Macromodelling of softening in non-cohesive soils

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Abstract. Considering non-cohesive material, the void ratio is used to control softening on the friction angle. In order to obtain well-posed boundary-value problems, the softening parameter is defined as a nonlocal state parameter, so that computational results remain independent of the FEM-discretization. The model is evaluated through a comparison of numerical analysis and experimental data on Hostun sand. For a calibration of the constitutive model triaxial tests and oedometer tests with near-homogeneous deformations were used. Biaxial tests with strong shear-banding for dense sand were used to study the evolution of strain localization. The resulting shear band thickness, the role of the internal length and the input of combining both material and geometric softening are discussed.

1 Introduction

In non-cohesive sand the degradation of the friction angle evolves from dilatant plastic shearing, being a consequence of particle motion and particle rearrangement. Especially densely packed sands become looser during plastic flow until reaching the so-called critical-(steady) state. During this process the peak friction angle, $\varphi$, decreases down to the critical state friction angle, $\varphi_{cs}$. Due to the fact that the number of particle contacts is hardly changed during dilatant shearing, the unloading stiffness remains insensitive to this type of material softening. As a consequence, constitutive models have to be formulated within the theory of rate-independent plasticity [1] rather than the damage theory of fracture mechanics [2]. The promising continuum models, as proposed in current mechanics literature, are Cosserat models [3] and nonlocal models [4], including gradient plasticity [5, 6]. In this paper the simplest framework of modelling is chosen, i.e. nonlocal plasticity as originally proposed by Eringen [7, 8] and extended by Bazant [9] a.o..

In contrast to concrete, very little quantitative comparisons of numerical and experimental data have been published for geological materials. To improve this situation, attention is focused on the well-known test results of Hostun ‘RF’ sand [10]. A large database on Hostun sand containing the results of axisymmetric and plane strain tests under drained conditions is used. The main part of the tests were performed at Grenoble [11–14].

The paper begins by formulating friction softening as an extension of the simple Drucker-Prager model. It is shown that the local form leads to considerable mesh-dependency of the post-peak load-displacement curve. On the other hand, the nonlocal form, which involves the input of an internal length, shows...
fully regularized curves and a qualitative agreement with experimental data. For obtaining quantitative agreement the simple Drucker-Prager model is replaced by a more advanced Hardening Soil model which includes deviatoric hardening/softening, a MC-yield criterion and additionally a cap [15–17]. First of all, it is shown that this model is well able to predict triaxial test data. Then full attention is paid to shear-banding in biaxial tests. For a quantitative back-analysis, both the use of an advanced nonlocal model and its embedment in an updated Lagrangian FE-formulation appears to be essential.

2 Approach to friction softening

Softening behaviour of dense sand is always accompanied with large changes of the void ratio in the zone of localization and involves a reduction of the friction angle. Using the triaxial test results for the ‘dense’ Hostun sand, one can observe in the stress-plane of Fig. 1 that the strength envelope rotates from a peak value to the residual critical state. It appears that the degradation of the friction angle can be specified by the void ratio $e$ as a softening parameter and a softening modulus $h_\phi$. A simple linear relation is indicated in Eq. (1), where a superimposed dot is used to denote time rates:

$$\dot{\phi} = -h_\phi \dot{e} \quad \text{for} \quad \phi > \phi_{cs}. \quad (1)$$

Evidence for this relationship is a.o. put forward by Teferra [18] and Schultze [19]. Both authors compared a lot of different equations with experimental data and advocated the use of a simple linear relation, i.e. a constant softening modulus until the critical state angle $\phi_{cs}$ is reached.

For the present study, the final decision to use only a constant softening modulus $h_\phi$ is based on the data for Hostun sand, an empirical relationship as presented by Bolton [20] and the Danish Code of Practice [21], as illustrated