Pillar deformation-induced surface subsidence in the Hengelo brine field, the Netherlands

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ABSTRACT: In the Hengelo area, East Netherlands, solution mining of rock salt is carried out by Akzo-Nobel from a 50 m thick salt deposit of Triassic age, located at about 350 m depth. Until recently surface subsidence was mainly ascribed to upward migration (stoping) above overmined caverns. However, in the oldest part of the brine field the extraction ratio is so high, that also deformation of the remaining salt pillars has to be taken into account. The effect of pillar creep on surface subsidence was investigated by the construction of a series of subsidence rate maps, per year from 1947 to 2003, and the analysis of the relationship of the pattern of these subsidence rates and the most likely cavern and pillar outlines.

This study not only confirmed the existence of several subsidence areas as a result of stoping, but also revealed evidence of a pillar deformation-induced subsidence area. The stress state in this pillar proved to be such that significant dilatancy must be considered. It was concluded that in the dilatant pillar solution-precipitation creep can contribute to the total deformation at the same amount as dislocation processes. It is recommended to incorporate solution-precipitation processes in future geomechanical models of pillar creep, even under non-dilatant conditions.

1 INTRODUCTION

Akzo-Nobel has mined salt since 1933 near the cities of Hengelo and Enschede. Until now about 300 mainly multiple-well caverns were created using more than 500 wells. Cavern diameters generally range from 50 to 150 m. The salt is produced from a 50 m thick, near-horizontal bedded salt-deposit of Upper Triassic age, situated at about 300 to 500 m depth. The salt layer is directly overlain by a relatively tough anhydritic layer of 20 m thickness, and then by 200 to 400 m of mainly friable claystones. In the south-western part of the brine field the upper part of the claystones contain limestone and dolomite layers. The Mesozoic rock formations do not continue up to the surface but are covered by about 70 to 140 m of clayey Tertiary and Quaternary soil units.

Due to inadequate mining methods in the past a number of areas have subsided and will continue to subside for several decades. More areas of surface subsidence may evolve in the future. At present six subsidence areas of significant trough subsidence have formed as a result of stoping, which is upward cavern migration due to subsequent failure and collapse of roof layers (Fig. 1). The troughs measure 150 to 300 m diameter and presently 1 to 3.5 m depth. In two cases the trough subsidence was preceded by sinkhole formation. The largest sinkhole measured 35 m diameter and 3.5 m depth. Additionally, in the oldest part of the brine field, where the above mentioned troughs and sinkholes also developed, deformation of the salt pillars in between the caverns could play a role as well. In the research project (Bekendam & Urai 2006, Urai & Bekendam 2006), described in this paper, it was investigated if creep deformation of pillars contribute to surface subsidence and, if so, which microphysical processes apply.

First the various types of ground movements in the subsurface and their expression of surface subsidence are outlined below.
2 TYPES OF SUBSIDENCE IN THE BRINE FIELD

2.1 Phase I subsidence

Phase I subsidence occurs as a result of convergence of the salt towards the intact cavern, situated completely within the salt formation (Fig. 1a). Surface subsidence is hardly detectable in this case (0.5 mm/year at most).

2.2 Phase II subsidence

This subsidence mechanism can only develop when the uppermost salt layers have collapsed or were dissolved due to overmining. Additionally, the cavern must be able to break through the anhydritic layer. At several caverns the roof migrated inside the anhydritic layer tens of years ago, but has remained there at the same level until now. Whether these caverns will migrate further, and if so when, is difficult to predict.

If the cavern breaks through the anhydritic layer, upward migration through the overlying claystones occurs at a more or less constant rate of 10-14 m/year (Bekendam 1997). During the process the roof debris is deposited at the bottom of the cavern, and a debris-filled chimney is formed, which steadily increases in height (Fig. 1b). This process is denoted as Phase II subsidence. Due to the bulking effect (broken rock occupies a greater volume than intact rock) the height of the cavern continuously decreases. Thus, caverns of relatively small initial height cannot reach the base of the Tertiary soils because they become completely filled with debris at a lower elevation. Analysis of a limited number of field cases revealed a bulking factor of 1.11 for the overburden rocks of the Hengelo brine field (Bekendam 2005).

On account of numerical experiments an increasing subsidence at the surface is to be expected during cavern migration due to the increasing deflection of the rock mass over the cavern roof and the increasing convergence of the walls of the debris chimney. However, Phase II surface subsidence is difficult to detect because its rates are small and often dominated or obscured by the much higher rates of nearby Phase III subsidence areas.

2.3 Phase III subsidence

If a cavity is capable of migrating up to near the base of the Tertiary, significant subsidence starts (Phase III), which exceeds Phase I and Phase II surface subsidence by far. Phase IIIA concerns the movements of the soil layer into the migrated opening (Fig. 1c) and is characterised by a sudden acceleration of surface subsidence (Fig. 2). Phase IIIB applies to long-lasting compaction of the debris chimney by the weight of the soil mass, accompanied by a continuous deceleration of surface subsidence (Bekendam 2000, 2005). In four of the six cases mentioned above the ductile soil mass of a relatively low stiffness gradually subsided over the migrated opening during Phase IIIA and a subsidence bowl developed at an angle of draw of about 45° from the rock-soil interface. In the other two cases a sinkhole developed during Phase IIIA, probably due to the relatively large height of the migrated cavern. For the largest sinkhole some influence of a nearby tectonic fault possibly existed. Phase IIIB always develops as trough subsidence, causing either a further deepen-
ing of the Phase IIIA trough or the formation of a new trough centered at the sinkhole. Phase IIIB subsidence proceeds for a long time, at least for several decades, because compaction of a generally more than 200 m high chimney of roof debris is involved.

2.4 Pillar deformation-induced subsidence
At some locations the horizontal extent of caverns and the distance between them is such that a relatively small pillar-like area of undissolved salt remains. The stability was analysed for elongated pillars, in between rows of caverns, by means of numerical models (e.g. Eickemeier & Heuermann 2004), and for pillars between three or more caverns, arranged in a cluster, using a modified tributary area method (Van Sambeek 1996, 2004). On the basis of these analyses mining was stopped in a number of caverns. Surface subsidence due to pillar deformation could not be detected at the locations investigated, because levelling points were not installed in between wells and the subsidence is probably too small to be measured at the levelling points near the wells.

However, the area of the oldest caverns (approximately wells 1-50) was not included in these studies. Generally, with the exception of the well 15, no sonar measurements exist of these caverns, and their boundaries can only be roughly estimated on the basis of production figures. Even such estimation is difficult because most caverns are interconnected and it is not known how much salt has been dissolved at each particular well. However, the cavern interconnections are known and the centres of the caverns are probably indicated correctly as well.

Until recently all surface subsidence was considered to be the result of stoping above overmined caverns. However, deformation of the salt pillars in between the caverns should be taken into account as well, especially in the oldest part of the brine field with the highest extraction ratio. The possible effect of pillar creep on surface subsidence was investigated by the construction of a series of subsidence rate maps and the analysis of the relationship of the pattern of these subsidence rates and the cavern and pillar outlines. Additionally, subsidence- and subsidence rate vs. time graphs were analysed for much more levelling points than had been done previously. Contrary to the more modern part of the brine field, a much more dense net of levelling points exists here fortunately, partly because of the vicinity of the salt production plant and other buildings.

3 APPROACH TO THE STUDY
It is not possible to derive subsidence maps directly from the levelling data, because different levelling points were measured at different time intervals. To circumvent this problem subsidence rates were mapped instead of subsidence. The levelling data were processed to create XYZ- data files for each year, where X and Y represent the coordinates and Z the subsidence rate in mm/year, as a basis for contour maps. Observations of uplift of 10 mm/year or more and extra levelling points with the same coordinates were eliminated. After the creation of contour maps for each year, inconsistent subsidence rates were removed from the data files, followed by the production of upgraded contour maps:

a) inconsistency in space: e.g. a rate of hundreds of mm/year amidst a further consistent and gradual pattern of rates of a few tens of mm/year at most.

b) inconsistency in time: e.g. a sudden rate of several tens or even hundreds of mm/year in a given year, where the rate is one order of magnitude less in the preceding and following years.

c) subsidence rates due to a waste dump near wells 60-62 and 86-89.
Then a statistical analysis of the residuals was performed. A residual is a quantitative measure of the degree of fit and equals the difference per data point between the actual subsidence rate in the XYZ-data files and the interpolated subsidence rate on the contour surface for a given year (Figs 3,4). On the basis of this analysis only contour values of less than $-5$ mm/year and more than $+5$ mm/year can be considered relevant.

For each year the relationship between the pattern of subsidence rate contours and the cavern and pillar outlines were analysed, in order to identify a component of surface subsidence due to pillar creep deformation. Special attention was paid to:

a) areas which are not located on a salt pillar and where stoping occurs
b) areas which are located on a salt pillar, outside the influence of stoping induced subsidence
c) areas which are located on a salt pillar, where stoping induced subsidence has either not evolved yet or has decreased to a relatively low rate.

4 RESULTS OF THE ANALYSIS

4.1 Evidence of Phase III stoping-induced subsidence

As expected, the areas of Phase III subsidence could be well distinguished in the contour maps. For example in Fig. 3, which shows subsidence rates in October 1976, two stoping-induced subsidence areas, at wells 4 and wells 18-24, are prominent. Subsidence at well 4 had just started in 1972, attaining a maximum rate of about 300 mm/year in the centre of the trough in 1974 (Fig.2). In October 1976 this rate had diminished to 200 mm/year. In 1995 (Fig. 4) the rate was less than 10 mm/year and the subsidence area can hardly be recognised on the contour map.

The Phase III subsidence area, centred at wells 18-24, had already developed in 1963, with an initial maximum rate of 1500 mm/year. This is the first and also deepest subsidence trough of the brine field. Subsidence had decelerated to 45 mm/year in 1976, and then to 15-20 mm/year in 1995. The present rate is just 10-15 mm/year.

Throughout the years, both subsidence troughs are characterised by a consistent pattern of rates,
which gradually increase towards its centre. For all levelling points within these areas the subsidence- and subsidence rate vs. time curves show the shape, which is typical for Phase III stoping-induced subsidence: a rapid acceleration in the first 1-2 years, followed by a gradual long-lasting deceleration (Fig.2). This consistency also applies to the later Phase III subsidence areas near wells 30, 31, 33-36 and 70, which started to develop in 1977, 1983 and 1989 respectively.

4.2 Evidence of pillar deformation-induced subsidence

The subsidence area at well 10, formerly considered as Phase III, proved to be based only on one levelling point, mounted at the well 10 itself. A rapid acceleration in 1975 seemed to occur only at this location, and did not develop at any of the other levelling points in its direct vicinity. Instead, all other levelling points in the area showed a subsidence development which completely differs from that of Phase III subsidence (Fig.5). Subsidence did not accelerate within 1-2 years, but its rate gradually increased during a much longer period, from the early sixties to 1995. At that time a maximum rate of about 70 mm/year was attained in the centre of the trough. Then the rate decreased until today. Additionally, the centre of the area where levelling points show this development of ground movements is located over a pillar. Therefore this subsidence area cannot be ascribed to Phase III. The observed ground movements can neither be considered to be completely due to Phase II phenomena, because rates of up to 70 mm/year are beyond the range of possible rates for this type of subsidence. The only possible explanation is deformation of the narrow, undisolved ring-shaped “pillar” salt, which surrounds well 14 (Figs. 3, 4). As explained in Section 2.4, the cavern outlines are approximate, but there is no doubt that the most intensive salt extraction occurred in this part of the brine field. Therefore, it is to be expected that the maximum pillar creep rates result at this location.

By means of the analytical calculation methods by Van Sambeek (1996, 2004) pillar shortening rates of the order of 50 mm/year were estimated for just a small part of the pillar-area, the circular area enclosed by caverns 10, 11, 14 and 15. This corresponds to a vertical strain rate of $10^{-10}$ to $10^{-11}$ s$^{-1}$ and a subsidence rate of about 15 mm/year, using a Litwiniszyn influence function with $n = 4$ (Bekendam, 2000). Subsidence rates due to creep of the complete pillar area can attain the observed 50-70 mm/year.
mining by two processes, dynamic recrystallization and intragranular microcracking. A decrease in the initial grainsize of 5 to 25 mm means an increased component of solution-precipitation creep. Therefore the actual creep- and subsidence rates may exceed the values estimated above, which are based on dislocation creep as the only microphysical process.

To estimate the importance of different deformation mechanisms under these conditions, a diagram is presented extrapolating the two deformation mechanisms to low strain rates, for different values of the grain size (Fig. 6). For the dislocation creep law commonly used parameters are taken, based on the creep parameters for the Hengelo halite reported by Hunsche et al. (2004), but noting that in these experiments a direct measurement of the stress exponent n has not been done, and therefore extrapolation to lower strain rates is somewhat uncertain.

Under the stress conditions in the pillar, the dynamically recrystallized grainsize is between 3 and 10 mm (Ter Heege et al. 2005). Therefore this process does not lead to significant grainsize reduction, except perhaps in the most coarse-grained layers.

Microcracking can occur along grain boundaries (intergranular) with no decrease in grain size, and in the grains (intragranular) which causes a significant decrease in grainsize. Unfortunately, there are no published data on the microstructure of halite deformed under dilatant conditions in the presence of brine. Therefore it is not possible to estimate the effective grainsize in dilated pillars. However, it seems reasonable that at the relatively low total strains in this pillar, the effective grainsize will be not reduced by more than a factor of two (each grain broken in half).

On the basis of Fig. 6 we can now estimate the contribution of solution-precipitation creep to the total strain rate of dilatant pillars. Accurate calculations are difficult because dry dilatant halite tends to creep faster than non-dilatant halite under otherwise the same conditions, the different halite layers have slightly different dislocation creep properties, clay may be present at grain boundaries in parts of the section, the effects of pore pressure in the dilated pillars are difficult to take into account accurately, and the possibility that part of the pillar was(is) in contact with a not 100% saturated solution. Keeping in mind these uncertainties, from Fig. 6 it can be seen that solution-precipitation creep in the dilatant pillar is a significant process. Its contribution to the total deformation can be of the same order as dislocation processes, although details of the process are difficult to quantify due to the lack of relevant data.

Creep rates in pillars which are considered stable (non-dilatant) and are loaded at deviatoric stresses lower than those in the dilatant pillars, are much lower than those in the dilatant pillars, are much

5 DEFORMATION MECHANISMS IN THE SALT PILLARS

According to the criteria for long-term stability (Hunsche et al. 2004), the pillar proved to be unstable, i.e. it could have entered a stress state under which plastic deformation was accompanied by significant dilantancy. However, it is important to consider that the stresses even in the dilatant pillar are far from the dry failure envelopes for the Hengelo salt, presented by Langer (1984). Dilatancy means that the porosity created in the pillar is filled by saturated brine.

In dilatant pillars the grainsize of halite can be modified in comparison with the conditions before
lower (Fig. 6). Although no measurements are available for very slow pillar deformation in areas with stable pillars, we can predict that (even without grainsize reduction) at this lower strain rate solution-precipitation creep may be dominant in the fine grained sections, and less important in the very coarse grained sections, activated by the small amount of brine present in grain boundaries of the Hengelo halite (Hunsche et al. 2004).
ANALYSIS OF THE INCREASE AND DECREASE OF THE PILLAR DEFORMATION-INDUCED SUBSIDENCE RATE

6.1 Acceleration of subsidence rate
The increase of the subsidence rate between 1960 and 1995 cannot be explained by an increase in pillar stresses due to decreasing pillar widths, because the wells 5-11 and 14 were already taken out of production in 1960, and the single well 15 in 1968. Possible explanations are:

a) increasing dilatancy and increasing solution-precipitation creep rates
b) dissipation of the pressure arches over the pillar areas. Cavern migration up to 50 m below the rock-soil boundary is known for well 15. Probably migration also started at several of the other wells 6-11 and 14 (Figs. 3,4), possibly at different times. Due to the resulting debris chimneys the pressure arches over the pillar areas were (partly) destroyed and the vertical pillar load increased significantly. On the other hand, the debris material within the tributary area of the pillar does not load the pillar anymore. However, this effect is considered less important than the increase of vertical load due to the breakdown of the pressure arch. In this regard it should also be noted that stoping did not proceed up to the Tertiary for most caverns concerned, and, accordingly, the pillar is still loaded by the soil overburden and an important part of the rock overburden.

c) a component of Phase II surface subsidence, as a direct result of the stoping process.

6.2 Deceleration of subsidence rate
The decrease of the subsidence rate could be attributed to:

a) an increase in cross sectional area of the pillar as a result of the creep deformation.
b) lateral support to the pillar, when the widening pillar comes into contact with the debris piles produced by the upward migration of adjacent caverns.
c) friction between the debris material and the chimney walls, resulting in a partial transfer of the vertical pillar stress onto the debris piles.

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REFERENCES


