measurements and production data. From the more recently drilled well HV-8, also geomechanical test data from laboratory core testing were obtained.

In order to develop a geomechanical model, the parameters for the time dependent material behaviour are of utmost importance. As will be shown in the paper, a powerful new procedure has been worked out for confidence building of the theoretical numerical model (prediction of volume convergence). The procedure is based on comparison of field observations (in terms of surface subsidence development) and production data (in terms of a mass balance of extracted and dissolved salt) with the theoretical numerical model.

This confidence building procedure results in a theoretical numerical model established on a unique database and is therefore best suited as the basis for an overall optimisation process for future development of the brine field.

1. Introduction

In order to predict future behaviour of the Hvornum brine field at Mariager, Denmark and to optimise production from the caverns a theoretical numerical model was developed, which has to achieve confidence to properly simulate the load bearing behaviour of the rock mass. This means that observed field data have to be in agreement with the predicted ones from the theoretical numerical model. Within the scope of this paper confidence building is focused on surface subsidence volume of the Hvornum brine field. Based on an excellent database, comprising various production data recorded over the 34 year operation period by Akzo Nobel, a second theoretical model predicting the total volume of surface subsidence could be developed. This provided an additional possibility to validate the theoretical numerical model. For the purpose of confidence building three independent procedures can now be compared with each other.

The *first model* directly makes use of the *observed surface subsidence*. The total amount of surface subsidence for the Hvornum brine field was calculated by Socon Sonar Survey, Germany on the basis of performed surface levelling measurements. The results are given for several points in time during the operating period and are represented in table 1.

Predicting the overall surface subsidence volume in time on the *basis of the recorded production data* is developed by the *second model.* It is established by a mass balancing procedure taking into account injected fresh water, dissolved mass of salt at subsurface and extracted mass of salt at the surface.

The *third model* generates the total volume of surface subsidence as a result of a *numerical calculation of the average rate of volume convergence* for the Hvornum brine field caverns in combination with an assumed development of the produced total cavity volume at subsurface with time. The cavity volume with time is determined from a mixed database of sonar surveys combined with production data. Creep rate of the salt was determined from Hv-8 core testing.

2. Investigated models for surface subsidence

2.1. Procedure to determine total volume of surface subsidence on the basis of observed data from levelling measurements

The surface subsidence volume was calculated by Socon Sonar Survey [1], Germany from measured levelling data, as represented by table 1.

2.2 Procedure to determine total volume of surface subsidence based on a mass balance between theoretically extractable and extracted salt volume

The input data for this procedure are provided by production data recorded by Akzo Nobel. The procedure takes into account the balance between the different salt mass portions that are generated during the solution mining process. The mass balance is expressed by eq. 1.

$$m_{salt}^{extracted} = m_{salt}^{theoretical\ extractable} + m_{salt}^{extracted\ by\ volume\ convergence} \quad (1)$$

with

$m_{salt}^{extracted}$ observed mass of salt extracted from the well

$m_{salt}^{theoretical\ extractable}$ mass of salt that theoretically can be extracted due to the injected volume of fresh water

$m_{salt}^{extracted\ by\ volume\ convergence}$ mass of salt squeezed out of the cavern due to volume convergence, as a result of creep of rock salt.

Year	Calculated volume of subsidence in total	Estimate of accuracy
	[m³]	[m³]
1967	0	-
1969	-	-
1975	5880	±5500
1977	-	-
1981	12295	±5500
1986	16482	±6300
1991	26566	±7200
1993	(15821)	(±5800)
1996	58167	±7500
1997	-	

Table 1
Hvornum brine field - calculated total volume of surface subsidence from levelling measurement data, by Socon Sonar Survey, Germany, 1998 [1]

The mass of salt squeezed out due to volume convergence leads to the calculation of the volume convergence itself by eq. 2. The cavern volume reduction due to convergence is assumed to be equal to the total volume of subsidence appearing at the surface.

$$\Delta V^C = \left(\frac{c_{H_2O}^{brine}}{c_{salt}^{brine}} + 1 \right) * \frac{m_{salt}^{extracted\,by\,volume\,convergence}}{\rho_{brine}} \quad (2)$$

with

ΔV^C volume convergence of the cavity due to creep of rock salt

$c_{H_2O}^{brine}$ mass concentration of water in brine

c_{salt}^{brine} mass concentration of salt in brine

ρ_{brine} density of brine

Solving eq. 1 for the mass of salt extracted as a result of volume convergence and substituting this parameter in eq. 2 leads to the computation of the volume of cavern convergence. Within this calculation procedure the input parameters such as

- the injected volume of fresh water,
- the extracted mass of salt,
- the concentration of dissolved salt mass in the extracted brine and
- the density of the extracted brine

can be determined from the production database. Whereas assumptions and/or calculations have to be made for

- the density of salt at subsurface,
- the density of water and
- mass concentration of water in the extracted brine.

This procedure of computing the increments of volume convergence has to be performed for every month of operation based on the production data.

Figure 1 : Accumulated volume convergence from production data model

Subsequently, these monthly values have to be summarised as accumulated values of volume convergence per year in order to gain the development of the volume convergence with time for the Hvornum brine field in total, which is assumed to be linked directly to the total volume of surface subsidence. The results of these calculations are shown graphically in fig. 1.

2.3 Procedure to determine total volume of surface subsidence based on a numerical computation of the rate of cavity volume convergence combined with the computation of the development of the total created cavity volume at subsurface

The theoretical numerical model for the prediction of the total volume of surface subsidence is based on two preconditions:

1. The development of the total produced cavity volume has to be determined with time and
2. The volume convergence with time due to creep of rock salt has to be calculated.

For the determination of the created cavity volume as a function of time sonar surveys can be applied. These measurements are however only depicting a few points in time. Therefore, this database has to be completed by the course of cavern volume development with time, derived from production data recorded by the operator using the values of: injected fresh water volume, density of the brine extracted and mass concentration of salt in the produced brine. This procedure was applied to every cavern of the field on a monthly data basis between the years 1979 and 1997. The monthly values of the created subsurface cavity volumes then were accumulated to the total underground cavity volume.

The second data set needed as input for the theoretical prediction model in order to calculate the surface subsidence with time is computed applying the theoretical numerical model.

This theoretical numerical model applies the finite element method in order to calculate the internal state variables of the rock mass taking into account the specific boundary conditions as: the geometry of the cavity (size and location), the material behaviour of the rock mass, the geology, the applied loads on the rock mass, the primary state of stress, the temperature of the rock mass and the operational conditions specific to the location.

A site map of the Hvornum brine field is shown in fig. 2. The representative cavern for the whole cavern field, when calculating an average rate of

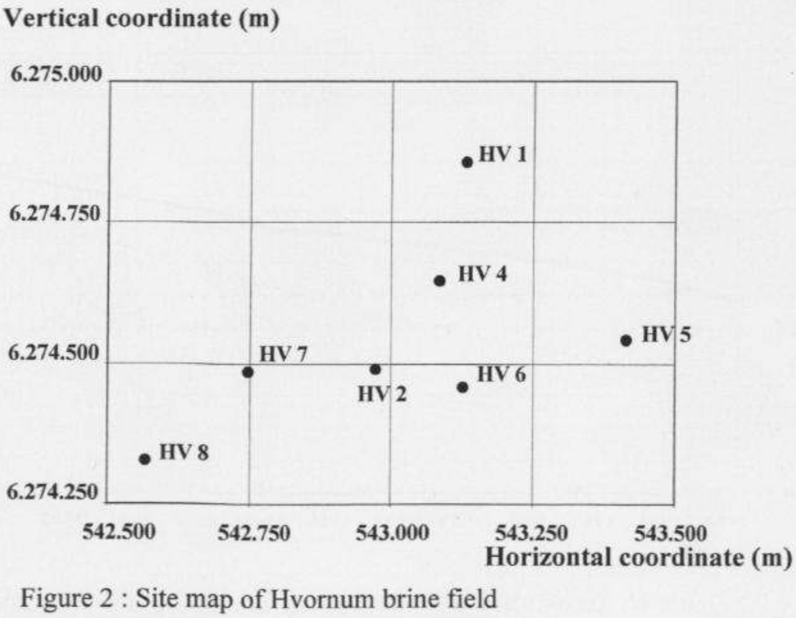

Figure 2 : Site map of Hvornum brine field

volume convergence, is assumed to be located in the centre of the field. Therefore the geological and geometrical situation from caverns Hv.2, Hv.4 and Hv.6 were taken into account. Though the load bearing between these caverns is more likely to be that of a field cavern, that means only a restricted pillar zone will contribute to the load bearing, with regard to the characteristic global layout of the Hvornum field it is supposed that enough salt extends in a lateral direction around the caverns resulting in a more single cavern behaviour of the typical representative cavern when looking at the volume convergence. The geometrical parameters chosen for this finite element calculation model are listed below.

- Layer of quarternary formation up to 220 m depth
- Anhydrite layer between depths 220 and 300 m
- Depth of salt level 300 m
- Depth of cavern roof at 500 m
- Depth of cavern sump at 1500 m
- Maximum radius of the cavern 22.5 m
- Outer bound radius of the calculation model 87.5 m

The time dependent material behaviour for the rock salt is modelled by the material law LUBBY2 [2] with its parameters determined from laboratory tests on Hvornum well Hv.8 core material.

Computations with the theoretical numerical model show a nearly steady state for the rate of volume convergence after a time period of about five years. This steady state value is used to calculate step by step the total volume of cavern convergence according to the development of accumulated total cavity volume with time. Subsequently the total accumulated volume convergence versus time is obtained, see fig. 3. Assuming that the volume of convergence originated from subsurface yields directly the volume of surface subsidence the course with time of the latter is given by the same curve.

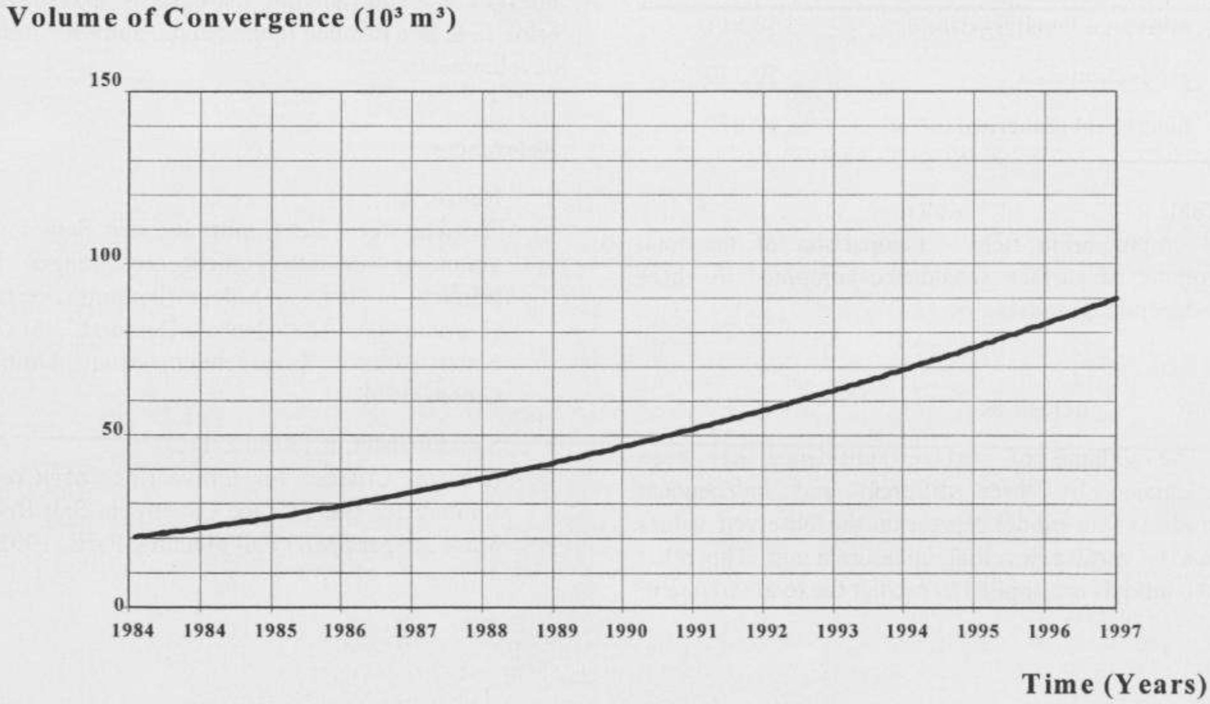

Figure 3 : Accumulated volume of convergence calculated from the theoretical numerical model

3.3 Findings

Reviewing the results for the observed, calculated and predicted volume of surface subsidence it points out that due to data uncertainties for the prediction model based on production data only the time period between the beginning of 1984 and the end of 1997 can be used for comparison. For this reason the levelling data computed by Socon have to be interpolated between the years 1981 and 1984 and extrapolated to the end of the year 1997. The increase in total volume of surface subsidence observed or predicted for this time span is summarised in table 2 for the three models investigated. The ratio between the predicted volume by the theoretical numerical model and the volume calculated from the observed levelling measurements is 1.4. The volume predicted by the theoretical model based on production data gives approximately the same result regarding the time period investigated.

Model	Total volume of subsidence [m^3]
measured levelling data	50,511
production data	50,340
theoretical numerical model	69,879

Table 2
Hvornum brine field - comparison of the total volume of surface subsidence computed by three independent models

3.4 Conclusions

The volume of surface subsidence has been calculated by three different and independent models. One model represents the observed values due to surface levelling measurements. The other two models are applied to predict the total volume of surface subsidence by using data recorded during production in case of the production data model and in case of the theoretical numerical model by using data to describe the development of the total created cavity volume (sonar surveys and production data) combined with a numerical calculation of the rate of volume convergence for the cavities due to several physical and geometrical assumptions.

Comparing the results, given in table 2 it can be stated that confidence is achieved to a very high degree between the three models.

In detail this means that the physical assumptions made for the theoretical numerical model represents to a very high degree the physical behaviour of the whole location of the brine field. Against the background that only one index laboratory test program on salt rock specimens specific to the location (only from cores out of well Hv.8) had been performed to determine the secondary creep parameters for the Hvornum rock salt this is a remarkable result.

In summary, confidence for the theoretical numerical model has been proven. Therefore it can be applied to simulate the load bearing behaviour of the rock mass surrounding the caverns at Hvornum brine field in a detailed optimisation study for future development.

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Salt Production

Rock salt

Evaporated salt

Sea/Solar salt

By-product salt

Electrodialysis