Optimized layout for Hengelo brine field cavities

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The technical and scientific basis for evaluating the stability and integrity of the rock salt barrier has been developed by means of investigating the state of stress with regard to the development of a disturbed rock zone. All states of stress resulting in dilatancy cause damage and an increase of permeability. A criterion for the onset of dilatancy may be determined from laboratory tests.

Results of a comprehensive computational study on the optimized layout for brine cavities carried out for Akzo Nobel Salt b.v. are: Cavity convergence and surface subsidence for the present design are rather small. In case of sufficient pillar width an enlargement of the cavity diameter leads to only slightly increased deformations. If a tight safety roof against the overlying strata exists to mitigate permeation of brine into the clayey overburden the stability of the safety roof is not compromised.

1. INTRODUCTION

The 50 m thick bedded Triassic rock salt deposit in Hengelo, East Netherlands, is found at about 300 to 500 m depth. The salt deposit and the overlying strata dip about 3 - 6 degree towards southwest. The Evaporite member comprises 4, locally 3 rock salt layers which are separated by shaly anhydritic claystones or anhydrites. The top of the salt layer is formed by an anhydrite layer with claystone interbeds. The overlying strata consist of silty claystones with gypsum and anhydrite nodules.

The salt deposit has been solution mined for over 60 years. More than 450 brine wells have been drilled, of which approx. 220 wells are still producing. Annual production 1998 amounted to 2 M tons of vacuum salt.

The prevalent production mode has been single well operation in the thirties, forties and fifties, the prevalent mining method nowadays uses triple wells, coalescence being enforced by the use of an oil blanket.

2. PROBLEM

The present cavern design according to plan is characterized through the following design parameters:

- 3 wells with a spacing of 40 m,
- max. cavern height: 40 m,
- max. allowable lateral expansion of cavern diameter: 80 m,
- min width of safety pillar to the adjacent cavern: 80 m,
- min. thickness of salt barrier to overlying strata: 5 m.

The pressure in the caverns will be always at least hydrostatic. The adjacent caverns are located parallel or orthogonal to each other.

Surface subsidence measurements, which have been performed since 1953, show, in general, only moderate subsidence rate corresponding to the moderate convergence of the caverns in relatively shallow depth. In the meantime, however, some severe subsidence troughs above the older cavern field have developed resulting from cavern collapse.

Cavern integrity, long-term stability and the limitation of surface subsidence have always been a matter of major interest. At first, simplified 2D finite element computations based on limited site-specific geology and geotechnical data were performed to investigate the stability of the caverns. However, 3D models are to be applied for realistic and reliable predictions of stress and deformations around cavity clusters with small ratios of cavity spacing to cavity diameter [1,2].

Recently, these early calculations have been revised using 3D computations and an extended database. The objective of the newly performed computations was obtaining:

- a stable cavern design,
- the permissible stress in the salt and adjacent layers and

- the permissible deformation of the cavern and the overlying strata.

Using these data, the minimal necessary thickness of the salt barrier to the overlying strata should be determined.

Furthermore, the maximum allowable increase of the cavern dimensions should be checked.

3. FUNDAMENTAL CRITERIA

A safety roof in the salt layer on top of the cavity towards the slightly dipping overlying strata is considered necessary to guarantee long-term cavern stability because the strength of the overlying claystone is very sensitive to a contact with brine. Laboratory experiments showed that dry claystone easily disintegrates and looses its strength almost completely once permeated with water or brine.

The technical and scientific basis for evaluating stability and integrity of this rock salt barrier has been developed by means of investigating the state of stress with regard to the development of a disturbed rock zone, which may allow the brine to penetrate into the overlying claystone.

The disturbed rock zone may be determined from a criterion for the onset of dilatancy shown in fig.1 [3].

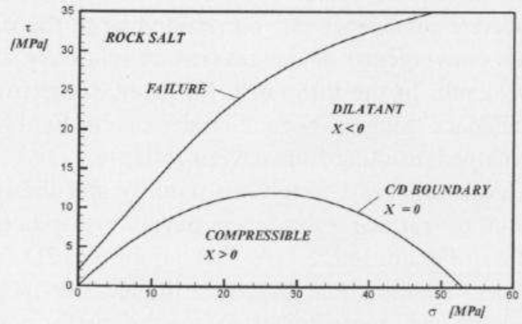

Figure 1. Criterion for the onset of dilatancy (after Cristescu/Hunsche)

Intact rock salt under isotropic stress is impermeable. At a certain deviatoric stress, well below failure, the volumetric strain of tested samples changes from a compressible to a dilatant mode accompanied by acoustic emission, which indicates microcrack opening and pore volume increase. This damage is accompanied by increase of permeability. The boundary between compressibility and dilatancy therefore gives the criterion when rock salt becomes permeable.

All states of stress still below failure but above the onset of dilatancy cause damage and an increase of permeability. Due to creep, healing of microcracks is possible simultaneously. However, healing only becomes a dominant mechanism if the state of deviatoric stress drops down to the compressive domain.

This criterion implies that the hydraulic behavior of rock salt can be traced back to the condition of mechanical integrity.

4. NUMERICAL MODELING

3D modeling was done to take into consideration the favorable spatial load-bearing capacity of underground structures.

Two cavity configurations, namely a parallel arrangement and an orthogonal arrangement have been considered. In both cases the spatial domain comprises a plane section of 120 m to 200 m and a depth of 120 m to 800 m below surface taking advantage of simplified vertical symmetry planes (s. fig. 2).

For both configurations the following notation was selected:

- borehole distance A
- cavity diameter D
- pillar width B
- min. thickness of roof S
- marker for row/orth. R/O,

e.g. A/D/B/S/R = 40/80/80/5/R.

In case of the parallel cavity arrangement, cavity *B* is missing. The cavities arranged in a row are considered to have a pillar width of 240 m - (D + 2 A). Two rows of cavities shall have a minimum spacing of 400 m.

In the computations the time dependent leaching process is not modeled realistically. Instead of investigating the sequential development of the cavities an instantaneous formation of all cavities is assumed. However, the relevant rock response can be reasonably approached by linearly lowering the rock pressure within the cavern to the final brine pressure. With regard to the relevant state of stress the exact leaching time needs not to be considered, an equivalent time period of about one years is sufficient.

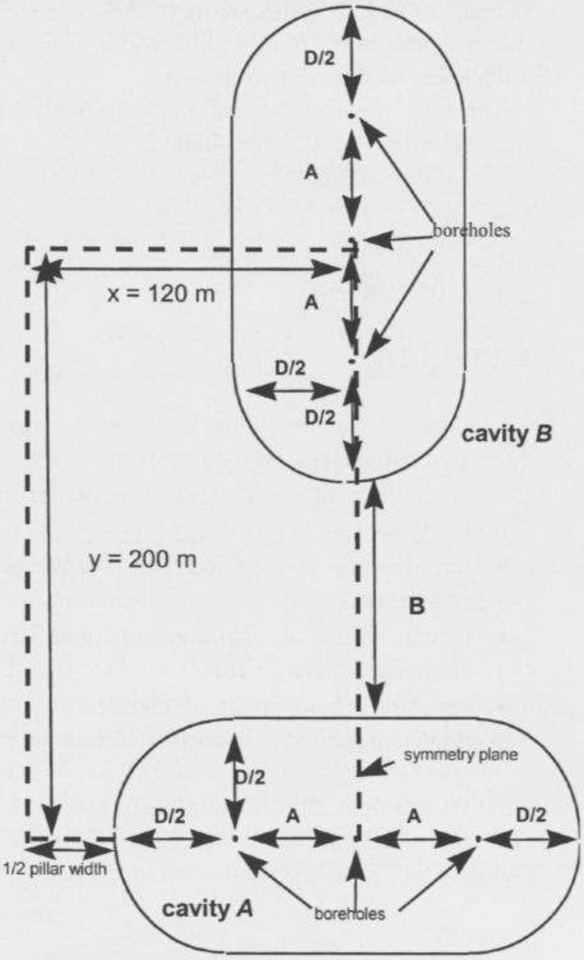

Figure 2. Plane view of cavity arrangement, not to scale

The geomechanical model used in the computations is based on the following assumptions:

- All cavities are considered with max. diameter and a constant height of 40 m.
- The rock salt layer is assumed to be horizontal and homogeneous without taking into account the inclination of the layer and the claystone interbeds. Due to their small thickness the interbeds do not play a significant role in increasing the stiffness of the salt layer. The depth of the Röt salt layer is conservatively adopted to 420 - 475 m below surface.
- The primary state of stress is considered to be isotropic and to increase with depth corresponding to the density of the rock mass.
- Salt shows the only relevant temperature dependent mechanical behavior. A constant temperature of 25 °C is assumed in the salt layer.
- Along the symmetry planes, appropriate displacement boundary conditions have been adopted.

Rock salt has to be modeled with it's distinct nonlinear creep behavior. From an engineering point of view, however, the computation of long-term processes may be based on a simplified constitutive model which takes into account elastic behavior and steady state creep only.

Creep law: $\dot{\varepsilon} = A \exp(-Q / R^{-1} T^{-1})(\sigma / \sigma^{*})^{n}$

All other rock types have been considered with their elastic behavior only.

Table 1
Mechanical parameters

layer	E [MPa]	ν	density [g/cm³]	A [1/d]	Q [kJ/mol K]	n
limestone	50.000	0,25	2,4	-	-	-
Upper Bunter	15.000	0,33	2,6	-	-	-
Rötsalt	25.000	0,25	2,17	0,5	54,0	5,0
Lower Bunter	15.000	0,33	2,6			
brine	-	-	1,0			

The mechanical parameters considered as input data in the computations are compiled in table 1.

The creep capacity of the Röt salt is relatively high. As a first step in the modeling, strength parameters for the distinct rocks have not been taken into account because of the relatively low stress level due to the shallow depth of the cavities. Failure due to exceeding rock strength has not been expected.

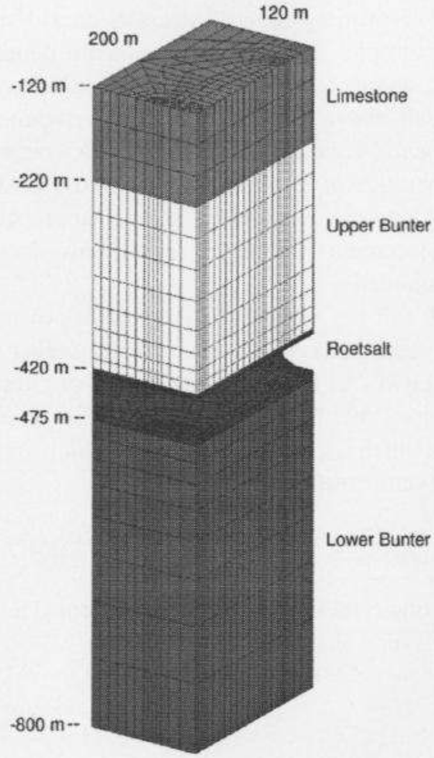

Figure 3. FE-mesh for case 40/80/80/5/O

From a conservative point of view, the density of brine has been assumed very low because reduction of the supporting brine pressure allows for higher cavity convergence.

Computations have been carried out using the finite element code ANSALT. A time frame of 100 years for cavern life time has been taken into account.

A typical 3D FE-mesh for the computations is shown in fig. 3. The model represents the case 40/80/80/5/O which stands for the orthogonal arrangement with a 40 m spacing of the three wells, a cavity diameter of 80 m, a pillar width of 80 m and a thickness of the safety roof of 5 m.

The following cavity configurations with an extraction ratio " " have been studied:

- 40/80/80/5/R, " " = 12%,
- 40/120/40/5/R, " " = 22%,
- 40/80/80/5/O, " " = 24%,
- 40/120/40/5/O, " " = 44%.

5. RESULTS

The model computations have been explicitly evaluated with respect to the following results:

- distribution of main stresses, particular in the safety roof,
- time history of displacements (convergence) and stresses at characteristic locations,
- contour plots of displacements and stresses along characteristic lines,
- development of stress at characteristic locations represented in a stress-invariant diagram.

As an example, the distribution of the minimum main stress around the caverns A and B of the configuration 40/80/80/5/O is plotted in fig. 4.

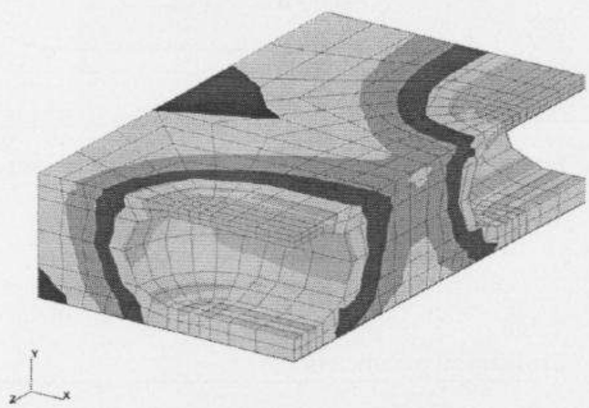

Figure 4. Distribution of minimum stress around the cavity in the salt layer after 100 years

Fig. 4 illustrates that stresses in the rock around the cavity and above are released. However, if the pillar width between the adjacent cavities does not undergoes a critical value the stress relief is restricted to the near field of the cavities. Because of the permanent action of brine pressure in the cavity, the deviatoric stress around the cavity remains low. In all computed cases no critical state of stress related to failure has been encountered.

According to the computations the stress redistribution around the cavity has already been completed at about 10 years. After that time a stable state of stress has developed with rather small almost constant convergence rates.

Table 2
Computed cavity convergence after 100 years

case	horizontal convergence		vert. conv.
	sm.ax. [m]	lg.ax. [m]	[m]
40/80/80/5/R	0,10	0,09	0,06
40/120/40/5/R	0,15	0,16	0,10
40/80/80/5/O cavity A	0,14	0,11	0,08
40/80/80/5/O cavity B	0,13	0,11	0,07

The accumulated maximum convergence of the cavities in horizontal and vertical directions after 100 years is compiled in table 2. The total amount of convergence remains small. The vertical convergence is a little bit lower than the horizontal. In general the horizontal convergence at the larger axis of the cavity is slightly smaller than that at the smaller axis.

The elevated horizontal convergence in case of the 40/120/40/5/R-configuration with a pillar width of only 40 m already indicates the higher loading on the pillar between adjacent cavities in row. It is still without consequences for stability and integrity.

The maximum surface subsidence rate for these cavity configurations is in the order of about 1 mm/year.

The design of orthogonally arranged cavities in case 40/120/40/5/O with a minimum pillar with of 40 m between adjacent cavities and an extreme extraction ratio of 44%, however, turned out to be critical with respect to convergence and subsidence. This design would not be stable. The decisive attribute related to stability is not the enlarged size or volume of the cavity but the reduction of the safety pillar width between adjacent cavities down to 30% of the cavity width.

In case of orthogonally arranged cavities a minimum of 80 m pillar width has imperatively to be met in order to avoid critical formation of stress and convergence or subsidence, respectively. Under these circumstances a new cavity design with enlarged diameter up to 120 m is feasible.

Due to the actual existence of slightly inclined salt layers, the technical realization of the cavities with respect to the adherence of a sufficient safety roof is of very great importance. Only a tight safety roof guarantees the favorable effect of the brine pressure on the stresses above the cavity.

The development of stress at characteristic locations of the roof were checked against the criterion of onset of dilatancy in a stress invariant diagram shown in fig. 5.

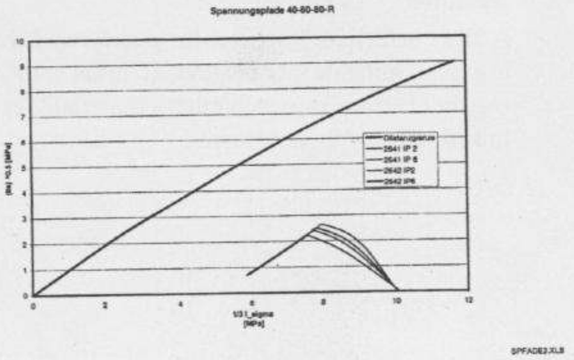

Figure 5. Development of stress path at characteristic locations in the safety roof, stress-invariant diagram

In all analyzed cases, the computed stress in the safety roof did not violate the dilatancy criterion. The computed results demonstrate that the 5 m thick salt layer is sufficient to mitigate the development of a disturbed zone with elevated permeability. Altogether, the model computations have shown that the optimized layout for the Hengelo brine field cavities is stable.

6. CONCLUSIONS

The technical and scientific basis for evaluating stability and integrity of this rock salt barrier has been developed by means of investigating the state of stress with regard to the development of a disturbed rock zone determined from a criterion for the onset of dilatancy.

Results of a comprehensive study carried out for Akzo Nobel Salt b.v. are:

- Time dependent stress redistribution and corresponding deformations due to creep are understood as the basic mechanism for long-term cavity stability and integrity.
- Cavity convergence and surface subsidence showing the dependence on creep parameter of rock salt and on cavity geometry have been investigated by numerical simulations. Cavity convergence and surface subsidence for the present design turned out to be rather small. No risks with respect to stability of the safety roof have been encountered under normal leaching conditions.
- A tight safety roof against the overlying is requisite to mitigate permeation of brine into the clayey overburden which otherwise would result in softening of these layers.

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