LAND SUBSIDENCE

Natural causes
Measuring techniques
The Groningen gasfields

Edited by
FRANS B.J. BARENDTS
Delft Geotechnics, Netherlands
FRITS J.J. BROUWER
Ministry of Transport, Public Works and Water Management, Delft, Netherlands
FRANS H. SCHRÖDER
The Netherlands Geodetic Commission, Delft, Netherlands

OFFPRINT

A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 1995
Production-induced convergence of solution mined caverns in magnesium salts and associated subsidence

P.A. Fokker  
*Delft Geotechnics, Netherlands*

J.L. Urai  
*Shell Research (KSEPL), Rijswijk, Netherlands*

P.V. Steeneken  
*Nedmag Industries Mining & Manufacturing BV, Veendam, Netherlands*

Abstract NEDMAG INDUSTRIES are currently producing highly concentrated magnesium brine by induced creep closure (squeeze) of solution mined caverns near Veendam (northern part of the Netherlands) by reduction of the wellhead pressure. The magnesium salts have a very low creep resistance and allow a fast cavern volume reduction. By adopting this method for all caverns, the drilling and development of new caverns can be postponed, saving on investments and operational costs.

The consequences of this operation, in particular surface subsidence and the change in ground water table, were investigated in this study. A pilot test was carried out, involving a 150,000 m³ cavern volume reduction, and simulated by finite element calculations. Measurements and calculations, based on independently determined input parameters, agree well. The final subsidence bowl, calculated for 2 million cubic metres of cavern volume reduction and some 10 years of squeeze mining, is predicted to have a maximum subsidence of some 20cm, and a diameter of some 6km.

INTRODUCTION

NEDMAG INDUSTRIES are producing solution mining magnesium salts in the northern part of Netherlands, thereby creating large (about 500,000 m³ each) brine filled caverns. NEDMAG's cavern field is located near Veendam in the province of Groningen at a depth between 1500 and 2,000m. The shape of the caverns is largely dominated by (i) the preferential dissolution of carnallite and bischofite and their respective stratification and (ii) by the application and effectiveness of an oil blanket during leaching (Coelwij et al., 1978). An artist's impression of the cavern shape is given in Fig. 1; the actual shape is likely to be more complex. Twelve such caverns have been created; six of them are still in the leaching phase.

Since magnesium salts (mainly carnallite and bischofite) have much less creep resistance than rocksalt, the caverns have a strong tendency to converge (Urai, 1983). Magnesium salt layers are squeezed into the cavern if some difference between the in situ lithostatic salt stress level and the fluid pressure in the cavern is present. The cavern fluid pressure is the sum of the hydrostatic brine pressure and an applied well head pressure. Convergence of the salt caverns results in surface subsidence, which was seen as an undesirable side effect of the mining process. For this reason, the convergence rate has been largely reduced during the mining
process up to now, by operating at almost lithostatic cavern fluid pressures, i.e. at high wellhead pressures.

Recent findings however (Fokker et al., 1992, 1995) indicate that caverns start to fracture and leak as soon as fluid pressures exceed the ambient salt stresses, which inevitably occurs after cavern sealing and abandonment as a result of density differences between cavern fluid (brine) and the salt rocks. This will lead to surface subsidence during the centuries to come.

For this reason abandonment of caverns by plugging the casing was not considered desirable and it was decided in early 1993 to investigate the feasibility of cavern size reduction by lowering the fluid pressures. This allows squeeze of the magnesium salts and surface subsidence to occur during operational periods of the mine rather than on an indefinite term thereafter. A great advantage of this method is that large quantities of valuable brine can be recovered from the mined out caverns, which value is expected to more than compensate the associated subsidence costs.

Squeeze brine production requires both proper in situ measurements as well as scientific assistance to determine operational risks - if any - and to predict shapes and sizes of future subsidence bowls.

**RESEARCH OBJECTIVES**

To be able to determine what measures should be taken during and after the squeeze operation, and to assess the associated costs, a forecast of the shape of the final subsidence bowl is required. Furthermore, a study is warranted whether or not hazardous situations may arise. To do so, finite element calculations were performed and a pilot squeeze test was initiated, with the following objectives:

- determination of squeeze rates as function of fluid pressure and squeeze volume
- time evolution and interpretation of shear stress distributions in salt and overburden
- prediction of the shape and size of subsidence bowl and its uncertainties.

The Finite Element package DIANA was used to simulate the cavern behaviour and subsidence measurements.
Simultaneously, a study was performed (by an independent engineering company) to assess the consequences and actions to be taken related to this subsidence bowl, which is expected after large scale squeeze. These actions will mainly be related to water table changes in the area of the bowl, which may have implications for the Veendam agriculture. It was decided to carry out the study in close co-operation with state and local authorities.

FINITE ELEMENT MODELLING OF THE CAVERN FIELD

Uncertainties and approximations

To simulate the behaviour of a cavern field, a number of assumptions and approximations have been made, as summarised below:

- The dip of the salt layers, having a maximum of 20% (1:5), was neglected to allow an axi-symmetric approach of the problem
- Only the most important stratification has been taken into account. The stratigraphic column was strongly simplified
- Because a cavern cluster cannot be modelled axi-symmetrically, the subsidence bowl resulting from a squeezing cluster has been calculated via two approximations: (i) cluster modelled as a central cavern surrounded by a circular (ring) shaped cavern and (ii) by superimposing the bowls resulting from single squeezing caverns
- It is assumed that at least half the fluid volume (2 million m³) can be squeezed out within 10 years. The fluid volume of the cavern field after finalising the leaching stage will be roughly 4 million cubic metres. As some part of this fluid will be trapped in wash-outs in the cavern wall or in the precipitate, it is not likely that all fluid can be squeezed out within operational time (10-30 years). More precise figures can only be obtained via squeeze experience
- The overburden was approximated as a homogeneous layer, with a single set of elastic parameters. A best estimate of (average) Young's modulus was 3 GPa, its limits 1 and 15 GPa. The best estimate of the Poisson's ratio is 0.25. Few measurements have been performed on the Bunter Sandstone overlying the salt, having a Young's modulus of 10 GPa. The extreme values have been used to calculate the extremities of the bowl shape; the best estimate was used to simulate the pilot test
- It was assumed that the overburden will remain elastic during all stages of the squeeze operation. That onset of non-linear deformation does not occur was confirmed by comparing calculated stresses with reasonable failure criteria
- Local effects in the vicinity of pre-existing faults was neglected. Pre-existing faults may influence the overburden response to deformation. Three dimensional seismic based information gave no indication of major faults in the vicinity of the cavern field (Coelewij 1978). Moreover, (large scale) shearing of existing faults is not to be expected as the shear stresses are hardly increased from the initial values and even decrease by the arching effect (increasing horizontal stresses and decreasing vertical stresses, see Figs. 2 and 5)

The spatial distribution of creep properties of the different salt species are not precisely known and assumptions were necessary.

Validation

The relation between the squeeze production-rate, its total volume and the fluid pressure in the cavern was compared to the results of a limited first squeeze test in 1987/1988. Creep values have been adjusted (within the limits of uncertainty) to match these data. Subsidence measurements over this period were inconclusive.
PILOT SQUEEZE TEST

It was decided to squeeze a single cavern (TR-4, Fig. 6) over a relatively short time, concentrating all subsidence in a relatively small area. Levelling was performed after each 50,000 m³ of squeeze production; both squeeze volumes and cavern fluid pressures are still continuously measured.

TEST EVALUATION

Production via squeeze proceeds virtually without problems, except for some recent tubing damages. At this moment more than 170,000 m³ of brine is produced from a single cavern (TR-4) with no indication of a limit to squeeze yet. The fluid pressure deficit compared to lithostatic, has been increased from 20 bars to roughly 140 bars, thus lowering the wellhead pressure from 150 bars to 30 bars to maintain an average brine production (before dilution) of 2500 m³ per week. The levelling based bowl displayed a maximum subsidence of some 1.6 cm after 150,000 m³, halved (0.8 cm) at roughly 1 km from the centre of the bowl.

In October 1993, some months after the initiation of the test (June) it appeared that a limited connection had been created with an adjacent cavern (TR-6), as shown by a slowly dropping fluid pressure in this cavern. A full connection between both cavern has not been established, since the pressure difference between them remained at a level of some 60 bars. This can be explained by stress arching effects around the squeezing cavern, which result in a vertical stress reduction extending to the adjacent cavern (wall). If this stress (Fig. 2) drops below the fluid pressure in the adjacent cavern, a fracture can be expected, partly connecting both caverns. When the fluid pressure in the adjacent cavern has dropped sufficiently the fracture will close again, by which a full connection is prevented (unless salts in the fracture

---

**Fig. 3**

**Fig. 4**

---

The amount of brine, w (smaller than 20,000 m³) can dissolve in case of t.

**SIMULATION OF SC**

A FE-simulation was performed (3 GPa, 435 ksi) and t calculated squeeze volume. Subsidence levels recorded levels are 1.1 and 1.2 cm halved subsidence are b cannot be measured as t
Fig. 3 Calculated vs. measured squeeze production at cavern TR-4

Fig. 4 Calculated vs. measured maximum subsidence levels

for some recent tubing leakages, and a relatively short time, the perforations were still tight. The fracture can dissolve in case of under-saturated brines). The fracture will act as a pressure relief valve. The amount of brine, which flowed to the squeezing cavern is believed to be relatively small (smaller than 20,000 m³).

SIMULATION OF SQUEEZE TEST

A FE-simulation was performed at appropriate values of both the stiffness of the overburden (3 GPa, 435 ksi) and the creep parameters (see for details, Fokker 1995). Measured and calculated squeeze volumes matched excellently (Fig. 3). Comparison of the maximum subsidence levels renders a good match (Fig. 4). The measured and calculated subsidence levels are 1.1 and 1.5 cm per 100,000 m³ of squeeze. The predicted and measured radii of halved subsidence are both 1 km. A radius of 2 km for decimated subsidence is predicted but cannot be measured as this subsidence is in the range of measurement uncertainty.
After 150,000 m³ of squeeze from TR-4, and a few squeeze-less weeks brines are being produced by squeeze from TR-4 and TR-6 directly, almost equalizing cavern pressures. Fluid flow from TR-6 towards TR-4 must have ceased for that reason.

CAVERN AND OVERBURDEN STABILITY DURING SQUEEZE

Squeeze disturbs the initial stress state in the salt and the overburden, by which the shear strength of the rocks or existing faults may be exceeded. Initially the shear stresses in the salt are small or absent, resulting from their creep behaviour (see also Carter and Hansen, 1983). The overburden has initial shear stresses with a K₀ ratio of about 0.4, based on (unpublished) leak off tests in the vicinity of the cavern field. A recalculation (neglecting pressure variations on weekly basis) has been performed with an increased stiffness (8 GPa, 1160 ksi) of the lower 460 metres of overburden. The 10 GPa measured stiffness of the lower Bunter Sandstone overburden is better represented here and the apparent underestimation of the total stiffness (resulting in an overestimation of the subsidence) is corrected. A contour plot of the shear stresses (Fig. 5) shows that differential stresses remain low in the rocksalt and even decrease in the overburden overlying the cavern.

This last result is due to the arching effect around the cavern, increasing horizontal stresses and decreasing vertical stresses. Therefore, faults, if present, are unlikely to slip. It is expected that squeeze is possible without loss of integrity of either overburden rock or rocksalt.

TRANSLATION OF SINGLE CAVERN SUBSIDENCE DATA TO MULTIPLE CAVERNS

The subsidence bowl resulting from the full cluster of caverns has been determined in two ways:

![Fig. 5 Octahedral shear stress distribution after 150,000 m³ of squeeze](image)

**Fig. 6 Predic**
weeks brines are being cavern pressures. Fluid

The extreme cases of both overburden stiffness and creep parameters gave subsidence bowls (for 2 million cubic metres) of 35 and 10cm maximum subsidence for the soft 1 GPa and the stiff 15 GPa overburden respectively. The respective subsidence bowls are correspondingly narrow (decimated at 2km, halved at 1km) respectively wide (halved at some 2km and decimated at some 4km). There appeared to be only minor differences in the bowl shapes resulting from the ring cavern or from the superposition of bowls, where changing the overburden stiffness had a much more pronounced effect. It is hence believed that superposition of the pilot test subsidence data - as function of the squeeze volume of each cavern - gives a good forecast of the bowl after 2 million cubic metres of squeeze.

Extrapolating and superposition of the squeeze results after having squeezed all caverns, renders a maximum subsidence of about 1cm per 100,000 m³, amounting to 20cm at 2 million m³ of squeeze (Fig. 6). The subsidence will be halved and decimated at respectively some 1.5km and 3km distance from the centre of the bowl.

Presently the consequences of subsidence are still under investigation. It is however clear that (at least for the area overlying NEDMAG’s cavern cluster and a squeeze volume of 2 million m³):

- The costs associated with a deep and narrow bowl exceed those of a shallow and wide bowl.

Fig. 6 Predicted subsidence bowl after 2 million cubic meters of squeeze
- Subsidence related costs are lower than the profits of squeeze and are mainly related to measures to be taken to adjust the water table, dike- and quay heads.

An important issue of discussion is the required compensation for future exploitation, maintenance and replacement costs of for instance, pump houses, which depends on the expected future effective interest (i.e. interest minus inflation). Where state authorities usually assume a 4.5 per cent rate, water boards believe it to be below 3 per cent. These assumptions on capitalization, which are hard to quantify, can result in large differences in the required funds.

A complicating issue is the fact that subsidence is created in an area where subsidence is already occurring due to gas exploitation.

MINE STRATEGY

Awaiting the final test evaluation, it is expected that brine production in the near future will be predominantly by squeeze, and only limited solution mining. Given the expected minimum squeezable brine quantities in the caverns (2 million m$^3$) and the (nett) brine requirement of some 25,000 m$^3$ per month, squeeze alone can satisfy the brine demands for at least 7 years. The fluid pressures in the caverns will be held at similar values during squeeze to avoid future cavern interconnections. Subsidence will be monitored regularly. Financial funds will be created for the measures to adjust the water table in the bowl to minimise agricultural losses, this in close co-operation with local authorities and water boards. After having squeezed the brine resources, one may decide to proceed leaching and subsequent squeezing from the old caverns. This results in higher subsidence costs per cubic metre of squeeze, but will save on new cavern development costs. Alternatively one can decide to develop caverns another location. This decision however can be postponed some 5 to 10 years.

CONCLUSIONS

It is favourable to precede abandonment of solution mined caverns in magnesium salts by squeeze, thus minimising the cavern volume before - and subsidence after - abandonment. Subsidence, which would otherwise occur anyway over a longer term as a result of cavern leakage, is now forced to appear within the operational period of the mine; hereby valuable magnesium brine will recovered. Drilling and development of new caverns can be postponed saving on investments and operational costs.

Research has indicated that squeeze can be a safe operation and can be well controlled. FE-calculations are well in line with the results of the current squeeze test. After squeezing 2 million cubic metres of brine, a subsidence bowl is expected with a depth of 20cm and radius for halved and declimated subsidence of 1.5 and 3 km respectively.

Squeeze is anticipated to be NEDMAG's most important means of brine production for the coming decade. Subsidence will be regularly measured and measures will be taken to minimise any negative effects related to subsidence.

REFERENCES


FROM THE SAME PUBLISHER:

Koerner, R.M., E. Gartner & H. Zanzinger (eds.) 90 5410 519 4
Geosynthetic clay liners – Proceedings of an international symposium, Nimberg, 14-15 April 1994
March 1995, 25 cm, c.350 pp., Hfl.135/$75.00/£50
A new type of geosynthetic material which is an excellent blend of natural soil and geosynthetics in the form of a composite barrier-system is currently available as wide width, factory manufactured products. Called Geosynthetic Clay Liners (GCL); Environmental applications have been a major use of GCL. They have been used as landfill liners, landfill covers, liquid impoundment liners, secondary containment liners for storage tanks & geomembrane protection layers. They have been deployed by themselves or as a composite system with an overlying geomembrane. Transportation applications of GCL as tunnel liners have been contemplated, as has their use as corewalls within earth dams.

Santvoort, G.P.T.M. van (ed.) 90 5410 604 2
Geosynthetics in civil engineering
April 1995, 25 cm, c.140 pp., Hfl.75/$40.00/£28
This handbook offers students in civil engineering, environmental engineers and land development the subject matter necessary for an orientation on the application possibilities of geosynthetics as building material. The book deals with the application of geosynthetics in soil structures, foundations engineering and bank and bed protection. The application of geosynthetics for other civil engineering purposes is mentioned only obliquely, like asphalt reinforcement and drainage of embankments. The book is divided in three parts:
- General: Design considerations and elaborated examples. In this book the state-of-the-art in the mid-nineties is presented.

Balasubramaniam, A.S. et al. (eds.) 90 5410 622 4
1994, 25 cm, 594 pp., Hfl.225/$130.00/£85
Developments of theory & practice in geotechnical engineering (including soil sampling, laboratory and field testing, design methods & construction works); Engineering behaviour of soils (including collapsible & expansive as well as problematic soils); Natural hazards & environmental geotechnics; Embankments, excavations & buried structures; Soil-structure interactions; Ground improvement techniques. 48 papers. Editors: Asian Institute of Technology, Bangkok.

Bui, H.D. & M. Tanaka (eds.) 90 5410 517 8
Inverse problems in engineering mechanics – Proceedings of the 2nd international symposium, Paris, 2-4 November 1994
1994, 25 cm, 492 pp., Hfl.185/$110.00/£60
Many inverse problems of great practical importance are found in engineering mechanics alone, and there is currently a dramatic increase of research activity in this area. This book contains about 65 selected papers by authors from Europe, Asia and America. The overall contents reflect the state of the art in this particular applied research area. The main topics are: Unknown shape determination; Identification of material properties; System determination; Boundary conditions and source identification; Defect identification; Mathematical and computational aspects; Experimental strategy.

Haan, E.deo, R. Termaat & T.B. Edli (eds.) 90 5410 366 3
Advances in understanding and modelling the mechanical behaviour of peat – Proceedings of the international workshop, Delft, Netherlands, 16-18 June 1993
1994, 25 cm, 440 pp., Hfl.180/$105.00/£67
Peat is one of the most compressible soils in nature. Whenever possible, geotechnical engineers will avoid this difficult material by building elsewhere, or removing it completely from underneath their structures. Topics: One-dimensional behaviour; Stress-strain & strength behaviour; Immediate issues in engineering practice.

Santvoort, G.P.T.M. van (ed.) 90 5410 172 5
Geotextiles and geomembranes in civil engineering
(No rights India)
A handbook for civil engineers. Contents: Geotextile & geomembrane history; Function analysis; Production technology; Properties; Project realization; Bank & bed protection; Roads & railways; Soil reinforcement; Drainage (in the building industry, land drainage, vertical drainage); Geomembranes.

Lancellotta, R. 90 5410 178 4
Geotechnical engineering
April 1995, 25 cm, c.400 pp., Hfl.190/$95.00/£70
(Student edn., 90 5410 179 2, Hfl.115/$60.00/£43)
This book is about the mechanics of soils and structures interacting with soils, based on the material collected at the Technical University of Turin over the past two decades. Contents: Nature and composition of soils; The principle of effective stress and the state variables; Fundamentals of continuum mechanics; The porous medium; steady flow; The porous medium; transient flow; Stress-strain & strength characteristics; In-situ investigations; The collapse of soil structures; Performance and serviceability of structures; References; Index. Author: Technical University of Turin, Italy.

Balasubramaniam, A.S., Yudhbir, D.T. Bergado, N. Phien-Wej, T.S. Seah & P. Nantaya (eds.) 90 5410 355 8
Prediction versus performance in geotechnical engineering
Proceedings of the symposium, Bangkok, 30-Nov-4 Dec 1992
1994, 25 cm, 350 pp., Hfl.185/$105.00/£69
Foundation engineering & field & laboratory testing; Ground improvement & reinforced earth; Embankments, excavations & buried structures; Earth structures, mines & slopes; Dynamic behaviour of soil & earthquake. 32 pages. Editors: Asian Inst. Techn., Bangkok.

Tassaoka, Fumio & Dov Leshchinsky (eds.) 90 5410 358 2
Recent case histories of permanent geosynthetic-reinforced soil retaining walls – Proceedings of Seiten symposium no. II, Tokyo, 6-7 November 1992
1994, 25 cm, 300 pp., Hfl.145/$80.00/£54
The application of the geosynthetic-reinforced soil (GRS) retaining wall to permanent and important structures, such as highway and railway embankments, is rapidly increasing. It replaces conventional RC retaining walls as well as metal-reinforced soil retaining walls. Invited case history papers; General contributions; Discussion. 34 papers. Editors: Univ. Tokyo and Univ. Delaware, USA.

All books available from your bookseller or directly from the publisher:
A.A. Balkema Publishers, P.O. Box 1675, Rotterdam, Netherlands
For USA & Canada: A.A. Balkema Publishers, Old Post Rd, Brookfield, VT, USA