Overall Model of a Flooded Mine in Rock Salt and its Consequences at Surface

O. Rolfs[a], C. Franks[b] and Chr. Döhner[c]

[a]Kavernen Bau- und Betriebs-GmbH (KBB), Karl-Wiechert-Allee 4, 30625 Hannover, Germany

[b]Eutech, PO Box 43, Brunner House, Northwich, Cheshire, CW8 4FN, Great Britain

[c]Kali-Umwelttechnik Sondershausen GmbH, Am Petersenschacht 7, 99706 Sondershausen, Germany

This paper concerns observations made at surface above a flooded mine in bedded salt near Northwich, UK, and a consideration of the hydrogeological and rock mechanical causes of the surface phenomena The objectives of the investigations presented here included explaining the measured surface subsidence and the extensometer measurements. The salt mines investigated are at very shallow depth and are now flooded because of the hydrogeological situation and the excessive level of extraction in some parts. The rock mechanical investigations into the overall load-bearing behaviour illustrate that the stress distribution established in the top salt zone brought with it the risk of disturbed zones forming along the margins of the mines as a result of tensile stresses. As a hydrogeological consequence, these disturbed zones at the boundary between the top salt and the wet rock head could have led to an increase in the surface area potentially affected by flowing water so that even today extensive subrosion processes are still taking place along the edges of the mines.

1. INTRODUCTION

There are a number of salt mines in the County of Cheshire, U.K.. The majority of these were flooded long ago and some have in part collapsed. In the area investigated a canal runs above several mines, and the measured continuous subsidence is a risk to the integrity of the canal and makes it necessary to periodically raise the levels of the banks of the canal. In recent years, this surface subsidence was observed in more detail and revealed that the highest subsidence rates are not located immediately above the mines, but in the area of the solid partition between the mines. This situation is shown in figure 1 which highlights the main subsidence trends along a section through the two neighbouring mines.The subsidence measured could be as a result of subrosion in the area of the wet rock head (leaching effects of the shallow halite deposits) and/or due to convergence in the underground workings. One approach to identify the two causes is to install magnetic extensometers which enable deformation measurements to be performed at different levels over the entire depth of a well.

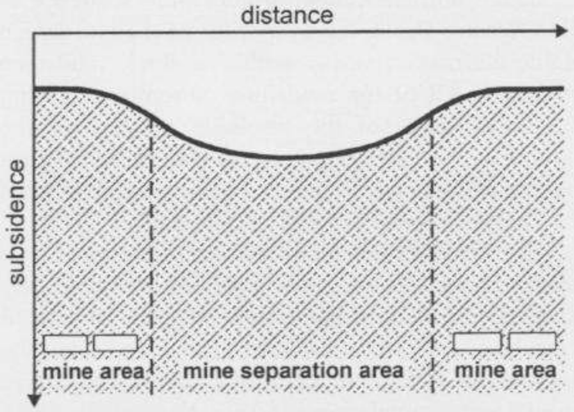

Figure 1. Subsidence along cross section above two neighbouring mines

Figure 2 shows as an example the results of an extensometer measurement which reveals that the measured surface subsidence is of the same order of magnitude as the vertical deformation in the borehole down to top salt and that the deformation within the salt (below the wet rock head) is only approx. 30 % of the overlying deformation. The aim of the geological/hydrogeological/rock mechanical investigation described here was to

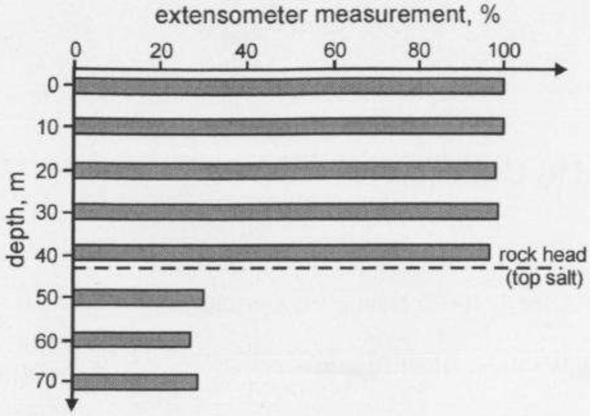

Figure 2. Magnetic extensometer measurement (in principle)

explain the results of this survey. The following does not precisely describe the actual conditions but looks instead at a simplified system to identify the main influences on the observed phenomena.

2. GEOLOGICAL AND HYDROGEOLOGICAL SITUATION

In the normal Keuper stratigraphic sequence in the Cheshire Basin, the evaporites of the Northwich Halite Formation occur within a thick mudstone sequence. All of the mudstone currently overlying the salt consists of the insoluble residues of the subroded evaporite sequence and is therefore considerably fractured. Figure 3 gives an impression of the geology around the area investigated.

The Cheshire Basin contains areas with wet rock head. These zones are subjected to continuing leaching of shallow halite deposits and associated subsidence of the surface. They indicate the presence of a faulted, permeable cover and active ground water circulation.

Natural subrosion in the area was diminishing before the situation changed as a result of human impact. With the initiation and expansion of brining and mining activities in the area since the 18th century subrosion was reactivated and considerably accelerated by the establishment of direct contacts between flowing water or unsaturated brines and the evaporite rock. The subrosion intensity associated with brine extraction at the wet rock head was already locally very variable and became even more differentiated and far more serious than any natural subrosion regime.

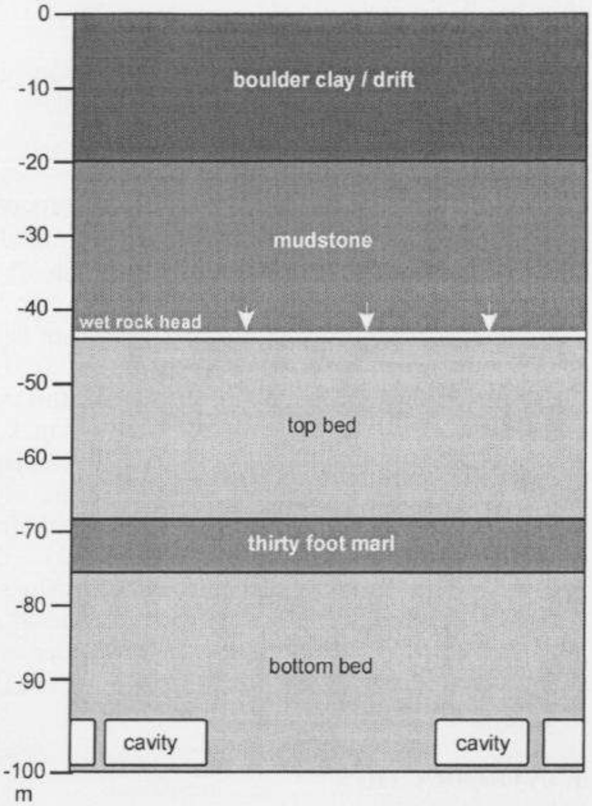

Figure 3. Rock mass model

These changes to the subrosion regime caused by human impact are irreversible. The regeneration of naturally controlled subrosion following eventual shutdown of brine extraction activity can be expected to be an extremely slow process the most significant phases of which are predicted to require periods of time measured in centuries rather than years.

3. MINING HISTORY

The Northwich salt reserves were exploited long before the Industrial Revolution. Initially, the naturally occuring brine springs covered the demand for salt. As demand rose, extraction was intensified in the 18th century The following salt extraction methods were the main influences on the hydrogeological situation:

• *wild brining*: The brine was extracted by shafts and boreholes penetrating the wet rock head which led to immediate activation of the subrosion processes

• *salt mining*: underground workings using the room and pillar system were constructed in the top bed salt and later in the bottom bed salt. The extraction percentage was over 90 %. Because of the inflow of brine these mines are flooded and because the pillars were inadequately dimensioned many partially collapsed.

• *bastard brining*: in some cases, the saturated brine was pumped out of the flooded mines. This led to the inflow of less saturated brine which caused further weakening of the pillar system and thus to the collapse of numerous mines.

The mines investigated in this paper were worked in the bottom salt bed over many decades up until the 1920s. They were then flooded because of breakthroughs into the surrounding rock but, according to the information currently available, have not yet collapsed.

4. ROCK MECHANICS

4.1. General

The aim of the rock mechanical investigations presented here was to determine:

➢ *Load bearing capacity*: assessment of the resulting stress state and the load bearing capacity of the rock zones surrounding the mines.

➢ *Deformation behaviour*: the consequences of convergence effects with respect to their influence on surface subsidence.

This publication will not go into a detailed description of the actual relationships. The investigation in this case involved a simplified system which was used to analyse the general phenomena. Figure 4 shows the simplified horizontal cross section of the problem which was investigated. It involves two neighbouring underground workings separated by an approx. 100 m wide solid partition. The width of the mines is approx. 275 m.

Underground workings always disorientate the original stress-state within the rock formation. Beside this such workings in evaporites are affected by an additional phenomenon: salt not only has elastic material behaviour, but also plastic and time-dependent viscous material behaviour. Depending on various parameters, underground workings in evaporites are to a greater or lesser degree subject to large time-dependent deformation leading to volume loss (convergence) of the chambers and galleries even in the post-operational (e.g. flooded) phase and associated surface subsidence.

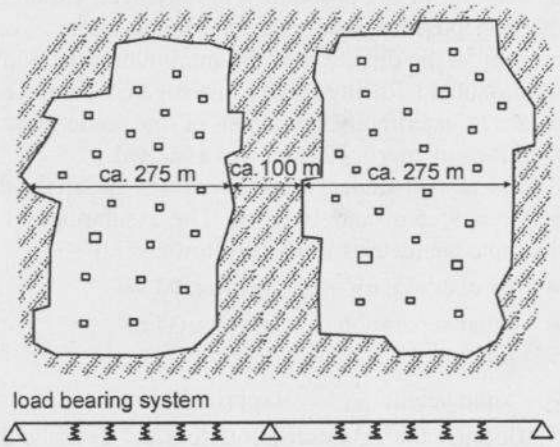

Figure 4. Horizontal cross section through two mines and the load bearing system

To be able to estimate the stress and deformation states occuring in the area looked at by this paper, numerical calculations were carried out based on idealisations concerning the geometries, mining history, influences of neighbouring mines, theoretical rock mass model and use of location-compatible parameters.

4.2. Theoretical rock mass model

The general geological situation is summarised in section 2. Because of the glacial and post-glacial erosion, and the subrosion processes previously described, the cover rocks above the Northwich Halite Formation must have experienced considerable fracturing and disturbance. The load bearing capacity of these layers is therefore ignored in these calculations. In addition, no exact information was available concerning the condition of the individual beds and the possible presence of faults and fractures in the 30ft marl. This was taken into account in the calculation by a reduction of the parameters derived from the laboratory.

The cover rock, the interbedded 30ft marl and the underlying rock formations were treated as elastic continua. A material law was selected for the halite which describes the non-linear time-dependent material behaviour.

4.3. Finite Element Modelling

The preparation of the theoretical calculation model requires a number of idealisations and simplifications of the real in-situ conditions.

The actual 3D conditions had to be incorporated to an adequate level of accuracy in the 2D description of the problem. This involved assuming the best possible load transfer for the mines. Load transfer in the direction of the minimum mine width was assumed for the mines investigated here. That means a maximum extension of the underground workings of approx. 275 m was assumed.

The actual underground workings lie at depths between 95.5 m and 102.0 m. The assumptions for the mine geometries were as follows:

- recovery factor approx. 93 %
- pillar separation approx. 34 m
- pillar cross section 9 m x 9 m
- mine height approx. 6.5 m

Because the 2D description does not describe the real room and pillar but a gallery system, the pillar width of 9 m (without taking into consideration weakening associated with flooding) reduces to approx. 2.4 m to match the recovery factor. Symmetrical considerations mean that the calculations just looked at half of the system of a mine (fig. 5).

The calculations did not consider the whole history of the mines. A period of 10 years was looked at during the operations period (atmospheric pressure), and another 10 years for the period during which the mine was flooded (brine column of approx. 90 m). These time periods are adequate to identify possible stress relocations and to assess the stationary situations occuring at the end of operations and in today's flooded mines.

4.4. Rock mechanical results

The calculations used in the above mentioned model with a finite limit to the mines clearly show that, in addition to the mine pillars, the rock zone above the underground workings also plays a major part in load transfer.

Figure 6 shows the largest principle stress within the whole of the rock formation surrounding the mine. A marked tensional stress state develops in the bottom bed salt in the central part of the mine during mining operations, and in the top bed salt in the bearing zone at the margins of the mine.

The investigation of the smallest principle stress in the whole rock mass showed a marked compressional stress state in the centre of the mine in the area of the top bed salt and in the bottom bed salt at the margins of the mine.

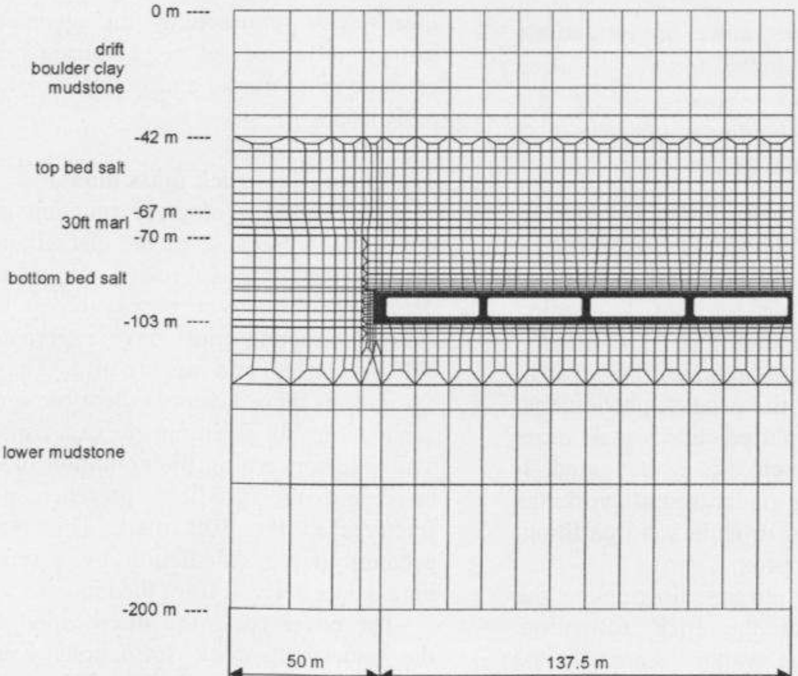

Figure 5. Calculation model

This stress distribution in the rock sequence overlying the mine indicates a load bearing behaviour analogous to a beam, and extrapolated to 3 dimensions, a plate. The whole load bearing system consisting of the mine pillars and the Northwich Halite Formation overlying the mines can be modelled in a simplified way as a continuous beam with spring bearings and rigid bearers at the margins of the mine and the unmined central zone between the mines (fig. 4).

Figure 7 shows the vertical stresses in the most severely stressed central pillars. During mining operations, the vertical stresses were approx. 19 MPa, but only approx. 8 MPa in the subsequent flooded mine state because of the supporting effect of the brine column. Comparison calculations using a model in which the whole load transfer is restricted to the pillar system, produced vertical stresses of approx. 30 MPa during mining operations and approx. 16 MPa during the post-operational phase. The marked reduction in the stress within the pillars associated with the combined load bearing system explains why there were no unusual rock mechanical events during the mine's history (approx. 50 years mining operations, and flooded since approx. 1939).

The tensile stresses shown in figure 6 at the margin of the underground workings in the top bed salt and in the bottom bed salt are of a size which is probably unsupportable, particularly for the period of mining operations, and especially over the long term. Consideration must be given here to the fact that these tensile stresses are based on a very conservative model. In reality, the following influences also need to be taken into consideration and would reduce tensile stresses to a level that can be borne by the salt without leading to total failure of the whole load bearing system:

- neighbouring underground workings with shorter spans
- a more favourable pillar distance/pillar thickness ratio in the real room and pillar system
- the involvement of the cover rock lying above the wet rock head

The computations revealed that a combined load bearing system consisting of mined pillars and the rock formation above the mine must exist, or at least have existed during the period of underground working - to explain why the underground workings have still not collapsed despite the extremely high level of extraction. The surface subsidence determined from the calculations is a few centimetres per year above the centre of the mine during the mining period. The supporting effect of the brine column in the current flooded condition effectively reduces subsidence to a few millimetres per year. This is incompatible with the subsidence rates of a few centimetres per year currently measured in the area around the mines. This means that the rock mechanical investigations also indicate that there must be other significant effects involved to explain the current surface subsidence in addition to the convergence effects induced by rock mechanics in the area of the mines.

5. ROCK MECHANICAL – HYDROGEOLOGICAL INTERACTION

It becomes clear when comparing the results of the surface subsidence and the extensometer measurements with the results of the numerical rock mechanical calculations that in general most of the measured surface subsidence is not attributable to the convergence effects in the underground but is attributable instead to the subrosion processes still continuing today in the wet rock head at the margin of the top bed salt. Another interesting aspect is that surface subsidence is much higher at the margins of the underground workings than directly above the mines. This is clarified by the rock mechanical calculations. These reveal a stress distribution system typical of a continuous beam. In other words, within the centre of the underground workings, tensile stresses occur at the base of the beam, and on top of the beam (at top bed salt at the boundary to the wet rock head) in the vicinity of the beam supports (in the rock area between the mine). These tensile stresses are undoubtedly largely overestimated by the use of a conservative model but existed, at least to a minor extent, during the mining operations. This means that the calculations for the mines indicate the possible existence of disturbed zones at the boundary between the top bed and the wet rock head. In the past, this could have led to more intense subrosion in these areas so that the surface area potentially affected by flowing water is still larger in these zones, in other words, that the zone between the mines is still a preferential area for subrosion even today. This means that these areas will be associated with more intense surface subsidence than the zones directly above the mines.

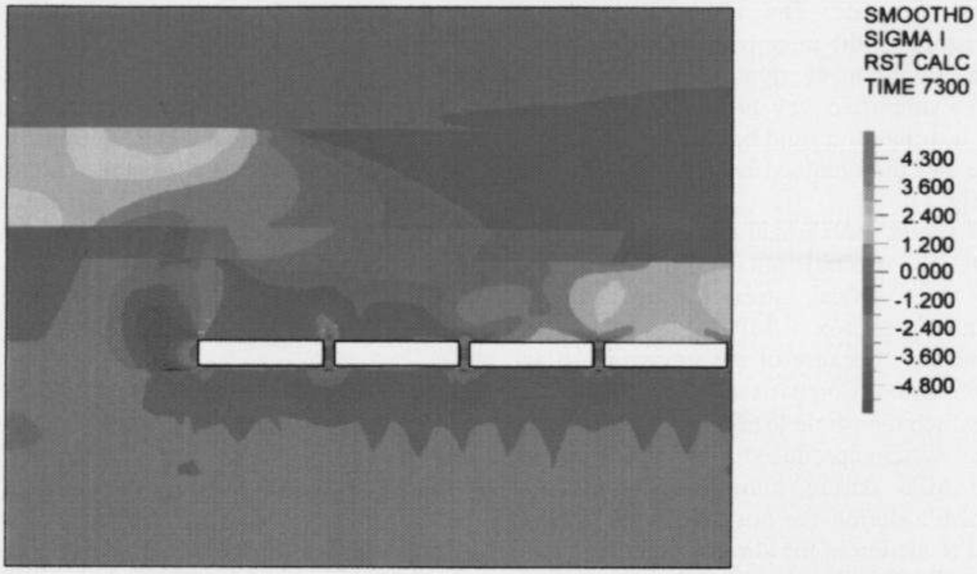

Figure 6. Principle stress σ_1 / flooded mine

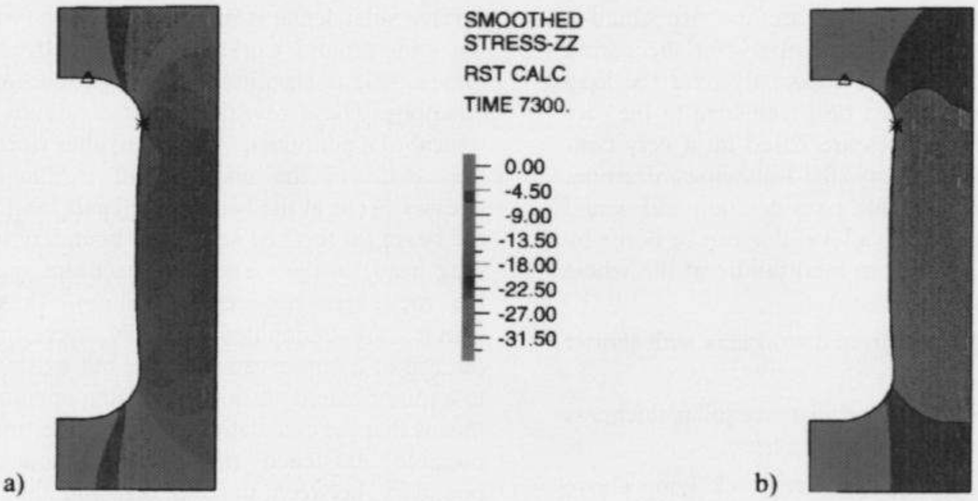

Figure 7. Vertical stress in central pillar
a) during mining operation
b) flooded mine