Simulation of long term thermal, hydraulic and mechanical interaction between buffer and salt host rock

Wenqing Wang, Robert Walsh
GeoSystemsResearch, Center for Applied Geoscience, University of Tübingen

Hua Shao
Federal Institute for Geosciences and Natural Resources (BGR), Hannover

Mingliang Xie
INTERA – Environmental Consultants, Ottawa, Canada

Olaf Kolditz
Environmental Informatics, Helmholtz-Center for Environmental Research (UFZ), Leipzig / TU Dresden

ABSTRACT: This work is focused on the numerical analysis of thermo-hydro-mechanical (THM) coupled processes in a hypothetical nuclear waste repository hosted in salt rock. Creep behavior of the salt rock is an important aspect of the present study. A temperature dependent quasi-stationary creep model, based on the BGR model, is utilized to represent time dependent deformation effects in salt rock induced by mechanical and thermal processes. The finite element method is employed for modeling the resulting THM coupled problem. Two comparative case studies (accounting to and neglecting creep effects) are carried out for a two-dimensional model of a nuclear waste repository scenario undergoing THM coupled processes. The importance of the creep processes in salt rock and crushed salt buffer materials is highlighted by comparing the results of the two scenario simulations.

Coupled Modelling of Physical/Chemical Retardation and Transport of CO_2/CH_4 for a Backfilled Salt Rock Repository

H. Alkan, W. Müller
ISTec, Institut für Sicherheitstechnologie, 50667 Cologne, Germany

ABSTRACT: A numerical study on the retardation/retention and transport of the gases generated in a backfilled salt rock repository system is performed using the reactive flow simulator TOUGHREACT and the results are presented. The basic retardation/retention mechanisms are investigated as the dissolution of the gases, the precipitation of carbonates and compressibility of the gas phase. The solubility of CO_2 in brines is higher than other generated gases. Its dependency on ionic strength as well as on electrolyte type is found to be considerable. If the thermodynamical and chemical conditions dominating in the emplacement caverns are favorable the carbonation may be an important retention mechanism. The buffering of pH lowering effect of dissolved CO_2 with suitable backfill materials contributes to the precipitation of carbonates which in turn decreases the porosity and permeability. If the thermodynamical conditions results in the formation of gas phase, the higher compressibility and density of CO_2 compared with other gases appears as another advantage for its retardation on the way to geosphere. The capillary trapping and self sealing due to precipitation in the flow paths can also give some minor contributions to the retardation even to the retention of the gases.

Comparison of advanced constitutive models for the mechanical behavior of rock salt - results from a joint research project
I. Modeling of deformation processes and benchmark calculations

O. Schulze[2)], U. Heemann[2)], F. Zetsche[2)], A. Hampel[1)], A. Pudewills[3)], R.-M. Günther[4)], W. Minkley[4)], K. Salzer[4)], Z. Hou[5,*)], R. Wolters[5)], R. Rokahr[6)] & D. Zapf[6)]

1) Consultant, Am Fasanenweg 4, 55270 Essenheim, Germany
2) Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover
3) Forschungszentrum Karlsruhe GmbH, Institut für Nukl. Entsorgung (INE), P.O.Box 3640, 76021 Karlsruhe
4) Institut für Gebirgsmechanik GmbH (IfG), Friederikenstr. 60, 04279 Leipzig
5) Clausthal University of Technology, Professorship for Disposal Technology and Geomechanics (TUC), Erzstraße 20, 38678 Clausthal-Zellerfeld,
**) now with: Clausthal University of Technology, Institute of Petroleum Engineering*
6) Leibniz Universität Hannover, Institut für Unterirdisches Bauen (IUB), Welfengarten 1, 30167 Hannover.

ABSTRACT: In this first part of the joint project, the partners document their constitutive models and the results of their recently performed comparative model calculations. An elaborated database is used for the reliable determination of salt-type specific parameter values of the respective models. Individual back-calculations of different types of laboratory tests allow to examine and to compare the features of the models in detail. The results demonstrate that the models have reached a high standard in describing various important deformation processes like creep, dilatancy, damage, failure, and post-failure behavior under different influences. It can be concluded that the partners do have appropriate tools for model calculations. Furthermore, the comparisons show, how the models and the numerical codes can be developed and improved further.

Comparison of advanced constitutive models for the mechanical behavior of rock salt - results from a joint research project II. Numerical modeling of two in situ case studies and comparison

Z. Hou[5,*)], R. Wolters[5)], R. Rokahr[6)], D. Zapf[6)], K. Salzer[4)], R.-M. Günther[4)], W. Minkley[4)], A. Pudewills[3)], U. Heemann[2)], O. Schulze[2)], F. Zetsche[2)], A. Hampel[1)]

[1)] *Consultant, Am Fasanenweg 4, 55270 Essenheim, Germany*
[2)] *Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover*
[3)] *Forschungszentrum Karlsruhe GmbH, Inst. f. Nukl. Entsorgung (INE), P.O.Box 3640, 76021 Karlsruhe*
[4)] *Institut für Gebirgsmechanik GmbH (IfG), Friederikenstr. 60, 04279 Leipzig*
[5)] *Clausthal University of Technology, Professorship for Disposal Technology and Geomechanics (TUC), Erzstr. 20, 38678 Clausthal-Zellerfeld*
[*)] *now with: Clausthal University of Technology, Institute of Petroleum Engineering, Germany*
[6)] *Universität Hannover, Institut für Unterirdisches Bauen (IUB), Welfengarten 1, 30167 Hannover*

ABSTRACT: In the second part of the joint research project, the partners performed model calculations on two different underground structures in order to check, demonstrate and compare the abilities of their constitutive models and calculation tools. The first structure was a 35-year-old horizontal drift in 720 m depth in the salt mine “Sondershausen”, the second consisted of a room-and-pillar model bearing system with a pillar slenderness of $\alpha = 1$ under three different loads. The results from the benchmark calculations of the project partners are discussed in comparison with each other and, in case of the horizontal drift, also with in-situ measurements. Except for two calculations of the slender pillar under very high loads, all partners got comparable results with a good agreement between the measured and the calculated minimum stresses, deformation rates as well as the permeability profiles of the 35-year-old drift in the Sondershausen salt mine.

Investigations on damage and healing of rock salt

Otto Schulze
Federal Institute for Geosciences and Natural Resources (BGR), P.O. Box 51 01 53, 30 631 Hannover (FRG)
otto.schulze@bgr.de

ABSTRACT: The dilatancy concept provides the criterion to decide whether creep deformation without volume increase or dilatant deformation with propagating damage will occur. Different observation methods are commonly used to detect dilatancy related effects. Since the different effects seem to suggest different dilatancy boundaries, the equations for the dilatancy boundary can be very different. We present our recent results and a comment on the various methods to detect dilatancy. The evolution of damage is discussed on the basis of the volumetric strain, and the energy to produce the irreversible volumetric strain yields a measure for the occurrence of failure. First results from our laboratory work on the compaction behavior of heavily damaged rock salt like that one in the EDZ are presented. Based on these results, the compaction and permanent healing are described by the evolution of the permeability during a transition from the dilatant into the non-dilatant stress domain.

Coupled modelling of the C: HM behaviour of self healing salt based backfill

F. Werunsky, Z. Hou*

Professorship for Waste Disposal and Geomechanics, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

**now with: Institute of Petroleum Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany*

H. C. Moog

GRS - Gesellschaft für Anlagen - und Reaktorsicherheit mbH, Braunschweig, Germany

ABSTRACT: Through underground sealing systems direct influx of brine or water in disposal cavities of underground waste repositories is initially ruled out. Therefore dam materials with restraint systems, in case of a water or brine intrusion, are a good choice. To simulate the behaviour of such a material with a chemical based restraint system, CHM coupling is essential. This paper deals with a numerical model which describes the coupled C: HM behaviour of a self healing salt based backfill “SVV”. Therefore with implemented thermodynamic equilibrium calculations the phase composition and solid phase integral volume can be predicted and thus the curing process during the injection of solution described. Concurrent samples of SVV have been produced and thereby measured data has been compared to the results of simulations. Afterwards the samples were disassembled and investigated with respect to their mechanical behaviour and composition in terms of mineral phases for further comparisons between simulation and experiment.

Geotechnical control of critical construction elements during the backfilling activities of the ERAM – Experience gained in using the observation method

R. Mauke
Federal Office for Radiation Protection (BfS), Salzgitter, Germany

B. Stielow & M. Mohlfeld
Zerna, Köpper & Partner, Bochum, Germany

ABSTRACT: In the Morsleben Radioactive Waste Repository (ERAM) 22 huge salt mine caverns have been backfilled with a hydraulic transportable salt concrete since October 2003. These backfilling activities are necessary to maintain the mine in a stable condition and to keep the salt barrier intact. The rock behaviour before, during and after the stabilising activities is systematically registered by an extensive geotechnical measurement and monitoring system. It was designed on the basis of preliminary calculations to predict the probable behaviour of the rock salt. The TM (thermal, mechanical) calculations should be calibrated by the measurement results to guarantee the operational safety during backfilling activities.

Deep salt cavern abandonment : a pilot experiment

G. Hévin, C. Caligaris, J.G. Durup, O. Pichayrou, & C. Rolin
Gaz de France, Direction des Grandes Infrastructure, Saint-Ouen, France.

ABSTRACT: Sealing a solution-mined cavern in a salt formation that has been used for mineral production, hydrocarbon storage, or waste disposal has been a contemporary topic for many years. As a result of knowledge gained from a series of succinct sealed well and cavern field tests performed in the late 1980s and early 1990s by Gaz de France, issues related to the abandonment of salt caverns became more focused. The main difficulty of the abandonment problematic is linked to fluid pressure increase in the cavern after sealing. This phenomenon is the result of different factors that interact with each other : creep, heat transfer, dissolution, percolation, for instance. All these factors must be taken into account for designing the abandonment process. This paper will discuss these factors and will highlight their practical impacts on a deep salt cavern abandonment experiment (1500 meters deep). First measurements will be also presented.

The influence of humidity on microcrack processes in rock salt

Jürgen Hesser & Thomas Spies
Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany

ABSTRACT: Field measurements of acoustic emission in salt mines indicate significant influence of humidity of the mine air on the microcrack activity in the rock mass, e.g. as mild seasonal variations in long-term measurements and as strong variations during the backfilling of large rooms with salt concrete. Laboratory tests were performed to gain more knowledge about this humidity induced microcrack processes in rock salt. Results of mechanical and ultrasonic measurements in the tests are presented and interpreted. The decrease of the flow stress and the rising activity of the acoustic emissions as a consequence of rising humidity in the experiments were caused by the reduction of the cohesion of the rock salt sample due to penetration of moisture into open microcracks and pores of the dilated sample.

The Composite Dilatancy Model: A constitutive model for the mechanical behavior of rock salt

A. Hampel
Consultant, Am Fasanenweg 4, D-55270 Essenheim, Germany, e-mail: hampel@online.de

O. Schulze
Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hannover, Germany, e-mail: otto.schulze@bgr.de

ABSTRACT: The Composite Dilatancy Model (CDM) describes transient and steady-state creep, the evolution of dilatancy and damage, failure, and the post-failure behavior of different types of rock salt under different loading conditions and temperatures. Creep is modeled by constitutive equations for the velocity of mobile dislocations and their interactions with other dislocations, particles of salt minerals and with the changing subgrain microstructure of the material. Above the dilatancy boundary the CDM takes into account the increasing influences of damage and humidity on deformation which result in a higher deformation rate and inelastic volumetric strains. After failure, the CDM describes the considerable reduction of the load-bearing capacity of rock salt and its approach to a residual strength which corresponds to a stress level near the dilatancy boundary. In this contribution the current stage of development of the CDM, its various features, and an example for its application are presented.

The effect of grain boundary water on deformation mechanisms and rheology of rocksalt during long-term deformation

J.L. Urai[1] & C.J. Spiers[2]

1 Endogene Dynamik, Faculty of Geo-Resources and Materials Technology, RWTH Aachen University, Germany

2 HPT Laboratory, Faculty of Geosciences, Utrecht University, The Netherlands

ABSTRACT: Reliable modeling of the deformation of rock salt under the very low strain rates characterizing long term engineering conditions or natural halokinesis requires extrapolation of experimentally -derived flow laws to rates much lower than those attainable in the laboratory. This extrapolation must be based on an understanding of the microscale deformation mechanisms operating under these conditions, from studies of natural laboratories. The engineering creep laws generally used in the salt mining industry are based on dislocation creep processes quantified in laboratory experiments of necessarily limited duration. However, a large body of evidence clearly demonstrates that under conditions of long-term deformation, grain boundary dissolution-precipitation processes, such as solution-precipitation creep (or "pressure solution") and dynamic recrystallization, play a significant role. In this contribution, we briefly review the microphysics of grain boundary water related, solution-precipitation processes in halite, together with the flow behaviour associated with these processes, and we discuss the contribution of these mechanisms to the strain rate during long-term creep.

Stress relaxation experiments on compacted granular salt: effects of water

X. Zhang, C. J. Peach, J. Grupa, & C. J. Spiers
Faculty of Geosciences, Utrecht University, Postbus 80.021, 3508 TA Utrecht, The Netherlands.

ABSTRACT: Stress relaxation experiments were carried out in 1-D compaction mode on granular salt with various pore fluid phases at room temperature. Merck salt (99.5% pure NaCl), sieved into different grain size fractions, was used as starting material. Samples were first compacted rapidly to a fixed porosity in the range 30-0.3% and the applied stress was then allowed to relax at fixed crosshead displacement. The effects of water content, applied stress, grain size, and porosity were systematically investigated. In fully dry, argon-flushed samples, the measured relaxation creep rates were insensitive to grain size but very sensitive to applied stress with an apparent power law stress exponent (n) of around 20. However, if the samples were exposed to lab air, the stress exponent dropped sharply (n=5.1) compared to the dry samples, showing significant weakening by moisture. In samples flooded with NaCl saturated solution, the stress exponent was found to be almost exactly 1 at the lower stresses investigated (<20-15 MPa). The creep rate of samples flooded with brine was sensitive to grain size. The mechanical results together with microstructural analysis showed that the dominant deformation mechanism in the dry, argon-flushed samples was probably dislocation glide whereas it was pressure solution in the brine-flooded samples at stresses <20-15 MPa. However, the relaxation behaviour seen in samples tested with lab air (n=5.1) is less easily explained. The dominant process is certainly not pure dislocation creep or glide, since it is activated by the access of lab air (moisture). Extensive recrystallization by grain boundary migration is observed in these samples and it must play a role in controlling relaxation and apparent n-value, possibly with a contribution from pressure solution and/or plasticity coupled solution transfer.

Excavation Damaged Zones in Rock Salt Formations

Norbert Jockwer, Klaus Wieczorek
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Germany

ABSTRACT: During an ongoing project which succeeds previous investigations of the excavation damaged zone (EDZ) performed in the Stassfurt halite of the Asse salt mine, the EDZ evolution, especially after cutting off the contour zone, is investigated. Three test locations have been prepared in the floor of an almost 20 year old gallery on the 800-m level of the Asse mine: (1) the drift floor as existing, (2) the new drift floor shortly after removing of a layer of about 1 m thickness of the floor with a continuous miner, (3) the new drift floor 2 years after cutting off the 1-m layer. Subject of investigation are the diffusive and advective gas transport and the advective brine transport very close to the opening. Spreading of the brine is tracked by geoelectric monitoring in order to gain information about permeability anisotropy. Results obtained up to now show that EDZ cut-off is a useful method to improve sealing effectiveness when constructing technical barriers.

Fundamentals and first Application of a new Healing Model for Rock Salt

K.-H. Lux
Professorship for Waste Disposal and Geomechanics, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

S. Eberth
DBE TECHNOLOGY GmbH, Peine, Germany

ABSTRACT: A new phenomenological model for the description of healing of damage and dilatancy in rock salt has been implemented in the *Hou/Lux* constitutive model *(Hou, Lux, 1998)*. It was tested in laboratory tests and applied to an in-situ project in rock salt. Based on the laboratory results, three phases to describe decrease of damage and dilatancy could be identified. A change in the applied load, i.e. a decrease of deviatoric stress and simultaneous increase of isotropic stress, creates a stress state that provides good healing conditions, so that in the first phase of the healing process (micro-)cracks are degenerated and closed to a large extend. This first phase is called the fissure closing phase. In the following second phase, which is called fissure sealing phase, cracks are closed as well, but not as fast as in the fissure closing phase as it is time-dependent contrary to the load-dependent fissure closing phase. When both, the fissure closing phase and the fissure sealing phase are concluded, the third and actual healing phase begins. It is assumed that in this phase, the mineral structure of nearly closed cracks in the rock texture and thus its mechanical properties are restored by rearranging grain boundaries, forming sub-grain structures and new grains via mass transport effects. The new healing model was validated by means of numerical simulations of a lab test, one in-situ situation, and of one hypothetical situation.

The Mechanical Behavior of Building Materials Based on the Hydration of Evaporite Minerals

Th. Leusmann & H.-J. Engelhardt
DBE Technology GmbH, Eschenstraße 55, D-31224 Peine, Germany

ABSTRACT: In Germany, radioactive and many types of chemotoxic waste must be disposed in deep mines. Among others, a suitable host rock for the ultimate disposal of the hazardous waste is salt. With respect to safety analyses a contact of the building materials used for backfilling and sealing measures with solutions must be considered. However, many conventional materials deteriorate in the saline milieu and/or their long-term behavior is difficult to describe. Moreover, questions exist concerning the reaction of these materials with gases. For this reason, a new family of building materials was developed. All recipes have in common the mixing of Mg-bearing salts with salt solutions. They harden as a result of salt hydrate crystallisation. After an initial contraction during the liquid phase several systems show a considerable swelling. Measurements have been carried out to quantify the increase in volume (open system) and the resulting crystallisation pressures in closed vessels. A constitutive law describing Young's modulus and creeping in the early age of the material enables the calculation of crystallisation pressure from swelling strain. The parameters of the constitutive equation for creeping were fit to results of the laboratory experiments.

Lode angle effects on the creep of salt

K.D. Mellegard, K.L. DeVries, & G.D. Callahan
RESPEC, Rapid City, South Dakota, USA

ABSTRACT: The steady-state creep rate of salt is typically described using only the maximum and minimum principal stresses and is generally considered to be independent of the intermediate principal stress; thus, the steady-state creep rate of salt is expected to be the same under both compressive and extensile states of stress. However, little experimental evidence has been obtained regarding the transient nature of salt under alternating states of stress between triaxial compression and triaxial extension; i.e. alternating Lode angles. Multi-stage creep tests were performed to investigate the time-dependent behavior of salt at two Lode angles. The data show that Lode angle does not affect the steady-state strain rate of salt; however, each time the Lode angle was changed, a significant transient response was observed. This transient response to changes in Lode angle is not predicted by constitutive models commonly used to evaluate natural gas storage caverns.

Deep salt-cavern abandonment

B. Brouard
Brouard Consulting, Paris, France
P. Bérest & M. Karimi-Jafari
LMS, Ecole Polytechnique, Palaiseau, France

ABSTRACT: When a salt cavern is sealed and abandoned, its pressure slowly changes due to various mechanical, hydraulic, thermal and chemical effects. These effects are described in this paper. Several of them can be predicted accurately. It is suggested that an abandonment test be performed before sealing a cavern in order to assess each effect separately, a prerequisite for credible long-term prediction.

Some aspects of the transient behavior of salt caverns

M. Karimi-Jafari & P. Bérest
LMS, Ecole Polytechnique, Palaiseau, France

B. Brouard
Brouard Consulting, Paris, France

ABSTRACT: The effects of transient creep in salt caverns are discussed. Salt behavior is viscoplastic: following a change in cavern pressure, a slow redistribution of stress takes place. This explains the long duration of any transient phase in a cavern. Stress redistribution also makes fracturing easier when cavern pressure is kept low for a long period of time. “Reverse” creep, a transient mechanical phenomenon that can be observed in the laboratory, also exists in salt caverns and may lead to misinterpretation of Mechanical Integrity Tests.

Modeling of hydro-mechanical behavior of rock salt in the near field of repository excavations

A. Pudewills
Forschungszentrum Karlsruhe GmbH, Institut für Nukleare Entsorgung
Postfach 3640, 76021 Karlsruhe, Germany

ABSTRACT: In this paper, the development of the Excavation Disturbed Zone (EDZ) in the rock salt around a disposal drift and the consolidation behaviour of backfill material are presented. In order to perform this analysis, finite element codes containing a set of time- and temperature-dependent constitutive models have been used. A new viscoplastic constitutive model for rock salt that can describe the damage of the rock is proposed. The results of the simulations show that under expected repository conditions the volume closure and the compaction of the backfill are mainly determined by the temperature increase and the lithostatic pressure. Furthermore, the numerical results demonstrate the importance of the increasing compaction pressure in the backfill on the evolution of the EDZ.

Self Sealing Backfill (SVV) – A salt based material for constructing seals in salt mines

H.-J. Herbert
GRS – Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Braunschweig Germany

ABSTRACT: A self-sealing salt backfill (SVV) based on anhydrous magnesium sulphate has been developed. Fine grained dry initial material (SVV) can be emplaced pneumatically. Artificial flooding of the pore space with brine initiates a reaction that leads to the formation of a brine tight seal. The reaction consumes the brine completely and forms an impermeable plug with a new mineralogy and greater volume of solids. The initial high porosity is reduced to 2-5 vol.-% of isolated pores. Mineralogical assemblages obtained in the experiments and measured by X-ray diffraction agree well with results of geochemical modelling with EQ3/6. The geochemical modelling allows the quantification of the short- and long-term volume changes in the system and demonstrates that in the long run stable mineral assemblages will be obtained. The volume increase leads to a considerable crystallization pressure. The porosity/permeability relationship resembles that of highly compacted crushed rock salt backfill. The mechanical properties are comparable with the values of undisturbed rock salt. These results indicate that SVV is a self-sealing long-term stable and to wide extend predictable predictable material.

Microstructural study of reconsolidated salt

G.M. Pennock, X. Zhang, C.J. Peach & C.J. Spiers
Faculty of Geosciences, Utrecht University, Postbus 80.021, 3508 TA Utrecht, The Netherlands.

ABSTRACT: In this study we examine the microstructures of reconsolidated rock salt after rapid pre-compaction to a porosity of 5%, followed by stress relaxation testing. Synthetic NaCl powder was used for the deformation experiments. Nominally dry material was exposed to laboratory air during stress relaxation at a nominal porosity of about 5 %. The relaxation behaviour of this material could be described by a power law with an (apparent) n value of ~5. The microstructure of polished and lightly etched material was characterized using scanning electron microscopy (SEM) and electron back scattered diffraction (EBSD). A large number of grains were strain free, although some extensively deformed grains were also present. Intra- and inter-granular porosity, grain indentations, and channel-island grain boundary microstructures, were also observed. These microstructural features confirm that, in addition to crystal plastic flow, several other mechanisms were operating during reconsolidation. In particular, extensive recrystallization by fluid activated grain boundary migration had occurred. When recrystallization occurs, the strained material is reset to an undeformed state. In view of this, and the drastic work hardening flow that must have occurred during pre-compaction, stress relaxation did not involve steady state deformation. Other mechanisms such as pressure solution may also have operated.

Long-term Laboratory Investigation on Backfill

D. Stührenberg
Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany, e-mail: dieter.stuehrenberg@bgr.de

ABSTRACT: Crushed salt is the preferred backfill material for a technical barrier in a final repository of radioactive waste in salt formations because it will have the same properties as the host rock after full compaction. However, it must be compacted by the convergence of the host rock to stabilize the underground openings and to reduce sufficiently the permeability in the EDZ and the backfill. High temperatures close to the waste containers favour the compaction process of pure crushed salt quite well. At lower temperatures, addition of bentonite supports the compaction process and favourably reduces the permeability. On basis of our laboratory test results we recommend a mixture of 85% crushed salt and 15% Ca-bentonite as a backfill barrier component in the lower temperature range.

Post-Tests on Thermo-Mechanically Compacted Salt Backfill

Chun-Liang Zhang, Tilmann Rothfuchs, Johannes Droste
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
Theodor-Heuss-Strasse 4, 38122 Braunschweig, Germany

ABSTRACT: To examine the geotechnical properties of salt backfill which had been compacted for more than 8 years at high temperatures of 90°C to 170°C in the TSDE test drifts in the Asse salt mine, post-tests were carried out on drilled cores. The triaxial compression behavior of the backfill was investigated on large samples of 280 mm diameter and 510 mm to 710 mm lengths. The bulk modulus increased with decreasing porosity. The strength measured on the pre-consolidated samples is comparable to that obtained on the same material but without pre-compaction. Coupled to the mechanical tests, permeability measurements by nitrogen gas were conducted at different porosities. The permeability decreases exponentially from $1 \cdot 10^{-12}$ m^2 at a porosity of 26% to $1 \cdot 10^{-13}$ m^2 at a porosity of 7%. The post-test results confirm the *in-situ* measurements and the constitutive models used for the prediction of the backfill behavior.

Monitoring of roof stability in salt mines

J.-P. Schleinig & V. Lukas
K+S Aktiengesellschaft, Kassel, Germany

ABSTRACT: Understanding the mechanical behavior of salt related to roof stability of drifts is of crucial importance for the safety of workers and installations in mines. In its potash and rock salt mines K+S uses different measures and instruments to collect geomechanical data and to monitor roof stability. Examples of the various methods to monitor the roof behavior are discussed for the potash mine Werra and the rock salt mine Borth. This monitoring supplies quantitative data for further geomechanical interpretation and is the base for a prognosis of the development of roof stability.

Influence of effective stress on strain rate around the gas storing cavern

J. Ślizowski
Polish Academy of Sciences, Mineral and Energy Economy Research Institute, Cracow, Poland

K.M. Urbańczyk
Research and Development Centre for Mining of Raw Chemical Materials - Chemkop, Cracow, Poland

ABSTRACT: Mogilno salt dome has very complicated geological structure, thus natural gas storage caverns had to be placed at various depths, in rock salt of different strength and creep properties. Creeping law parameters given by laboratory testing of core samples can be inadequate. The paper presents selected results of the sensitivity study on influence of exponent in Norton law and boundary conditions on strain and stress state of rock formation around the storage cavern and its convergence. It was found that, in several cases, lower exponent and thus lower creeping rate leads to greater strains on the cavern wall and higher cavern convergence. This behavior can be caused by greater influence of effective stress reduction than that of strain rate resulting from the creeping law. It means that caverns in rock salt of smaller creeping rate reaction on effective stress change can be less stable than in case of greater creeping.

THMC Numerical Simulation and a Solution Mining Method for Thin Salt Deposits

W. G. Liang & Y. S. Zhao
Mining Technology Institute, Taiyuan University of Technology, Taiyuan, Shanxi Province,China

C. H. Yang
Rock and Soil Mechanics Institute, Chinese Academy of Sciences, Wuhan, Hubei Province,China

M. B. Dusseault
Earth Sciences Department, University of Waterloo, Waterloo, Ontario, Canada

ABSTRACT: Thin salt deposits present different solution mining issues than thick ones. For thin salts, traditional single-well plus annular casings solution mining methods are neither feasible nor economic. Here, we propose and model the hydraulic coalescence solution mining method for thin salt deposits, based on circulation between wells linked through hydraulic fracturing, using the non-salt interfaces to constrain fracture propagation. Solution mining of salt is a chemicothermal process, and the salt deposit will deform viscously under the combined effects of cavity growth and gravity-induced stresses during the mining process. This is clearly a THMC process (Thermal, Hydrological, Mechanical, Chemical process). In this paper, the coupled THMC process is addressed theoretically, then a set of numerical simulations are carried out.

Effects of Cavern Shapes on Cavern and Well Integrity for the Strategic Petroleum Reserve

S.R. Sobolik and B.L. Ehgartner
Sandia National Laboratories, Albuquerque, New Mexico, USA

ABSTRACT: This report presents computational analyses to determine the structural integrity of different salt cavern shapes. Three simple characteristic shapes (caverns with enlarged tops, bottoms, and mid-sections) are evaluated for increasing cavern volumes and compared to the baseline shape of a cylindrical cavern. The intent of these calculations is to develop some guidelines to predict cavern performance and damage in salt, utilizing the three-dimensional modeling capabilities of high-performance analytical codes and sophisticated material models.

Usability evaluation of the existing solution-mined caverns for gas storage

C.H. Yang & Y.P. Li
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P.R. China.

Q.H.Qian
Engineering Institute of Engineering Corps, PLA University of Science & Technology, Nanjing, P.R. China.

D.H. Wei
West-east Pipeline Company, PetroChina Company Limited, Beijing, P.R. China

F. Chen & X.Y. Yin
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P.R. China.

EXTENDED ABSTRACT: Salt rocks are commonly used as the ideal geologic host rocks for storage of gas and crude oil, and are being considered for the disposal of radioactive waste. However, the sediment characteristics of salt rocks in China are greatly different with that in the many other countries. According to the requirement of the West-East Gas Transmission Pipeline Project in China, the existing salt caverns in Jintan Salt Mine, Jiangsu province, were selected to be natural gas storages after appropriate reconstruction. In this paper, the feasibility studies of the gas storage for the construction of Jintan gas storage project were introduced. The geological investigation of the host salt rock formation, the experimental analysis on the mechanical and creep characteristics of salt rocks and mud rocks, numerical study on deformation and stability of these caverns, and in-situ test in brine-filled cavern tests for two salt caverns were presented, respectively. It was concluded that the six salt caverns, Xi-1, Xi-2, Dong-1, Dong-2, Gang-1 and Gang-2 caverns, were suitable to be utilized as gas storages. The conclusions about usability and some suggestion for the old cavern reconstruction and running were as follows:

1. The mechanical and creep test showed that the creep characteristics of rock salt and rock salt containing mudstone were similar. Under differential stress 15.0 MPa, the steady creep strain rate of salt rocks was $(2.5\sim5.0)\times10^{-5}$ /h, that of salt rocks containing mudstone was $(1.9\sim3.8)\times10^{-5}$ /h, and that of mud rocks containing salt was $(0.5\sim1.0)\times10^{-5}$ /h. The steady creep strain rates of the three rocks were in the same order, so the cavern cap rocks would not have to suffer incompatible creep deformations.
2. The breakthrough pressures of the cavern roof rocks were between 6.68~21.25MPa, which provided the caverns a good sealability. The six caverns were far from the faults, so, these faults would not affect the stability and sealability of gas storage.
3. The numerical analysis results of cavern stability and deformation showed that, with the increase of internal pressure, the maximum displacement and the volume reduction of salt caverns decrease gradually. Increasing internal pressure could restrain obviously the cavern volume reduction, so, in order to prolong the service life of gas storage, it was strongly recommended that the running time under low internal pressure should be reduced as soon as possible.
4. Allowable operational pressure difference between the adjacent caverns depended on the design service life and the minimum operational pressure. The results showed that the cavern stability could be guaranteed if the operational pressure was between 6 to 14.5 MPa. For safety, it was suggested that the operational pressure difference between two adjacent caverns should not exceed 3.0 MPa.
5. Based on the data of volume reduction rates of each cavern under different pressure reduction rate, a volume reduction rate of 0.015% /day was suggested to be the ultimate limit during a gas extraction phase. The maximum pressure reduction rate should not exceed 0.55 MPa/day during gas extraction phases.
6. The results of brine pressure and discharge tests of Xi-1 cavern and Xi-2 cavern showed that the two caverns were sealed well, and they could withstand the maximum internal pressure up to 15.43 MPa. Under differential stress of 5~10MPa, the creep rate of rock salt 2.36×10^{-5} /h obtained from laboratory tests agreed well with the result 2×10^{-5} /h by inversion analysis of the cavern pressure test. Therefore, from the numerical simulation of a former gas storage running process, it was reasonable to adopt the above-mentioned creep parameters of the salt rocks from the Jintan Salt Mine.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from National Natural Science Foundation of China (50374064, 50334060) and the Project of National Basic Research Program of China (2002CB412704).

Deformation mechanisms and rheology of Pre-cambrian rocksalt from the South Oman Salt Basin

J. Schoenherr, Z. Schléder*, J.L. Urai
Geologie - Endogene Dynamik, RWTH Aachen University, Germany
*(*now Midland Valley Exploration Ltd., United Kingdom)*
P.A. Fokker
Shell International Exploration and Production B.V. Rijswijk, The Netherlands
O. Schulze
Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany

ABSTRACT: The Neoproterozoic to Early Cambrian Ara Salt from the South Oman Salt Basin has been investigated for creep behavior and microstructure. The salt behavior is of relevance for oil production out of intra-salt carbonate "stringers". Test and in-situ conditions are about T = 100 °C and p_c = 70 MPa. Strain rate stepping and temperature stepping tests have been performed, with creep rates varying from 5 10^{-8} to 10^{-5} s^{-1}. All tests were run to a total strain of 25 - 30%. Both secondary and primary creep parameters have been determined. Secondary creep is basically reached only at rates of 10^{-7} s^{-1} or lower (15 MPa differential stress or lower), still orders of magnitude faster than expected in situ rates, except perhaps borehole closure related creep during drilling. Microstructural observations revealed that the main deformation mechanism during the tests was dislocation creep associated with grain boundary migration recrystallization. This is evidenced by subgrain size reduction, the development of slip lines and the formation of new strain-free grains growing at the expense of subgrain-rich grains. Comparing literature data, the Ara Salt appears to be quite common (average), both under the microscope as in creep behavior.

Pillar deformation-induced surface subsidence in the Hengelo brine field, the Netherlands

R.F. Bekendam
GeoControl, Maastricht, the Netherlands, geocontrol@planet.nl

J.L.Urai
GeoStructures, Maastricht, the Netherlands, j.urai@geostructures.nl

ABSTRACT: In the Hengelo area, East Netherlands, solution mining of rock salt is carried out by Akzo-Nobel from a 50 m thick salt deposit of Triassic age, located at about 350 m depth. Until recently surface subsidence was mainly ascribed to upward migration (stoping) above overmined caverns. However, in the oldest part of the brine field the extraction ratio is so high, that also deformation of the remaining salt pillars has to be taken into account. The effect of pillar creep on surface subsidence was investigated by the construction of a series of subsidence rate maps, per year from 1947 to 2003, and the analysis of the relationship of the pattern of these subsidence rates and the most likely cavern and pillar outlines.

This study not only confirmed the existence of several subsidence areas as a result of stoping, but also revealed evidence of a pillar deformation-induced subsidence area. The stress state in this pillar proved to be such that significant dilatancy must be considered. It was concluded that in the dilatant pillar solution-precipitation creep can contribute to the total deformation at the same amount as dislocation processes. It is recommended to incorporate solution-precipitation processes in future geomechanical models of pillar creep, even under non-dilatant conditions.

Modeling of strain softening and dilatancy in the mining system of the southern flank of the Asse II salt mine

P. Kamlot & R.-M. Günther
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

N. Stockmann & G. Gärtner
GSF – Forschungszentrum für Umwelt und Gesundheit GmbH, FB Asse, Remlingen, Germany

ABSTRACT: In the Asse II salt mine's southern flank an array with relatively small pillars and stopes was excavated between 1916 and 1964 in the course of halite extraction. Most of the volume of the chambers (in total approx. 3.5 Mio. m^3) was exposed to free convergence until 1995, when a backfilling campaign by pneumatic transportation of a granular salt material started, which lasted until 2003. The barrier to the overburden rocks is formed by rock salt with a minimal thickness of only 15 m in the upper part. The flank dips by approx. 70° in a SW direction. The rock mechanical evolution has been monitored for decades by displacement observations, stress and strain measurements in the pillars, and recording of the backfill pressure built-up in the chambers. Furthermore, microseismic activity in the mine and the adjacent overburden has been recorded. Softening and damaging in the pillars and stopes of the mining horizon have led to stress redistributions into the overburden rocks, where fracturing processes were generated as well. Hence, because of the small dimensions of the bearing elements on the southern flank and the close distance to the overburden, far reaching geomechanical interactions exist. The purpose of the project was the modeling of mining history and of observed rock mechanical behavior aiming at the stability proof and prediction until the end of operating phase. For that a time-dependent elasto-visco-plastic constitutive law was used which describes softening, dilation, and creep. The material parameters were found in special laboratory experiments determining the residual strength after exceeding the peak of the stress-strain curves in the domain of dilatancy. In the 3D-modeling course all calculated stresses, deformations, and geomechanical reactions could be confirmed as measured in situ. Therefore, the model can be considered as validated and qualified for prediction.

A model for rock salt, describing transient, stationary, and accelerated creep and dilatancy

R.-M. Günther & K. Salzer
Institute for Rock Mechanics GmbH, Leipzig, Germany

ABSTRACT: In the scope of a unified approach to describe the creep behavior the constitutive model as presented here describes comprehensively the mechanical behavior of rock salt in a good approximation. In this model, hardening is used as an inner variable of state. This model has been verified by the results which were obtained when recalculating a plurality of different laboratory tests. Evidently, hardening is governed by the processes of deformation and recovery on the one hand and by those of damage on the other one, i. e. the formulation of the constitutive laws is based just on those processes of crystal physics which are the origin of the mechanical behavior of salt rock. These considerations have allowed to demonstrate that the hardening-reducing effect of damage can be put on the same level as the dilatancy, the latter being a function both of deformation work performed above the dilatancy boundary (damage work) and minimum stress which has to be determined from triaxial tests. The paper contains a complete set of equations, which are used in model calculations.

Dynamic processes in salt rocks – a general approach for softening processes within the rock matrix and along bedding planes

W. Minkley & J. Mühlbauer
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

G. Storch
K+S Kali GmbH, Germany

ABSTRACT: Understanding of the relevant failure processes is a prerequisite for dimensioning of underground mining openings. Investigation of brittle failure processes in potash mining and their simulation by rock mechanical modelling clearly demonstrate that the fracture mechanisms of slender and compact pillars are quite different. The collapse of a compact pillar is only possible if besides an overall softening of the rock coevally an accessory loss of cohesion occurs at pronounced weakness planes, particularly along the bedding planes towards the hanging and the underlying layers of the pillars. For the description of the different dynamic processes specialised constitutive models are available, which were verified with various case studies. Exemplarily, the dynamic failure event that actually occurred at the mined top of a domal carnallitite structure has been recalculated. The pronounced seismological s-wave signal which had been recorded during the event has been convincingly referred to development of a shear fracture as the relevant failure mechanism.

Constitutive models to describe the mechanical behavior of salt rocks and the imbedded weakness planes

W. Minkley & J. Mühlbauer
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

ABSTRACT: Up to now salt rock mass has been predominantly regarded as a continuum and the mechanical effect of the present discontinuities and bedding planes have been neglected to a great extent. However, for a complete understanding of a couple of geomechanical phenomena this approach proves to be insufficient. When solving numerous practical problems in potash and rock salt mining it clearly turned out that a treatment without taking the existing bedding planes and discontinuities into account will not provide a satisfying explanation of the observed rock mechanical processes. Therefore, for a mechanical description of the complex properties of the salt rock mass a visco-elasto-plastic constitutive model is presented, which comprises the hardening/softening behavior and dilatancy effects for salt rocks, as well as a specific friction model, which comprises displacement- and velocity-dependent shear strength softening for salt bearing bedding planes.

Gas transport in dry rock salt – implications from laboratory investigations and field studies

T. Popp & M. Wiedemann
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

A. Kansy & G. Pusch
TU Clausthal - Institut für Erdöl- und Erdgastechnik, Clausthal, Germany

ABSTRACT: Gas transport properties are key issues in the long term assessment of storage of high level radioactive or toxic waste in salt formations. Whereas extensive knowledge exists regarding the initial and dilatant rock salt properties, little is known about consequences due to the long term gas generation in a radioactive waste repository. Because rock salt is attributed to be impermeable for gases and fluids gas pressures will be built up with time until a level that may exceed the fracturing pressure of the rock (generally discussed as gasfrac-scenario). For an assessment of the provable impact of increasing gas pressures on the integrity of rock salt we present preliminary results from a long-term field test with progressive gas injection in a gas-tight sealed borehole. To detect micro-cracking a highly sensitive micro-seismic network was installed. Remarkably, in the multi-stage injection tests the gas-breakthrough was obtained at a gas pressure of 140 bar slightly above the primary stress state inducing a pressure build-up in two neighbored control bore holes. Due to the associated permeability increase of 3 orders (up to 10^{-20} m^2) transient pressure decay occurs coevally in the pressurized injection-borehole. Reaching equilibrium at around 100 bar the primary gas-integrity is partly restored in the order of 10^{-22} m^2. Most important, no pressure induced micro-seismic activity was observed during the gas-breakthrough which clearly contradicts the gas-frac-scenario. For comparison, we performed additional laboratory investigations highlighting the impact of increasing pore pressures on permeability whereby the effect of the gas-breakthrough could be attributed to pressure induced opening of grain boundaries. In addition, special account is taken to the effect of anhydrite bearing intercalations which may canalize the spatial gas migration in salt.

The Bernburg Test Cavern – in situ investigations and model studies on cavern abandonment

Brückner, D., Lindert, A. & Wiedemann, M.
Institut für Gebirgsmechanik GmbH, Leipzig, Germany (IfG)

ABSTRACT: This paper summarizes test results obtained during the so-called “Test Cavern” project performed in the salt mine Bernburg (Saxony-Anhalt, D) aiming on the long term behaviour of a sealed brine filled cavern. Because its evolution depends on the system’s geomechanical and hydraulic properties and their interactions, an extensive research program were done comprising in-situ tests in a brine filled model cavern and bore holes, rock mechanical investigations and modelling. Only for the purpose of well defined test conditions and for facilitating a latter direct inspection of the brine pressure affected rock wall a model cavern with a total volume of around 22 m^3 was leached of at an underground level of around 420 m. Major part of the research program were the pressure build up tests performed as well in the test cavern and as well in boreholes for over a duration of 2.5 years allowing an estimate regarding scale effects. With respect of interpreting the in situ results an accompanying rock mechanical investigation program was carried out to prove the deformation behaviour of the surrounding rock mass, the stress state in the solid by hydro-fracturing and the rock mechanical behaviour of rock salt samples from the surrounding rock mass. Finally, the observed time dependent coupled processes were numerical modelled using a modified FLAC-Code allowing the quantitative simulation of pressure dependent brine permeation in into the wall.

Petrophysical and rock-mechanical characterization of the excavation-disturbed zone in tachyhydrite-bearing carnallitic salt rocks

T. Popp, K. Salzer & M. Wiedemann
Institute for Rock Mechanics GmbH (IfG), Leipzig, Germany

T. Wilsnack
Consulting for Mining, Water and Waste Disposal Engineering (IBeWa), Freiberg, Germany

H.-D. Voigt
Freiberg University of Mining and Technology, Institute of Drilling Engineering and Fluid Mining, Germany

ABSTRACT: Drift sealing systems requiring long-term stability are important components in technical barrier concepts for hazardous-material disposal sites in salt formations. In contrast to rock salt, special problems for sealing systems in potash formations arise because of the ease of dissolving minerals such as carnallite and tachyhydrite-kieserite mineral. Therefore, besides the geo-chemical and technical aspects (e.g. development of an appropriate dam building material) the main emphasis of current investigations is to understand the excavation-disturbed zone (EDZ) because of its importance as a potential “short circuit” pathway around the sealing structure. Results of numerous geophysical in-situ investigations (e.g. permeability and electrical-resistance measurements) in the abandoned potash mine Teutschenthal (D) are presented in this paper. These investigations identified local geological and hydraulic problem areas which may affect the sealing efficiency of the dam building. Additionally rock-mechanical laboratory tests on the carnallitic host rock prove to be a prerequisite for characterizing near-field properties in potash mines.

Mechanical and permeability properties of highly pre-compacted granular salt bricks

K. Salzer, T. Popp & H. Böhnel
Institut für Gebirgsmechanik GmbH, Leipzig, Germany

ABSTRACT: In the salt concept for the disposal of high level radioactive waste in deep geological rock formations granular salt is the favorite for backfilling of remaining openings because of its advantageous physical properties. However, its initial sealing capacity is low due to the high porosity. Besides others, the usage of pre-compacted blocks of crushed salt offers an alternative sealing concept. Our investigations are aiming to investigate both the mechanical compaction behavior and the evolution of transport properties in salt bricks (artificial pressed granular salt with a porosity of ~8%), as a prerequisite to develop mechanism-based constitutive models describing these processes in the low porosity region (10 - 1%). A key factor is the role of water, since it affects in a complex manner the coupled hydraulical/mechanical properties of granular salt.

Performance of a mining panel over tachyhydrite in Taquari-Vassouras potash mine

Leo Rothenburg
University of Waterloo, Canada
Afonso L. P. Carvalho Jr.
CVRD, Brazil
Maurice B. Dusseault
University of Waterloo, Canada

ABSTRACT:
Taquari-Vassouras is an underground potash mine in northeastern of Brazil operated by Companhia Vale Do Rio Doce. Sylvinite is mined at depths ranging from 430 to 640 m where room and pillar panels are excavated using continuous mining equipment. The stratiform ore deposit consists of a lower and upper sylvinite layers separated by a barren halite interval. The underlying evaporites include a massive tachyhydrite layer separated from the lower sylvinite by a halite layer that in some areas is very thin or non-existent. Tachyhydrite is highly hygroscopic, weak, and creeps two orders of magnitude faster than the surrounding salts under similar conditions. One of the mine panels was successfully excavated in the area where tachyhydrite is in direct contact with sylvinite. An extensive array of convergence stations was installed in the panel and the panel was closely monitored. A series of room-and-pillar scale and panel-scale numerical analyses were carried out with the objective to establish the mechanism of tachyhydrite influence on the panel performance. It was established that despite operating difficulties related to floor heave, the presence of tachyhydrite has a positive influence on the stability of the roof.

Crack-Initiation and Propagation in Rock Salt under Hydromechanical Interaction

U. Heemann
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

W. Sarfeld & C. Hillmann
Scientific Research and Development (SRD), Berlin, Germany

B. Faust
Ingenieurbüro Faust & Fritsche (IFF), Berlin, Germany

ABSTRACT: For the finite-element modelling of macroscopic cracks in geomechanics a “smeared crack”-element has been developed. When tensile strength has been exceeded, it opens in direction of maximum tensile stress till tension is reduced to zero. Opening of the elements is strictly modelled sequentially – element by element – in order to simulate consistent growth of a macroscopic crack. The cracked elements are able to close again taking account of friction and sliding. In case of rock salt this fracture property has to work also under the action of creep and dilatancy. Last, but not least, opening and closure can be modelled under the further influence of fluid pressure.

In-situ measurements and 3-D model calculations of backfill compaction and EDZ development in waste disposal drifts in salt rock

S. Heusermann & U. Heemann
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

ABSTRACT: To improve methods and tools for the prediction of the long-term thermomechanical behaviour of a repository for radioactive waste in salt, experimental and theoretical studies were performed in the framework of two R&D projects at the Asse mine regarding the behaviour of disposal drifts, backfill material and host rock. Experimental studies included the long-term measurement of thermally induced stress change as well as permeability tests in the host rock and the excavation damaged zone (EDZ) around the test drifts. Theoretical investigation comprised the 3-D modelling of the in-situ experiment using the JIFE finite-element code. Results of calculations show that dilatancy and porosity occur in the near vicinity of the emplacement drifts. Calculated permeability increases in the vicinity of the test drifts and decreases to negligible values within a short distance. The experimental data are compared to the results of model calculations.

Three-dimensional geomechanical modelling of old mining rooms in the central part of the Bartensleben salt mine

S. Fahland, S. Heusermann, R. Eickemeier & H.-K. Nipp
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

J. Preuss
Bundesamt für Strahlenschutz, Salzgitter, Germany

ABSTRACT: Finite-element calculations have been made to analyse the stability of large old mining rooms and the integrity of the salt barrier in the Bartensleben salt mine. The recent state of stress and deformation around the rooms as well as dilatancy in the salt rock has been investigated. Several finite-element codes and two- and three-dimensional models were used taking two different dilatancy models into account. Roofs and pillars of the rooms are subjected to high creep deformations and partly to tensile stresses. Extended zones of dilatancy occur in the vicinity of the rooms and in the salt rock between rooms and anhydrite layers. As expected, the 3-D modelling yields lower stresses and deformations as well as reduced dilatant salt rock zones compared to the 2-D models.

THERMOMECHANICAL MODELLING OF THE BEHAVIOUR OF DRIFTS IN ROCK SALT

S. Olivella and A. Gens
Department of Geotechnical Engineering and Geosciences, UPC

ABSTRACT: This paper presents analyses of problems related to radioactive waste disposal in salt formations including crushed salt backfills. The large in situ test performed in ASSE mine which simulates an emplacement of a heat emitting waste in a drift has been modeled in 3D. The drift was backfilled with crushed salt, and the model includes also observation drifts. The second part of the paper, shows analyses that attempt to predict the permeability variations induced in the EDZ zone induced both by cavity excavation and by thermal loading.

Experimental research on deformation and failure characteristics of laminated salt rock

Y.P. Li & C.H. Yang
Institute of Rock & Soil Mechanics, Chinese Academy of Sciences, Wuhan, P.R. China.

Q.H. Qian
Engineering Institute of Engineering Corps, PLA University of Science & Technology, Nanjing, P.R. China.

D.H. Wei & D.A. Qu
West-east Pipeline Company, PetroChina Company Limited, Beijing, P.R. China

ABSTRACT: For investigation of the mechanical and failure characteristics of the laminated salt rock, a series of conventional test were carried out. Three types of samples, pure salt rock samples, pure interlayer (mud rock) samples and salt rock samples with interlayer, were prepared in this study. Uniaxial and triaxial compression experiments showed that the presence of mud rock interlayers in salt rocks affects the mechanical properties and failure pattern of the salt rock significantly. The presence of hard mud rocks in salt rock formations enhances the stiffness and strength of the composite rocks. An interesting ‘stress drop’ phenomenon was observed and then was interpreted by using the Cosserat medium model. The present results may be expected to provide useful reference for the site selection and design of oil/gas storage cavern in bedded salt rock formations.

Investigation on the long-term stability of gas storage in Jintan Salt Mine

X.Y. Yin, C.H. Yang, Y.P. Li & J.W. Chen
Institute of Rock & Soil Mechanics, Chinese Academy of Sciences, Wuhan, P.R. China

ABSTRACT: The solution-mined salt caverns can be utilized to store the natural gas and also the high-radioactive waste, so it is important to analyze the long-term stability of salt caverns. A user-defined creep constitutive model is compiled as a dynamic link library (DLL) file that can be loaded whenever it is needed and implemented into the software FLAC^{3D}. The stability after excavation and the law of the long-term volume convergence ratios of salt caverns selected in Jintan Salt Mine have been studied by the numerical method. The computation parameters are obtained from previous experimental results. The results show that the higher internal pressure will benefit the stability of salt caverns. The volume convergence ratios of salt caverns are below 22 percent as the running internal pressure of gas storage varies from 6 to 14.5 MPa. Based on the results of the numerical analysis, some useful advice has been provided for the construction and management of the gas storage in Jintan Salt Mine.

The engineering thermal analysis for natural gas storage in deep salt formation

J.W. Chen, C.H. Yang, Y.P. Li & X.Y. Yin
Institute of Rock & Soil Mechanics, Chinese Academy of Sciences, Wuhan, P.R. China.

ABSTRACT: Engineering thermal analysis for natural gas storage in deep salt formation is one of the bases of stability evaluation and running control. The presented analysis, in which the actual shape of the cavern and the thermal field were considered, is based on the variable mass system thermodynamics and it is performed on the FLAC^{3D}. The numerical analysis results show that: the pressures of the wellbore top and the cavern increase linearly during injection phase and decrease linearly during production phase; the change of temperature of the cavern and its wall obey parabola law during injection phase; during production phase, the temperature decreases firstly, then the decrease tendency slows down, and the temperature even increases a few at last; the temperature of the wellbore bottom and top changes as that of the cavern does during the whole cycle but the former change magnitude is smaller than the later one. Though the influence range of the temperature field during the performance is only 7-15 m around the cavern, the temperature gradient is very greater comparatively. This high gradient of temperature may affect the stability of the cavern.

Determination of mechanical homogeneous areas in the rock salt mass using creep properties for a classification scheme

Ingo Plischke
Federal Institute for Geosciences and Natural Resources, Hanover, Germany

ABSTRACT: The knowledge of the mechanical behavior of rock salt, especially the creep behavior, is important for the dimensioning and the long-term safety analysis of underground openings. The multiple internal configuration of the salt structures has to be taken into account in the corresponding model calculations. A mapping and characterization procedure based on laboratory creep tests is outlined. The results demonstrate the suitability and the efficiency of the method in which the classification of the rock mass is performed by the identification of areas of similar creep ductility. It provides the basis for the derivation of a site specific geo-mechanical model. The method was used for the site characterization of the Morsleben salt structure and the Gorleben salt dome. For the Morsleben site an example is given concerning the influence of several geological-mineralogical parameters on the creep behavior.

PREDICTION OF FUTURE EVOLUTION OF THE KŁODAWA SALT STRUCTURE (POLAND) BASED ON GEOLOGICAL RECORD AND ANALOGUE MODELLING DATA.

Stanisław BURLIGA[1)], Hemin A.KOYI[2)], Piotr KRZYWIEC[3)], Jacek GUTOWSKI[3)]
[1)] Institute of Geological Sciences, University of Wroclaw, pl. M. Borna 9, 50 – 204 Wroclaw, Poland, email: burliga@ing.uni.wroc.pl; [2)] Hans Ramberg Tectonic Laboratory, Department of Earth Sciences, Uppsala University, Villavägen 16, Uppsala, Sweden
[3)] Polish Geological Institute, ul. Rakowiecka 4, 00 – 975 Warsaw, Poland

Post-depositional redistribution of salt masses within a basin infill depends mainly on basin-scale tectonic and sedimentary processes. They initiate salt structures development and control both their shape and rate of salt mass migration throughout the sedimentary sequence. Although at a basin scale salt formations flow as a uniform mass, their lithological and structural heterogeneities actually lead to internal differentiation of the salt strain and flow rate throughout the salt series. Identification of strongly strained domains within salt bodies is of fundamental significance for safe location of underground repositories. These domains largely correspond to most easily mobilized portions of the salt structure, thus, they may endanger long-term stability of repositories. This study aimed at the recognition of high strain zones within the Klodawa Salt Structure and, basing on geological record and analogue modelling, at prediction of the most likely future development of its internal and external structure.

The Kłodawa Salt Structure (KSS), located in central Poland within the Danish – Polish Trough, is built of Zechstein salt series, which is excavated at a depth of 450-750 m below the ground surface. This structure is considered as a possible repository for various wastes, including radioactive. According to geophysical data, it is a narrow, about 60 km long ridge rising from more than 6 km depth up to the shallow subsurface in places. It extends NW-SE, parallel to the Trough alignment. Seismic sections and geological record reveal that salt series deformation started in the Early Triassic. The KSS evolution included several stages of rapid growth, stagnation as well as salt extrusion episode in the Late Triassic. Additionally it was tectonically modified during basin inversion in the Late Cretaceous/ Early Palaeogene. At present it is overlain by thick (more than 100 m) cover of Cainozoic sediments.

The complexity of the KSS rise history is also reflected by its internal structure – superposed folding, faulting, shearing and discontinuity of lithological units. Detailed geological mapping and analysis of tectonic features enabled distinguishing between weakly and strongly strained portions throughout the diapiric structure. Microstructural investigations, including subgrain piezometry, provided further evidence on strain distribution in rock salt units. All these observations enabled to outline zones of possible flow reactivation within the KSS.

The analysis of seismic and borehole data allowed to reconstruct detailed evolution of the KSS in the Mesozoic and to infer its modern dynamics. These constraints were used to perform a series of scaled analogue models in order to assess scenarios of future evolution of the structure and its surroundings. The models indicated possible fault location in sediments above the structure – both in a case of subsequent regional shortening or extension. These fault zones may propagate into the cap rock and initiate dip water circulation within a salt body. Colouring of the ductile layer (equivalent of rock salt in analogue models) enabled to outline internal flow patterns within a diapirc structure and to balance ductile mass flow during various stages of the structure development. This also indicated the most mobile portions of a diapiric structure during possible flow reactivation.

DIAGENETIC ALTERATION OF GYPSUM CAP ROCKS OF THE MOGILNO AND WAPNO SALT DOMES – PRELIMINARY RESULTS

Pawel WILKOSZ[1)], Stanislaw BURLIGA[2)], Joanna JAWORSKA[1)], Rafał RATAJCZAK[1)]

[1)] Adam Mickiewicz University, Institute of Geology, ul. Maków Polnych 16, 61-606Poznan, Poland; wilkosz@amu.edu.pl

[2)] University of Wrocław, Institute of Geological Sciences, pl. M. Borna 9, 50-204 Wroclaw, Poland; burliga@ing.uni.wroc.pl

Salt structures located in the Polish Lowlands are built of Zechstein evaporite series. They developed dominantly in the Mesozoic in response to tectonic and sedimentary events occurring in the Mid-Polish Trough – the SE segment of the Danish-Polish Trough. A few of them have also Cainozoic activity recorded. All structures piercing through the Mesozoic cover are topped by gypsum-clayey caps composed of insoluble residuum left after the dissolution of Zechstein rocks. The cap rocks make up a natural barrier protecting the structures' interiors from the inflow of unsaturated brine or ground water, therefore the recognition of cap rocks structure and potential permeable zones in them is crucial for safe underground waste disposal or hydrocarbon warehousing. This study aimed at the investigation of internal structure and diagenetic evolution of cap rocks of two salt structures – the Mogilno and Wapno Salt Structures (MSS and WSS, respectively), which are located in the axial part of the Mid-Polish Trough.

The cap rock mantelling the MSS has a varying thickness (77-190 m) and irregular upper boundary occurring at depths between 30.4-78.7 m below the ground surface. It is built of anhydrite, gypsum and clays, and it is covered by Cainozoic sediments. The cap rock above the WSS generally occurs at depths of 20-40 m below the ground surface, however in two locations it is exposed on the ground surface, which evidences Cainozoic activity of this salt structure. Alike the MSS cap rock, it has irregular upper boundary and it is composed either exclusively of gypsum or of a gypsum-clayey mixture. Additionally, karstic and subrosive structures which had developed in it are filled with allochtonous sediments (clays, muds, sands, gravels, lignite) deposited at various stages of the WSS development. Karstic structures locally incise into the cap rock down to the salt table level. Overall thickness of the WSS cap rock ranges between 5 and 160 m.

Petrographic studies carried within both cap rocks have revealed variation in mineral, structural and textural composition throughout these caps. The gypsum domains are built either of selenite or of massive, nodular or laminated, fine- to coarse-grained gypsum. The anhydrites appear as fine-grained, massive, nodular or brecciated types. Additionally they occur as blocks of original Zechstein anhydrite beds incorporated into the cap rock. Clays grade from uniform rocks to clay-gypsum interlayers in the vicinity of the gypsum domains. There are also clays with dispersed gypsum crystals or clay pockets located among selenite crystals. All these rocks are cut by joints and shear fractures filled in places by massive or fibrous gypsum.

Microscopic observations enabled to evidence common transformation of anhydrite into gypsum and rather accidental reverse transformation of these minerals. Alteration of Zechstein anhydrite blocks and residual cap rock anhydrite into gypsum took place predominantly at outer parts of those anhydrite bodies, as well as along shear fractures and joints. Alteration of anhydrite into gypsum at a grain scale was also observed along grain boundaries and cleavage planes. Gypsum occurs either as pseudomorphs after singular

anhydrite grains or as a substitution of several anhydrite grains by a single gypsum crystal. Locally lenticular crystals of gypsum were also substituted by anhydrite pseudomorphs.

Detailed analyses of shear fractures, shear zones, veins and gypsum interlayers showed that most occurrences of gypsum in clays originated from substitution of clays by diagenetic gypsum. This process seems to have been initiated by the development of joints and shear fractures in clays, which led to formation of fibrous gypsum vein or gypsum coatings with slickensides, respectively. In less localized shear zones in clays, individual fibrous gypsum crystal have grown subparallel to shear zone boundaries and only locally they have joined into continuous veinlets. Progressive growth of gypsum crystals within the fractures and shear zones has resulted in formation of continuous veins of varying thickness and orientation, which in consequence led to separation of clay layers into isolated, gypsum-vein-bounded clay domains. It seems that only within such domains selenite crystal free growth occurred, leading to formation of diagenetic gypsum layers and to removal of clay from those domains. The source of diagenetic sulphates was also located in the cap rocks – it is evidenced by partly dissolved anhydrite and gypsum grains. All the observations indicate that tectonic deformation may significantly contribute to diagenetic alteration of primary lithological composition and structure of the cap rock.

Evolution of a young salt giant: The example of the Messinian evaporites in the Levantine Basin

C. Hübscher & G. L. Netzeband
Institute for Geophysics, Center for Marine and Atmospheric Sciences, University of Hamburg, Germany

ABSTRACT: Recently published academic and industrial 2D- and 3D-seismic data elucidate early stages of the evolution of the Messinian evaporites in the Levantine Basin/eastern Mediterranean. The tabular evaporites within the basin represent a salt giant which was deposited in a deep basin-shallow water environment. Six evaporitic sequences have been identified within the entire basin. Four units are interpreted as massive halite units and two of them as alternating successions of clastic sediments and/or evaporitic facies. Individual deformation of the intra-evaporitic sequences like folding and thrusting strongly suggests tectonic shortening during the depositional phase. A second thin-skinned tectonic phase started at the upper Pliocene when the prograding shelves and slopes squeezed the evaporites basinward. There is a clear line of evidence for fluid flow through and out of the evaporites.

Execution and Analysis of Sonar Surveys to Support Rock-Mechanical Evaluations

A. Reitze & H. von Tryller & F. Hasselkus
SOCON Sonar Control Kavernenvermessung GmbH

ABSTRACT: The echometric surveillance of caverns is especially important with regards to their safe and effective operation. As opposed to brine production caverns, storage caverns are generally subject only to convergence and do not undergo large and irregular changes of shape under normal conditions. Echometric surveillance is therefore primarily employed to obtain proof of the cavern stability and convergence.

Applying the state-of-the-art tool technology it is possible during an echometric survey to measure and process besides the geometry all relevant parameters such as speed of sound, pressure and temperature with a single tool run. Only when considering the physical parameters it is possible to achieve high-accurate results from sonar surveys.

To support rock-mechanical evaluations it is sometimes advantageous to make measurements for specific regions of a cavern with a higher density of measuring points. So-called spiral measurements as well as surveys with an extremely high measuring point density can provide very accurate and detailed information.

In the first instance of the presentation the techniques used for surveying caverns as well as the survey procedure are described in general. Subsequently some interesting results of sonar surveys in regard to rock-mechanical evaluations and questions are presented.

Reactive transport modelling in salt material based on Gibbs energy minimization

Mingliang Xie[1], Helge C. Moog[2], Wenqing Wang[1], Horst-Jürgen Herbert[2]
Hua Shao[3]& Olaf Kolditz[1]
1 GeoSystemsResearch, ZAG, University of Tübingen, Sigwartstr. 10, D-72076 Tübingen, Germany
2 GRS, Theodor Heuss Str. 4, 38122 Braunschweig, Germany
3 BGR, Germany

The German concept for the geological disposal of high level radioactive waste (HLW) considers salt formations as a suitable host rock for underground repositories. To prevent aqueous solution from accessing waste containments, these need to be sealed off with a material compatible to the host rock. One candidate material for this purpose is anhydrous salt which upon contact with aqueous solution forms hydrates with higher specific volumes thereby closing flow paths. This paper presents a new model to deal with reactive transport in a high-saline environment. It covers conditions where all accessible pores are filled with solution as well as conditions where no aqueous solution is present at all. This paper reports about the conceptual model and provides demonstration test cases.

1 INTRODUCTION

Salt rock is considered to be one of the potential bed rock for high level radioactive waste (HLW) repositories. This is because of the fact that salt rocks are isolated from fresh water system and thus indicates stable and isolated geological and hydrogeological conditions. The permeability of salt rock is very low. The plastic-viscoplastic properties enables the salt rock to self-seal EDZ. Such effect can be enhanced owing to the heat generation of the HLW-canisters.

The free water content in salt rock is very low. Crystal water, however, can exist to some extent. During excavation, e.g. construction of the room and draft system, and during emplacement of the waste (i.e. operation period), and even after the enclosed period, water/vapor can be released to the EDZ and absorbed by salt and exist as crystal water. Heat generated by nuclear waste canister can even dehydrate the salt rock in the pore system and transport the vapor into the surrounding rock. Hydration or crystallization can change the volume of the minerals and consequently the pore system and/or pressure under constrained condition.

Consider progress has been made in the past decade in modelling reactive transport in nature systems (Noorishad et al. 1987), (Yeh and Tripathi 1991), (Lichtner 1988), (Steefel and MacQuarrie 1996), (Parkhurst and Appelo 1999), (Xu and Pruess 2001), (Hummel et al. 2002), (Xie et al. 2006). Numerically, three major approaches have been used to couple multi-species transport and geochemical reactions: global implicit approach, sequential non-iterative approach (SNIA) and sequential iterative approach (SIA). Two major approaches have been achieved in chemistry, chemical engineering and geochemistry: the law of mass action and the free energy minimization technics (GEM). The geochemical reactions of most reactive transport approaches are based on the law of mass action for groundwater system, which is difficult for the simulation of complex geochemical reactions like redox reactions. This is owing to the fact that most of the equations of geochemical reactions which appear in equilibrium systems are nonlinear. Free energy minimization technics (GEM) is a more robust numerical method, which is widely developed in chemistry, chemical engineering (Steefel and MacQuarrie 1996). However, GEM is rarely used in reactive transport codes.

This paper provides a new reactive transport model that coupled a chemical simulator ChemApp (Eriksson et al. 1996) based on GEM into the transport code GeoSys/RockFlow. It is verified against the coupling of GeoSys/RockFlow with PHREEQC based on the law of mass action and applied to simulate the complex coupled thermo-hydro-chemical (THC)

Deformation of a halite-anhydrite sequence under bulk constriction: Preliminary results from thermomechanical experiments

G. Zulauf & J. Zulauf
Institut für Geowissenschaften, Universität Frankfurt a.M., Altenhöferallee 1, D-60438 Frankfurt a.M., Germany, g.zulauf@em.uni-frankfurt.de

O. Bornemann
Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D-30655 Hannover, Germany

ABSTRACT: A new deformation apparatus has been used to model the internal kinematics of salt diapirs. We deformed layers of Gorleben anhydrite, embedded in Asse halite, under bulk constriction with the layers being oriented parallel to the major stretching axis, *X*, of the finite strain ellipsoid. Further deformation conditions were as follows: T = 345°C, σ_{max} = 4.59 MPa, $d\varepsilon/dt = 10^{-7}$ s^{-1}, $e_{X(max)}$ = 122%. 3D-images, based on computer tomography, suggest a strong interaction between folds and boudins, both of which affecting the anhydrite layer. D_1-folds, with axes subparallel to *X,* are hardly developed. D_2-folds, with axes subperpendicular to the layer, affect the boudins resulting in oblique orientation of the latter. With increasing layer thickness the length of boudins increases. However, the geometric data are not in line with results of analytical solutions derived for power-law material and with geometric data of folds and boudins produced by analogue experiments.

Geomechanical investigations on the integrity of geological barriers with special regard to laboratory tests

U. Düsterloh & K.-H. Lux
Professorship for Waste Disposal and Geomechanics, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

Abstract: Two criteria are currently used for verifying integrity of geological barriers. We shall describe them as mechanical criterion and hydraulic criterion. The mechanical criterion states that the integrity of the geological barrier is deemed to be proven if the state of stress which is computed in a model calculation is unsuitable for creating dilatancy deformations in the surrounding rock. The hydraulic criterion is fulfilled if the minimal principal stress in a model calculation is higher than the respective, depth-dependent hydraulic pressure of brine. There is currently no scientific consensus whether the proof of barrier integrity must only fulfil one of the two criteria or whether the criteria are mutually independent and must be seen as complementing each other. New tests on large rock salt cores on which a hydraulic fluid pressure is imposed in addition to the triaxial mechanical stress will be presented. As a result of the tests, it can be demonstrated that the aforesaid criteria must be considered as mutually independent.

Long-term behaviour of sealed brine-filled cavities in rock salt mass – A new approach for physical modelling and numerical simulation

K.-H. Lux
Professorship for Waste Disposal and Geomechanics, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

ABSTRACT: The load-bearing behaviour of caverns constructed in salt formations to extract minerals or to store energy has been the focus of scientific research for many decades. This research previously concentrated on confirming the stability and safety of the caverns during construction and operation. During the past 10 years, the focus has also partially fallen on the questions involving the abandonment of caverns and their long-term behaviour. Various options are available for abandoning caverns: the preferred option in most cases is filling the caverns with water / brine and sealing the access borehole. The load-bearing behaviour of fluid-filled closed caverns has therefore been the focus of technical and scientific investigations. This paper presents a new approach to the analysis of the load-bearing behaviour of sealed fluid-filled salt caverns. This primarily concerns the process of brine infiltration into the originally impermeable salt rock, and the physical modelling and numerical simulation of this process.