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Strain localization and elastic-plastic coupling during deformation of porous sandstone

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ABSTRACT

Results of axisymmetric compression tests on weak, porous Castlegate Sandstone (Cretaceous, Utah, USA), covering a range of dilational and compactional behaviors, are examined for localization behavior. Assuming isotropy, bulk and shear moduli evolve as increasing functions of mean stress and Mises equivalent shear stress respectively, and as decreasing functions of work-conjugate plastic strains. Acoustic emissions events located during testing show onset of localization and permit calculation of observed shear and low-angle compaction localization zones, or bands, as localization commences. Total strain measured experimentally partitions into: A) elastic strain with constant moduli, B) elastic strain due to stress dependence of moduli, C) elastic strain due to moduli degradation with increasing plastic strain, and D) plastic strain. The third term is the elastic-plastic coupling strain, and though often ignored, contributes significantly to pre-failure total strain for brittle and transitional tests. Constitutive parameters and localization predictions derived from experiments are compared to theoretical predictions. In the brittle regime, predictions of band angles (angle between band normal and maximum compression) demonstrate good agreement with observed shear band angles. Compaction localization was observed in the transitional regime in between shear localization and spatially pervasive compaction, over a small range of mean stresses. In contrast with predictions, detailed acoustic emissions analyses in this regime show low angle, compaction-dominated but shear-enhanced, localization.

1. Introduction

Sandstones exhibit a range of deformational responses under stress conditions typical of the earth's subsurface. Understanding these responses, and quantifying their behavior mathematically (i.e., constitutively), is necessary to predict sandstone response for a variety of sub-surface geo-engineering pursuits such as oil and gas production and exploration, and geologic carbon storage[1–3]. An important aspect of rate-independent sandstone deformation is the transition between localized deformation, in the form of shear and compaction zones or bands (i.e., concentrated tabular zones of strain that lack a discrete surface of discontinuity), and spatially pervasive pore collapse. The formation and development of localization can have important consequences for reservoir quality. Predictability of localized deformation from advanced constitutive modeling is thus a relevant consideration for waste injection or resource extraction[4–6].

Localization in sandstones has been studied since the late 1970′s[7–9], and recently identified variants in sandstone localization behavior include shear bands and compaction bands[10–31] and extension (dilation) bands[32–34]. Aydin et al.[35] note that the earliest reports of compaction bands in the field were by Hill[36], and possibly the first experimental evidence of compactional deformation bands produced in the laboratory were by Muhuri[37]. Recent detailed descriptions by Eichhubl et al.[29] discern between pure compaction bands and shear-enhanced compaction bands.

While it is desirable to link constitutive response of laboratory samples to field examples, the disparate time scales and complex boundary conditions existing in field settings versus experiments make such comparisons difficult[38]. As such, direct comparison of geological examples and laboratory experiments is fraught with uncertainty. It is relevant however to understand laboratory constitutive response in order to gain some insight on field observation. In axisymmetric compression experiments ($\sigma_1 > \sigma_2 = \sigma_3$, where the principal stresses are $\sigma_1 \geq \sigma_2 \geq \sigma_3$, positive in compression), compaction localization has

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been observed to form in high porosity sandstones (20–28%)[11–13,25,27,39–42]. Work by Olsson[39], Holcomb and Olsson[11] and Vajdova et al.[42] demonstrate that localized compactive behavior results in order of magnitude changes in permeability.

This research examines mechanical response and localization behavior of a porous sandstone reservoir analogue rock, the Upper Cretaceous Castlegate Formation sandstone of east central Utah, USA[43], a dominantly fluvial sheet sand facies of the Mesaverde Group. A suite of axisymmetric compression tests are conducted over a wide range of mean stresses under triaxial and constant-mean stress loading conditions. While compaction localization is of particular interest, Castlegate samples are also observed to fail via shear localization or uniform (non-localized) pore collapse, depending on mean stress. The localization theory of Rudnicki and Rice[44] is applied toward predicting observed failure modes, and focus is placed on elastic-plastic coupling (i.e., modulus degradation with plastic strain) as an important consideration for constitutive modeling of porous sandstone deformation.

2. Theoretical background

2.1. Constitutive Response and Elastic-Plastic Coupling

To evaluate localization predictions from Rudnicki and Rice[44], the total strain determined in experiments must be separated into elastic and inelastic components. This section describes the model used to conduct this strain separation. We start with common assumptions in elastic-plastic constitutive models, namely the separation of total strain into elastic and plastic parts (denoted by 'e' and 'p' superscripts)

$$d\varepsilon_{ij}^{t} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \tag{1}$$

where, upon unloading to zero stress, elastic strain vanishes and total strain equals plastic strain.

We additionally assume an elastic strain that follows from

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}^{e} \tag{2}$$

With assumptions of isotropy and with usual definitions of invariants, (2) becomes

$$\varepsilon^{e} = \frac{\sigma}{K},\ \gamma^{e} = \frac{\tau}{G} \tag{3}$$

For the axisymmetric compression (ASC) tests used here, mean stress $\sigma = \frac{I_1}{3} = \sigma_{kk}/3$ is determined by $\sigma = (\sigma_A + 2\sigma_L)/3$ and Mises shear stress $\tau = \sqrt{J_2} = \sqrt{\frac{1}{2}s_{ij}s_{ij}}$, (where I_1 and J_2 are the first and second invariants of the stress tensor, and the deviatoric stress is $s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$) is given by $\tau = \frac{\sigma_A - \sigma_L}{\sqrt{3}}$, $\sigma_A = \sigma_1$ is the axial stress and $\sigma_L = \sigma_3 = \sigma_2$ is the confining pressure. The elastic volumetric strain is found from $\varepsilon^{e} = \varepsilon_A^{e} + 2\varepsilon_L^{e}$, and the elastic shear strain from $\gamma^{e} = 2(\varepsilon_A^{e} - \varepsilon_L^{e})/\sqrt{3}$ during elastic portions of deformation, where ε_A is the axial strain and ε_L is the lateral strain. The bulk modulus and shear modulus are K and G, respectively.

We examine stress and plastic strain dependence of (secant) elastic moduli as the following, which will be justified by observations of elastic moduli from unloading-reloading loops in the later section on experimental results,

$$K = K(\sigma, \varepsilon^{p}),\ G = G(\sigma, \tau, \gamma^{p}) \tag{4}$$

In our experiments, we do not observe a τ dependence of K and so do not include this in our formulation. Placing the above equation into the former relations and expressing in incremental form, these become

$$\begin{aligned} d\varepsilon^{t} &= d\left(\frac{\sigma}{K(\sigma, \varepsilon^{p})}\right) + d\varepsilon^{p} \\ d\gamma^{t} &= d\left(\frac{\tau}{G(\tau, \gamma^{p})}\right) + d\gamma^{p} \end{aligned} \tag{5}$$

Expanding the total derivative yields

$$\begin{aligned} d\varepsilon^{t} &= \frac{d\sigma}{K} - \frac{\sigma}{K^2}\left(\frac{\partial K}{\partial \sigma}d\sigma + \frac{\partial K}{\partial \varepsilon^{p}}d\varepsilon^{p}\right) + d\varepsilon^{p} \\ d\gamma^{t} &= \frac{d\tau}{G} - \frac{\tau}{G^2}\left(\frac{\partial G}{\partial \tau}d\sigma + \frac{\partial G}{\partial \gamma^{p}}d\gamma^{p}\right) + d\gamma^{p} \end{aligned} \tag{6}$$

Note that along constant mean stress loading paths, G will not vary due to mean stress, and so we do not account for this dependence here. From (6), there are eight strain increments that we label

$$\begin{aligned} d\varepsilon^{A} &= \frac{d\sigma}{K};\quad d\varepsilon^{B} = -\frac{\sigma}{K^2}\frac{\partial K}{\partial \sigma}d\sigma;\quad d\varepsilon^{C} = -\frac{\sigma}{K^2}\frac{\partial K}{\partial \varepsilon^{p}}d\varepsilon^{p};\quad d\varepsilon^{D} = d\varepsilon^{p} \\ d\gamma^{A} &= \frac{d\tau}{G};\quad d\gamma^{B} = -\frac{\tau}{G^2}\frac{\partial G}{\partial \tau}d\sigma;\quad d\gamma^{C} = -\frac{\tau}{G^2}\frac{\partial G}{\partial \gamma^{p}}d\gamma^{p};\quad d\gamma^{D} = d\gamma^{p} \end{aligned} \tag{7}$$

where the superscript 'A' refers to strain due to change in stress at a constant modulus, 'B' is due to the stress dependence of the modulus, 'C' is the coupled strain due to plastic strain dependence of the modulus, and 'D' is the plastic strain. Strains A, B and C are mechanically recovered upon unloading to zero stress, and only strain D (plastic) is not recovered.

Following Rudnicki[45], we distinguish between an "increment of inelastic strain" which arises from only irrecoverable (plastic) strain,

$$d\varepsilon^{p} = d\varepsilon^{D} \text{and}\ d\gamma^{p} = d\gamma^{D} \tag{8}$$

versus an "inelastic increment of strain" that includes both irrecoverable plastic strain and recoverable strain arising from degradation of elastic moduli (and as such combines C and D strains). The inelastic increments of strain are required to evaluate localization predictions[44,45]. Consistent with Rudnicki[45] after Hill and Rice[46], we use the following notation for inelastic increments of strain:

$$d^{p}\varepsilon = d\varepsilon^{C} + d\varepsilon^{D} \text{and}\ d^{p}\gamma = d\gamma^{C} + d\gamma^{D} \tag{9}$$

The C increments, being elastic, vanish upon unloading and so are recoverable, but irreversible. If the elastic moduli do not evolve with stress, then the B strain increment vanishes and (7) is equivalent to Eq. (2) of Collins[47] and to Eq. (1) (with different sign convention) of Rudnicki[45].

2.2. Localization theory

The strain localization framework of Rudnicki and Rice[44] predicts conditions for the onset of localization in the form of a planar band of deformation, consisting of shear parallel to the band and/or compaction or dilation normal to the band[14]. Localization is attributed to a constitutive instability in an initially uniform, inelastic deforming, pressure-dependent material; formation of a planar band of localized strain is an alternative solution to continued homogeneous deformation. The localization condition was found to be $det|n_i L_{ijkl} n_l| = 0$, where n_i are the components of the band normal and L_{ijkl} is the modulus tensor in the constitutive relation $d\sigma_{ij} = L_{ijkl}d\varepsilon_{kl}$. Using the localization condition, and assuming that the hardening modulus decreases with continued loading, Rudnicki and Rice[44] determined the predicted band orientation and the expression for the critical hardening modulus. Here, we present the relevant expressions, specialized for axisymmetric compression testing[14] referring to the idealized yield surface in the space of Mises equivalent shear stress τ and mean stress σ (Fig. 1). Shear bands are predicted when

$$-\sqrt{3} < \beta + \mu < +\sqrt{3}\left(\frac{2-\nu}{1+\nu}\right), \tag{10}$$

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