Improvement of design of storage cavity in rock salt by using the Hou/Lux constitutive model with consideration of creep rupture criterion and damage

利用Hou/Lux本构模型考虑蠕变破坏标准和损伤改进盐岩储存硐库的设计

HOU Zheng-meng(侯正猛), WU Wen(吴 文)

(1. Technical University of Clausthal, Erzstrasse 20, 38678 Clausthal-Zellerfeld, Germany; 2. Institute of Rock & Soil Mechanics, the Chinese Academy of Sciences, 430071 Wuhan, China)

Abstract: The introduction of damage mechanics and a new material model including structural damages into design concepts for the construction of salt cavities reduces some deficits of previous knowledge and modeling. This seems to set out the scientific foundation for a more realistic and thus more economical cavity design while the same level of safety is kept. This paper introduces the major statements worked out by the authors about the further development of salt cavity dimensioning as well as its practical applications. As examples, the calculated load-bearing behavior of the so-called prototype cavity at the Asse mine and the minimum permissible internal cavern pressure for a storage cavern are examined, comparing the results of the Hou/Lux material model with those of 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 increasing the profitability of storage cavities through reduction of the minimum pressure.

Key words: storage cavity; rock salt; constitutive model

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Biography: HOU Zheng-meng(1960-), male, Ph. D and professor, engages in calculation of storing engineering and study on constitutive modeling of rocksalt. He had published more than 30 papers and one monograph.

摘　要: 损伤力学和新材料模型(包括结构损伤)引入到盐岩硐库的设计概念中,能够减少以前知识和计算模型的不足。在保持同样安全的情况下,新模型能为设计更经济的盐岩储存硐库建立科学基础。本文通过一个实际例子,对Asse盐矿(德国)的一个原形储存硐库进行了承载性能和最小容许内压的计算验证,并把使用Hou/Lux模型和Lubby2模型的计算结果进行了对比。比较结果显示,新材料模型有许多优点,如:通过减少内压,储存硐库的围岩应力重分布、扩容、损伤、软化及片帮区域等均得到改善。

关键词: 本构模型; 盐岩; 储存硐库

0 Introduction*

The major elements of a dimensioning concept for the design of storage caverns are the used material model and the proof criteria with their limits and safety margins. A main characteristic of a material model based on Continuum Damage Mechanics (CDM) is the qualitative integration of the structural damage prior to material failure into the numerical simulation of the bearing behaviour. By detecting the structural damage starting as the dilatancy strength is exceeded, it is possible to quantify the time-dependent load-bearing capacity for loads between the dilatancy strength and the fracture strength. As compared to the conventional calculation methods, this method offers the possibility of predicting the time of a potential material failure or to activate bearing reserves not verifiable so far.

It has become evident, also in connection with the results of extensive laboratory and field investigations, that in spite of the further developed proofing instrument, 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 storage cavity design.

With this background, this essay uses the Hou/Lux material model with creep rupture criterion and damage to design cavities as well as to analyze the safety with special emphasis on the life time. The details about the Hou/Lux material model can be found in earlier publications, e.g. references[1, 2].

1 Evaluation criteria for classical design

For the evaluation of the calculation data regarding the calculated proof of safety and the usability suitable criteria and limit values must be defined. The rock formation surrounding the cavern can generally be divided into the bearing elements of roof pillar, salt pillar and basement rock. These bearing elements must be designed in way that they can bear the states of stress initiated by the cavern building and operation with sufficient safety (= bearing reserve). Experience shows that in case of slim cylindrical caverns and a homogenous rock formation in the evaluation range, the stress intensity of the rock is the largest around the area of the bottom half of the salt pillar. At the level of the so-called reference depth, the rock stress reaches its extremal values. The largest amount of rock stress is to be found at

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reference depth at the contour of the cavern. With this background, the determination or representation of the state variables in the case of a sufficiently extended salt rock formation is generally done for Gauss points or intersections on the level of the reference depth.

For the proof of safety of the investigated cavern configuration the following proofs are demanded following independent of the location and exemplarily for this analysis without any mentioning of safety margins[3]:

(1) Proof that the cavern contour will not spall at minimum pressure for an (exemplary) period of 3 months time. The locally calculated rock stress at the cavern contour at reference depth may at an internal pressure reduction to minimum pressure only utilize the rock strength derived from short-term investigations (> peak strength) to a certain degree. The maximum permissible so-called factor of utilization at the cavern contour is assumed to have the exemplary numerical value of $\eta_C = 50\%$[3]:

$$\text{maxvirh}\,\eta_C = \frac{\sigma_v(\sigma_3, \theta)}{\beta(\sigma_3, \theta)} \leqslant 50\% = \text{zul}\,\eta_C(\Delta t = 90\ \text{d}). \tag{1}$$

(2) Proof that the extension of those rock areas, which will be exposed to stress exceeding the long-term strength, are limited to areas close to the cavern. The rock stress locally calculated for a pillar core area r_{pk} at reference depth may at an internal pressure reduction to minimum pressure after a period of 3 months not exceed the long-term strength derived from short-term investigations (> pillar criterion). As a maximum permissible factor of utilization in the area of the pillar core an exemplary value of $\eta_{pk} = 30\ \%$ is assumed:

$$r \geqslant r_{pk}: \text{maxvirh}\,\eta_{pk} \leqslant 30\ \% = \text{zul}\,\eta_{pk}(\Delta t = 90\ \text{d}). \tag{2}$$

(3) Proof that the increase of the effective creep strains resulting from a time-limited load on the bearing structure will not exceed a defined limit value within a storage cycle. The effective creep strain locally calculated at the cavern contour at reference depth may for the duration of the internal pressure decrease and the following time at minimum pressure does not exceed the exemplary maximum value of zul $\varepsilon_{eff} = 3\ \%$:

$$\text{maxvorh}\,\Delta\varepsilon_{eff} \leqslant 30\% = \text{zul}\,\Delta\varepsilon_{eff}. \tag{3}$$

For the determination of the minimum permissible internal cavern pressure the procedure of the following analysis was such that the corresponding internal cavern pressure was considered to be permissible, at which none of the limit values allocated to the individual criteria was exceeded. Vice versa, this means that the criterion, whose limit value is exceeded first, determines the amount of the minimum permissible internal cavern pressure.

It must be noted again, that the above-mentioned criteria and limit values have been stated for the purpose of the evaluation of state variables required for methodical reasons and that they are merely examples. In a cavern project with its special geological and geomechanical as well as operative conditions, these criteria and limit values as well as safety margins must be derived for the location and must be proofed correspondingly.

2 New crieria for storage cavity design

The old criteria were developed in 1980's. Conservative statements may have to be included into the criteria due to existing deficits in the formulation of constitutive relations. With an improved knowledge of the complex material behavior of ductile-viscoplastic saliniferous rocks, the new criteria can be developed by using the Hou/Lux constitutive model in consideration of dilatancy, damage and damage healing:

(1) Proof that dilatancy does not exist in the cavern contour. The locally calculated rock stresses cal σ_v at the cavern contour at reference depth don't exceed the dilatancy strength β_{Dil} (dilatancy limit) following equation

$$\text{cal}\,\sigma_v(\sigma_3, \theta) \leqslant \beta_{Dil}(\sigma_3, \theta) \text{ or } D(= 3.04). \tag{4}$$

No any damage and no any dilatancy will be caused under this condition.

(2) Proof that the cavern contour is not in the tertiary creep phase. Depending on the location-specific conditions, time-dependent damages of $D > 0$ without harm to the contour stability and without causing the tertiary creep are permissible, if corresponding cavern operations guarantee that the damages generated at the application of the minimum pressure will not cause fractures and spalling and will heal due to a subsequent increase of the internal pressure. The locally calculated maximum damage at the cavern contour at reference depth don't exceed exemplary maximum value of zul$D_{st} = 0.005$[4]:

$$\text{maxvorh}D \leqslant 0.005 = D_{st}. \tag{5}$$

3 Case study: a 10.000 m^3 cavity at the Asse mine

In the following, the load-bearing behavior of a 10.000 m^3 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[3].

The rock salt is characterized as elastic-viscous with the elastic parameters $E = 20$ GPa and $\nu = 0.4$. The material parameters of the applied Hou/Lux material model are taken from reference[5], neglecting transient creep. Figure 1 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 Hou/Lux material mode until $t = 22$ a[6].

Figure 2 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 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 3.

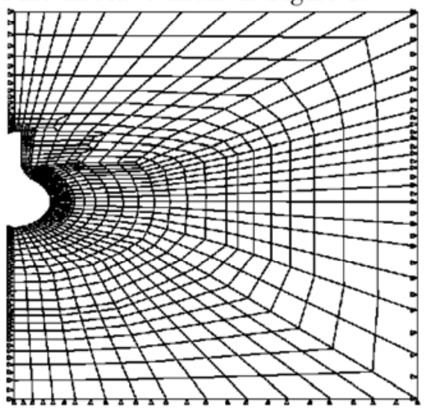

Fig. 1　Calculation model of the cavity at the Asse mine

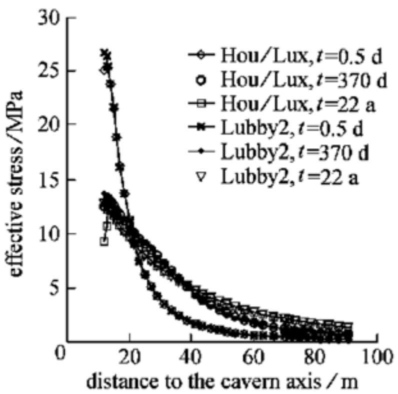

Fig. 2　Comparison of the effective stresses in a horizontal section at a reference depth of z = 980 m at the time t = 0.5 d, 370 d and 22 a

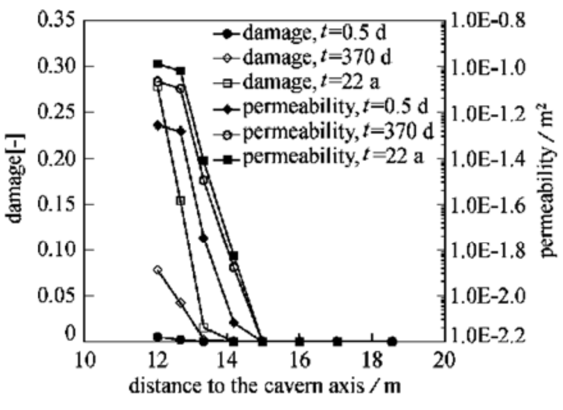

Fig. 3　Damage and permeability in a horizontal section at a reference depth of z = 980 m at the time t = 0.5 d, 370 d and 22 a

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.

4　Optimisation of the minimum internal cavern pressure

As an example, the minimum permissible internal cavern pressure for a storage cavern is examined by using the Hou/Lux and Lubby2 material models. The storage cavern has a cylindrical shape with a maximum diameter of d = 80 m and a total height of h = 200 m. The volume of the cavern is V_0 = 871700 m^3. The cavern roof depth and the reference depth are z_{roof} = 1115 m, z_R = 1250 m[7].

With storage caverns there are usually maximum states of stress following the reduction of the internal pressure, e.g. as the storage medium is withdrawn. The deviatory rock stress increases and becomes less favorable regarding the situation of the bearing structure load, the higher the internal pressure difference is during pressure release and the more the lowered internal cavern pressure approximates the level of the atmospheric pressure. Figure 4 shows the numerically simulated operation[7].

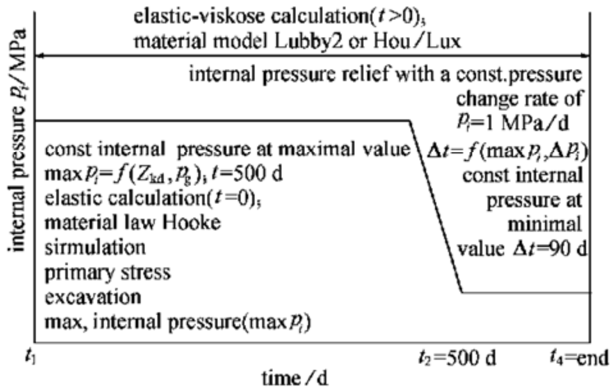

Fig. 4　Idealized operation

As a result of the theoretical investigations on the exemplary minimum pressure dimensioning for storage caverns, Table 1 shows the minimum pressures for a model cavity derived using different design concepts[4].

Consequently the minimum pressure calculated using classical dimensioning without consideration of the damage, can be reduced from min p_i = 7.9 MPa to minp_i = 4.7 MPa, if the dimensioning is based on CDM and done with the material model Hou/Lux and if the new criterion D = 0 is used. Another extended observation shows that damages of D > 0 are permitted location-specifically. For the numerical value of D_{st} = 0.005 used in the example, a minimum pressure of min p_i ≈ 3.0 MPa is calculated. The currently available knowledge on the consideration of healing shows that a further reduction of the permissible minimum pressure at a time-dependent simulation of the damaging and healing seems possible. Particularly interesting is that by means of the quantitative determination of structural damages and healing a much more flexible cavern operation becomes possible as compared to classical dimensioning, because especially the time at certain minimum pressures can be handled very flexible and the required amount and duration of increased internal cavern pressures can be quantified for a healing process.

Table 1 Minimum internal cavern pressures according to different dimensioning concepts for a reference cavity without any safety margins

Design method	Min p_i / MPa
traditional design	7.9
Design with the Hou/Lux constitutive model: $D = 0$	4.7
Design with the Hou/Lux constitutive model: $D = 0.005$	3
Design with with the Hou/Lux constitutive model, regard to damage and damage healing	< 3

5 Discussion and summary

The material models used for cavity 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 are introduced, which allow an evaluation of the calculated stress and strain field variables with sufficiently conservative distances to failure states, based on dilatancy, damage and damage healing.

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 storage cavity design:

(1) The spatial and temporal development of the softening zones and the dilatancy zones can be determined.

(2) Intensities of the softening zone and resulting spalling over time can be calculated.

(3) The dilatancy and the additional creep deformations induced by 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.

(4) Design parameters as well as changes to the primary permeability resulting from dilatancy can be more realistically deviated than before.

(5) It must be assumed that the conservativities of the cavity 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.

(6) 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).

(7) If the healing of damages is also considered, the operational phase of the internal pressure increase can be more accurately registered[8]. The research results about this aspect will be published in a later paper.

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 significantly lower minimum pressures and therefore a more economically efficient dimensioning of storage cavities are showed by using the Hou/Lux constitutive model as well as by using the new evaluation criteria. This dimensioning concept is based on developments to be found e.g. in references [1, 5~9].

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