Three-dimensional Geological and Geomechanical Modelling of Repositories for Nuclear Waste Disposal in Deep Geological Structures

Sandra Fahland¹, Michael Hofmann¹, Otto Bornemann¹ & Stefan Heusermann¹

¹Federal Institute for Geosciences and Natural Resources, Stilleweg 2, D-30655-Hannover, Germany;
Sandra.Fahland@bgr.de

ABSTRACT

To prove the suitability and safety of underground structures for the disposal of radioactive waste extensive geoscientific research and development has been carried out by BGR over the last decades. Basic steps of the safety analysis are the geological modelling of the entire structure including the host rock, the overburden and the repository geometry as well as the geomechanical modelling taking into account the 3-D modelling of the underground structure. The geological models are generated using the special-construction openGEO™ code to improve the visualisation and interpretation of the geological data basis, e.g. borehole, mine, and geophysical data. For the geomechanical analysis the new JIFE finite-element code has been used to consider large 3-D structures with complex inelastic material behaviour. To establish the finite-element models needed for stability and integrity calculations, the geological models are simplified with respect to homogenous rock layers with uniform material behaviour. The modelling results are basic values for the evaluation of the stability of the repository mine and the long-term integrity of the geological barrier. As an example of application, the results of geological and geomechanical investigations of the Morsleben repository based on 3-D modelling are presented.

1 INTRODUCTION

Over the last three decades, the Federal Institute for Geosciences and Natural Resources (BGR), Germany, has been carrying out extensive geological and geotechnical research and practical project work on domal salt structures to prove their suitability for the disposal of hazardous chemical or radioactive wastes and the storage of oil or gas in salt caverns. The objective of a hazardous waste repository, i.e., prevention of hazardous substances from entering the biosphere, is attained through the use of a system of barriers. Public acceptance of a waste repository depends on the assurance that these barriers are sufficient to provide the necessary protection. The safety analysis, therefore, is central to the planning and authorization of a repository.

The natural geological barriers are an important part of the multiple-barrier system of repositories. Thus, the load-bearing capacity and geomechanical integrity of the rock, its geological and tectonic stability, and its geochemical and hydrogeological development are important aspects of the safety analysis. It is, therefore, not only an engineering problem, but must include geological aspects. The safety analysis must be based on a safety concept that takes into consideration the possibilities for failure that could occur during excavation, operation, and post-operation phases, as well as measures to avoid such failures.

The safety analysis must include several steps [see 1] as geological investigations to provide the basic geological data, mine observations and mining experience, geotechnical in-situ measurements to provide the necessary parameters of the host rock and the overburden, monitoring of the long-term rock behaviour, geomechanical laboratory investigations to determine the relevant properties of the rock and to develop adequate material models, geomechanical and, if required,
thermomechanical or hydromechanical model calculations to analyse the stability and integrity of the structure and the repository, as well as evaluation and assessment of the safety taking all geological, experimental and theoretical investigation results into account.

Basic steps of the safety analysis are the geological modelling of the entire structure including the host rock, the overburden and the repository geometry as well as the geomechanical modelling to provide the necessary results for a long-term safety prediction.

2 METHODOLOGY OF GEOLOGICAL 3-D MODELLING

Originally, the method of geological 3-D modelling has been developed by BGR to provide the necessary geological data base for the investigation and safety assessment of radioactive waste repositories. In addition, this method is presently used for the planning and design of solution mined caverns in domal salt structures to determine unfavourable layers in the host rock and to find out the best possible configuration and arrangement of the cavern field.

To enable the generation of 3-D models, the openGEO™ has been developed in a cooperation between BGR and BICAD company, Hannover, over several years. This special-construction tool is based on the AutoCAD software.

Different basic exploration data, e.g. borehole data, mine data, geophysical data, and other data, can be taken into account to develop and to construct a geological 3-D model (Fig. 1). All the data are based on true coordinates. The correlation of the several data and their interpretation is done by geologists.

![Diagram showing selection of basic data used for geological 3-D modelling](image)

*Figure 1: Selection of basic data used for geological 3-D modelling.*

Borehole data as interpreted geophysical log measurements, e.g. gamma-ray and density logs, are an important data source. The stratigraphic correlation derived from the drilling cores is used to ensure these interpretations. For the correct positional arrangement of syncline and anticline
structures or the strike and dip of layers the orientation measurements from the drilling cores are applied. In the openGEO™ code the dips of strata are displayed in form of small plates along the drilling course.

Mine data include the geological mapping of underground openings like drifts, rooms and shafts, maps of depth and thickness of the several layers as well as the mapping of the position, size and geometry of the underground openings.

Depth contour lines, which are derived from the interpreted seismic and boreholes are used as construction lines for the 3-D bodies. Additionally, the lines of interpreted seismic can be used. Further information obtained from ground penetrating radar (GPR) data can be inserted into the 3-D model. In particular, the border between the rock salt and the potash seam in a salt dome can easily be detected by GPR and gives additional information of the position and orientation of the potash seam.

At least, a bromine analysis of rock samples may help to refine the stratigraphic classification and correlation of the strata. Other geological data like digital terrain models can be optionally imported during the 3-D construction process.

The first step of 3-D construction is the specification of the working area in form of a basemap (left hand side of Fig. 2). After importing and editing all existing data the construction of the model can be started. The second step may include the transfer of existing cross sections and the creation of new sections. Furthermore it is possible to construct directly in the “3-D space”. Contour lines are drawn in different 3-D views to construct 3-D bodies of geological units. The surfaces of the bodies are built-up by a triangulation which uses the border line information of the sections and the contour lines. This means that the geological interpretation is transferred to open strata bodies by the process of construction. It originates in a consistent 3-D model of the underground (Fig. 2).

The openGEO™ code offers the construction of very complex bodies like multiple curved axial-faces of foldings and a complex disturbed overburden. Thin layers with outcrops can be constructed too without any interpenetration. At the end of the construction process every geological body is unique and every single point within the 3-D model is well defined.

Compared to other methods and codes the openGEO™ code provides very detailed results. A certain disadvantage of the code may be that usually long working times are required in opposite to interpolation method of other codes which generate faster results. But especially for the construction of the internal structures of a salt dome, where a high level of details of the intensively folded beds is essential, the line based 3-D triangulation of the openGEO™ code yields much better results. Similar to the results of construction, the interpretation of the basic data in the 3-D space leads to a consistent and high grade image of the underground. Complex geological structures can be visualised in such a manner that an easy understanding also by non-experts is possible.

Figure 2: Step by step (from the left to the right) construction of a complex fold.
Geological 3-D models can be used for a number of additional applications (Fig. 3) as generating profiles and intersections in any direction, viewing of virtual drillings to optimize position and orientation of new exploration boreholes, determination of the distance between selected points and of volumes of the geological bodies, as well as construction of maps at different depths and of contour lines.

The openGEO™ code is applicable for salt rocks as well as for sediments or other intensively folded hard rocks and offers a broad spectrum of application. The discrete 3-D bodies generated with the code can be transferred to other codes and applications, e.g. geomechanical modelling tools (see chapter 3). To this aim, the openGEO™ code provides various controlling tools to guarantee the geometrical uniqueness of the bodies.

3 METHODOLOGY OF GEOMECHANICAL MODELLING

Especially for the disposal of radioactive waste in deep geological formations, a geotechnical safety analysis must be performed to guarantee that the repository mine and the geological barrier is stable and will not represent a risk to the environment as a result of unacceptable deformation and stress or leakage. Thus, the safety analysis is a fundamental part of the planning, excavation and subsequent sealing and closure of the repository. In particular for repositories in ductile rock types like salt rock, the analysis must include an evaluation for very long time periods which can not be based on measurement results or observations usually carried out for short time periods. Consequently, theoretical models are required to predict the physical processes in the host rock expected for the long term.

In detail, the geotechnical safety analysis encompasses the following steps (Fig. 4):
• the construction of the geological structure of the host rock and the geometry of the mine or repository
- description of the material behaviour, i.e. constitutive models and parameters for the time-, temperature- and stress-dependent deformation and strength behaviour of the host rock,
- definition of the loading of the structure, i.e. initial stress state and development with time, thermal effects caused by heat-generating wastes, additional mechanical effects caused by backfilling,
- geomechanical modelling of the structure including the simplification of the geological and geometrical situation, the determination of homogenous parts with similar material behaviour as well as the definition of the thermal and mechanical loadings of the structure,
- discretization of a finite-element model based on the geomechanical model,
- calculation of thermal and mechanical strains, stresses and displacements and related results,
- comprehensive assessment of numerical results as well as in-situ measurements and mine observations.

![Diagram](image.png)

**Figure 4: Necessary items of a geotechnical safety analysis.**

The stability at the following scales has to be analysed (see [2]):
- local stability of the salt rock, considering especially the risk of roof fall,
- stability of medium-size areas of the repository, considering especially the risk of the collapse of pillars and roofs,
- overall stability of the entire structure, including the impact of observed fractures and potential damage zones near the mining rooms.

To analyse the integrity of the salt rock barrier from a geomechanical point of view, the following criteria must be taken into account (see [3]):
- Dilatancy criterion (Fig. 5): The geomechanical integrity of the barrier is guaranteed if rock stresses do not exceed the dilatancy boundary; if this boundary is exceeded, microcracks will form and will cause progressive damage and increasing permeability of the salt rock.
- Hydraulic criterion (Fig. 6): The geomechanical integrity of the barrier is guaranteed if the hydrostatic pressure of an assumed column of brine extending to the ground surface does not exceed the minimum principal rock stress at the considered location of the salt body contour (e.g. top of the salt structure, contact area between salt and anhydrite blocks connected hydraulically to the overburden).

*Figure 5: Illustration of the dilatancy criterion (see [3]).*

*Figure 6: Illustration of the hydraulic criterion (see [3]).*
4 APPLICATION OF THE GEOLOGICAL AND GEOMECHANICAL 3-D MODELLING

The BGR has been involved in several waste disposal projects, e.g. exploration of the Gorleben salt dome to prove its suitability for the disposal of high-level wastes and investigation of the Morsleben repository. Geological exploration and modelling as well as numerous geomechanical model calculations to analyse the stability of the mine and the integrity of the geological barrier were an important part of the safety assessment.

As an example, the geological and geomechanical 3-D modelling of the Morsleben repository is shown. The repository was used from 1972 until 1998 for the disposal of low- and medium-level radioactive wastes and was established in the old Bartensleben mine, a former salt and potash mine consisting of several mining parts, e.g. the southern, the western, and the eastern part as well as the central part. Figure 7 depicts an overview of the mining situation with numerous old mining rooms excavated a couple of decades ago and located at different levels of the mine. The central part shows the most unfavourable number and configuration of rooms with respect to size, shape, and arrangement in steep rows due to the strong inclination of salt layers (see [4]). Consequently, from a geomechanical point of view it is the most critical and important part of the mine, although it is not used for waste disposal.

Figure 7: Mine situation in the Morsleben repository: Mapping and scanning data by DBE company, model generated with ERAM-SIS (see [7]).

4.1 Geological modelling of the central part of the Morsleben repository

Based on the former 2-D modelling of the Morsleben repository (see [5] and [6]) a geological 3-D model of the central part (Fig.9) has been developed by BGR in recent years to improve the visualisation of the structure and the interpretation of the existing geological basic data. The geological 3-D model serves to support the planning of the actual backfilling of selected mining rooms and the future closure of the repository.
The 3-D model is based on already existing and interpreted 2-D basic data (Fig. 8). Additionally, the results of new drillings have been considered. Within the frame of the backfilling and closure of the repository several new drifts and boreholes are planned. As an efficient planning tool the 3-D model serves to determine the exact positioning of boreholes or technical barriers. The possibility for interpreting new generated data, e.g. microacoustic and ground penetrating radar (GPR) data created during an accompanying monitoring, will be improved in the future.

In the 3-D model of the central part of the Morsleben site the assignment of the stratigraphy (see [8]) for the different salt rocks was combined to nine main units (Tab. 1). Due to this approach the different geological units can be displayed separately or in any combinations. The digital 3-D mine layout (see [7]), which also exists in a digital version, can be visualized together with the geological model (Fig. 10). It is also possible to generate intersections of the geology and the drifts.

Table 1: Combined stratigraphic units in the 3-D model.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cr</td>
<td>cap rock</td>
</tr>
<tr>
<td>z2+z3</td>
<td>Staßfurt- and Leine-formation, memberless</td>
</tr>
<tr>
<td>z2SF</td>
<td>Kaliföz Staßfurt</td>
</tr>
<tr>
<td>z2DS-z3LK</td>
<td>Decksteinsalz up to Leine-Karbonat</td>
</tr>
<tr>
<td>z3HA</td>
<td>Hauptanhydrit</td>
</tr>
<tr>
<td>z3BS-BK/BD</td>
<td>Basissalz up to Bank-/Bändersalz</td>
</tr>
<tr>
<td>z3AM</td>
<td>Anhydritmittelsalz</td>
</tr>
<tr>
<td>z3SS-z3TM</td>
<td>Schwadensalz up to Tonmittelsalz</td>
</tr>
<tr>
<td>z4</td>
<td>Aller-formation, memberless</td>
</tr>
</tbody>
</table>
Figure 9: Complete geological 3-D model of the central part of the Morsleben repository.

Figure 10: Special 3-D view of the central part of the Morsleben repository showing the 3-D bodies of the main anhydrite (z3AM, dark green) and of the younger fillings (z3BS-BK/BD, z3AM, z3SS-z3TM and z4) of the main syncline as well as the mine layout. The top face shows the outcrops of the different geological units representing the salt mirror.
4.2 Geomechanical modelling of the central part of the Morsleben repository

For reasons of simplification, the geomechanical 3-D model has been generated in a first step on the basis of the geological 2-D model. Recent work serves to consider the entire 3-D structure and to develop a special interface to transfer the geometry data of the geological 3-D model directly to the geomechanical and numerical model.

To establish a geomechanical model for subsequent numerical calculations, the model of the geological structure had to be idealized on the basis of a characteristic geological cross section perpendicular to the axis of the structure and the mining rooms. The idealized geological layers were classified with respect to the steady-state creep behaviour. The main units of the Zechstein strata (salt layers z2HS, z2SF, z3LS, z3OS, z3BK/BD, z3AM/SS, and anhydrite layers z3HA) and, if necessary, composites of the main units (z3OS/BK/BD) were considered. The Hauptsalz z2HS was separated into two several parts (z2HSW and z2HSO), due to different creep behaviour. The structure of the overburden was idealized taken into account the main layers caprock cr, DGL layer (including layers of Deckanhydrit, Grauer Salzton, and Leinekarbonat) within the caprock, Keuper k, Jurassic-Cretaceous j-kr, and Quaternary q (Fig. 11).

![Figure 11: Idealized geological structure of the central part.](image)

The deformation behaviour of the ductile rock salt layers was described by a constitutive equation including both elastic and steady-state creep deformations. In addition, the dilatant behaviour of rock salt was considered using a new dilatancy concept according to [9]. Calculations were made using the finite-element codes ANSALT developed by BGR and the new commercial JIFE code for THMC processes developed by SRD company, Berlin. Pre- and post processing of the data was done with the INCA/PATRAN tool.
The 3-D finite-element model included half of the length of the rooms and of the pillar at the head of the rooms for reasons of symmetry. Figure 12 shows a plot of the entire 3-D model, 750 m in height, 850 m wide and 75 m in length, comprising about 120,000 nodal points and 120,000 isoparametric 8-node elements. It was assumed that the rooms were instantaneously excavated in the year 1940. Thus, up to now a time elapse of about 67 years had to be regarded to analyse the recent stress and deformation state.

As an example, the calculated dilatant rock zones are plotted in Figure 13. Excavation of the rooms and creep of the salt rock cause the development of dilatancy in major parts of the roofs and pillars around the rooms as well as in larger rock zones between rooms and the anhydrite layers. Comparing the results of 3-D modelling to former 2-D calculations, a certain reduction of dilatancy in the salt rock is obtained. This is caused by the more favourable three-dimensional structural behaviour and the related lower amount of deviatoric stresses. The geomechanical 3-D calculations show that the integrity of the salt barrier is given for most parts of the salt rock, especially at the top of the salt structure. Since significant zones of dilatancy occur between the rooms and the anhydrite layers, potential migration of brine from the caprock into the mining rooms via the jointed anhydrite layers and the dilatant salt rock cannot be excluded.
5 CONCLUSIONS

The safety assessment of radioactive waste repositories in deep geological structures must primarily include geological investigations to provide the basic geological data and geomechanical model calculations to analyse numerically the mechanical behaviour of the entire structure.

The starting point of exploration of repository sites should be extensive geological investigations to achieve the necessary database for generating geological 3-D models. To this aim, the special-construction openGEO™ code has been developed based on the AutoCAD software. Different basic exploration data, e.g. borehole data, mine data, geophysical data, and other data, are taken into account to develop and to construct the 3-D model. The code provides the construction of very complex bodies like multiple curved axial-faces of foldings and a complex disturbed overburden.

Geomechanical modelling of underground structures includes the idealized and simplified geological structure of the rock, constitutive material models to describe the time-, temperature- and stress-dependent deformation and strength behaviour of the host rock, the geometry of the repository, the initial stress state and development with time, thermal effects (e.g. heat-generating wastes, ventilation), as well as mechanical effects (e.g. mining activities, backfilling). The stability of the repository during operation and the long-term integrity of the geological barrier are evaluated on the basis of several criteria, e.g. the dilatancy and the hydraulic criterion.

As an example, a practical application of the geological and geomechanical investigation methods to the central part of the Morsleben waste repository is presented. A complete geological 3-D model of the central part has been established based on geological 2-D cross sections and drillings, on geological mappings, on GPR measurements and on additional current exploration results. Additionally, the mine geometry is included in the model.
Geomechanical model calculations have been performed to analyse the stability of old mining rooms and the integrity of the salt barrier. A 3-D model was used considering half of the length of the rooms and of the pillar at the head of the rooms for reasons of symmetry. The calculations comprised the analysis of the recent state of the rooms and the salt barrier as well as the evaluation of stability and integrity.

The analysis of the recent status of the mine shows that the local and medium-scale stability of the mine is strongly influenced by an unfavourable shape of the rooms, especially of the roofs between the rooms. However, this local phenomenon does not affect considerably the present large-scale stability and integrity. The integrity of the salt barrier is given for most of the salt rock, especially at the top of the salt dome. However, significant zones of dilatancy occur around the rooms and near the anhydrite layers. Thus, potential intrusion of brine from the caprock into the mining rooms via the anhydrite layers cannot be excluded.

Both geological and geomechanical modelling methods are used as main parts of the exploration and assessment of other waste disposal sites located in salt rock or different rock types. For the future, the direct transfer of the data of geological 3-D models to comparable geomechanical models is planned.

REFERENCES


