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Parameter calibration for high-porosity sandstones deformed in the compaction banding regime

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ABSTRACT

This paper discusses the parameter calibration procedure for an elastoplastic constitutive model for high-porosity rocks. The model selected for the study is formulated in the frame of the critical state theory, which is here used in a form able to accommodate non-associated plastic flow and softening effects due to volumetric and deviatoric plastic strains. The goal of this study is to generate a set of model constants able to capture both the stress-strain response and the compaction localization characteristics (e.g., stress and inclination at the onset of the deformation bands). For this purpose, data about the compaction localization properties of four extensively characterized sandstones have been considered. In particular, the strain localization theory has been used as a calibration tool, using explicitly information about the pressure-dependence of the localization mechanisms observed in experiments. The model constants have been defined by matching the constitutive response upon hydrostatic compression, as well as the stresses at the transition from high-angle shear bands to pure compaction bands, and from compaction bands to homogeneous cataclastic flow. It is shown that such procedure generates a set of model constants able to capture satisfactorily both the rheological response upon triaxial compression and the salient features of the compaction localization process.

1. Introduction

High-porosity rocks are characterized by complex mechanical properties, which encompass the transition from brittle to ductile response [1], the tendency to dilate or contract upon shearing [2,3], and widely variable forms of strain localization [4,5]. The ability to reproduce such complex patterns through numerical models is crucial for various engineering applications that involve the extraction of hydrocarbons and the underground storage of fluid and solid waste [6,7]. In such applications it is indeed pivotal to capture both pre- and post-failure deformations (e.g., for the assessment of borehole stability [8]), as well as the variations in porosity associated with inelastic strains (e.g., to estimate changes in permeability [9,10]). In this context, compaction localization has attracted considerable attention because of its detrimental effects on fluid flow [11] and because of the challenges it poses to connect the findings at laboratory scale [12–14] to the rare evidences of compaction banding in the field [15,16]. Various constitutive laws have been used for interpreting compaction localization, often focusing on elastoplastic modeling frameworks [17]. From this point of view, a pivotal task is to constrain the model parameters in a way that enables the integrated study of pre-failure deformations, strain localization patterns, and post-localization response.

Numerous authors have addressed the problem of connecting the predicted patterns of strain localization with model-specific features. For example, Issen [18] used various plastic models to study the onset of strain localization in porous rocks, finding that multiple yielding mechanisms can provide a better match of the experimental findings compared to models characterized by a single yield surface. Baud et al. [19] have instead compared the performance of cap models [20] and critical state models [21], pointing out that both approaches require further parameters to accommodate non-associated plastic flow and capture strain localization processes. Similar conclusions were suggested by Rudnicki [22], who used an elliptic cap to study the pressure dependence of the band inclination. Based on such analysis, Grueschow and Rudnicki [23] proposed an enhanced cap model able to capture both hydrostatic and shearing response. Nevertheless, to achieve this goal the evolution of shape and size of the cap had to be expressed as a function of both volumetric and deviatoric plastic strains, thus increasing the number of parameters required for calibration.

Similar issues have been discussed in subsequent studies by Das et al. [24–26] and Tengattini et al. [27], who used Breakage models to study compaction localization in porous sandstones, and

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by Buscarnera and Laverack [28], who used a plastic model with two internal variables to capture the response of two high-porosity rocks. In the former studies, it was found that a constitutive parameter associated with pore collapse played a key role in the localization potential. In the latter, it was pointed out that the phenomenology of localized compaction was captured satisfactorily only by assigning appropriate values to the constants that control the evolution of the yield surface upon plastic shearing. It is thus readily apparent that the practical use of phenomenological models in actual applications must face the difficulty of calibrating numerous material constants from limited information. It is therefore arguable that, to benefit from the advantages of sophisticated constitutive models, the adopted calibration strategy must extract as much information as possible from a limited set of available experiments.

For this reason, experimental data related to localized failures might represent an additional ingredient to enrich the calibration procedure by correctly capturing both constitutive response and discontinuous modes of bifurcation. An example of this logic has been discussed by Schreyer and Neilsen [29] who formulated a simplified analytical criterion to identify the loss of uniqueness of the incremental response, and by Gajo et al. [30] who pointed out that plastic flow characteristics play a critical role in the shear strain localization of granular solids. More recently, Buscarnera and Laverack [28] addressed this problem with reference to compaction banding, showing that the calibration procedure could be optimized by cross-correlating strain localization data from multiple stress paths, thus benefiting from the path-dependent properties of the localization characteristics. Such strategy was later used also by Das and Buscarnera [31] to study numerically the role of boundary conditions and kinematic constraints.

Here we adopt a similar approach, in that we integrate the localization analysis within the process of model calibration to obtain a set of constants able to reproduce both pre- and post-yielding rheology, as well as the patterns of compaction localization at different stress confinements. At variance with the analysis by Buscarnera and Laverack [28], however, we do not focus exclusively on pure compaction bands (i.e., on compaction localization orthogonal to the maximum compressive stress), but we rather focus on the pressure-dependence of the strain localization characteristics predicted by a specific critical state model for porous rocks. More specifically, we account explicitly for the stress-dependence of the band angle, using evidences of such variability for the purpose of model calibration. Reference has been made to extensive data on compaction localization available for four widely tested sandstones (Bentheim, Berea, Rothbach, and Bleurswiller), considering the transition from mixed shear/compaction bands to pure compaction bands within the frame of the same analysis. In accordance with the choice of using a constitutive framework for porous rocks, the analyses have been restricted to compaction localization. In other words, no attempt has been made to capture also brittle/dilative failure mechanisms within the context of the same simulations. The goal of the study is indeed to illustrate how the direct consideration of data about the pressure-dependence of the compaction localization mechanisms is a useful tool to constrain and optimize the set of model-specific constitutive parameters, as well as to discuss advantages and disadvantages of the selected modeling framework with reference to different classes of strain localization processes.

2. An elastoplastic model for high-porosity rocks

The elastoplastic law selected for this study has been proposed by Nova et al. [32] on the basis of previous contributions by Gens and Nova [33] and Lagioia and Nova [34]. The selected model relies on the framework of critical state plasticity [35], which is enhanced to capture the phenomenology of cemented soils and porous rocks. In particular, the model reproduces the transition from softening to hardening through an additional plastic variable mimicking the loss of structure upon hydrostatic compression and/or plastic shearing [33]. In this way, it is possible to replicate the most salient macroscopic process taking place in both the brittle–ductile transition regime and the plastic cap region. It is worth noting that the model postulates isotropic response, and it is therefore inadequate to capture anisotropic effects associated with the relative orientation of bedding planes and applied stresses. Nevertheless, extensions in such direction are possible by incorporating specific features to cope with elastic and plastic anisotropy [36,37]. The yield function f and plastic potential g adopted for plastic modeling purposes is expressed in the form proposed by Lagioia et al. [38]

$$\left.\begin{matrix} f \\ g \end{matrix}\right\} = \frac{p}{p_c^\star} - \frac{\left(1+\dfrac{\eta}{M_h K_2}\right)^{K_2/(1-\mu_h)(K_1-K_2)}}{\left(1+\dfrac{\eta}{M_h K_1}\right)^{K_1/(1-\mu_h)(K_1-K_2)}} \quad \text{with } \eta = \frac{q}{p+p_t}, \tag{1}$$

$$K_{1/2} = \frac{\mu_h(1-\alpha_h)}{2(1-\mu_h)}\left(1 \pm \sqrt{1-\frac{4\alpha_h(1-\mu_h)}{\mu_h(1-\alpha_h)^2}}\right), \tag{2}$$

where p represents the mean pressure and q the deviatoric stress $q = \sqrt{(3/2)s_{ij}s_{ij}}$ where $s_{ij} = \sigma_{ij} - p\delta_{ij}$. The same expression is here used also for the plastic potential g, obtaining associated flow when the two functions are characterized by the same model constants. In the most general case, however, different shape parameters must be used for plastic potential and yield surface (i.e., M_h, α_h and μ_h, where the subscript h is referred to f and g). The pressure at hydrostatic yielding, $p_c^\star$, consists of the sum of two contributions, p_s and p_m. The former describes the effect of previous compaction history (in a way similar to the preconsolidation pressure of critical state models), while the latter reproduces the macroscopic effects of lithification and inter-particle bonding

$$p_c^\star = p_s + p_m + p_t \quad \text{with } p_t = rp_m. \tag{3}$$

The term p_t in Eq. (3) reflects the tensile strength of the rock, which for simplicity is expressed as a function of p_m (with r representing an additional model parameter). The evolution of the yield surface is governed by the hardening laws that control the relationship between p_s and p_m and the plastic strains. Hereafter, the following laws are adopted

$$\begin{cases} \dot{p}_s = \dfrac{p_s}{B_p}\dot{\varepsilon}_v^p \\ \dot{p}_m = -\rho_m p_m\left(|\dot{\varepsilon}_v^p| + \xi_m \dot{\varepsilon}_d^p\right). \end{cases} \tag{4}$$

The evolution of p_s reflects the usual hardening/softening mechanism of critical state plasticity, according to which the growth and/or contraction of the elastic domain is governed by plastic compaction and/or dilation, respectively. By contrast, the evolution of p_m captures the loss of structure of the cemented material, introducing softening mechanisms that depend on both volumetric and deviatoric plastic strains. The constitutive parameters B_p, ρ_m and ξ_m control the plastic hardening, with the former two playing a key role in the hydrostatic compaction response. The plastic strain increments are computed using the flow rule:

$$\begin{Bmatrix} \dot{\varepsilon}_v^p \\ \dot{\varepsilon}_d^p \end{Bmatrix} = \Lambda \begin{Bmatrix} \partial g/\partial p \\ \partial g/\partial q \end{Bmatrix}, \tag{5}$$