Approaches for Validation and Application of A New Material Model for Rock Salt Including Structural Damages

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The introduction of damage mechanics and of a new material model including structural damages into design concepts for the construction of salt cavities and salt mine pillars reduces some previous knowledge and modeling deficits. This seems to set out the scientific foundation for a more realistic and thus more economical cavity and pillar design while keeping the same level of safety. The following paper introduces the major statements worked out by the authors about the further development of salt cavity and salt pillar dimensioning as well as practice-oriented applications.

As examples, the calculated load-bearing behavior of a drift at the Sondershausen mine and the so-called prototype cavity at the Asse mine are examined, comparing the results of the newly developed *Hou/Lux* material model with the *Lubby2* material model. The comparison shows the advantages of the *Hou/Lux* material model, such as stress rearrangements from the contour into the rock mass formation as well as the identification of dilatancy, damage, softening and spalling zones and last but not least permeability changes.

Based on the methods by *Menzel* and *Uhlenbecker* and taking into account the methodical approaches of continuum damage mechanics, the newly developed method of salt mine pillar design by *Hou/Lux* is introduced.

1. INTRODUCTION

The development of design and geotechnical safety proofing methods for cavities and pillars in saliniferous formations is described in literature, e.g. in *Lux (1984)*, *Düsterloh (1993)* and *Hou (1997)*.

It has become evident, also in connection with the results of extensive laboratory and field investigations, that in spite of the further developed proofing equipment, conservative statements may have to be included into the proofing methods due to still existing deficits in the formulation of constitutive relations (material models). With an improved knowledge of the complex material behavior of ductile-viscoplastic saliniferous rocks, these conservative statements may still allow some leeway towards a more economical cavity and salt mine pillar design.

One tool for answering these questions could be "Continuum-Damage-Mechanics", which allows the description of material damage caused by external stress and thus the "damage process" down to the fracture.

With this background, this essay uses a new material model -based on the material model *Lubby2* according to *Lux (1984)* and based on the continuum-damage-mechanics, e.g. according to *Kachanov (1986)* or *Lemaitre (1992)* to design cavities and salt mine pillars as well as to analyze the safety with special emphasis on the life time.

2. MATERIAL MODEL *HOU/LUX* WITH CREEP RUPTURE CRITERION AND DAMAGE

The material model *Hou/Lux* is a material model, which includes in a more phenomenological way the effects of different deformation mechanisms, e.g. diffusion and dislocation, hardening and recovery as well as damage and damage healing, and which is thus capable of meeting the major demands on a material model for viscoplastic rock salts, at least in principle. The above mentioned mechanisms directly contribute to the formation of inelastic strain/strain rates and thus the respective current states of deformation and also contribute indirectly to the state of stress via the changing rigidity of the load bearing elements.

The details about the material model *Hou/Lux* are written in *Hou (1997, 2000)* and in *Hou & Lux (1998, 1999a)*.

3. Estimation of the parameters for the *Hou/Lux* material model by means of reanalysis of test data (*axially perforated salt sample*)

Model experiments with axially perforated rock salt samples from different locations under a constant axial and confining pressure as well as atmospheric pressure in the axially arranged bore hole have been performed as part of a BMBF research project at the Professorship for Disposal Technology and Geomechanics of the Technical University of Clausthal and have been described in *Lux et al. (1997)*.

Figure 1 shows the softened areas of such a large rock salt sample, subjected to triaxial stress over a period of 69 days, originating from the bore hole contour and visualized as lighter areas by means of tracing.

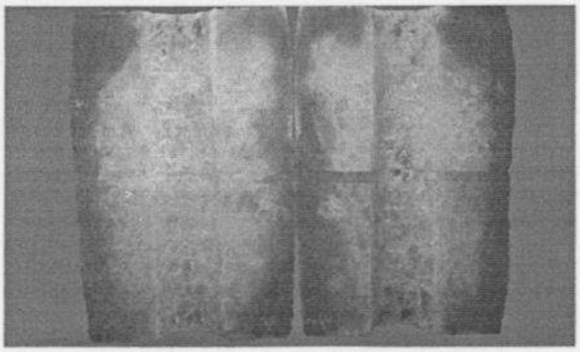

Figure 1. Axially perforated rock salt test sample with softened area (vertically cut after removal of the totally loosened salt rock of the fracture zone near the contour)

Since the tests for the explicit determination of the parameters that are to become part of the material model *Hou/Lux* could only be performed partially for metrology-related reasons, those parameters which are not yet explicitly determinable by means of tests, can so far only be estimated and validated regarding their numerical obviousness by means of validation analyses. The results of the model tests on axially perforated samples serve as a basis.

Figure 2 shows the test equipment used for these investigations. A closer specification of the equipment and the tests can be found in *Lux et al. (1997)*.

Figure 3 compares the contour of the large sample shown in Figure 1, measured after completion of the test, with the contour calculated numerically using the *Hou/Lux* and *Lubby2* material models (by means of parameter variation). The good correspondence in tendency and quantity between the measured contour and the contour calculated by means of the *Hou/Lux* material model is clearly visible. The deformation directed into the axial bore can only be calculated with the *Hou/Lux* material model or a corresponding material model that takes into account structural damage and dilatancy.

The parameters estimated this way can be found in *Hou (2000)*.

The following Figure 4 shows the stress distributions on the middle horizontal section at a time t = 69 d accordingto the *Hou/Lux* material model

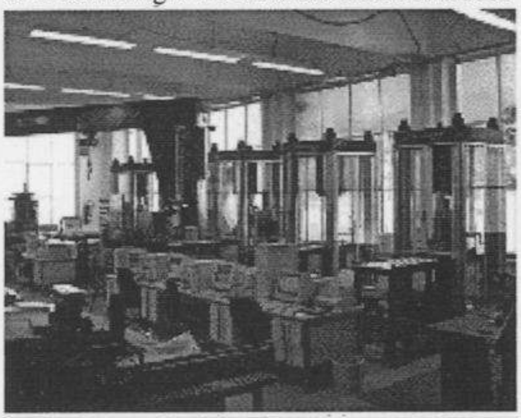

Figure 2. Some triaxial test machines of the geomechanical laboratory at the Professorship for Disposal Technology and Geomechanics at the TU Clausthal

and the *Lubby2* material model. The conclusions are:

- The stress distributions determined with the *Lubby2* material model after a creep time of 69 days still correspond more or less to the elastic stress distribution, *Lux et al. (1997)*.
- In this special case, the stress intensities are not large enough to make existing or new crack structures unstable and able to spread, so that neither creep rupture nor sudden failure of the

axially perforated rock salt sample nor a clearly accelerated creep phase can be observed or calculated.

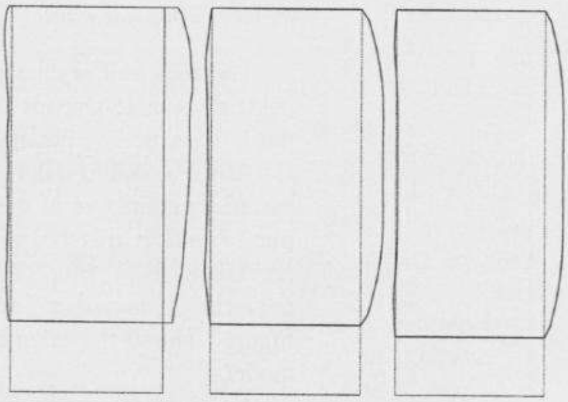

Figure 3. Comparison of the measured and calculated contour of an axially perforated rock salt sample (σ_1/σ_3 = 35/6 MPa; t = 69 d)

In summary, the *Hou/Lux* material model is capable of qualitatively and quantitatively determining the major mechanical phenomena observed during model tests on axially perforated rock salt samples. It is thus possible to validate the *Hou/Lux* material model with its parameters and consequently, a basis for new types of mechanical framework analyses begins to emerge.

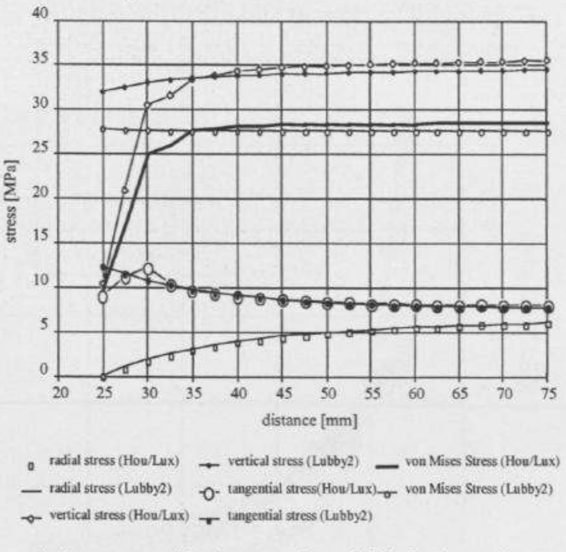

Figure 4. Stress contributions on the middle horizontal section of a large sample of rock salt with an axial bore hole

4. Validation of the reliability of the *Hou/Lux* material model - recalculation of the permeabilities around a drift measured during a field experiment

During a BMBF research project, *Häfner et al. (1999)* have determined the permeability in rock salt formations near a drift with a circular cross-section and the denomination EU 1 in the former Sondershausen potash mine. The permeabilities derived from the measured values shall in the following be used as a basis for a first validation of the reliability of the theoretical statement for predicting the rock damage. The drift EU 1 was driven about 37 years ago by means of a heading machine at a depth of approximately 700 m in the lower part of the Stassfurt rock salt. The point of measuring is located in a straight horizontal blind drift with a circular cross-section of approximately 3.00 m nominal diameter, which branches off the actual "machine drift EU 1", at a distance of about 70 m from the branching. Due to the distance of at least 800 m to the former mining fields, no mining influences are to be assumed according to *Häfner et al. (1999)*. In view of this situation, the peripheral conditions thus support the statement using a simplified even deformation model (plain strain).

Corresponding to the depth, the primary rock stresses assumed to be isotropic, are estimated to be p_G = 17 MPa. After the mathematical excavation of the drift, a creep calculation is carried out using the *Hou/Lux* material model to determine the dilatancy, material softening, damage and stress rearrangements caused by the damage over a period of 37 years. In view of a comparison, the hydromechanical model according to *Stormont et al. (1992)* is used to determine the permeability. The measured and calculated minimum stresses on one hand and permeabilities on the other hand near this drift after 37 years are compared in Figure 5 and Figure 6.

Without a closer discussion of details, a surprisingly good agreement tendency between the measured and the calculated minimum stresses as well as permeability profile for a first estimation is evident. It must be taken into consideration that the parameters of the *Hou/Lux* material model were estimated on the basis of a reanalysis of trial data of off-site salt rocks and that the porosity-permeability relation

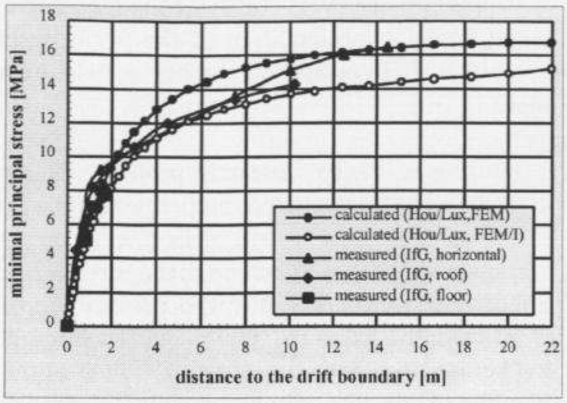

Figure 5. Comparison of the measured and calculated minimal stresses close to drift EU 1 (FEM/I: use of infinite element)

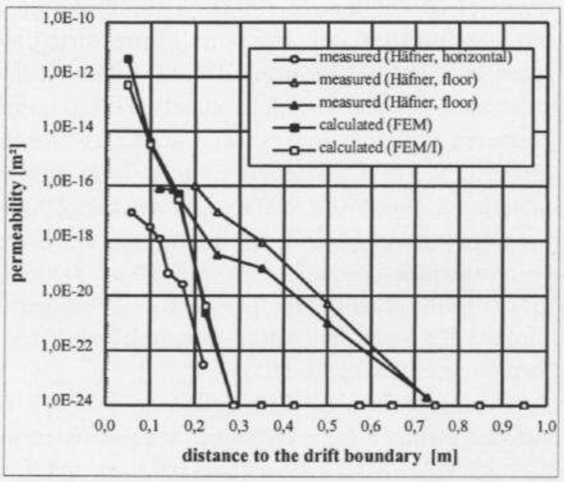

Figure 6. Comparison of measured and calculated permeabilities in the dilatancy zone of drift EU 1 (FEM/I: use of infinite element)

following *Stormont* was developed for rock salt from the USA. The fundamental suitability of the *Hou/Lux* material model for such analyses has hereby been confirmed.

5. CASE STUDY: A 10.000 m³ CAVITY AT THE ASSE MINE

In the following, the load-bearing behavior of a 10.000 m³ cavity at the Asse mine is examined as an example. The cavity was excavated during 1976/1977 for field testing and demonstration of a particular disposal method for solidified intermediate radioactive waste. The top of this cavity is situated at a depth of 959 m. The cavity has a shape of a prolate ellipsoid, main axis ratio 1.34:1. The total height is 37 m with a maximum diameter of 24 m at a depth of 979 m below the surface, *Lux (1984)*.

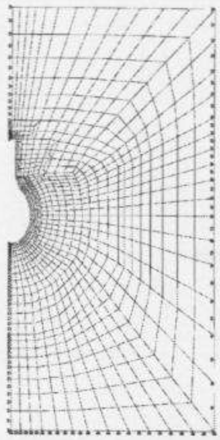

Figure 7. Calculation model of the cavity at the Asse mine

The rock salt is characterized as elastic-viscous with the elastic parameters $E = 20$ GPa and $\upsilon = 0.4$. The material parameters of the applied *Hou/Lux* material model are taken from *Hou (2000)*, neglecting transient creep. Figure 7 shows the calculation model.

An internal pressure of $p_i = 0$ MPa represents the extreme case in a storage cavity. Following the momentarily idealized excavation, the calculations continue according to the known *Lubby2* material model and according to the new *Hou/Lux* material mode until t = 22 years (1999).

Figure 8 shows the effective stresses according to the *Lubby2* material model and according to the *Hou/Lux* material model in the horizontal section at a reference depth of z = 980 m at the time t = 0.5 d, 370 d and 22 a. It is evident that the intensity of the

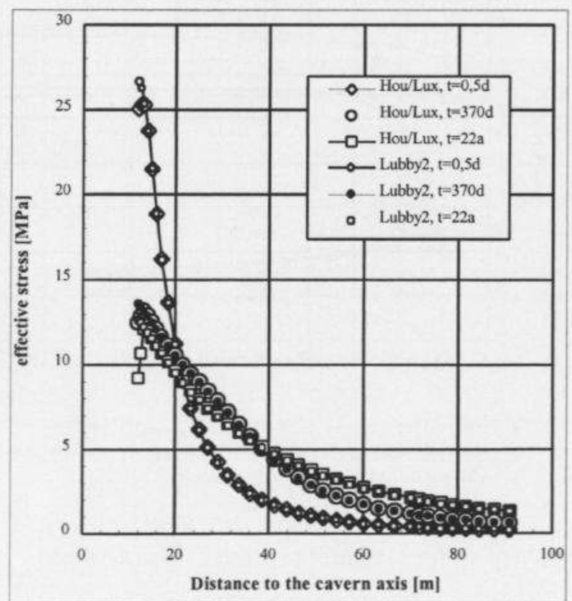

Figure 8. Comparison of the effective stresses in a horizontal section at a reference depth of z = 980 m at the time t = 0.5 d, 370 d and 22 a

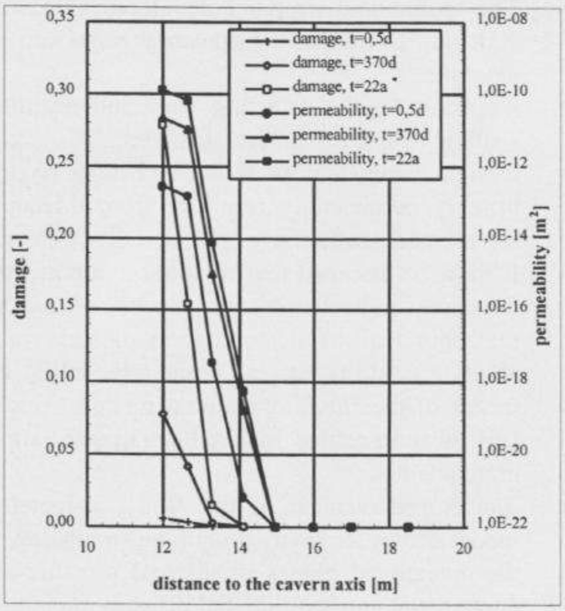

Figure 9. Damage and permeability in a horizontal section at a reference depth of z = 980 m at the time t = 0.5 d, 370 d and 22 a

softening as well as the area of the softening zone increase over time. The comparison shows a serious difference: with the *Hou/Lux* material model, the extreme stress is not at the cavity contour but deeper inside the rock formation with the advantage of the higher strength. At the cavity contour, the stress on the rock formation has dropped due to stress rearrangements - a result of loosening/-softening of the mechanical framework near the contour, which consequently leads to a reduced material rigidity and a simultaneous increase in the ability to creep. The stress rearrangements induced near the contour are thus a result of softening due to damage at an exceeded dilatancy strength.

Damage and permeability are shown in accord with the effective stress in Figure 9. The damage and the increase of permeability during the observed time span in a contour range of 1.5 to 3.0 m are limited and their intensity increases with a decreasing distance from the cavity and with the time.

6. CONCEPT FOR PILLAR DESIGN IN ROCK SALT

In *Hou (1997)* and in *Hou & Lux (1999b)* the methods for solving the individual questions regarding a complex pillar design method are described and exemplarily applied with respect to a certain location.

The new pillar design method by *Hou/Lux* is based on the same material model including structural damages and takes up the theoretical statements and experiences for the determination of the short-term load-bearing capacity of pillars and the necessary safety coefficients already to be found in the methods by *Menzel* and *Uhlenbecker*. However, it also follows up on and integrates discoveries of continuum damage mechanics into the field of pillar design. Furthermore, the probabilistic safety concept for taking account of the uncertainties resulting from scattering, calculation processes and imponderables, used in the fields of foundation engineering and constructive engineering, is integrated into the design concept. This procedure can be used to determine the short-term load-bearing capacity of pillars, the time-dependent load-bearing capacity of pillars, the permissible pillar load in conjunction with a failure probability, the necessary rheological safety coefficient, the probabilistic safety coefficient for the uncertainties resulting from scattering, calculation processes and imponderables as well as the necessary safety coefficient for the pillar design and for the safety analysis of existing pillar systems.

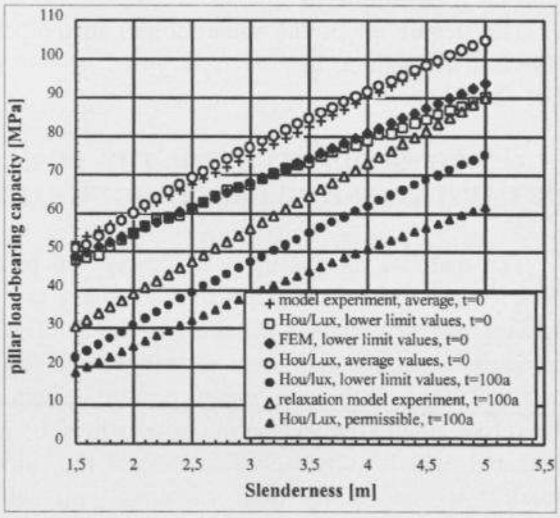

Figure 10. Short-term (t -> 0) and time-dependent (t = 100 a) load-bearing capacities as well as permissible load of square pillars of salt rock from a location C according to different methods

Figure 10 shows the short-term (t -> 0) and time-dependent (t = 100a) load bearing capacities of square pillars of salt rock from a location C determined exemplarily for illustration purposes using different methods. The terms 'average' and 'lower limit' refer to the approach of the failure strength determined in the laboratory.

It must be emphasized at this point that the permissible pillar load is independent of the method used, because the uncertainties resulting from scattering and process have been evened out by the probabilistic safety coefficient, according to the probabilistic safety concept, with an equal failure probability, although the short-term and time-dependent load bearing capacity of the pillar as well as the rheological, the probabilistic and the necessary safety coefficient can differ depending on the different methods.

The permissible pillar load is the fundamental measure for the design of new pillars and thus for the determination of the system layout of new working fields. The exemplarily determined permissible pillar load for a life of 100 years for salt rock pillars (location C) is also shown in Figure 10 for a safety class II.

If the calculated life-related safety coefficient of a pillar is smaller, equal or larger than vorhξ_t = 1.31(location C), the failure probability of the pillar under these idealized conditions is larger, equal or smaller than $p_f = 10^{-6}$ in the time 100 years after the excavation.

The details about the pillar design method by *Hou/Lux* are written in *Hou (1997)* and in *Hou & Lux (1999b)*.

7. CONSEQUENCES FOR THE DESIGN OF CAVITIES AND PILLARS IN ROCK SALT

The material models used for cavity and pillar design so far neither considered the dilatancy or the damage nor the resulting softening or the additional creep deformations and stress rearrangements. Neither did they include a creep rupture criterion. Therefore, alternative evaluation criteria must be introduced, which allow an evaluation of the calculated stress and strain field variables with sufficiently conservative distances to failure states, based on stresses as well as on deformations.

The *Hou/Lux* material model, at least in principle, eliminates these disadvantages and thus offers new possibilities for the determination of the mechanical behavior of salt rocks and for cavity and pillar design:

- The spatial and temporal development of the softening zones and the dilatancy zones can be determined.
- Intensities of the softening zone and resulting spalling over time can be calculated.
- Design parameters as well as changes to the primary permeability resulting from dilatancy can be more realistically estimated than before.
- It must be assumed that the conservativities of the cavity and pillar designs can be reduced by the more realistic determination of state variables (e.g. stress, strain, strain rate, DRZ) by means of the *Hou/Lux* material model. Consistent location-related material parameters are a prerequisite.
- The current version of the *Hou/Lux* material model allows for cavity design the simulation of the operational phases of internal pressure reduction and constant internal pressure including the special case of atmospheric pressure (blow-out).
- If the healing of damages is also considered, the operational phase of the internal pressure increase can be more accurately registered.

8. DISCUSSION AND SUMMARY

Some of previous deficits have been eliminated by introducing new developments in the field of salt mechanics into the design concepts for salt cavities and salt mine pillars, particularly in the field of constitutive relations (material models). This article introduces the most important statements by the authors about the further development of salt cavity and salt mine pillar dimensioning.

The dilatancy and the additional creep deformations induced by the structure damage as consequences of the damage, can be calculated by means of the *Hou/Lux* material model. Further consequences of the damage to the structure such as e.g. increased porosity and permeability, can generally be represented in dependence of the dilatancy.

Parameter variations have made it possible to use the *Hou/Lux* material model to qualitatively and quantitatively determine phenomena such as softening, dilatancy, loosening, structural damage, radial deformations into the axial bore as well as spalling, observed during model tests on axially perforated rock salt samples.

A very good agreement between the measured and the calculated minimum stresses as well as the permeability profiles of a 37-year old drift confirm the fundamental suitability of the *Hou/Lux* material model for such types of analyses, although the parameters of the *Hou/Lux* material models have been estimated on the basis of a reanalysis and the porosity-permeability relation following *Stormont* has been developed for rock salt in the USA.

As an example, the calculated load-bearing behavior of a salt cavity at the Asse mine is examined, comparing the results of the *Hou/Lux* material model with the *Lubby2* material model. The comparison shows the advantages of the *Hou/Lux* material model, such as stress rearrangements from the contour into the rock formation as well as the identification of dilatancy, damage, softening and sheeting zones. A more economically efficient dimensioning of e.g. salt cavities coinciding with reduced uncertainties but with the same degree of safety as today, seems possible with the application of this newly developed material model.

Based on the methods by *Menzel* and *Uhlenbecker* and taking into account the methodical approaches of continuum damage mechanics, this mixed method is suggested by *Hou/Lux.*

Based on these new theories, the authors expect that apart from a deeper insight into the load-bearing behavior e.g. in view of the development of loosening in geological barriers, it will also be possible in the future to design salt cavities or mine pillars more economically.

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