

Assessment of Surface Subsidence above a Cavity Field Resulting from Cavity Diameter Enlargement

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ABSTRACT

Akzo Salt currently operates an array of eight solution mined cavities in the Zuidwending salt dome. In order to best utilize available salt volume and existing wells, Akzo plans to enlarge the cavity diameter from 100 m to 120 m, which would lead to an almost 45% volume increase. Due to this diameter enlargement, the cavity spacing to cavity diameter ratio will approach a factor of 2. Since surface subsidence due to cavity convergence is an important design parameter in The Netherlands, comprehensive geotechnical computations were carried out to assess (a) changes in surface subsidence and (b) changes in cavity stability.

The present cavity configuration shows very little surface subsidence and cavity convergence. Three-dimensional FEM computations explain this stable load-bearing behaviour in terms of a bridging effect; the inner region of the cavity array relaxes and stresses are transferred to the outer region of the salt dome. The prediction of stresses and strains for the cavities with enlarged diameter results in slightly increased though still acceptable surface subsidence. Along with the design computations, a fundamental study on stability and surface subsidence for a single isolated cavity, a small cluster of cavities, and an infinite array of cavities has been performed. Results of axisymmetric computations are compared with 3D model computations.

INTRODUCTION

Akzo Salt and Basic Chemicals operates two brine fields in the concession 'Adolf van Nassau' in Groningen, the northeastern province of The Netherlands. Within this concession the diapirs of Winschoten and Zuidwending are situated.

The Zuidwending salt dome has been exploited by a total of eight solution mined cavities. Wells have been drilled in a regular hexagonal pattern with a spacing of at least 250 m. A horizontal cross-section of the cavity array is shown in Fig. 1. A typical Zuidwending cavity has the following dimensions: the roof is located at an average depth of 850 m below surface, the average height of the cavity is 500 m, and the sump is at a depth of 1350 m. Figure 2 gives a representative profile across the brine field, showing the actual shape of the cavities as surveyed by sonar. Most cavities have reached a maximum diameter beyond 90 m and some are close to a diameter of 100 m.

The Zuidwending salt dome has been explored by means of seismic investigations and boreholes. The diapir has an elongated shape with a northern and a

southern culmination (Harsveldt, 1980). The cavities are located in the central part of the northern section of the salt dome. The top of the salt dome is at a depth of about 180 m, whereas the base of the salt formation is between 2500 and 3000 m below surface. The diapir is covered by a gypsum-anhydrite caprock reaching a maximum thickness of 40 m.

Geological information obtained during drilling shows that the cavities are leached in very pure, coarse-grained rock salt with few impurities in the form of anhydrite stringers. There is no evidence on the presence of layers or deposits of highly soluble and very deformable potassium or magnesium salt in the central part of the salt dome. Further evidence on the excellent quality and homogeneity of the salt can be found in the chemical composition of the brine and the results of many sonar surveys.

Regular subsidence monitoring by means of precise levelling has been performed on a yearly basis since the beginning of solution mining in that area (Wassmann, 1993). Since the first levelling campaign was undertaken in 1969, a maximum total subsidence of 49 mm has been measured above the brinefield.

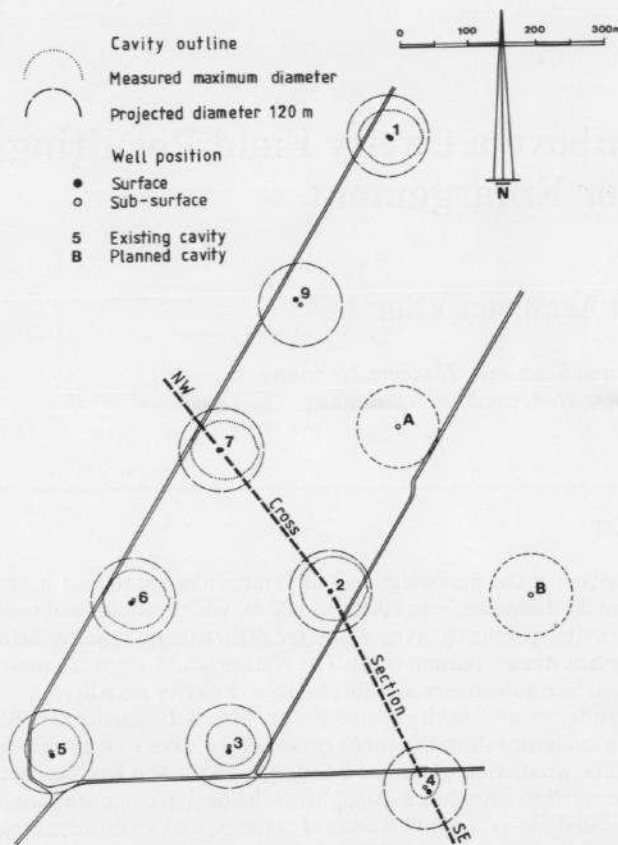


Fig. 1. Brinefield Zuidwending. Cavity layout.

In judging the data, external effects not related to solution mining should be considered. Firstly, and most important, subsidence due to gas production has to be taken into account. The salt mining concession is situated within the far-field subsidence area related to gas production from the Groningen gasfield. Results of subsidence measurements reported by the operator of the gasfield show that gas reservoir compaction contributes about 29 mm to total subsidence measured in this area. Secondly, compaction as a result of lowering the groundwater table, a consequence of re-allotment activities in this agricultural area, is estimated to have added another 3 mm (Wassmann, 1993). This leaves 17 mm of subsidence which may be attributed to solution mining and cavity closure over a period of 22 years.

When one of the cavities was shut in for several months, almost no increase of internal pressure was noticeable. Temperature and saturation effects, however, superimpose pressurization of the brine inside the cavity and complicate interpretation. Both observations, i.e. small surface subsidence and very low pressurization of the brine within the closed cavity, indicate that the cavities are stable and convergence rates are very low.

The purpose of the project is to assess the effect of diameter enlargement on cavity stability and surface subsidence. Enlarging the maximum diameter of a cavity from 100 to 120 m could result in an increase in salt recovery of 45% being achieved. Productive life is substantially prolonged and the wells are better utilized.

The objectives of the computational study are to verify the deformation behaviour observed and to demonstrate that changes in stress distribution and deformation as a result of cavity diameter enlargement will not lead to unacceptable changes in surface subsidence while cavern integrity remains guaranteed.

NUMERICAL MODELLING

Stability of a single isolated cavity or an array of cavities can be defined as the capacity of the rock mass to sustain additional loading due to solution mining, so that stress redistribution results in a new state of equilibrium in the rock mass without failure and without unallowable convergence of the cavities. The principal item of an adequate design concept is to assess all possible risk situations and to take necessary actions to keep off those risks (Langer et al., 1984). In view of this geotechnical design concept computations play an essential role.

Computation of stresses and strains by means of a sensitivity analysis is necessary to determine the influence of characteristic parameters on the load bearing capacity and the deformations, as well as to allow an assessment of the consequences and a demonstration of the stability for the appropriate design (Wallner, 1988; van Eekelen, 1988).

In accordance with this general stability demonstration concept computations for the Zuidwending cavity field were carried out, analyzing the influence of the cavity diameter enlargement on:

- changes of stresses and strains in the near-field of the cavity with respect to cavity stability,
- changes in the far-field behaviour with respect to surface subsidence.

The study aimed at establishing a reference model describing the actual situation, and at comparing these results with those for cavity arrays with identical geometry and spacing but with increased diameter.

The fundamental basis for a reliable assessment of the stability and the convergence of the cavities is a consistent constitutive law for the mechanical behaviour of rock salt. Intensive international research on the mechanical behaviour in conjunction with the nuclear waste management programs have led to a comprehensive knowledge of the rheological behaviour of rock salt (Langer, 1979).

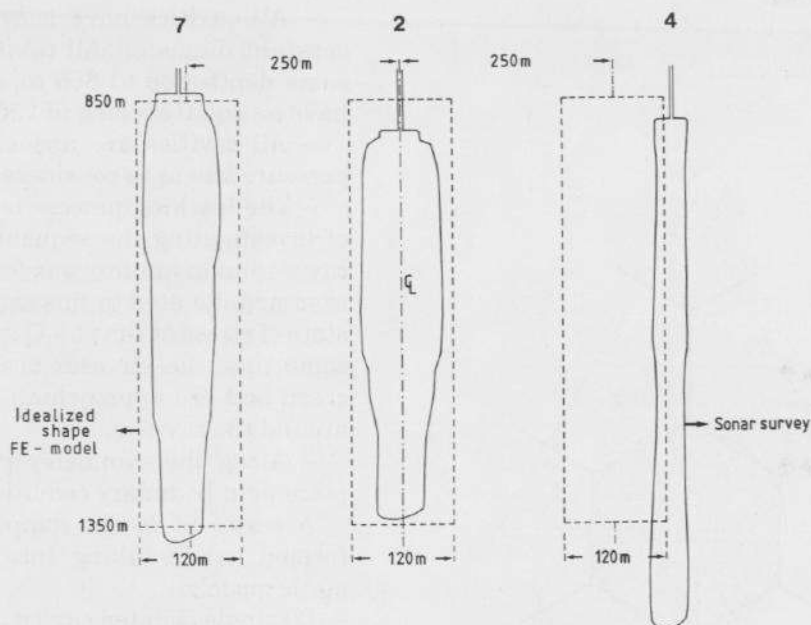


Fig. 2. Profile NW-SE cavity field Zuidwending.

TABLE 1

Reference mechanical properties

Rock mass	Density	Elastic properties		Creep properties		
	ρ (kg/m ³)	E (MPa)	ν (-)	A (d ⁻¹)	Q (kJ/mol)	n (-)
1 Salt, halite	2200	25,000	0.27	0.18	54.0	5
2 Overburden	2200	300	0.27	-	-	-
3 Adjacent rock	2200	10,000	0.27	-	-	-

Nomenclature: ρ = Density (kg·m⁻³); E = Young's modulus (MPa); ν = Poisson's ratio (-).

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

where $\dot{\epsilon}$ = Strain rate (d⁻¹); T = Temperature (K); σ = Stress (MPa); A = Structural factor (d⁻¹); Q = Activation energy (kJ·mol⁻¹); n = Stress exponent (-); R = Gas constant = 8.3143·10⁻³ (kJ·mol⁻¹·K⁻¹); σ^* = Normalization stress = 1.0 (MPa).

Rock salt shows a distinct non-linear rate sensitive mechanical behaviour which is particularly dependent on stresses and temperature. 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 behaviour and steady state creep only. Failure deformation is not implicitly incorporated in the constitutive model. However, stresses may be analyzed with respect to long-term strength represented by a Drucker-Prager yield criterion. Validity of this simplification has been sufficiently proven by comparing computed and measured results of *in situ* tests. Moreover, laboratory tests on some Zuidwending rock salt samples have confirmed that a reference creep law for very pure rock salt is applicable. The relevant data for rock salt are presented in Table 1.

Correct numerical modelling of the Zuidwending cavity field actually requires a three-dimensional analysis taking the time related sequence of the solution mining process into account. However, the present computer abilities and computer codes still require simplifications with respect to the geomechanical model and the static model before the computation can efficiently be performed.

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

- The salt dome is assumed to be isotropic and homogeneous.
- The caprock is not taken into account. The overburden and the adjacent rock are assumed to behave elastically. Deformation moduli have been appraised due to experience.
- The primary state of stress is considered to be isotropic and to increase with depth corresponding to

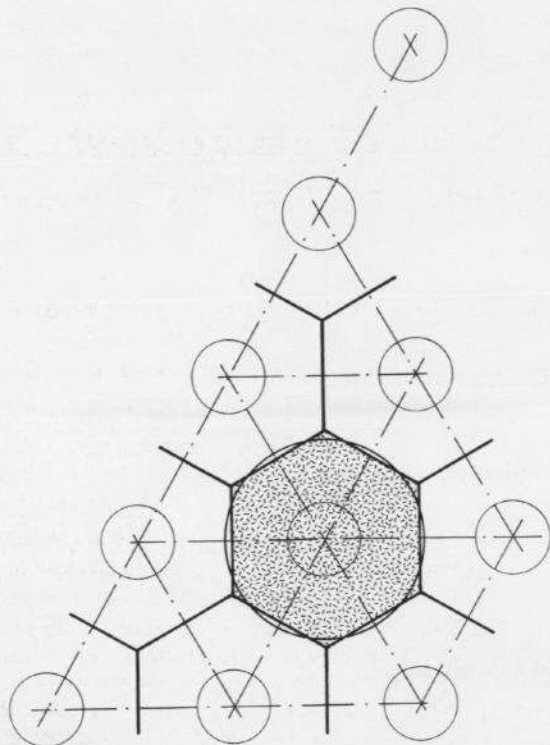


Fig. 3. Plane of symmetry for an infinite array of cavities.

the density of the rock mass. An increase of temperature with depth of 3 degrees per 100 m is assumed.

All static models are based on the following assumptions:

- The cavity field is situated in the centre of the salt dome, so that a relevant diameter of 2400 m can be taken into account in view of axisymmetric reduction.

- All cavities have a cylindrical shape with a constant diameter. All cavities are situated at the same depth (top at 850 m, bottom at 1350 m) and have an equal spacing of 250 m.

- All cavities are unsealed, so that only brine pressure has to be considered inside the cavities.

- The leaching process is not simulated. Instead of investigating the sequential development of the cavities an instantaneous formation of all cavities is assumed. Related to this assumption the respective state of stress at time $t = 0$ is not realistic. Only after some time the stresses are changing according to creep and are approaching the true state of stress around the cavities.

- Along the symmetry planes, appropriate displacement boundary conditions are adopted.

A series of model computations has been performed, while taking into account the following static models:

- (1) single isolated cavity,
- (2) infinite array of hexagonally arranged cavities,
- (3) axisymmetric "ring model" with equivalent fluid pressure for a cluster of 7 cavities,
- (4) axisymmetric "ring model" with brine pressure for a cluster of 7 cavities,
- (5) 3D model for a cluster of 7 cavities,
- (6) 3D model for a cluster of 10 cavities.

The main objective of this extensive computational study was to prove the validity of the computed results by comparing all results with each other, bearing in mind that some results represent upper or lower limits respectively.

The model of an infinite array of cavities is shown

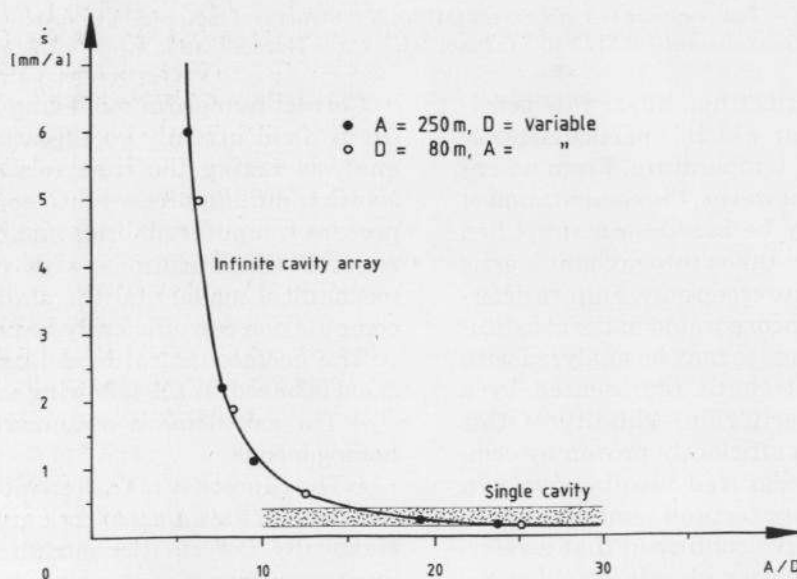


Fig. 4. Surface subsidence rates above an infinite array of hexagonally arranged cavities depending on cavity spacing to cavity diameter ratio A/D . A , cavity spacing; D , cavity diameter; mm/a, millimeter per year.

in a horizontal cross-section in Fig. 3. This model is equivalent to the thick-walled cylinder problem. It is questionable whether this model adequately represents the load-bearing behaviour of a cavity field with only a limited number of cavities (Durup, 1990). To illustrate this, Fig. 4 shows the surface subsidence rate above an infinite array of hexagonally arranged cavities plotted against the cavity spacing to cavity diameter (A/D) ratio. For comparison, subsidence rates above a single isolated cavity are also given. The lower bound of the shaded strip in Fig. 4 defines maximum surface subsidence rate for a cavity of 80 m diameter, whereas the upper bound is valid for a cavity diameter of 120 m. For high A/D ratios, e.g. $A/D > 20$, the surface subsidence rate will be equal to that of a single cavity. This implies that cavities with such high A/D ratios will not interact with each other. On the other hand low A/D ratios signify a strong interaction with very high convergence rates or surface subsidence, respectively. It will be shown later, that this model becomes invalid in particular for a cavity field with a limited number of cavities and a small A/D ratio.

As a first approximation to the Zuidwending cavity field, axisymmetric "ring models" (Fig. 5) have been applied similarly to the suggestions of Serata (1978), Fischer (1984) and Fischer and Light (1988). The axisymmetric "ring models" have been loaded with an equivalent fluid pressure, taking constant brine pressure inside the cavity and constant primary rock stress outside the cavities into account. Furthermore, this model has also been calculated with only brine pressure in the circular slot as an extremely conservative assumption. Although some general aspects of stress redistribution inside the cavity field have been revealed as a result of these

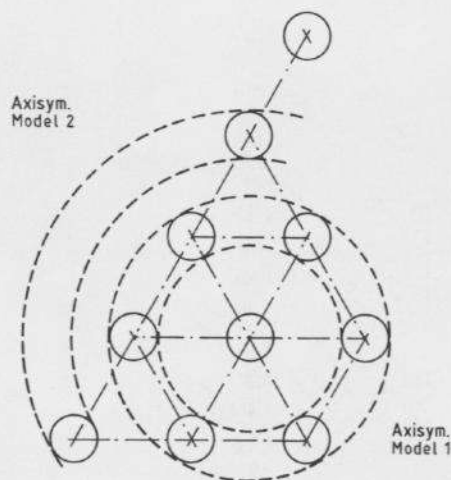


Fig. 5. Axisymmetric models for Zuidwending cavity field.

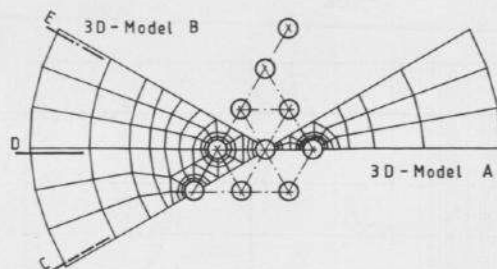


Fig. 6. Three-dimensional models for cavity field Zuidwending, reduced mesh.

computations, the validity of the model, particularly for small A/D ratios, is questionable.

Principal investigations were done on three-dimensional models shown in Fig. 6. With fewer simplifications, model A represents an array of 7 cavities, while model B describes a configuration of 10 cavities. A vertical cross-section of the finite element mesh for 3D model A is shown in Fig. 7. Model A consists of 1344 elements, 7084 nodes and 18,121 degrees of freedom (DOF), respectively. Model B has a total number of 2084 elements, 10,128 nodes and 27,360 DOF. Both models take into account a cylindrical shape of the salt dome with a radius of 1200 m, the overburden and the adjacent rock. The data applied for the mechanical behaviour of the rock masses are compiled in Table 1.

The computations were carried out with the finite element code ANSALT (Morgan et al., 1987).

RESULTS

Some selected results gained from the computation of the 3D models are worth being explained in some detail, because they exhibit fundamental understanding of the load-bearing behaviour and deformation of a cavity field with a limited number of cavities.

Figure 8 shows the deformed mesh scaled by a factor of 4 for characteristic sections of the cavity field 100 years after cavity formation. From the vertical cross-section the computed convergence of the cavity and the deformations in the salt rock can be recognized. Due to the increase of temperature and stresses with depth, a remarkable increase of convergence with depth is also determined. The rock beneath the cavities is likewise highly deformed. Over long periods of time unsealed cavities will, therefore, affect a large volume of the surrounding rock. From the horizontal representation it can be realized how the cavities affect each other. Flow of rock salt from outside the actual cavity field results in a non-uniform convergence of the peripheral cavities showing larger displacements of the outer cavity walls than of the inner walls.

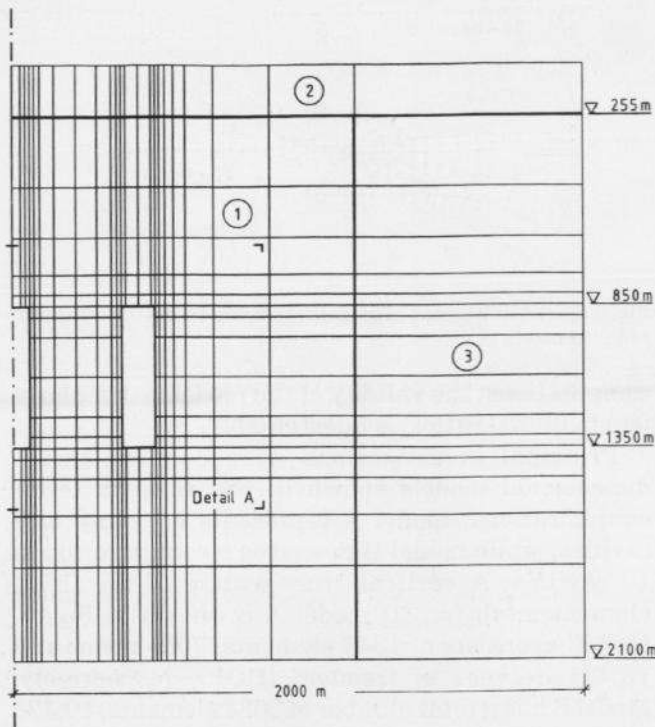


Fig. 7. Finite element mesh for 3D model A. 1, Salt dome; 2, overburden; 3, adjacent rock.

The reason for the computed deformations becomes evident, when the alteration of the stresses in the adjacent salt rock is evaluated. In Fig. 9 the change of radial rock stress due to cavity formation for a characteristic section is plotted. Figure 10 represents the equivalent changes of the vertical rock stress for 3 typical cross-sections. All stresses inside the cavity field decrease with time once the cavities have been created. The formation of peripheral cavities initiate horizontal stresses in the pillars to relax.

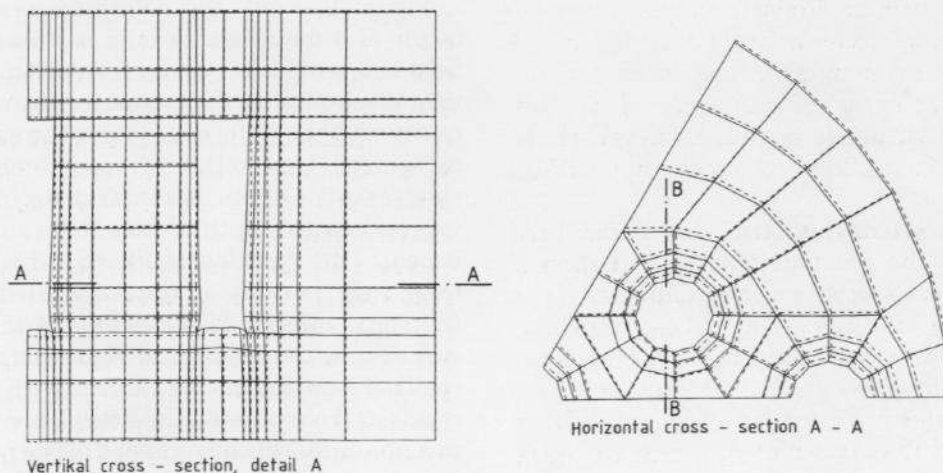


Fig. 8. Deformed mesh 100 years after cavity formation, deformation scaled by a factor of 4.

Subsequently, the small initial increase of the effective stress in the pillars between the cavities causes creep deformations. Through that, the pillars withdraw themselves from carrying the overburden load, which forces the rock above the cavities to transfer stresses to the virgin rock outside the cavity field.

This bridging effect is typical for a small cluster of cavities and leads to a transient increase of stress in the adjacent rock. The horizontal stress in the centre of the pillars between the cavities drops to about 60% of the primary stress after a time interval of 10 years. The vertical stress in the pillars is reduced at an average of about 20% after 10 years. This stress relaxation continues at a small rate as long as the cavities are unsealed.

For the Zuidwending cavity configuration, this stress redistribution increases stresses outside the cavity field only moderately. A maximum stress increase of less than 2 MPa after 10 years has been predicted. The cluster of cavities with a low A/D ratio finally behaves like a large single cavity without significant loss of stability. Since the stresses around the various cavities remain low, integrity of the salt pillars is not endangered.

Whereas stability of the rock mass inside the cavity field is not in question as long as the internal pressure inside the cavities is kept constant, long-term deformation resulting from continuous creep has to be taken into serious consideration with respect to design requirements. Since surface subsidence is closely related to cavity convergence, the surface subsidence rate is taken as a characteristic design parameter.

All computations made for the Zuidwending cavity field have been summarized in Fig. 11, showing the dependency between cavity diameter and surface subsidence rate. On a semi-logarithmic scale this

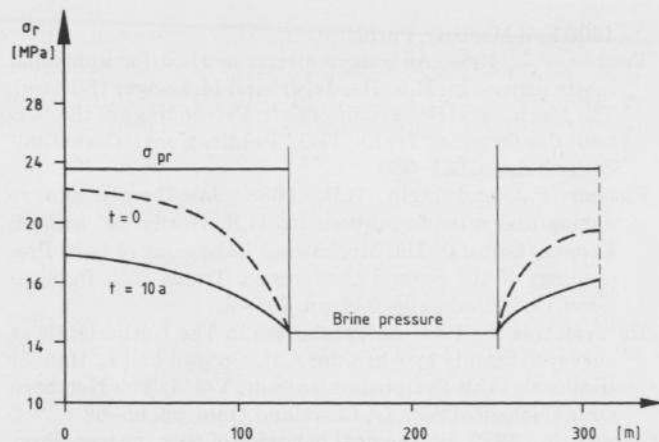


Fig. 9. Change of radial rock stress due to cavity formation, cross-section B-B as indicated in Fig. 8.

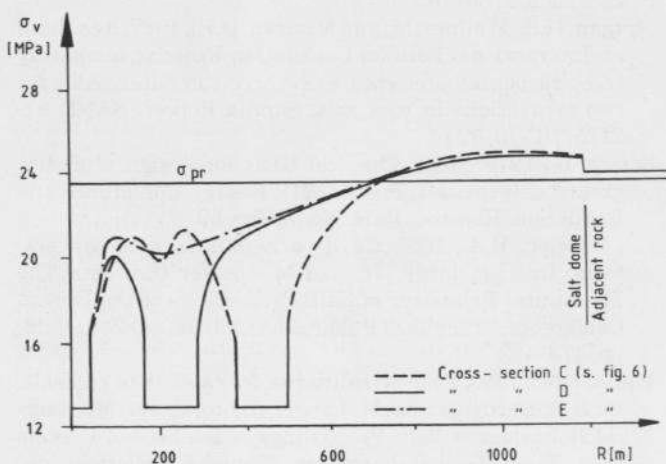


Fig. 10. Change of vertical rock stress due to cavity formation, depth 1070 m.

dependency is described by a straight line indicating a slightly over-proportional relationship.

The results computed for a single cavity (curve 1) give the lowest bound for surface subsidence. Accordingly, the results for an infinite array of cavities (curve 2) lead to an upper bound. However, these results differ from each other by nearly three orders of magnitude.

The results of the axisymmetric "ring models" are situated between the previous bounds, but show a very low dependency on the cavity diameter. It is worth mentioning that this result indicates the inability of these models to predict the real dependency between subsidence and cavity diameter.

From the 3D models (curves 5 and 6) a subsidence rate is calculated that is consistent with the more conservative results, and in accordance with field observations. As a consequence of conservative as-

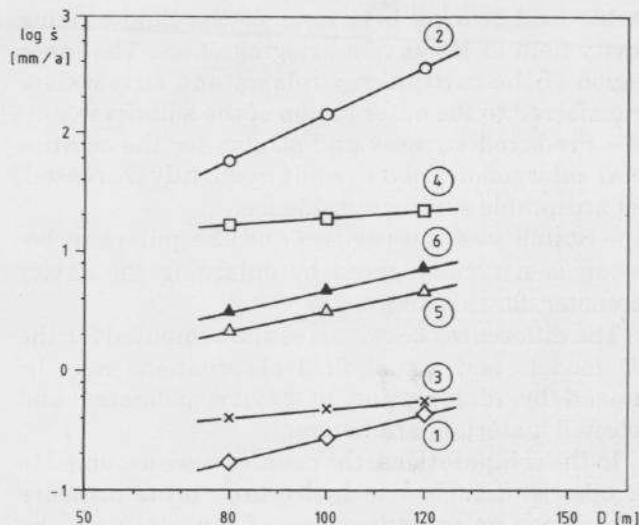


Fig. 11. Surface subsidence rate in millimeter per year (mm/a) for a cavity array depending on cavity diameter, semi-logarithmic scale. 1, Single isolated cavity; 2, infinite array of cavities, $a = 250$ m; 3, axisymmetric model 1, equivalent fluid pressure; 4, axisymmetric model 1, brine pressure; 5, 3D model A (cluster of 7 cavities); 6, 3D model B (cluster of 10 cavities).

sumptions in the 3D model, the results computed have still to be regarded as an upper bound of the real behaviour. Hence, convergence of the cavities in the Zuidwending brine field and surface subsidence respectively will remain small even if the cavity diameter is enlarged to a maximum of 120 m. Compared with the reference design, surface subsidence rates are expected to increase by a factor of 1.5 in the event of the cavity diameter being enlarged from 100 to 120 m.

CONCLUSIONS

The objective of the study was to verify whether enlargement of the cavity diameter in the Zuidwending brine field up to a value of 120 m, resulting in a cavity spacing to diameter ratio of nearly 2, is still safe from a geotechnical point of view. The present cavity configuration with a total of eight cavities with maximum diameters beyond 90 m is evidently stable, and shows very little surface subsidence and convergence.

From this comprehensive finite element study the following conclusions can be drawn:

- 3D models are to be applied for realistic and reliable predictions of stresses and deformations around a small cluster of cavities with small cavity spacing to cavity diameter ratios.
- It is recommendable to feed back computational results to *in situ* measurements and observations.
- 3D FEM computations explain the present

stable load-bearing behaviour of the Zuidwending cavity field in terms of a bridging effect. The inner region of the cavity array relaxes and stresses are transferred to the outer region of the salt dome.

– Predicted stresses and strains for the cavities with enlarged diameter result in slightly increased, yet acceptable surface subsidence.

– Stability of the cavities and the pillars in between is not endangered by enlarging the cavity diameter, for this array.

The differences between results computed for the 3D models and actual field observations may be caused by idealization of cavity geometry and selected material parameters.

In the computations, the cavities were assumed to be open and subject to hydrostatic brine pressure only. Since no pressurization of the cavity on the inside has been taken into account, the subsidence rates predicted are only valid as long as the cavities remain open. Any form of additional support of the cavity wall will have a significant impact on deformation behaviour and consequently on surface subsidence. Before venturing into long-term subsidence forecasts, cavity abandonment and sealing criteria will have to be developed and tested. This matter is expected to be subject of substantial research effort and study in the years to come.

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