Development of comprehensive 3D-models for geomechanical stability proof of the operation phase and the planned radioactive waste retrieval in the Asse II mine

Wolf-Peter Kamlot[1], Johannes Kupper[1], Ralf-Michael Günther[1], Grit Gärtner[2], Frank Manthee[2]*

[1]Institute for Geomechanics GmbH (IfG), Germany; [2]Federal Company for Radioactive Waste Disposal (BGE), Germany

* *peter.kamlot@ifg-leipzig.de*

ABSTRACT: The Asse II mine is an over 100 years old salt mine in a steep inclining structure of a salt ridge in which radioactive waste was embedded from 1967 to 1978. Due to instability in a long-term sense, fracturing in the pillars and overhand stopes took place and a brine inflow has been observed since 1988. Considering the Atomic Energy Act (Lex Asse) the mine shall be closed after complete retrieval of all radioactive waste. IfG Leipzig is charged by the BGE, which is the operator of the mine, to give geomechanical expertise. This is mainly done by means of geomechanical modelling. In this article, a three-dimensional model using FLAC3D is presented that focuses on global and local assessment. Selected calculation results on stress development in the mining system and on barrier integrity are given confirming the feasibility of one particular retrieval method at the complicated geomechanical conditions.

1 Introduction

The Asse II mine in Lower Saxony, nearby Brunswick, Germany has experienced a long and varying history. First, it was a commercial salt extraction mine. Then, low-level and intermediate-level radioactive waste was emplaced. After all, comprehensive R&D projects aiming at final disposal of radioactive waste in salt formations took place. Currently, the mine is prepared for closure. Since 2009, the mine is under Atomic Law. The Federal Company for Radioactive Waste Disposal (BGE) is in charge as operator. According to the Atomic Energy Act (§ 57b AtG “Lex Asse”) the mine shall be closed after complete retrieval of all radioactive waste, but only if the geomechanical and radiation conditions allow a safe removal and no brine inflow escalation takes place. Following current plans, the retrieval will start in about 2033 and will last several decades. Facing the geomechanical stability problems and on account of the permanent risk of brine inflow escalation, all abandoned openings (drifts, blind shafts and infrastructure rooms) and still open gaps in the backfilled chambers have to be filled using a special Sorel concrete (for more information see Kamlot et al. 2012). IfG Leipzig has developed different modelling concepts and material laws to reproduce and understand the geomechanical processes as revealed by mine surveying (details in Kamlot et al. 2007, 2015, 2018). The bearing elements are mainly characterized by post-failure behavior. They sustain the overburden load with a residual strength only, but under the backfill support. Therefore, it was fundamental to simulate softening (rupturing), dilatancy and creep using a visco-elasto-plastic constitutive law. The IfG Leipzig is charged by the BGE to give geomechanical expertise for the further operation of the mine until retrieval. This article comprises the latest state of model-development by IfG and presents a FLAC3D-model of the whole mine in which for grid generation modern meshing tools were used. Selected calculation results on stress and integrity development validate the feasibility of one particular retrieval method in principle and deliver the basis for the further planning steps.

2 Geology of the Asse ridge

The Asse II mine is situated in an 8 km long ridge, striking from NW to SE. The geology of the Asse ridge is portrayed in Figure 1. The saliniferous layers are visible in the center of the figure, which predominantly comprise rock salt of the Stassfurt, Leine and Aller Formation (blue, violet-blue and cyan color). The carnallitite seam is located in the saliniferous layers of the Stassfurt series (rose color). Between the layers of the Leine and Aller series there is the red salt clay (pink color).

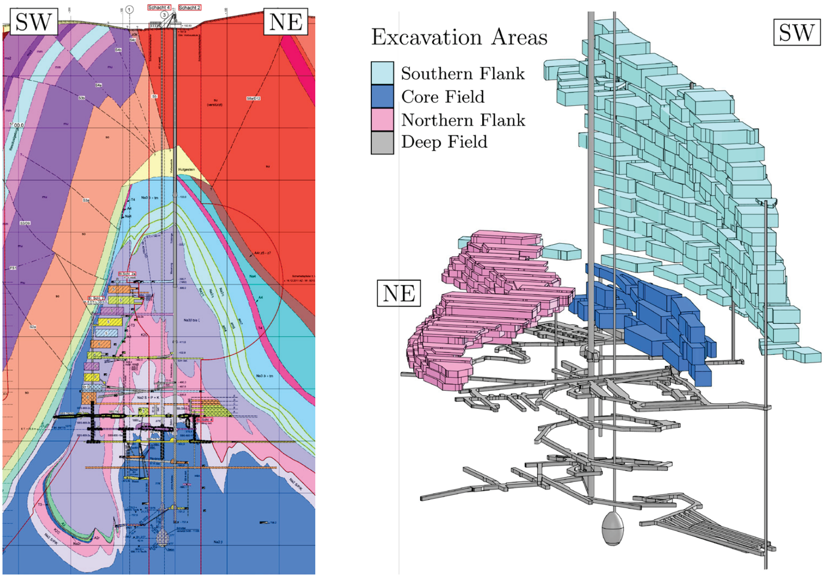

Figure 1: Cross section through the salt ridge in the middle of the NW-SE extension (left) and main mining fields in the Asse II mine (right)

The overburden rocks consist of Triassic Buntsandstein, Muschelkalk and Keuper rocks, followed by Jurassic and Cretaceous rocks. The overburden rocks at the northern edge are older than those at the southern edge. On top of the salt ridge there is a caprock (yellow color).

Due to the close distance of the openings in the upper part of the mine to the overburden (Fig. 1) and the long operation time without backfilling, a loss of integrity of the rock salt barrier to the southern overburden took place. An inflow of brine from the overlaying layers, which are separated tectonically, was first observed in 1988 and is now in the order of 13 m³ per day. The brine is saturated with NaCl and $CaSO_4$, but not with $MgCl_2$. It must be emphasized that the geologic model of the Zechstein and overburden rocks is examined and revised currently.

3 Mining fields and research areas in the Asse II mine

The Asse II mine consists of three mining areas. The first mining area excavated is the carnallitite field at the northern edge of the salt ridge in the Stassfurt series. The excavation of this field took place from 1909 to 1925. This field comprises 25 panels with different lengths across the strike reaching from ca. 40 m to ca. 120 m. The typical width of a panel amounts to ca. 20 m and the pillar between two panels has a width of ca. 10 m. The maximum heights of the panels amounts to ca. 40 m. This field covers a depth between 750 m and ca. 708 m. The volume of the entire field amounts to ca. 1,000,000 m³. Around 99 % of this volume is backfilled with residues from the factory processing of salt.

The second mining area is positioned at the southern flank. It was excavated in the rock salt of the Leine Formation from 1916 to 1964. The southern flank represents a room and pillar system with 13 levels on top of each other and generally 9 rows of rooms per level. The lowest level is located in a depth of 750 m. The depth of the highest level amounts to 490 m. The typical room length in strike direction reaches 60 m and the width across the strike is 30 m to 40 m. The pillars between two adjacent rooms have widths of ca. 12 m (except for the pillar between the mining rows 4 and 5 with a thickness of ca. 20 m). The overhand stopes between the levels are ca. 6 m thick. The typical height of a room amounts to ca. 15 m. The rooms at the level of 750 m pose a height of ca. 10 m. The volume of the whole field amounts to ca. 3,350,000 m³. The chambers were, after decades of free convergence, partially backfilled during the R&D phase from excavation of single drifts and in a backfilling campaign using pneumatic transportation of granular salt from 1995 to 2004. Today, about 93% of the volume is backfilled (including Sorel concrete in the open gaps above the settled backfill bodies).

A smaller rock salt area was excavated in the center of the salt ridge in the Stassfurt series between 1927 and 1964. This field has also a room and pillar structure with three levels reaching from depths of ca. 775 m to ca. 725 m with a volume of only ca. 450,000 m³. Today, ca. 89% of the volume contains pneumatically backfilled crushed salt and Sorel concrete.

Single drifts and a cavern were excavated below the 800-m-level for research reasons between 1984 and 1992. These excavations belong to the deep field with a volume of ca. 240,000 m³. About 72 % of this volume was backfilled up to today. The excavation structure of the mine is illustrated in Figure 1. Drifts above the 800-m-level used for entrance to the openings are not depicted to maintain clarity.

Low- and intermediate-level radioactive waste is embedded in chambers of the southern flank at 750-m- and 511-m-level and in chambers of the center field at 750-m- and 725-m-level.

4 Comprehensive 3D-model of the Asse II mine

4.1 Model description

The calculation model described in the following represents a significant advancement of the model used for the geomechanical stability proof and forecast of the further operation phase in Kamlot et al. 2018. The model in 2018 covered only the western part of the mine. The shape of the chambers and the geological structure had to be idealized because of limitations of the numerical tools. Nowadays, modern tools are available and using the progress in hardware the complete mine could be reproduced in agreement with the mine map. However, an abstraction of the stratigraphy remains necessary furthermore. This is acceptable because the main focus aims at the interaction of the large openings in the mining system.

In the model in Figure 2, the overburden rocks are divided into layers of Rötanhydrit, Buntsandstein, Muschelkalk, Keuper, Jurassic and Cretaceous rocks. Additionally, the caprock is included. The saliniferous layers are divided into rock salt, carnallitite and red salt clay. A sub-saliniferous layer exists in the underground. Anhydrite accessories inside the saliniferous layers are not incorporated. The rock salt layers are not distinguished between different stratigraphic sequences of the Stassfurt, Leine and Aller series. Following the requirements of BGE a more detailed stratigraphy can be integrated, if necessary, for evaluation purposes.

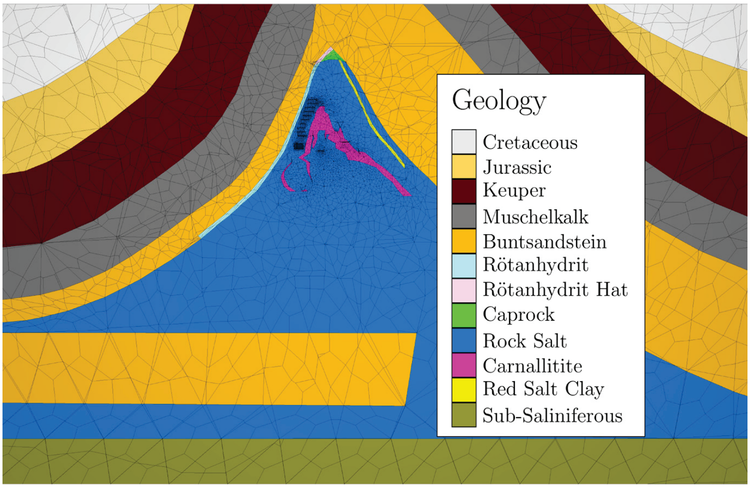

Figure 2: Geological abstraction of the 3D-model

The geomechanical behavior of the overburden rocks is described by an elasto-plastic constitutive law known as Hoek-Brown-Model (Itasca 2017). For the saliniferous layers a visco-elasto-plastic constitutive law, developed by IfG, is used (Günther & Salzer 2007). The backfill from crushed salt is simulated with a Double-Yield-Model (Itasca 2017). In regions backfilled with Sorel concrete an own visco-elasto-plastic material law (Minkley & Mühlbauer 2007) was applied.

The model size is quite large in comparison to the dimensions of the mine. The model dimensions are 6.3 km in across strike direction, 1.6 km in strike direction and 2.5 km in vertical direction (see Figure 3). The model consists of ca. 3.2 million elements. The basic stress state was determined by initializing each element with gravitational forces and solving for equilibrium state subsequently.

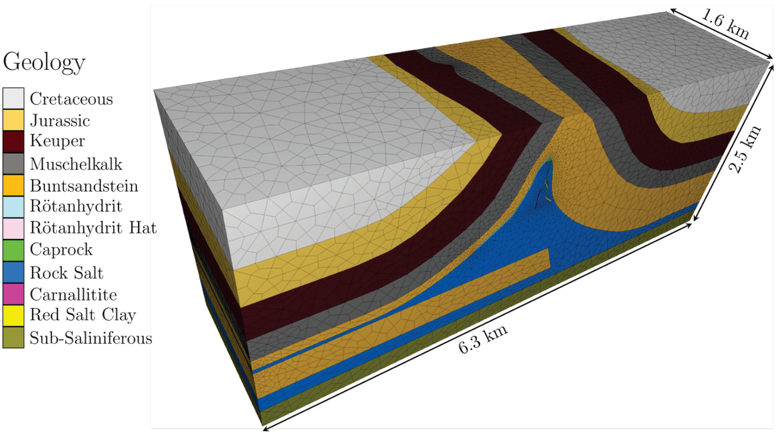

Figure 3: Dimensions of the comprehensive FLAC3D-model

The algorithm of Fast Lagrangian Analysis of Continua in 3D (FLAC3D) was used (Itasca 2017) which is a three-dimensional explicit difference element program. The large model dimensions were necessary to avoid any influence from the boundary conditions. Furthermore, the exaggerated size allows stress redistribution between the southern flank and the overburden rocks which has to be expected because of the high order of excavation. The vertical boundaries and the basis are fixed perpendicular to the edge, and the top is free.

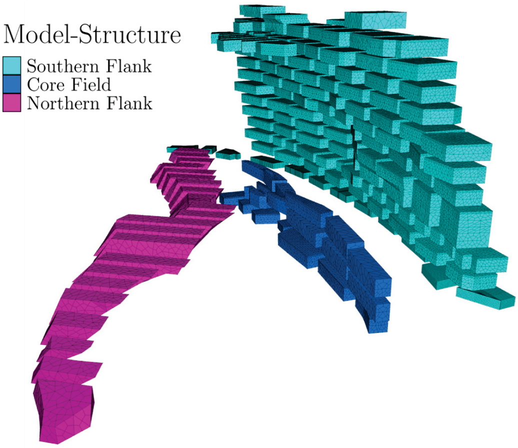

Figure 4: Structure of the three mining fields in the model

The two rock salt mining fields at the southern flank (light blue) and in the centre of the mine (dark blue) are portrayed in Figure 4. The carnallitite field has the magenta color. The model comprises the large rooms and separating pillars only. Excavations below the 775-m-level and all drifts are not part of the model. These simplifications have to be made for getting a compromise between details and calculation time. They are regarded as acceptable because the geomechanical behavior of the mine is governed by the mining fields due to their large excavation volume. On the other hand, the depicted mesh represents a basic discretization for calculation of the primary stress state and the mining history until the present. As already outlined for geology, in dependence on geomechanical questions of the operation phase or focusing on the retrieval process, a finer discretized mesh with drifts can be incorporated in special areas. For such a mesh transformation, the so far calculated stresses, deformations and damages can be transferred into the finer grid (see chapter 4.3).

Similar experiences and a procedure using extended 3D-models of the Asse II mine are described in Lux et al. 2018. A numerical toolkit was developed for increasing the degree of refinement in several phases aiming at calculation of geomechanical behavior (total and local).

4.2 Modelling course

After reaching the primary stress state, the mining history and the backfilling with crushed salt were simulated on basis of the recorded time scales. Recognizing the use of a visco-elasto-plastic material law, it was essential to manage the room excavation and the backfilling gently in many single steps. While calculation, strong disturbances of the equilibrium state in the model have to be restricted (more information about the explicit calculation scheme in Itasca 2017).

In the course of temporal simulation of the mining activities inclusive backfilling it is vital to compare the calculation results at significant locations (e.g. pillar deformation rates) with mine surveying. Only after confirming the correctness of the calculated deformations, stresses and particularly damaging processes the calculation can be continued. If not, calibrations (mainly in material behavior or in time scale of changing boundary conditions) are necessary. This statement has a special meaning in case of geomechanical prediction for a limited time period under the prerequisite of unchanged system conditions. As outlined above, geomechanical stability of one particular retrieval method has to be evaluated, and the simulated start shall be in 2035.

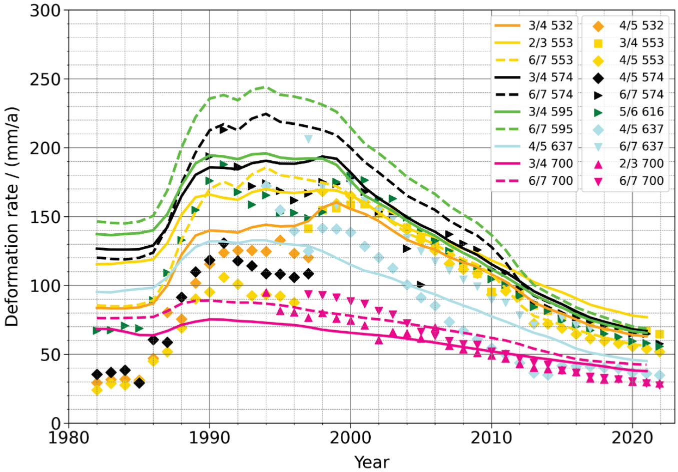

Figure 5: Course of the pillar deformation rates at the southern flank (modeled values with lines, measured values with symbols)

The most important result of mine surveying regarding model verification is the observation of the pillar deformation rates at the southern flank. The pillars are compressed in a horizontal direction as a consequence of the overburden load. As it can be seen in Figure 5, the model describes these deformation rates in general (regarding the tendency and the scattering) very good. The deformation rates increased considerably in the late 80's because of strain-softening processes in pillars and fragmentation in stopes. In the mid 90's, the peak was exceeded and the deformation rates fell down. From 1995 to 2004, the pneumatic backfilling campaign generated increasing reinforcement pressure stabilizing the mining system. Since 2009, the backfilling of small gaps between backfill bodies and chamber roofs with Sorel concrete is been leading to a rate drop down in model and reality. In conclusion, the model is in good agreement with the in-situ measurements and the use for simulation and evaluation of the radioactive waste retrieval is justified.

4.3 Different model meshing in relation to problem formulation

Different degrees of abstraction were used in the modelling course. These models distinguish from each other referring to the model mesh. For solving the primary stress state and modelling the mining activities until 1956, a model with ca. 2.2 million elements was used. For the period from 1956 to 2020, a model with 3.2 million elements came in use. The two models consist of non-structured hexahedral meshes, but the model with 3.2 million elements has a finer mesh in the vicinity of the excavations. A special subroutine was created to transfer all calculated magnitudes (state of stress, deformation and damaging) from the coarser mesh to the finer one. Considering the element midpoints, a mesh related interpolation of the physical field quantities takes place and after reaching a new equilibrium state the modelling course can proceed.

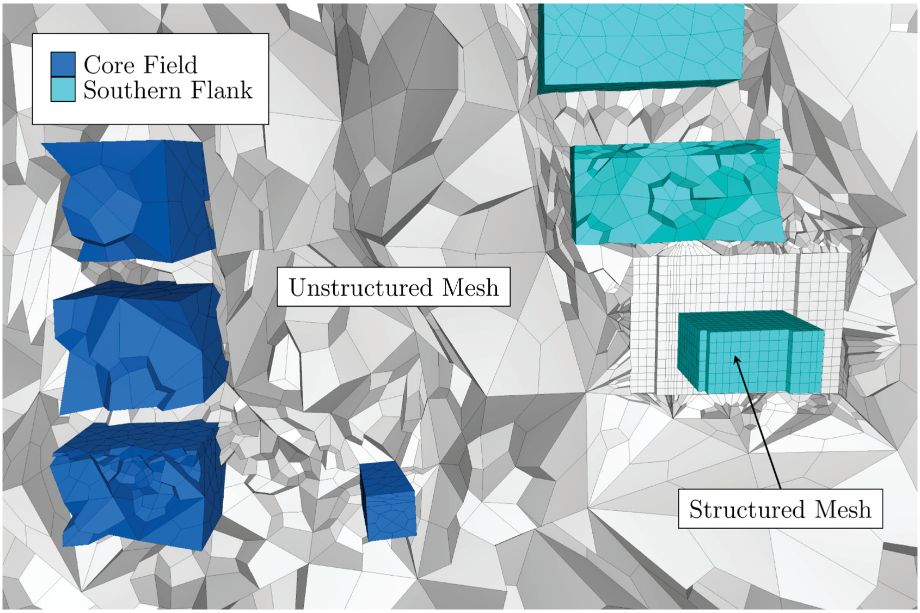

Figure 6: Structured and unstructured hexahedral meshes stitched together

For modelling the retrieval of the radioactive waste, the development of a third model was necessary. The mesh of this model consists of ca. 1.8 million elements. It is composed of two different meshes, one unstructured hexahedral and one structured hexahedral mesh (see Figure 6). The simulation of tunneling with a rectangular shield was only possible within the structured mesh. The two meshes were stitched together by use of special 3D meshing techniques.

5 Retrieval of radioactive waste by use of modified shields

5.1 Description of the procedure of re-excavation

In the study “Alber Geomechanik, IfG Leipzig 2019” the impact of a special retrieval method using shields on stability in the mining system and on integrity of the halite barrier to the overburden was investigated and the feasibility could be confirmed in general. To demonstrate the performance capability of the comprehensive 3D-model, the retrieval sequences shall be reproduced in the following. The description of the process, the technical parameters of the shields and the time schedule of the measure are given in the study. The most radioactive waste chambers are located in the southern flank at the 750-m-level and could be re-excavated in strike direction (see Figure 7).

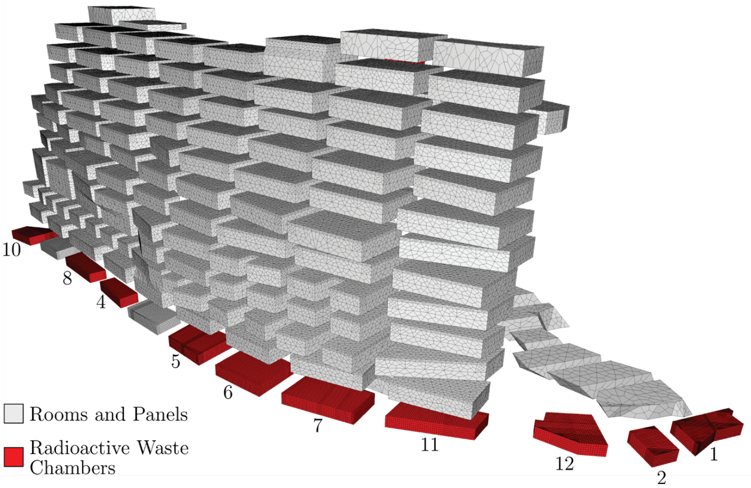

Figure 7: Locations of the radioactive waste chambers at the 750-m-level of the southern flank

In this variant, altogether seven modified excavation shields are set up one after the other in waste-chamber 1. This chamber is previously re-excavated with another retrieval method. After assembling, shield number 1 starts excavation in direction of waste-chamber 2. In the trace of the shield, the pillar between has to be mined as well.

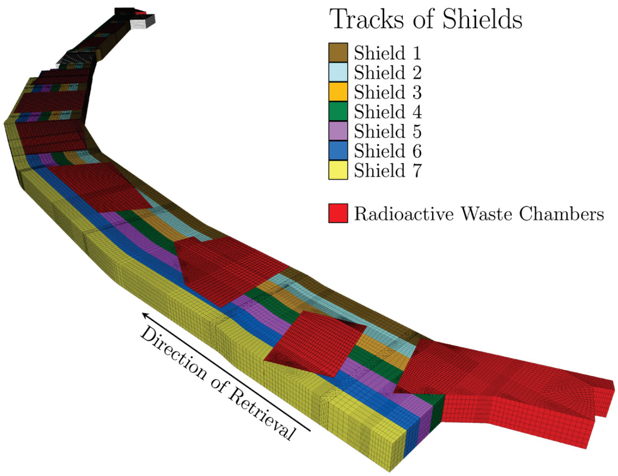

Figure 8: Tracks of excavation shields

After shield 1 has left the pillar between the two chambers, shield number 2 is going to start excavation alongside of the track of shield 1. Afterwards, shields 3 to 7 start excavation in such a way that the tracks of all shields together cover the width of the chambers across the strike. The shields numbers 1 to number 4 continue re-excavation until reaching the last chamber 10 at the edge of the mining field. Contrary to this, the shields number 5 to 7 will be stopped after re-excavating chamber 5. That can be done because the width across the strike of the chambers in western direction amounts only to ca. 20 m and is covered by shields number 1 to 4 (see Figure 8). The width of one shield was drafted in the study by 6 m. After retrieval, the tunnel of each shield is filled by Sorel concrete, but tubes have to be constructed inside for transport and infrastructure reasons.

5.2 Modelling results and assessment

5.2.1 Stress redistribution in a chamber during retrieval of radioactive waste

While re-excavating a chamber the model reveals that the compaction pressure of the backfill body in the whole chamber decreases very quickly after entrance of shield 1 (see Figure 9, compressive stresses positive).

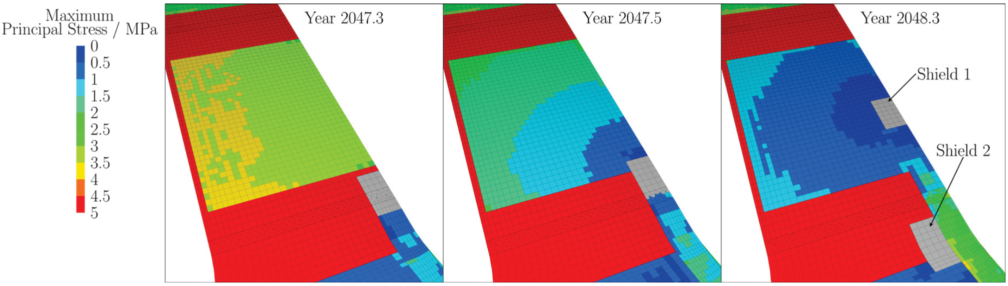

Figure 9: Stress redistribution in chamber 6 during retrieval of radioactive waste

This is a geomechanically important result and has to be regarded in the further planning phases. Due to the reduction of support generated by the backfill, fracturing processes in the stopes above the chambers could be activated.

5.2.2 Evaluation of pillar stability

Figure 10 presents the distribution of maximum principal stress in the pillar between chamber 6 and 7 for two different time points (compressive stresses are positive). At the top of the figure, the corresponding time is year 2035 before start of retrieval. At the bottom of the figure, the corresponding time is year 2048.3 after shield 1 has left the pillar and shield 2 is now pushing his track through this pillar. The comparison of the two stress fields reveals that stress redistributions have taken place. Especially above the excavated and backfilled track of shield 1, stress concentrations have evolved. Within the backfilled Sorel concrete, the compressive stress is still very low. Fortunately, significant strain softening processes were not produced in the model. Therefore, there are no hints of stability problems in the modelled pillar until to this time point. The tracks of the shields are sketched for clarity reasons.

5.2.3 Evaluation of barrier integrity

The evolution of the minimum principal stress at the top of the southern flank for a depth of 451 m nearby row number 3 (at the western part of the flank) is illustrated in Figure 11. As visible, the minimum principal stress begins to rise in the time interval before 2030 when the Sorel concrete filling of the open gaps between backfill and roof in several openings of rows 2 and 4 was simulated. Before, the stress development was characterized by stress interactions in the mining system. There can be stated the most important conclusion, that the retrieval which is in progress since 2035 does not impair this trend of stress increase.

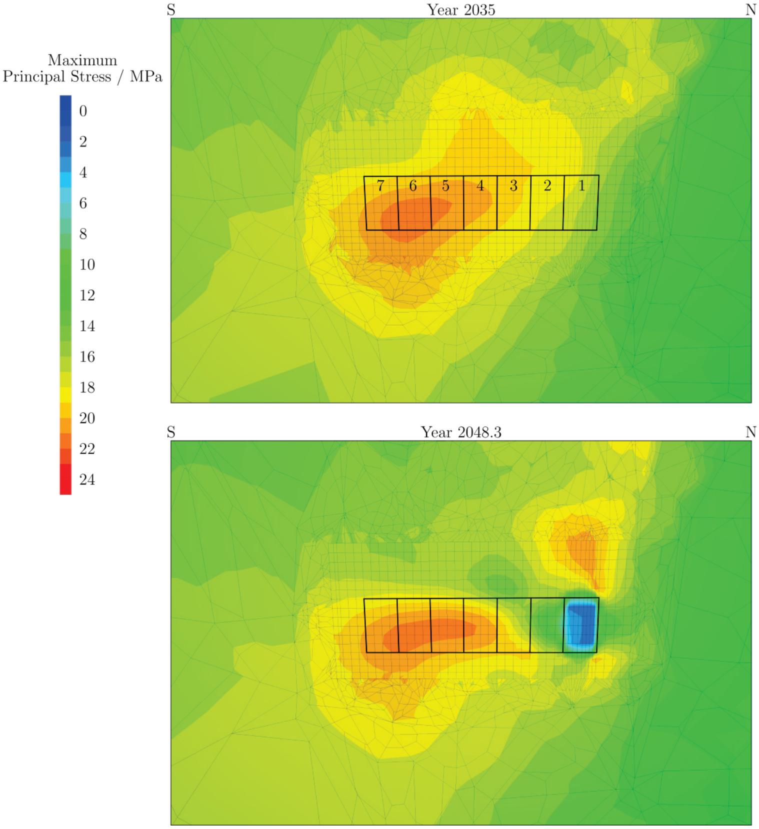

Figure 10: Maximum principal stress in a vertical cut-plane through the pillar between chamber 6 and 7 for two time moments year 2035 and year 2048.3

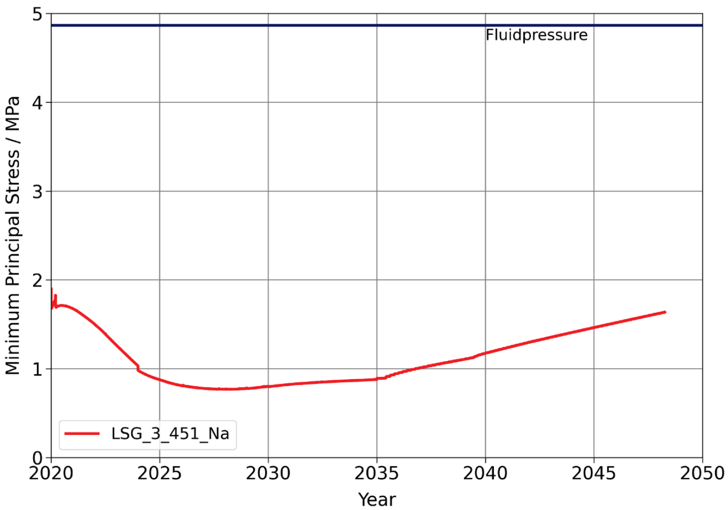

Figure 11: Evolution of minimum principal stress at a depth of 451 m nearby row number 3 of the southern flank

But, for the entire time plotted in Figure 11 the potential fluid pressure, calculated on basis of brine column, exceeds the minimum principal stress. The risk of brine inflow escalation remains present all the time.

Figure 12 presents the development of the maximum and minimum principal stress in the depth of the radioactive waste chambers at two points in the halite barrier 15 m in southern direction of the chamber 6 and the pillar to chamber 7. In the near field, a remarkable influence of the re-excavation can be seen, but the potential fluid pressure does not exceed the minimum principal stress.

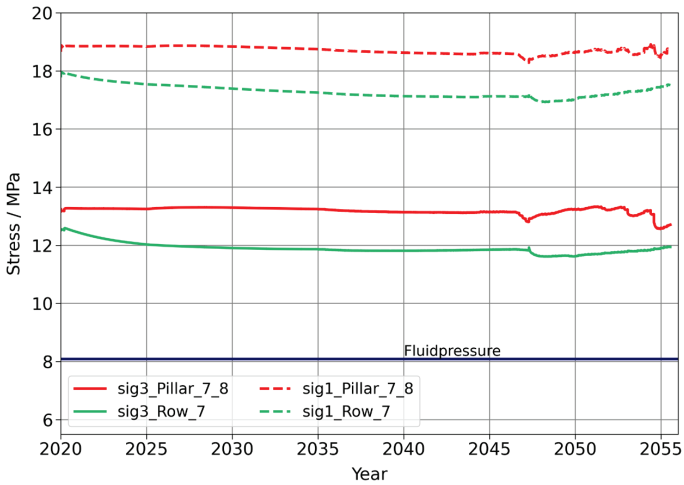

Figure 12: Evolution of maximum and minimum principal stress at a depth of 750 m nearby row number 7 (radioactive waste chamber 6)

6 Summary

IfG Leipzig is involved for about 25 years in giving geomechanical expertise for the Asse II mine. For that, different modelling concepts and material laws have been developed to reproduce and understand the geomechanical processes as shown by mine surveying. In the article, as latest state of model-development, a comprehensive FLAC3D-model of the whole mine is presented. Modern meshing tools for the grid generation were used and a procedure for transmission of calculated magnitudes between grids of different discretization was written. The calculation results until the present are in agreement with the mine surveying. To demonstrate the performance capability of the model, the retrieval sequences of a special method using rectangular mining shields are re-evaluated.

It was found, that the unloading of the backfill while re-excavation has a crucial impact on the roof support of the chambers. Regarding pillar stability, no significant strain softening takes place. The course of re-excavation is slow enough that the backfilled Sorel concrete can harden and is able to bear rock loads again. The geomechanically positive increase of the minimal principal stress in the top of the halite barrier is not impaired by the retrieval. But, the risk of brine inflow escalation remains present all the time. The simulated retrieval method is evaluated as feasible in general. The further planning phases pursue other technical concepts, but the minimal invasive philosophy, which means stepwise re-excavation and fast support, remains valid as well.

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