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Effects of soil aggregates on debris-flow mobilization: Results from ring-shear experiments

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ABSTRACT

Rates and styles of landslide motion are sensitive to pore-water pressure changes caused by changes in soil porosity accompanying shear deformation. Soil may either contract or dilate upon shearing, depending upon whether its initial porosity is greater or less, respectively, than a critical-state porosity attained after sufficiently high strain. We observed complications in this behavior, however, during rate-controlled (0.02 m s^{-1}) ring-shear experiments conducted on naturally aggregated dense loamy sand at low confining stresses (10.6 and 40 kPa). The aggregated soil first dilated and then contracted to porosities less than initial values, whereas the same soil with its aggregates destroyed monotonically dilated. We infer that aggregates persisted initially during shear and caused dilation before their eventual breakdown enabled net contraction. An implication of this contraction, demonstrated in experiments in which initial soil porosity was varied, is that the value of porosity distinguishing initially contractive from dilative behavior can be significantly larger than the critical-state porosity, which develops only after disaggregation ceases at high strains. In addition, post-dilative contraction may produce excess pore pressures, thereby reducing frictional strength and facilitating debris-flow mobilization. We infer that results of triaxial tests, which generally produce strains at least a factor of ~4 smaller than those we observed at the inception of post-dilative contraction, do not allow soil contraction to be ruled out as a mechanism for debris-flow mobilization in dense soils containing aggregates.

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1. Introduction

Debris flows commonly originate as landslides that lose strength as their movement begins, resulting in rapid acceleration and transformation to fluid-like flow (e.g., Johnson, 1984; Iverson et al., 1997b). A leading hypothesis for this weakening invokes coupling between changes in soil porosity and pore-water pressure during shear deformation. With sufficient deformation soils attain a critical state in which their porosity and shearing resistance become steady at values independent of the initial soil porosity and dependent on the effective normal stress (e.g. Schofield and Wroth, 1968; Atkinson, 1993). Thus, soils with porosities larger than the critical-state value initially contract upon shearing. This contraction can cause pore-water pressure to transiently increase in saturated soils, reducing their frictional strength as deformation proceeds (e.g., Casagrande, 1976; Sassa, 1984; Ellen and Fleming, 1987; Fleming et al., 1989; Iverson et al., 1997b, 2000; Dai et al., 1999a; Wang and Sassa, 2003; Moriwaki et al., 2004; Iverson, 2005). The magnitude of the effect depends on the extent to which the characteristic time scale of excess pore-pressure dissipation exceeds that of pore-space contraction (Iverson et al., 1997b). In contrast, soils less porous than in their critical state dilate upon shearing, potentially causing pore-pressure reductions that increase shearing resistance and thereby slow or stop landslide motion (Ellen and Fleming, 1987; Iverson et al., 1997b, 2000; Moore and Iverson, 2002; Iverson, 2005).

Iverson et al. (2000) conducted field-scale landslide experiments that demonstrated the sensitivity of landslide rates and styles to initial soil porosity. Prisms of loamy sand soil (6 m^3) with porosities greater than 0.5, after failing due to externally imposed pore-pressure increases, accelerated within 1 s to speeds greater than 1 m s^{-1}, while exhibiting high excess pore pressures and fluid-like deformation. The same soil, when compacted to an initial porosity of 0.41 ± 0.01, dilated upon failure and episodically slid, with down-slope displacement rates averaging only 0.002 m s^{-1}. Sliding episodes were slowed or halted by concomitant decreases in pore-water pressure. At intermediate initial soil porosities of 0.42–0.44 ± 0.03, pore pressures indicated a mixture of dilative and contractive behavior, with styles of motion that included slow sliding of a rigid block, episodic sliding of several blocks, and more rapid sliding (0.1 m s^{-1}) of a single block that ended after less than 0.5 m of displacement.

The experimental evidence of debris-flow mobilization caused by soil contraction (Iverson et al., 2000) does not explain evidence that

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some soils exhibiting dilative behavior during the early stages of shearing transform into debris flows. This evidence derives primarily from triaxial and simple-shear tests on undisturbed soil samples collected near headscarps of landslides that transformed into debris flows. These test specimens dilated during deformation to axial or shear strains of 1–12% (Fleming et al., 1989; Anderson and Sitar, 1995; Dai et al., 1999b; Gabet and Mudd, 2006).

Several hypotheses have been offered for debris-flow mobilization in dilative soils. Inertial grain interactions associated with sufficiently rapid soil motion – not considered in critical-state soil mechanics – may dilate soil past its critical-state porosity, thereby enabling subsequent contraction and development of transient excess pore pressure (Iverson and LaHusen, 1989; Iverson et al., 1997b). Shear stresses driving failure may increase in the early stages of deformation due to spatially non-uniform deformation and associated stress redistribution (Anderson and Sitar, 1995). Sufficiently rapid and sustained input of water into a failing, dilating soil may increase pore pressure, overwhelming the effect of dilation on pore-pressure reduction and promoting transformation into a rapid flow (Casagrande, 1976; Dai et al., 1999a,b; Iverson, 2005). In addition, as strain accrues in a quasi-statically shearing, dilating soil, the rate of dilation decreases and eventually becomes zero in the critical state, eliminating the dilatant strengthening associated with pore-pressure reduction and potentially enabling unstable acceleration. This destabilizing effect, dependent on strain magnitude, was included in the landslide model of Iverson (2005), emphasized in a subsequent application of it (Gabet and Mudd, 2006), and observed in stress-controlled, ring-shear experiments (Moore and Iverson, 2002).

Herein, we consider another explanation for debris-flow mobilization in initially dilative soils. With a series of rate-controlled, ring-shear experiments on the same soil used in the landslide experiments of Iverson et al. (2000), we test whether the presence of multi-particle soil aggregates can cause contraction of initially dilative soils as aggregates break down during shear. This hypothesis merits testing because fine-grained soils are almost invariably composed of aggregates (Mitchell and Soga, 2005, p. 111), and their crushing may cause excess pore pressures to develop. No extrinsic factors, such as post-failure rainfall or increases in shear stress, would in this case be required for flow mobilization.

2. Apparatus

Our ring-shear device, as configured for these experiments (Fig. 1a), shears an ~11 liter (0.011 m^3) annular soil specimen at a constant rate under a constant stress applied normal to the shearing direction (see Iverson et al., 1997a, for a detailed description). The specimen occupies a chamber (Fig 1b) that has an outside diameter of 0.6 m and a width of 0.115 m. Specimen thicknesses are 0.06–0.07 m.

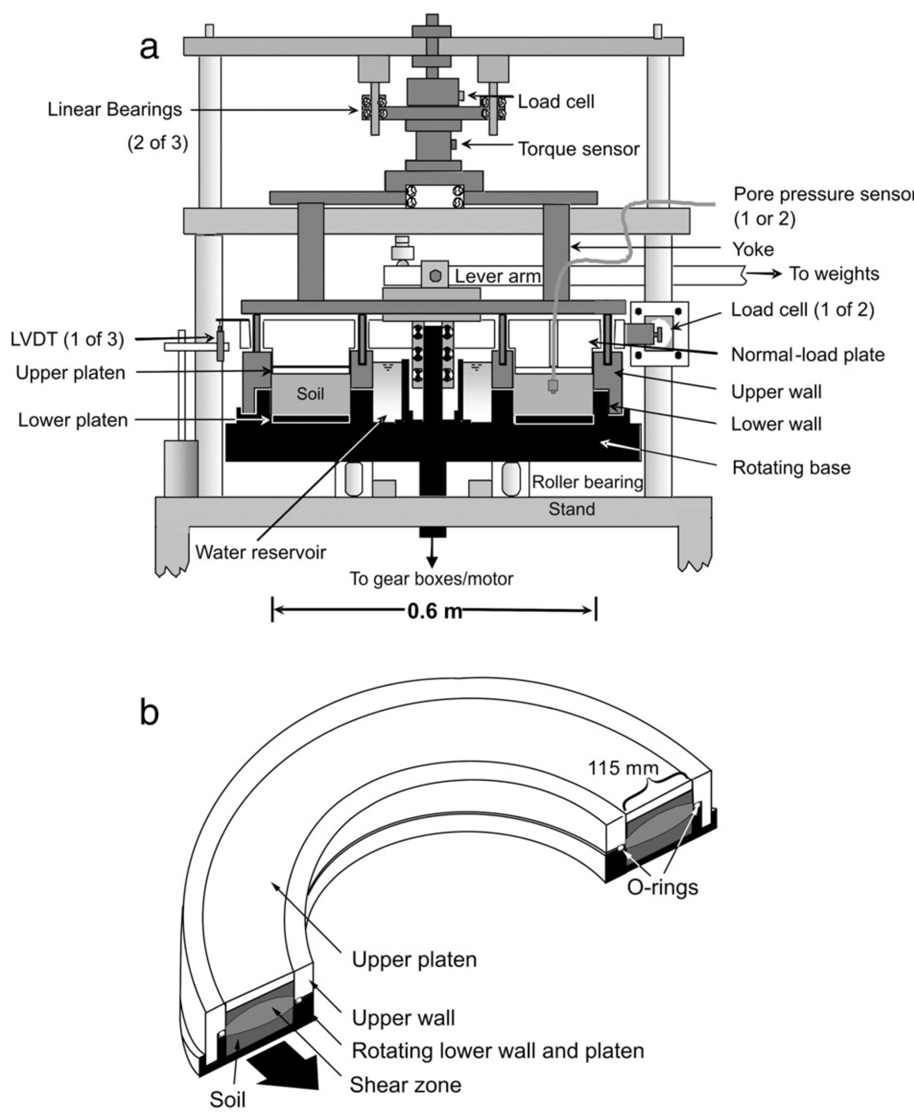

Fig. 1. (a) Cross-section of the ring-shear device. (b) Oblique view of the specimen chamber. All components shaded black rotate.

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