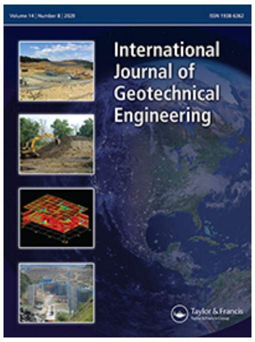

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A review on sand sample reconstitution methods and procedures for undrained simple shear test

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ABSTRACT
This paper discusses the common methods available for reconstituting sand samples that are used for soil strength characterization. Reconstituted samples are preferred to undisturbed samples because the current field sampling procedures cannot retrieve granular soil specimens at a reasonable cost. Water sedimentation is generally recognized as the better one than the other common methods such as moist tamping and air pluviation. Most of the existing literature about sand specimen reconstitution is designated for triaxial set-up, and there is no study specifically for simple shear set-up in this topic. Therefore, this paper discusses the differences in reconstituting sand specimens between triaxial and simple shear setups. Two reconstitution methods particularly designed for undrained simple shear tests were introduced and tested through a CSS testing programme. The CSS test data are also compared with the results from published literature, and the strain-based criteria for liquefaction initiation are reviewed.

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sand; simple shear; liquefaction; laboratory; reconstitution; moist tamping; air pluviation; water sedimentation; sand densification

Introduction

Sand shear strength characterization

Soil strength characterization is important for civil engineering designs, and typically requires obtaining high-quality samples for laboratory testing. While undisturbed cohesive soil samples can be easily obtained by typical conventional tube sampling methods, it is very difficult to retrieve cohesionless (sand) samples from field since there is no cohesion to hold the particles together after removing the confining stresses provided by the ground. Moreover, the dynamic behaviour of saturated sand is important for evaluating the potential of liquefaction initiation at a given sand-deposited site. To acquire and advance the understanding of the fundamentals of sand behaviour and calibrate constitutive models for numerical analysis, conducting element-level laboratory sand tests is essential.

Ground freezing methods allow for recovering undisturbed sand samples, but they are extremely expensive. A few site investigation projects (Robertson et al. 2000; Ghionna and Porcino 2006) were launched in the past by utilizing ground freezing technique to retrieve undisturbed sand samples, but they are very rare due to the high cost. Gel-Push method (Taylor, Cubrinovski, and Haycock 2012; Umehara et al. 2015) reduces the cost of retrieving undisturbed sand samples but this technique still remains as an emerging technique. Because of the constraints, sand specimens are commonly prepared by the reconstitution of representative samples of sandy soils collected from fields for the purposes of both practice and research.

Triaxial and simple shear tests

Distinct types of boundary conditions and loading mechanisms (i.e. stress paths) provide different strengths of soil. For example, the bearing capacity that can be depicted as a circular slip surface underneath an embankment is composed of a combination of compression, simple shear, and extension type of loading mechanism. Therefore, several types of laboratory testing are designated to provide the required stress path. Triaxial testing can simulate the compression and extension loading for a soil element, and Direct Simple Shear (DSS) can simulate the shear mechanism. Moreover, for assessment of liquefaction resistance, Cyclic DSS is preferred to Cyclic Triaxial test, because the simple shear mechanism allows the principal stress axes to rotate smoothly during cyclic loading, which displays a better simulation of upward propagating shear waves generated from earthquakes (Boulanger et al. 1993). On the other hand, the principal axes instantaneously rotate 90 degrees upon loading reversal in Cyclic Triaxial test. This paper focuses on simple shear testing so only the background of simple shear testing is mentioned in the following.

The requirements for simple shear testing are uniform strains along the height of the specimen, and plane strain (no strains in the plane perpendicular to the direction of shear loading), which are both typically achieved by rigid lateral confinement. Latex membrane reinforced with a spiral winding of wire or Stacked Rings are commonly used for lateral confinement. (Roscoe 1953) has proven that the shear stresses at the specimen's top and bottom could be non-uniform during the shearing stage. The non-uniformity is severe at the edges and can be explained by the

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lack of complimentary shear stresses on the sides. While the shear stress is horizontally applied from the top or bottom platen, the smooth inner surface of latex membrane cannot impose a vertically balanced shear stress at the sides. The imbalance in forces creates a tendency for soil specimens to tilt in monotonic loading or rock in cyclic loading. The rocking problem can be minimized by using a larger diameter to height (*D/H*) ratio of specimen. (Amer et al. 1987) compared saturated DSS sand specimens with *D/H* ratios ranging from 3 to 12 and found comparable results. (ASTM D6528-17, 2017) requires simple shear specimens of a *D/H* ratio of at least 2.5. Many research projects (Boulanger et al.1993; Kammerer, Pestana, and Seed 2002; Hazirbaba 2005; Rutherford 2012; Kwan 2015) adopt a *D/H* ratio of four for Cyclic Simple Shear (CSS) liquefaction research studies. The specimen *D/H* ratio is one of the key differences in preparing triaxial verse simple shear specimens. On the other hand, for triaxial testing, (ASTM D4767-11, 2011) requires specimen to have a *D/H* ratio of 0.4 to 0.5 to avoid effects of buckling (too tall) and end plates (too short).

This paper discusses the techniques for reconstituting sand specimens specifically used for simple shear testing. There are many studies on sand reconstitution method for triaxial specimens, but one is missing for simple shear set-up. In the author's opinion, there are two reasons to explain this situation. First, it is generally believed that reconstituting a simple shear sand specimen is not different from a triaxial one since both represent a soil element. Nevertheless, this research project points out that the specimen *D/H* ratio does matter when reconstituting simple shear or triaxial specimens. Second, triaxial apparatus is more commonly available than that for simple shear. Therefore, previous studies in this subject are predominately investigated through triaxial testing.

Sand specimen reconstitution methods

Among the many different reconstitution methods available, this paper only discusses three main types: Air Pluviation (AP), Wet Sedimentation (WP), and Moist Tamping (MT). These three methods are selected because they are commonly adopted in both research and practice, and do not require complicated and custom-made parts such as a vacuum chamber (Kildalen and Stenhamar 1977) and mechanical pluviator (Gade and Dasaka 2016). From the standpoint of reconstituting triaxial sand specimens (before data interpretation), Table 1 summarizes the pros and cons of each method. Figure 1 depicts each method, and general procedures for creating a triaxial sand specimen are summarized in the following.

Table 1. Comparison of the three popular sand reconstitution methods.

	Pro	Cons
Air pluviation (AP)	• Simple to prepare • No fine separation • Can achieve a wide range of density	• Sensitive to drop height • Large particles migrate to the specimen edge during taping
Water sedimentation (WS)	• Simulate the natural sedimentation process • Achieve better saturation without an extra stage of CO_2 flushing	• Fine separation • Heavy particles sediment faster than lighter particles
Moist tamping (MT)	• Simple to prepare • No fine separation • Good density control • Can achieve a wide range of density	• Apply high stresses • Layer formation

Air pluviation (AP)

Sandy soil particles are placed with a funnel that is initially placed at the bottom of a split mould. Then, the funnel is slowly raised, and the sand particles are deposited with very small drop heights to form very loose specimens (generally relative density, D_r ~ 30% or less). If a denser specimen is desired, vibration can be applied by tapping the split mould in a symmetrical pattern. The deposition and tapping procedures can be performed up to seven layers (the number of layer increases with desired density), and typically allows creating sand specimens up to 85% D_r without excessive effort of tapping.

Wet sedimentation (WS)

This method is generally similar to AP, except that the processes of deposition and tapping are performed under water. Firstly, place sand particles in a volumetric flask with water; then saturate the sand–water solution by either boiling or applying vacuum. The flask is then inverted and lowered to the bottom of the split mould and raised up slowly while sand–water mixture is syphoned under water. Fine sand that is lighter than water suspend in the volumetric flask to cause separation, and therefore, this method only works for reconstituting clean sand. Like the procedures of AP, soil specimens can be tapped along the split mould to achieve desired relative density for triaxial specimens.

Moist tamping (MT)

Dry sand is initially mixed with water that represents 3 to 6% water content of the specimen. Then, the moist coarse-grained sand is compacted (or tamped) into four to seven layers inside a split mould. Each layer is compacted into a designated portion of the required dry unit weight of the specimen using a method of 'undercompaction', which considers the factor that the bottom layers also absorb the tamping efforts from the layers above (Ladd 1978).

Literature review in the effects of different preparation methods

Many past experimental research projects show that the stress–strain behaviour of sand highly depends on its reconstitution method. Different methods provide different fabrics of sand (the orientation of the contacts between sand grains), which is the primary reason for the observed differences in the stress–stain curves.

(Mulilis et al. 1977) studied the effects of different preparation methods through a cyclic triaxial programme on clean sand, Monterey Sand No. 0. They studied the effects of different methods (Vibration, Tamping, and Pluviation) at various vibration frequencies and numbers of layer construction. The authors conclude that the following factors are crucial to resistance to sand liquefaction: preparation method, number of layers and frequency of vibrations. The major concern for the WS method is fine separation.

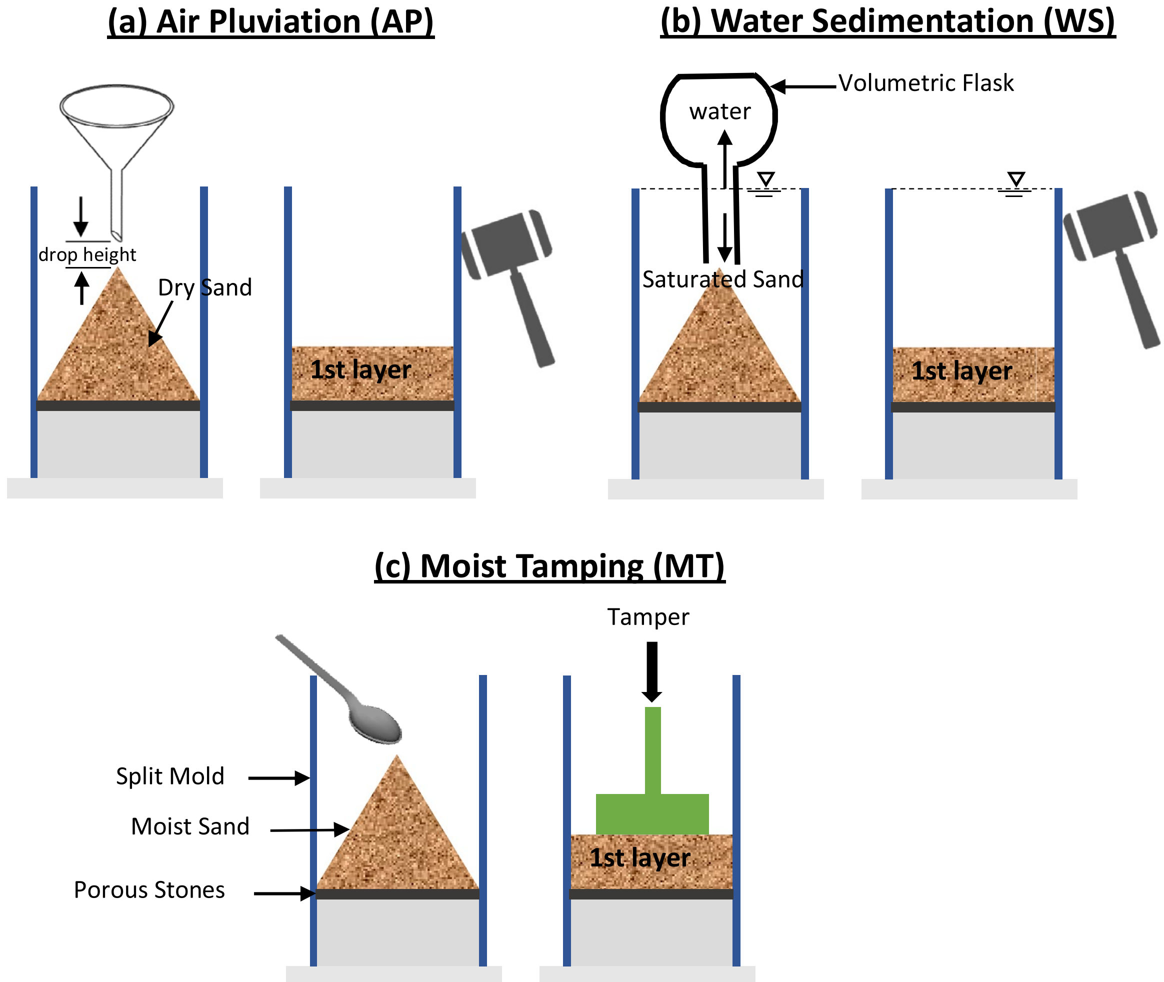

Figure 1. Schematic diagram showing sand reconstitution methods for triaxial testing: (a) Air Pluviation (AP); (b) Water Sedimentation (WS); (c) Moist Tamping (MT).

(Vaid, Sivathayalan, and Stedman 1999) compared the stress–strain sand behaviour from AP, WS, and MT reconstituted Fraser sand specimens with undisturbed samples that were retrieved by ground-freezing method through simple shear and triaxial testing. The study concluded that WS specimens provide the closest response when compared with undisturbed samples.

(Høeg, Dyvik, and Sandbækken 2000) compared undisturbed silty sand specimens (Triaxial) with those reconstituted by MT and WS methods and concluded that WS method likely provides the most promising results. The paper also mentions that the laboratory results from reconstituted specimens on silt and silty sand should not be used in the design analyses of associated engineering projects, because the engineering evaluations were changed significantly when results from reconstituted specimens were used instead of results from undisturbed specimens.

(Wood, Yamamuro, and Lade 2008) tested on Nevada 50/200 sand containing 10–40% of silts with several types of reconstitution methods: AP, WS, Slurry Deposition, and Mixed Dry Deposition. The authors concluded that undrained triaxial tests performed on specimens with high densities reveal no significant effects on depositional method. Medium densities indicated significant differences. Specimens formed by Water Sedimentation exhibited stable behaviour while those formed by AP in some cases underwent temporary liquefaction.

(Ghionna and Porcino 2006) documented a study that compares reconstituted sand and gravels samples with undisturbed ones collected by ground freezing methods. The reconstituted methods used were AP and WS, and the authors concluded that WS closely replicates the *in situ* fabric of the investigated deposit.

(Frost and Park 2003) critically assessed the MT method, and pointed out that the vertical stresses applied by tamping can be higher than the typical confining stresses in triaxial testing. Also, the bottom layer on top of the rigid bottom platen experiences greater compaction force than the layer above it.

In summary, through the past studies, including a few that were able to retrieve undisturbed sand samples, reconstituted WS sand specimens show closer stress–strain response to natural fabric than AP and MT methods. Therefore, the experimental study described in this paper focuses on WS method. Nevertheless, the results from reconstituted sand specimens should always be treated with great care because none of them can perfectly reflect the natural fabric of a sand deposit.

Undrained cyclic simple shear testing programme

An undrained CSS testing programme (Table 2) was set up to search for and investigate the optimal ways of reconstituting sand specimens through the WS method and was performed at the

Table 2. CSS testing programme for investigations of optimal procedures reconstituting sand specimen through the water sedimentation method at two different densities.

Test No.	Reconstitution Method	D_r (%)	CSR	Test No.	Reconstitution Method	D_r (%)	CSR
1	WS	74	0.159	9	WS-M1	73	0.230
2	WS	73	0.150	10	WS-M1	71	0.177
3	WS	73	0.149	11	WS-M1	69	0.176
4	WS	65	0.174	12	WS-M2	65	0.228
5	WSS	49	0.176	13	WS-M2	65	0.176
6	WSS	39	0.200	14	WS-M2	81	0.125
7	WSS	41	0.226	15	WS-M3	76	0.259
8	WSS	44	0.101	16	WS-M3	74	0.207
				17	WS-M3	77	0.202
				18	WS-M3	82	0.152
				19	WS-M3	73	0.125
				20	WS-M4	85	0.152
				21	WS-M4	85	0.202
				23	WS-M4	79	0.304
				24	WS-M4	78	0.350

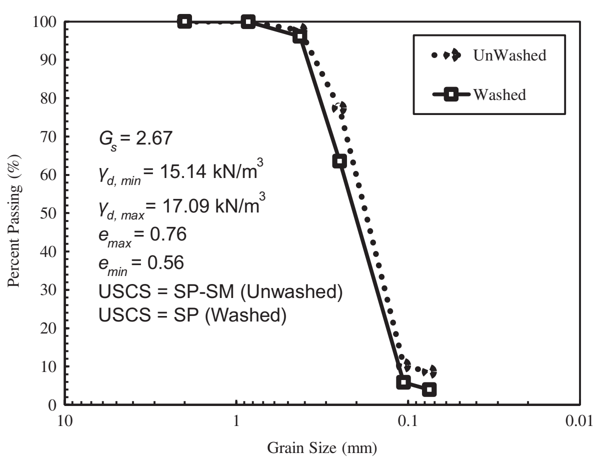

Figure 2. Grain size distribution curves and sand properties for tested Nevada Sand, before and after pluviation (Kwan 2015).

University of Texas at Austin using the modified Geotechnical Consulting and Testing System (GCTS) manufactured CSS apparatus. The WS procedures discussed above are adopted for reconstituting triaxial specimens. The experimental research programme introduced here focuses on undrained simple shear configuration. Liquefaction resistance curves (Cyclic Stress Ratio, *CSR* vs. No. of cycle reaching liquefaction initiation, N_f) are used to assess the performance of proposed reconstitution procedures. *CSR* is defined as the applied amplitude of applied shear stress normalized by the initial vertical initial effective stress, σ'_{vo}. An ideal reconstitution procedure should able to generate consistent liquefaction resistance curves reflecting the effect of soil density.

For this testing programme, Nevada sand was tested, and the sand properties are summarized in Figure 1. The Nevada sand used in this testing programme is a fine, uniform (C_u = 2), and angular sand with the mean grain size of 0.2 mm (Figure 2). All reconstituted specimens were about 1-inch high and of 4-inch diameter and consolidated to 100 kPa vertical effective stress before subjected to undrained cyclic loadings. More details about the testing apparatus can be found in (Kwan 2015; Kwan et al. 2017).

Procedure for reconstituting specimens with loose to medium relative density

Reconstituting uniformly loose specimens in simple shear set-ups is more challenging than in triaxial set-ups because of the larger cross-sectional area of simple shear specimens. To create tall and long triaxial specimens, the sand–water mixture is syphoned by raising the inverted volumetric flask along the axis of symmetry of the centre of specimen. This procedure can promisingly reconstitute a specimen with uniform density throughout its length. However, for short and wide simple shear specimens, the deposition process requires going around the specimen area in circles while raising up the inverted volumetric flask, and therefore it is harder to maintain a constant drop height necessarily to provide uniformity. To address this shortcoming, an additional screen procedure (modified after Kammerer, Pestana, and Seed 2002) can improve the sand–water mixture syphoning process. A screen with a diameter slightly less than the soil specimen of which the opening is slightly larger than the size of the largest grain was placed at the bottom of the split mould under water prior to placement of the sand. After syphoning the saturated sand, the screen was then pulled up slowly to drain the sand particles through the screen opening with a constant drop height (Figure 3).

To investigate into the effects of an additional screening procedure, three specimens were reconstituted with typical WS procedure, and compared with four CSS specimens that went through an additional screening procedure after sand–water syphoning (hereby WSS). All seven tests (with and without additional screening) were subjected to various undrained cyclic loading. For the tested Nevada sand and syphoning at almost zero drop height, the typical WS procedure reconstituted sand specimens at a D_r range of 60 to 70%, while WSS produced specimens of a D_r range of 40%. Figure 4 summarizes the test results in a semi-log plot of *CSR* vs. N_f, where liquefaction initiation is defined as the excess pore pressure ratio equal to unity (excess pore pressure equals to σ'_{vo}). Even with a lower D_r range, the WSS specimens show stronger resistance to liquefaction than WS specimens, which implies that WS specimens' density was non-uniform. Since the syphoning process requires going around in a circular pattern to cover the large area, it gives a high potential on syphoning under inconsistence drop heights. This renders a global density that falsely represents the soil specimen. Yet, this screen procedure is not ideal for triaxial specimen because of the smaller *D/H* ratio.

Procedure for reconstituting specimens with dense to very dense relative density

Densification of sand is usually achieved by some forms of vibration, and the most typical method in reconstituting triaxial specimens is by tapping along the side of split mould (longer dimension). Tapping must be performed at the larger dimension (i.e. along the specimen height for triaxial specimen; and along diameter face for simple shear specimen) so that the vibration provided by tapping can penetrate through the entire specimen. Otherwise, only the portion of sand near the edge is densified, but the centre part remains loose. For creating WS specimens, drainage is also important while vibration is being applied. Drainage is

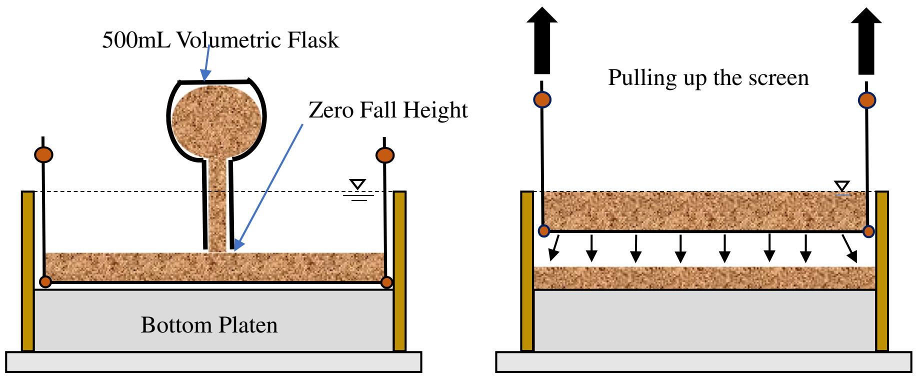

Figure 3. Picture on the left shows the soil syphoning; picture on the right shows the screen procedure afterward. The soil particles rain through the screen (Kwan 2015). This method allows to reconstitute simple shear sand specimen with relative density of loose to medium.

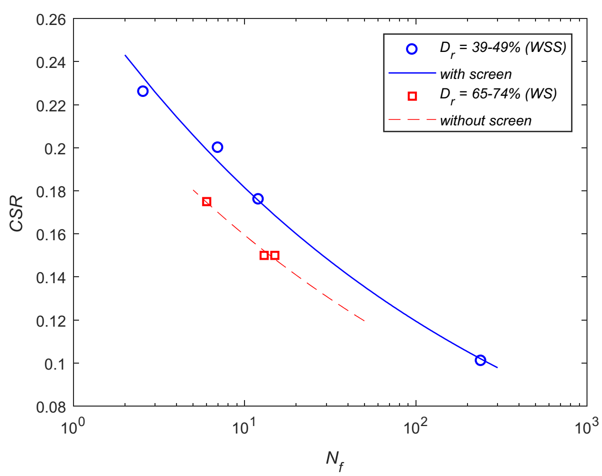

Figure 4. Illustration of 'Surface vibration with two layers (WS-MP4)' preparation procedure (Kwan 2015). This method allows to reconstitute simple shear sand specimen with relative density of dense to very dense.

needed to dissipate the excess pore pressure induced by vibration, so the sand particles can rearrange into denser configurations. To vibrate (tap) a simple shear specimen reconstituted by WS method, one feasible way is to tap the underside face of bottom platen after syphoning sand–water mixture and before placing the top platen (Kammerer, Pestana, and Seed 2002). In such way, the applied vibration can penetrate the specimens through the shorter dimension and induced excess pore pressure can be dissipated through the open face at the top of specimen. However, this method only works if the underside face of the bottom platen is accessible. For some simple shear apparatus, the bottom platen required to be mounted on the shaking table before pluviation, and therefore tapping cannot be applied.

The CSS apparatus used in this study does not allow access to the underside face of the bottom platen after sand syphoning. The experimental programme investigated into four different densification methods following typical WS procedure. Table 3 describes the methods and comments on the performance of each method. Method 1 utilizes the shear actuator to provide vibrations; however, there is a lack of channel for excess pore pressure dissipation. Method 2 densifies the sand specimen by tapping the side of split mould (like the tapping procedure of triaxial specimens); however, tapping the longer dimension (horizontal direction) does not allow the vibration to penetrate the four-inch specimens thoroughly and uniformly. Method 3 provides vibration vertically (i.e. shorter direction) using an inverted small vibratory table, and meanwhile, allows excess pore pressure to dissipate through a simple custom-made plate, which contains small holes for drainage as shown in Figure 5. Method 4 is very similar to Method 3 but requires two layers of reconstitution. After syphoning half of the designated soil mass by the WS procedures, vertical vibration is applied as in Method 3. The same procedure is repeated for the second layer.

Figure 6 shows the CSS test results from all different densification methods (D_r = 65 to 85%) and are compared with the results of those with relative density of loose to medium specimens (reconstituted by WSS method, D_r = 39 to 49%). The test results show that Method 4, 'surface vibration with two layers', provides a significantly higher resistance than the loose sand curve, which is an indication that it effectively densifies the sand. On the other hand, the other three methods produce specimens with only a slightly higher resistance than the loose samples, which indicates that the applied vibration could not uniformly penetrate the whole sample.

Data analysis and discussion

Liquefaction initiation criteria

Liquefaction initiation is commonly defined as the generated excess pore pressure (Δu) is equal to (100% of) the initial vertical effective stress σ'_{vo}. Δu can also be expressed as the excess pore pressure ratio (r_u), which is a ratio of $\Delta u/\sigma'_{vo}$. This criterion is theoretically sound because when r_u is very close to unity, the shear strength of the sand becomes almost zero and liquefaction is initiated causing ground failure that is associated with lateral spreading and settlement. However, some past studies show that liquefaction can be initiated at lower r_u values for some circumstances. (Ishihara 1993) reports that the highest achievable r_u values could be levelled out at 0.9 for sandy silts and silty sands. (Kammerer er al., 2004) shows that for simulation of sloping ground condition (K_α effect) using bi-directional simple shear loadings, the maximum r_u value can be limited to 0.7 or less, because the superposed static shear stress suppresses the generation of γ while excessive deformations develop. Moreover, a r_u of 0.95 or greater may not be achievable in very dense sand deposit.

Table 3. Different methods of preparing CSS water-pluviated dense to very dense specimens, Kwan (2015).

Methods	Procedures	Comments/Remarks
[M1] Vibration with the shear actuator under a normal load	First, the sand was syphoned into the mould/membrane. After the top platen was applied (before the split mould was dissembled), a dead weight (5.5 kg) was added on top of it. The specimen was then vibrated by applying a 2 Hz, strain-controlled vibration of 2 mm peak-to-peak amplitude from the shear actuator	With the applied top platen, the sand specimen was vibrating almost at an 'undrained' condition. Since the pore pressure cannot be dissipated, this method cannot densify the sand efficiently
[M2] Tapping on the side of split mould	After depositing sand under water, vibration was applied by tapping the side of the slit mould with a rubber hammer	The vibration cannot penetrate through the longer dimension (4″ Dia). So, the specimen was heavily disturbed at the circular edge, but remained undensified at the centre
[M3] Surface vibration with one layer	A custom device (Figure 5) was created for applying uniform vibration to the sand surface. The device included a metal thread attached to a 3.96″ Dia plastic plate. Holes were drilled on the plastic plate to allow drainage. The device was placed on the top sand surface, and an inverted vibratory table was turned on and attached to the tip of metal thread, to provide vibration to the soil specimen. After the water–sand mixture escaped from the plastic plate drainage holes, the vibratory table was removed. The escaped sand was dried and weighed	The drilled holes on the plastic plate were designed for pore pressures dissipation during vibration. However, this set-up was found to be ineffective, because the vibration could not penetrate the one-inch thickness
[M4] Surface vibration with two layers	The method is like the one above, except reconstituting the soil specimen with two layers. Figure 5 illustrates this preparation method	The ½″ layers allowed vibration to penetrate through the entire thickness, when Δu dissipated through the holes. This method was found to be effective

Shear strain (γ) can also be served as a criteria for accessing liquefaction initiation because it closely relates to pore pressure generation (Ladd et al. 1989). Wu et al. (2004) recommends a single (SA) or double amplitude (DA) shear strain of 6% (here by γ_{DA} = 6%) as the failure criteria of the initiation of flow-type deformation after examination from an uni-directional CSS study on Monterey #0/30 sand. (Ishihara 1993) recommends using 5% DA axial strain (ε_a) after studying many results from cyclic triaxial tests, which correspond to 3.75% SA (hereby γ_{SA} = 3.75%) in simple shear set-up because $\gamma = 1.5\varepsilon_a$. This study utilizes the CSS test data from this study and compares the performances of the two liquefaction triggering criteria. An ideal criterion should provide liquefaction resistance curves at both loose and dense densities that are very close to the ones that are provided by a high r_u range such as 0.8 to 1.0. Figure 7 shows the liquefaction resistance curves (WSS and WS-M4) determined from both criteria of γ_{DA} = 6% and γ_{SA} = 3.75% and compared with liquefaction resistance curves determined from r_u = 0.8, 0.9, and 1.0. Figure 7 provides the following insights:

(1) The comparison shows that the two shear strain criteria provide liquefaction resistance slightly less than the ones determined from r_u = 1.0 and are generally within the ranges of r_u = 0.8 to 1.0, which validates the two liquefaction initiation criteria.

(2) The tail part of the dense liquefaction resistance curves (high density and small CSR values) show that the two shear strain criteria provide liquefaction resistances greater than the one determined from r_u = 1.0. At high density, pore pressure is generated with limited strain (cyclic mobility), and this effect is especially manifested under smaller loading amplitude. Therefore, for the combination of small *CSR* values and high density, the threshold values for liquefaction initiation should be decreased and further investigation is needed.

(3) The liquefaction resistance curves provided by γ_{SA} = 3.75% are slightly higher than those provided by γ_{DA} = 6%.

CSS test data comparison and discussion

The undrained CSS test results obtained from the optimal reconstitution methods (WSS and WS-M4) that are described above are compared with other published undrained CSS test results. Since there are no available test result acquired under the exact testing conditions as this study, three past studies (Arulmoli et al., 1992, Kammerer et al. 2000, and Kammerer et al. 2004) with similar testing conditions are selected for comparison. These three studies have the same conditions of no initial static shear stress (i.e. k_α = 0), no pre-shearing effect, and under uni-directional loading. The stress level of selected tests from the other research projects is similar, about 100 kPa. However, Arulmoli et al. (1992) and Kammerer et al. (2000) adopted AP as the specimen reconstitution method, and Kammerer et al. (2004) tested on Monterey #0/30 sand. Figure 8 compares the results from the four projects (the author's study and other comparable three projects) and summarizes the testing conditions.

For loose to medium density tests (D_r = 30 to 50%), the reconstitution method has the most significant effect on liquefaction

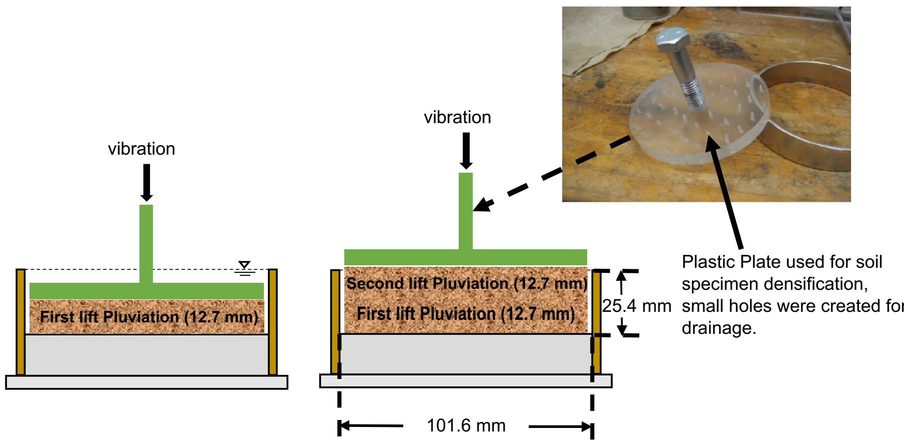

Figure 5. Liquefaction resistance curves from the sand specimens reconstituted by the methods of Water Sedimentation (WS) and Water Sedimentation with Screen (WSS).

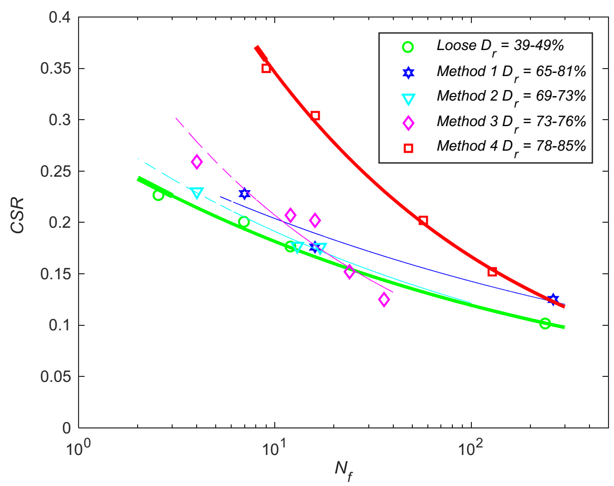

Figure 6. Comparison of four different densification methods for reconstituting water-pluviated sand specimens for Simple Shear testing. The green curve represents test results from specimens reconstituted by water sedimentation with screen (WSS). Descriptions and procedures of each method are listed in Table 3.

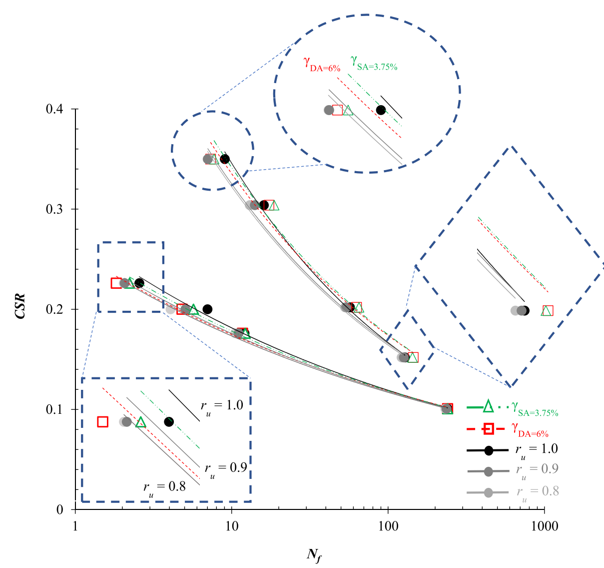

Figure 7. Liquefaction resistance curves obtain from the two initiation criteria: γ_{DA} = 6% and γ_{SA} = 3.75%, and compared with establishments based on r_u of 0.8, 0.9 and 1.0. The CSS data are from specimens that are reconstituted by the WSS and WS-M4 methods.

resistances. The tests reconstituted with WSS method (Kammerer et al. 2004 and Kwan 2015) provide higher liquefaction resistance than those by AP (Arulmoli el al., 1992). Typical WS method creates soil fabric that is more stable than those reconstituted by AP method (Wood, Yamamuro, and Lade 2008), and (Mulilis et al. 1977; Wood, Yamamuro, and Lade 2008) showed experimental results that WS specimens provide higher liquefaction resistance than AP specimens. Despite the differences in sand type (Nevada sand vs. Monterey #0/30 sand), test results from Kwan (2015) agree very well with those from Kammerer et al. (2004). At loose to medium density, reconstitution method provides significant effects in liquefaction resistance, while the effect of mean grain size (D_{50}) could be minor.

For dense to very dense density tests (D_r > 75%), the tests reconstituted with WS-M4 method (Kwan 2015) agree very well with the test with the same sand type (Nevada sand) but was reconstituted by AP method. It implies that the differences in fabric created by AP vs. WS have an insignificant effect in denser density configurations because the sand particles are packed much closer to each other. Wood, Yamamuro, and Lade (2008) also reports that dense specimens show no significant effect of reconstitution method. However, significant differences in terms of liquefaction resistance are found in both Kwan (2015) and Kammerer et al. (2004), which adopted similar WS procedures (WS-M4 and WS with tapping at the bottom face) and a similar vertical effective stress (100 vs. 80 kPa). The key different testing condition between the two studies is the sand type (Nevada vs. Monterey #0/30). While both sand types are very uniform (C_u = 2 and 1.29), Nevada sand is angular with D_{50} = 0.2 mm whereas Monterey #0/30 sand is rounded with D_{50} = 0.36 mm. (Seed & Idriss, 1971) also reports that coarser sand provides higher liquefaction resistance than finer sand. At dense configuration, D_{50} provides significant effect in liquefaction resistance, while the method of reconstitution could be minor.

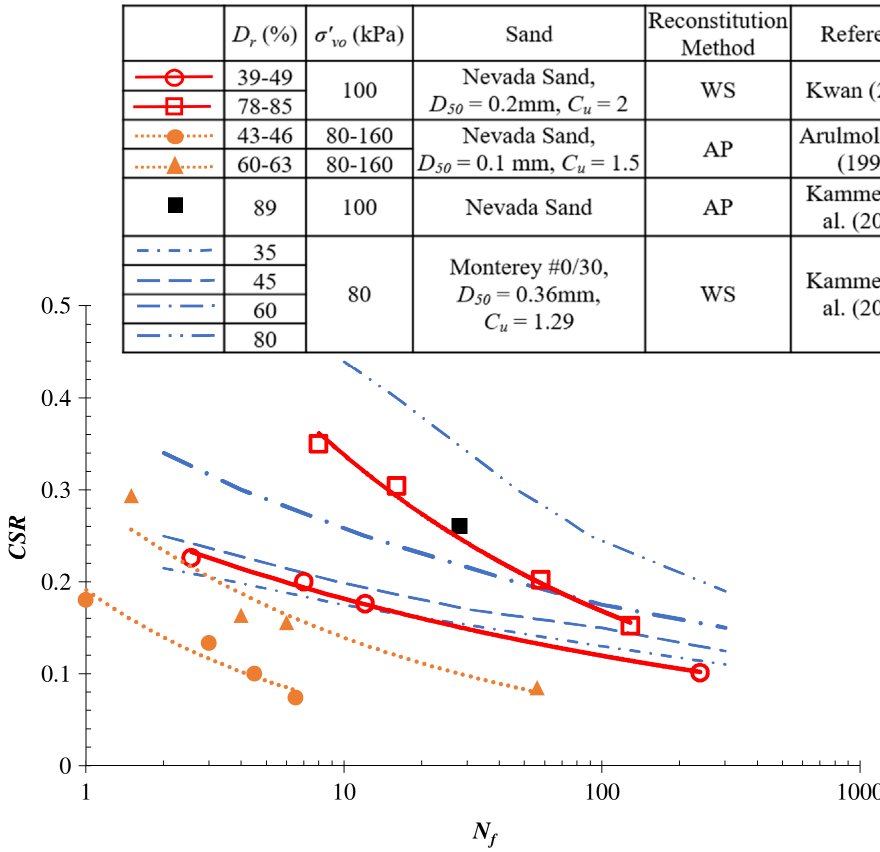

Figure 8. CSS data from reconstitution methods of WSS and WS-M4 compared with other published CSS data (Arulmoli et al.1992 ; Kammerer et al. 2000; and Kammerer et al. 2004). The liquefaction initiation criteria for Kammerer et al. (2004) and Kammerer et al. (2000) is γ_{DA} = 6%, and Kwan (2015) is r_u = 1.0.

Summary and conclusion

Sand specimens are commonly reconstituted in geotechnical laboratories instead of retrieving undisturbed ones. There are a few popular methods available, including (Air Pluviation, Water Sedimentation, and Moist Tamping), and they are briefly reviewed in this paper. Past studies have shown that the water sedimentation methods provide the closest simulation to results from undisturbed granular sand specimens retrieved from ground freezing techniques. Nevertheless, the typical reconstitution methods are set up for Triaxial specimens, and there is no evaluation on these procedures when applying to simple shear specimens, which have a very different diameter to height ratio.

Through an undrained CSS testing programme, two optimum reconstitution procedures for sand specimens, 'Water Sedimentation with Screen (WSS)', and 'Vertical Surface Vibration with Two Layers (WS-M4)' are established, and the results are compared with other published CSS data that have similar testing conditions. The results show general agreements, and the discrepancies are due to different testing conditions. Reconstitution method is the major factor that affects liquefaction resistance for low density tests, and mean grain size is the major factor for high density tests. Moreover, the performance of two popular strain-based liquefaction initiation criteria, 6% shear strain double amplitude and 3.75% shear strain single amplitude were evaluated. In terms of liquefaction resistance curve, the two criteria generally agree with those developed from high excess pore pressure (r_u = 0.8 to 1.0), except that when the amplitude loading is small (*CSR* < 0.2) and relative density is high (dense to very dense).

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