COMPACTION LOCALIZATION IN POROUS SANDSTONE: ACOUSTIC EMISSION ACTIVITY, MICROSTRUCTURAL DEVELOPMENT AND DISCRETE ELEMENT SIMULATION

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ABSTRACT

Since strain localization can significantly influence the stress field, strain partitioning and fluid transport in many geological and geotechnical settings, it is important to have a fundamental understanding of its mechanics. Recently laboratory investigations in sandstones with porosities ranging from 13% to 28% indicate that localized failure in a compactant rock is commonly associated with stress states in the transitional regime from brittle faulting to ductile flow. While compaction localization is manifested by a broad spectrum of geometric complexity, two end-members can be identified in the most porous and compact sandstones, respectively: arrays of discrete compaction bands subperpendicular to the maximum compression direction, and shear bands at relatively high angles. In sandstones with intermediate porosities a hybrid localization mode involving high-angle shear bands and diffuse compaction bands was observed.

Important insights into the mechanics of compaction localization has been gained from the continuum analysis of its inception as a bifurcation in the constitutive response of a porous medium. Critical conditions for the onset of localization and orientations of the high-angle shear and compaction bands can be derived as functions of the constitutive parameters. While bifurcation analysis provides a very useful framework, it has an intrinsic limitation in that the continuum analysis only addresses the onset of constitutive instability in an initially homogeneous material but not the subsequent propagation behavior of the compaction localization or development of their geometric complexities. In particular this continuum approach cannot explain why compaction bands may preferentially develop as an array of many discrete bands or as one or two diffuse structures that widen laterally. These differences have been attributed to microstructural heterogeneities which are difficult to capture in a continuum model. To address these questions on how microstructure influences the evolution of compaction localization and geometric complexity, it is necessary to consider a micromechanical model accounting for grain-scale heterogeneity.

In this study we use the discrete element method (DEM) to model porous sandstone as a bonded assembly of circular disk subjected to three damage mechanisms. First, the bonds are assigned finite tensile and shear strengths and once either of these threshold stresses is exceeded grain cohesion is lost. Second, relative movement among grains may occur if the bond has been broken and the shear stress exceeds the frictional resistance. Third, intragranular cracking may develop if one of the normal contact forces exceeds a threshold. This third mechanism automatically triggers two additional damage processes: the impacted grain undergoes a shrinkage of its radius (typically by ~1%) and breaks off all remaining bonds with neighboring grains. This DEM model captures key failure modes associated with the brittle-ductile transition with increasing confinement. It also underscores the critical role of grain-scale heterogeneity in controlling the development of compaction localization. While discrete compaction bands preferentially develop in assemblage of disks with relatively uniform sizes, diffuse bands are promoted in assemblages of disks with a broad range of radii.

1. INTRODUCTION

Since strain localization can significantly influence the stress field, strain partitioning and fluid transport in many geological and geotechnical settings, it is of fundamental importance to have a physical understanding of this phenomenon. Localized failure involving shear and extensile discontinuities in the forms of faults and joints has been thoroughly investigated in the field and laboratory. These two failure modes can occur on many scales and are commonly manifested by dilatancy. In contrast the development of localized failure in a compactant rock has not been studied as systematically, and indeed there is sometimes the misconception that strain localization does not develop in a compactant rock. However, recent geologic [*Mollema and Antonellini*, 1996] and laboratory [*Olsson and Holcomb*, 2000; *DiGiovanni et al*., 2000; *Klein et al*., 2001] studies in porous sandstones have documented the common occurrence of compaction localization.

Laboratory investigations in sandstones with porosities ranging from 13% to 28% indicate that localized failure in a compactant rock is commonly associated with stress states in the transitional regime from brittle faulting to cataclastic flow [*Wong et al*., 2001]. While compaction localization is manifested by a broad spectrum of geometric complexity, *Baud et al*. [2004] identified two end-members which have been observed in the most porous and compact sandstones, respectively: arrays of discrete compaction bands subperpendicular to the maximum compression (σ_1) direction, and shear bands at relatively high angles to σ_1 . In sandstones with intermediate porosities a hybrid localization mode involving high-angle shear bands and diffuse compaction bands was observed. The different compaction localization modes are manifested by distinct acoustic emission (AE) signatures, and microstructural observations show intense grain crushing and pore collapse inside the compaction bands.

The discrete compaction bands in laboratory samples are akin to localization structures observed in the field. Compaction bands were first described in aeolian Navajo sandstone by *Mollema and Antonellini* [1996] as tabular zones of localized cataclasis and compaction, with no visible shear offset. Similar localized structures have also been documented by *Hill* [1989] and *Sternlof and Pollard* [2002] in Aztec sandstone in the Valley of Fire, Nevada. The compaction bands are relatively narrow, with characteristic widths on the order of 1 cm. Many discrete bands may extend over tens of meters to form a subparallel array.

2. PREDICTIONS OF BIFURCATION ANALYESES

Important insights into the mechanics of compaction localization has be gained from the continuum analysis of its inception as a bifurcation in the constitutive response of a porous medium [*Olsson*, 1999]. Critical conditions for the onset of localization and orientations of the high-angle shear and compaction bands can be derived as functions of the constitutive parameters. Adopting *Rudnicki and Rice's* [1975] constitutive model (with a yield envelope and inelastic volumetric change characterized by a pressure-sensitivity parameter μ and dilatancy factor β, respectively) *Issen and Rudnicki* [2000] derived the general condition $\beta+\mu<-\sqrt{3}$ for the inception of compaction band under axisymmetric compression. *Wong et al*. (2001) observed that their mechanical data on sandstone samples that failed by compaction localization fall in the range $0>\beta>-\sqrt{3}/2$ and $\mu>-\sqrt{3}/2$, with the implication that $\beta+\mu>-\sqrt{3}$ which apparently contradicts the theoretical prediction. More elaborate constitutive models that incorporate two yield surfaces [*Issen*, 2002] or stress-induced anisotropy [*Rudnicki*, 2002] predict the inception of compaction localization over a wider range of conditions, and in this sense they seem to be in better agreement with the laboratory data.

While bifurcation analysis provides a very useful framework for understanding compaction localization, it has an intrinsic limitation in that the continuum analysis only addresses the onset of constitutive instability in an initially homogeneous material but not the subsequent propagation behavior of the localization structures or development of their geometric complexities. In particular this continuum approach cannot explain why compaction bands may preferentially develop as an array of many discrete bands or as one or two diffuse structures that widen laterally. These differences have been attributed to microstructural heterogeneities which are difficult to capture in a continuum model. *Baud et al.* [2004] observed that although in their study arrays of discrete compaction bands were observed only in the Bentheim and Diemelstadt sandstones with the highest porosities (23% and 24%, respectively), porosity cannot be the only microstructural attribute that promotes the development of discrete bands since *Olsson and Holcomb* [2000] reported that in Castlegate sandstone compaction localization actually involves diffuse and not discrete bands, even though it has an initial porosity of 28% which is higher than all five sandstones investigated by *Baud et al.* [2004]. *Klein et al*. [2001] speculated that discrete compaction band is predominant in the Bentheim sandstone possibly due to its relatively homogeneous mineralogy (with 95% quartz, 3% orthoclase and 3% kaolinite) and well-sorted grain sizes. In comparison diffuse bands develop in the Castlegate sandstone with 70-80% quartz and 5-10% clay.

3. NUMERICAL SIMULATION OF MICROSTRUCTURAL DEVELOPMENT

To address these questions on how microstructure influences the evolution of compaction localization and geometric complexity, it is necessary to consider a micromechanical model accounting for grain-scale heterogeneity. The discrete element method (DEM) has proved to be an effective tool for simulating the micromechanics of failure and shear localization in unconsolidated materials, such as soil, sediment and fault gouge [e.g., *Cundall and Strack*., 1979; *Antonellini and Pollard*, 1995; *Mora and Place*, 1998; *Morgan and Boettcher,* 1999; *Aharonov and Sparks,* 2002; *Hazzard and Mair,* 2003]. Recently the method has been extended to bonded granular material, and used accordingly to model the micromechanics of failure in both compaction and porous rocks [e.g. *Hazzard and Young*, 2000].

In this study a porous sandstone is modeled as a bonded assembly of circular disk subjected to three damage mechanisms. First, the bonds are assigned finite tensile and shear strengths and once either of these threshold stresses is exceeded grain cohesion is lost. Second, relative movement among grains may occur if the bond has been broken and the shear stress exceeds the frictional resistance. Third, intragranular cracking may develop if one of the normal contact forces exceeds a threshold. This third mechanism is specifically incorporated here to simulate grain crushing and pore collapse which are, according to microstructural observations, the dominant damage processes during the development of compaction localization. To capture these processes in our model the activation of intragraular cracking mechanism automatically triggers two additional damage processes: the impacted grain undergoes a shrinkage of its radius (typically by ~1%) and breaks off all remaining bonds with neighboring grains.

This DEM model captures key failure modes associated with the brittle-ductile transition with increasing confinement: typically dilatant failure involves shear bands and compactant failure involves either compaction bands, high-angle shear bands or distributed cataclasis. The temporal development and spatial clustering of damage mimic laboratory observations of AE activity and microstructural observation of compaction localization. Geometric attributes of the damage clusters are also similar to those associated with discrete and diffuse compaction bands. The DEM model also underscores the critical role of grain-scale heterogeneity in controlling the development of compaction localization. While discrete compaction bands preferentially develop in assemblage of disks with relatively uniform sizes, diffuse bands are promoted in assemblages of disks with a broad range of radii.

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