THE HENGELO CASE: SUSTAINABLE RAW BRINE PRODUCTION AND BRINE FIELD DEVELOPMENT

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Summary

This paper gives an overview of more than 75 years of solution mining in the Hengelo brine field, the Netherlands and provides an outlook for the development of a sustainable new brine field.

Starting with an historical overview of the methods of solution mining applied, the present mining process is described. The mode of operation is strongly influenced by the introduction of new mining legislation in 2003 and the present and foreseeable urban development in the mining area. The overview concludes with the management of subsidence due to former mining activities

Driven by geological and spatial constraints the development of a new brine field outside the limits of the present mining license is planned. Instrumental in the execution of the project is the analysis of available spatial surface and subsurface data in the public domain, followed by a dedicated exploration campaign. The use of a Geographical Information System (GIS) is instrumental in handling and analyzing vast amounts of spatial data in order to obtain information relevant for the decision making process. A step-wise approach is adopted in order to secure efficient and effective project execution and to minimize uncertainties and risks. Experience shows that non-technical issues play a crucial role in the realization of sustainable raw brine production capability.

Key words: solution mining, subsidence, urban development, spatial data

1. Introduction

The Hengelo Röt salt formation (Triassic, Upper Bunter) is a bedded deposit with a thickness between 35 – 70 m at a depth between 350 – 500 m below surface *(see Figure 1)*. Inclination is moderate with 3 – 5 degrees to the SSW. The salt formation consists, from base to top, of the A, B, C, and (occasionally) D salt members. Mining is concentrated in the A and C members, the B member being very thin. The brine field extents between the cities of Hengelo and Enschede and has dimensions of approx. 6 x 4 km^2 *(see Figure 2)*. Salt production by means of solution mining started as early as 1933. Since then, in total 200 caverns have been developed of which 80 are still in production. Presently, yearly production amounts to 2.3 million tons of vacuum salt. To the extent that developed salt reserves are depleted, new wells are drilled.

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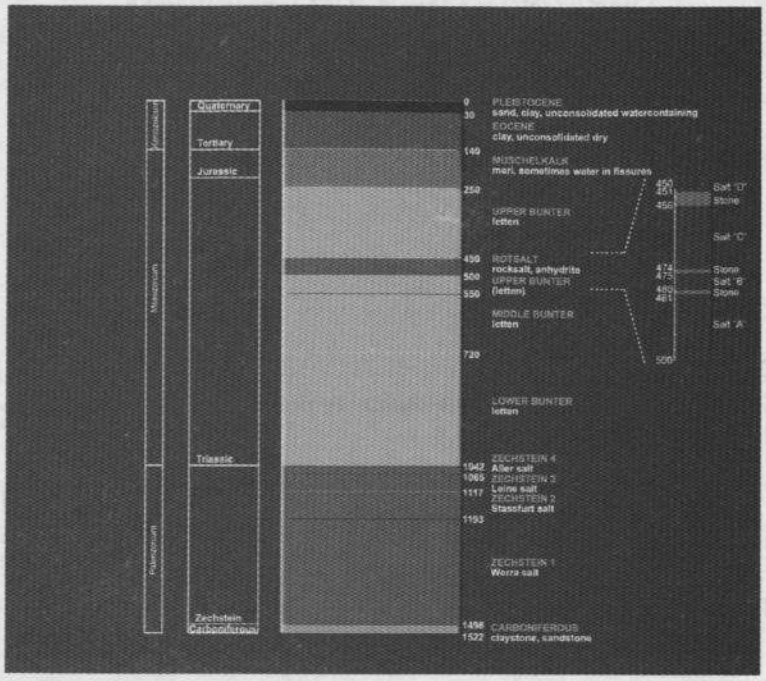

Figure 1: Stratigraphical column Hengelo brine field

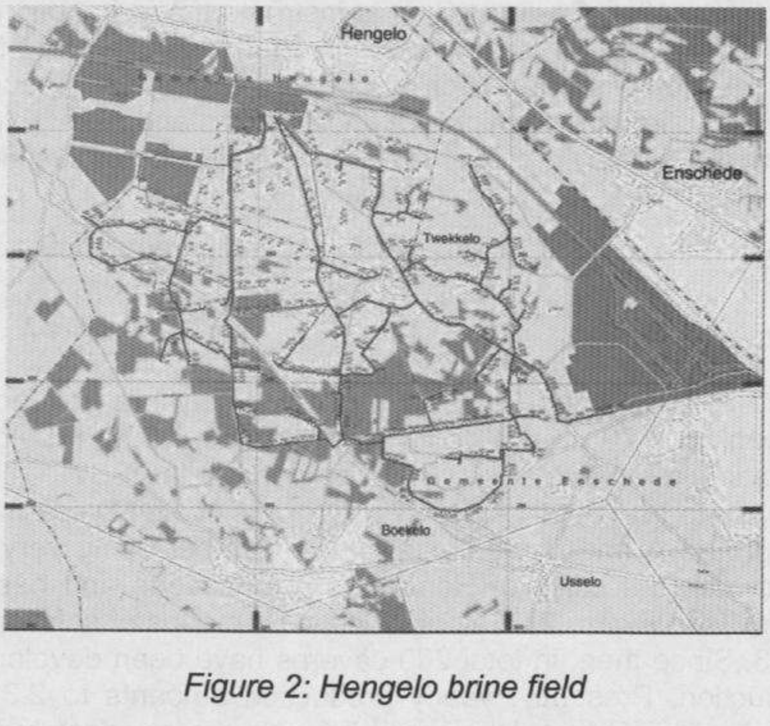

Figure 2: Hengelo brine field

2. Evolution of the solution mining method over time

Caverns were initially leached as single caverns but, due to lack of understanding of the leaching process and of tools to manage and monitor cavern development, eventually got connected hydraulically *(see Figure 3)*. Over time, this mining method evolved to a configuration where three wells gave access to one cavern with elliptical dimensions 80 - 120 x 160 m *(see Figure 4)*. Caverns were separated by pillars of 40 – 80 m width; in the C salt on top of the void a safety pillar with a thickness of at least 5 m was maintained. Using the existing topography, caverns were developed parallel or perpendicular to existing roads. This resulted in an irregular 'caverns in line' and 'caverns in orthogonal configuration' pattern of the brine field. This mining method, although having some major disadvantages like slow development and troublesome roof and diameter control, was maintained until the end of last century. The extensive mining in the 'old part' of the brine field resulted in bowl- and through-like subsidence, which will be addressed later in this paper.

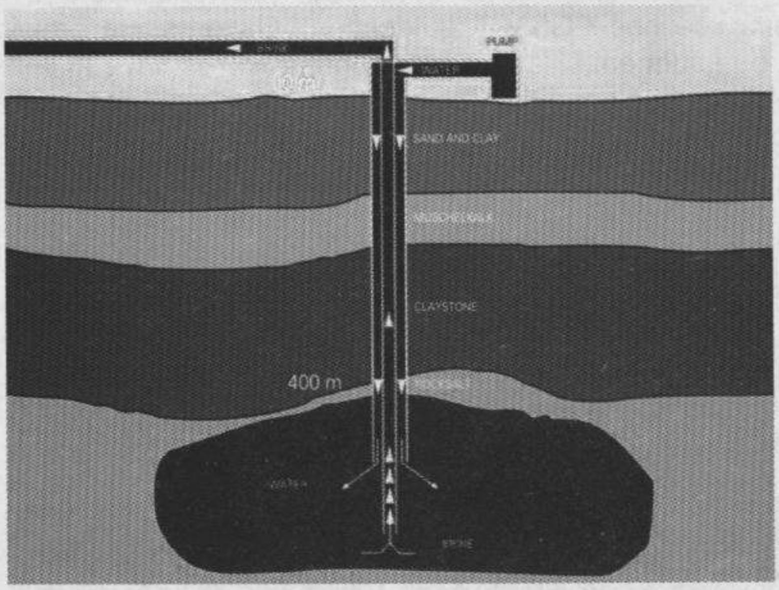

Figure 3: Initial 'Wild brining'

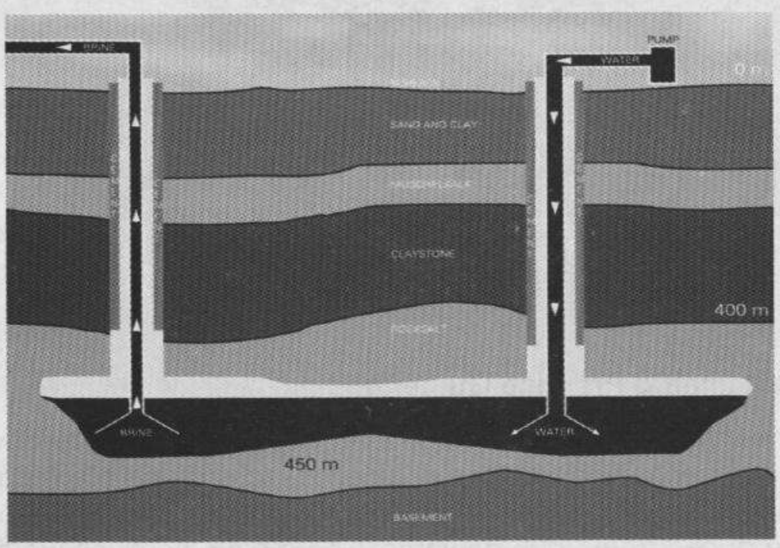

Figure 4: Multiple well entry

Whereas in the past cavern development took place in an agricultural setting, the ongoing urbanization as well as the use of abandoned mining areas for industrial development and the change in public perception of mining and subsidence in general became a threat for the mining method applied so far.

The introduction of new mining legislation in 2003, which required the submittal of production and leaching plans, which are subject to reviews by external advisors, public hearings and final approval by the ministry of economic affairs, urgently required the development of a new mining concept for the Hengelo brine field. The concept needed to be simple, robust, flexible and integral. The latter meant that societal aspects, like environmental protection, public safety and urban development needed to be weighted equally with mining and economic aspects. This resulted in a sustainable mining method, which is described - in headlines – by the Good Salt Mining Practice Guidelines ("GSMP" guidelines). Caverns are developed in parallel lines separated by abutment pillars. Furthermore caverns have a limited height and a thick safety roof, thus implementing the concept of inherent safety *(see Figure 5)*. In doing so, creep induced surface subsidence is minimized to an extent accepted by third parties.

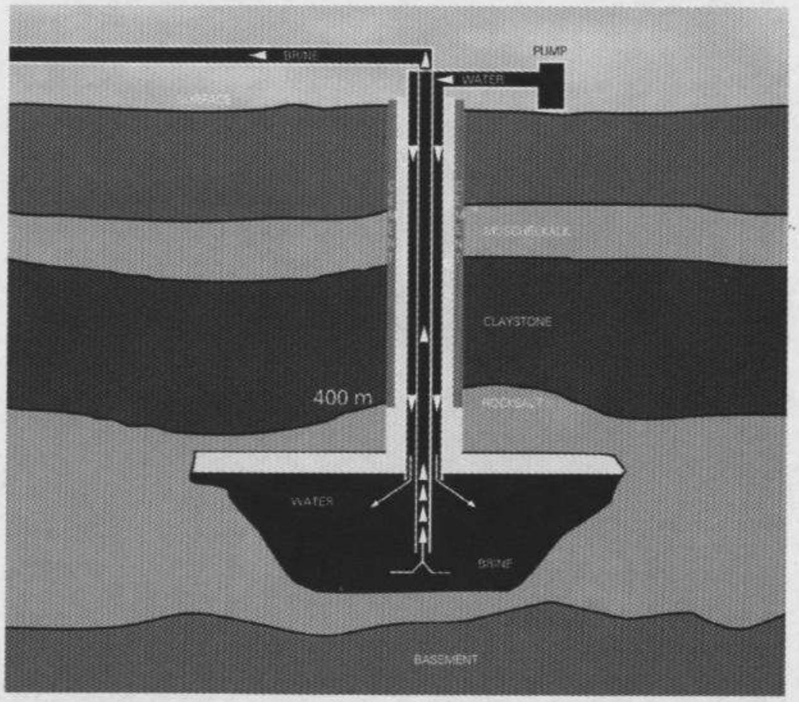

Figure 5: Single well entry

3. The Good Salt Mining Practice Guidelines

Driven by the new mining legislation 2003 a novel mining concept was developed, which includes geomechanical, well completion, leaching and blanketing, subsidence and surface impact as well as external communication aspects. The concept was successfully introduced from 2005 onwards. The main objectives were to control and manage cavern development during every stage of its life cycle and to minimize land use, while increasing flexibility with respect to urban constraints. Furthermore subsidence had to be predicted and the impact on the surface be minimized. As stipulated in the mining law, effective and efficient mining in order to maximize the use of the natural resource had to be taken into account as well. To fulfill these requirements a set of rules was developed, referred to as the GSMP guidelines. Since 2005, more then 20 new caverns have been developed using GSMP. An important aspect of these rules is the fact that they incorporate not only technical features but also organizational and communication aspects. As such, the guidelines are a strong means, not only for present-day operations but also for future development.

GSMP consists of five elements:

- A 'plain strain' geomechanical model, on which the cavern field layout is based
- A single well completion scheme for each stage of cavern development, thus abandoning the multiple-well-entry concept applied so far
- A leaching program and blanket control system for each stage of cavern development, enabling the implementation of the concept of inherent safety
- A subsidence prognosis for a period of 100 years ahead and an assessment of the consequences of the induced subsidence by independent experts
- Communication with third parties on all aspects mentioned during the life cycle of a cavern, which is expected to be ca. 15 years

GSMP is operated using the Deming quality circle 'plan – do – check – react'. All GSMP elements are part of the production and leaching plan, which is to be submitted to and agreed upon by the ministry of economic affairs. By incorporating GSMP at an early point in time unnecessary delays and misunderstandings are avoided.

3.1 The 'plain strain' geomechanical model

The geomechanical model was developed by the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany [1]. It consists of parallel rows of caverns separated by abutment pillars. To take account of variations in subsurface conditions, three robust and simple 2-D FE models are applied:

- Cavern height 25 m with compact anhydrite on top of the salt formation
- Cavern height 40 m with both compact and jointed anhydrite on top of the salt formation
- Cavern diameters of 80, 100 and 120 m

Planning foresees the development of cavernes with a maximum diameter of 120 m and a height, depending on the depth of the salt formation, between 35 and 40 meters.

A constitutive law for elasticity and steady-state creep behavior (BGRa, Hengelo specific Röt salt creep parameters) is applied; furthermore hydrostatic pressure inside the cavern and constant temperature (25° C) are assumed. The assessment of the pillar loading is according to the η-criterion (stress intensity index η, Lux 1984) while for the assessment of the loading of the anhydrite on top of the Röt salt the Drucker-Prager strength criterion is applied.

The results are presented as stress points in invariant diagrams with curves of selected η-values (25, 30 and 35%) and dilatancy boundary *(see Figure 6).*

Furthermore diagrams with system failure boundaries as a function of cavern diameter, pillar width and applied failure criterion and a table with cavern diameter vs. pillar width for compact anhydrite, cavern heights of 25 and 40 m and stress intensity indexes η = 25, 30 and 35 % are provided *(see Figure 7)*. An important feature is the calculation of the extraction ratio resulting from pillar width and cavern diameter.

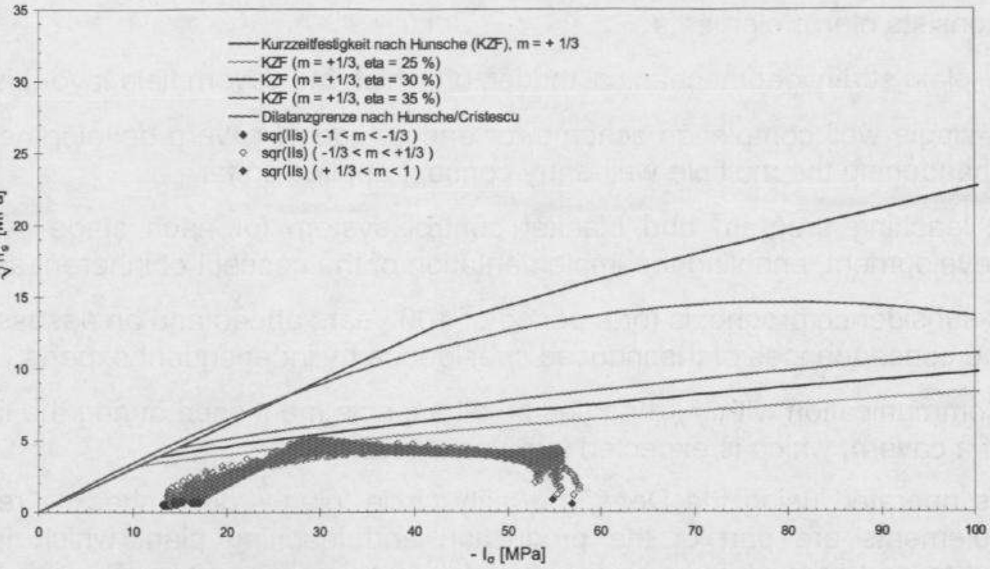

Figure 6: Invariant diagram, stress points after 200 years
(D = 160 m, P = 100 m)

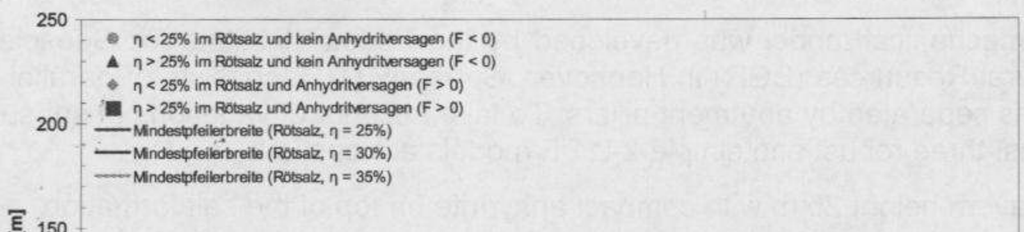

Figure 7: P-D graphs after 200 years

3.2 The single well completion scheme for each stage of cavern development

The well completion is simple and straightforward. The shoe of the 9 $^5/_8$" last cemented casing (LCC) is set 1.0 m underneath the sterile rock layer between the A and B salt member. The shoe of the 4½" production string (deepest point of the sump of the cavern) is positioned 0. 5 m above the base of the A salt member, the shoe of the of the 7" production string 2. 5 m above the base of the A salt member. The blanket control system BCS-D, delivered by Socon Sonar Control in Giesen, Germany, with a length of 2. 0 m is set 0. 5 m above the shoe of the 7" casing.

The leaching program is developed together with DEEP Underground Technology in Bad Zwischenahn, Germany, using the leaching simulation software WinUbro of Chemkop in Cracow, Poland *(see Figure 8)*. The undercut (diameter 80 m, height 2. 5 m) is developed in the shortest possible time with a flow rate of 15 m^3/h; consequently re-saturation is applied during the 14-month sump development phase.

After completion of the sump phase, the first main leaching stage is developed. The shoe of the 4 ½" production string is again set at 0. 5 m above the deepest point of the sump, the shoe of the 7" production string is set at 3. 0 m above the roof of the sump, whereas the blanket oil level again is set 7. 0 m above the roof of the sump. The flow during the main leaching stage presently is set at maximum 20 m^3/h brine, although it believed that a flow of 40 m^3/h of saturated brine is feasible as well *(see Figure 9)*. It is emphasized that the leaching process and the cavern development is subject to optimization; more improvements in terms of process simplification (number of workovers, reduction of time for development, increase of flow) and process control (blanketing, diameter control) are expected to be made in the years to come.

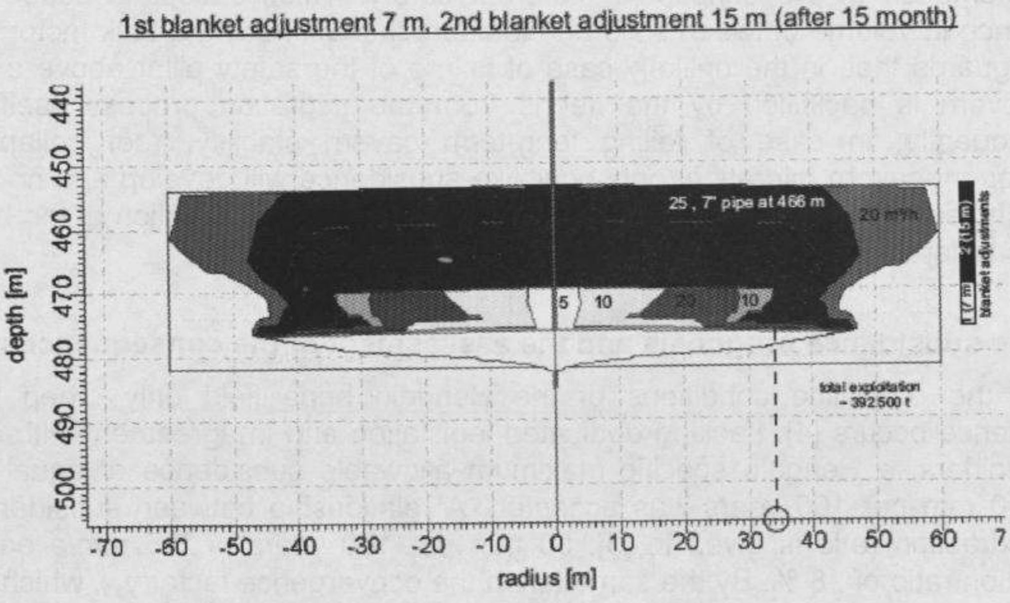

Figure 8: Leaching simulation, depicting sump development and 1st and 2nd main leaching phase

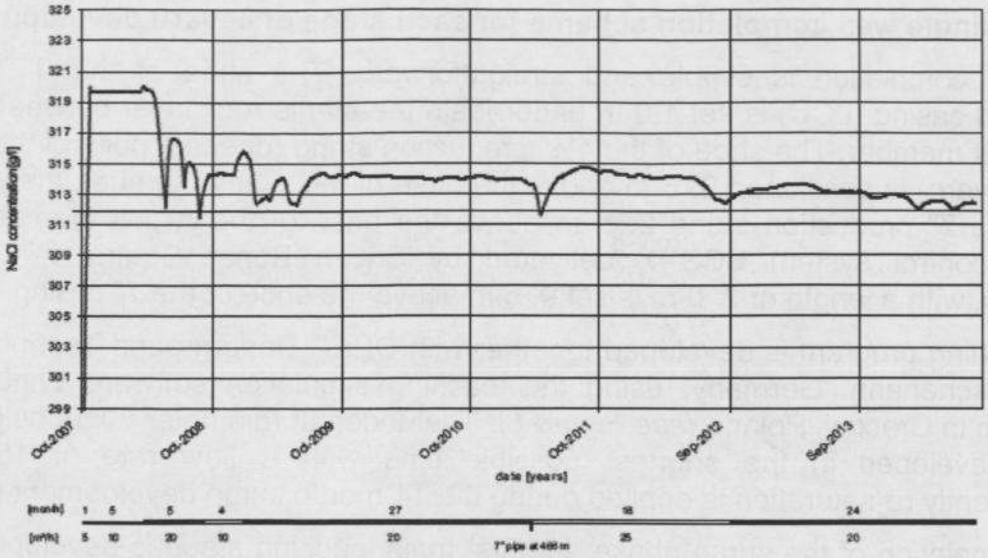

Figure 9: NaCl concentration development

3.3 The blanket control system and the concept of inherent safety

Diesel oil is used as blanketing fluid. Initially, two flow control lines – 0. 1 m apart - were used to monitor the blanket oil level. As it turned out, the control of the minimum and maximum readings was troublesome and labor intensive. The use of a blanket control system, with the ability for continuous readings over an interval of 2.0 m, proved to be an optimal solution, being less labor intensive and more reliable.

The consequent and reliable management of the blanket level is a prerequisite for the implementation of the concept of inherent safety. This concept is based on the difference in volume between solid and loose rock mass, using a bulk factor of 1.14. It safeguards that, in the unlikely case of failure of the safety pillar above a cavern, the cavern is backfilled by the debris from the migration process itself [2, 3]. Consequently, in case of failing long-term cavern stability, roof collapse and subsequent cavern migration, only bowl-like subsidence will develop and no through or sinkhole will occur at the surface. This is achieved by the limitation of the height of a cavern depending on the depth of Röt salt formation.

3.4 The subsidence prognosis and the assessment of the consequences

Under the prevailing conditions of the Hengelo brine field only creep induced subsidence occurs [4]. Lacking dedicated legislation and in agreement with external stakeholders, a Hengelo specific maximum allowable subsidence of equal or less than 50 mm per 100 years was accepted. A relationship between subsidence rate and extraction ratio is given in [5]: 50 mm per 100 years or 0.5 mm/a equals an extraction ratio of 18 %. By the same token the convergence factor y_{ss}, which is used in the Salt_Subsid subsidence prediction software, developed by Respec in Rapid City, South Dakota and licensed by the Solution Mining Research Institute (SMRI), was determined to be .00008 per year. The subsidence prediction calculations, which include tilt and extension-compression as well, are based on a given cavern field layout, in this case for the Usseler Es area [6] *(see Figure 10)*. The independent assessment of the consequences of the predicted subsidence for urban housing, infrastructure and surface water/ground water was done by Deltares in Delft, the Netherlands. The overall conclusion was that (i) effects on existing infrastructure and surface water /ground water table are negligible and (ii) structural damage to urban housing won't occur [7].

Figure 10: Cavern field layout and subsidence prediction in mm/100 years

3.5 The communication with third parties

Caverns, according to GSMP, were developed from end of 2005 onwards. Since then more than twenty wells were drilled and caverns developed.

The importance of good communication with third parties is illustrated by the example of the development of the Usseler Es. In 2004, the city of Enschede and AkzoNobel agreed to jointly and simultaneously develop the Usseler Es area east of the existing brine field *(see Figure 11)*. The Usseler Es presently serves agricultural purposes. Enschede municipality planned to develop an industrial estate from 2010 onwards, AkzoNobel planned to develop thirty five caverns with total developed reserves of around 18 million tons of salt between 2007 and 2013. GSMP proved to be instrumental in achieving agreement between parties; it served as the basis for the various permit applications as well. The first well was drilled in November 2007; as the drilling activities are executed at a point earlier in time than the development of the industrial estate, extensive communication and coordination between the municipality, the land owners etc. and AkzoNobel is indispensable. GSMP serves as the tool to obtain our 'license to operate'.

Figure 11: Final surface and subsurface development Usseler Es

4. Subsidence in abandoned mining areas

Subsidence is a direct consequence of mining. As such it is a highly disputed subject in society in general and in Hengelo and Enschede in particular because of a history of subsidence occurrences in the old, abandoned mining area.

Subsidence in solution mining results from:

- Collapse of the roof of a cavern by gravity force as a consequence of overmining. A critical situation arises when the hydraulic head in the cavern is not effective due to the absence of a salt pillar on top of the cavern;
- Cavern convergence and/or pillar deformation induced by salt creep. Creep is a temperature dependent phenomenon and can't be avoided under normal operating conditions. Creep induced pillar deformation is enhanced when the pillar dimensions are critical relative to the weight of the overburden.

Both mechanisms occur in the Hengelo brine field. Subsidence by roof collapse has a specific S-shaped signature in time (mm/year), depending on the position of the migrating caverne in the deep subsurface. Subsidence by pillar deformation has a linear signature in time. Both types of subsidence occur long after solution mining has been terminated and extent over a prolonged period of time (tens of years).

The initial mode of operation – at times when the development of a cavern wasn't fully understood, blanketing wasn't applied and sonar surveys were non-existent – resulted in the development of 'morning glory' type of caverns, in which only the upper part of the salt formation was mined and the effective height of the caverns was limited. By the quasi-blanketing properties of the anhydrite layer on top of the salt formation, adjacent caverns eventually got hydraulically connected, resulting in massive overmining. The subsequent roof collapse resulted in cavern migration. As a result of bulking and the limited initial cavern height, subsidence developed as bowl-like depressions on the surface.

As times progressed and solution mining became more effective in terms of salt extraction - use of blanketing and sonar surveys from the sixties onwards - but not in terms of long term cavern stability and integrity, subsidence became more severe and resulted in trough-like depressions.

As a consequence of the too large cavern diameters, dimensions of pillars between adjacent cavernes can become too small. This results in surface subsidence with a linear signature. Although, because of overprinting, it is sometimes difficult to distinguish between both types of subsidence, they both can be found in abandoned part of the Hengelo brine field. As stated before, GSMP has overcome these problems, so that the present solution mining can be considered sustainable.

The policy related to existing or expected subsidence in abandoned mining areas is laid down in the "Subsidence Management Policy" (SMP) [8], which contains such items as stakeholder analysis, cavern classification according to the probability to cause significant subsidence, surface impact assessment and internal guidelines for action according to a prioritization with respect to the risk involved. Practically spoken, important tools to deal with subsidence related issues are:

- A simple geometrical model, which answers the question of potential cavern instability and migration. The model was developed by back analysis of actual subsidence over time. Each cavern is assessed and classified at end of productive life.
- A monitoring program, in which caverns with a probability of instability and resulting surface subsidence are sonar surveyed on a regular basis. Stability is assessed by comparison of subsequent sonar surveys. If necessary, plugged wells are re-opened to enable sonar surveying;
- An Excel spreadsheet, which has been developed to quantify future subsidence, also in terms of tilt and extension-compression. The spreadsheet takes the geometrical model as a starting point and applies methodologies developed in the coal mining industry, using a 'worst case approach';

The potential for urban development is based on the outcome of a formal risk assessment, which includes the probability of subsidence and the impact of planned activities on the surface. If necessary in case of existing activities, caverns are stabilized with solid material from the brine purification in the vacuum salt plant or other measures, based on the outcome of a cost-benefit analysis, are taken. All these measures are in line with GSMP and SMP and constitute the basis for understanding and agreement with third parties.

5. Future development

The future of the Hengelo solution mining operation depends on the development of a new brine field at some extent from the existing mining area. The reason for this are existing subsurface and surface constraints and limitations and the need for further rationalization of the solution mining process. A sustainable approach is adopted, which means that a reduction of the footprint of the mining operation in terms of land use and limitation of subsidence is sought after. At the same time the salt production in terms of brine flow and extraction of developed salt reserves will be optimized.

In a first step spatial data in the public domain on the subsurface and surface conditions were analyzed for an area of 15 x 20 km2 around the existing brine field using a Geographical Information System (GIS). This resulted in the identification of six areas of potential interest, of which eventually three areas of special interest were selected. In a next step an exploration program will be executed, which includes drilling of exploration well(s) as well as the acquisition of seismic data. Moreover, an environmental impact assessment (EIA) will be made to support the final decision and approval process.

Following the acquisition and analysis of the new data, the location of the new brine field will be selected and all necessary permit applications will be submitted. Apart from the mining specific applications, these also include permits related to environmental protection, urban planning and protection of flora and fauna as well as archeological remains. Presently additional work in the field of geological modeling, geomechanical modeling, well completion, leaching and cavern development, production planning, subsidence prognosis, surface layout, infrastructure and the like is done. Start of the solution mining operation is planned in 2013.

6. Conclusions

The historical development of the Hengelo brine field has been described from the start of the solution mining operation in 1933. It has been shown that initially the focus was on technical issues not fully understood until the point in time that societal, legal and environmental developments became more important. As it turned out AkzoNobel was able to respond in a swift, accurate and responsible way. In doing so not only the way for the present, 'best-of-class' solution mining operation in Hengelo was paved, but also the necessary understanding and tools for the future ahead were developed. The development of a new, sustainable brine field is the culmination of a history of more than 75 years and gives confidence to the ability to also respond to challenges, not yet known, in the future.

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