Time dependent finite element modelling for mining systems in salt domes

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For a stability analysis of mining in salt domes in the operating phase and after the close down a correct modelling of the geological, tectonical and hydrological data of the salt dome and the overburden as well as the devolution of the mining and supporting structures is needed. At the example of a backfill mine with a nearly vertical room and pillar system the method of modelling and the numerical calculation will be visualized. With two dimensional cross sections covering the mining area and the overburden, the boundary conditions for three dimensional modelling of the vertical room and pillar system will be extracted.

Stratigraphy, fault zones, pore water pressure and rock mass anisotropy which are results from in-situ measurements and laboratory testing will be taken in account at the 2D-models. The realistic calculation requires the modelling of anisotropic material behaviour of the overburden, the time dependent material behaviour of salt and backfill and the mining in the correct order of time. 3D-models include on one hand the finite element calculation the vertical room and pillar system with local failure of the crowns and on the other hand the finite element calculation of single pillars over the total height of the salt mine.

1. INTRODUCTION

The time dependent finite element modelling for mining systems in salt domes is presented by means of the example of the Asse salt mine, located in the Asse salt dome near Braunschweig (Brunswick) in the northern part of Germany.

Numerical calculations of vertical cross sections covering the mining area and the overburden and of three dimensional models of single pillars and crowns are carried out as a part of the stability analysis.

The investigation of the operating phase and the close down needs a correct modelling of

- the geological situation,
- the tectonical data and
- hydrological parameters

for the salt dome and the overburden. The numerical analysis has to cover following situations:

- primary state of stress
- devolution of the mining system
- time schedule for the backfill.

The time dependent effects in finite element modelling for mining systems in salt domes are

- the mining history,
- the backfill planing and
- the period of prediction

as well as the material behaviour of saliferous rocks with time and deformation rate dependent deformation and strength due to

- creep and
- relaxation.

1.1. Salt dome and overburden

A geological description of the Asse salt dome and its overburden is given in a vertical cross section normal to the strike of the Asse saddle nearly in North South direction. The stratigraphy is reduced to the ‘reference model 2’, which is developed with special consideration of geophysical, geological and mine surveying aspects.

The saliferous rocks are subdivided into

- rock salt and
- carnallite.

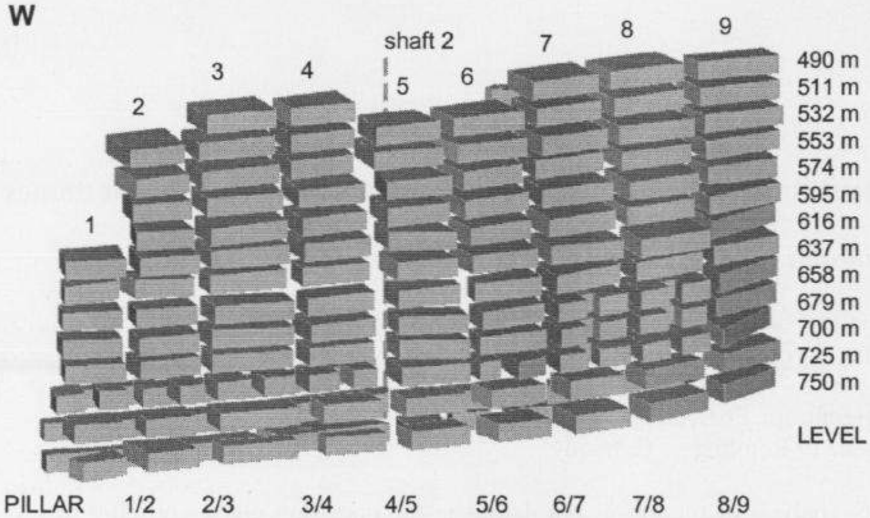

Figure 1: Three-dimensional view of the Asse Salt Mine (schematic, room are solid)

For the overburden the following rock mass layer groups are considered:

- bunter sandstone
- shelly limestone
- keuper.

The layers of the overburden are mostly perpendicularly intersected by fault zones. In the southern and upper part of the Asse saddle kinematic or partial kinematic blocks of rock mass are caused.

1.2. Mining system

The mining system of the Asse salt mine is a vertical room and pillar system with 13 rows and 9 columns of rooms. The typical dimensions of the rooms are length 60 m, width 40 m and height 15 m; the thickness of the crowns between the rooms is about 6 m; the average thickness of the pillars is 12 m with the exception of pillar 4/5 (20 m). The plane of the mining system is almost W-E orientated and has a slight dip (20°) to the north (figure 1).

The first Asse mining company 'Gewerkschaft Asse' was founded in 1899 and ten years after the beginning of the mining the exploitation of rock salt started in the year 1916. The 131 rooms in 13 levels with a volume of 3.35 millions m^3 were built from 1916 (750 m level) until 1964 (490 m level).

In 1965 the Asse salt mine became the German research mine under the organisation of the GSF (Gesellschaft fuer Strahlenforschung) for the research for the final disposal of radioactive and chemical-toxic wastes. Until 1995 research work on emplacement technologies, final storage of high level radioactive waste and geotechnical barriers was carried out by in-situ testing programs. From 1967 to 1978 more than 125000 containers with low and medium level radioactive waste were placed.

Since 1966 deformations of the rooms and stresses in the pillars are measured in a rock mass observation program. The evaluation of the convergences and crown falls lead to the conclusion that the long term stability of the mining system can only guaranteed with backfilled excavations. Actually the Asse salt mine is going to be backfilled with crushed salt from the Ronnenberg heap (near Hannover).

1.3. Main objectives

For the judgement of the global stability analysis of the whole mining system the following items must be addressed by numerical simulations using the Finite Element Method (FEM):

- state of stress of the pillars and crowns
- state of deformation of the pillars and crowns respectively the convergences of the rooms
- control of the stabilizing effect of the backfill
- examination of the bearing behaviour of intact, partially broken and fallen crowns

The following time history must be considered in the numerical calculations:

- primary state of stress (10^6 years back from now)
- excavation phase (1916 - 1964)
- convergence of the open rooms
- backfill phase (1995 - 2005)
- extrapolation until the time after close down.

2. FINITE ELEMENT MODELLING

The numerical calculations are carried out with finite element program ABAQUS®. The entire load and time history of the Asse salt mine is simulated in several two- and three-dimensional models respecting the behaviour of the overburden and the saliferous rock.

2.1. Two- and three-dimensional models

The following list shows the two- and three-dimensional models, for which the computations are already finished or at least planned. The items in brackets are or will be reported in other contributions.

Two-dimensional models:

- vertical cross section normal to Asse saddle axis
- (vertical cross section parallel to saddle axis)
- (horizontal cross section)

Because none of the two-dimensional models contents all of the bearing elements (pillars, crowns and surrounding rock mass) the stability of the mining system can only be judged with the help of simulations on volumetric models.

Three-dimensional models:

- detail with parts of crown, pillar and room
- single pillar with parts of crowns and rooms
- (whole salt dome with mining system)

2.2. Material behaviour of the overburden

The numerical finite element calculations consider the geological layer groups. The material behaviour of the rock mass is simulated using the isotropic elasto-plastic DRUCKER-PRAGER law with special parameter sets for all layers. The values of the angle of friction and the cohesion for the residual rock strength are known from a large series of rock mechanical laboratory tests.

The fault zones through the layers of the overburden and the transition zone between overburden and salt dome are realised in the finite element models with contact formulations. For all interfaces within the numerical models the contact cohesion was neglected and the same angle of friction in the contact was considered.

2.3. Material behaviour of saliferous rock

Both saliferous rocks in the numerical models, the rock salt and the carnallite, are simulated with two different parameter sets for a special type of power creep law, the BGRa creep law:

$$\dot{\varepsilon} = A \exp\left(-\frac{Q}{RT(z)}\right)\left(\frac{\sigma}{\sigma_0}\right)^n \quad \text{(eqn. 1)}$$

The creep rate in equation 1 depends beneath the physical constants (Q, R) and the material parameters (A, n) mainly on the normalized effective stress σ/σ_0 and the temperature T. Corresponding to the geothermal gradient, the temperature T(z) increases with a rate of 0.02 Km^{-1}. The behaviour of the saliferous rocks is simulated with a visco-elastic material law without any criterion for rock strength.

The backfill material (crushed rock salt) is computed assuming elastic behaviour with strain hardening option.

3. TWO-DIMENSIONAL MODEL

3.1. Model and load cases

The finite element model of the vertical cross section through the mining system consists of 8706 elements with plane strain conditions and 8993 nodes. A region with a 7000 m length and 2200 m height is covered by the model (figures 2 and 3).

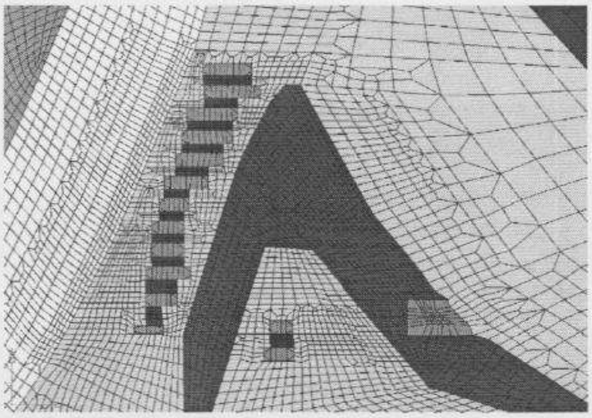

Figure 2: 2D FE model (mining system in detail)

The load time history is considered as follows:

- primary state of stress due to gravity loading
- visco-elastic creep for 10^6 years
- excavation of the mining system
- hydrostatic pressure on the southern part of the salt dome in height of the mining area
- emplacement of backfill
- extrapolation without any changes

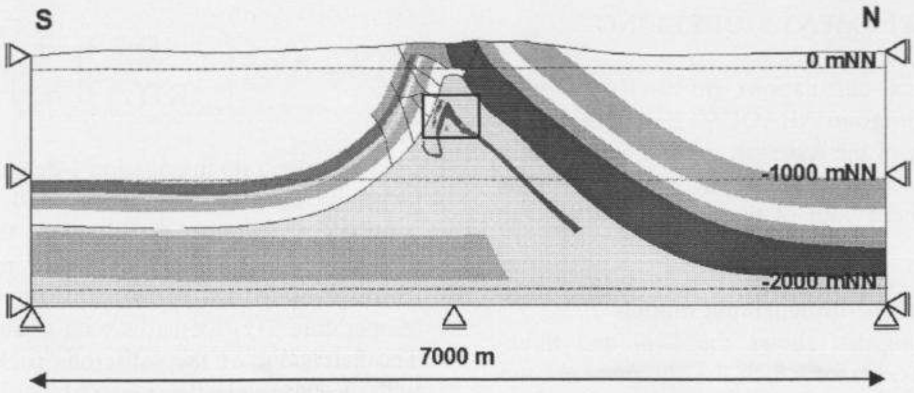

Figure 3. Two-dimensional finite element model (detail see figure 2)

3.2. Results

The general results of the numerical analysis in this cross section of the Asse salt mine are confirmed by the in-situ observations and measurements, such as deformations, convergences and stresses. Through the consideration of the fault zones in the overburden and the hydrostatic brine pressure on the southern part of the salt dome, the results became more realistic than in former calculations.

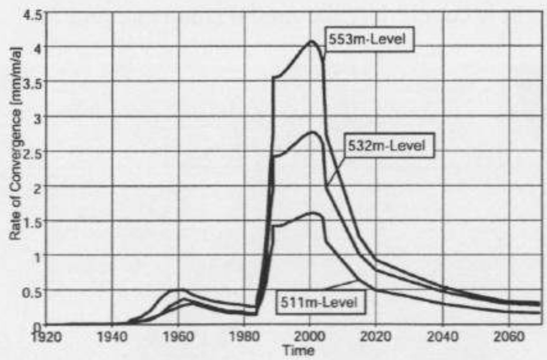

Figure 4: Convergence rates of the rooms on three levels before and after backfill

The interpretation of the convergences at the example of the 553 m, 532 m and 511 m level show very clear the effect of the backfill (figure 4). From the beginning of mining activity until 1985 we find very small convergence rates; in the mid eighties a very sharp and fast increase of convergence rate takes place and leads to very high, almost constant rates. With beginning of backfill emplacement (from 2001 to 2003) the calculation postulates a very quick decrease of convergence rate with reduction by a factor of two in about ten years.

The main results for the two-dimensional model can be summarized in the points:

- good reproduction of measured displacements and convergences
- confidence in the estimation of the backfill effect

4. 3D-MODEL FOR CROWN FAILURE

Since the year 1978 more than 25 crown falls are observed at the Asse research mine. The openings in the broken crowns are mostly of elliptical shape with different sizes. One of the key questions concerning partial broken crowns is the knowledge about their static function.

4.1. Model and boundary conditions

The use of symmetry conditions leads to a three-dimensional finite element model with 21 m height (crown and two half rooms), 36 m width (half long side of room and half pillar) and 250 m depth (half short side of room and surrounding rock mass). The boundary conditions are set to the stresses σ_x =10.0 MPa (left to right), σ_y =3.8 MPa (front to rear) and σ_z =10.0 MPa (top to bottom) and the corresponding constrained translation conditions.

The examination of broken crowns are realized by deactivation of finite elements in the centre of the crown. For 5 submodels the calculation of the stresses and displacements are carried out:

- intact crown
- elliptical hole 20 m x 13 m
- elliptical hole 40 m x 26 m (figure 5)
- elliptical hole 60 m x 40 m
- missing crown

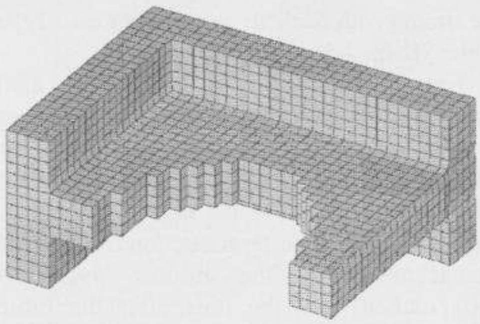

Figure 5: Broken crown (Section of 3D FE model)

4.2. Results

The main result of the finite element simulation of broken or breaking crowns is shown in figure 6. The loading of the pillars and the area of plastified zones depend on the area of the central hole in broken crowns.

For the situation in the Asse salt mine can be shown, that small holes (up to 40 % of the crown area) have a very small effect (less than 10 % of the pillar area is plastified) on the bearing capacity of the pillars.

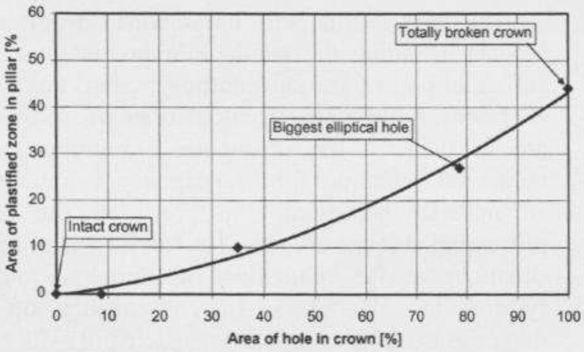

Figure 6: Result of 3D FE simulation

In the case of the biggest elliptical hole in the crown is still an enormous bearing capacity available. The difference to the totally broken crown is about 20 % increase of plastified area in the pillar. The crown therefore doesn't bear as a plate, but the stabilizing effect results from the stiffness of even small crown zones in the edges of the rooms.

5. 3D-MODEL FOR A COMPLETE PILLAR

The two-dimensional model (chapter 3) does not include the pillars as main bearing elements. The numerical estimation of the state of stress and deformation is necessary for the judgement of the reserves in bearing capacity and of the stability behaviour and must be carried out only in a three-dimensional finite element analysis.

5.1. Model and boundary conditions

The three-dimensional FE model of a complete pillar (figure 7) consists of a real pillar, the adjacent complete columns of rooms and half the pillars in the left and right. The FE model with 7134 3D linear brick elements and 8385 nodal points has the dimensions of 350 m (front to rear), 145 m (left to right) and 365 m (top to bottom).

The model is calculated assuming gravity loading, geostatic pressure on the top of the model and symmetric displacement boundary conditions on all other sides. The history of excavation and backfill is as well simulated and the brine pressure from the southern part of the overburden (front of the model) is applied. A visco-elastic numerical calculation is carried out including the extrapolation until the year 2020.

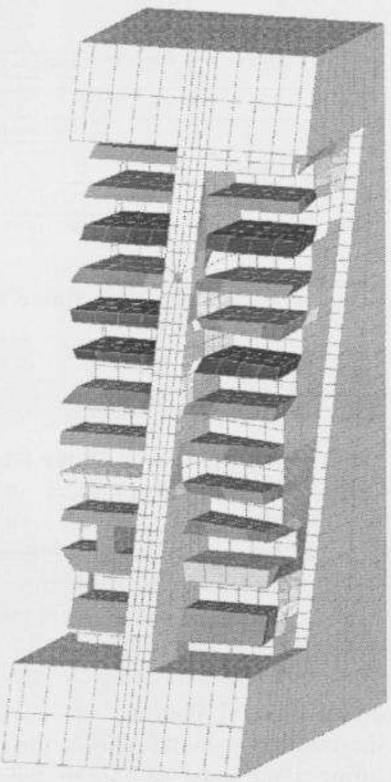

Figure 7: 3D FE model (section) of a complete pillar

5.2. Results

The results of the three-dimensional FE model of the complete pillar are quite similar to those of the 2D-analysis (section 3). Figure 8 shows the development of the rate of room convergences for the levels 511 m, 532 m and 553 m. After a long phase of small convergence rates in the beginning of the mining activity the rates increase in the mid eighties through the brine pressure activation.

The beginning backfill in the lower levels in the mid nineties let the convergence rate decrease immediately. The backfill in the rooms itself causes a light slow down of the convergence rates. Against the very confidential results of the 2D-analysis, the calculated effectiveness of the backfill takes place some years later in the 3D model. The reached convergence rate in the year 2015 are almost three times higher than in the 2D-analysis.

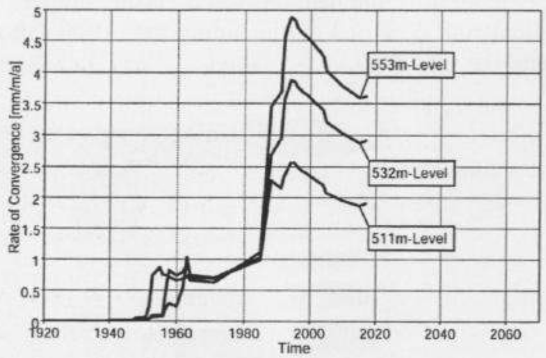

Figure 8: Convergence rates of the rooms (3D result)

6. CONCLUSIONS

The shown numerical simulations (section 3-5) indicate, that there is no typical or standard numerical model, which covers all possible questions on the bearing capacity and the stability of mining systems in salt domes. All numerical models for simulations with the finite element method have specific advantages and disadvantages.

6.1. Two-dimensional models

For the two-dimensional models the orientation of the cutting plane must be chosen suitable to the problem. In the calculated cross sections all bearing elements should be present. Neither in horizontal nor in vertical cross sections the pillars, the crowns and the rooms with backfill are simultaneously available in the 2D-models.

Nevertheless the two-dimensional analysis is very good suited to get results with very high geometrical resolution and non-linear material models with the recent computer capacities in relative short time. For the example of the Asse salt mine a very realistic reproduction of the stresses and displacements in the mining system and a extrapolation until the time after the future close down could be obtained.

6.2. Three-dimensional models

In three-dimensional finite element models for details of the mining system it is much more better possible to take in account all important bearing elements in a geometrical correct manner. The main problem of these models is to find proper boundary conditions, which allows to simulate the reaction of the not modelled rock mass region outside the 3D-model. This means, that in the example of the Asse salt mine, the global bearing behaviour of the salt dome with its arch of overburden, which leads to reduced vertical stresses, must be considered.

The best results will be obtained from large models including the whole mining system and a sufficient part of the surrounding region. For those enormous finite element calculations all tools still are available. The computer programs with numerical techniques for time dependent simulations an material behaviour, the pre- and the post-processing systems are ready to solve such complex situations as the modelling of complete mining systems in salt domes. In consequence of the immense need of computing capacity, it will be a task for the next generation of super-computers.

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