Effect of Sample-Preparation Method on Critical-State Behavior of Sands

ABSTRACT: It is well-known that specimen-preparation method and the resulting sand fabric significantly affect sand behavior. In many cases, the fabric and behavior of reconstituted sand samples do not represent those of in-situ deposits. Therefore, understanding the influence of specimen preparation and sand fabric on its behavior, particularly at the critical state, is important for relating the behavior of laboratory reconstituted specimens to in-situ soil response. In this study, the effect of sand fabric and specimen-preparation method on the shearing behavior of three sands is studied using ring-shear tests. Ring-shear tests are used to reach large shear displacements and determine critical states, particularly for dense sand specimens. Moist tamping and air pluviation are used to prepare the specimens. The results indicate that the shearing behavior of sand in ring-shear tests is not only affected by the specimen-preparation method (i.e., sand fabric), but also by particle damage and compressibility. However, these mechanisms do not affect the critical states at which particle rearrangement and damage are complete and the initial sand fabric is completely erased.

KEYWORDS: sand, fabric, ring shear, specimen-preparation method, critical state, particle damage.

Introduction

Several methods have been developed to reconstitute specimens of granular soil in geotechnical laboratories. Moist tamping and pluviation (through air or water) are among the most popular techniques. Numerous studies (Oda 1972; Ladd 1974; Mullilis et al. 1977; Ishihara 1993; Vaid et al. 1999; Frost and Park 2003; Yamamuro and Wood 2004) have shown that different specimen-preparation methods result in different soil fabrics and stress-strain response of reconstituted specimens at small to moderate shear strain levels.

Studies by Oda (1972) and Ladd (1974) were among the first attempts to study the effects of the specimen-preparation method on reconstituted sand behavior. Ladd (1974) observed that the method of specimen preparation significantly affected the cyclic shear strength of sand. Similarly, Mullilis et al. (1977) reported that different specimen-preparation procedures significantly affected the liquefaction characteristics of sand in undrained stress-controlled cyclic triaxial compression tests. Zlatovic and Ishihara (1997) performed undrained triaxial compression tests on loose silty sands and found that the shear response depended significantly on the preparation method. However, nearly all earlier studies of the effect of specimen-preparation method on critical-state behavior involved loose sands sheared to limited shear displacements under undrained conditions using triaxial devices. Studies investigating the effects of different specimen-preparation methods on the stress–strain response of sand sheared in plane strain to very large shear displacements are rare, even though many field problems (e.g., cone penetration testing, pile driving, slope failures, and liquefaction flow failures) commonly involve large shear displacements. Therefore, the effects of specimen-preparation method and sand fabric on the plane-strain response of sand at large shear displacements and whether the critical states obtained from specimens prepared by one method could be extended to specimens prepared by other methods are poorly understood. In particular, the particle fabric of laboratory sand specimens may not resemble the fabric of natural soil deposits.

The main objective of this paper is to illustrate the effects of specimen-preparation method and sand fabric on critical-state behavior. A suite of \(k_c\)-consolidated, large displacement ring-shear tests are conducted on three different sands prepared by moist tamping (MT) and air pluviation (AP), and the results are compared and discussed. These two reconstitution methods yield distinctly different sand fabrics (as reflected in the stress-displacement responses). Note that “fabric” is used here to describe the arrangement of sand particles of all sizes, shapes, and associated pores, whereas “structure” describes the combination of fabric and bonding, i.e., interparticle forces including cementation, electrostatic and electromagnetic attractions, or any other force that holds particles together (Lambe and Whitman 1969; Mitchell 1993).

Testing Program

We selected three sands for this study: Ottawa 20/40 sand (OT), an Illinois River sand (IR), and a Mississippi River sand (MR). Figure 1 presents average particle size distributions of these sands. OT sand is a commercially available, medium to coarse grained, uniform, clean, pure quartz sand with rounded particles from Ottawa, IL. It has a specific gravity \((G_s)\) of 2.63, and maximum \((e_{\text{max}})\) and minimum \((e_{\text{min}})\) void ratios of 0.679 and 0.391,
respectively. IR sand is a fine to coarse grained, uniform, clean, alluvial sediment from the Illinois River, with $G_s = 2.63$, $e_{\text{max}} = 0.757$, and $e_{\text{min}} = 0.464$. IR sand particles are rounded to sub-rounded, and consist primarily of quartz with traces of muscovite, chlorite, and hematite (Mueller 2000). MR sand is a very fine grained alluvial silty sand with an average fines content of 38 % that we sampled near Cape Girardeau, MO. It has subangular to sub-rounded particles, and contains about 70 % albite, 21 % quartz (both determined by x-ray diffraction technique), and 5 % calcite (determined by acid dissolution method). It has $G_s = 2.65$, $e_{\text{max}} = 1.038$, and $e_{\text{min}} = 0.563$. We used ASTM (2006) to determine $G_s$ and the procedure described by Yamamuro and Lade (1997) to consistently evaluate $e_{\text{max}}$ and $e_{\text{min}}$ because the relatively high fines content of MR sand precludes the use of ASTM standards. In this method, we obtained $e_{\text{min}}$ by placing approximately 50 g of sand into a graduated cylinder and tapping on the sides of the cylinder with a rubber mallet. This procedure was repeated until 800 g of sand was deposited in the graduated cylinder and the volume of the sand was read to determine $e_{\text{min}}$. Maximum void ratio was then obtained by covering the end of the cylinder by a cardboard sheet and turning it upside down and back again with very slow motion (about 45–60 s). The new volume of the sand was read to obtain $e_{\text{max}}$. These methods were repeated three times for each sand, and the average void ratios are reported for each sand.

**Specimen-Preparation Methods**

We used both air-pluviation and moist-tamping methods to prepare ring-shear specimens. Moist-tamped specimens of MR sand deformed excessively during preparation and the application of the initial seating pressure before shearing, and, therefore, the majority of MR sand specimens were prepared by air pluviation.

Moist tamping simulates cases where moist sand is dumped as a fill and subsequently submerged as the water table rises (Olson et al. 2000; Chiu and Leong 2003), or loess soils formed by slow dry aggradation of windborne dust held in a loose state by means of pore water suction (Dijkstra et al. 1994). We used the moist-tamping method to obtain very loose specimens that would exhibit entirely contractive and strain-softening behavior. In this method, we thoroughly mixed dry sand with 5 % water (of the weight of dry sand), and then poured and gently tamped the moist sand in 20 layers into the specimen mold. This moisture content developed a capillary force among sand particles that produced a stable sand fabric at very large void ratios and kept the specimen shape once the split mold was removed. As a result, some moist-tamped specimens of OT sand were prepared at void ratios larger than $e_{\text{max}}$ (determined by pluviating dry sand into a cylinder) and thus yielded negative initial relative densities ($D_{\text{r},e}$). To improve bonding between successive layers, the upper surface of each layer was scarified prior to the placement of the next layer. Air pluviation on the other hand is considered to replicate the natural alluvial and marine depositional processes (Vaid et al. 1999). In the air-pluviation method used in this study, we poured dry sand into a funnel attached to a tube that rested on the bottom of the specimen mold. Then we slightly raised the tube to deposit sand particles with nearly zero drop height in a circular motion. This technique produced the loosest possible fabric using air pluviation (Ishihara 1993) and minimized segregation between the fine and coarse particles in MR sand specimens. Denser air-pluviated specimens were formed by increasing the pluviation height or by gently tapping on the sides of the mold after pluviation.

**Specimen Uniformity**

Density variation and void ratio non-uniformities exist in both moist-tamped and air-pluviated specimens. In the early development of the moist-tamping method, specimens were prepared in a number of layers of equal dry weight, and each layer was compacted to the same target density. This typically resulted in the lower portion of the specimen becoming denser than the global specimen density as compaction of each overlying layer also slightly densified the underlying layers (Mullis et al. 1977). In this study, we used under-compaction as proposed by Ladd (1974) to achieve a relatively uniform density throughout the specimen. In this method, each sand layer was compacted slightly looser than the target global density so that the final density of each layer, even with the effects of compaction of the successive overlying layers, would be equal to the target global density. Despite the improvements in preparing moist-tamped specimens, several studies (Vaid and Negussey 1988; Vaid et al. 1999; Frost and Park 2003) have shown that void ratio distribution in pluviated specimens is generally more uniform than moist-tamped samples.

Regardless of specimen-preparation method, it is practically impossible to eliminate non-uniform density distribution within sand specimens (Gilbert and Marcuson 1988). Even after carefully preparing a specimen, leveling the specimen surface prior to placing the upper platen densifies the upper portion of both air-pluviated and moist-tamped specimens, causing additional specimen non-uniformity. In this study, we assessed specimen uniformity for both preparation methods by preparing a number of specimens in four lifts and measuring the weight and height of the sand deposited in each lift and at different locations along the circumference of the ring-shear specimens. We observed that the void ratio of an individual lift deviated by less than 5 % from the average void ratio of the entire specimen for both moist-tamping and air-pluviation methods (Sadrekarimi 2009).

![Average particle size distributions of test sands.](image-url)
Ring-Shear Tests

In a ring-shear test, an annular specimen is confined between inner and outer rings and is sheared at its bottom surface (or top, or mid-height depending on the configuration and fixity of the rings). A fixed platen on a specimen’s top surface measures soil shear resistance. Sadrekarimi and Olson (2009) summarize the advantages that the ring-shear test provides for measuring the large displacement shearing resistance of sands. We performed constant volume and drained ring-shear tests using the solid confining rings-type ring-shear apparatus designed and built at the University of Illinois (Sadrekarimi 2009; Sadrekarimi and Olson 2009). The University of Illinois ring-shear apparatus has a ring-shaped specimen chamber with inner \( R_i \) and outer \( R_o \) radii of 10.2 cm and 13.5 cm, respectively, and a height of 2.6 cm. The ratio of the outer to inner specimen diameter is 1.33, which results in an error of less than 2% in measuring peak shear strength caused by shear strain non-uniformity and progressive mobilization of peak shear strength (Sadrekarimi 2009). The wide sample section (3.3 cm) further minimizes wall friction effects. The mode of shearing in this ring-shear device is similar to a plane strain mode of simple shear and reasonably represents conditions in many geotechnical field situations, such as some landslides, embankments, soils beneath strip footings, and behind retaining structures. All ring-shear tests were performed on dry air-pluviated or moist-tamped specimens, in which the specimen was not saturated. In these tests, each sand sample was deposited in the ring-shaped specimen mold of the apparatus, and the dry mass and height of the specimen were measured to define specimen global void ratio at an average precision of ± 0.007 (Sadrekarimi 2009). Specimens were compressed to the target consolidation normal stress \( (\sigma'_{nc}) \) and sheared in either constant volume or drained conditions at a speed of 18.6 cm/min. As these specimens were not saturated, primary consolidation (as a result of particle rearrangement and reorientation) was complete within few seconds after the application of the normal load. A constant volume was imposed after the application of \( \sigma'_{nc} \) by locking the loading platens of the apparatus against vertical movement, and shearing was applied by rotating the bottom platen, which was deeply serrated to prevent particle slippage. For drained testing, the upper loading platen was left free to move up and down as the specimen dilated or contracted, respectively. A load cell measured the total normal force \( (F_n) \) applied on the specimen and a torque cell measured the shearing torque resisted by the sand specimen at its upper surface \( (T_s) \). Secondary load and torque cells measured normal force \( (F_n) \) and shearing torque \( (T_s) \) carried by the sand above the shear band at its contact with the confining rings. Normal force \( (F_n) \) and shearing torque \( (T_s) \) on the shear band were then calculated by deducting \( F_n \) and \( T_s \) (of the sand above the shear band) from \( F_n \) and \( T_s \), respectively. Assuming uniform distributions for the average shear \( (\tau) \) and normal \( (\sigma'_{n}) \) stresses on the shear band, these stresses were calculated from the following relationships (La Gatta 1970; Bishop et al. 1971):

\[
\tau = \frac{3T_{sb}}{2\pi (R_o^3 - R_i^3)} \tag{1}
\]

\[
\sigma'_{n} = \frac{F_{sb}}{\pi (R_o^3 - R_i^3)} \tag{2}
\]

Values of \( \tau \) and \( \sigma'_{n} \) on the failure surface were measured as principal stresses are not controlled or measured in ring-shear tests. As described above, \( \tau \) and \( \sigma'_{n} \) were calculated from direct measurements of total and friction forces and torques in the ring-shear tests, and auxiliary load and torque cells measured any friction along the confining rings (Sadrekarimi and Olson 2009). Sadrekarimi and Olson (2009) provide further details of the ring-shear device, specimen preparation, testing methods, and device calibration.

A linear variable differential transformer (LVDT) was used to measure the vertical movement of the upper loading platen, and shear displacement was obtained from the rotation of the specimen chamber measured by the driving motor encoder. Shear localization and shear banding occurred in the ring-shear tests after about 0.5 cm of shear displacement (Sadrekarimi and Olson 2010c). Local void ratio within the shear band \( (e_{sb}) \) changes significantly after shear band formation (whereas the global void ratio remains constant), and thus the void ratio inside the thin shear band should be measured and used to describe the state of the specimen (Desrues et al. 1996; Finno et al. 1996; Frost and Jang 2000). To observe and quantify this local behavior, indirect methods have been used, such as x-ray computed tomography (Desrues et al. 1996) and stereophotogrammetry (Finno et al. 1996). Although these approaches provide an excellent view of the shear band within a specimen, there are limitations in the resolution that can be achieved using these techniques for local volume-change measurement.

Shear band void ratio changes (i.e., volumetric compression within the shear band) result from particle damage and rearrangement. During constant volume shear tests, elastic and plastic volumetric strain components are equal but opposite. Thus, particle damage and rearrangement that produce contractive plastic (irrecoverable) volumetric strains within the shear band, cause \( \sigma'_{n} \) reduction by elastic rebound of the entire specimen to maintain the constant volume condition (Jeffries et al. 1990; Vermeer 1999). In ring-shear tests performed with a Plexiglas outer ring (Sadrekarimi and Olson 2010b), we observed that after shear band formation, sand within the shear band contracted during shear as a result of particle rearrangement and damage. In contrast, sand particles above the shear band were stationary and did not experience any rearrangement/reorientation or damage. Similar observations have been reported in discrete element models. For example, Cheng et al. (2008) observed that after shear band formation, particle rearrangement and damage occurred only within the shear band in discrete element analysis. Similarly, in constant volume discrete element models, Zhang (2003) observed that the zones away from the shear band did not show any significant volume change and localized volume changes occurred only within the shear band. Therefore, shear-induced volume change was negligible in the sand above the shear band, and it only swelled as \( \sigma'_{n} \) decreased. Swelling in constant volume ring-shear tests is estimated by changes in \( \sigma'_{n} \) and sand swelling index. This value is subtracted from the global volume change of the specimen to estimate shear-induced volume change of the shear band. Thus, \( e_{sb} \) is estimated as follows:

\[
\Delta V_{\text{global}} = \Delta V_{\text{above}} + \Delta V_{sb} \tag{3}
\]


\[ e_{sb} = \frac{V_{s, sb} - V_{s, sb}}{V_{s, sb}} = \frac{V_{s, sb} - (V_{s, sb} - \Delta V_{sb})}{V_{s, sb}} = \frac{V_{s, sb} - (\Delta V_{global} - \Delta V_{above})}{V_{s, sb}} \]

where \( \Delta V_{global} \) = volume change of the entire specimen estimated from changes in specimen height (resulting from minor system compliance during constant volume tests, and from shear-induced volume change in drained tests in response to sand volumetric dilation or contraction); \( \Delta V_{above} \) = swelling of sand above the shear band as \( \sigma'_{n} \) decreases during shear band contraction in constant volume ring-shear tests; \( \Delta V_{sb} \) = volume change of the shear band; \( V_{s, sb} \) = volume of voids in the shear band sand; \( V_{sb} \) = volume of sand particles (solids) in the shear band; and \( V_{s} \) = total volume of the shear band. In Eq 4, \( \Delta V_{above} \) is estimated by:

\[ \Delta V_{above} = C_s \cdot \log\left( \frac{\sigma'_{n}}{\sigma'_{n, sb}} \right) \cdot V_{s, above} \]

where \( C_s \) = swelling index (\( \equiv \Delta V / \Delta \log(\sigma'_{n}) \)) of the original sand above the shear band, \( V_{s, above} \) = volume of sand particles above the shear band, and \( \sigma'_{n, sb} \) = effective normal stress when shear band forms. We measured swelling indices of 0.0028, 0.0039, and 0.0053 for OT, IR, and MR sands, respectively, in unloading cycles of one-dimensional compression tests. The most important advantage of estimating \( e_{sb} \) analytically using Eq 4 over indirect techniques (x-ray computed tomography and stereophotogrammetry) is that the sheared sand is not disturbed and \( e_{sb} \) is calculated directly from high resolution measurements of the global volume change of the specimen during shear. However, this method also introduces some uncertainties with respect to visual measurement of shear band thickness, and estimating specimen volume change above the shear band using Eq 5.

For comparison, we also measured \( e_{sb} \) at the end of some ring-shear tests from the weight of sand collected from the shear band alone and the measured height of the shear band. According to our comparisons, Eq 4 may underestimate \( e_{sb} \) up to 3.6 %, 3.2 %, and 9.0 % in OT, IR, and MR sands, respectively. This error decreases at larger \( e_{sb} \). These small errors are acceptable given the simplicity of Eq 4, and are likely caused by two factors: (1) difficulties in directly measuring the shear band thickness (particularly for finer sands with very thin shear bands); and (2) the inevitable migration of a small volume of the very fine particles of MR silty sand or the fines produced by crushing of OT and IR sands, into the mechanical clearances and gaps of the ring-shear specimen chamber. We also performed a series of pre-production ring-shear tests on thicker (5.0 cm) specimens that exhibited shear bands of equal thickness and similar \( e_{sb} \) to the production ring-shear tests on 2.6-cm-thick specimens. This further validates Eq 4 for the calculation of \( e_{sb} \).

**Typical Test Results**

Table 1 provides the preparation methods and consolidation conditions for each of the ring-shear tests performed for this study. Figures 2–13 present typical stress paths, and variations of \( \tau, \sigma'_{n}, \) and \( e_{sb} \) with shear displacement for some of the ring-shear experiments performed in this study. Sadrekarimi and Olson (2009) present the results of all ring-shear tests listed in Table 1. Moist tamping creates a collapsible honeycomb sand fabric produced by capillarity. The collapse of this honeycomb fabric during undrained or constant volume shear results in rapid pore water pressure generation, strain-softening, and liquefaction (Casa-grande 1975; Sladen et al. 1985; de Gregorio 1990; Vaid et al. 1999). A wide range of consolidation relative densities, ranging from \( D_{rc} = –8 \% \) to \( 39 \% \), were produced in moist-tamped OT and IR sand specimens, all of which exhibited strain-softening or contractive behavior without any strain hardening or dilation. Careful evaluation of \( \sigma'_{n} \) and \( e_{sb} \) in contractive specimens (e.g., for constant volume and drained ring-shear tests in Fig. 14) indicated that a temporary state of constant \( \sigma'_{n} \) and \( e_{sb} \) was reached after shear band formation and at shear displacements less than 50 cm, before they continued to decrease as a result of particle crushing. This constant state typically was maintained for about 10 cm in strain-softening and contractive specimens, corresponding to a large shear strain (\( \approx \)2000 %) for OT and IR sand specimens based on their shear band thickness \( \approx 0.5 \) cm), and thus represents the critical state of the original sand prior to the onset of particle damage (\( C_{S,v} \)) achieved essentially through particle reorientation/rearrangement (Sadrekarimi and Olson 2011a).

As indicated by values of \( D_{rc} \) in Table 1, void ratios looser than the loosest possible void ratios achieved by air pluviation and looser than \( e_{max} \) were produced by moist tamping. In contrast, the loosest possible void ratios produced by air pluviation were denser than \( e_{max} \) determined using the Yamamuro and Lade (1997) approach. Similar to the water-pluviated Fraser River sand specimens tested in triaxial compression by Vaid and Thomas (1995), air-pluviated specimens of OT and IR sands all strain-hardened or dilated (after a brief initial contraction and before particle crushing occurred) during shearing because of their dense fabric. However, these specimens exhibited a second phase transformation from dilative to contractive behavior at shear displacements of about 0.60–1.36 cm during constant volume shearing (e.g., Figs. 2 and 6) as particle damage suppressed dilatancy and caused strain softening (Sadrekarimi and Olson 2010a). The shear resistance subsequently decreased and then reached a constant volume at larger displacements (exceeding 1000 cm). This ultimate plateau corresponds to a large displacement state of constant \( \tau, \sigma'_{n}, \) and \( e_{sb} \) for the crushed sand, termed the crushed sand critical state (\( C_{S,v} \)) that involves shear band formation and complete particle damage within the shear band.

As illustrated by the \( e_{sb} \) changes in Figs. 2–13, particle damage resulted in markedly contractive behaviors, and even dense air-pluviated specimens that experienced particle damage exhibit contracting and strain-softening behavior to the \( C_{S,v} \). In this case, very large shear displacements (>10 ms) were required to exhaust particle damage (by particle crushing producing a broader particle size distribution and reducing particle contact stresses) and reach a large-displacement critical state for the damaged sand. This level of shear displacement in laboratory element tests is only achieved in a ring-shear device.

Dilative, strain-hardening ring-shear specimens approached \( C_{S,v} \) through increasing \( \sigma'_{n} \) (strain-hardening) or increasing \( e_{sb} \) (dilation). For these specimens, \( C_{S,v} \) was taken at the maximum \( \sigma'_{n} \) (in
constant volume shear) or maximum $e_{sp}$ (in drained shear) before these values decreased as a result of particle damage. Figure 15 demonstrates these criteria for dilative specimens sheared in constant volume and drained conditions. As indicated in Figs. 14 and 15, $C_S$ was reached at smaller shear displacements for dilative specimens than for contractive specimens, likely because of the larger confinement and limited particle mobility in dense sands.

Effect of Sample-Preparation Method at Small to Moderate Displacements

Air-pluviated specimens of OT and IR sands exhibited larger peak shear stress and initial stiffness than their moist-tamped counterparts in constant volume shear, partly because of the different particle-level deformation mechanisms governing the behavior of these specimens. In strain-softening, moist-tamped specimens (Figs. 3 and 7) in which no strain hardening occurred, the peak shear stress was mobilized through particles pushing and moving over each other. Comparison of initial and post-shear particle size distributions, and visual observations of the shear band during ring-shear tests conducted with a Plexiglas outer ring, indicated that particle damage was minimal in these specimens (Sadrekarimi and Olson 2010a), and therefore strain softening resulted from the collapse of the sand fabric through particle rearrangement and reorientation. However, in air-pluviated specimens (Figs. 2 and 6), strain softening occurred during constant volume shear as a result of significant particle damage (indicated by comparing post-shear particle size distributions of sand in the shear band and visual observation of the shear band during ring-shear tests conducted with a Plexiglas outer ring) after the second phase transformation stage, and the peak shear stress was thus limited by fracture strength of the particles.

As illustrated in Figs. 10–13, all moist-tamped and air-pluviated specimens of MR sand, regardless of their larger $D_{rc}$, contracted (decreasing $e_{sp}$) or strain softened throughout the ring-shear tests without significant particle crushing occurring (Sadrekarimi and Olson 2010a). As discussed by Sadrekarimi and Olson (2008), we anticipate that MR sand was entirely contractive (regardless of specimen-preparation method) because of the

<table>
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<tr>
<th>Test No.</th>
<th>$\sigma_{uc}$ (kPa)</th>
<th>$e_c$</th>
<th>$D_{rc}$ (%)</th>
<th>Test No.</th>
<th>$\sigma_{uc}$ (kPa)</th>
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*MT and AP in test numbers indicate moist-tamping or air-pluviation preparation methods, respectively. OT, IR, and MR indicate OT, IR, and MR sands, respectively. CV and DR indicate constant volume or drained shearing, respectively. Relative density after consolidation.

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presence of angular fines that made the initial sand fabric more compressible by the greater number of large-to-small-to-large unstable particle contacts, as well as its more compressible mineralogy (albite and calcite) compared to the less compressible OT (rounded quartz) and IR (rounded to sub-rounded quartz and feldspar) sand particles. Particle arrangement among the angular fines and the rounded larger particles allowed a relatively unstable fabric to develop during deposition. Once sufficient stress was applied to overcome particle interlocking, significant volumetric contraction occurred, consistent with the observations of Yamamuro and Wood (2004) for silty sands. Therefore, because of the softer and more angular particles of MR sand, there was almost no effect of specimen-preparation method and sand fabric on the mobilized peak strength and initial stiffness.

As illustrated above, sand fabric and specimen-preparation method (air pluviation and moist tamping in this study) influence the initiation of yielding and strain-softening mechanisms at small to moderate shear displacements for sands with relatively incompressible particles. As liquefaction is triggered by the initiation of instability and yielding at small shear displacement, initial sand fabric and specimen-preparation methods affect liquefaction susceptibility and triggering in these sand deposits. Therefore, for liquefaction-triggering analysis and evaluating yield shear strength, specimens should ideally have the original in-situ soil fabric. Samples obtained by ground freezing or from high-quality tube sampling that are corrected for sample disturbance effects (Poulos et al. 1985) or specimen-preparation techniques that closely replicate field depositional method (e.g., moist tamping for moist dumped sand and air pluviation for natural alluvial and marine deposits) should be used.

**Effect of Sample-Preparation Method at Large Displacements**

**Critical-State Line**

The results of this testing program demonstrated that shear band formation and particle damage play an important role in the critical-state response of sands, and two types of critical states were proposed by Sadrekarimi and Olson (2011a): (a) \( C_{So} \), the critical state of the original sand without particle damage achieved solely through particle reorientation and rearrangement; and (b) \( C_{Sc} \), the critical state including particle damage and crushing that involves shear band formation and particle damage within the shear band. As described earlier, ring-shear specimens commonly reached a \( C_{So} \) after shear band formation but prior to significant particle damage occurring. The loci of the \( C_{So} \) and \( C_{Sc} \) data in \((e,\sigma''_n)\) space can be observed in the figure.

FIG. 2—(a) Stress path, and (b) shear displacement behavior of an air-pluviated OT sand specimen (APOTCV54) in constant volume ring-shear test.

FIG. 3—(a) Stress path, and (b) shear displacement behavior of a moist-tamped OT sand specimen (MTOTCV54(2)) in constant volume ring-shear test.
log\(\sigma'_n\) space are termed the CSL\(_o\) (original sand critical-state line) and CSL\(_c\) (crushed sand critical-state line), respectively.

Several researchers (Lee and Seed 1967; Tatsuoka and Ishihara 1974; Vasquez-Herrera and Dobry 1989; de Gregorio 1990; Vaid et al. 1999; Vaid and Sivathayalan 2000; Chang et al. 2011) have found that sample-preparation methods (i.e., initial sand fabric) strongly influence the CSL\(_o\). For example, Fig. 16 shows CS\(_o\) data from triaxial compression tests performed by Vasquez-Herrera and Dobry (1989) on sand from the Lower San Fernando Dam, and by de Gregorio (1990) on Ottawa F-70 sand. These results
suggest that the position of $\text{CSL}_0$ depends on the sample-preparation method.

In contrast, other researchers (Poulos et al. 1985; Been et al. 1991; Ishihara 1993; Negussey and Islam 1994; Zlatovic and Ishihara 1997; Murthy et al. 2007) have shown that specimens prepared by slurry deposition, moist tamping, and water pluviation reach a unique $\text{CSL}_0$. Papadimitriou et al. (2005) and Jefferies and Been (2006) stated that tests like those in Fig. 16 did not reach $\text{CS}_0$ within the shear displacements that can be achieved in triaxial tests. In fact, Verdugo et al. (1995) proposed to divide the initial
fabric of a sand into two groups: (1) fabrics that are completely erased at large shear strains (attained in triaxial tests), and (2) fabrics that are not fully erased at large shear strains (again in triaxial tests). As illustrated earlier, soil fabric affects the undrained behavior of sand at small to moderate displacements where phase transformation or quasi-critical-state conditions are mobilized (Ishihara 1993; Zlatovic and Ishihara 1997). Experimental evidence (Ishihara 1993; Riemer and Seed 1997; Mooney et al. 1998; Yoshimine et al. 1998) suggests that the quasi-critical-state line is influenced by the specimen-preparation method, and mode
of shear (e.g., triaxial compression and ring shear). Thus, the influence of specimen-preparation method and sand fabric on CSL$_o$ is a manifestation of the failure to reach CSo in triaxial tests, and using quasi-critical states to construct CSL$_o$. Figures 17–19 present $\sigma'_n$ and $e_{ab}$ data at CSo and CSLc, and the corresponding CSL$_o$ and CSLc, for OT, IR, and MR sands, respectively. As illustrated in Fig. 14, CSo was obtained in contractive specimens (i.e., moist-tamped OT and IR and air-pluviated MR...
sand specimens) at constant $\sigma'_n$ and $\epsilon_{ph}$ before particle damage became significant. Initially dilative and strain-hardening specimens (air-pluviated OT and IR sand specimens) approached $C_{So}$ through increasing $\sigma'_n$ (strain-hardening) or increasing $\epsilon_{ph}$ (dilation). Therefore, as illustrated in Fig. 15, $C_{So}$ for these specimens was taken at maximum $\sigma'_n$ (for constant volume tests) or maximum $\epsilon_{ph}$ (for drained tests) before they decreased by particle damage. $C_{Sc}$ data were obtained at large displacement when values of $\sigma'_n$ and $\epsilon_{ph}$ stabilized. The ring-shear test data in Figs. 17–19, illustrate that both moist-tamped and air-pluviated specimens yield essentially the same CSLs for both the undamaged ($C_{So}$) and damaged ($C_{Sc}$) sands.

**Critical-State Friction Angle**

Figures 2–13 also include the friction angles mobilized at $C_{So}$ ($\phi'_{cso}$), and at $C_{Sc}$ ($\phi'_{csc}$). Because the horizontal failure plane in the ring-shear tests is the plane of maximum shear stress (Roscoe et al. 1967; Stroud 1971; Mandl et al. 1977; Dyvik 1981), these friction angles were obtained from the following relationship (Skempton 1985; Negussey et al. 1988; Infante-Sedano 1998; Luzzani and Coop 2002; Holtz et al. 2010): 

$$\phi'_{cs} = \tan^{-1}\left(\frac{\tau_{cs}}{\sigma'_{n,cs}}\right)$$

where $\tau_{cs}$ and $\sigma'_{n,cs}$ are stresses measured at $C_{So}$ and $C_{Sc}$ (defined as illustrated in Figs. 14 and 15) for calculating $\phi'_{cso}$ and $\phi'_{csc}$.
respectively. According to Figs. 2–13, $\phi'_{cs,c}$ is greater than $\phi'_{cs,o}$ because of the more angular particles and wider particle size distributions developed by particle crushing at CS$_{c}$. These friction angles do not vary with specimen-preparation method as the initial sand fabric was erased at large displacements and effective stress paths of both air-pluviated and moist-tamped specimens asymptotically approached the same constant stress ratio lines (i.e., $\phi'_{cs,c}$ and $\phi'_{cs,o}$).

Figure 20 presents the variations of $\phi'_{cs,o}$ with consolidation void ratio, $e_c$, and $\sigma_{nc}'$. These data suggest that $e_c$ does not affect $\phi'_{cs,o}$. In turn, this further validates that the initial sand fabric (reflected by $e_c$) was erased as particle rearrangement and reorientation were complete at CS$_{o}$, prior to the onset of significant particle damage. On the other hand, similar to some other studies (Fukushima and Tatsuoka 1984; Bolton 1986; Kolymbas and Wu 1990; Infante-Sedano 1998; Lancelot et al. 2006; Sadrekarimi and Olson 2011b), $\phi'_{cs,o}$ decreased with increasing $\sigma_{nc}'$ (for $\sigma_{nc}' < 150$ kPa) in Fig. 20(b). At $\sigma_{nc}' < 100$ kPa, particles experienced less damage (Sadrekarimi and Olson 2010a) and more relative displacement; thus mobilizing larger $\phi'_{cs,c}$. Values of $\phi'_{cs,c}$ at $\sigma_{nc}' < 100$ kPa are $44^\circ$ for OT and IR sands, and $46^\circ$ for MR sand. As $\sigma_{nc}'$ increases, $\phi'_{cs,c}$ decreases as particle interlocking was suppressed by the increasing normal load and relative particle sliding was enhanced. However, at $\sigma_{nc}' > 200$ kPa, $\phi'_{cs,c}$ slightly increased in OT and IR sands as particle damage produced a wider particle size distribution and more angular particles. In these sands, the decrease in friction angles by suppressing particle interaction and interlocking was compensated.
by an increase in friction angle resulting from the creation of more angular particles. On the other hand, MR sand does not exhibit any significant increase in $\phi'_{c,s,c}$ at $\sigma_{uc} > 200$ kPa because of its originally wider particle size distribution, resulting in reduced particle damage (Sadrekarimi and Olson 2010a). At $\sigma_{uc} > 200$ kPa, wider particle size distributions are created in all specimens by particle damage and crushing for which $\phi'_{c,s,c}$ becomes constant (34°, 38°, and 41° for OT, IR, and MR sands, respectively) and insensitive to $\sigma_{uc}$, in agreement with the findings of Insley and Hillis (1965), and Bishop (1966). As explained before, $\phi'_{c,s,c}$ exceeds $\phi'_{c,s,o}$ as a result of particle damage creating more angular particles and wider particle size distributions. Overall, $\phi'_{c,s,o}$ and $\phi'_{c,s,c}$ are independent of initial sand fabric (i.e., specimen-preparation method), $e_{c,s}$ and $\sigma_{uc} (>200$ kPa), and primarily depend on particle mineralogy and shape, reasonably consistent with the concepts of critical-state soil mechanics (Schofield and Wroth 1968).

As shown above, the specimen-preparation method does not affect the determination of critical state, as at critical state the initial sand structure has been largely destroyed. Therefore, the critical-state behavior obtained from laboratory tests (irrespective of the particular preparation method) is also applicable for describing the flow liquefaction potential, liquefaction severity, and liquefied strength of in-situ field soils based on the in-situ void ratio. Void ratio of in-situ field soil should be determined from representative field samples obtained by ground freezing or from high-quality tube sampling techniques and then correcting for sample disturbance effects (Poulos et al. 1985). Correct estimation of the undrained liquefied shear strength is particularly necessary for the design of large soil structures such as mine tailings impoundments, earth dams, and building foundations to protect them against liquefaction flow failure. The main concern in critical-state testing is the preparation of contractive specimens that easily reach a true critical state before reaching the displacement limits of laboratory shear test. Among all laboratory specimen reconstituting techniques, moist tamping has the advantage of producing sufficiently loose contractive samples that most likely reach a true critical state within the strain limits of the most laboratory shear testing equipment and define the CSL.

Conclusions

The effect of sand fabric and specimen-preparation methods on the shearing behavior of three sands was studied in this paper using ring-shear test results. A wide range of low relative densities were produced by moist tamping. These specimens strain-softened or contracted throughout shearing, and reached a critical state. In contrast, air-pluviated specimens of sands with less compressible particles (rounded particles and harder mineralogy) exhibited strain-hardening and dilative behavior before strain-softening and contraction as a result of particle crushing. Whereas, both moist-tamped and air-pluviated specimens of a sand composed of compressible particles (angular particle shapes and softer particle mineralogy) experienced strain softening and contraction during shearing, regardless of higher relative densities. It is possible that particle compressibility outweighed the influence of specimen-preparation method and sand fabric on the shearing behavior of the sand with compressible particles. Thus, the effects of both “initial sand fabric” (reflecting particle arrangement/orientation and depositional method) and “particle characteristics” (reflecting mineralogy, particle shape, and particle size distribution) should be considered in understanding the behavior of sandy soils.

At moderate to large shear displacements before the onset of particle crushing, the critical-state behavior (mobilized friction angle, critical-state strength, and critical-state line) of the sands studied in this paper was independent of specimen-preparation methods. At large shear displacements reached in the ring-shear tests, particle damage (i.e., abrasion, crushing, and shearing of particle asperities) occurred within the shear bands and significantly altered sand gradation and particle shapes. Particle damage produced strain softening (during constant volume shear tests) and contractive response even in initially dilative specimens, and required considerably larger shear displacements (>1000 cm) to reach critical states. The critical state where particle damage and subsequent particle rearrangement were complete (at which the measured specimen volume and stresses did not longer change) was also independent of specimen-preparation methods.

References


Sadrekarimi, A. and Olson, S. M., 2009, “A New Ring Shear Device to Measure the Large Displacement Shearing Behavior...


