Self-healing of excavation-disturbed rocks in the nearfield of underground cavities – exemplary measurements in rock salt and interpretation of preliminary results

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Abstract: Excavation disturbed zones develop in all kinds of rock as a consequence of the opening of cavities. Such zones are characterized by a change in hydraulic behaviour which can form a problem with regard to the sealing of waste disposal areas.
Rocks showing a plastic behaviour, like rock salt, have the potential of healing when the stress state which was disturbed by excavation returns to an advantageous state. If healing can reliably be predicted, the excavation disturbed zone may not form a long-term safety issue in rock salt. Investigations of permeability and stress state around lined and open excavations have been performed in order to relate hydraulic behaviour to stress state. First results which are presented here are promising.

1. INTRODUCTION

The mechanical and hydraulic response of rock to excavation has been subject of continuous investigation in the frame of underground repository safety research. During the last years, the excavation disturbed zone (EDZ), which can be roughly described as the zone near an opening where the hydraulic behaviour is changed, moved into the centre of interest [1]. Excavation disturbed zones are formed in all types of rocks as a consequence of the opening of cavities. The quality and degree of disturbance may vary from purely hydraulic disturbance (e.g., drying effects near the surface of the opening as a consequence of ventilation) to considerable mechanical damage (e.g., macrofracturing caused by high effective stresses). In any case, the hydraulic properties, such as effective permeability, are altered in the affected zone, and so the EDZ can form a potential pathway for liquids or gases. This, of course, is of special concern with regard to sealing of disposal areas.
In crystalline rock, like granite, the mechanical damage is irreversible, so that measures have to be taken to reduce fracturing as far as possible or seal fractures where they are considered as problematic for the effectiveness of seals. Rocks showing also plastic behaviour, like clay or rock salt, have the potential of healing when assuming an appropriate stress state. This is especially interesting regarding the fact that the emplacement of a sealing structure in an opening may result in the rock salt returning to such an "appropriate" stress state. Thus, the EDZ may not be a long-term safety issue, if its healing can be proven.
The final repository safety research division of GRS has been running an experimental programme on the EDZ in rock salt since 1996 [2, 3]. The second phase of the project, which started in 1998 and is still going on, deals mainly with the issue of EDZ healing. It is funded by the German ministry of economy (FKZ 02 E 9118 8) and by the Commission of the European Communities in the frame of the BAMBUS II project (contract N° FIKW-CT-2000-00051).

2. CHARACTERIZATION OF THE EDZ IN ROCK SALT: DILATANCY

Natural rock salt found in German salt domes is typically very dry (e. g., total moisture content below 0.02 wt% for 75 % of 202 samples from the Asse salt mine [4, 5]), so pure hydraulic effects like drying do not play a significant role with regard to EDZ formation. The mechanical disturbance of the salt introduced by excavation can, however, not be neglected.

When a cavity is opened in rock salt, the more or less homogeneous stress state is changed to a highly inhomgeneous state in the nearfield of the opening. Due to the viscoplastic behaviour of the salt, the deviatoric stresses are reduced with time by the so-called creep of the salt, which results in continuous convergence of the opening. An inhomogeneous stress state will, however, be kept as long as there remains an opening. Deviatoric stress may result in dilatancy of the rock salt, that means volume increase by microfracturing and thus increase of porosity and permeability. Various dilatancy criteria were proposed for rock salt by different authors:

Spiers et al [6]: $$\sqrt{J_2} \geq 0.83 \cdot \sigma_m + 19 \quad (1)$$

Ratigan et al. [7]: $$\sqrt{J_2} \geq 0.81 \cdot \sigma_m \quad (2)$$

Hunsche [8]: $$\sqrt{\tfrac{2}{3} \cdot J_2} \geq 0.86 \cdot \sigma_m - 0.0168 \cdot \sigma_m^2 \quad (3)$$

With σ_m being the mean stress and J_2 the second stress invariant, defined as

$$J_2 = \tfrac{1}{6} \cdot ((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2) . \quad (4)$$

All equations have in common that a prerequisite for dilatancy is a high deviatoric stress (i.e., a high difference between the principal stress components σ_1, σ_2, σ_3). The above dilatancy criteria can be plotted as curves in a diagram showing the deviatoric stress as a function of mean normal stress, as shown in figure 1. The criteria are fulfilled in the region above the corresponding curve, i.e., dilatancy may occur when the rock salt is in a stress state above the curve.

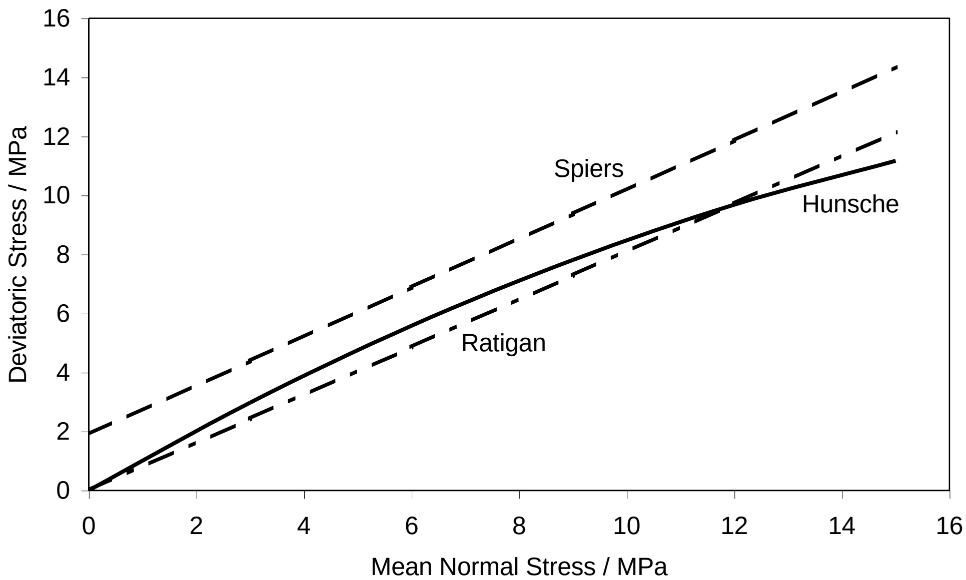


Figure 1: Dilatancy criteria of Ratigan [6], Spiers [7], and Hunsche [8]

On the other hand, the viscoplastic behaviour of rock salt bears the potential for healing, that means reversal of previous dilatancy, when the stress state changes to the region below the criteria. In other words, compressive stress will close fractures and reduce porosity/permeability again.

Since dilatancy is the cause of the alteration of hydraulic behaviour, the EDZ in rock salt may be characterized as the region around an opening where a dilatancy criterion is fulfilled. Dilatancy criteria give only a "yes/no"-statement on dilatancy. There is no quantification of the impact on hydraulic parameters, especially permeability, which is necessary for safety assessment.

3. PERMEABILITY OF THE EDZ

In order to be able to relate permeability of the rock salt to its stress state, in-situ measurements of permeability are being performed at various test sites in the Asse salt mine near Braunschweig, Germany. By numerical modelling of the mechanical state, confirmed by in-situ stress measurements, the determined permeability values can be related to stress states. Of special interest is a test site on the 700-m level, where a cast-steel bulkhead was installed already in 1914, so that a partial healing of the EDZ could be expected. The results of the permeability measurements performed at that test site are presented here.

For permeability testing, a multipacker probe which can be emplaced in boreholes with 86 mm diameter was employed. Four boreholes were used for the measurements: A horizontal, a vertical and a 45°-inclined borehole were drilled through the steel liner into the rock salt. A fourth borehole was drilled vertically into the floor outside the lined part of the drift in order to have a comparison between the lined drift and the open drift. The figures 2 and 3 show photos of both parts of the drift. The liner is made of cast steel tubbings, and the void between the liner and the drift surface is backfilled with concrete.

Figure 2: View into the bulkhead drift showing the permeability measurement system (on the right)

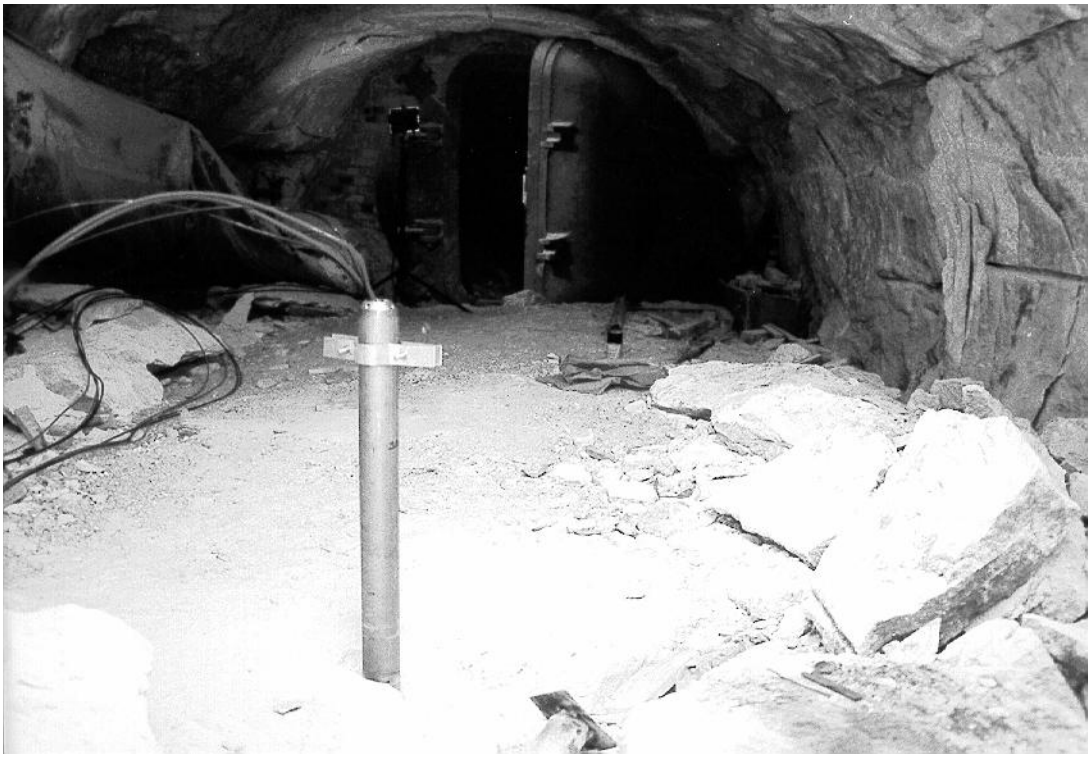


Figure 3: Open part of the drift with the packer probe installed in the borehole (in the foreground) and the door to the lined part (in the background)

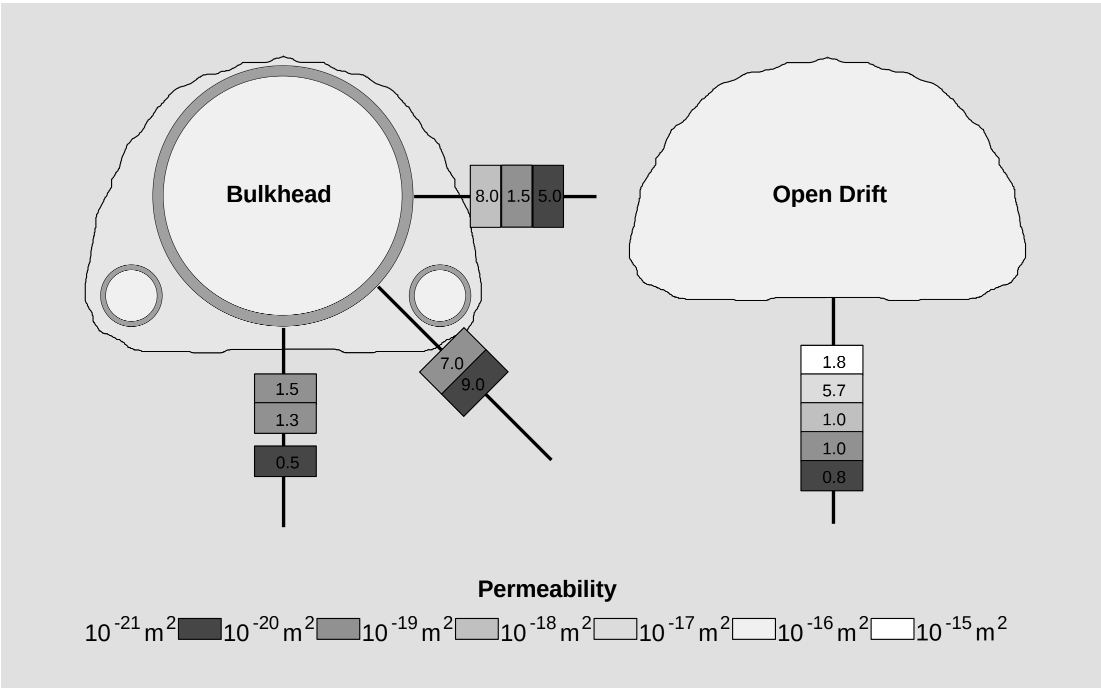


Figure 4: Measured permeability values in the boreholes around the steel liner (left) and below the open drift (right); the shades of the rectangles denote the order of magnitude, the numbers inside the rectangles the multiplier

The permeability measurements were performed as gas injection tests: An interval of the test borehole was sealed against the top and bottom by hydraulic packers, and nitrogen was injected. During the flow phase and the subsequent shut-in phase, the pressure development in the test interval was recorded.

The permeability was determined from the flow rate and pressure readings using a commercial computer code for well test analysis [9]. Various measurements were performed at different borehole depths. The results are summarized in figure 4.

The permeability distribution below the open drift is typical: A zone of increased permeability extends about 1.5 m into the floor of the drift, and the permeability goes up to more than 10^{-16} m^2 (with the permeability of the undisturbed rock being in the range of 10^{-21} m^2). Similar results had already been obtained at other test sites [2, 3, 10].

The results from the lined part of the drift are completely different: Except for the measurement closest to the wall in the horizontal borehole, all permeability values are below 10^{-19} m^2, and most of them close to 10^{-20} m^2. This supports the assumption that, due to the stress redistribution after emplacement of the liner, the EDZ has at least partially healed.

4. RELATION BETWEEN PERMEABILITY AND STRESS STATE

For a detailed comparison between permeability and stress state at the bulkhead test site, results of stress measurements are needed as input to mechanical calculations. While these results are not yet available, it is still possible to perform a mechanical analysis with a plausible initial stress state in order to get a first idea on the stress field around the lined and the open drift. This was performed using the finite element code ANSYS [11]. The model used was a two-dimensional plane strain model. Calculation started with mining of the drift in 1911 and a homogeneous stress state with 15 MPa on the drift level. Two calculation sequences were performed: One with the bulkhead emplaced after three years, and one with the drift left open until today. Figure 5 shows the total displacement around the open drift after 85 years. It can be seen that the largest deformations take place in the region below the floor, where the permeability increase was measured.

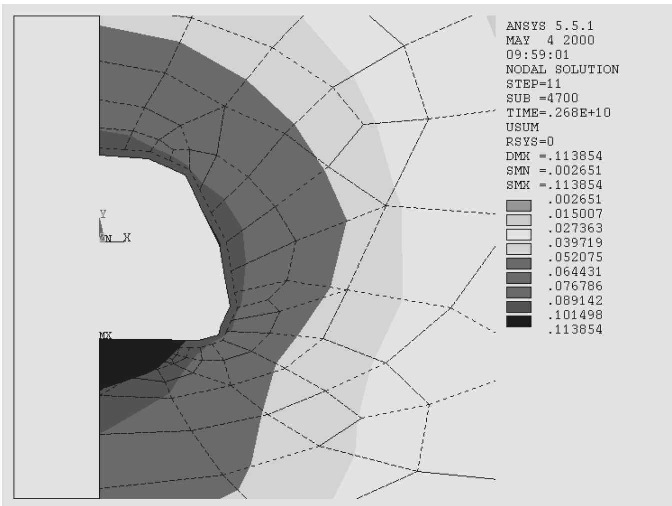
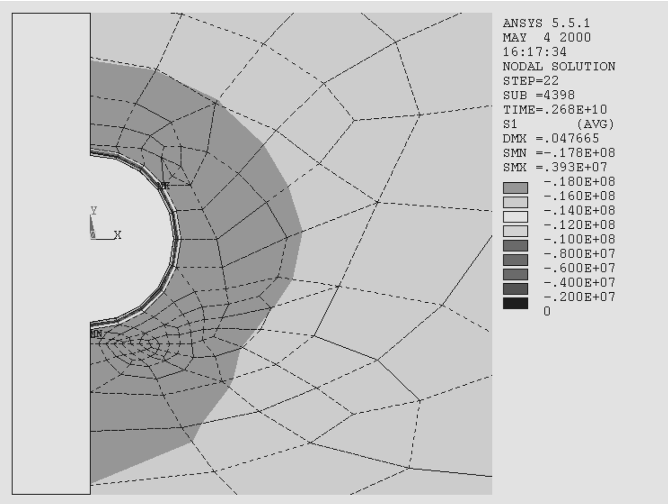


Figure 5: Total deformation around the open drift after 85 years

The least principal stress for both the lined and the open drift is shown in figure 6. A low value of the least principal stress is a hint to high differences in the stress components and thus to a possible excess of the dilatancy criteria. Finally, the dilatancy criterion of Ratigan is shown in figure 7 for the two models.
Looking first at the least principal stresses in figure 6, one can observe an increased stress around the liner in the range of 17 MPa, which is due to the rigid inclusion of the liner. Around the open drift, a zone of extremely diminished least principal stress (below 1 MPa) is present, which extends farthest below the floor. The graph of the dilatancy criterion (figure 7) shows the consequences: In the lined drift, the criterion is fulfilled only in the liner itself, where it is, of course, not applicable. Interestingly, a small "dent" extends into the salt at drift midheight, where also the highest permeability was measured (see figure 4, left). Around the

open drift, a larger zone below the floor and a s
criterion is fulfilled. This is again in agreement wit



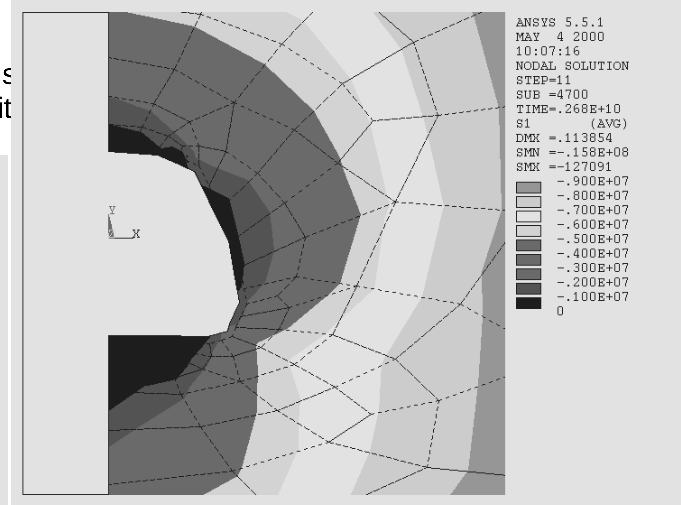
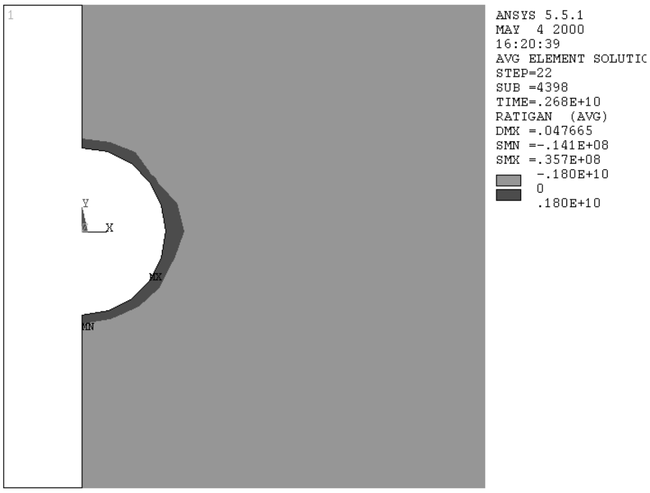


Figure 6: Least principal stress distribution after 85 ye
(right)



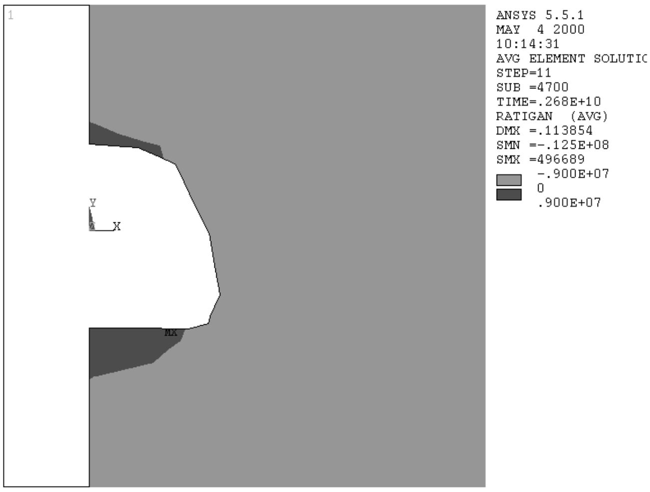


Figure 7: Dilatancy criterion of Ratigan after 85 years around the lined drift (left) and the open drift (right); dark: the criterion is fulfilled, light: no dilatancy

Summarizing one can say that there is a good qualitative agreement between measured hydraulic behaviour and stress state as modelled. Modelling, however, has to be refined and confirmed by pressure measurements which have already been performed and are currently being evaluated.

5. OUTLOOK

The permeability values and the corresponding data regarding the stress state (as soon as reliable data supported by measurements are available) can be used to derive a quantitative relation between permeability and stress which is needed for the prediction of EDZ performance and healing. Of course, data from a single test site will not be sufficient for this task. Two additional test sites where similar investigations are performed are a drift on the 800-m level of the Asse mine and the pillar between two large chambers on the 532-m level.

These measurements will provide data on permeability at different stress situations. Additional laboratory tests will be performed under stress states which are not obtained in situ.

The final outcome should be a mathematical relation between permeability and stress state. Of course, permeability is also dependent on other parameters than stress, such as mineralogy, structure, fluid content. Thus, an exact relation cannot be obtained. Regarding the change of permeability between undisturbed rock salt and EDZ by four or five orders of magnitude, it will, however, be a great improvement for safety assessment if the permeability can be predicted with an accuracy of one order of magnitude or better, which is considered achievable.

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