

## Preliminary Safety Analysis Gorleben – Design of a Bentonite Shaft Sealing Element

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### 1 Introduction

The main goal of the Preliminary Safety Analysis Gorleben is a comprehensive and clearly documented safety analysis of the Gorleben site with the focus on long-term safety. One important aspect when designing a repository for heat-generating radioactive waste is the development of a sealing system for the geologic barrier whose penetration is unavoidable during repository construction and operation. The basic functionality of the shaft seal system was assessed in an analytic structural pre-analysis [2]. Non-linear behaviour and coupled processes, which could not be included in the pre-analysis, were now included in a detailed verification using numerical methods.

The functional element closest to the surface is made of bentonite. It is located just below the overburden. In case of fluid inflow from the overburden, the bentonite element is the first to be loaded by hydraulic pressure. In a hydro-mechanical coupled simulation, the forces caused by the fluid were examined. The swelling process of the bentonite was also integrated.

### 2 Criteria

To check for crack formation in the salt, the following criteria were used [1]:

Dilatancy criterion:

$$\frac{\tau}{\sigma^*} \leq -0,01697 \cdot \left( \frac{\sigma_0}{\sigma^*} \right)^2 + 0,8996 \cdot \frac{\sigma_0}{\sigma^*} \quad (1.1)$$

with

$$\tau = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad : \text{octahedral shear stress [MPa]}$$

$$\sigma_0 = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \quad : \text{mean stress (also hydrostatic pressure) [MPa]}$$

$$\sigma^* = 1 \text{ MPa} \quad : \text{reference stress}$$

From experience gained in mining practice, it is known that – at shallow depths – the application of the dilatancy criterion leads to inaccurate results due to influences that can be neglected at higher depths, i.e. the damaged areas are actually larger than those identified by the dilatancy criterion. Therefore, all zones under 1 MPa minor stress pressure are assumed to be damaged (EDZ = excavation-damaged-zone). The new criterion is based on the results of different measurements.

The hydraulic resistance is evaluated by the criterion of effective fluid pressure. The criterion of effective fluid pressure is used for the salt and the bentonite.

$$\sigma_3 > p_{fl} \quad (1.2a)$$

$$\sigma'_3 = \sigma_3 - p_{fl} > 0 \quad (1.2b)$$

with

$\sigma_3$ : smallest total principal stress

$p_{fl}$ : fluid pressure (pore pressure)

$\sigma'_3$ : smallest effective principal stress

Within the scope of the Preliminary Safety Analysis for the Gorleben site, a sealing system for a repository for heat-generating radioactive waste and spent fuel elements was developed. The sealing system consists of shaft and drift seals, which in turn consist of multiple functional elements. One vital functional element of the shaft seal is a sealing element that is made of bentonite and consists of multiple filter layers and bearings. It is located near the overburden. After closure of the repository, this sealing element becomes immediately effective to brine inflow due to the swelling capacity of the bentonite.

### 3 Bentonite

Bentonite is characterized by its local isotropic swelling capacity. Swelling pressure develops under restrained deformation. Without restrained deformation, the volume of the bentonite increases. Immediately after closure of the repository, i.e. when there is no rock pressure caused by convergence, the swelling capacity is very important for the minimal principal stress.

### **3.1     *Restriction of bentonite decompaction***

In areas where the bentonite element is not rigidly mounted, the effective fluid pressure criterion is mathematically always exceeded. In these areas, local decompaction can be assumed. However, a muddy suspension forms which has the characteristics of a support liquid. Such local exceedances of the effective fluid pressure criterion cannot be avoided. However, continuous areas of decompaction with low swelling pressure must be avoided. In a material analysis, it was detected that a decompaction of less than 3% volume percent is uncritical for the parameters of swelling and hydraulic conductivity [4]. Therefore, the restriction of the decompaction of the bentonite can be regarded as a requirement for guaranteeing limited hydraulic conductivity and sufficient swelling pressure.

## **4        Model description**

The necessary calculations for the bentonite element have been carried out using the simulation software FLAC3D 4.00 by Itasca. Due to the long computational time for hydro-mechanical coupled calculations, a rotationally symmetric model was chosen which corresponds to the in-situ geology. The validity of the simplifications was checked by comparing the time-dependent convergence of the rock salt measured in-situ with the calculation results. Figure 1 shows the model geometry with the geology and functional elements.

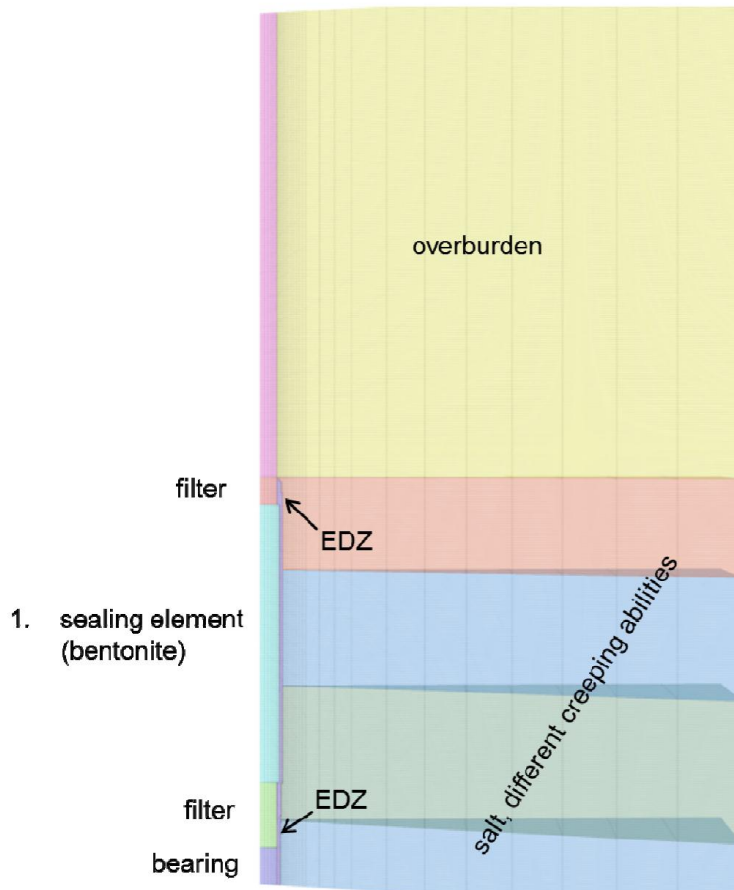


Fig. 1

#### 4.1 Modelling

The overburden and the functional elements were modelled using a linear-elastic constitutive law. For the salt, the elastic-viscoplastic constitutive law BGRa was chosen, taking into account different creep classes. For the hydro-mechanical coupling, the concept of effective stress (Terzaghi) was used.

The maximum swelling capacity of the bentonite depends on its dry density upon installation. Results from the large-scale experiment "shaft seal Salzdetfurth" show that the maximum swelling pressure is limited to 1 MPa. Therefore, the swelling pressure in the simulation was also limited to 1 MPa. For dry bentonite, a Poisson's ratio of 0.3 is used. Due to saturation and the beginning swelling pressure, the Poisson's ratio increases to 0.45 at total saturation. A Poisson's ratio of 0.45 corresponds to highly plastic clay. This has the

effect that changes in stress due to load increase are distributed isotropically. This change in material behaviour is due to the complete saturation of the bentonite and the increasing influence of the incompressible pore solution.

## 5 Results

Time-dependent saturation:

The large-scale experiment “shaft seal Salzdettfurth” showed that a fast hydraulic pressure build-up leads to crack formation and, thus, to the formation of a continuous pathway in the bentonite sealing element [3]. In reality, such a critical event cannot be excluded due to the high permeability of the overburden. From the same experiment, a saturation regime was derived that prevents crack formation in the bentonite seal. Figure 2 shows the assumed pressure development. The maximum is at 5.13 MPa (fluid up to ground level + 50 m rise of the sea level).

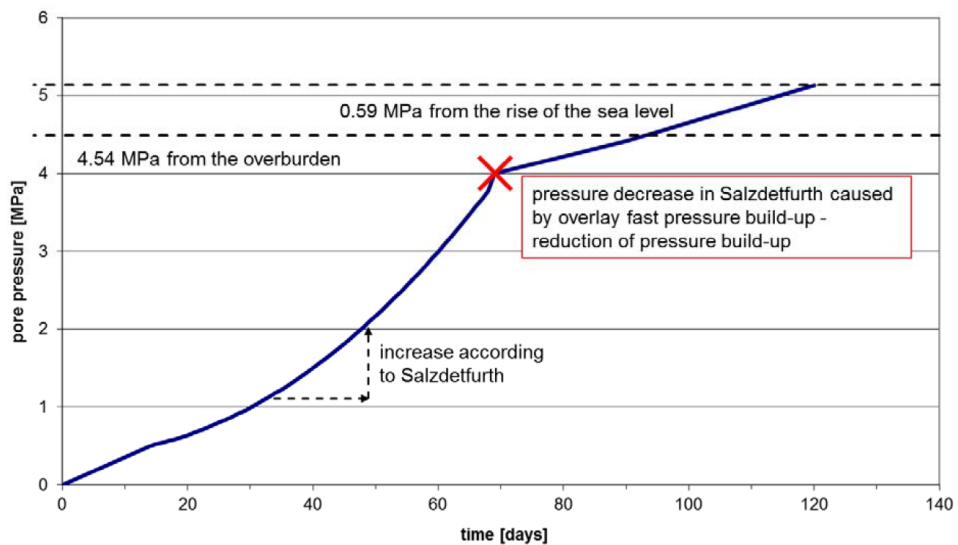


Fig. 2

Figure 3 shows the saturation 120 days after pressure build-up. The right side shows how the elements are located in the shaft (including the permeability).

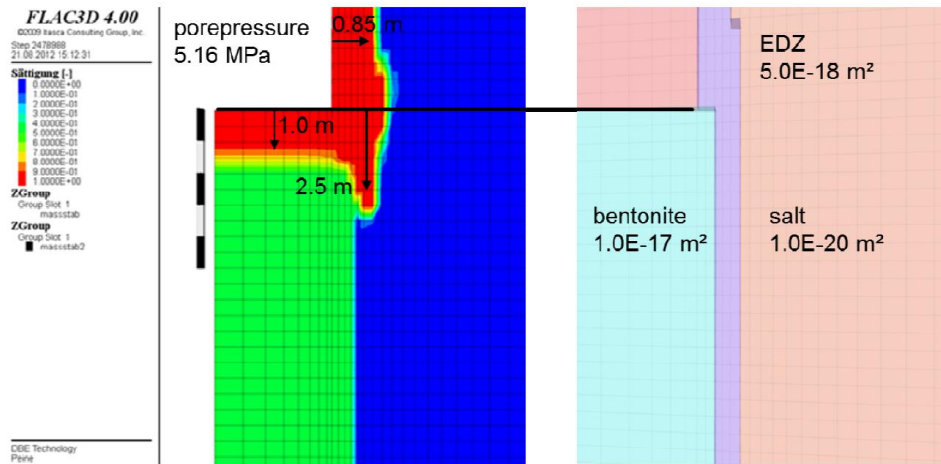


Fig. 3

It can clearly be seen that the saturation in the EDZ proceeds faster than in the bentonite or in the salt. This is caused by the smaller storage volume in the EDZ. Despite a lower permeability, the zones of the EDZ are faster fully saturated than in the bentonite. The time-dependent saturation process was calibrated based on the large-scale experiment “shaft seal Salzdetfurth”.

## 6 Evaluation

Subsequently, the functionality of the bentonite sealing element was verified. As the highest hydraulic gradients occur during the saturation phase, this early period was taken as the design basis.

To verify the functionality of the bentonite element, the criterion of effective fluid pressure and the decompaction criterion were used. With the exception of a small, transient area, all areas in the EDZ comply with the effective fluid pressure criterion. In the bentonite, it is not strictly necessary to meet the criterion; but an analysis will indicate areas where the pore pressure may exceed the principal minimum stress. For these areas, compliance with the decompaction criterion was assessed with the result that the criterion is met in all areas. In conjunction with the large-scale experiment in Salzdetfurth, the functionality of the first sealing element has been verified based on current knowledge.

## References

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