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Numerical simulation of geomembranes as bottom sealing below salt heaps

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1 INTRODUCTION

The K+S company is operating underground mines for the production of potassium raw salts in Thuringia and Hessia. The mined potassium salts are delivered to the surface, where they are processed to potassium and magnesium products that are used as fertilizer and base material for the chemical and pharmaceutical industry. Salt residuals that are not further used are heaped up at the surface. K+S is continuously investigating and improving this process. Nonetheless, the ongoing mining process is more and more demanding for heap space. Thus, heap expansions associated with onward changes in the overall environmental protection standards are an inevitable part of the future investigations.

The usage of a geomembrane (GMB) as an element of a basal seal for salt residual piles was examined. Besides technical restrictions by the specific establishment of a GMB as a basal seal, the potential of its applicability, as well as its influence on the system "heap - basal seal - underground", have to be evaluated in advance. The numerical modelling of salt residual heaps has to consider several aspects: the large-scale relations of salt heaps, the basal seal and the underground, including their complex interaction with the GMB and especially the settlement induced deformations, as well as the viscous movement, which is important for long-term predictions. Special attention has to be paid to the simulation of the GMB and its two respective interfaces: one to the subsoil and one to the salt heap. So far, no comparable experience exists.

2 METHODS AND MATERIALS

2.1 *Simulation software and model setup*

The 2D numerical simulations are conducted by using *FLAC* (Itasca 2016). The implementation of distinct planes on which separation or sliding can occur is possible. Individual built-in stress-strain laws prescribe these interfaces simulating the border between heap and GMB as well as GMB and underground. Beam elements are used for modelling the GMB. Therefore, the linearly elastic behavior including an axial tensile strength limit is used. The continuum based approach of *FLAC* in combination with interfaces and beam elements is well suited for modelling a system consisting of a large scale residual salt heap coupled to a millimeter thin GMB laying on a particular underground.

The 2D numerical model is based on a conceptual model emphasizing typical in-situ conditions in terms of dimensions and underground situations (Fig. 1). The underground within the numerical model consists of individual homogenous layers. Its inclination, including the geological layers, is about two degrees. Two other additional underground models with different layering were also investigated, but they are not presented in this paper. Roller boundaries are applied at the left and right model side. The lower boundary is fixed in vertical direction. Land surface as well as the heap are able to move freely.

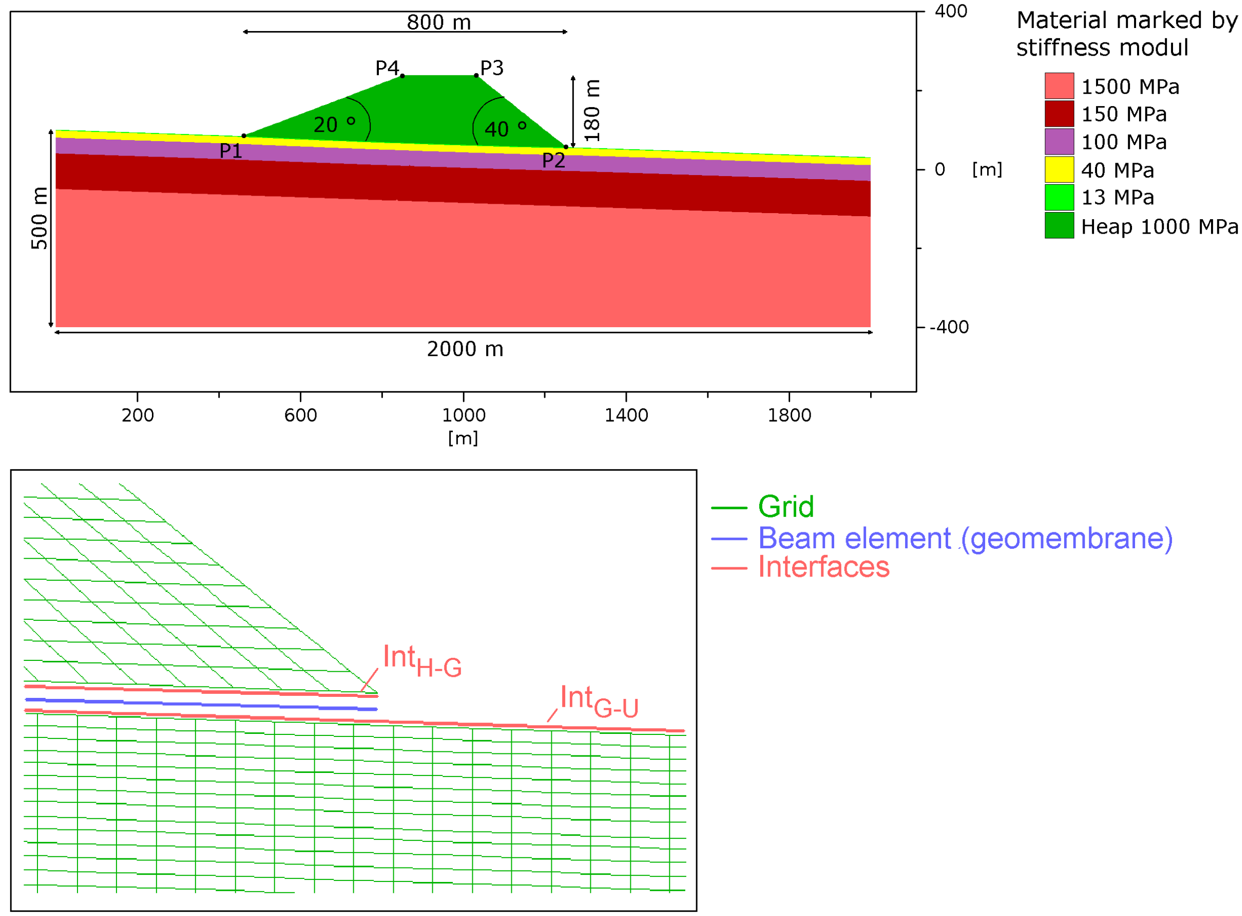

Figure 1. Conceptual model with layered underground indicated by stiffness values and scheme of the "three layer system".

The GMB is implemented via a beam element with two interfaces (Fig. 1). One interface is located between the heap and the GMB (Int_{H-G}) and another one between the GMB and the underground (Int_{G-U}). A coupled multi-layer system of heap - interface - GMB - interface - underground originates. After grid generation and parameter initialization, the numerical simulation is divided into the following steps:

1. Elastic calculations until initial equilibrium incl. heap up of dump and considering ongoing density increase in salt heap,
2. Elasto-plastic calculation for operation phase,
3. Elasto-visco-plastic calculation for post-operation phase until lifetime of 30 years.

The complete heap is set-up suddenly. Subsequently a *FISH*-routine is implemented to model the density increase from the top of the heap to its core. After a simulated lifetime of 30 years results of the model and especially the GMB can be examined in terms of creep behavior of the heap, settlements and horizontal displacements on the surface, strain on the surface, forces and strain inside the GMB as well as its failure.

2.2 *Material laws and parameters*

The Mohr-Coulomb (M-C) constitutive model with non-associated flow rule and tension cut-off models the underground below the salt heap. Elasto-plastic and viscous deformations of the heap material are considered separately. Elasto-plastic behavior is simulated by M-C constitutive model with non-associated flow rule and tension cut-off. The crushed salt model (Itasca 2016) simulates creep behavior.

The GMB is modelled by a beam element with linear elastic behavior including an axial tensile strength limit. Since GMB below salt heaps are a new kind of usage, thickness and tensile strength of the GMB are assumed according to governmental regulations (regulatory limits) for repositories (BAM 2014). Especially the tension limit is a critical parameter for failure of the GMB. BAM 2014 also gives a critical axial tensile strain limit of 6 % (for a temperature of 20 °C) which should not be exceeded in order to guarantee the integrity of the GMB.

The mechanical parameters of the simulated GMB are highlighted in Table 1. Other aspects like temperature or deformation depending stiffness of the GMB as well as aggressive fluid impact are not considered within this feasibility study. The interfaces are modelled with specific stiffness, zero cohesion, and are able to slip. The friction angle ($\phi_{Int\text{-}H\text{-}G}$, $\phi_{Int\text{-}G\text{-}U}$) controlling slip is 20 °.

Table 1. Mechanical parameters for the GMB including limiting values of BAM 2014.

Parameter	**Value**
Thickness [mm]	2.5
Width [m]	1
Density [kg/m3]	950
Young's modulus [MPa]	200
Tensile strength [MPa]	15

2.3 *Case studies*

The aim of the present simulations is to get a general feeling about the opportunities for modelling the GMB behavior below residual salt heaps and to reveal the influence of the contact (interface) parameters. Therefore, it is necessary to not only investigate intact GMB behavior (H1), but also an activated failure scenario (H2). The simulation H2 is performed in order to generate failure of the GMB by reducing its tensile strength ($\sigma_{t\text{-}G}$). The documented simulation cases with the characteristic interface and GMB properties are summarized in Table 2.

Table 2. Case studies (other parameters are according to Table 1).

Simulation case	**Variation**
H1	$\sigma_{t\text{-}G}$ = 15 MPa , $\phi_{Int\text{-}H\text{-}G} = \phi_{Int\text{-}G\text{-}U}$ = 20°
H2	$\sigma_{t\text{-}G}$ = 3 MPa, $\phi_{Int\text{-}H\text{-}G} = \phi_{Int\text{-}G\text{-}U}$ = 20°

3 RESULTS AND DISCUSSION

The presented results focus on the mechanical behavior and failure state of the GMB and its attached interfaces. Figure 2 shows the failed sections of the GMB and the occurring slip at the interfaces. In case H1 (Fig. 2a) a friction angle of 20° leads to some slip events in the interfaces at the left and right end below the heap. The normal stress on the interfaces in these areas is not high enough to prevent slip. These slip events have negligible influence on the creep behavior of the residual salt heap and no failure of the GMB occurs.

When reducing $\sigma_{t\text{-}G}$ to 3 MPa (Fig. 2b) several sections of the GMB fail. According to model H1, the load and creep behavior of the heap generates similar stresses inside the GMB. Differing from model H1, the weight of the heap and its deformation now generate axial loading on the GMB, which exceed the yield criterion defined by $\sigma_{t\text{-}G}$. Interface states show similar pattern as in case H2.

The resulting axial forces and axial strains inside the GMB, due to the loading and creep deformation of the residual salt heap, are also given in Figure 2. Blue bars showing in upwards direction and red bars pointing downwards, respectively, represent tensile forces and tensile deformations. Figure 2 shows the maximum values for tensile strain and force.

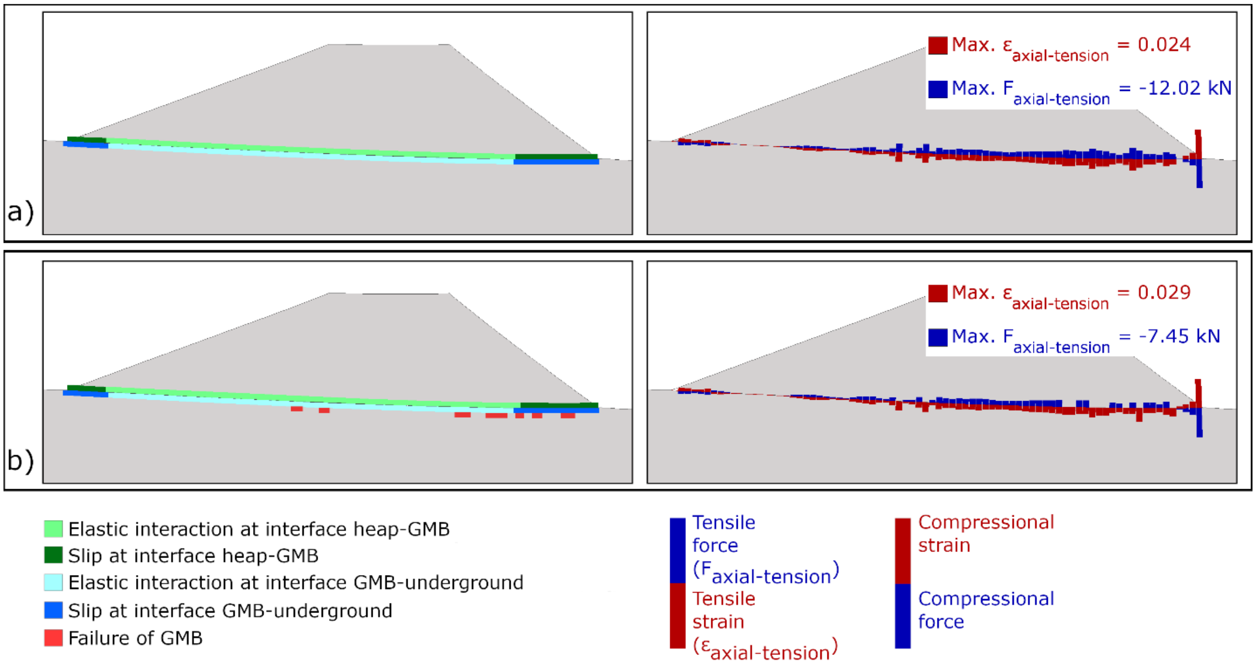

Figure 2. State of interface interaction and failure sections of the GMB as well as distribution of axial strain and force inside the GMB for a) H1 and b) H2.

For model H1 (Fig. 2a) a maximum tensile force F_{axial} of about 12.02 kN is developed after a lifetime of 30 years. This equals an axial tensile stress of about 4.81 MPa. The axial deformation ε_{axial} develops similar to the axial force with a maximum strain of about 2.4 %. In the areas at the left and right end of the heap a slight uplift (arching) of the underground is observed which results in some local compressional forces and deformations. This is visualized by the upwards pointing red bars representing compressive strains and by blue bars with downwards direction for compressive forces. Due to the slope inclination of underground the deformations and forces are the highest beneath the right end of the heap. Axial tensile stresses and deformations in the GMB are lower than the limit values according to BAM 2014.

The distribution of F_{axial} and ε_{axial} for model H2 is given in Figure 2b. Nearly the same characteristics as for model H1 are noticed. However, there are sections where the GMB is not able to carry axial tensile load. The bars of F_{axial} are vanishing at the failed sections (compare Fig. 2b failure areas and tensile force). Axial tensile deformation is the highest within these sections. The beam-segment is torn in the failed areas showing plastic material behavior without influencing the intact beam-segments. The remaining maximum tensile force F_{axial} inside the intact GMB segments is about 7.45 kN which equals an axial stress of about 2.98 MPa. This value correlates with the tensile strength of the GMB ($\sigma_{t\text{-}G}$ = 3 MPa) and indicates that the next segment is going to fail in the near future. Maximum tensile strain ε_{axial} is about 2.9 %.

4 SUMMARY

This feasibility study documents that the deformation and potential failure behavior of a GMB beneath a large residual salt heap can be investigated in a suitable manner with 2D models. Different constellations in respect to GMB properties can either show an intact GMB behavior (see H1) or cause local failure under assumption of reduced tensile strength (see H2). The simulations are able to detect individual sections of GMB failure and allow evaluating each individual part of the system $Int_{H\text{-}G}$ - GMB - $Int_{G\text{-}U}$.

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