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The importance of Thermo-Hydro-Mechanical couplings and microstructure to strain localization in 3D continua with application to seismic faults. Part I: Theory and linear stability analysis

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ABSTRACT

A Thermo-Hydro-Mechanical (THM) model for Cosserat continua is developed to explore the influence of frictional heating and thermal pore fluid pressurization on the strain localization phenomenon. A general framework is presented to conduct a bifurcation analysis for elasto-plastic Cosserat continua with THM couplings and predict the onset of instability. The presence of internal lengths in Cosserat continua enables to estimate the thickness of the localization zone. This is done by performing a linear stability analysis of the system and looking for the selected wavelength corresponding to the instability mode with fastest finite growth coefficient. These concepts are applied to the study of fault zones under fast shearing. For doing so, we consider a model of a sheared saturated infinite granular layer. The influence of THM couplings on the bifurcation state and the shear band width is investigated. Taking representative parameters for a centroidal fault gouge, the evolution of the thickness of the localized zone under continuous shear is studied. Furthermore, the effect of grain crushing inside the shear band is explored by varying the internal length of the constitutive law.

1. Introduction

Strain localization is of major importance in fault zones as it affects shear heating and pore pressure build up during seismic slip (Kanamori and Brodsky, 2004). In this paper we investigate the effect of microstructure and of various Thermo-Hydro-Mechanical (THM) couplings on the behavior of geomaterials and, in particular, on the behavior of mature faults zones during pre- and co-seismic slip. Seismic slip is accompanied by extreme shear strain localization into a narrow, thin zone, which is commonly called Principal Slip Zone (PSZ). According to field observations, the PSZ has a finite thickness (see for instance Punchbowl fault, San Andreas system (Chester and Chester, 1998), Big Hole normal fault, Utah (Shipton et al., 2006), Median Tectonic line, Japan (Wibberley and Shimamoto, 2003)) and varies from hundreds of microns to few centimetres (Sibson, 2003), depending on the size of the microstructure and of THM mechanisms. The PSZ lies within a zone of highly fragmented, granulated material called fault gouge (Ben-Zion and Sammis, 2003).

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Theoretical and experimental research shows that strain localization is caused and enhanced by weakening mechanisms that can either be of pure mechanical origin (e.g. geometrical and mechanical changes of the solid skeleton (e.g. Togo and Shimamoto, 2012), such as grain cataclasis, reorientation, debonding etc.) or of a combination of various physico-chemical couplings (e.g. Sulem and Stefanou, 2016). For instance, thermal pressurization of the pore fluid in saturated fault materials is a THM mechanism that plays a fundamental role in the weakening of fault zones (Lachenbruch, 1980; Viesca and Garagash, 2015). Thermal pressurization is a consequence of the contrast between the thermal expansion coefficient of the pore fluids and the solid matrix (Rice, 2006) and leads to a decrease of the effective mean stress and consequently to a reduction of the shear strength of the gouge. The thickness of the PSZ governs the temperature build-up and the overall energy budget. It is worth mentioning that the activation of other multi-physical phenomena that involve chemical processes are also controlled by the thickness of the localization zone (Brantut et al., 2011; Platt et al., 2015; Sulem and Stefanou, 2016; Veveakis et al., 2013).

Models that are able to describe the localization thickness and its evolution have to take into account both the size of the microstructure of a fault gouge as well as the multi-physical couplings that take place during seismic slip. Cosserat theory allows in a natural way to account for the aforementioned characteristics, leading to a shear band of finite thickness even under low strain rates (Mühlhaus and Vardoulakis, 1987). The use of this theoretical framework is also justified by the fact that it can cover a large spectrum of strain rates, i.e. from very low (pre-seismic) to quite high (co-seismic). Notice that existing models for fault gouges based on the classical, Cauchy continuum (also called Boltzmann continuum (Vardoulakis, 2009)) lead to an infinitely small localized zone (slip on a mathematical plane, Vardoulakis, 1985) unless rate-dependent constitutive behavior is considered for high strain rates and/or THM couplings are explicitly taken into account (Platt et al., 2014; Rice et al., 2014). Moreover, grain size cannot be considered in the constitutive description of Cauchy continua, despite the fact that it has been recognized to play an important role on fault gouge behavior (Anthony and Marone, 2005; Cashman et al., 2007; Phillips and White, 2017).

Cosserat continuum (Cosserat and Cosserat, 1909) is a special case of micromorphic continua (Germain, 1973; Godio et al., 2016), also called generalized or higher order continua. In addition to the translational degrees of freedom of the Cauchy continuum, Cosserat theory considers rotational degrees of freedom at the material point that allow for a better representation of the physics and the mechanical behavior of heterogeneous solids with non-negligible microstructure. Cosserat continuum theory naturally incorporates one or several material lengths related to the microstructure in the constitutive equations of the material (see Appendix B).

Cosserat continuum has been previously used for studying the behavior of fault gouges and strain localization (Sulem et al., 2011; Veveakis et al., 2013). In these works the conditions for the onset of localization were investigated under THM couplings with a microstructure of given size. In the present papers (Part I and II) we extend the aforementioned works by studying (a) the evolution of the localization zone thickness and its dependency on various parameters such the size of the microstructure, (b) the full stress-strain response of the fault gouge, which is related to the transition from seismic to aseismic slip (Scholz, 2002; Tse and Rice, 1986) and (c) the apparent rate dependency of the system due to THM couplings even under rate-independent constitutive laws.

In part I, we focus mainly on point (a) using bifurcation theory and Linear Stability Analysis (LSA). The approach is analytical and it allows to explore qualitatively the influence of the evolution of the hardening parameter and of the grain size on the thickness of the localized zone. In Sections 2 and 3 we present the momentum, mass and energy balance equations and the full constitutive equations for general Cosserat elasto-plastic continua. The bifurcation analysis in this framework is presented in Section 4 and linked with classical results like the singularity of the acoustic tensor. Finally, the bifurcation analysis is applied to the problem of slip in a fault zone (Section 5) and the influence of the main parameters of the model is investigated as far it concerns the onset of localization and the shear band thickness evolution.

2. Basic concepts of three-dimensional cosserat continuum mechanics and balance equations

The Cosserat continuum is a special case of first order micromorphic continua, for which the particle is considered rigid (Godio et al., 2016; Stefanou et al., 2010). In the frame of Cosserat theory the kinematics of a material point in three-dimensional (3D) space is described by six degrees of freedom, which are three translations u_i and three rotations ω_i^c ($i = 1, 2, 3$). In this section, the basic concepts of Cosserat theory are outlined.

2.1. Cosserat kinematics

Compared to a Cauchy continuum formed by a set of particles identified by their coordinates x_i, we attach to every particle a system of axes parallel to the Cartesian one and with M, the center of mass of the particle, as origin.

If we consider a point M', in the particle of center M, defined by its coordinates x'_i, the displacement field in M', u'_i, can be written as follows, considering only terms of first order.

$$u'_i = u_i + \chi_{ij}\, x'_j \tag{2.1}$$

Einstein summation convention is followed herein. χ_{ij} is the micro-deformation tensor. As the microstructure is considered rigid in Cosserat theory, the micro-volume cannot deform and can only rotate. Thus, the micro-deformation tensor χ_{ij}