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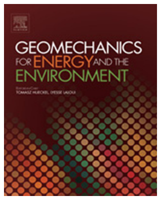

Thermal and chemical effects in shear and compaction bands

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HIGHLIGHTS

- Instabilities can be triggered by positive feedback of chemical softening and acceleration of the chemical reaction rate.
- A linear stability analysis with appropriate shear localization limiters can provide an estimate of the thickness of the deformation band in relation with the dominant wave length of the instability.
- A comparison is proposed between rate dependent Cauchy continuum and rate independent generalized continua (Cosserat continuum) in the scaling of the localized zone thickness.

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ABSTRACT

Strain localization zones in the form of shear bands or compaction bands in geomaterials are observed across scales from sub-millimetric (grain size) to kilometric scale (geological structures). Triggering and evolution of such narrow zones of localized deformation depend on many factors. The mechanical behavior of geomaterials is central for the formation of such zones. However, thermal, pore-pressure and chemical effects play a crucial role in shear and compaction banding. Temperature increase and activation of chemical reactions such as mineral dehydration, carbonate decomposition, as well as dissolution/precipitation control the triggering and the evolution of localized deformation zones. Moreover, the inherent heterogeneous microstructure of geomaterials plays a significant role during strain localization. The purpose of this paper is to provide a review of recent research regarding the effects of temperature, pore-pressure, chemical reactions and microstructure on strain localization in geomaterials. Examples have been taken in relation with seismic slip and with compaction banding. Strain localization is treated as an instability from a homogeneous deformation state. Different types of instabilities may (co-)exist depending on different multi-physical couplings and micro-mechanisms. Finally, a comparison of rate dependent Cauchy continuum and rate independent generalized continua (Cosserat continuum) is made. This comparison leads to an analog expression for the instability condition and the thickness of the localized zone.

1. Introduction

Deformation zones in the form of shear bands or compaction bands in geomaterials are observed on a very large range of scales from sub-millimetric (grain size) to kilometric scale (geological structure). Strain localization refers to physical processes that control the bifurcation of a deforming body from a previously homogeneous deformation to a point for which critical conditions are met for the deformation pattern to drastically change into a highly localized deformation band. This heterogeneity of deformation is associated with an induced heterogeneity of strength and of other material properties (e.g. porosity, grain size, pore size, permeability, etc.) in relation with the

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transformation at the micro-scale of the microstructure of the rock inside the band.

Failure of many engineering structures is characterized by the formation and propagation of shear bands. Shear zones play also a major role in the nucleation of earthquakes, landslides and slope failure. They also are of prime importance in the flow of water, gas and oil in the subsurface as they can serve as conduits or barriers for fluid and heat fluxes. On the other hand, the formation of compaction bands corresponds to failure zones in the direction perpendicular to the major principal stress. They indicate a transition between brittle failure and cataclastic failure. The presence of compaction bands in nature may provide useful information on various geological processes as it is an indication of the stress state history of a geological formation. Compaction bands are usually characterized by a significant reduction of the pore space, which in most cases is accompanied by an important reduction in permeability.[1] Their presence can lead to largely anisotropic flow in fluid infiltrated porous rocks. Therefore, compaction bands are also of primary importance in reservoir mechanics for hydrocarbons production, CO_2 storage and mineral exploration.

Although strain localization in the form of shear band formation can occur with negative or positive rate of strain hardening, the latter being possible for deformation states close to plane strain,[2] softening behavior definitely favors shear banding. This softening behavior may correspond to a mechanical degradation of the rock properties (microcracking, grain crushing and grain size reduction, etc.),[3] but various other physical processes can be responsible for it.[4] The effect of an infiltrated pore fluid which interacts with a rock mass can lead to a hardening or softening behavior depending on the volumetric response of the rock (dilatant or contractant). The effect rapid heating of a saturated geomaterial leads to pore-fluid pressurization due to the discrepancy between the thermal expansion of water and solid grains. Thermal pressurization is a softening mechanism as it results in a decrease of the effective mean stress and thus of the shear strength. Chemical reactions such as dissolution/precipitation, mineral transformation at high temperature (dehydration of minerals, decomposition of carbonates, etc.) affect the solid phase of the rock, sometimes release a new fluid phase in the system (dehydration reactions) and can induce a positive feedback in the progressive mechanical degradation. On the other hand, mechanical damage increases the reaction surface between the reactive fluid and the solid and enhances dissolution and further material weakening.[5,6]

A key parameter when studying multi-physics effects on the formation and evolution of deformation bands is the actual width of the localized zone. Obviously, this parameter plays a major role in the energy budget of the system as it controls the feedback of the dissipative terms in the energy balance equation. As emphasized by Rice et al. [7] narrow deforming zones concentrate the frictional heating, which leads to large temperature rises and thus to more rapid weakening. The width of the deforming zone is determined by the various physical processes involved in the weakening mechanisms but it also controls the multi-physics couplings which occur during dynamic slip.

It is well known that strain localization analyses performed for rate-independent materials within the frame of classical continuum theories lead to infinitesimally narrow localized zone. This reflects the ill-posedness of the underlying mathematical problem and can be traced to the absence of a material length in the constitutive equations. Viscous regularization by considering strain rate hardening is commonly considered to overcome this problem. Another approach is to resort to continuum models with microstructure to describe on a more physical basis the localization phenomena. These generalized continua usually contain additional kinematical degrees of freedom (Cosserat continuum) and/or higher deformation gradients (higher grade continuum). They introduce material internal lengths and also characteristic time scales. The internal length and the micro-inertia introduced from generalized continua permit to describe localization phenomena in zones of finite thickness and lead to a finite evolution rate of a deformation band like in strain rate dependent constitutive laws.[8–10]

In this paper, we review some multi-physics couplings, which enhance strain localization in geomaterials. The first part of the paper focuses on shear banding, emphasizing thermal and chemical effects in relation with shear heating. As mentioned above the localization zone thickness can be captured either by considering rate dependency of the constitutive law or by resorting to higher order continua that possess an internal length. In order to explore the link between the two different modeling approaches a comparison between (a) rate dependent Cauchy continuum and (b) rate independent Cosserat continuum is shown for the scaling of the localized zone thickness. The comparison is made on the basis of a simplified example in order to illustrate the main differences and aspects of each modeling strategy. The last part of the paper is focused on compaction band formation in porous materials triggered by dissolution as an example of another type of chemo-mechanically induced strain localization.

2. Thermo-chemo-chemical couplings and stability of shear zones

2.1. Problem statement

We consider a layer of saturated rock with thickness D deformed in shear at a slip rate V (Fig. 1). Several investigations have shown that the ultracataclastic gouge zones forming the fault core have a much lower permeability ($<10^{-19}$ m^2) than that in the surrounding damage zone (e.g. [11,12]). Therefore, as fluids and heat are trapped inside the slip zone during an earthquake, it is interesting to investigate the stability of undrained adiabatic shearing of such a gouge layer. This is done by assuming that drainage and heat flux are prohibited at the boundaries of the layer. It is also assumed that the normal stress σ_n acting on the layer is constant.

In this 1D-model the velocity components, $u_1(x_2, t)$, and $u_2(x_2, t)$ in the direction parallel and normal to the fault respectively depend only on the time since the onset of slip and on the position x_2 in the direction normal to the band. Inside such a shear-band the pore pressure p and the

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