ANISOTROPIC FAILURE CRITERION FOR AN ARGILLACEOUS ROCK: FORMULATION AND APPLICATION TO AN UNDERGROUND EXCAVATION CASE

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Abstract. A cross-anisotropic extension of an elastoplastic constitutive model is described, based on a non-uniform scaling of the stress tensor. The Mohr-Coulomb yield condition is employed, although this concept can be applied to any other stress-based criterion. It has as main advantage the possibility of being incorporated into an already implemented constitutive model with only minor modifications. The resulting constitutive model has been applied to the coupled hydromechanical simulation of an excavation of a horizontal tunnel in the underground research laboratory at Bure (France). The orientation of the tunnel ensures that the transverse in situ stress state is nearly isotropic. The tunnel excavation has been intensely monitored and the nature and extension of the damaged zone have been studied by a variety of field techniques. It is shown that the analysis performed using the elastoplastic model incorporating the anisotropic failure criterion is able to reproduce the observed geometry of the damaged zone. The anisotropy of displacement measurements is also matched satisfactorily.

1 INTRODUCTION

Because of their limited strength, an important issue in underground excavations in argillaceous rocks is the generation of a damaged zone around the cavity caused by the process of excavation itself. Field observations show that the extent and features of the damaged zone are often affected by the anisotropic nature of the material concerning especially the failure conditions of the rock. This becomes especially apparent in cases where the in situ stress is quasi-isotropic where the non-uniform configuration of the damaged zone can only be attributed to the anisotropic properties of the material

In this contribution a novel procedure is described for the anisotropic extension of an elastoplastic constitutive model, based on the non-uniform scaling of the stress tensor. The idea of incorporating anisotropy by modifying the stress tensor can be traced back to the Barlat anisotropic yield function [1], employed for metals, in which anisotropy was included by affecting the deviatoric stress tensor by a series of factors that control the anisotropic characteristics of the material. A similar idea has been employed here to incorporate inherent cross-anisotropy in an elastoplastic constitutive model. Although the Mohr-Coulomb yield criterion has been adopted, the proposed extension can be applied to any stress based criteria. The main advantage lies in the fact that it can be easily incorporated to an already implemented isotropic constitutive model with only minor changes. Some selected results of the performance of the procedure are presented concerning laboratory tests and an excavation in the Meuse-Haute Marne Underground Research Laboratory (M-HM URL) in France.

2 ANISOTROPIC FAILURE CRITERION

As indicated above, a simple elastic-perfectly plastic model using the Mohr Coulomb failure criterion is adopted although the method is in fact completely general and independent of the constitutive law selected. In that case, the isotropic failure criterion can be expressed as:

$$f = \left(\cos\theta + \frac{1}{\sqrt{3}} \sin\theta \sin\phi \right) J - \sin\phi \left(p + c \cot\phi \right) \tag{1}$$

where ϕ is the friction angle, c the cohesion and p, J and θ are invariants of the stress tensor defined as follows:

$$p = \frac{1}{3}\left(\sigma_{xx} + \sigma_{yy} + \sigma_{zz} \right) \tag{2a}$$

$$J = \left(\frac{1}{2} \operatorname{tr} \underline{\mathbf{s}}^2 \right)^{1/2} \tag{2b}$$

$$\theta = -\frac{1}{3} \sin^{-1}\left(\frac{3\sqrt{3} \det \underline{\mathbf{s}}}{2J^3} \right) \tag{2c}$$

and $\underline{\mathbf{s}}$ is the deviatoric stress tensor $\underline{\mathbf{s}} = \underline{\boldsymbol{\sigma}} - p\mathbf{I}$. *x*, *y* and *z* are the global coordinates of the problem.

The principal directions of anisotropy are denoted by 1, 2, and 3 and, of course, they may not coincide with the orientation of the global system of coordinates. In that case it is necessary to modify the stress tensor by applying the usual rotation matrix. Working now in the local anisotropy-based system of coordinates, the cross-anisotropic extension of the model is obtained by replacing p J and θ in Eq. (1) by p^{ani} J^{ani} and θ^{ani} respectively. These variables are invariants, with the same definition as shown in Eq. (2), but calculated from the anisotropic stress tensor $\underline{\boldsymbol{\sigma}}^{ani}$. This tensor is obtained through the non-uniform scaling of the stress tensor orientated according to the local coordinate system ($\underline{\boldsymbol{\sigma}}^{r}$), as shown below:

$$\underline{\boldsymbol{\sigma}}^{ani} = \begin{bmatrix} c_{11}\sigma_{11}^{r} & c_{12}\sigma_{12}^{r} & c_{13}\sigma_{13}^{r} \\ c_{12}\sigma_{12}^{r} & c_{22}\sigma_{22}^{r} & c_{23}\sigma_{23}^{r} \\ c_{13}\sigma_{13}^{r} & c_{23}\sigma_{23}^{r} & c_{33}\sigma_{33}^{r} \end{bmatrix} \tag{3}$$

where c_{ij} are the scaling factors affecting each one of the components of the rotated stress tensor.

If the material is cross-anisotropic (a common assumption in geological materials), then the scaled stress tensor (taking 2 as the anisotropy axis) has the following form:

$$\underline{\boldsymbol{\sigma}}^{ani} = \begin{bmatrix} \dfrac{\sigma_{11}^{r}}{c_N} & c_S\sigma_{12}^{r} & \sigma_{13}^{r} \\ c_S\sigma_{12}^{r} & c_N\sigma_{22}^{r} & c_S\sigma_{23}^{r} \\ \sigma_{13}^{r} & c_S\sigma_{23}^{r} & \dfrac{\sigma_{33}^{r}}{c_N} \end{bmatrix} \tag{4}$$

where only two parameters are required to define the anisotropy: c_N and c_S.

The derivatives required to implement the resulting constitutive model are easily computed using the chain rule. For instance, the yield surface derivative is expressed as:

$$\frac{\partial f}{\partial \boldsymbol{\sigma}} = \left(\frac{\partial f}{\partial p^{ani}} \left(\frac{\partial p^{ani}}{\partial \boldsymbol{\sigma}^{ani}} \right)^T \frac{\partial \boldsymbol{\sigma}^{ani}}{\partial \boldsymbol{\sigma}} + \frac{\partial f}{\partial J^{ani}} \left(\frac{\partial J^{ani}}{\partial \boldsymbol{\sigma}^{ani}} \right)^T \frac{\partial \boldsymbol{\sigma}^{ani}}{\partial \boldsymbol{\sigma}} + \frac{\partial f}{\partial \theta^{ani}} \left(\frac{\partial \theta^{ani}}{\partial \boldsymbol{\sigma}^{ani}} \right)^T \frac{\partial \boldsymbol{\sigma}^{ani}}{\partial \boldsymbol{\sigma}} \right)^T \tag{5}$$

The modifications of the Mohr-Coulomb failure criterion for two sets of anisotropy parameters are illustrated in Figure 1.

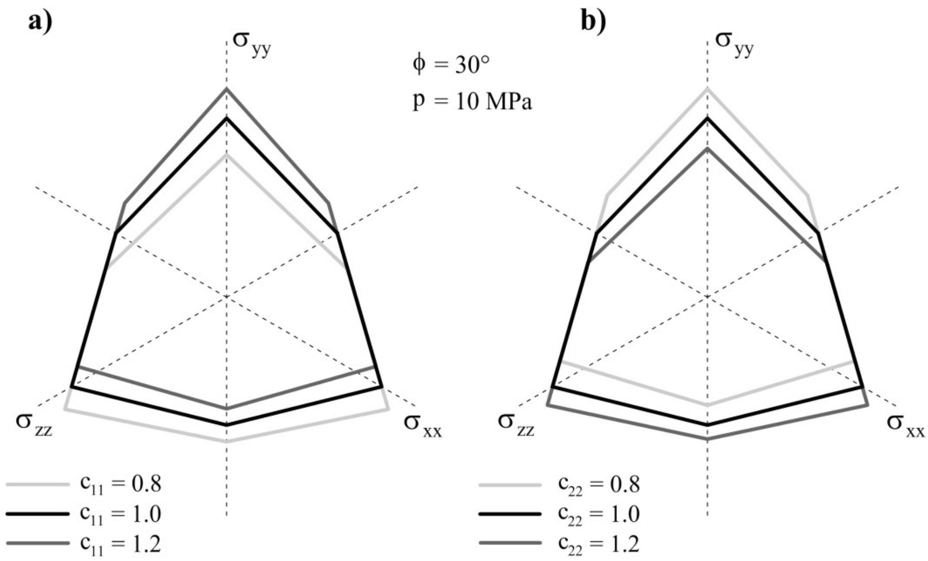


Figure 1: Effect of stress scaling on the Mohr-Coulomb failure criterion in the deviatoric plane

As an example of application the triaxial test results on a slate reported in [2] are presented together with the results of expressing anisotropy in the way outlined above. It can be observed that quite a reasonable match is obtained.

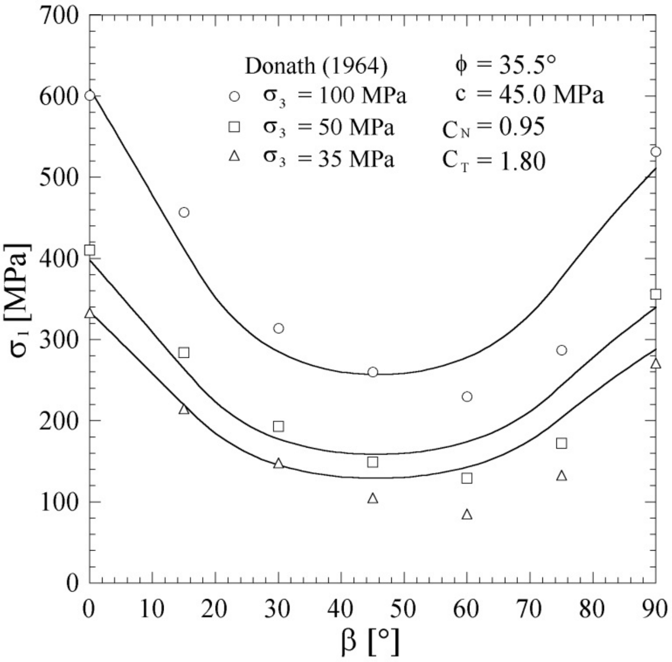


Figure 2: Comparison of the cross-anisotropic criterion and triaxial test results from [2].

3 APPLICATION TO AN UNDERGROUND EXCAVATION

The anisotropic model has been applied to the excavation of the GCS drift in the M-HM URL where the host rock is Callovo-Oxfordian argillite. The main features of the gallery excavation have been described in [3]. The GCS drift is oriented parallel to the major horizontal stress, and there is a nearly isotropic stress state in the plane orthogonal to the drift axis, with a ratio between the horizontal and vertical stresses very close to 1. This excavation exhibits convergences larger in the horizontal direction than in the vertical one and an Excavation Damaged Zone (EDZ) configuration that extends significantly more in the horizontal direction (Fig. 3).

The analysis uses a coupled hydromechanical formulation and plane strain conditions are assumed. The stress gradient due to gravity was neglected. The model was first brought to equilibrium by applying the corresponding radial forces in the tunnel wall, which corresponds to the initial state. Then, these forces were gradually reduced to simulate the excavation as a function of the distance between the analysis section and the excavation front. In this way, the three-dimensional nature of the problem is considered in an approximate manner. Radial stresses are not taken down to zero, but to a mean residual value of 0.3 MPa, that simulates the presence of the flexible support system employed in the drift.

An initial liquid pressure of 4.7 MPa was considered in the entire model, as the one measured at the main level of the URL (-490 m), close to the GCS drift. This value was also applied as a boundary condition in all the boundaries of the mesh. In the tunnel wall, the liquid pressured was also considered a function of the distance of between the analysis section and the excavation front. Furthermore, in order to reproduce the observed permeability increase in the EDZ, a dependency of the intrinsic permeability with plastic multiplier was incorporated in the simulation according to:

$$K_i = K_{i0} e^{\gamma \lambda} \tag{6}$$

where K_i is the intrinsic permeability of the damaged material, K_{i0} is the intrinsic permeability of the undamaged material, λ is the plastic multiplier and γ is a constant that controls the rate of change. Saturated conditions were assumed throughout the simulation. The strength anisotropy obtained from the constitutive model is depicted in Figure 4.

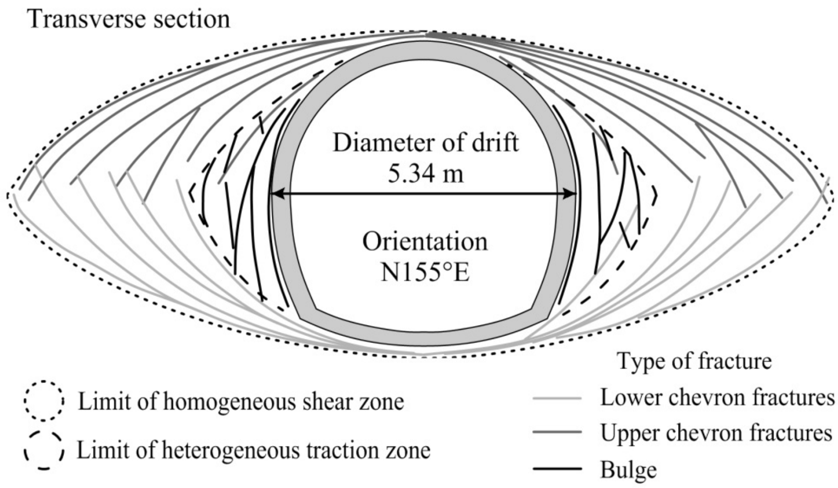


Figure 3: Conceptual picture of the EDZ around the excavated GCS drift [3].

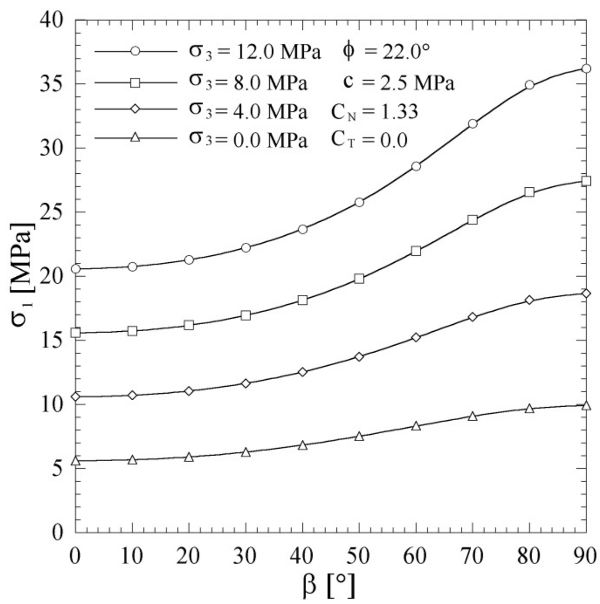
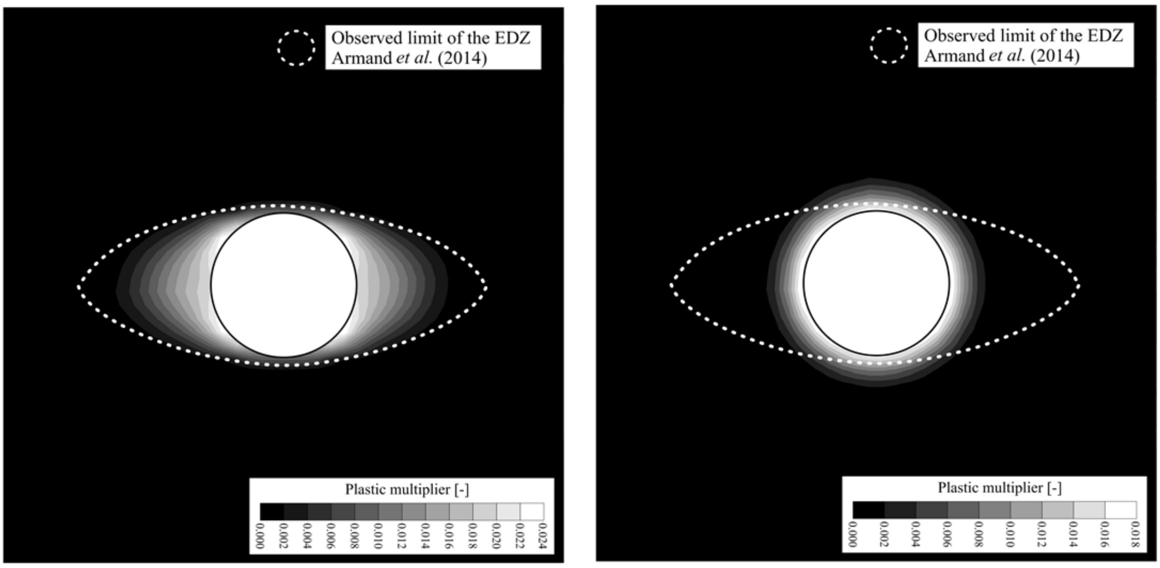


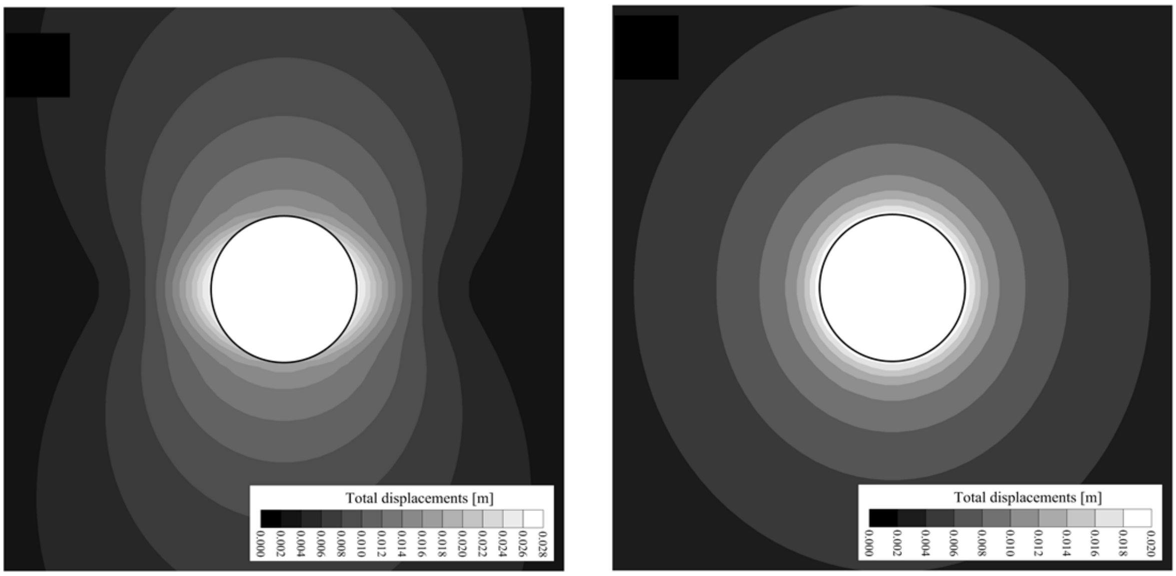
Figure 4: Strength anisotropy adopted in the analysis.

A good estimate of the EDZ can be obtained plotting contours of the value of the plastic multiplier. It can be observed that the anisotropic model (Figure 5a) results in an EDZ shape similar to that observed. Naturally, if isotropy were assumed a perfectly circular EDZ would ensue (Figure 5b). In the case of the anisotropic model, displacements are also larger in the horizontal direction than in the vertical one (Figure 6), which also agrees with the pattern of *in situ* observations [3].



a) b)

Figure 5: Plastic multiplier contours. a) Anisotropic model, b) Isotropic model



a) b)

Figure 6: Total displacement contours. a) Anisotropic model, b) Isotropic model

4 CONCLUSIONS

A cross-anisotropic extension of an elastoplastic constitutive model based on a non-uniform scaling of the stress tensor has been described. This concept can be applied to any stress based yield/failure criterion; its main advantage is the possibility of being incorporated to an already implemented isotropic constitutive model with only minor modifications. The example of application to the excavation in an argillaceous rock illustrates the importance of considering anisotropy if realistic distributions of the damaged zone and total displacements are to be obtained.

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