Seventh Symposium on Salt, Vol. I 425–431 (1993)
Elsevier Science Publishers B.V., Amsterdam

Mining Subsidence above Cavities Created by Solution Mining of Rocksalt

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ABSTRACT

Akzo Salt and Basic Chemicals produces salt at several locations in north-western Europe. The method of winning is in all cases that of solution mining. However, the geological situation of the productive salt strata can differ considerably from a simple diapir to a very complicated dome structure or a relatively shallow and thin salt layer. In all cases Akzo measures the subsidence by regular measurements at the drilling sites. On top of cavities in salt domes the surface subsidence measured is rather small and dependent on the situation *in situ*, whereas subsidence above underground cavities in the salt layer can in some cases be very serious even causing substantial damage on the surface. We can therefore identify the causes of subsidence above cavities as follows: (1) subsidence by convergence; (2) subsidence by disintegration of the roof formation; and (3) subsidence caused by over-mining.

The interpretation of the results of level measurements can be rather complicated, particularly in the flat regions of north-western Europe. Various influences caused for instance by alterations in the groundwater level, or the production of natural gas from underlying formations can mask the actual extent of surface subsidence from solution mining in the ground movements measured. The difficulties in the interpretation of the results of level measurements will be highlighted using several field cases from Akzo's drilling sites in north-western Europe, with the emphasis being placed on the differences between fields.

INTRODUCTION

The former Koninklijke Nederlandse Zoutindustrie (KNZ) started solution mining of salt from a shallow Triassic rocksalt layer in the Boekelo area, east Netherlands in 1918 (Fig. 1). KNZ moved their operations to the nearby Hengelo area in 1933 and has produced there ever since. Small single caverns were developed in Boekelo, while in Hengelo two or three caverns were connected underground to one production unit. The height of these caverns in not more than 30 m with a length of 160 m and a width of about 80 m (Wassmann, 1980b).

In 1957 a new salt and soda-ash plant was built on the coast at Delfzijl, in the north-eastern most part of Holland. The brine for this factory is produced from a salt dome near the city of Winschoten, about 20 km from Delfzijl. A second brinefield was developed on a nearby salt dome in 1968 and connected through a separate pipeline with the factory at Delfzijl.

Akzo took over the salt factory of the Norddeutsche Salinen at Stade, Northern Germany, in 1963, and developed a new brinefield on the flanks of the very complicated double diapir of Stade.

Huge single cavities have been developed by Akzo in all their salt domes with volumes well over 2 million m^3. The maximum diameter is normally 100 m (Wallner and Van Vliet, 1993) with a height between 500 and 600 m.

The striking differences in geological setting, and thus the shape and size of the solution mined cavities, are responsible for variations in the surface subsidence above the cavities. Three causes of subsidence can be distinguished within Akzo's brinefields. They are:

1. Subsidence by convergence of a cavern
2. Subsidence by disintegration of the roof formation above a cavern
3. Subsidence by over-mining.

Besides these causes, the subsidence can be masked by other movements of the surface for various reasons.

Normal computer techniques can be used to forecast the rate of subsidence, but programs have to be adjusted to the special circumstances of each brinefield.

In some cases the behaviour of the rocksalt formation *in situ* is quite different from the laboratory results of rock mechanical investigations on cores. In this case the rock mechanical parameters used in the computer programs must be altered using the level measurements on the surface as reference.

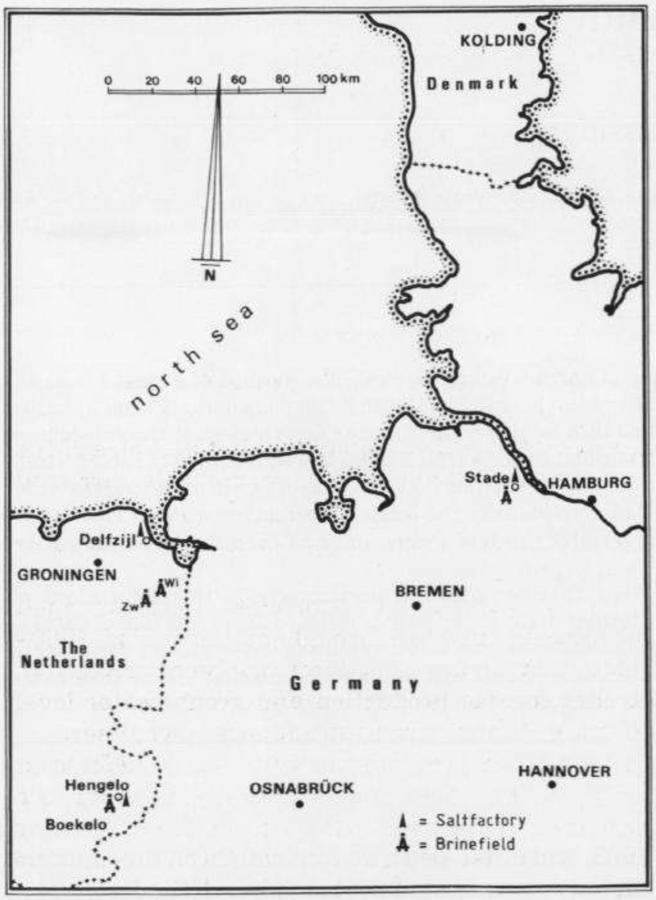

Fig. 1. Akzo brine production locations in north-western Europe.

STADE

Akzo started solution mining from three wells in the new brinefield on the flanks of the complicated salt dome structure of Stade in 1964. Four new production wells were drilled between 1970 and 1980. Of these wells, T4 and T7 were abandoned after only a short production time because of the poor salt quality. From the first three wells T3 remained very small (77,000 m^3) and T2 was cemented after reaching a total volume of 1,025,000 m^3. The wells T1, T5 and T6 are currently the main producers.

This brinefield is an excellent example of the normal behaviour of the rocksalt strata around existing and expanding cavities. The measured surface subsidence is due only to the convergence of the cavities.

Level measurements started in Stade in the year 1963, just before the start of the brine production in this field and are repeated every year (Fig. 2).

The influence of the two main producers (T1 and T6) on the subsidence can easily be detected by comparison of the development of the subsidence bowls over the periods 1973–1984 and 1973–1991 (Fig. 3). Only the extension of the subsidence bowl towards the south cannot be explained from the rocksalt geology. Presumably this is due to the geology of the overburden on this locality.

There are no other causes for the measured surface subsidence, and no subsidence is measured outside the influenced area of the brinefield (Durup, 1990). A normal computer program can be used to forecast the development of the subsidence bowl for many years to come.

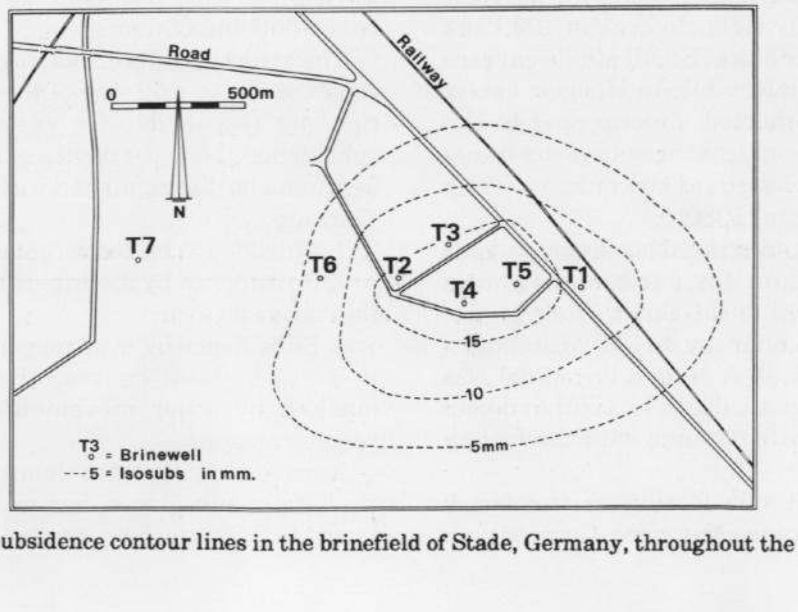

Fig. 2. Surface subsidence contour lines in the brinefield of Stade, Germany, throughout the period 1973–1984.

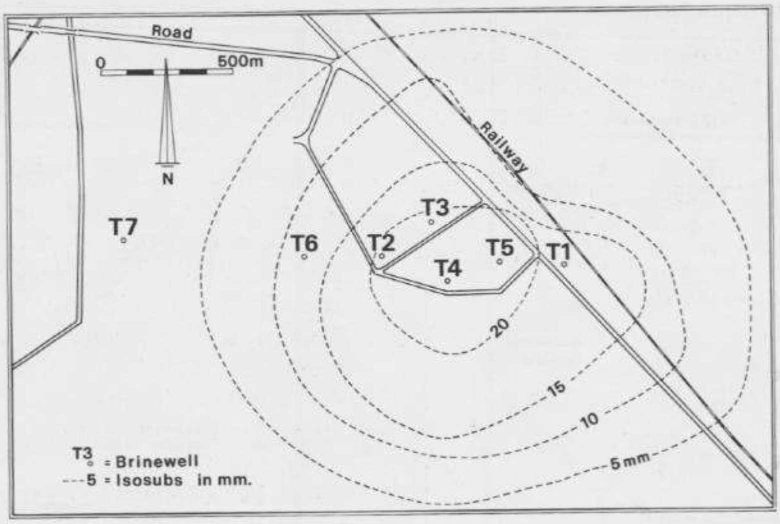

Fig. 3. Surface subsidence contour lines in the brinefield of Stade, Germany, throughout the period 1973–1991.

ZUIDWENDING

The salt dome of Zuidwending is one of the biggest domes in The Netherlands. Akzo's brinefield is situated at the centre of the northern culmination of the dome (Harsveldt, 1980). The rocksalt formation is from the Permian age and the salt is found at a depth of 180 m, covered by a cap-rock of 40 m. The rocksalt is uniform and very pure. There is no evidence on the presence of layers or deposits of highly soluble and deformable potassium or magnesium salts in the central region of the dome.

A rate of convergence of 0.04% was measured in one of the wells during a stop in production lasting nearly 5 months. This rate of convergence is in good agreement with the measured, but corrected, small surface subsidence. What is very interesting, is the discrepancy in time between the rate of convergence measured and the rate of convergence resulting from the finite element calculations. Rocksalt parameters resulting from (triaxial) rock mechanic laboratory tests on salt cores from this dome have been used for this finite element calculations. The rocksalt formation, however, seems to be more creep resistant *in situ* than the core investigation would have us believe (Van Vliet and Wallner, 1993).

The measured subsidence in this brinefield has to be corrected to account for other influences on the subsidence in this region. This is due to the fact that the brinefield is situated on the flanks of the well-known Slochteren natural gas field. An average of 30 mm of subsidence by gas production has been measured during the period 1969–1990. Also the re-allotment of this agricultural area has slightly changed the groundwater level resulting in minor vertical ground movements. The already small surface subsidence figure of 49 mm in the centre of the brinefield over the past 20 years has to be corrected by 66% to allow for the subsidence by gas production, and 6% for the effects of the lowering groundwater level (Table 1).

Figure 4 gives the uncorrected lines for equal subsidence (isosubs) throughout the period 1969–1990. In Fig. 5 the subsidence has been corrected to account for gas production and groundwater level effects, so that a normal subsidence bowl arises.

A computer program can still be used to forecast the yearly rate of subsidence. Firstly, however, the rock mechanical parameters from the laboratory core tests must be altered to take into account the behaviour of the rocksalt *in situ*. Secondly corrections for gas production and groundwater level effects must be entered into the program.

TABLE 1

Total surface subsidence and corrections to account for gas production and lowering groundwater level in the Zuidwending brinefield, Groningen, north-eastern Netherlands, throughout the period 1969–1990

Bench mark	Surface subsidence in mm in 21 years			
	Total	Gas production	Re-allotment	Brine production
3100	40	32	1	7
3210	43	29	2	12
3300	45	27.5	3	14.5
3400	42	26.5	3	12.5
3500	45	28	3	14
3600	49	29	3	17
3700	43	30	2	11

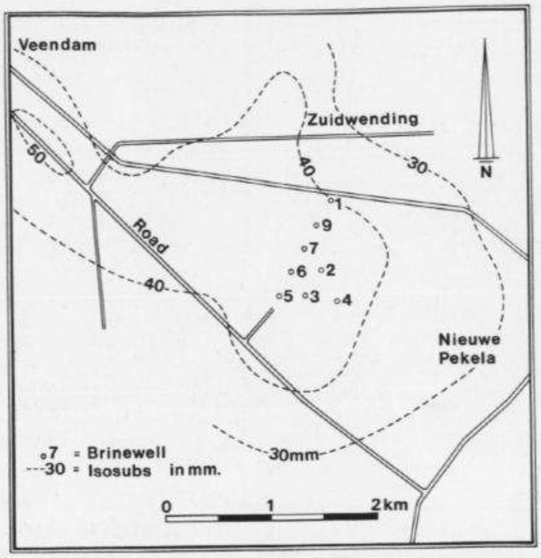

Fig. 4. Uncorrected surface subsidence contour lines in the brinefield of Zuidwending, Groningen, north-eastern Netherlands, throughout the period 1969–1990.

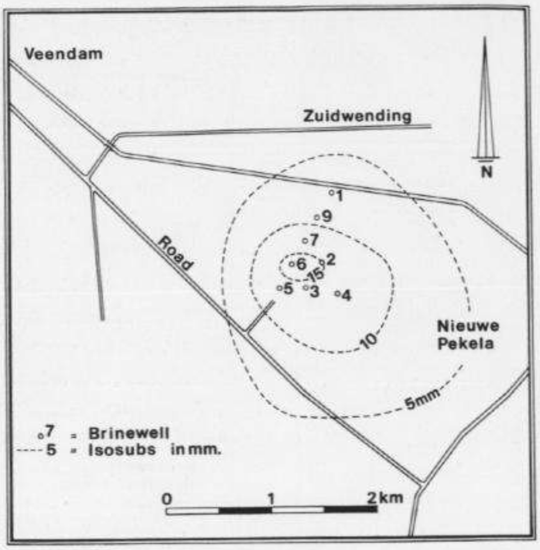

Fig. 5. Surface subsidence contour lines in the brinefield of Zuidwending, Groningen, north-eastern Netherlands, throughout the period 1969–1990, corrected to account for other influences on the subsidence such as gas production from underlying formations and groundwater level alterations by re-allotment.

WINSCHOTEN

The situation at the Winschoten salt dome, in north-eastern Holland, is even more complicated. The geological profile can be compared with Zuidwending. The brinefield is situated near the centre of the dome. The wells reach the cap-rock at a depth of about 470 m and the rocksalt at a depth of 500 m. The rocksalt is again very pure and uniform to a depth of well over 1500 m. A thin layer of anhydrite is only found in one of the twelve wells drilled on this dome.

The rate of convergence for this field has been calculated using several tests in two brine produc-

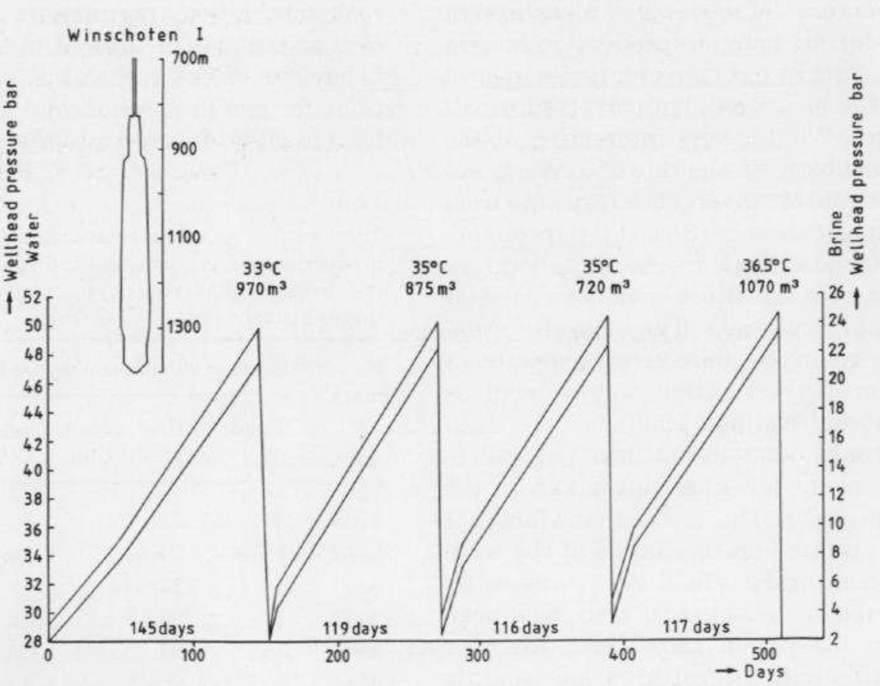

Fig. 6. Determination of the convergence rate of cavities in the brinefield of Winschoten, Groningen, north-eastern Netherlands by alternate pressurization and pressure relief of a cavity.

tion wells as 0.15–0.22% (Fig. 6), where the smaller but slightly deeper cavern has the higher convergence rate. This convergence rate means that about 3000 m^3 of rocksalt moves into the cavities mentioned each year which have a volume of 1,225,000 m^3 and 2,165,000 m^3, respectively. Thus the cavity diameter will only decrease for this reason by approximately 5 cm or less than 1‰ every year. The effect on the surface is dependent on the structure of the 500 m thick overburden. Nearly 1 mm subsidence per year can be calculated from these figures (Langer et al., 1984).

The level measurements in this brinefield were also started in 1969. A total surface subsidence of 123 mm was measured in a 20 year period, from which nearly 40 mm were measured during the last five years. This brinefield is situated on the southern part of the natural gas field Slochteren, therefore about 45% of the subsidence is due to the gas production from the Slochteren field. Besides the effects of the gas production on the subsidence, this area is also effected by the re-allotment of the agricultural structure as well as by Akzo's own groundwater production. Finally some isolated areas within the brinefield are subject to some form of surface subsidence caused by compaction due to lateral changes of shallow unconsolidated layers. Subsiding areas caused by these deflections are widely recognized in this part of The Netherlands using level measurements, long before gas- and salt production started.

It can be concluded therefore that for the surface subsidence in the centre of this brinefield, gas production contributes about 45%; rocksalt exploitation 30%; groundwater production 15% and finally, the effects of the re-allotment for a further 10% (Table 2). In the isolated areas with lateral changes in the subsurface formation the subsidence can be increased by more than 45% (Fig. 7).

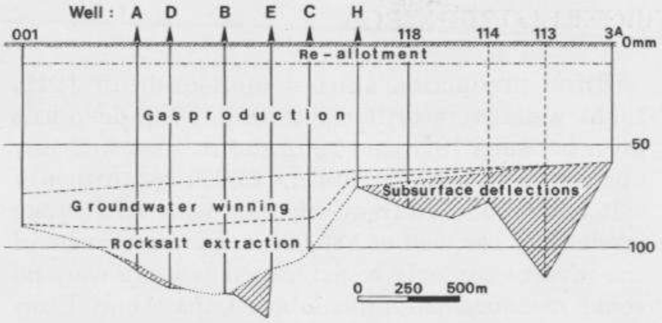

Fig. 7. Subsidence profile above Winschoten brine production cavities throughout the period 1969–1990, divided into subsidence due to re-allotment, production of natural gas, groundwater production and rocksalt extraction.

The application of computer techniques can hardly be used to forecast the subsidence in coming years as there are too many unpredictable factors influencing the surface subsidence. A computational study of the surface subsidence meets several difficulties in this brinefield. For example, the present cavity array makes it clear that a 2D grid can only be used for the wells drilled along the north–south principal road. The influence on the surface subsidence from the other wells, drilled at random in the field, can hardly be calculated with the help of a simple program (Fischer, 1984). Therefore any such forecasts would be inaccurate and unreliable.

TABLE 2

Total surface subsidence and corrections to account for gas production, groundwater production, effects of re-allotment and deflections of shallow unconsolidated layers in the Winschoten brinefield, Groningen, north-eastern Netherlands, throughout the period 1969–1990

	Surface subsidence in mm in 21 years					
Bench mark	Total	Gas production	Re-allotment	Water production	Brine production	Deflect
3A	58.4	48.2	10.2	–	–	–
113	114.5	51.2	10.2	–	1.0	52.1
114	78.0	51.7	10.2	–	2.1	14.0
118	80.9	52.0	10.2	2.2	3.9	12.6
Well H	71.2	52.8	10.2	3.4	4.8	–
Well C	101.4	54.1	10.2	21.0	16.1	–
Well E	110.1	55.3	10.2	21.0	23.6	–
Well B	122.8	57.1	10.2	21.0	34.5	–
Well D	119.5	58.8	10.2	21.0	27.5	2.0
Well A	112.0	59.9	10.2	21.0	16.9	4.0
001	91.2	63.9	10.2	15.0	2.1	–

BOEKELO/HENGELO

Brine production started in Boekelo in 1919. Eight wells were drilled into the 300 m deep salt layer between 1918 and 1932 and the last well was abandoned in 1952. In total 1,445,000 metric tons of salt were produced from this field with an average production per well of 180,000 t. The dimension of the caverns can only be estimated as there were no sonar measurements available at that time. However, the cavities are relatively small and presumably nicely shaped. They are created by a very slow solution mining process extracting only 20,000 t/year per well. The total salt production per year increased from 25,000 t in 1922 to 80,000 t in 1939 and decreased again to an average production of about 40,000 t in the following years.

After cementing the wells a small pressure buildup was noticed until an equilibrium was established. The underground situation stabilized and no subsidence has been measured in this abandoned brinefield until now.

The production in the Hengelo area started in 1933. The same production methods were used as in Boekelo in the beginning, but during the period of the second world war, many wells were over-mined. In other wells the relatively unstable roof formation was reached and the roof above the cavity caved in.

The first level measurement was dated 1941, but is was not until 1953 that regular measurements were performed. It soon became clear that some subsidence could be observed. A subsidence of 112 mm was measured over a period of 28 years for a single well without taken into account the influence of neighbouring wells. This subsidence can be identified as mainly subsidence by convergence.

In 1963, however, the first subsidence caused by over-mining was measured. An area with a diameter of 300 m was affected by a higher subsidence rate. A subsidence of 1100 mm was measured in the centre of the subsidence bowl within the first year. At this moment the centre has subsided in total about 3450 mm with an average rate of 22 mm per year during the last couple of years. Several new subsiding areas developed and six of these areas can be distinguished in the older part of the Hengelo brinefield.

If the produced tonnage of salt extracted from each individual well is known, and there is some idea about the shape of the cavern, a rather good prediction can be made regarding the subsidence patterns. Akzo published a prediction of subsidence for the centre of a subsidence bowl in 1979 (Wassmann, 1980a). This prognosis is updated in Table 3 with the subsidence actually measured for a much longer period.

The first case of subsidence by disintegration of the roof formation was observed in the Hengelo area in 1991. The cavity of well 70 already reached into the roof formation in the early stages of brine production. In this particular location the roof was also weakened by geologic faulting.

The brine easily penetrated deep into the roof, causing the roof to cave in slowly but steadily. The roof collapse reached the surface in January 1991 and a crater of 35 m diameter was thus created within a couple of hours (Fig. 8). The crater had a depth of about 4.5 m and a volume of nearly 3000 m^3. A public road was destroyed and a water-main pipe was broken. Fortunately, a nearby farmhouse was saved and is still habitable. In the meantime the crater has been filled up and the road is now open again to the public.

The surface subsidence by convergence of the cavities in Hengelo can be predicted by using a computer model. However, the shallow position of the rocksalt formation makes the cavities very much insensitive to convergence. Many years experience made it perfectly clear that surface subsidence is very small and normally constant. Figures of not more than 0.5 mm/year are common in the Hengelo field. After ending the brine production and cementing the well, the cavity will be pressurized to a certain degree and the convergence will be completely stopped. For that reason Akzo is not using a computational method for the prediction of the surface subsidence by convergence in the Hengelo field.

TABLE 3

Prognosis of the subsidence of bench mark H in comparison with the actually measured subsidence in the Hengelo brinefield, eastern Netherlands, for the period 1973–1991

Year	Surface subsidence (mm)		Year	Surface subsidence (mm)	
	Prognosis	Actual		Prognosis	Actual
1972	21	21	1982	60	44
1973	311	311	1983	50	38
1974	300	299	1984	40	37
1975	200	196	1985	35	30
1976	125	113	1986	30	27
1977	75	94	1987	25	24
1978	64	70	1988	25	23
1979	60	61	1989	20	20
1980	60	53	1990	20	16
1981	60	45	1991	20	16
			Total	1601	1538

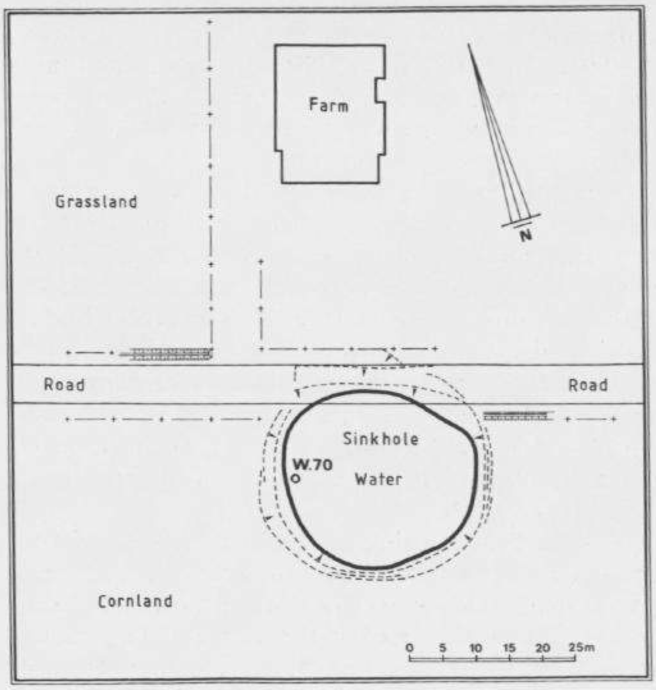

Fig. 8. Surface cratering by roof collapse of an old brine production cavity in the brinefield of Hengelo, east Netherlands.

Subsidence by over-mining or disintegration of the roof formation can be expected at several suspected areas in the oldest part of the Hengelo brinefield. The exact suspected wells cannot be defined, because the wells were cemented long ago and the underground situation was unknown as there were no sonar measurements from these old wells. Akzo is studying the possibility of installing deep reference points above some of these old cavities. The deep reference points can give valuable information on the behaviour of the roof formation and a early warning of dangerous situations.

A computer program can only be used if subsidence caused by means other than convergence has been measured in the field. Vertical and horizontal ground movements can be calculated and the effects on buildings and other structures can be predicted. However, the size and shape of the original cavities must be known to a certain degree. In such a case old production figures can be extremely valuable in reconstructing the old underground situation.

CONCLUSIONS

The object of comparing the surface subsidence of Akzo's various brinefields was to investigate the possibilities of using computational calculations to predict the surface subsidence over long periods of time. Following these comprehensive investigations the following conclusions can thus be drawn:

- Subsidence by convergence can be predicted by computational models.
- Computational results must be compared with the results of precise levelling, and amended to account for external influences on the rate of subsidence.
- The surface subsidence calculated by means of the rate of convergence of a finite element cavity model using rock parameters from laboratory tests of cores must be adjusted using the actual measured surface subsidence.
- Subsidence can be minimized if any form of additional support to the cavity wall can be safely applied, for example, the pressurization of the cavity.
- Subsidence by over-mining and/or disintegration of the roof formation cannot be predicted by computational studies.
- The effects of the subsidence by over-mining and/or disintegration of the roof formation can be calculated.

In this case a good knowledge of the underground situation has to be known, as, for example, the geologic profile, the production figures and from this the shape and size of the cavern.

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