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A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part II – Validation and localization analysis

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ABSTRACT

We study the mechanical failure of cemented granular materials (e.g., sandstones) using a constitutive model based on breakage mechanics for grain crushing and damage mechanics for cement fracture. The theoretical aspects of this model are presented in Part I: Tengattini et al. (2014), *A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables, Part I – Theory* (Journal of the Mechanics and Physics of Solids, http://dx.doi.org/10.1016/j.jmps.2014.05.021). In this Part II we investigate the constitutive and structural responses of cemented granular materials through analyses of Boundary Value Problems (BVPs).

The multiple failure mechanisms captured by the proposed model enable the behavior of cemented granular rocks to be well reproduced for a wide range of confining pressures. Furthermore, through comparison of the model predictions and experimental data, the micromechanical basis of the model provides improved understanding of failure mechanisms of cemented granular materials. In particular, we show that grain crushing is the predominant inelastic deformation mechanism under high pressures while cement failure is the relevant mechanism at low pressures. Over an intermediate pressure regime a mixed mode of failure mechanisms is observed. Furthermore, the micromechanical roots of the model allow the effects on localized deformation modes of various initial microstructures to be studied. The results obtained from both the constitutive responses and BVP solutions indicate that the proposed approach and model provide a promising basis for future theoretical studies on cemented granular materials.

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1. Introduction

Cemented granular materials (CGMs) are a broad class of geomaterials that share a common micro-scale structure made of grains connected by cement that partially or completely fills the voids. Inelastic strain in these materials is accommodated through the micro-mechanisms of grain crushing, cement damage and fragment reorganization (Mendedez et al., 1996).

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In part I (P-I) of this work we formulated a novel constitutive description for the CGM class of materials, connecting quantifiable measures of the micro-mechanical processes with the macroscopic mechanical behavior. In particular, breakage mechanics (Einav, 2007a,b), which provides a description of the evolution of the granular component and fragment rearrangement, is augmented with a novel definition to characterize the evolution of the cement phase using a cement size distribution (*csd*).

P-I focused on the formulation of the model and the analysis of the relationship of each of the internal variables, parameters and indices with the measurable physical quantities. In this second part (P-II) we focus on the comparison between the predictions of the model, both at the constitutive and at the structural (specimen) scale, with experimental data on different cemented granular materials tested at different mean stress levels.

A number of constitutive models have been proposed for cemented granular materials, which are all formulated in the framework of elasto-plasticity (e.g., Gens and Nova, 1993; Lagioia and Nova, 1995; Vatsala et al., 2001; Sheldon et al., 2006; Navarro et al., 2010). All these models show a good capability to reproduce experimentally observed macroscopic behavior. Nonetheless, these models are all phenomenological in nature, i.e., they overlook the micro-scale inelastic phenomena and require a wide, and sometimes hard to calibrate, set of parameters, some of which have little to no relation with the mechanical features of the material. On the other hand, the model proposed herein is micro-mechanics based, which implies that the parameters it requires have a clear physical meaning. It is worth noting that these parameters can and will be derived using only a limited number of classical geotechnical tests.

An experimentally observed feature of the behavior of CGMs is the brittle–ductile transition with increasing mean stress (Menendez et al., 1996; Wong and Baud, 2012), which shows a sharp shear strain localization connected to modest grain crushing towards compaction bands and diffuse cataclastic flow. Also, several studies reveal how these features are influenced by material properties, such as the amount and type of cement (Airey, 1993; Schnaid et al., 2001; Ismail et al., 2002).

In this paper, the study of the onset and orientation of strain localization is carried out within the framework of bifurcation analysis, through the investigation of the loss of positive definiteness of the determinant of the acoustic tensor (Rudnicki and Rice, 1975; Vardoulakis and Sulem, 1995). We analyze the influence of material properties on strain localization, with particular focus on those properties that have stronger impact on the brittle–ductile transition.

Several experimental tests and field observations (Aydin, 1978; Hill, 1989; Mollema and Antonellini, 1996; Klein et al., 2001; Baud et Al., 2004; Tembe et al., 2008) reveal that the post-localization behavior of CGMs is often dominated by multiple localization bands, or even more complex localization patterns. This not only affects the mechanical behavior, but also other aspects such as the hydraulic properties. Localized deformation can even compartmentalize material, creating preferential flow patterns by inhomogeneously affecting porosity and permeability, which has clear consequences for important engineering applications such as hydrocarbon extraction. While several studies successfully reproduce the experimentally observed localization patterns (e.g., Katsman et al., 2005; Katsman and Aharonov, 2006; Chemenda, 2009, 2011), the macroscopic mechanical response is not always validated. In other studies (e.g., Oka et al., 2011; Stefanov et al., 2011) the comparison of band orientation, as predicted by the model and the experimentally observed one is missing.

To study the patterns of localized deformation in CGMs with our model, we solve BVPs at the structural (specimen) level by means of the commercial finite element (FE) code ABAQUS (ABAQUS standard 6.8, 2008), in which we have implemented our constitutive model. The set of constitutive parameters are not obtained by fitting the localization predictions, but rather from a set of mechanical tests. It is well known that when solving BVPs using constitutive models that are not equipped with an internal length, a number of numerical troubles can occur (e.g., Jirásek and Bažant, 2001; Chambon et al., 2004). These numerical issues have a mathematical origin, in that they are due to the ill-posedness of BVPs, and result in non-objective predictions – the most striking of which is the fact that the width of the localization band is dictated by the resolution of the FE mesh. Several remedies have been suggested to overcome this lack of objectivity, including higher order continua (Chambon and Moullet, 2004) and regularizations of different kinds. Herein, a Perzyna-type (Perzyna, 1966), rate-dependent viscoplastic extension of the model is introduced to regularize the BVP.

The micromechanical foundation of our model means that, in addition to comparing the model with macroscopic (global) behavior and localization patterns, we can also compare the micromechanical variables that characterize the evolution (e.g., as a function of mean-stress). We have chosen three specific materials, which exhibit a broad range of failure modes particularly in brittle–ductile transitional regime among the several CGMs experimentally studied in the literature. Bentheim sandstone (Baud et al., 2006) has been selected because it is one of the most commonly used in benchmarking numerical simulations of strain localization. In contrast, homogeneous cataclastic flow is the dominant failure mode in Adamswiller sandstone (Wong et al., 1997). Gravina Calcarenite (Lagioia and Nova, 1995) shows a complex failure mode with dominant pore collapse feature. This last example has been purposely picked as an example of a more "complex" material, i.e., a material for which the simplest possible description proposed in P-I is not sufficient to properly describe the macroscopic mechanical response. With Calcarenite, we intend to demonstrate the solidity of the proposed modeling approach by showing how, if and when needed, further physical understanding can be simply and effectively injected into the model. Furthermore, these examples allow a comparison with reference constitutive models for CGMs.

The paper is organized as follows. A summary of the constitutive model proposed in P-I is presented in Section 2 to provide a basis for further investigations in this study. The model is then assessed against experimental observations. As mentioned above, both constitutive behavior (Section 3) and localization characteristics (Sections 4 and 5) are addressed at length, highlighting the novel features of the proposed model. This is followed by a post-localization analysis, where the

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