Support Structures for Potential German Repository in Claystone and their Design by THM-Modelling – Paper 23296

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ABSTRACT
Claystone as potential host rock for radioactive waste repositories offers low permeability, high sorption capacity, and, in a certain way, self-sealing capacities. However, the mid to low strength and the complex hydro-mechanical material behavior place high demands on the excavation techniques and the support structures. A regular support structure is essential in order to guarantee stability of the galleries and, thus, operational safety. Further requirements can be deduced from long-term safety stipulations and the from the regulatory framework. For example, retrievability is a design criterion stipulated by German law. As a result, a unique and complex set of requirements will influence the design of the support systems for a future German repository in claystone. BGE TECHNOLOGY GmbH takes into account different directions when developing suitable support structures. On the one hand, numerical parametric studies have been performed to determine the most promising support structures in various geo-mechanical conditions. On the other hand, advanced hydro-mechanical material models are being used and extended to develop a basis for the numerical analysis and performance assessment of support systems in claystone. This paper gives an insight into these activities.

INTRODUCTION
In 2017, the German site selection process was restarted. A first screening showed that approximately 55% of the German area meet the exclusion and minimum requirements stipulated by the German site selection act. Among others, claystone is one of the potential host rocks within the identified number of sub-areas. Nine sub-areas of claystone, covering an area of almost 130.000 km², have favorable geologic conditions.
In general, claystone is a sedimentary rock formed by geologic processes such as transport, deposition, and cementation. Claystone formations, considered for radioactive waste disposal, have generally been deposited in marine environments several million years ago. The source rock can be magmatic, metamorphic or other existing sedimentary rocks. Typically, the mineral composition is characterized by a high amount of clay minerals and a certain amount of other minerals such as quartz or carbonate. The geologic history in between and the diagenesis of the sediments led to the claystone that is present today. In the context of the German site selection process, a distinction is made between pre-Tertiary and Tertiary formations because of their different degrees of diagenesis. In general, Tertiary claystones, with a shorter geologic history, can be characterized by a more plastic behavior, relatively low strength, and higher natural water contents. Pre-Tertiary, and thus older, claystones typically show less plastic behavior and higher strength and stiffness. Typically, the claystone is located at great depths. Such formations are present in wide areas of northern and southern Germany (Figure 1). The claystone formations in both areas have already been considered in generic R&D studies, as well as in the development of generic repository designs (see e.g. [1] and [2]).

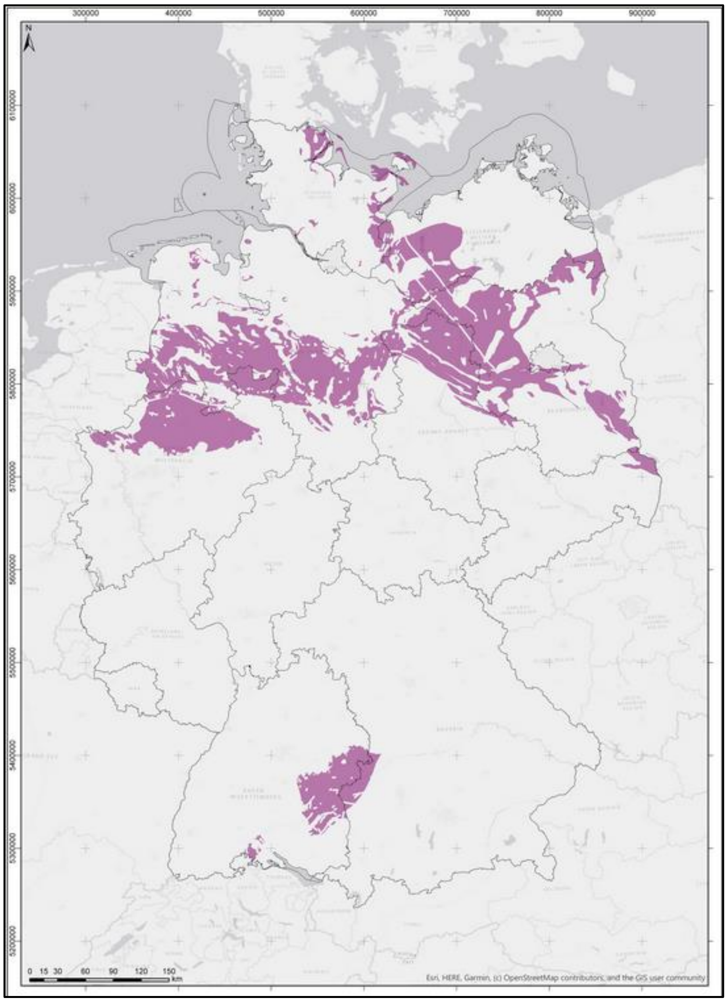

Figure 1: Overview of all sub-areas in pre-Tertiary claystone as identified by [1]

The composition of the deposits varies in both areas. The claystone in the south is thin-bedded with an average thickness of approximately 100 m. The claystone in the north is characterized by a higher thickness of up to several hundred meters. The generic repository designs consider both horizontal emplacement of self-shielding disposal waste packages (DWP) and vertical borehole disposal of unshielded DWP. In any case, the repository layout is characterized by the emplacement drifts, main drifts, and a number of intersections. Different functions and requirements are associated with the drift designs. For example, the different types of drifts are characterized by different cross-section sizes. [4] collected the basic requirements for these drifts related to:

- Regulatory framework, repository-specific, mining-related, and nuclear-related;
- Operational requirements such as cross sections, lifetime, retrievability;
- Geomechanical requirements; and
- Long-term relevant aspects such as long-term stability of construction materials and interaction between different materials.

Based on the expected geomechanical conditions and the operational requirements (e.g. main functions, workflow, timeframe, cross-section, length), suitable lining systems and materials have been identified and compared with each other. In absence of a definite site, numerical analyses of the behavior of support structures and their interactions with the host formation were carried out by adopting generic rock parameters or parameters known from comparable sites.

BASIC GEOMECHANICAL PROPERTIES

In Germany, mining activities in claystone formations relevant for repository construction were very limited in the past. Coal and iron ore mining just passed the formations, but without significant effort or attention to the claystone. Tunneling projects partly cross such formations, but at shallow depths. As a result, there is little data related to the material behavior and geotechnical conditions. Information exists for only a limited number of sites, which are irregularly distributed over the identified sub-areas. For instance, [1] collected information and defined two generic geological models as a basis for further work. [4] extended the dataset by considering comparable materials, e.g. from other claystone formations in other countries, which are also being considered as host rocks for radioactive waste disposal. Particularly, the Callovo-Oxfordian (COx) claystone formation in France exhibits similar mechanical behavior as claystone formations in northern Germany. On the other hand, the Opalinus clay in Switzerland shows similar characteristics as pre-Tertiary claystones in southern Germany. In any case, it is important to stress that mineralogical compositions and geo-mechanical properties can vary significantly over distance and therefore, the adopted parameters are only valid for preliminary designs.

The information available was used to define a range of potential geo-mechanical properties. Within this range, parametric studies were performed to identify suitable support structure concepts for different geomechanical conditions. Based on [4], the following general conditions and geo-mechanical properties were considered:

- a potential depth between 500 m and 1,000 m below ground surface is assumed for the future repository (available data includes shallow depths);
- average density of about 2.4 g/cm^3;
- porosity varies between 5 % to 20 % (decreases with depth);
- water content varies between 5 % to 10 % (shows a weak correlation with depth);
- uniaxial compressive strength varies between 10 MPa to 35 MPa;
- cohesion varies between 1 MPa to 6 MPa;
- internal friction angle varies between 15° to 35°;
- peak strength, as well as residual strength, increases with decreasing water content;
- young modulus varies between 2 GPa to 18 GPa (increases with depth); and
- poisson ratio is approximately 0.26.

In general, mechanical parameters tend to improve with increasing depth. However, the latter is offset by the fact that rock pressures also increase with depth, thus increasing the loads that act on the support system. In this context, the parametric analyses performed provide relevant insights into the behavior of different support structures, under different geomechanical conditions, to identify the optimal design configuration for the future repository.

IDENTIFICATION OF SUITABLE SUPPORT STRUCTURES

[4] performed a detailed numerical parametric analysis that compares the results from assuming different geomechanical properties and different support structures. First, the effect of different cross-sections was analyzed. For instance, Figure 2 shows the expected degree of damage, in terms of contours of equivalent plastic strain, around drifts with different cross-sections and different support structures under the same geomechanical setting.

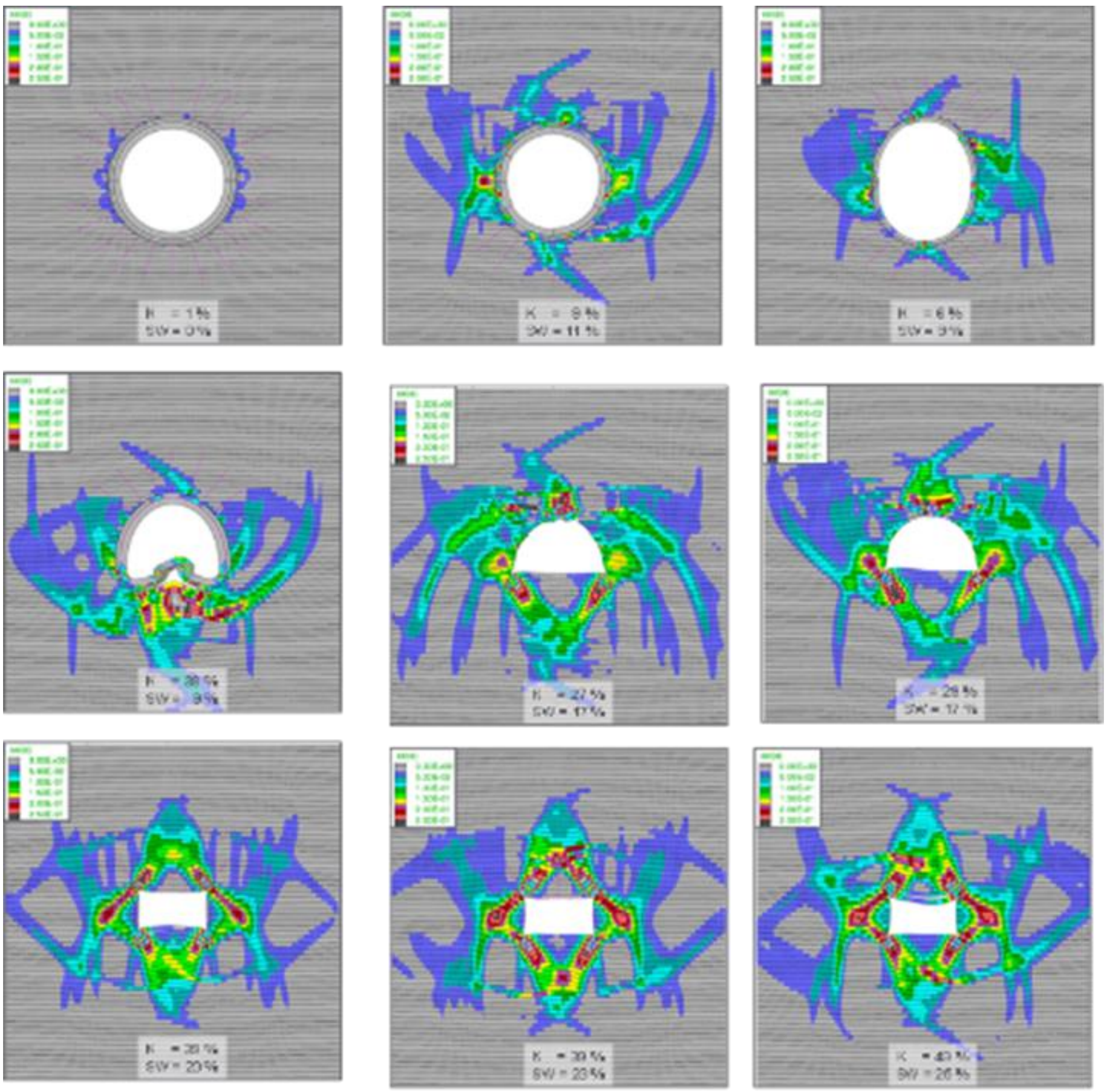

Figure 2: Damage around drifts with different cross-sections and different support structures, in terms of contours of equivalent plastic strains, under similar geomechanical conditions (1,000 m depth and 15 MPa.

As expected, circular or elliptic cross-sections result in less damage around the drift. Arch-shaped sections, which are typical for German hard coal mining in comparable rock conditions, are only suitable in a limited range of geomechanical properties and depths. The analyses showed that the use of slender or less complex support structures is related to short-lived, small-diameter drifts and favorable geomechanical conditions. Favorable, in this context, refers to high strengths and moderate depths. Shotcrete and bolts can for instance be suitable for blind-ending drifts for horizontal disposal. In this case, an arch-shape cross-section seems adequate. However, it is assumed that the contour of the drifts is not completely closed; the floor remains open. The rock pressure will result in an uplift of the floor within a limited time. Without additional maintenance, the lifetime of such drifts is limited to between one or two years.

For long-lived, large-diameter drifts, a circular cross-section supported by a closed concrete liner has been identified as the most promising and robust solution. In this case, “long-lived” refers to operating periods of up to several decades. During this time, swelling and creep effects play an important role in the design. The detailed design of the concrete liner must be defined as a function of the claystone material behavior. Especially under creep conditions and plastic behavior, the installation of double-layered support structures and the implementation of compressible elements seem necessary.

In the mining and tunneling industry, various technical solutions on how to implement compressible elements are known. For a repository, an outer layer of compressible grout is preferred. To further investigate the required material behavior, additional numerical analyses were performed.

The constitutive model used to characterize the behavior of the host rock formation is that put forward by [5]. The model was developed within the framework of the elasto-viscoplasticity theory [6] and the plasticity creep partition approach [7], and it incorporates a number of features that are considered relevant for a satisfactory description of indurated clays, such as:

- a nonlinear yield criterion,
- strength and stiffness anisotropy,
- a non-associated flow rule,
- rate-dependency,
- strain softening,
- nonlocal regularization,
- creep deformations, and
- permeability increase with damage.

The design of the support structure considers the use of a compressible grout in the extrados to moderate the interactions between the host rock and the segmental lining system. The grout fills the gap between the rock and the lining and controls the load that can be transferred to the latter through a yielding mechanism. It allows the rock to deform more or less freely, once the yield pressure has been reached. The benefits of using a deformable lining system have been discussed by [8].

Two-dimensional (plane strain), fully coupled hydromechanical finite element analyses were performed to assess the behavior of the support system. In order to approximately account for the tridimensional nature of the problem, excavation was simulated by gradually reducing equilibrium stresses at the excavation boundary as a function of the distance between the analysis section and the excavation front. Particularly, the deconfinement curve from Seyedi et al. (2017) was adopted, shown in Figure 3. It is assumed that the support structure is installed when the excavation front is 0.5 m ahead of the analysis section (Figure 3). This installation distance of 0.5 m may represent an unrealistic scenario with respect to potential excavation technologies. Excavation will probably be done by a full-face tunnel boring machine or a road header. Both devices are several meters in length, and the liner installation occurs at a larger distance from the excavation front. However, with the installation distance assumed, higher stresses occur and, therefore, it represents a conservative assumption.

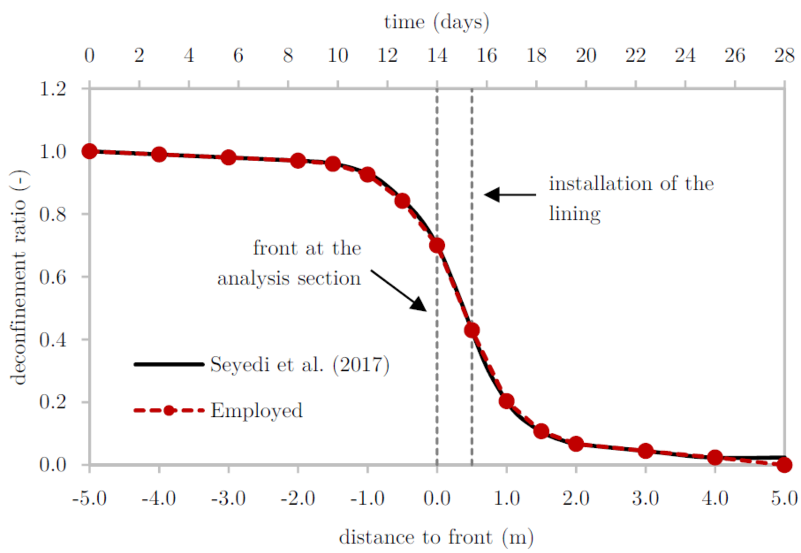

Figure 3: Deconfinement curve considered (Seyedi et al., 2017) and discretization employed in the analyses

The compressible grout was explicitly included in the simulation as 20-cm cluster adjacent to the excavation wall. The segmental lining is being simulated through a beam element and, therefore, its 40-cm thickness was considered in its stiffness properties. It is important to notice that, even with the presence of the lining system, radial stresses are still being controlled at the boundary of the host rock during deconfinement. With the front face at 0.5 m, there still exist about 40% of the equilibrium stresses. As the remaining radial stresses are reduced, the host rock deformation displaces the compressible grout, which reacts against the lining beam element, loading the latter. Therefore, this load transfer mechanism between the host rock and the lining is moderated by the compressible grout behavior.

The configuration of localized deformations, in terms of shear strains at the end of the simulation, is shown in Figure 4. Horizontal and vertical convergences are shown in Figure 5. The relatively small displacements in the lining are related to the amounts of load transferred by the rock due to the presence of the compressible grout.

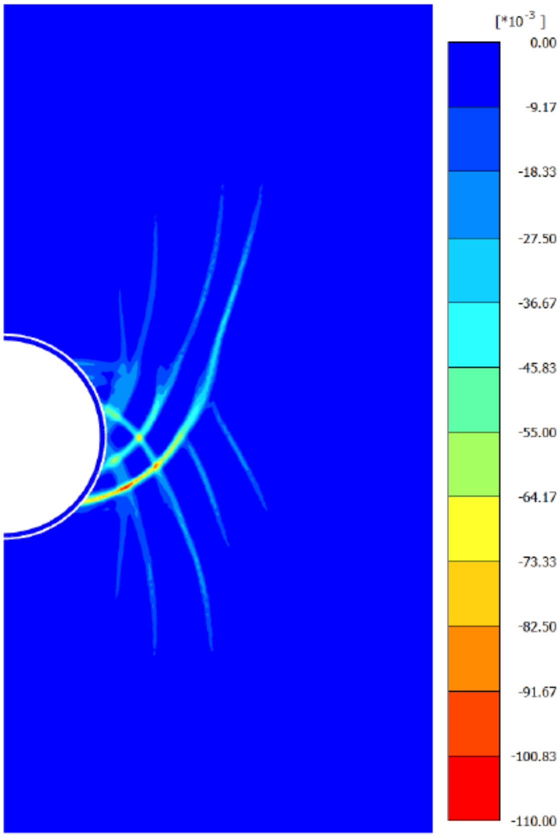

Figure 4: Contours of shear strain around the supported drift after 50 years

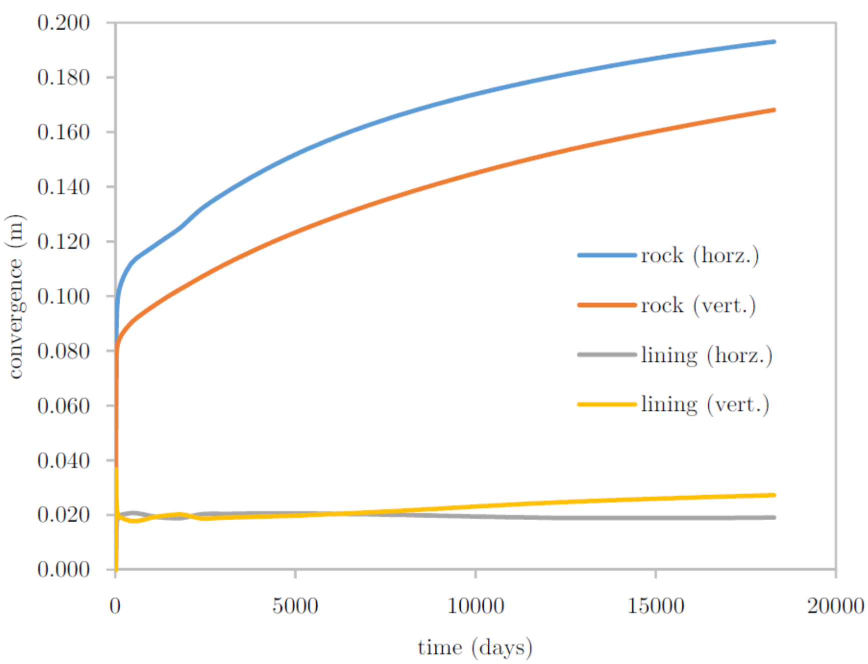

Figure 5: Horizontal and vertical convergences for the supported excavation

DIFFERENT YIELD PRESSURES OF THE COMPRESSIBLE GROUT

Although no decision has been made regarding the specific grout to be used, the behavior of the grout can likely be engineered to some extent. For instance, the yield pressure may be controlled by increasing the proportion of the binding agent in the grout mix. In this context, additional analyses were performed to assess the influence of different yield pressures of the grout on the behavior of the excavation. In the previous section, a yield pressure of p_c = 900 kPa was used. Three additional analyses were performed considering yield pressures of 1800 kPa, 3600 kPa, and an elastic behavior of the grout.

As already identified, increasing the yield pressure of the grout has beneficial effects, such as significantly reducing the deformations in the rock and the extension of the excavation damaged zone (Figure 6). The effect of the compressible grout in moderating the interactions between the rock and the lining can be observed in Figure 7, which shows the vertical and horizontal convergences in the rock and in the lining. Convergences in the rock are reduced considerably by increasing the yield pressure of the lining. However, it can be noticed that the vertical convergence in the lining increases while the horizontal convergence decreases and can even become negative, i.e. the diameter along with this direction increases with respect to the original value. Grouts with higher strengths enhance the ovalisation of the tunnel, thus decreasing convergences in the horizontal direction. This effect tends to reduce horizontal convergences in the rock. For the grout with p_c = 3600 kPa, the long-term behavior of the horizontal convergence is prevented and, for the elastic grout, the lining even pushes back the rock, which causes a negative convergence rate in the long-term. It also tends to increase the compression of the grout at the side faces of the excavation.

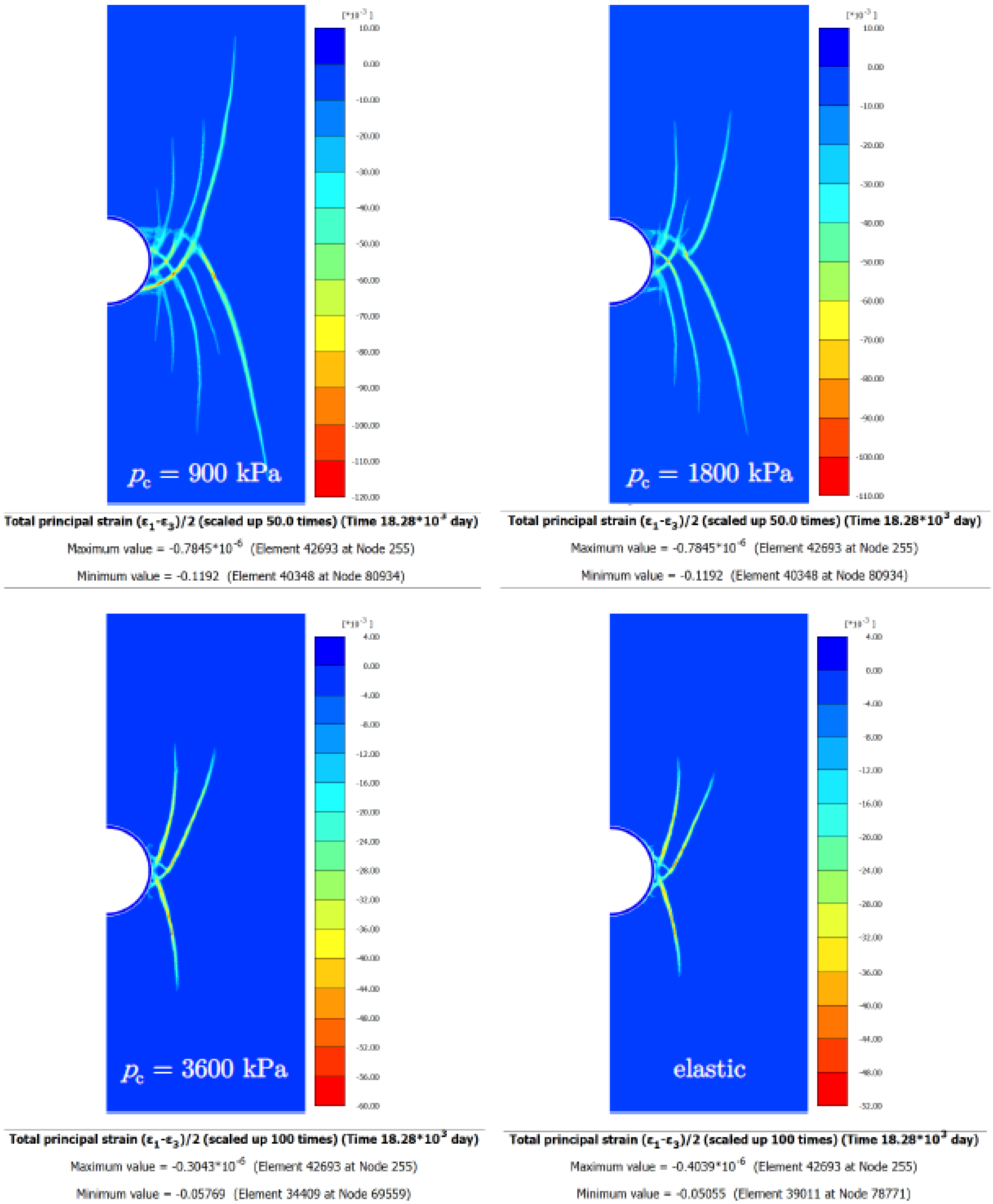

Figure 6: Contours of shear strain for the different compressible grouts

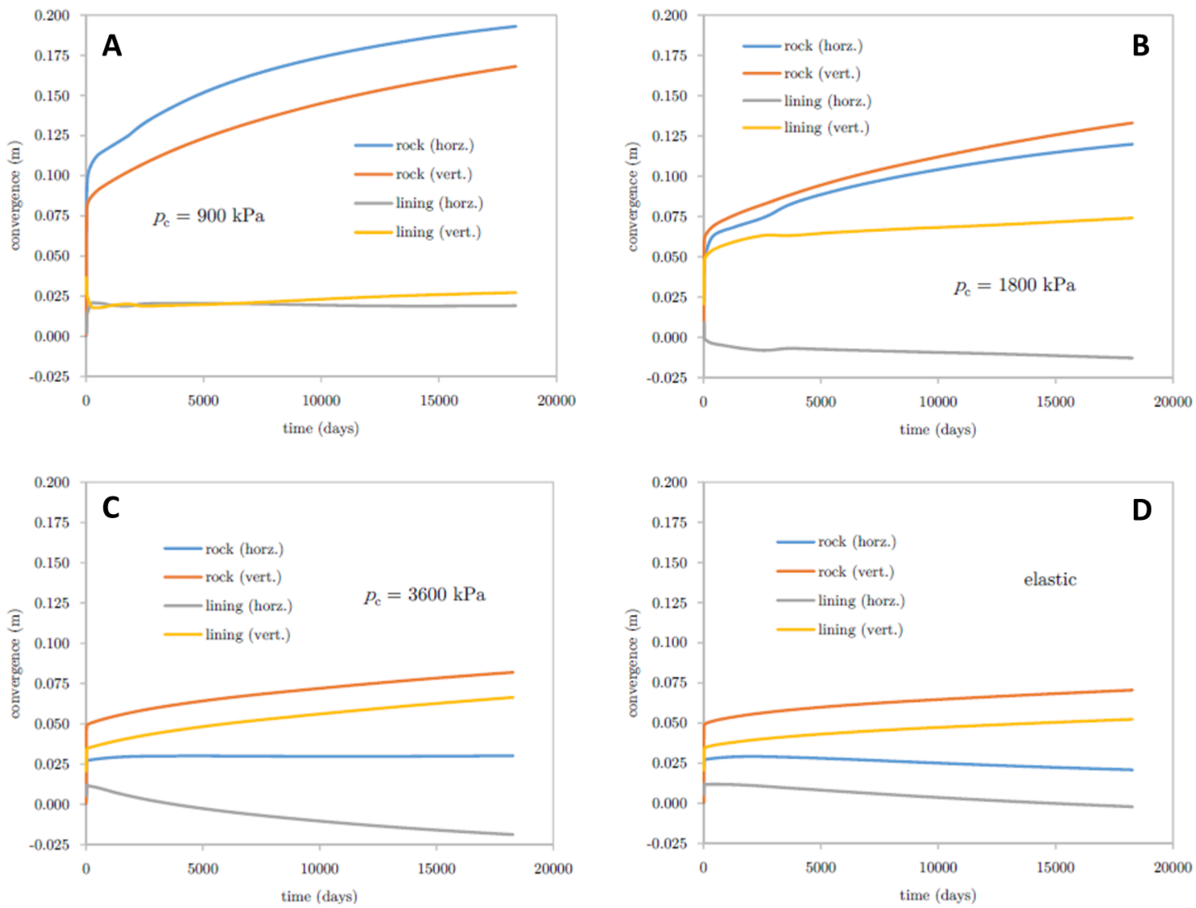

Figure 7: Horizontal and vertical convergences for the different compressible grouts considered

Figure 8a corresponds to the base case, where the behavior of the compressible grout was calibrated from an oedometer test in [9]. It can be observed that radial stresses are only slightly anisotropic, with somewhat larger values in the horizontal direction. By increasing the yield stress of the compressible grout, more interaction occurs between the host rock and the lining before yielding of the grout, increasing radial stresses during excavation. Maximum values of 3.1 MPa, 5.1 MPa, and 5.2 MPa were obtained at t = 28 days, for the analyses with pc equal to 1800 kPa and 3600 kPa and for the analysis with the elastic grout respectively. However, increases in time for the analysis with pc = 1800 kPa are comparable to the base case. This is due to the fact that yielding of the grout is achieved during excavation and, therefore, time-dependent deformations of the host rock only increase stresses according to the very low stiffness zone of the grout material. In the analysis with pc = 3600 kPa, very limited yielding is achieved during excavation and, therefore, there are more significant increases of radial stresses in time. This is also why the radial stresses of this analysis after excavation are quite similar to the analysis with the elastic grout (Figure 8d). Due to the very limited yielding, the grout basically behaves elastically during excavation. However, due to the time-dependent deformations of the rock, complete yielding of the grout eventually occurs. In result, the radial stress increases with time (Figure 8).

These results suggest that the use of the compressible grout entails finding a balance between the amount of displacement allowed in the rock, controlling the extent of the damaged zone, and the magnitude of internal forces in the lining to avoid an excessively robust and costly support system.

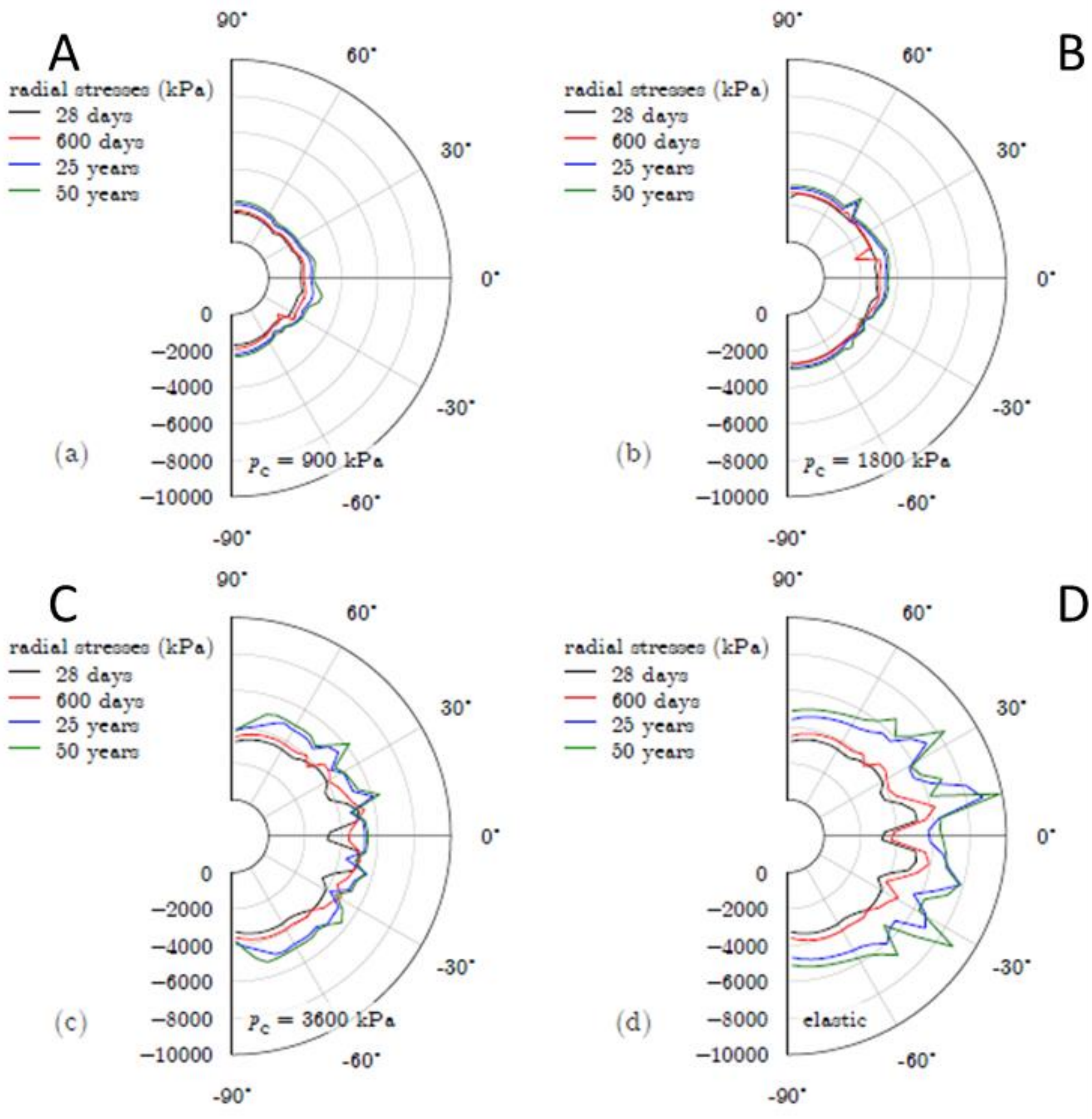

Figure 8: Radial stresses in the rock at the contact with the lining for the analyses with different yield stresses of the grout material (Manica, 2020.

SENSITIVITY ANALYSES OF CREEP PARAMETERS

A major concern regarding the design of the repository is the long-term behavior of excavations. In the constitutive model employed, this is controlled to a major degree by the creep deformation mechanism. Therefore, a sensitivity analysis of the parameters that control creep deformations was also performed. The main objective is to identify the effects of each parameter on the response of the excavation and, particularly, its consequences on the internal forces in the lining. A detailed description of the constitutive model employed can be found in [5]. However, the creep deformation component can be summarized as follows:

$$d\boldsymbol{\epsilon}^{\mathrm{c}} = \dot{\boldsymbol{\epsilon}}^{\mathrm{c}} dt \tag{1}$$

$$\dot{\boldsymbol{\epsilon}}^{\mathrm{c}} = \begin{cases} \mathbf{0} & \text{if } \epsilon_{\mathrm{eq}}^{\mathrm{p}} \leq \epsilon_{\mathrm{thr}} \\ \gamma \mathrm{e}^{\left(-m\epsilon_{eq}^{\mathrm{c}}\right)}(\boldsymbol{s} + \mu p'\mathbf{I}) & \text{if } \epsilon_{\mathrm{eq}}^{\mathrm{p}} > \epsilon_{\mathrm{thr}} \end{cases} \tag{2}$$

$$\epsilon_{\mathrm{eq}}^{\mathrm{c}} = (\boldsymbol{\epsilon}^{\mathrm{c}} : \boldsymbol{\epsilon}^{\mathrm{c}})^{1/2} \tag{3}$$

where $\boldsymbol{\epsilon}^{\mathrm{c}}$ is the creep strain tensor, t is time, $\boldsymbol{s}$ is the deviatoric stress tensor, p' is the mean effective stress, $\mathbf{I}$ is the identity tensor, $\epsilon_{\mathrm{eq}}^{\mathrm{p}}$ is a state variable computed from the plastic strain tensor $\boldsymbol{\epsilon}^{\mathrm{p}}$, $\epsilon_{\mathrm{eq}}^{\mathrm{c}}$ is a state variable computed from the creep strain tensor, γ is a parameter controlling the initial creep strain rate, μ is a parameter controlling the relative magnitude of volumetric to deviatoric creep strains, m is a parameter controlling the reduction of the creep strain rate over time, and ϵ_{thr} controls the amount of plastic deformations required for the activation of creep.

Results from the sensitivity study are compared with the base case analysis described in the previous section. All the features, parameters, boundary conditions, etc., of this analysis are adopted for the sensitivity study; only the creep parameters are different. The sensitivity analysis followed a monothetic approach, where the studied parameters were varied one at a time.

In general, parameters increasing creep deformations result in a greater evolution of shear bands and, therefore, a larger excavation damaged zone. The exception was the analysis without volumetric creep deformations, i.e. with $\mu = 0$, where horizontal convergences increased significantly, but a limited evolution of the EDZ was obtained. This parameter has also a significant influence on the resulting distribution of displacements and, in turn, on the evolution of internal forces in the lining.

If the magnitude of creep deformations in the rock is high enough to exhaust the compression capacity of the grout, its stiffness will increase rapidly, in turn increasing the internal forces in the lining. As the latter does not occur in all the grout simultaneously, load increases will tend to be anisotropic and, therefore, they can significantly increase shear forces and bending moments. If the repository design involves a compressible grout to limit deformations and internal forces in the lining, it should be guaranteed that the time-dependent deformation of the rock will not exhaust the compression capacity of the grout during service life, or the originally estimated internal forces can easily be exceeded.

SUMMARY

Claystone represents one of the potential host rocks for a future spent fuel and high-level waste repository in Germany. The geomechanical properties of the rock in combination with the requirements for the drifts, call for the installation of a support structure within every drift. In generic R&D studies, BGE TECHNOLOGY GmbH investigated the design of such support structures and identified suitable options for different types of drifts. A series of fully coupled hydromechanical finite element analyses of a large diameter main drift of a repository in claystone were carried out. The simulations do not represent the conditions of a specific site. Therefore, results are expected to provide only qualitative insights into the behavior of the support system and the host rock and can aid preliminary design stages.

From the analyses carried out, the potential of the compressible grout to moderate the interaction between the host rock and the lining was demonstrated. It can limit the load transferred to the lining and, therefore, can significantly reduce its internal forces. However, the latter causes further relaxation of the claystone resulting in a larger EDZ. The results obtained suggest that the use of the compressible grout entails finding a balance between the amount of relaxation allowed in the rock, controlling the extent of the EDZ, and the magnitude of internal forces in the lining to avoid an excessively robust and costly support system. The latter may be achieved by engineering the specific grout to be used.

In general, the long-term behavior of the drifts, mainly controlled by the creep deformation mechanism, can result in significant increases in the internal forces in the lining. Therefore, the time-dependent behavior of the host rock cannot be overlooked in the design of the repository.

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