Contraction-driven shear failure in compacting uncemented sediments

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ABSTRACT

Shear failure in sediments is universally linked with active boundary conditions, such as those imposed by tectonic stresses. Under conditions of no lateral strain, and in the absence of tectonic stress, soil mechanics theories predict a simple one-dimensional compaction in which sediment particles displace vertically without shear failure during pressure diffusion. Conflicting with this theory, shear failure planes are often found in sediments that formed under near-horizontal burial conditions. We investigated the effect of particle-scale volume contraction as a potential cause of shear failure in uncemented particulate materials and found that loss of particle volume under confined conditions (no external loading) resulted in pronounced lateral stress reduction, often reaching Coulomb frictional failure conditions. Shear strain localization was analytically predicted and modeled numerically, due entirely to volume loss at the grain scale. We define this mode of internally driven shear failure as "contractile" to distinguish it from that caused by external loading, and show that it can explain many natural fracture systems without invoking regional tectonics.

INTRODUCTION

Shear failure in sedimentary rocks is a fundamental process in all sedimentary basins, and leads to the growth of all types of geological faults (Jaeger and Cook, 1976). Shear failure is not considered possible under normal geomechanical burial conditions that typify basin evolution unless there is a modification of the state of stress by the addition of tectonic stresses (either regional or local, such as due to local flexure or tilting). Furthermore, classical geomechanical theories predict that sediment compaction under zero lateral strain conditions takes place at a quasi-constant ratio between the horizontal effective stress and the vertical effective stress (Terzaghi et al., 1996; the response in structured sediments was discussed in Burland, 1990).

Mineral dissolution and reprecipitation is a common geological phenomenon that contributes to changes in porosity and sediment compaction (Berner, 1980; Renard et al., 2001; He et al., 2003; Cailly et al., 2005; Herrera et al., 2007; Zhang et al., 2007). It is surprising that there has been no formal study of the evolution of the internal state of stress in uncemented particulate media (such as sediments) during mineral dissolution. Many regionally extensive fracture networks that occur in sedimentary basins with complex diagenetic histories are often attributed to regional tectonic stresses or to the unloading effects of regional uplift, and the diagenetic history is never implicated in their formation (Engelder, 1993).

The aim of this study is to investigate the changes in the stress state in an uncemented soil or sediment during grain-scale dissolution, and to test whether stress changes induced by dissolution could lead to shear failure. In contrast to previous investigations of tensile fracturing in cohesive solids caused by dissolution and/or corrosion (e.g., Yakobson, 1991; Boeck et al., 1999; Malthe-Sorenssen et al., 2006), we focus on uncemented granular sediments that exhibit cohesionless, stress-dependent frictional behavior. We use complementary analytical, numerical, and experimental techniques to investigate the effects of particle-level volume contraction on the evolution of the state of stress under constant overburden at zero lateral strain boundary conditions, and pay special attention to the ensuing deformation field and the potential development of shear planes.

THEORETICAL CONSIDERATIONS

Typically, the state of stress in level-ground sediments under constant vertical load is determined by the displacement of lateral boundaries. Under zero lateral strain conditions, the coefficient of Earth pressure at rest, $k_o = \sigma'_h/\sigma'_z$ between the horizontal effective stress σ'_h and the vertical effective stress σ'_z, depends on the friction angle φ as predicted by Jacky's equation $k_o \approx 1 - \sin\varphi$ (Mayne and Kulhawy, 1982; Terzaghi et al., 1996). When lateral boundaries move out, the sediment deforms laterally to accompany the wall movement, the internal shear strength in the sediment is mobilized, and the horizontal effective stress decreases to a limiting value that defines the "active" Earth pressure coefficient and can be derived from the Coulomb frictional strength of the soil to be $k_a = (1 - \sin\varphi)/(1 + \sin\varphi)$.

Analytically, a homogeneous isotropic elastic medium undergoes a reduction in horizontal stress from $k_o\sigma'_z$ to $k_a\sigma'_z$ when the volumetric strain in the medium, ε_v, is

$$\varepsilon_v = 3(1-\nu)(k_o - k_a)\sigma'_z/E, \quad (1)$$

where E is Young's modulus and ν is Poisson's ratio. The ratio σ'_z/E is a small number in granular materials (~10^{-3}); therefore, it is anticipated that relatively small volumetric strains can produce significant horizontal stress reduction.

NUMERICAL AND EXPERIMENTAL ANALYSES

We conducted a set of finite element simulations to capture the behavior of uncemented particulate sediments subjected to dissolution of a small component of the solid grain fraction (Drucker-Prager frictional model with nonassociated flow rule; see the GSA Data Repository[1] for additional description of methods). After zero lateral strain loading, a selected volume fraction of randomly distributed elements

[1]GSA Data Repository item 2008237, supplementary information on the numerical simulation, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

v_{cont} was subjected to a volumetric contraction strain ε_v (Fig. 1). As the volumetric contraction $\varepsilon_v \cdot v_{cont}$ increases, an increasingly higher number of elements reach the Coulomb failure condition within the medium (Fig. 1A), and the mean horizontal stress at the boundaries lessens so that the global stress ratio $k = \sigma'_h/\sigma'_z$ gradually decreases from k_o to the failure k_a state. The vertical load applied on the top boundary is homogeneously transferred through the medium before volume contraction; however, as volume contraction develops, the load is preferentially transferred along columns of vertical stress concentration. In all cases, the stress drop takes place at relatively low volume contractions, in agreement with equation 1 (Fig. 1B).

We conducted a complementary experimental study to corroborate the evolution from k_o to k_a during dissolution in real granular materials, using a simple binary mixture in which one particle type would be prone to dissolution (see the Data Repository). We placed a mixture of small glass beads and NaCl salt grains, homogeneously mixed in NaCl brine, inside a calibrated zero lateral strain oedometer cell instrumented with strain gauges to measure the horizontal stress. The evolution of vertical strain was monitored using a linear variable differential transformer. Edge effects were minimized by keeping the height/diameter ratio below 0.6. First, the granular mixture was allowed to reach chemomechanical equilibrium under a nominal vertical effective stress, σ_z = 40 kPa. Then, the fluid concentration was gradually decreased during advective flow, resulting in controlled dissolution of the salt grains. Tests were repeated with near-identical boundary conditions but for varying mass fractions of salt, m_{salt} (5%–20%). All test results for the different m_{salt} values show a similar pattern: an initial decrease in horizontal stress followed by a gradual recovery after a minimum value is reached (Fig. 2).

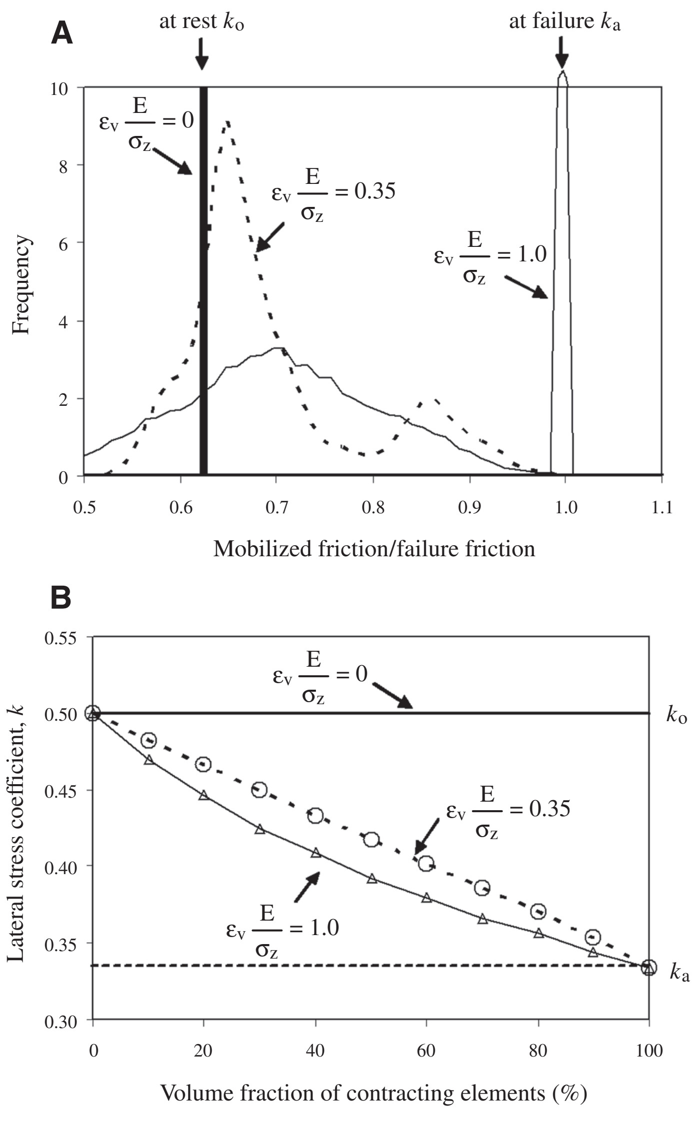

Figure 1. Numerical finite element simulation of volume contraction in frictional material (φ = 30°). Without particle contraction, the modeled material exhibits horizontal stress coefficients equal to k_o = 0.5 for zero lateral strain, and k_a = 0.33 for the active failure condition. A: Histogram of local stress ratio at each element when volumetric contraction ε_v = 0.1% is imposed on 20% of the elements under constant vertical stress and zero lateral strain. B: Value of *k* measured at boundaries as function of percentage of contracting elements and amount of volume contraction.

Discrete element simulations of sediment modeled with the particles satisfying Newtonian equations were run to obtain particle-scale information unattainable in experimental studies (Cundall and Strack, 1979). We used both two-dimensional (2-D) (particle flow code, PFC-2D) and three-dimensional (discrete element modeling, EDEM) configurations and tested different mechanisms that can lead to volume contraction, such as particle stiffness reduction and particle size reduction (for simulation details, see the Data Repository). In all cases, we obtained consistent results that resemble the experimental evolution in lateral stress, i.e., a drop in the effective stress ratio *k* followed by horizontal stress recovery. A representative model run is shown in Figure 3. The internal mechanisms for the observed lateral stress reduction can be inferred from the evolution of internal parameters of the simulations during particle volume contraction. We observed that the anisotropy in coordination number increases, and force chains become increasingly more focused and vertically aligned as particle dissolution takes place. Interparticle coordination and forces reach maximum anisotropy near the minimum value of the effective stress ratio *k*; thereafter, particle chains start buckling and global contact anisotropy diminishes. (Note that while the stress ratio *k* recovers toward the end of the simulation, the final fabric is quite different from the initial fabric [Fig. 3B].) The evolution in the internal anisotropy of contacts, normal forces, and shear forces can be combined to estimate the mobilized friction (Rothenburg and Bathurst, 1989; Fig. 3A): the mobilized friction angle reaches the limiting value by the time the horizontal stress ratio approaches the minimum $k = k_a$. Therefore, boundary measurements and internal parameters corroborate the shear failure of the granular skeleton during mineral dissolution under zero lateral strain conditions.

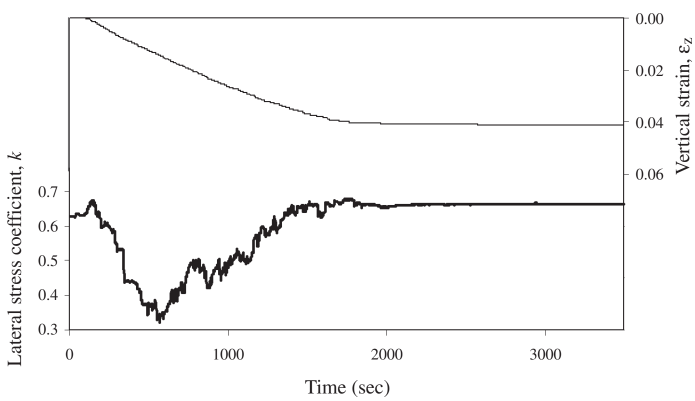

Figure 2. Experimentally determined evolution in lateral stress during grain dissolution. Study conducted using instrumented, zero lateral strain oedometer cell. Results shown for mixture of 90% unsoluble glass beads and 10% soluble granular NaCl salt.

DISCUSSION

Strain Localization

The analytical, experimental, and numerical studies demonstrate unequivocally that particle level contraction can cause a macro-scale stress drop from the initial at-rest k_o condition to the at-failure k_a condition; i.e, grain dissolution in a natural environment can advance the uncemented sediment to a state of failure. This has major implications for the potential coupling between diagenetic and deformational processes, but it does not by itself account for fracture development. To properly link grain dissolution to fracture formation, we need to consider the conditions for strain localization.

Strain localization is the energetically preferred deformation mechanism when the rate of deviatoric stress change to plastic shear strain increment $h = \partial\sigma_d/\partial\gamma_{pl}$ exceeds a critical value h_{cr} that is material and stress-path dependent (Rudnicki and Rice, 1975; Lade, 2002). In sediments that have undergone particle-level volume contraction, the stress in the vertical direction is the maximum principal stress and the two horizontal stresses are of the same magnitude. For this stress condition, shear faulting occurs in the strain-softening regime in homogeneous media; therefore, the formation of shear faults associated with volume contraction will take place in materials that exhibit post-peak strength softening. This could be the case in the undrained failure of shear-contractive soils or sediments (e.g., fast shear of normally consolidated clays), in the drained shear of sediments with low residual friction angle (from smectites to micaceous sands; Skempton, 1985), or in sediments with some degree of heterogeneity.

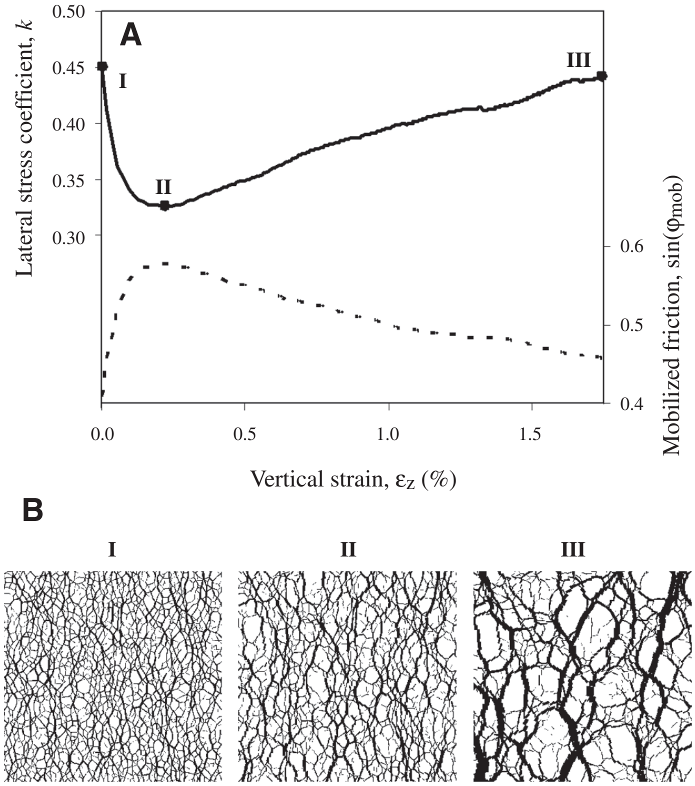

Figure 3. Evolution in horizontal stress during particle dissolution. Discrete element simulation of two-dimensional packing of 9999 disks. Diameter of 20% of the particles, selected at random, is gradually reduced while keeping zero lateral strain and constant vertical stress boundary conditions. A: Lateral stress coefficient *k* and mobilized friction. B: Interparticle force networks at different stages of dissolution (refer to I, II, and III in A). Boxes are 100 × 100 particles in size.

To gain further insight into the potential development of shear strain localization during particle-level contraction, we conducted finite element simulations of a medium subjected to constant vertical stress under zero lateral strain boundary condition using a Drucker-Prager frictional model with nonassociated flow rule. The nucleation of localization was facilitated by creating a correlated random field for volume contraction (see the Data Repository). Results show diffused strain localization in perfectly plastic media $\varphi_{residual} = \varphi_{peak}$ (Fig. 4A) and marked shear strain localization when the medium was modeled with post-peak strength softening $\varphi_{residual} < \varphi_{peak}$ (Fig. 4B).

In summary, our results, based on complementary analytical, experimental, and numerical analyses, show that particle-level volume reduction in uncemented granular media causes a decrease in horizontal stress, leading to internal shear failure conditions and the potential development of shear strain localization. It is noted, however, that other potential localization mechanisms may develop in relation to cemented soils and soils made of crushable aggregations.

Implications

These results prompt a fundamental reappraisal of how sediments can fail in shear, and have wider implications for fracture and fault development in sedimentary basins and residual soils. Regional diagenesis of sediments commonly involves loss of granular volume through mineral-specific dissolution. For some of these reactions, well-documented links already exist between diagenesis and regional fracture development (e.g., the fractured Monterey Formation; Eichhubl et al., 2001). For others, our results may prompt a reevaluation of the impact of diagenetic reactions on deformation. Furthermore, there is potential coupling between coeval

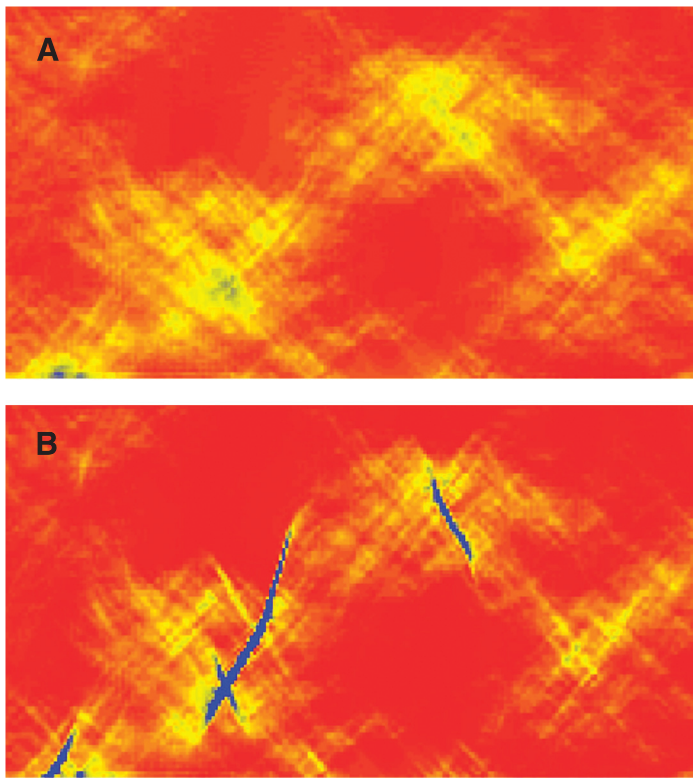

Figure 4. Finite element simulation. Correlated random field of volume contraction within frictional material. A: Diffused deviatoric strain distribution in perfectly plastic media without softening $\varphi_{residual} = \varphi_{peak} = 30°$. B: Shear strain localization is facilitated in media with post peak strain softening ($\varphi_{peak} = 30°$, $\varphi_{residual} = 10°$). Correlation length is 20% of the model height.

volume contraction, fluid expulsion, and fracture propagation, which can provide a positive feedback with the driving reaction (Davies and Cartwright, 2007). The dissociation of gas hydrates in marine sediments may trigger this sequence of events. Our study also raises questions concerning the long-term stability of engineering solutions such as the geological storage of CO_2 by highlighting the potential for fracturing through acidification of pore fluids and grain dissolution in underground reservoirs (Renard et al., 2005; Le Guen et al., 2007). The proposed mechanism may offer a simple explanation for the genesis of the enigmatic but widely developed polygonal fault systems (Cartwright and Dewhurst, 1998; Cartwright et al., 2003): the stress history and deformation field that accompanies particle-level volume contraction can account for the development of polygonal faults in uncemented sediments, and strain-softening behavior (e.g., low residual friction; Goulty, 2001) enhances localization.

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