SYNTHESIS REPORT

FOR PUBLICATION

CONTRACT No: BRE2.CT92.0316

PROJECT No: BE-5889

TITLE: **HIRES SESOM**
High Resolution 3D Seismic Reflection Applied to Subsidence Evaluation and Solution Mine Design

PROJECT COORDINATOR: Akzo Nobel Chemicals b.v. - Amersfoort

PARTNERS: Osservatorio Geofysico Sperimentale - Trieste
Deutsche Montan Technology - Bochum
Montecatini (ITSOS) - Milano

STARTING DATE: 01.02.1993 DURATION: 40 months

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME

DATE: 01.01.1997

1. **Front page given in Annex 1**

2. **Title, Authors names and addresses**

3. **Abstract**

4. **Introduction**

5. **Technical description**

6. **Results**

7. **Conclusions**

8. **Acknowledgments**

9. **References**

2. High Resolution 3D Seismic Reflection Applied to Subsidence Evaluation and Solution Mine Design.

Authors:

Vliet, A.J.J. van and Wassmann Th.H.
Akzo Nobel Chemicals bv - Minerals Department
P.O. Box 25, 7550 GC Hengelo, The Netherlands
Tel. 31.74.443221 - Fax. 31.74.443041

Heil, R. W., Kunz, E. and Lintker, S.
Deutsche Montan Technology
Institut für Lagerstätte, Vermessung und Angewandte Geophysik
Herner Strasse 45, W-44787 Bochum, Germany
Tel. 49.234.968.3267- Fax. 49.234.968.3607

Musso, L.
Montecatini (Itsos) Miniera Di Belvedere Spinello
88070 Belvedere Spinello, Catanzaro, Italy
Tel. 39.96.25.17.12- Fax. 39.96.25.17.14

Coren, F., Dordolo, G., Nieto, D. Y., Persoglia, S. and Snidarcig, A.
Osservatorio Geofisico Sperimentale
Dipartimenta Di Geofisica Della Litosfera
P.O. Box 2011 ; 34016 Trieste, Italy
Tel. 39.40.21401- Fax. 39.40.327307

Meekes, J. A. C., Scheffers, B.C. and Wijn, S.P.
TNO Institute for Applied Geoscience
P.O. Box 6012 ; 2600 JA Delft, The Netherlands
Tel. 31.15.696730- Fax. 31.15.564800

Bekendam, R.F. and Langen, M.W.P. van
Delft University of Technology - Faculty of Mining and Petroleum Engineering
Section Engineering Geology
Postbus 5028, 2600 GA Delft, The Netherlands
Tel. 31.15.786843- Fax. 31.15.784891

3. ABSTRACT

The objectives of this Brite Euram Research project were to develop and assess the possibilities of a new technique for the evaluation of subsidence and to improve planning of salt solution mines. Adequate prediction of subsidence will improve safety and will reduce environmental impact of existing and future solution mining operations. The method shall allow the evaluation of the risk of subsidence in producing or abandoned mine sites or in other areas where sinkholes occur, in order to reclaim these areas for other uses. The other object in view of this 3D-HRS method is the detection and delineation of underground cavities in salt formations or in limestone.

The technical objectives have been focused on the assessment of geotechnical parameters obtained from 3D-HRS data. The seismic investigation in the Hengelo brinefield, The Netherlands, has provided detailed and accurate information on the structural geology, stratigraphy and geotechnical parameters related to subsidence. The method has been verified at two different test sites so as to determine the general applicability of the method and to assess the importance of site specific factors.

This method has been a great success at the Dutch site due to a favorable geologic situation with various excellent seismic reflectors. In the far more complicated geologic situation of the Belvedere Spinello brine field, Calabria, Southern Italy, with less seismic reflectors this expensive 3D-HRS did hardly give better results as conventional 2D - seismic methods.

4. INTRODUCTION

Salt can be produces in three different ways: as sea salt, by conventional dry mining and by solution mining through oil field type wells.
Especially solution mined cavities in relatively shallow rocksalt layers can cause serious subsidence problems resulting in sudden ground collapse, better known as sinkholes or slow developing subsidence bowls.

Although the subsidence phenomena on the surface can differ from place to place they have mostly one thing in common: the subsidence will start many years after solution mining operations has been stopped, the cavity has been abandoned and the well has been closed by cementation of the bore hole.

These subsiding problems are a consequence of inadequate mining techniques often in combination of insufficient knowledge of the geology and longterm geotechnical behavior of the overburden formation above brine filled cavities.
Subsidence, in particular the formation of sinkholes, is considered to be a safety and environmental hazard that often give rise to costly damages and restorations to be carried out.

These subsidence phenomena have been noticed all over the world and already for many years, Four different causes can be considered for surface subsidence due to the production of brine from a rocksalt formation i.e.:

- convergence of the wall of a cavity
- collapse of the cavity caused by overmining
- physico - chemical deterioration of the roof formations
- geological anomalies as for example faults of other dislocations

The convergence of cavity walls is due to the physco-plastic properties of rocksalt and more pronounced in relatively deep and large cavities in salt domes.
This phenomena is studied thoroughly and very well understood.
The other causes of surface subsidence were partly known and partly suspected, but serious research in the mechanism was not yet performed. This Brite Euram project has been focused on the mechanism of physico - chemical deterioration of the roof formations in combination with overmining and geological anomalies.

5. TECHNICAL DESCRIPTION

The project started with a 2D High Resolution Seismic [I-IRS] survey and a check-shot in an existent well in the Hengelo brinefield, The Eastern Netherlands.
This 2D survey was meant to verify the applicability of HRS in the area before carrying out an expensive 3D survey.
The objective was obtaining an optimum imaging of formation boundaries, faults and cavities in the depth range of 80-600 m. The sections of this survey were compared with the results of a previously acquired 2D Mini Sosie survey (1987).
On the test-site Hengelo two lines were shot (figure 1).

Line	Number of Shots	Length
Hengelo HRS 9301	107	1,070 m
Hengelo HRS 9302	192	1.920 m

Several gaps occurred in the source pattern and multiple shooting was applied before and after these gaps in order to recover the Common Mid - Point coverage.
A check-shot was carried out in well 103 on line 9301 at the same time.

The data of the seismic survey were processed using the seismic processing software ProMAX on a SUN-IPX workstation. A database was created with the definition of the geometry of the lines, including elevations from checkpoints and other field recording information.
The quality of the data is generally good, however some remarks must be made. The shifting of shot locations because of caps by civil works causes absence of shallow information at these places in the seismic lines. The pronounced reflection around 160 ms generates surface multiple signals which interferes with the reflection around 320 ms and possible 480 ms and finally the migrations show so-called smiles especially for late times.
The seismic line 9301 partly overlaps with a line shot in a previous survey applying a Mini Sosie surface source. The comparison of the Mini Sosie line and line 9301 shows a better generation of higher frequencies using a buried source. The application of a recording instrument with high sampling rates allows the recording of these higher frequencies and results in an improved resolution. Information of shallower depth is also available in line 9301 due to the more densely spaced station intervals and the closer offset to the nearest geophone pattern. The 2D field test has proved the validity of the HRS method with regard to former seismic surveys in this area.
The geological data of the wells along the seismic lines were converted from depth into two-way-traveltime with the velocity model for the different formations from the check-shot survey in well 103. These data were overlain on the seismic sections and the following reflectors were tracked along the lines:

- A continuous Tertiary reflector; CTR
- Base Tertiary: the most pronounced reflector; BTR
- Near top Salt reflector; NTS
- Near base Salt reflector; NBS

The results of the structural interpretation are presented in figure 2 and 3.

The base Tertiary reflector is very pronounced. Small dips in this reflector can be noticed at three locations of which two locations are corresponding to subsidence areas and the other to the sinkhole of well 70.
The signature of the salt reflector with the high resolution seismic signal consists of a regular periodical signal of about 4 cycles. The uppermost and pronounced cycle does not coincide with the top of the salt, but with a anhydritic layer within the base of the Upper Röt Claystone.
This typical complete salt signature is not present at various locations in the sections. This is probably caused by the absence of the top of the salt formation, what can be associated with a collapsed roof of the underground cavities in this formation.
The interpretation of faults - either stacks or migrations - is not unambiguous, because the exact position and the inclination of these faults could not established accurate. In the areas of more dense faults and fractures, the rock has brecciated to such an extent that the seismic propagating velocity has diminished. The same can be said from the seismic velocity in brine filled cavities. They appear in the travel time related seismic profiles at a greater depth than their real position.
We can observe a relation between the salt signature and the presence of subsiding areas and cavities. It must be noted, however, that a 2D seismic section also contains reflection energy from outside the vertical plane through the seismic line. Therefore, also a continuous reflector maybe seen at locations where only the outer boundary of a cavity is crossed. It is also observed that subsidence areas are related to interpreted faults. It must be realized in this case that the image concerns the present situation after subsidence.
[n the winter of 1993 a nearly 3 square kilometers of High Resolution Seismic data was acquired in a 3D survey in the Hengelo field after the promising results of the 2D survey in the same field. The 3D survey was carried out with the newly by DMT-Bochum developed SUMMIT system, the only system allowing the acquisition of 3D HRS data. The system was used for the first time in this true field survey.
The objective of this survey was the optimum imaging of formation boundaries, faults and cavities in the depth range of 100-600 m that are possibly related to subsidence and sinkhole formation.
The selected field parameter for the shallow target 3D-HRS survey could be optimized after a study of the field procedures. The main items of the modified approach were:

- number of channels: 80 (64 active and 16 for roll-along)
- number of lines of active spread: 4
- source and receiver line spacing: 80 m
- source and receiver station spacing: 20 m
-bin size: 10 x 10 m
- coverage: 4

These parameters represent a practical optimal balance between the opposing requirements of a small bin size, limited field effort and limited useful offset.
The total area of 3 square kilometers was divided in strips for the receiver stations and traverses for the shot stations. Every strip was subdivided in blocks of 4 receiver lines and 16 receiver stations on each line. Every traverse was subdivided in blocks with
4 shotlines and 6 shotstations on each line.
Inherent to the high resolution character of the survey great care was taken to guarantee accurate positioning of shot- and receiver points. Each individual point was staked out and marked. In total 1800 shot points and 1600 receiver points were mapped with a high accuracy.

For the processing of the data in the DMT-ILG data processing center the following sources were used:

1. Field tapes from the telemetric high resolution 24 bit field system SUMMIT-video 8 tapes, format SEG-Y.
2. Transfer 9 track tapes, format SEG-Y.
3. Normal DAT tape, format SEG-Y.
4. Coordinates of shot and receiver points listed on a spread sheet.

The data were processed using the seismic processing software DISCO. The 3D data processing steps do not differ mainly from the 2D processing steps.
A check shot survey and well measurements were carried out in the new drilled, normal brine production well 399 in the investigated area in the mean time.
A downhole hydrophore cable was used consisting of 13 elements with a spacing of 2 m between the receivers. A geophone group was also placed next to the well, to record uphole times which can be used for static corrections.

This data were processed using the seismic processing software ProMAX on a SUN-IPX workstation.
In well 399a series of supplementary well measurements has been carried out:

. Caliper
. Gamma - Gamma (density log)
. Gamma
. Spontaneous Potential
. Resistivity (Short - Long - normal)
. Full wave sonic.

The sonic log together with the gamma - gamma log were used to compute a synthetic surface seismogram of the well.
The same pronounced seismic reflectors were distinguished from the 3D-HRS, and the gamma-, sonic- and density logs from well 109 and 399. From cores and cutting material the geological history of the brinefield Hengelo was described comprehensive by M. W. P. van Langen, Delft University of Technology in “The Development, Geology and Lithology of the Central-Northern Part of the Hengelo Rocksalt Solution Mining Area and its Geotechnical Characterization”. This study formed the basis for a structural interpretation of the different features seen in the seismic profile lines. For example in the northwestern part of the 3D-seismic area trough subsidence can be seen in the western part of in-line section 190 (figure 4). The whole quartet of the near salt reflections, including the NTS-reflection is disturbed. This disturbance must be associated with the collapse of the roof layers of an old salt solution cavity as is proven from the results of an exploration well next to the old production well 24. Also the BTR-and CTR reflections and the reflections within the Muschelkalk show a distinct, sharp depression at the same location. This location corresponds almost exactly with the centre of the surface subsidence area indicated in figure 5. The maximum deflection of the CTR- and BTR reflections and the 185 ms reflections within the Muschelkalk rang from 8 to 10 ms. This corresponds with about 6.5 to 8 m subsidence assuming a seismic velocity of 1600 m/s. This amount of subsidence is possible considering the present maximum surface subsidence of about 3.5 m in the centre of the subsidence bowl.

The section of the BRT deflection is about 60 m wide. Since the base Tertiary is situated at 126,5 m depth, the width of the subsidence bowl at the surface must be about 300 m, assuming the 45° angle of draw. This corresponds quite well with the measured outline of this subsidence area.

The disturbance of the NTS reflection and the reflections immediately above the wells 45/46 in the same figure indicate also the failure of the roof formations above the old cavity of these wells. However, the reflections near the base of the Tertiary are undisturbed, which is in agreement with the absence of surface subsidence over these wells. Apparently the caving process did not reach such a level that the base of the Tertiary was affected. This is probably the result of the thickness of the salt formations at this location, the height of the original cavity and the bulking factor of the broken rock material resulting in a complete filling of this cavity.

The In-1ine 193 (figure 6) nearly crosses well 69 en 71 and intersects exactly well 70 and the sinkhole, formed in 1991. All the four near salt reflections are disturbed and appear to be offset abruptly down ward. Sonar measurements had revealed that already in the 70’s the cavity of well 70 reached into the roof formations of the salt.

The BTR- and CTR reflections and the upper Mesozoic reflection are deflected downward centrally above well 70 and the sinkhole. The deflections in the center are about 6 to 8 ms. A reflection can be observed in the middle of this depression which is significantly stronger than the normal CTR reflection adjacent to it. This local intensification, not observed at trough subsidence areas, corresponds clearly with the observed sinkhole.

Several contour maps are constructed from the seismic information. The most interesting map is reproduced in figure 7 and shows the well locations, the two-way travel time of the NTS-reflection and the lateral extent of the NTS-reflection disturbances. The southwestern dip of the Triassic formations is illustrated by the increasing travel times. The “holes” indicate the NTS-reflection disturbances and hence represent the areas of cavity roof collapse. The most eastern area corresponds with significant surface subsidence near well 9-10, 30-31 and 33-36. Apparently the caving process did not reach the base of the Tertiary formations at wells 27, 32 and 42-43, where no important surface subsidence has been measured.

The gap over well 17-26 is also related to strong surface subsidence.

The subsidence bowl is centered in between well 18 and 24 and also effects the wells 19-22.

Over the well 44-50 no subsidence has been observed at the surface, possibly as a result of the filling of the cavities of wells 44-47 and 49-50 with residual products from the salt purification. The same goes for the area of wells 64-65. A continuous gap can also be observed between the wells 69-71 and that this gap is confined in the south - southwest by a normal fault. The steep fault could have facilitated the collapse of layers directly over the initial cavity and might have played a certain role in the caving process at higher levels and may have affected the ground movements within the Tertiary and Quaternary and caused the formation of a sinkhole.

The areas of subsurface subsidence are smaller in all cases than the gaps in the NTS-reflection. This suggests that within a cavity height was not constant. This is in agreement with the old solution mining methods producing “morning glory” type cavities. However, the minimum horizontal dimension of the disturbed zone at the top of the salt formation and at the base of the Tertiary are more or less identical. This could be implied that the caving process results in nearly vertical chimney walls. Well designed cavities under intact roof formations and completely situated within the salt layer, are rather difficult to distinguish in wiggle trace seismic sections. Reflection amplitude sections proved to give better results.

Figure 8 shows, for example, the reflection amplitudes of in-line section 10. High amplitude wavelets near the base of the salt can be observed near the wells 251 and 252. The cavity width of about 100 m, indicated by this seismic section, corresponds well with the dimensions measured by sonar. These results indicate that near base salt high amplitude wavelets can be associated with intact underground cavities as also has been proved by an acoustic model developed by OGS to study the behaviour of a brine filled cavity in a seismic record. The model adopted a finite high-order polynomial element grid, also called a spectral element analysis. The model was calibrated simulating a cavity located at well 28 of the brinefield Belvedere Spinello, Italy.
In figure 9 t/m 11 is reported one example, where the time is fixed at the arrival of the top cavity reflection (TCR) and the upgoing bottom cavity reflection (BCR) running into the sedimentary overburden.

A2D-HRS seismic survey was carried out by Osservatorio Geophysics Sperimentale - Trieste under commission of Montecatini S.p.A. (Itsos) in the brinefield Belvedere Spinello, Calabria, Southern Italy during the first half of the year 1993. The purpose of this survey was a test to investigate the applicability of HRS in this highly complicated geological area before carrying out an expensive 3D-survey. This 2D-survey should be useful for the determination of the geological boundaries, faults and eventually subsurface cavities, Three areas of the mine were selected for a thorough analysis of the results: North area - multiple well mining, cavities and the presence of sinkholes.
South area - partly mined by single wells and cavities measured by sonar.
East area - multiple- and single well cavities of which some were measured by sonar and the presence of sinkholes.

In total 8,800 m length of seismic lines were shot, divided over 9 different lines. A real-time quality control was applied during the field operations. The corrections for elevation and weathering, together forming the static correction, were calculated delineating the subsurface structure.
The pre-processing was done on a Galaxy graphic workstation and for a more complete sequence processing was applied to one line. The processing required a series of tests to determine the optimal parameters for the final sequence. The spectral analysis demonstrated useful frequencies from 30 to 90 HZ. So a bandpass pre-filter was used to eliminate ground-roll (15 -30 HZ). The need for a bidimentional balance to compensate for variations in signal penetration due to the different geological structures was noted after display of the records.

The target of the interpretation phase was to construct a geological model and highlight all the particular features related to the presence of dissolution cavities. The final results were displayed as Depth Converted sections, where the depth conversion was done using the velocity function defined by the velocity analysis used for the stacking procedure.
For the interpretation of the seismic lines the following data were used;

- geological data from exploration and production wells,
- gamma- and resistively logs of wells,
- direct records of casing cut shots,
- sonar measurements of cavities,
- general geological information.

The seismic data were interpreted using either screen displays - running the Western Atlas SEISTAR package based on a RISC 6000 series workstation - or paper displays. The paper displays are in cases like this very useful because of the large quantity of geological data to introduce and for greater flexibility.
The interpretation has allowed the identification of many seismic - stratigraphic units that are associated with geological units. The structural setting of the area could be describe as a three phase sedimentary system. The Serra Filetto fault strikes north-south and can be easily recognized at the surface. This fault can also be recognized in the eastern most end of the line TDS-13 (figure 12), but with a smaller calculated displacement as on the surface. The fault disappears southward in line TDS-02 (figure 13). In this line same other fault systems can be seen.
OGS acquired 3,5 sq kms of 3D-HRS data in Belvedere Spinello in the autumn of 1994. The aims of this survey was to image the salt formation to a depth of 700 metres and to identify structures that may be related to the presence of cavities or subsidence above cavities. The area of greatest interest for this survey was chosen between the central and south part of the mine. The SUMMIT-acquisition system of DMT was not used, but instead a conventional SERCEL SN368 telemetric system, but further the experiences gained in Hengelo were used again during the acquisition in Italy. Due to topography and near surface conditions, the quality of this 3D survey was not as good as might be expected under better conditions. After a first processing of the data two major problems arose. The first problem was how to apply field and residual static corrections and secondly how to control the bidimensional coherency of the final results, despite the very low coverage and the consequent poor signal to noise ratio. However, the results of this survey demonstrate that high definition can be obtained using the 3D technique in a complex area. The recorded data at the Belvedere Spinello mine is very noisy due to the complex geological situation together with the presence of salt extraction wells. These factors produce anomalies in amplitude, frequency, velocity and above all in the travel-path of the recorded signal. The main aim of the processing can be described as establishing a sequence that addressed these anomalies and improved the signal-to-noise ratio of the data.
The interpretation was done using the SEISX package from Cogniseis Ltd. The seismic package was run on a RISC 6000 series workstation. This package allows the use of many different representations modes for the seismic data, as well as screen displays of seismic attributes as instantaneous phase, envelope and instantaneous frequency, The stratigraphic records from the wells were used as marker identifiers and depth converted using the velocity function defined by the velocity' analysis used for stacking in the 3D survey. The depth maps of horizons, together with the isopack maps constituted the final product of the interpretation (figure 14, 15, 16, 17 and 18).

A number of trough subsidence areas have developed in the old part of the brinefield at Hengelo since 1963, followed by the sudden development of a sinkhole over well 70 in 1991. A striking feature of the development of all subsidence areas is that surface subsidence is first noticed long after ending of the brine production. This means that a substantial delay in time of subsidence has been observed of over more than 10 years.
Three different reasons for subsidence, besides convergence, can be mentioned:

1. Big roof span by overmining.
2. Physico-chemical deterioration of the marley roof by brine.
3. Geological disturbances as faults.

The aim of geomechanical modelling is to describe the process of subsidence development from the first deterioration of the initial cavern roof- until the development of subsidence at the surface and to explain the differences in the expression of surface subsidence from slow till fast developing troughs and the formation of sinkholes.
In figure 19 a normal subsidence and horizontal strain profile is given from the subsidence trough wells 18/24. The stationary points of zero strain indicate a constant lateral extension of the underground opening.

It has become clear now that the subsidence process over the salt solution cavities within the Twenthe-Rijn concession can generally be subdivided into three stages:

- Collapse of the immediate anhydrite-claystone roof at the top of the Rot Evaporite Member. This is not a question of roofspan but of degradation of the roof material. The roof stability is not a pure rock mechanic issue, but mainly depends on physico-chemical deterioration.
- Stoping due to the upward movement of the deterioration process. Here the cavity migrates upwards and a chimney is created, with almost vertical side walls and filled with broken rock from the collapsing roof. It is believed, that the deterioration process is only possible in an upward direction in the immediate roof of the cavity, where the overburden pressure is more or less relieved in contrast of the side walls which remain under stress. The cavity roof might finally meet the base of the unconsolidated Tertiary clay, which are not weakened by a physio-chemical process but behave plastically. Here the stoping process ends.
- Subsidence of the Tertiary clay over the chimney. Subsidence and horizontal strain data suggest that a subsidence bowl develops with an angle of draw of about 45° and an angle of break of about 80°.

According to Hendron et al. (1979), who studied sinkhole formation in the area of Hutchinson, Kansas, the development of sinkholes requires four basic conditions:

1) The presence of a large unsupported span at the top of the salt formation. Overlying shale, often encountered over salt layers, will be exposed to brine or water and its strength will be reduced. The immediate roof will deteriorate and co] lapse into the cavity.

2) The presence of a large volume of salt cavity under the unsupported roof to accommodate the bulk volume of failed roof materials. This process is referred to as stoping. As the cavity migrates upwards its height tends to decrease continuously because the volume of broken rock material increases in the cavity. This effect is known as bulking and can be described by the formulas:

$$B = \frac{\sqrt{broken}}{\sqrt{int\,act}} \quad \text{and} \quad H = \frac{h}{H-1}$$

where h is the height of the original cavity and H the maximal height the chimney can penetrate above the original cavity roof.

3) The appropriate geomechanical properties and geometrical and in-situ stress conditions which preclude any arching effect above the cavity and allow the progressive roof failure to develop up to the rock head or ground surface.

4) A trigger mechanism that reduces critical support from a marginal I y stable roof, e.g. the reduction of brine pressure inside the cavity, a reduction of buoyancy effect on the roof materials, an enlargement of the upper cavity span or a reduction of roof support by compaction of the debris pile.

If only condition 1) and 4) are satisfied, merely trough subsidence may develop. Obviously the stoping process does not develop all the way up to the rock head or ground surface.

The subsidence development in Hengelo is, however, more complicated, because of the considerable thickness of 120 m of the unconsolidated clayey formations on top of the Mesozoic marls and claystones.

For this Mesozoic formations the action of a pressure arch has to be considered. Due to this pressure arch most of the overburden load is transferred to the sides of the cavity. This arching action has to be distinguished from a second arching action which applies only to the immediate roof beams (Sterling & Nelson, 1978). This arching enables the rocks in the immediate roof to span the opening. The large-scale pressure arch maintains its lateral load up to a certain span (maximum pressure arch; Adler, 1973) and beyond this point the complete overburden load will be transferred directly to the immediate roof.

While the large-scale arching affects the complete rock mass, the stability of the immediate roof layers must be estimated initially by the beam and plate theory. A roof layer over a mine opening deflects downward and bed separation might occur. In the beam theory of Obert & Duval (1967) such a roof layer is assumed to act like a clamped beam which flexes under its own weight. It is also generally known, that moisture lower rock strength and facilitates brittle fracturing under mechanical stress. In the Hengelo case a combination of mechanical and physio-chemical breakdown has to be considered, as also proved by an exploration well just in between the two collapsed production wells 18/24.

It depends on the bulking factor, the geometry of the initial cavity and of the collapsing chimney whether stoping will be stopped by bulking or by arching before the unconsolidated Tertiary clay has been reached. This case has also been reported in the Hengelo brinefield.

Surface measurements of horizontal and vertical ground movements in Hengelo have been analyzed thoroughly. Field data show that the subsidence trough develops gradually with a decreasing tendency in time. Subsidences as a function of time *t* has been formulated by Salustowitcz (1 958) as follows:

$\frac{ds}{dt} = c\,(s_{end} - s)$ and at time t = o this differential equation can be written as

$s = s_{end}(1-e^{-ct})$.

This formulation corresponds to the theological model of a spring and dashpot in parallel.

According to Missavage et al. (1986) a trough will form over a cavity migrated to the base of the unconsolidated overburden, if this overburden is thick with a high clay content. In the Hengelo case the Tertiary clayey overburden will behave as a ductile material and deflect gradually over the underlying cavity. However, it should be postulated, that if the height of the cavity at the base of the overburden is such that the downward deflected clayey overburden cannot reach the bottom of the cavity, caving might still occur. After this stage the trough subsidence develops further due to the compaction of the debris column. Because the height of the debris column is generally 200 m or more subsidence will continue for many years.

In order to assess the circumstances, which resulted in the sinkhole formation at well 70 instead of gradual subsidence it was necessary to analyze the stoping process and subsidence development in general at salt solution wells in the Hengelo field.
As already mentioned the height of the initial cavity and as a consequence the height of the cavity reaching the base of the Tertiary is decisive for the subsidence development at the surface. Whether failure will take place or not depends on the height and width of the cavity, and on the thickness, average density of the overlying soil and its mechanical parameters as cohesion and angle of friction. Also the role of water is not to be forgotten. Essential for sinkhole formation is that width and height of the cavity are such that the base of the Tertiary clays cannot reach its bottom by deflection. If the Tertiary and Quaternary strata are supported by the underlying debris stresses within the cavity roof are relieved for the greater part and failure does not occur. Hence an increase in height of the migrated cavity will augment the sinkhole hazard.

The 3D Seismic data showed, however, a continuous disturbance near the top of the saltlayer around wells 69, 70 and 71. This “gap” is confined in the south-southwest by a near vertical normal fault, which is dipping towards the north-northeast.
The first question which arises is: did this fault facilitate the stoping process up to the base of the Tertiary? This does not seem likely. Cavity migration occurred at a rate comparable with values observed at other wells.
The second question is: did the fault affect the mechanical behavior of the soil overburden? According to Harsveldt (1977) normal faults predate the Tertiary but more recent 2D-seismic research of 1987-1988 and the interpretation of well data in the direct vicinity prove that in general normal faulting has continued during the Tertiary, including the Eocene. So it can be concluded that the fault near well 70 might well extend (close) to the surface.

It has to be noticed that the fault runs more than 50 m south of well 70 and the center of the sinkhole. Nevertheless, subsidence might have concentrated along the fault, but if this has resulted in the development of a sinkhole is unlikely. The height of the initial cavity will be the main reason for sinkhole development is this case. Three phases of subsidence can be identified. The subsequent stages are depicted in figure 20. The general surface subsidence vs. time curve is depicted in figure 21. The three phases are generally characterized as follows:

- phase I:

  the cavity is situated completely within the salt formation Some convergence of the solution cavity occurs due to creep deformation of the salt. At the surface subsidence is negligible in the Hengelo case.

- phase II:

  if the cavity roof attains the overlying anhydrites of the Rot Evaporite Member the stoping process begins. The cavity migrates upward through the anhydrites, the Upper Rot Claystone and eventually the Muschelkalk at a rate of several meters per year. Surface subsidence increases at a more or less constant rate of several mm per year.

An overview of surface subsidence and stoping rates is given in Table 1. The stoping rate through the relatively tough anhydrites of generally about 5 to 15 m thickness is low in comparison with the rate within the less competent claystones and calcareous rocks of the Upper Rot Claystone and Muschelkalk.
Hence in some cases a subdivision could be made into phase IIA (cavity within the anhydrites) and IIB (cavity at higher levels) subsidence. The observed phase IIA stoping rates are less than 4 m/year. At well 15 sonar measurements showed that stoping within the anhydrite can be stopped completely for at least ten years. The anhydrite at the top of the Rot Evaporite Member appears to slow down the stoping process.

Well	Subsidence rate (mm/year) Phase I	Phase II		Stoping rate (m/year)		Cavity width Top Salt (m)		
		IIA	IIB	IIA	IIB	Prod. Fig.	3D Seis.	so-nar
B3-4 {P-H)			12.1	1.5	12.5 URC	160	-	-
BIO	<0.5	3.0	9.0	3.8	13.0 URC + MU	120	-	-
B15		5.0	8.5	≤ 1.4	9.8 URC	100	-	100
B18-24 (P18-3)	-	13.6		≥ 17.5 AN+URC+MU		200	200	-
830-31 (P30-2)	< 0.5	6.9		15.2 AN+URC+MU		130	130	-
B33-36 (P-BK)	< 1	P-BK:11.2 B33: 14.6 B34:17.0		1.8 AN P-BK 12.4 AN+URC+MU B33-34:		220 150	190 130	- 140
B40-41(P41-2)	< ().5	6.3				120	-	-
1342		5.0					100	“
B59	0.8	2.1		<14 AN + URC + MU		-		70
B66-68		1.3						65
B70		0.3	2.2	1.0	13.5 URC	-	100	50

AN: Top anhydrite of Rot Evaporite
URC: Upper Röt Claystone
MU: Muschelkalk

Table 1: Stoping rates and phase II surface subsidence rates for various cavities.

The phase IIB cavity migration rate is considerable higher, about 10 to 20 m/year, and more or less constant in the overlying Upper Rot Claystone and Muschelkalk. At some studied wells the cavity did not reach the Tertiary base, due to bulking and/or filling operations. There is evidence that the end of cavity migration is indicated by a decrease of surface subsidence rate (figure 21 and figure 22).

-<u>phase III:</u>

if stoping is not arrested by bulking the cavity reaches the base of the Tertiary soils. Void migration stops. The Tertiary and Quaternary soil mass subsides over the cavity resulting in a significant acceleration of subsidence at the surface. Then the surface subsidence rate decreases continuously. Within 1 to 5 years the surface subsidence rate generally increases to more than 100 mm/year and thence gradually decreases again. The determined average angle of draw in the Hengelo field is 45° and the average angle of break is 83°.

The beginning of phase III subsidence is the result of downward deflection of the Tertiary and Quaternary soil mass into the underlying opening, This process might be slowed down by strongly deflecting Mesozoic rock strata when the cavity roof has almost reached the base of the Tertiary (figure 23). Further acceleration occurs when the Mesozoic roof becomes thinner during further stoping. In this way the overlying soil mass does not suddenly "fall" into the opening but subsides more gradually. The debris chimney under the opening is not loaded yet.
Then the subsidence rate is strongly decreasing. This probably indicates that the soil mass is starting to load the debris chimney. If this is true then it can be imagined that the maximum surface subsidence rate and the time interval between the onset of phase III and the beginning of subsidence deceleration both increase with the height of the migrated cavity.
The decelerating part describes the compaction of the debris chimney under the weight of the soil overburden. The beginning of the decelerating subsidence cannot be fitted by power laws. The subsidence rate is lower than to be expected from the power laws. This relatively low subsidence rate could signify a transition period during which the downward deflecting soil mass is increasingly loading the debris chimney until it is fully supported.

The area near wells 18 and 24 is a special case. Here, apart from the usual trough subsidence concentric normal faults were formed at the surface. At more or less the same time the decreasing phase III subsidence rate increased again. The height of the migrated cavity might have been such that the subsiding soil formations were initially slowed down by the uppermost rock layers but thence, when the last layer of claystone had collapsed, subsided quickly and unsupported into the still open cavity (see figure 24), This considerable migrated cavity height might have brought about the abnormally high subsidence rate at the centre of the subsidence bowl and some kind of localized, brittle failure of the soil formations. Indeed seismic sections show that the migrated cavity height exceeds those at other wells. Complete failure and eventual sinkhole formation did not occur probably because the base of the Tertiary reached the floor of the cavity in time.

At well 70, where the sinkhole was formed, a comparable mechanism could apply. Also here the migrated cavity might have been such that the subsiding soil failed in a brittle way before it could be supported by the debris chimney at the bottom of the cavity. Seismic data and bulking calculations indeed suggest that the migrated cavity height is considerable, exceeding those of most other subsidence areas apart from the area near wells 18-24.
Numerical experiments were carried out to study the mechanical behaviour of the Tertiary clays over a migrated cavity of a certain height and width. It was concluded before that sinkhole formation might be the result of some kind of brittle failure of the soil overburden, It was suggested that the height of the migrated cavity can be so considerable that the clay roof cannot reach the bottom of the cavity by mere gradual deflection, The unsupported clay roof might then fail due to high shear and/or tensile stresses. Secondly, the influence of the already existing normal fault on the mechanical behaviour of the clays was studied. Finally surface subsidence during cavity migration through the Mesozoic rocks was modeled.

Numerical experiments were performed using two different computer programs as the finite difference program FLAC and the finite element program DIANA.

The FLAC version used here is 2D (with an axisymmetric option) and applies the full force, in this case the gravitational force, on the model from the beginning of the

experiment. FLAC is an **explicit program: for small calculation steps a disturbance at a** given gridpoint is only experienced by the gridpoints in the direct vicinity. During the successive calculation steps the model approaches an equilibrium situation. At each step out-of balance forces are determined at each gridpoint from zone stresses. These give rise to gridpoint displacements and strain rates, resulting in new zone stresses etc. The 'maximum unbalanced force" expresses in how far equilibrium has been attained. During the calculation this unbalanced force approached zero. In FLAC Lagrange-equations are used. This means that the model is not geometrically linear, i.e. changes in geometry during the calculation affect the stress situations.
In DIANA the force is applied in small steps, but during each step equilibrium is attained at all gridpoints at one time. This method is known as the implicit approach. Furthermore DIANA is geometrically linear because Gauchy equations are used, which means that the program is computing stresses and strains as if the grid elements were undistorted. The program is 3D but mainly the axisymmetric option was used.

The behaviour of the Tertiary Clay is simulated in the first test. The geomechanical parameters were taken from the results of the triaxial tests of the Dongen Formation.
This experiment shows that the clayey roof must have collapsed long before it meets the bottom of the cavity. This roof failure occurs only in the direct vicinity of the cavity. No faults up to the surface are formed. The resulting arch-shaped roof might again collapse, give rise to a stoping process resulting eventually in a sinkhole development.

Phase II surface subsidence was modeled in the second experiment. Since this type of subsidence is considered to be the result of roof deflection over the open cavity only elastic behaviour was modeled. Hence in this experiment only surface subsidence is studied and not the stoping process.

Surface subsidence over an upward moving cavity can be explained by two effects. In the first place the area of surface subsidence decreases according to the angle of draw. Hence subsidence will increase in the central part of the subsidence bowl. In the second place subsidence at the surface is related to the amount of roof deflection at depth. When the cavity is at relatively great depths roof deflection will decrease slightly during upward migration, because the stresses around the cavity are somewhat relieved, albeit not much since a pressure arch is formed over the cavity. But when the cavity approaches the overlying clays the pressure arch will disappear for an important part and the claystone roof, substantially decreased in thickness and still loaded by the clay mass above, will deflect much more than previously. Surface subsidence will thence dramatically increase. If the stoping rate is more or less constant the subsidence rate will increase as well.

The increase of surface subsidence rate due to deflection of the claystone roof, which becomes thinner and thinner, is actually observed.

More or less the same model and material parameters are used in the DIANA experiments as in the first FLAG simulation. But the E-modulus of 90 MPa is considerably higher and the angle of friction is 24° in stead of 21.5°. Also here elastic-perfectly plastic behaviour is modeled. In stead of the Mohr-Coulomb failure criterion, applied in the FLAC experiment, the Rankine/Drucker-Prager criterion is used here.

The Drucker-Prager yield model is often used for soils and described yielding in the compressive stress region. This combination proved to give the best results with minimal instability. The ‘experimental set-up is depicted in figure25.

Roof failure proved to occur in this experiment as well, resulting in upward cavity migration. Figure 26 shows the maximum shear stresses near the cavity at various depths. For each situation the percentage of the total gravity load is given. A higher gravity load causes instability. High shear stresses develop at the side walls of the cavity, but also in an arch shaped zone in the roof.
Similar to the FLAC experiments it is shown that failure is likely to occur in an unsupported clay roof over a cavity.

In the next experiment grid elements which fail either in shear or in tension are removed from the cavity roof and deposited on the floor. Then a new calculation is performed resulting in new zones of roof failure, etc. In this way the stoping process is simulated, without incorporating the bulking effect. Failure of the cavity walls does occur, but spal led fragments will immediately loaded by the roof prohibiting significant sideward movement. Figure 27 shows the upward migration of the cavity. Finally a crater of 16 m depth and 19 m diameter is formed at the surface.

It can be concluded that once the cavity roof has collapsed new roof failures will develop resulting in a kind of stoping process.

Finally the influence of a fault on the mechanical behaviour of the soil mass over the cavity was studied. In a 3D model a vertical fault plane was applied bounding the cavity. To investigate exclusively shear failure the Mohr-Coulomb criterion was used. The interface grid elements representing the fault plane were of negligible tangential stiffness compared with the stiffness perpendicular to the plane. The orientation and the negligible tangential stiffness of the fault represent a worst case scenario. Furthermore the cavity dimensions and depth and the mechanical parameters of the clay are similar to those applied in the preceding experiments. The same experiment was carried out with and without a fault plane (figure 28 and 29). The vertical displacement of the cavity roof is more or less similar and equals about 1.2 m without and about 1.5 m with fault plane. A major difference in surface subsidence is to be noted: 0.05 to 0.1 m without and 0.25 m with fault plane.

This experiment illustrates that the present of a fault augments subsidence considerably at one side of the fault. It might be speculated that the presence of the steep normal fault near well 70 was contributing in an unknown extent to the sinkhole formation.

6. RESULTS

The advantages of 3D shallow high resolution seismic reflection methods have been favorable compared against conventional 2D high resolution and 2D MiniSosie seismic data, as well as in the Hengelo solution mine as in the mine of Belvedere Spinello. Successful application in the first mine was followed by a test in Italy and this provided a basis for evaluation of site specific factors for the 3D-HRS method.
Subsidence models have been developed after a detailed study of the geology and tectonic history was made of the area under investigation.
Concealed subsurface cavities were accurately delineated and controlled by sonar measurements as far as possible.
An acoustic simulation model was developed to study the behaviour of a brine filled cavity by seismic pick-up. The subsidence models were simulated and proved by numerical experiments using two different computer programs, as the finite difference program FLAC and the finite element program DIANA.

Now the potential of the method has been demonstrated it may be applied at sites where more or less similar geologic conditions prevail for detection of expected underground cavities when accurate knowledge of the position and dimension of the caverns and the condition of the roof rock formation is unknown.
Major achievements will be realized in the area of safety management and environment. This will increase the public image and acceptance of solution mining operations and may help to sustain strategically and economically important industries in the EU.

7. CONCLUSIONS

The 30 high resolution seismic sections and the structural contour maps enable the detection of collapsed roof formations- directly over salt solution cavities in the Hengelo brinefield.

By means of the seismic data areas of subsurface subsidence in the vicinity of the base of the Tertiary - CTR and BTR reflectors - can easily be detected. The amount of subsurface subsidence can be assessed semi-quantitative. The presence of intact salt solution cavities is indicated by high amplitudes near the base of the salt formation. The extent of these cavities in all directions can be mapped from the successive seismic sections and controlled by sonar surveys if available.

Surface subsidence due to convergence of cavities which are situated completely within the salt formation, denoted in this study as phase I subsidence, is negligible even after a period of 25 years.

Stoping van be recognized at the surface by amore or less constant subsidence rate, denoted here as subsidence phase II. This rate varies between 2 and 20 mm/year, depending on the cavity width.

This phase II subsidence is ascribed to the deflection of the rock and soil mass over the migrating cavity. This concept is supported by numerical experiments.

Cavity migration can be arrested by bulking. Whether a cavity might reach the base of the Tertiary or not and its eventual remaining height after reaching the base Tertiary depend on the initial cavity height, the height difference top salt-base Tertiary and the bulking factor of these intermediate layers. For the Mesozoic overburden the bulking factor ranges between 1.07 and 1.11.

Surface subsidence accelerates when the cavity approaches the base of the Tertiary. This phase is denoted phase III subsidence. The deflection of the uppermost Mesozoic rock strata, reduced in thickness and still loaded by the soil overburden, becomes much more important than when the cavity was at greater depths. This was also indicated by numerical experiments. Evidence exists that, due to this strong deflection, the cavity roof (almost) meets the cavity floor before the arrival of the cavity at the base of the Tertiary. In this way the overlying soil mass does not suddenly “fall” into the opening but subsides more gradually.

The maximum phase III surface subsidence rate, which is normally several hundreds of mm/year, increases with increasing cavity height at the base of the Tertiary.

When the cavity roof has subsided to the floor the debris chimney under the opening becomes loaded. Further surface subsidence at a decreasing rate is brought about by compaction of the debris chimney. Due to the considerable height of the chimney subsidence will continue for at least hundred years.

Ample evidence exists that roof collapses within the Mesozoic rocks occur over a height of several meters a time, Stoping through the relatively tough Top Anhydrite of the Rot Evaporite is slow with rates of only a few meters per year at most. With an average thickness of the Top Anhydrite of 15 meters it will take about 10 years to migrate through this layer. The cavity migration through the Upper Rot Claystone and Muschelkalk proceeds much faster with rates between 10 and 20 m/year. The stoping rate increases with the cavity width. Wth an average thickness of the Claystone and the Muschelkalk in this part of the Hengelo brinefield it takes about another 20 years before the migrating cavity has reached the base of the Tertiary.

This explains that pronounced surface subsidence will remeasured long after brine production has stopped.

The sinkhole formation at well 70 must be ascribed, at least partly, to the considerable height of the migrated cavity. The seismic data show that the salt solution cavities 69, 70 and 71 were bounded in the SSE by a (sub)vertical normal fault. The presence of this fault might have aggravated the situation but there is no hard evidence, what so ever, that this fault is the keyfactor in the sinkhole development. On the contrary, numerical experiments show, that an unsupported Tertiary clay roof spanning a cavity might fail including a kind of stoping process in the soil mass which eventually gives rise to the formation of a sinkhole at the surface.

8. ACKNOWLEDGEMENTS

This Brite Euram II research project BE-5889 HIRES SESOM or" High Resolution 3D Seismic Reflection Applied to Subsidence Evaluation and Solution Mine Design" was made possible by a considerable grant under contract No. BRE2.CT92.0316.

The management committee was formed by:

1) Akzo Nobel Chemicals bv - Minerals Department - The Netherlands - Ir. A.J. J. van Vliet and Ir. Th. H. Wassmann.
2) Deutsche Montan Technology; Institut fur Lagerstätte, Vermessung und angewandte Geophysik - Germany - Dr. M. Will
3) Montecatini (Itsos) Miniera Di Belvedere Spinello - Italy - Ir. L. Musso
4) Osservatorio Geofysico Sperimentale; Dipartimenta Di Geofisica Della Litosfera - Dr. S. Persoglia

The management committee wishes to thank Drs. S. Meekes, Dr. B.C. Scheffers and Ing. W. Otte of TNO, Institute for Applied Geoscience - Delft, NL, for their contribution during the 2D- and 3D-acquisition and check-shots in the Hengelo brinefield.

Much effort was put into the processing and interpretation of the 3D-HRS Hengelo by Dipl. Geophys. S. Lintker, Dipl. Geologe Dr. E. Kunz and Dipl. Geologe Dr. R.W. Heil, all from Deutsche Montan Technology.

The seismic acquisition at Belvedere Spinello was managed by Mr. Dordolo, Marchi and Brancolini. Specific contributions were provided by Mr. Barbagal 10 and Vascotto (3D survey), Mr. Warden and Sinceri (data processing), Mr. Prolo and Pregarz (modeling) and Mr. Coren (geological- and geophysical interpretation), al l of Osservatorio Geofisico Sperimentale.

The geotechnical research and modeling was carried out by Ir. R.F. Bekendam of the Delft University of Technology, Faculty of Mining and Petroleum Engineering, Section Engineering Geology and supervised by Prof. Dr. D.D. Genske, Prof. D.G. Price and Drs. P.N. W. Verhoef. The geomechanical tests were performed by Ir. M.W. P. van Langen, Ing. Verwaal and A. Mulder, W. Kuilman (FLAC) and Drs. M. van Tooren (petrographic descriptions). At last we thank Drs. Van Eijs, Dr. W. Zijl, both from TNO-Geo Energy Department and F. Voncken, TU Delft performing the numerical experiment using the program DIANA.

9. REFERENCES

* Adler, L. , 1973, Roof and ground controll, in: SME mining engineering handbook (ad. by A.B. Cummins & 1. A. Given), Vol, 1, p 13-9 to 13-36.

* Bekendam, R. F., 1996 (in progress), Methods of stability assessment of the calcarenite mines in Southern Limburg, The Netherlands, PhD thesis TU Delft.

* Bekendam, R.F. & Van Vliet, A. J. J., 1995, Delineation of solution cavities and subsidence evaluation by means of high resolution 3D seismic reflection in Twente, East Netherlands, accepted paper for Fifth Int. Symp. on Land Subsidence, The Hague.

* BGR, 1985, Geomechanical investigations on cores of the roof formations of the salt solution cavities in Hengelo, Hannover.

* Blyth, F.G.H. & De Freitas, M. H-, 1984, A geology for engineers, Edward Arnold, London.

* Brady, B. H. G., & Brown, E. T., 1985, Rock mechanics for underground mining, George Allen & Unwin, pp 527.

* Coenen, M. J., 1965, Geologische resultaten van de proefboring 01 der Koninklijke Nederlandse Zoutindustrie te Hengelo, RGD rapport DR 516.

* Cook, J. C., 1966, Seismic delineation of solution cavities, Proc. on the Sec. Symp. on Salt, Vol. 2, 131-139.

* Cook, J. C., 1975, Yes, we can locate solution cavity boundaries, Fourth. Symp. on Salt, 33-40.

* Cruden, D. M., 1971, The form of the creep law for rock under uniaxial compression, Int. J. Rock Mech. Mining Sci. & Geomech. Abst., V8, 105-126.

* Cruden, D. M., Leung, K. & Masoumzadeh, S., 1987, A technique for estimating the complete creep curve of a sub-bituminous coal under uniaxial compression, Int. J. Rock Mech. Mining Sci. & Geomech. Abst., V24, N4, 265-269.

* Duvall, W. 1., 1976, General principles of underground opening design in competent rock, Proc. 1 7th Symp. on R. Mech- , paper 3Al.

* Eeckhout, M. van, 1976, The mechanisms of strength reduction due to moisture in coal mine shales, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. V 13, 61-67.

* Einstein, H., 1989, ISRM suggested methods for laboratory testing of argillaceous swelling rocks, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. V 26, N 5, 415-426.

* Eijs, R. van, & Voncken, F., 1996, Numerical modeling of subsidence caused by sub-surface mining: a possible explanation of the development of sinkholes, Diana World.

* Fairhurst, C., & Cook, N.G. W., 1966, The phenomenon of rock splitting parallel to a free surface under compressive stress, Proc. 1st Congr. Int. Sot. R. Mech., Lisboa, V 1, p 687-692.

* Fenk, J., 1981, A theory on the development of sinkholes over cavities in soil (in German), Freiburger Forschungshefte A 639, VEE Verlag, Leipzig, 138 pp.

* Galvin, J. et al., Feather edging, Strata Control Newsletter 1, Publ. School of Mines, University of New South Wales, p 2.

* Galvin, J. et al., Feather edging, Strata Control Newsletter 2, Publ. School of Mines, University of New South Wales, p 5.

* Garrard, G. F. D., & Taylor, R. K., 1988, Collapse mechanisms of shallow coal-mine workings from field measurements, in: Engineering Geology of Underground Movements (ad. by F.G. Bell et al.), Geol. Sot. Engng. Geol. Spec. Publ., 5, p 181-192.

* Goetz, D., Roussel, V., and Tincelin, E., 1994, Cave ins linked to mine flooding, 5th Int. Mine Water Congr., Nottingham (UK), 29-42.

* Goodman, R. E., 1989, introduction to rock mechanics, John Wiley& Sons, pp 562.

* Guarascio, M. Fernandez, G. & Thorns, R., 1994, Updated evaluation of sinkhole potential at Belvedere Spinello Brinefield, SMRI-Fall meeting 1994, Hannover, Germany, 43 pp.

* Hawkins, A.B. & McConnell, B. J., 1992, Sensitivity of sandstone strength and deformability to changes in moisture content, Quaterly Journal of Engineering Geology, 25, 115-130.

* Harsveldt, H. M., 1977, Des praetertiair von Suedost-Twenthe (Niederlande), Meded. Rijks Geol. Dienst, N.S. 28(~), 1-16.

* Harsveldt, H. M., 1980, Salt resources in the Netherlands as surveyed mainly by AKZO, Fifth Int. Symp. on Salt, 1,65-81.

* Hendron, A. J., Fernandez, G. & Lenzini, P., 1979, Study of sinkhole formation mechanisms in the area of Hutchinson, Kansas, SMRI Report No. 79-0007 -SMRI, pp 48.

* Hock, E., & Brown, E. T., 1982, Underground excavations in rock, The Institution of Mining and Metallurgy, London, pp 527.

* Huang, S. L., Aughenbaugh, N.B. & Rockaway, J. D., 1986, Swelling pressure studies of shales, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. V 23, N 5, 371-377.

* Jeremic, M. L., 1994, Rock mechanics in salt mining, Balkema, Rotterdam, pp 532.

* Kratzsch, H., 1983, Mining subsidence engineering, SpringerVerlag, Berlin.

* Lama, R.D. and Vutukuri, V. S., 1978, Handbook on mechanical properties of rocks, Vol. II., Trans Tech Publications, Clausthal.

* Lambe, T.W & Whitman, R. V., 1979, Soil Mechanics, John Wiley & Sons, New York, pp. 553.

* Langen, M.W.P. van, 1994, The development, geology and lithology of the central-northern part of the Hengelo rock salt solution mining area and its geotechnical characterisation, MS-thesis TU Delft, pp. 77.

* Meekes, J. A. C., and Wijn, S. P-, 1 993, Acquisition, processing and interpretation of 2D high resolution seismic and checkshot data Hengelo, TNO report OS 93-46-B.

* Meier, G., 1988, On the calculation of sinkhole hazard in rock (in German), Neue BergbautechnikV18 N9, 352-354.

* Menzel, W., 1968, The stress distribution in the immediate roof for long pillar mining (in German), Freiberger Forschungshefte A 445, pp 75.

* Missavage, R. J., Chugh, Y.P. & Roscetti, T., 1986, Subsidence prediction in shallow room and pillar mines, Int. J. Min. Eng., 4, 39-46.

* National Coal Board, 1975, Subsidence engineers' handbook, Mining Department, National Coal Board, London.

* North of England Safety in Mines Research Committee, 1948-49, Seventh progress report of an investigation into the causes of falls and accidents due to falls, Transactions Institution of Mining Engineers, London, V 108, p 490.

* Obert, L. & Duvall, W. I., 1967, Rock mechanics and the design of structures in rock, John Wiley & Sons, pp 650.

* Pasamehmetoglu, A. G., 1972, An investigation into time-dependent aspects of mining subsidence, PhD-thesis, University of Nottingham, UK.

* Passaris, E. K. S., Ran, J. Q., & Mottahed, P., 1993, Stability of the jointed roof in stratified rock, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. V 30, N 7, p 857-860.

* Piggott, R. 1. & Eynan, P., 1977, Ground movements arising from the presence of shallow abandoned mine workings, in: Proc. Conf. Large Ground Movements and Structures, UWIST, Cardiff (cd. by J. D. Geddes), Pentech Press, London, 749-780.

* Politick, G. & Wassmann, T. H., 1965, Final report of the exploration well 01 Hengelo (in Dutch), Internal report KNZ.

* Price, N.J. , 1964, A study of the time-strain behavior of coal measure rocks, Int. J. Rock Mech. Mining Sci., VI, 277-303.

* Prinz, H., 1991, Abrisz der Ingenieursgeologie, Enke Verlag, Stuttgart, pp. 466.

* Salustowicz, A., 1958, New ideas considering the stress and deformation state near mine openings, Proc. Int. Bureau on Rock Mechanics, 5/11, Akademie-Verlag, Berlin.

* Stealing, R. L. & Nelson, C. R., 1978, An experimental investigation of the ultimate strength of laterally constrained rock beams, Experimental Mechanics, 18, p 261 268.

* Taylor, R. K. & Smith, T. J., 1986, The engineering geology of clay minerals: swelling, shrinking and mudrock breakdown, Clay minerals, 21, 235-260.

* Verhoef, P. N. W., 1992, The methylene blue adsorption test applied to geomaterials., Memoirs of the centre of engineering geology in The Netherlands, Delft, pp 76.

* Vutukuri, V.S., Lama, R.D. & Saluja, S. S., 1974, Handbook on mechanical properties of rocks, Volume 1, Trans. Tech, Publications, Clausthal, 280 pp.

* Wassmann, T. H., 1980a, Mining subsidence in the East Netherlands, Fifth Int. Symp. on Salt, 1, 463-475.

* Wassmann, T. H., 1980b, Oplosmijnbouw, De winning van steenzout via boorgaten in Nederland, Jaarboek van de Mijnhouwkundige Vereniging te Delft 49, 131-159.

* Wassmann, T. H., 1993, Mining subsidence above cavities created by solution mining of rocksalt, Seventh Symp. on Salt, Vol. 1, 425-431.

* Whittaker, B.N. & Pye, J. H., 1977, Ground movements associated with the near surface construction of a mine drift in Coal Measures strata, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. V 14,67-75.

* Wright, F. D., 1972, Arching action in cracked roof beams, in: 5th Int. Strata Control Conf., paper 29.