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CONSTITUTIVE MODEL AND STRAIN LOCALIZATION ISSUE IN ELASTOPLASTIC SATURATED POROUS MEDIA

X. Liu[*]**, A. Scarpas**[*]

[*] Faculty of Civil Engineering and Geosciences, Section of Structural Mechanics,
Delft University of Technology,
Stevinweg 1, 2628 CN, Delft, The Netherlands
e-mail: X.Liu@Citg.tudelft.nl

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Summary. *In order to properly characterize the mechanisms of strain localization, the investigations of strain localization are needed both numerically and experimentally. The aim of this investigation is to provide insight into the phenomenon of strain localization in fluid saturated sands by means of numerical modelling. A constitutive model capable of describing the elastoplastic response of geomaterials including model nonassociativity is developed. The importance of the presence of fluid on the formation and evolution of strain localization in fully saturated 3D sand specimen are identified.*

1 INTRODUCTION

The analysis of strain localization is of importance in engineering practice because localization is a precursor to sudden failure. Localized deformations in the form of narrow shear bands are often observed to develop after large inelastic deformation in materials. Strain localization has been extensively studied in recent years, in particular in connection with single phase solids. Due to the complexities associated with solid fluid phase interactions, the mechanisms responsible for strain localization in multiphase porous media can vary significantly from case to case. Several problems need to be addressed such as: the role of the fluid components in localization, the significant influencing factors in the development of strain localization, the question of why localization pattern vary between different tests.

The aim of this investigation is to provide insight into the phenomenon of strain localization in fluid saturated sands by means of numerical modelling. In order to achieve this goal, a constitutive model capable of describing the elastoplastic response of porous media including model nonassociativity is developed.

Two examples are chosen for numerical investigation. The importance of the presence of fluid on the formation and evolution of strain localization are identified. The role of influencing factors, such as soil permeability, water suction etc. is presented. Various combinations of material characteristics are examined.

2 CONSTITUTIVE MODELLING

In order to be capable of simulating strain localization phenomena, an appropriate constitutive model needs to be specified. In this contribution, the Desai yield surface as proposed by Desai[1] in the context of the hierarchical approach is utilized to simulate the elastoplastic characterization of the porous media.

One attractive feature of the surface is that it includes most of the currently common used plasticity models as special cases. The surface is continuous and hence avoids the problems of multi-surface models. The chosen form of the surface is:

$$\mathrm{F} = \frac{\mathrm{J}_2}{\mathrm{p}_\mathrm{a}^2} - \left[-\alpha \cdot \left(\frac{\mathrm{I}_1 + \mathrm{R}}{\mathrm{p}_\mathrm{a}}\right)^\mathrm{n} + \gamma \cdot \left(\frac{\mathrm{I}_1 + \mathrm{R}}{\mathrm{p}_\mathrm{a}}\right)^\mathrm{m}\right] \cdot \mathrm{F}_\mathrm{s} = 0 \tag{1}$$

where I_1 and J_2 are the first and second stress invariants respectively, p_a is the atmospheric pressure with units of stress, parameter m controls the nonlinearity of the ultimate surface, Liu et al.[2], R represents the triaxial strength in tension, F_s is the function related to the shape of the flow surface in the octahedral plane,

$$\mathrm{F}_\mathrm{s} = (1 - \beta \cdot \cos 3\theta)^{-0.5} \tag{2}$$

with $\cos 3\theta = 1.5\sqrt{3} \cdot \mathrm{J}_3 \big/ \mathrm{J}_2^{3/2}$ and J_3 is the third invariant of the deviatoric stress, θ is the Lode angle.

The isotropic hardening/softening of the material is described by means of parameter α. Parameter γ is related to the ultimate strength of the material and parameter n is related to the state of stress at which the material response changes from compaction to dilation.

In the hierarchical approach, a nonassociative model is obtained by defining the potential function as a correction/modification to the yield function. Thus, the plastic potential Q is expressed as:

$$\mathrm{Q} = \frac{\mathrm{J}_2}{\mathrm{p}_\mathrm{a}^2} - \left[-\alpha_\mathrm{Q} \cdot \left(\frac{\mathrm{I}_1 + \mathrm{R}}{\mathrm{p}_\mathrm{a}}\right)^\mathrm{n} + \gamma \cdot \left(\frac{\mathrm{I}_1 + \mathrm{R}}{\mathrm{p}_\mathrm{a}}\right)^\mathrm{m}\right] \cdot \mathrm{F}_\mathrm{s} \tag{3}$$

in which $\alpha_\mathrm{Q} = \alpha + \kappa_\mathrm{c}(\alpha_0 - \alpha)(1 - \chi_\mathrm{v})$. Parameter α_0 is the value of α at the initiation of nonassociativeness, parameter κ_c is the nonassociative material parameter, parameter χ_v controls the contribution of volumetric plastic deformation to the expansion of the potential surface and is defined by $\chi_\mathrm{v} = \xi_\mathrm{v} \big/ \xi$.

In order to simulate material hardening, parameter α of the yield surface in Eq. (1) is expressed as a function of both volumetric and deviatoric hardening components, α_V and α_D:

$$\alpha = \eta_\mathrm{h} \cdot \alpha_\mathrm{V} + (1 - \eta_\mathrm{h}) \cdot \alpha_\mathrm{D} \tag{4}$$

with

$$\alpha_\mathrm{V} = \mathrm{a}_1 \cdot \mathrm{e}^{\mathrm{b}_1 \cdot \xi_\mathrm{v}} \tag{5}$$

$$\alpha_\mathrm{D} = \mathrm{c}_1 \cdot \left[1 - \frac{(\mathrm{M}')^2}{27\gamma} \cdot \left(\frac{\xi_\mathrm{d}}{\mathrm{d}_1 + \xi_\mathrm{d}}\right)^2 \cdot \left(\frac{3\mathrm{p}_\mathrm{c}}{\mathrm{p}_\mathrm{a}}\right)^{(2-\mathrm{m})}\right] \tag{6}$$

$$\eta_\mathrm{h} = \frac{\xi_\mathrm{v}}{\xi_\mathrm{v} + \xi_\mathrm{d}} \tag{7}$$

α_V and α_D are the volumetric and deviatoric hardening components respectively. $\mathrm{a}_1, \mathrm{b}_1, \mathrm{c}_1$

and d_1 are hardening parameters. The ratio η_h in Eq. (7) denotes the contribution of volumetric hardening to the overall material hardening response. Details of the development of the mathematical expressions for α_v and α_D including the determination of the corresponding hardening parameters are presented in Liu et al.[2]

Simulation of the material softening phase can be achieved by means of specifying the variation of parameter α, after response degradation initiation, as an increasing function of the monotonically increasing equivalent post fracture plastic strain ξ_pf:

$$\alpha = \alpha_\mathrm{R} + \eta_\mathrm{s} \cdot \left(\alpha_\mathrm{u} - \alpha_\mathrm{R}\right) \tag{8}$$

in which $\eta_\mathrm{s} = \mathrm{e}^{-\kappa_1 \cdot \xi_\mathrm{pf}}$ and α_u and α_R are the values of α corresponding to material ultimate stress response and residual stress state respectively. Parameter κ_1 determines the material degradation rate.

4 NUMERICAL EXAMPLES OF STRAIN LOCALIZATION IN 3D SPECIMEN

4.1 3D Specimen subjected to triaxial load

A fully saturated cubic 3D specimen with impermeable boundaries is selected for the numerical simulations, Figure 1. The dense sand is chosen for the numerical investigation.

The material parameters have been derived on the basis of triaxial tests on ‘Eastern Scheldt’ dense sand. A confining pressure of 150 kPa is applied to all boundaries of the specimen and kept constant throughout the analysis. Incremental displacements are applied on a rigid platen at the top of the specimen.

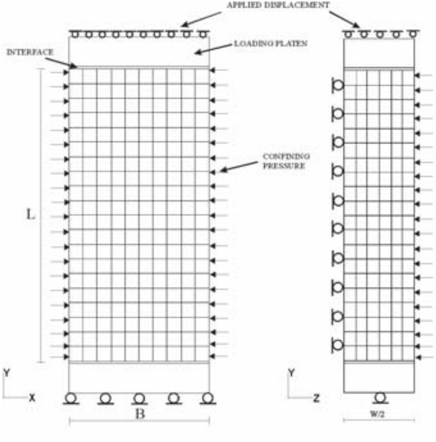


Figure 1: 3D specimen subjected to triaxial load

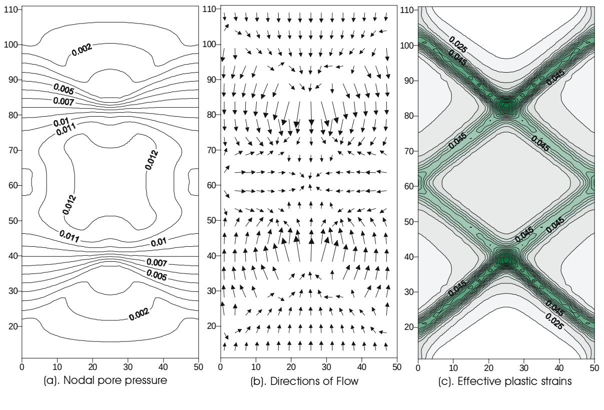


Figure 2:Plots at vertical displacement =1.6297mm

At a vertical displacement of 1.6297 mm, two pairs of dominant shear bands formed and propagated to the boundaries of the specimen, Figure 2(c). During shear band development, large material dilatancy occurs inside the shear bands. As a consequence, high excess pore pressure gradients develop within the dilated regions, Figure 2(a), and water flows mostly towards them, Figure 2(b).

4.2 3D Specimen subjected to in/out flow

It is of interest to investigate what happens on onset and development of strain localization in the specimen when the pore water suction field in the specimen is disturbed. To achieve this, the similar specimen utilized in the previous example has been chosen as the numerical example, but the water outflow and inflow are applied separately on the center four elements of the specimen during the whole period of the test, see Figure 3.

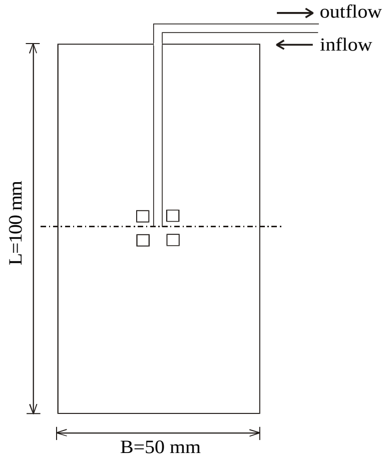
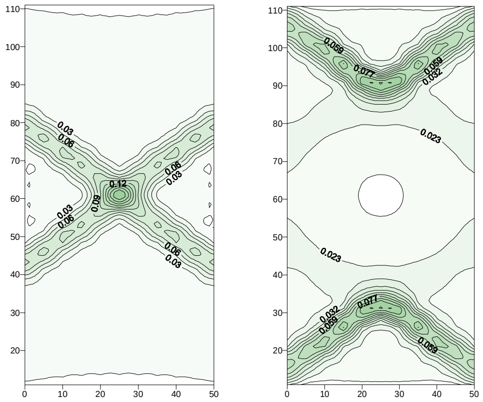


Figure 3: 3D specimen subjected to in/out flow.



(a).inflow at center (b). outflow at center

Figure 4: Contour plots of effective plastic strain

Figure 4 presents the effective plastic strain in the specimen when in/out flow is applied in the central part. It can be clearly seen that the additional outflow and inflow can influence significantly the development of the shear bands in the specimen. In the case of outflow induced test, the shear bands move towards the platens and in the case of inflow induced test, the shear bands develop in the centre of the specimen.

12 CONCLUSIONS

- The fluid (water) phase plays an important role in porous media strain localization. The formation and evolution of strain localization are influenced both by the material behaviour of the solid medium and the interaction between the fluid and the solid components.
- Additional outflow and inflow applied to a specimen can greatly modify the pattern of the pore water pressure and effective plastic strain development.

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