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Simulation of localized compaction in high-porosity calcarenite subjected to boundary constraints

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ABSTRACT

This paper studies the mechanics of localized compaction in porous rocks subjected to axisymmetric deformation. The material selected for the study is Gravina calcarenite, a soft rock prone to pore collapse and compaction banding. The stress–strain response has been simulated through a plasticity model capturing inelastic processes in the brittle–ductile transition, while the bifurcation theory has been used to calibrate the model constants and identify stress paths able to generate heterogeneous compaction. The onset of strain localization upon application of the selected paths has been assessed numerically, simulating the global response of calcarenite specimens via the Finite Element Method. Simulated triaxial compression tests have been compared with published experiments, showing good agreement in terms of both macroscopic response and localization patterns. In addition, oedometric compression has been simulated to inspect the role of material heterogeneity, kinematic constraints and boundary effects. The results show that the interplay between these factors has important implications for the resulting localization process. In particular, heterogeneity and boundary conditions have been found to control the formation of unexpected strain patterns, such as compactive shear zones that do not reflect the symmetry of the imposed constraints. Moreover, the simulations have suggested that such forms of heterogeneous compaction may not be easily identifiable from global measurements, as they tend to disappear with further strains and the averaging of the quantities measured at the boundary tends to generate global signatures not easily distinguishable from those associated with pure (horizontal) compaction banding.

1. Introduction

High-porosity rocks display a wide range of localization mechanisms controlled by microstructural attributes and stress conditions [1]. In particular, when such rocks are loaded at high confinements they tend to exhibit compaction bands orthogonal to the maximum compressive stress [2–5]. These modes of localization have attracted the interest of different communities, such as structural geology, geophysics, geotechnical and petroleum engineering. This interest is motivated by the ability of these structures to reduce the permeability of reservoir rocks and threaten the stability of deep boreholes [6,7]. After being identified in the field by Mollema and Antonellini [8], the mechanisms leading to the formation of compaction bands have been studied via laboratory tests [2–4,9–14], theoretical investigations [15–20] and numerical analyses [21–25]. These studies, together with microstructural inspections, identified grain crushing and pore collapse as the key micromechanical processes that control the formation of compaction bands. While these processes induce a local loss of strength, they also increase the frequency of intergranular contacts, thus promoting the rearrangement of the crushed fragments, the reduction of the local porosity and the re-hardening of the post-localization regime. As a result, unlike single shear bands observed at low confinements, the brittle–ductile regime promotes multiple compaction zones that propagate across the sample until a complete re-hardening of the specimen [26].

The systematic observation that compaction bands tend to form in such a peculiar regime of deformation has inspired testing procedures based on pre-selected triaxial compression paths, i.e., stress paths designed to pass through the transitional regime of the tested rock [2,3,13]. While these methods have disclosed important characteristics of compaction banding, the conditions imposed in the laboratory may significantly differ from those occurring in the field [27,28]. For example, recent experiments have pointed out the importance of anisotropic stress paths for the onset of strain inhomogeneities [29,30], while theoretical studies have suggested that non-axisymmetric loading [31] and kinematic constraints [32] may hinder the formation of compaction bands. Insights on this matter have been recently provided by Soliva et al. [33], who discussed the effect of

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factors such as burial history and local tectonics on stress paths and consequent strain localization mechanisms.

It is therefore arguable that the theoretical/numerical inspection of different kinematic conditions and stress paths is a valuable tool to improve the understanding of compaction bands and identify the key processes that control their formation in the field. For these reasons, here we study the relation between the axisymmetric stress paths that derive from imposed kinematic constraints and the onset of compaction banding. In particular, numerical modeling will be used to explore the influence of kinematic conditions, boundary restraints and material heterogeneity. The reference material selected for the study is Gravina calcarenite, a porous rock from Southern Italy prone to pore collapse, degradation of its cement matrix and strain inhomogeneities [14,34–36].

The study consists of two distinct parts. In the first one, the constitutive response of the selected soft-rock is simulated through an elasto-plastic model developed by Nova and co-workers [35,37,38], which has been chosen for its ability to capture inelastic mechanisms in the brittle–ductile transition. The model predictions are then inspected via a bifurcation criterion for strain localization [39], identifying a set of stress paths able to generate localized compaction. In the second part, numerical simulations are used to model the response of calcarenite specimens as boundary value problems. The objective of the numerical study is to inspect onset and propagation of localized compaction and elucidate the role of imposed kinematic constraints. For this purpose, a Finite Element model enriched with a rate-dependent regularization scheme [40,41] has been used to reproduce triaxial compression and oedometric compaction in presence of different boundary conditions. The computed response is finally compared with experimental data, discussing the interplay between the imposed conditions and the predicted patterns of heterogeneous compaction.

2. Constitutive analysis of localized compaction

2.1. Constitutive model for porous rocks

An essential component for compaction band analyses is a constitutive law able to replicate the rheological response of specimens loaded in the brittle–ductile transition zone, as well as to capture the associated strain localization processes. A popular strategy involves the use of cap plasticity [42], which allows the simulation of inelastic compaction during compression. While parabolic cap models [43] and elliptic caps [42] are typical choices, numerous enhancements have been proposed in recent years to better fit the data [44,45]. Another option for constitutive analyses is critical state plasticity [46,47], which links the stress–strain response to the evolving plastic volumetric strains. Despite these features, cap plasticity and critical state theories have been typically used to assess the potential for localized compaction at yielding [45,48,49], and only few studies have considered the interplay between stress–strain response and patterns of localized compaction [22,24,50]. In addition, most of the existing works do not include a description of the irreversible processes that control the mechanics of compaction, such as bond/grain breakage and pore collapse. A notable exception is the work by Das et al. [16,21], in which the explicit incorporation of grain crushing allowed the authors to point out the importance of the rheological response on the simulation of both onset and propagation of compaction bands.

Here we use a similar logic, in that we use a constitutive law able to reproduce realistically the rheology of porous rocks observed in experiments. The selected model derives from a series of contributions by Nova and co-workers [35,38,51,52], and is here chosen for its ability to capture the transition from brittle to ductile behavior in a wide range of porous geomaterials [14,32,35]. At variance with typical models, this law includes multiple internal variables mimicking a number of inelastic processes involved in compaction banding (i.e., rupture of microstructural compounds and subsequent pore collapse, as well as compaction hardening). A major advantage of this strategy is the possibility to naturally reproduce the porosity loss generated by the degradation of the cement, which is captured by the plastic compensatory mechanism created by the competition between an internal variable that increases with compaction (thus mimicking a denser skeleton packing) and a second term that decreases (thus reflecting a strain-induced degradation of the microstructure, [35]). Experimental and theoretical studies have demonstrated the ability of this model to capture the macroscopic signatures of compaction banding upon oedometric compression [53], while a recent study by Buscarnera and Laverack [32] has discussed the possibility to use it for capturing localized compaction in both porous sandstones and carbonate rocks subjected to triaxial compression.

Hereafter we provide a brief description of the constitutive formulation, focusing on the functions that allow the incorporation of non-normality. In particular, the yield function and the plastic potential are assumed to be given by the expressions proposed by Lagioia et al. [37]:

$$\left.\begin{matrix} f \\ g \end{matrix}\right\} = A_h^{K_{1h}/C_h} B_h^{-K_{2h}/C_h} p^* - p'_{hs} = 0 \tag{1}$$

$$A_h = 1 + \frac{1}{K_{1h} M_h} \frac{q}{p^*} \tag{2}$$

$$B_h = 1 + \frac{1}{K_{2h} M_h} \frac{q}{p^*} \tag{3}$$

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

$$C_h = (1-\mu_h)(K_{1h} - K_{2h}) \tag{5}$$

$$M_h = \frac{2 M_{ch} c_h^M}{1 + c_h^M - (1 - c_h^M)\sin(3\vartheta)} \tag{6}$$

where $p^* = p^* + rp_m = \sigma_{ij}\delta_{ij}/3 + rp_m$ is a modified mean effective stress; $q = \sqrt{(3/2)s_{ij}s_{ij}}$ is the deviatoric stress ($s_{ij} = \sigma_{ij} - p'\delta_{ij}$) and the subscript h indicates either the yield function (h=f) or the plastic potential (h=g). The size of the elastic domain (p_{fs}') is measured along the hydrostatic axis (Fig. 1c) and is defined by a linear combination of independent internal variables, here referred to as p_s and p_m (i.e., by $p_{fs}' = p_s + p_m + rp_m$, where the term rp_m represents the hydrostatic yield threshold in the tensile stress regime).

As summarized by Eqs. (1)–(5), independent parameters are needed to reproduce non-associated plastic flow. In particular, the shape of yield surface and plastic potential is defined by two sets of four parameters (α_h, μ_h, M_{ch} and M_{eh}). The constants α_h and μ_h control the shape of the surfaces in meridian sections of the stress space (Fig. 1c), while M_{ch} and M_{eh} control the geometry of the surfaces in the region of compression and extension loading, respectively. In particular, the ratio $c_h^M = M_{ch}/M_{eh}$ defines the shape of the deviatoric section (Fig. 1b), which is expressed as a function of the Lode angle, ϑ, according to Eq. (6) [54]. These two sets of parameter must be calibrated based on experiments, thus defining the shape of the yield surface from observed yielding points, and that of the plastic potential from the irreversible strain increments measured in the post-yielding regime [32]. The typical shape of the initial yield envelope in the principal stress space and deviatoric plane is presented in Fig. 1.

The most notable features of the model are embedded in the hardening laws [51,52]. Indeed, unlike conventional critical state