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

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Keywords
Soil, Debris flows, Aggregates, Ring-shear, Porosity

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Comments

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

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A B S T R A C T

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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; Mori, 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 m³) 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 downslope 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 pore-water pressures.
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 headscars 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 m³) 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.
The soil is gripped on the top and bottom by platens with teeth. A uniform normal stress is applied to the soil by a lever arm with dead weights that presses downward on a thick plate (normal-load plate, Fig. 1a). This plate is fixed rotationally but is allowed to move vertically as the specimen thickness changes during shearing. Shearing of the specimen is accomplished by rotating the base and lower platen (black in Fig. 1a) beneath the normal-load plate. The walls bounding the lower half of the specimen are fixed to the lower platen and therefore rotate, whereas the upper walls do not. Thus, strain in the specimen is focused in a lens-shaped zone that is centered on the interface between the upper and lower walls and thickens toward the specimen center, usually to a thickness of 20–45 mm (Fig. 1b). Similar strain heterogeneity is common to all ring-shear tests (e.g., Bishop et al., 1971; Sassa et al., 2004; Coop et al., 2004).

The upper and lower platens that grip the soil are permeable, so that water can move into or out of the soil as pore volume changes during shear. The platens are hydraulically connected to a water-filled reservoir that is open to the atmosphere, with level of the water surface 30–40 mm above the top of the shear zone (Fig. 1). These are, thus, drained experiments, but this drainage does not preclude development of pore pressures that deviate from hydrostatic values if porosity change is sufficiently rapid during shear. This condition is sometimes referred to as “naturally” or “partially” drained (e.g., Okada et al., 2004; Wang et al., 2007; Fukuoka et al., 2007). Quantitative analysis of pore-pressure response to porosity change is limited by the uncertainty of the shear-zone thickness as deformation proceeds during experiments.

Measurements include shear resistance, pore-water pressure, and specimen thickness. Shear stress was measured with two load cells (Sensotec, model 41) that resisted rotation of the normal-load plate. Pore-water pressure was measured with one or two screened, miniature, electrical piezometers (Honeywell Microswitch, model 26PCCFA6D) that were positioned within the shear zone of the soil and were free to move with it during shearing, owing to leads that could be drawn through the normal-load plate and into the specimen. To record changes in specimen thickness necessary to determine porosity change, vertical movement of the normal-load plate was measured with three displacement transducers (Sensotec, model 060-3611-02) positioned around its perimeter (Fig. 1a).

The apparatus was modified in two ways for these experiments. To enable shear rates commensurate with incipient debris-flow motion, the 44 W (1/17 hp) motor used to turn the lower platen at glacial rates in studies of till deformation (e.g., Iverson et al., 1998) was replaced with a 373 W (½hp) Leeson gear motor (model 4017FZ26B). Also, o-rings were installed along the sliding interface between the upper and lower walls at both the outside and inside of the specimen chamber. The rings inhibited loss of soil along that interface during shear (e.g., Bishop et al., 1971), allowing changes in specimen thickness to be accurately measured from vertical movement of the normal-load plate. However, due to this second modification the upper walls necessarily pressed downward on the lower walls, with no intervening gap. Thus, downward stresses on the walls exerted by the soil could not be measured as they normally are with the axial load cell in the yoke of the apparatus (Fig. 1) (Iverson et al., 1997a, 1998). Such stresses reduce the total normal stress on the shear zone (up to ∼35%), so correcting for this effect (see also Bishop et al., 1971) was not possible. Accurately determining total normal stresses and friction angles was less important for meeting our objectives than it was precisely measuring specimen thickness during shear.

### Table 1

Mean physical properties (±1 SD from the mean) of the experimental soil at two values of porosity (modified from Iverson et al. [2000]).

<table>
<thead>
<tr>
<th>Soil property (method)</th>
<th>Porosity: 0.52±0.02</th>
<th>Porosity: 0.41±0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean texture</td>
<td>89% sand, 6% silt,</td>
<td>89% sand, 6% silt,</td>
</tr>
<tr>
<td>(wet sieving and sedigraph)</td>
<td>5% clay</td>
<td>5% clay</td>
</tr>
<tr>
<td>Hydraulic conductivity, m s⁻¹</td>
<td>2.5×10⁻⁴</td>
<td>2.2×10⁻⁵</td>
</tr>
<tr>
<td>(permeameter tests)</td>
<td>±7×10⁻⁵</td>
<td>±5×10⁻⁷</td>
</tr>
<tr>
<td>Hydraulic diffusivity, m² s⁻¹</td>
<td>1.1×10⁻³</td>
<td>2.8×10⁻³</td>
</tr>
<tr>
<td>(consolidometer tests)</td>
<td>±4×10⁻⁴</td>
<td>±6×10⁻⁴</td>
</tr>
<tr>
<td>Friction angle at failure, degrees</td>
<td>29±2</td>
<td>41±1</td>
</tr>
</tbody>
</table>

*a* These tests were conducted on reconstituted soil compacted to the indicated porosity. Diffusivity was determined from consolidometer tests using the method described by Bowles (1986, p. 115).

### 3. Procedure

The soil used in this study was a loamy sand used in the field-scale landslide experiments of Iverson et al. (2000) (Table 1). Soil particles were clumped naturally as aggregates. The size distribution of these aggregates, owing to their fragility, could not be measured reliably, but their ubiquity and size diversity is illustrated by photomicrographs of the soil in its virgin state (Fig. 2a) and after it was saturated, vigorously stirred, and deflocculated with a sodium hexametaphosphate (CAlg) solution (Fig. 2b). No aggregates larger than ∼10 mm in diameter were noted, and the largest aggregates, which are weakest (McDowell and Bolton, 1998), were likely partially crushed during consolidation prior to shearing. Thus, diameters of aggregates, if treated as rock particles, largely satisfied the convention that they not exceed 10% of the smallest specimen dimension (e.g., Head, 1989), which was the specimen thickness (60–70 mm).

One group of experiments was aimed at studying the contrasting behavior of remolded soil without and with its aggregates (Table 2). In two experiments (1A and 1B), soil was disaggregated by slurrying it with distilled, deaired (boiled) water, adding the deflocculant, and mixing the soil gently with an electric paint stirrer. The slurried soil was then poured into the specimen chamber, and stirred again in situ with the goal of destroying grain alignment possibly caused by pouring. In two other experiments (1C and 1D), moist soil with its aggregates largely intact was added to the specimen chamber and subsequently saturated by adding distilled, deaired water to the internal water reservoir (Fig. 1). To induce dilatancy in both kinds of experiments, specimens were compacted to overconsolidation ratios of 6.5 (under normal stresses of 264 kPa), and then sheared under a nominal normal stress of 40.6 kPa. This was an arbitrary but reasonable value, equal to total static normal stress beneath a debris flow ∼2.5 m thick.

A second group of experiments was aimed at determining effects of initial porosity on the evolution of porosity, shear stress, and pore pressure during shear (Table 2). To achieve this goal, specimens containing their natural aggregates were systematically compacted to different initial porosities (0.60 to 0.39, experiments 2A–2D) by applying different static normal stresses. In the fifth experiment (4E), to achieve a minimum initial porosity (0.34), the specimen was first hammered into the sample chamber with a plate and mallet and then loaded impulsively again by repeatedly raising and dropping the loaded lever arm on the normal-load plate. Strain associated with compaction likely caused some crushing and comminution of aggregates. Thus, the state of aggregation likely differed among these experiments when shearing commenced. Specimens were saturated with distilled, deaired water after consolidation and sheared under a nominal normal stress of 10.6 kPa, comparable to

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1 Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

2 A slightly smaller value (0.32) was obtained in one experiment of the other group, but before those experiments the soil was first slurried and deflocculated.

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Initial soil porosity was determined in two ways: by measuring the dry mass of the entire soil specimen and its initial thickness and by measuring the post-experimental porosity of the shear zone, as delimited by marker beads. The latter method involved excavating ~150 cm³ of sediment at four locations within the shear zone and measuring both the dry mass of the sample and the volume of the excavation to determine the final shear-zone porosity. The initial porosity could then be calculated from the measured change in specimen thickness during shearing, assuming all deformation and hence volume change were confined to the shear zone (e.g., Stephens and Bridgewater, 1978; Desrues et al., 1996). Only the first method for measuring initial porosity was used for the first group of experiments because measurements of marker-bed locations yielded highly variable shear-zone thicknesses that were considered untrustworthy. The unreliable shear-zone thicknesses from the first group of experiments did not allow porosity of the shear zone to be determined during shearing, so only specimen thickness changes, rather than porosity changes, are reported from those experiments. Probable errors of reported initial porosities, which were largest using the excavation method and determined from porosities of four samples, did not exceed 0.03.

4. Results

Soil specimens with and without their natural aggregates behaved differently. Specimens without aggregates (Fig. 2b) dilated to thicknesses that remained relatively steady with continued shearing (1A and 1B, Fig. 3a), as anticipated from normal critical-state soil behavior. This dilation was accompanied by prominent peaks in shear stress (Fig. 3b) and a ~25 kPa reduction in pore pressure (Fig. 3c). After reaching a minimum value when dilation ceased, pore pressure then increased slowly back toward the hydrostatic value. In contrast, specimens with their aggregates intact (1C and 1D) dilated only slightly and then contracted monotonically to thicknesses that were smaller than initial values (Fig. 3a). Contraction began at shear displacements smaller than those required for full dilation of disaggregated specimens. Shear stresses peaked at values ~35% smaller than those for disaggregated specimens (Fig. 3b). Reductions in pore pressure during and immediately after dilative periods were only a small fraction of those during shearing of disaggregated specimens (Fig. 3c). Pore pressures then rose slightly above hydrostatic values as the soil contracted for the remainder of the experiments. Peak friction angles – uncorrected for wall forces and hence underestimated but calculated accounting for non-hydrostatic pore pressure during shear – were 5–7° smaller than for soil without aggregates.

Fig. 4 illustrates how shear behavior of soil with aggregates depended on initial soil porosity in the second set of experiments. In two experiments in which initial porosity exceeded 0.55 (2A, 2B), specimens contracted monotonically. This contraction resulted in no peak in shear stress and a conspicuous peak in excess pore pressure during the initial, most rapid contraction. In contrast, in experiments with initial soil porosities of 0.46 (2C) and 0.39 (2D), the soil first dilated, with associated shear-stress peaks, and then contracted to porosities less than initial values. Dilation was accompanied by pore pressures less than hydrostatic but subsequently rose to slightly above hydrostatic values during contraction. The degree of dilation was proportional to shear-stress peaks and the initial soil density.

In the fifth experiment of this series (2E), in which the soil was hammered and cyclically loaded to attain an initial density of 0.34, porosity increased ~15%, more than twice that of experiment 2D (7%) and remained high, in contrast to the subsequent contraction observed in experiments 2C and 2D (Fig. 5). A peak in shear stress accompanied dilation, as did a reduction in pore pressure approximately twice that of experiment 2D.

**Table 2**

Summary of ring-shear experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Aggregates</th>
<th>Nominal normal stress, kPa</th>
<th>Initial porosity (±0.01)</th>
<th>Post-dilative contraction?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Destroyed</td>
<td>40.6</td>
<td>0.34</td>
<td>No</td>
</tr>
<tr>
<td>1B</td>
<td>Destroyed</td>
<td>40.6</td>
<td>0.32</td>
<td>No</td>
</tr>
<tr>
<td>1C</td>
<td>Retained</td>
<td>40.6</td>
<td>0.35</td>
<td>Yes</td>
</tr>
<tr>
<td>1D</td>
<td>Retained</td>
<td>40.6</td>
<td>0.38</td>
<td>Yes</td>
</tr>
<tr>
<td>2A</td>
<td>Retained</td>
<td>10.6</td>
<td>0.60</td>
<td>No</td>
</tr>
<tr>
<td>2B</td>
<td>Retained</td>
<td>10.6</td>
<td>0.56</td>
<td>No</td>
</tr>
<tr>
<td>2C</td>
<td>Retained</td>
<td>10.6</td>
<td>0.46</td>
<td>Yes</td>
</tr>
<tr>
<td>2D</td>
<td>Retained</td>
<td>10.6</td>
<td>0.39</td>
<td>Yes</td>
</tr>
<tr>
<td>2E</td>
<td>Destroyed*</td>
<td>10.6</td>
<td>0.34</td>
<td>No</td>
</tr>
</tbody>
</table>

* Inferred, see text.
Fig. 6 summarizes porosity evolution with shear displacement for experiments 2A–2E. Monotonically contractive behavior in initially porous soil transitioned to transiently dilative but ultimately contractive behavior at lower initial porosities. Only at the lowest initial porosity, produced by hammering and cyclic loading of the soil, was there dilation with little subsequent contraction. Porosities at the conclusions of experiments 2A–2D were very different, ranging from 0.51 to 0.37 for soils with initial porosities of 0.60 and 0.39, respectively, despite shear displacements in excess of 1200 mm. In these four experiments after shear displacements of $\sim 150$ mm, rates of contraction were similar (Fig. 6).

5. Discussion

5.1. Effects of aggregates

Many studies indicate how crushing of rock particles can cause departures from normal critical-state behavior. These departures include porosity reduction that continues to very high strains (e.g., Coop et al., 2004), reduction of both dilation and associated peak shear stresses in dense soils (e.g., McDowell and Bolton, 1998), and development of excess pore pressures caused by crushing-induced contraction and exacerbated by permeability reduction due to plugging of pore spaces with fine particles (e.g., Okada et al., 2004; Fukuoka et al., 2007). Indeed, contraction associated with rock-particle crushing may contribute to acceleration of some long run-out landslides (e.g., Sassa, 1996). However, crushing of rock particles is likely negligible at the small effective stresses and strain rates that characterize deformation during the early stages of debris-flow mobilization from shallow landslides that are typically no more than a few meters thick.

On the other hand, millimeter-scale aggregates of loamy sand and sandy-loam soil can have tensile strengths of only 10–50 kPa even when not fully saturated (Munkholm and Kay, 2002; Park and Smucker, 2005), at least two orders of magnitude weaker than rock particles of the same size (McDowell and Bolton, 1998). Owing to their fragility, aggregates likely have a negligible influence on post-yield soil behavior at sufficiently large effective normal stresses.
Fig. 4. Porosity, shear stress, and pore pressure (deviation from hydrostatic) during shear of aggregated soil compacted to different initial porosities.

Fig. 5. Porosity, shear stress, and pore pressure (deviation from hydrostatic) during an experiment in which soil containing aggregates was hammered into the specimen chamber to minimize initial soil porosity. Aggregates are inferred to have been largely destroyed during compaction prior to shear.
However, at the small total normal stresses of our experiments ~ 40.5 and 10.6 kPa, comparable to values in many shallow landslides – aggregates may persist transiently during shear, effectively behaving as coherent particles subject to pervasive crushing.

Our data show that overconsolidated soil specimens containing aggregates dilated during the initial stages of shear but then contracted to attain thicknesses and porosities less than initial values. Magnitudes of dilation in soil with aggregates were about an order of magnitude less than in their absence (Fig. 3a). Soil without aggregates compacted slightly more during consolidation prior to shear than did soil with aggregates (Fig. 3a), which may partly explain its reduced dilation. However, the soil contraction that followed dilation of the aggregated soil indicates that aggregate breakage also helped limit dilation. Similar post-dilative contraction of the soil with aggregates was observed at sufficiently small initial porosities in the second set of experiments (Fig. 4: 2C, 2D). At higher initial porosities (2A, 2B), aggregates were apparently not packed tightly enough to result in transient dilation. In experiment 2E there was dilation without significant subsequent contraction (Fig. 5). However, we infer that this behavior, which is similar to that observed in soil without aggregates (Fig. 3a), was due to nearly complete aggregate destruction caused by local hammering and impulsive loading of that specimen aimed at minimizing its initial porosity.

Dilation reduction due to breakage of aggregates resulted in peak shear stresses that were smaller than those observed in the aggregate-free case (Fig. 3b). Smaller peak shear stresses were, in part, due to peak friction angles being smaller (Fig. 3d), just as crushing of rock particles during shear limits peak friction angles (McDowell and Bolton, 1998). In addition, however, smaller peak shear stresses were due to effective normal stresses that were smaller in soil containing aggregates, owing to pore pressures that were reduced only slightly during the early stages of shear (Figs. 3c and 4: 2C, 2D). In contrast, by undergoing more rapid and sustained dilation, soil without aggregates developed larger negative pore pressures and hence larger peak shear stresses.

In addition to documenting post-dilative net contraction, our data revealed that the presence of aggregates caused a second deviation from classical critical-state behavior: soil specimens with differing initial porosities did not attain a common porosity with shear (Figs. 6 and 2a–d). The different final porosities can be attributed to different degrees of disaggregation at the ends of experiments. Excess pore pressures caused by rapid initial contraction of the two loosest specimens (Figs. 4, 2a and b) helped preserve aggregates by reducing effective normal stresses during the early stages of shear. In contrast, the specimens that were denser initially (2C and 2D) were subjected to higher effective normal stresses due to negative pore pressures during dilation. After the pore-pressure transients resulting in these different effective stress histories ceased at shear displacements of ~150 mm, rates of porosity reduction with shear were similar (Fig. 6).

Thus, at shear displacements greater than ~150 mm, aggregates in experiments 2A–2D were likely crushing at only mildly dissimilar rates, with soils from the different experiments retaining porosity differences inherited from the early stages of shear.

Two aspects of the performance of the ring-shear device bear on our interpretations of post-dilative contraction. Post-experimental measurements indicate that the o-rings sealing the upper to the lower walls allowed no more than about 0.01% of the masses of soil specimens (~2 g) to escape. Thus, post-dilative contraction was not due to soil loss from the specimen chamber (e.g., Bishop et al., 1971; Iverson et al., 1997a; Coop et al., 2004). Performance of the device, however, limited the total shear displacement to which experiments were conducted. Shearing was continued until displacement transducers indicated undesirable periodic wobbling of the normal-load plate about its axis. Installing new bearings in the normal-load plate failed to fix this problem, so experiments were terminated when wobbling ensued at shear displacements at the specimen centerline ranging from 0.5 to 1.5 m.

If experiments could have been conducted to higher shear displacements, we infer that with sufficient strain all specimens would have attained a common, steady-state porosity. The very large strain apparently necessary to reach this porosity must reflect the low total normal stress of these experiments, 10.6 kPa. This value is at the low end of ranges of reported tensile strengths of soil aggregates of similar texture (Munkholm and Kay, 2002; Park and Smucker, 2005). Porosity evolution of the soil of experiment 2D, which contained aggregates, and that of experiment 2E, which we infer had most of its aggregates destroyed, indicate convergence to a steady-state porosity of ~0.37 (Fig. 6). This value is likely close to the critical-state porosity of the soil after a constant state of disaggregation is reached.

In soil that underwent post-dilative contraction (Figs. 3, 1C and D, and 4, 2C, D), the contraction caused only small excess pore pressures. This observation can be understood by comparing the characteristic time scale of shear-zone contraction, $h/c$, with that of pore-pressure diffusion, $h^2/D$, where $h$ is the shear-zone thickness, $c$ is the rate of contraction of the shear zone, and $D$ is its hydraulic diffusivity. The ratio of these time scales is $R_c = D/c h$ (based on R of Iverson and LaHusen (1989)). For $R_c < 1$, the time scale for contraction greatly exceeds that of pore-pressure diffusion, such that substantial excess pore pressures are not expected. The smallest value of $R_c$ during post-dilative contraction in these experiments is ~90 ($D = 1100 \text{ mm}^2 \text{s}^{-1}$ (Table 1), $h = 41 \text{ mm}$, and $c = 0.3 \text{ mm s}^{-1}$), so lack of significant excess pore pressure during the post-dilative contraction in these experiments is not surprising.

5.2. Debris-flow mobilization

An implication of our results for debris-flow mobilization is that soils containing aggregates can have a transitional porosity – which divides initially contractile from initially dilative behavior – that is larger than the critical-state porosity. As shown in Fig. 6, the transitional porosity lies between 0.46 and 0.56 but probably is closer to the former value given the minimal dilation that occurred in experiment 2C (Fig. 4). In contrast, the critical-state porosity is significantly smaller, ~0.37, as a result of aggregate crushing.

The transitional porosity dividing contractile from dilative behavior in these experiments is broadly consistent with results of landslide experiments conducted with the same soil and under approximately the same total normal stresses and ranges of initial soil porosity (Iverson et al., 2000). The transitional range of porosity in those experiments was 0.41–0.50, with errors not larger than 0.02. This range overlaps the transitional porosity range bracketed by the
aggregates undergoes significantly less dilation in the early stages of shear, thereby reducing peak shear stresses and mutating pore-pressure reductions caused by dilation. In soil containing aggregates, the transitional initial porosity that divides contractive from dilative behavior is larger than the critical-state porosity, which is attained only after the state of disaggregation and hence porosity become steady at a sufficiently high strain.

Depending upon contraction rate, shear-zone thickness, and soil hydraulic diffusivity, post-dilative contraction associated with aggregate crushing may cause excess pore pressures and landslide acceleration. Strains of triaxial tests used to demonstrate dilation of soils that have transformed from landslides to debris flows are too small to detect this contraction.

6. Conclusions

During shear under sufficiently small effective normal stresses, soil aggregates can transiently behave as coherent particles before they break down. Thus, aggregates can cause initially dilative behavior followed by contraction that persists to high strains. Relative to equally overconsolidated soil without aggregates, soil containing aggregates undergoes significantly less dilation in the early stages of shear, thereby reducing peak shear stresses and mutating pore-pressure reductions caused by dilation. In soil containing aggregates, the transitional initial porosity that divides contractive from dilative behavior is larger than the critical-state porosity, which is attained only after the state of disaggregation and hence porosity become steady at a sufficiently high strain.

Depending upon contraction rate, shear-zone thickness, and soil hydraulic diffusivity, post-dilative contraction associated with aggregate crushing may cause excess pore pressures and landslide acceleration. Strains of triaxial tests used to demonstrate dilation of soils that have transformed from landslides to debris flows are too small to detect this contraction.

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References


