New aspects on the rate dependent creep and strength properties of rock salt

Nouveaux aspects sur l'influence de vitesse du fluage et les propriétés de résistance de sel gemme

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ABSTRACT: In order to judge the long term stability of creeping slopes the time and velocity dependent material properties have to be respected by adequate constitutive laws. For one example, stability calculations of salt stockpiles make it necessary to model the viscous creep deformations as well as the plastic fracture deformations of the banked-up material. Within the here presented research program which has the aim to improve the predictability of long term deformations and stability of moving slopes a new constitutive law was developed for the visco-plastic behavior of crushed salt. It belongs to the family of superposition models with separation of elastic, plastic and viscous strains rates. The governing equations have been included in a Finite-Element-Program. The material model, its implementation and the effects on the modeling of creeping salt stockpiles are discussed below.

RÉSUMÉ: Pour évaluer la stabilité des talus, il est nécessaire de prendre en considération le comportement du matériel dépendant du temps et de la vitesse par des lois de comportement. Pour de calculs de stabilité des endroits de déposition de sel il est par exemple d'importance de modeler les déformations de fluage et les déformations plastiques dans l'etat du rupture du matériel déposé. Dans le programme de recherche une loi de comportement a été développer pour le sel granulaire, qui est présentée ci-dessous avec des exemples d'application.

1 INTRODUCTION

Within superposition models different strain rates are calculated separately and superposed in one increment. In general the total strain rate $\dot{\varepsilon}$ is given by

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{vi} + \dot{\varepsilon}_{pl} \tag{1}$$

where the indices mean elastic (el), viscous (vi) respectively plastic (pl) deformations. Elastic deformations are simply calculated by Hooke's law, viscous deformations are given by creep functions. Plastic deformations occur when the stress path touches the yield surface. They are calculated on the basis of a strain-hardening function.

2 VISCOUS DEFORMATIONS

These deformations are characterized by the fact that they increase under constant load. The calculation of the equivalent viscous deformations is achieved by a model which was in the original form first published by Munson and Dawson (1982). Stationary and transient creep are respected. Transient creep deformations depend on an internal variable which itself depends on the already accumulated transient strains. The viscous equivalent deformations for two load stages are shown in Fig. 1.

In Fig. 1 q is the equivalent Mises stress (deviatoric part of the stress tensor). The stationary creep deformations are calculated by a classical power law (Dorn 1957) with the constants C and n. The additional transient deformations are limited by an ultimate value, which is a function of the stress level q divided by the elastic shear modulus G and two constants K and m. The decrease of the transient velocity is expressed by the internal variable F as shown in Fig. 2. The variable F itself is controlled by the decrease parameter Δ, which is found by fitting the logarithmic equivalent strains to the ratio of already accumulated transient strains for several creep tests.

Equivalent strains occur only due to deviatoric loads. When any

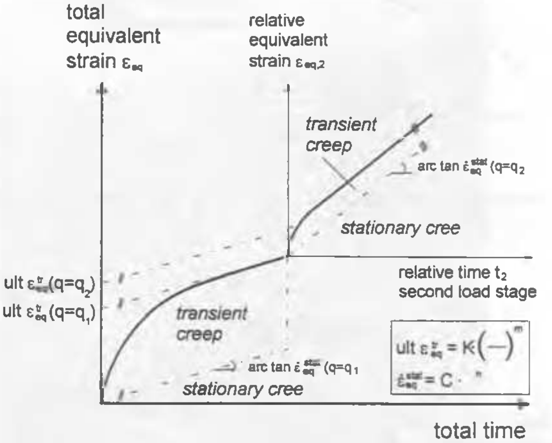


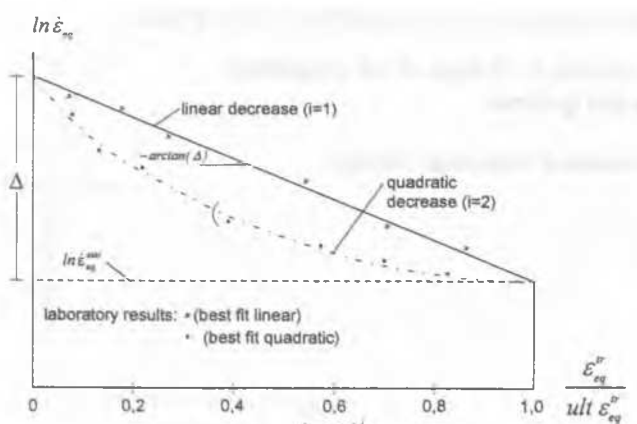
Figure 1. Equivalent viscous strains for two load stages

load stage is applied to a sample also volumetric viscous deformations occur as a function of the hydrostatic pressure *p*.

The volumetric strain velocity is controlled by the actual density ρ. It is limited by the ultimate density ult ρ, which itself is a function of the load level *p*. The duration of the transient creeping depends on the duration of volumetric decrease. The reason is that transient creeping has its origin in the hardening of the material what is expressed by volumetric decrease.

After implementing the creep law in the Finite-Element code long-term creep tests carried out in the laboratory have been simulated numerically in order to verify the constitutive model. Explicit time integration was used. There were used 4 node isoparametric continuum elements with a bilinear displacement function. Stresses and strains were calculated numerically by the Gaussian method.

Fig. 3 shows the comparison of numerical and measuring results. It is obvious that transient deformations have large influence on the results. This is typically for the behavior of crushed salt where viscous deformations are mainly controlled by the hardening, i.e. the compaction of the material.



$$\dot{\varepsilon}_{eq} = F \cdot \dot{\varepsilon}_{eq}^{stat} \qquad F = e^{\Delta\left(1-\frac{\varepsilon_{eq}^{tr}}{ult\,\varepsilon_{eq}^{tr}}\right)^{i}} \qquad i = 1 \ldots 2$$

$$\ln F = \Delta \cdot \left(1-\frac{\varepsilon_{eq}^{tr}}{ult\,\varepsilon_{eq}^{tr}}\right)^{i} \qquad \ln \dot{\varepsilon}_{eq} = \ln \dot{\varepsilon}_{eq}^{stat} + \Delta \cdot \left(1-\frac{\varepsilon_{eq}^{tr}}{ult\,\varepsilon_{eq}^{tr}}\right)^{i}$$

Figure 2. Control of the decrease of the equivalent transient strain rates

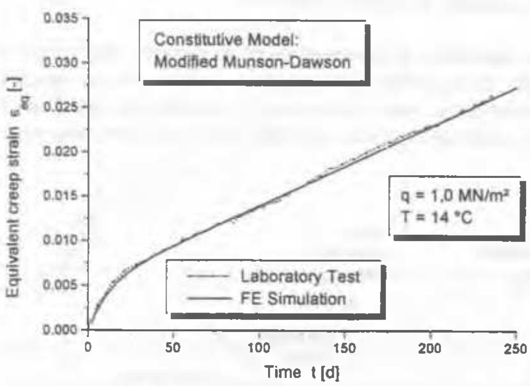


Figure 3. Comparison of numerical and measuring results for a long-term creep test

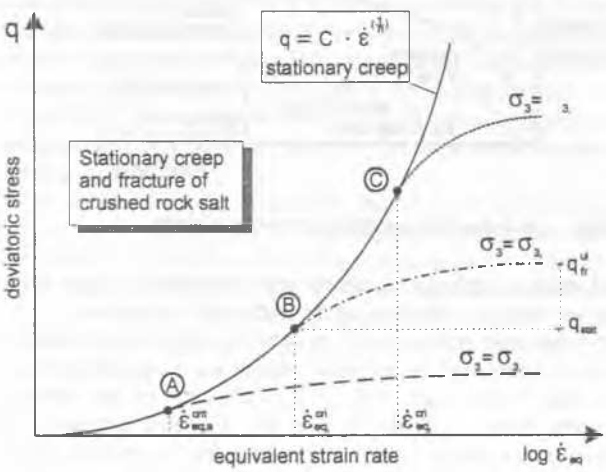


Figure 4. Plastic failure as a function of the critical strain rates

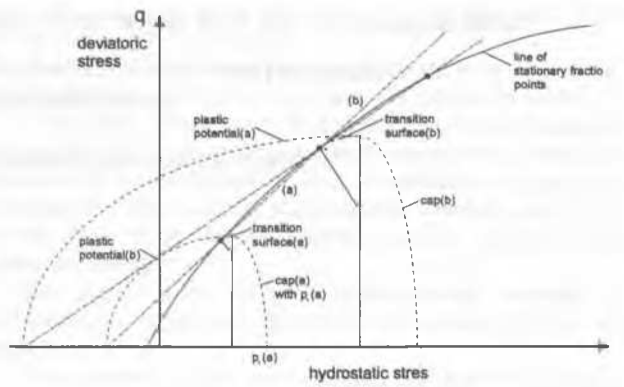


Figure 5. Yield surface and plastic potential in the p-q-plane

3 STRAIN RATE DEPENDENT PLASTIC FLOW

Plastic failure is respected by a cap model with nonlinear yield surface which was derived from a modified Drucker-Prager model (Hibbit et al., 1996). The model takes into account that materials like salt which are loaded with a certain hydrostatic pressure p fail above a so-called critical strain velocity. The principal behavior is shown in Fig. 4:
A sample is loaded with a certain cell pressure σ_3. The deviatoric load is increased in several steps. After a certain time stationary creep with a corresponding strain rate can be observed: The stress path moves on the stationary creep line. Above the critical strain velocity stationary equilibrium is no longer possible. Tertiary creep is dominating and the sample fails. The points A, B and C in Fig. 4 represent the failure states for given σ_3 and q, respectively p and q for the corresponding critical strain rates.

A, B and C are called stationary failure points. In the next step the connection of the failure points gives the yield surface in the p-q-plane and the corresponding plastic potential surface (Fig. 5). By doing so the combination of stationary creep equilibrium and the strain rate dependant failure has been achieved.
A detailed description of the new constitutive law is given by Boley (1999).

4 APPLICATION TO SLOPE STABILITY CALCULATIONS

With the here presented more precise description of the material behaviour the prediction of the long term stability of moving slopes could be improved enormously. In the process of potash mining salt stockpiles are in certain cases banked up in blocks (see Fig. 6).
In reality one block is banked up in several months. In the Finite-Element analysis the bank-up process is simulated by including a couple of blocks in one step. The deformations due to transient creep were in the same order as those due to stationary creep.

Moreover the plastic deformations have been observed. It could be shown that in the toe region plastic failure occurs. The reason is that the material can only resist relatively low shear stresses in this region because of the low normal stress level. Failure of the

Fig. 6. Banking up a salt stockpile in blocks

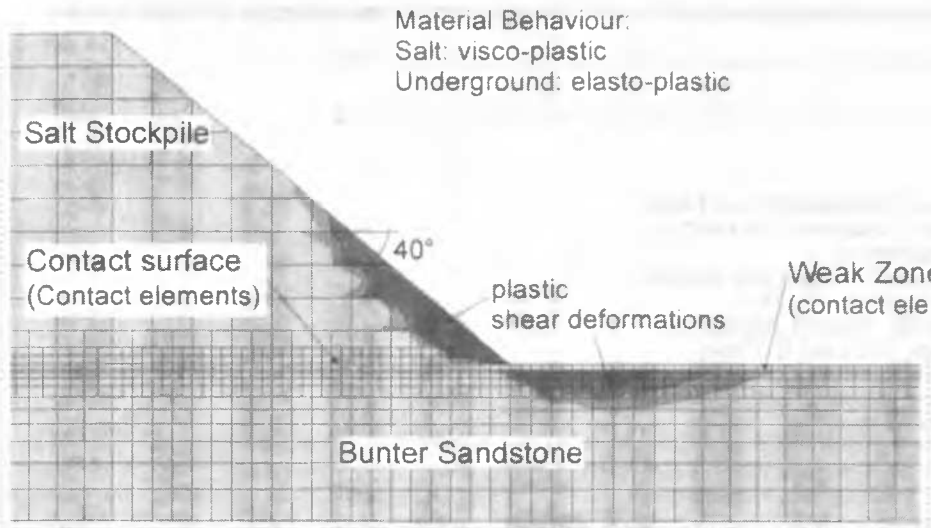


Fig. 7. Plastic shear deformations in a 200 m high salt stockpile as a result of Finite-Element calculations under application of the new constitutive law

Fig. 8. 200 m high salt stockpile in Neuhof (Northern Hessia, Germany) built up of 80 million tons of granular potash salt

whole slope always occurred as a consequence of damages at the toe. Fig. 7 shows the plastic deformations on the shear surface for a 200 m high salt stockpile. It is located in Northern Hessia and has been banked up over more than three decades with granular potash salt which remains within potash mining. Fig. 8 shows a view from the stockpile in the actual state.
Under the ground surface of the stockpile a weak zone is located in the Bunter Sandstone, what causes the underground fail similar to bearing resistance failure in this region.

5 CONCLUSIONS

The new constitutive law makes it possible to respect all types of deformations leading to long term displacements of high slopes banked up with viscous material. It could be shown that transient deformations as well as plastic deformations influence the solution significantly. On the basis of the developed constitutive model stabilization concepts are now studied by 3D-Finite-Element simulations.

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