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UNDISTURBED SAMPLING AND LABORATORY SHEARING TESTS ON A SAND WITH VARIOUS FINES CONTENTS

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ABSTRACT

The effects of plastic or non-plastic fines on the static and cyclic strength of sand have been a subject of laboratory studies for many decades. These studies have not lead to a concensus as to how fines can affect the behavior of sand. Earlier studies have mostly been limited to tests on reconstituted specimens. Some of the controversies stem from the concerns that reconstituted specimens may not be able to duplicate the soil fabric in the field. The authors used Laval sampler to retrieve high quality samples with a wide range of fines contents in Central Western Taiwan. A test site was developed in Yuan Lin Township where standard penetration test (SPT), seismic piezocone (SCPTU) and field shear wave velocity (V_s) measurements were performed in addition to Laval sampling. A series of monotonic and cyclic triaxial tests with V_s measurements were conducted on natural and reconstituted Yuan Lin Soil (YLS) specimens with fines contents ranging from 18 to 89%. While the study confirmed some of the earlier findings which indicated that fines tend to weaken the soil specimens, the results also showed that the effects of fines may be exaggerated according to tests on reconstituted specimens.

Key words: alluvial deposit, dilatancy, laboratory test, sampling, sand, shear strength (**IGC**: B11/C6/D6/D7)

INTRODUCTION

Studies on the behavior of granular material have been biased towards the clean, uniformly graded sands. Natural sands often contain various amounts of fines (particles passing #200 sieve). Experience shows that mineral contents, grain shapes and plasticity of the fines are important contributing factors to the monotonic or cyclic behavior of sand that contains fines (Ishihara, 1993; Lade et al., 1998). Available studies on the effects of plastic or non-plastic fines on the behavior of sand have mostly been based on reconstituted specimens. These studies have not lead to a consensus as to whether fines can increase or decrease the undrained strength or cyclic resistance of sand (Polito, 1999). In addition to mineral contents as pointed out by Ishihara (1993), the controversies may arise from the method of specimen preparation (Vaid et al., 1999; Yamamuro and Wood, 2004). Høeg et al. (2000) demonstrated, using undisturbed samples taken in shallow depths, that there could be significant differences in undrained shear strengths between the undisturbed and reconstituted silty soil specimens. The reconstituted specimens showed a low peak strength and very brittle behavior while the undisturbed specimens, even with significantly higher void ratios, had a dilative behavior. Recognizing the potential limitations, the existing studies have mostly been focused on relative comparisons amongst reconstituted sand specimens with fines, in terms of strengths (Polito, 1999; Salgado et al., 2000; Thevanayagam et al., 2002), density states (Lade et al., 1998) and microstructures (Yamamuro and Wood, 2004). Some of the commonly used methods in reconstituting silty sand specimens include moist tamping (MT) and water sedimentation (WS).

The Chi Chi earthquake ($M_L = 7.3$, $M_W = 7.6$) of September 21, 1999 triggered extensive soil liquefaction in Central Western Taiwan. The majority of the sand deposit in this region was relatively compressible and had significant amounts of low to medium plastic fines (Huang et al., 1999, 2004). When performing back analysis of sand liquefaction potential in this region, the selection of field test method, its cyclic resistance ratio (CRR) correlation and the associated fines content corrections could lead to significantly different results (Huang et al., 2003, 2005), under the framework of simplified liquefaction potential assessment procedure (Youd et al., 2001). In order to provide a basis for validating the simplified liquefaction potential assessment procedure, it would be highly desirable to first establish an understanding of how the fines affect the undrained stress-strain and strength relationships of the silty material in this region. Judging from the earlier experiences, such a study should preferably be performed on undisturbed samples.

Taking undisturbed or high quality samples in low cohesion soils has always been a difficult task. The available reports on the undisturbed sampling in clean sand below

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ground water table have mostly been limited to the ground freezing method (Yoshimi et al., 1994; Hofmann, 1997). By freezing the ground water, the sand particles and their matrix were fixed in the frozen ground. The sand samples were taken by coring and remained frozen until laboratory shearing test. Experience has indicated that the CRR of undisturbed specimens taken by ground freezing method can be significantly higher than that of reconstituted specimens with similar densities (Tokimatsu and Hosaka, 1986; Ishihara, 1993). The magnitude of CRR reduction increases as the sand becomes looser (Seed et al., 1982) and thus more difficult to keep the natural specimens intact. The process of ground freezing however, is time consuming and prohibitively expensive. Høeg et al. (2000) had limited success in their attempt to obtain natural silt samples at 3 m below ground surface. A 50 mm inside diameter Swedish Geotechnical Institute piston sampler was used to take the silt samples under ambient temperature, in the capillary zone right above the ground water table. To retrieve undisturbed silty sand mine tailings samples at 2.5 m below ground surface, Høeg et al. (2000) pushed a 260 mm long, 73 mm diameter tube sampler by hand in a test pit. The vibration during transportation and specimen extrusion from the sampling tube can cause disturbance to the silty soil samples as indicated by Høeg et al. (2000). Konrad et al. (1995) reported their success in obtaining undisturbed sand samples using Laval sampler, from below the ground water table without freezing. A 200 mm diameter and 500 mm high sample can be obtained with the Laval sampler. In order to prevent soil structure damage during transportation for low cohesion sand, Konrad et al. (1995) developed a method to freeze the Laval sample above ground.

The main objective of the study to be presented herein is to evaluate the effects of fines on the undrained strength of the alluvial material typically found in Central Western Taiwan under monotonic and cyclic loading conditions. The alluvial material in this region may consist of silty fine sand (SM), clayey sand (SC), silt (ML) and silty clay (CL). A test site was developed for the study where a series of in situ tests were conducted and Laval samples taken at selected depths from 3 to 12 m below the ground surface. The in situ tests included standard penetration tests (SPT), seismic cone penetration tests with pore pressure measurement (SCPTU) and P-S logging tests. The target depths of Laval samples were selected according to the tests on SPT split spoon samples so that soil samples with low (less than 20%), medium (close to 50%) and high (close to 90%) fines contents could be retrieved. The Laval samples of low fines content were frozen above ground following the procedure reported by Konrad et al. (1995). The rest of the Laval samples were extruded from the sampling tube in the field, wrapped by plastic film and wax before transporting to the laboratory. Monotonic and cyclic triaxial tests were performed on undisturbed and reconstituted soil specimens. The shear wave velocity (V_s) of all the triaxial specimens was measured using the bender elements. The in situ test results and V_s measurements can also be used to validate the correlations between CRR and SPT blow counts (N value), CPT cone tip resistance (q_c) and V_s taken in the field as well as laboratory. However, because of the limited range of densities for the tests presented in this paper, correlations among CRR, N, q_c and V_s for the undisturbed silty sand will not be discussed herein. Only the monotonic and cyclic triaxial test results will be presented in this paper.

FIELD TESTING AND SAMPLING PROGRAM

The test site was located in Yuan Lin Township of Chang Hua County, approximately 20 km west of the epicenter of Chi Chi earthquake. The boreholes and other in situ test locations were distributed within a diameter of 10 m as shown in Fig. 1. The ground water table was at 2.6 m deep at the time of field testing/sampling. Three 20 m deep, SPT profiles (SPT-1 to SPT-3) were performed with three different types of hammers and all with energy efficiency measurements. Figure 2 describes the profiles of N values (blow counts for 30 cm penetration of the split spoon sampler driven by a 63.5 kg hammer falling 760 mm), fines contents (FC), water contents (w), and energy efficiency from the SPT. The SPT and the following SCPTU data have indicated a rather uniform soil condition within the tested area. The fines contents of the tested soil ranged from less than 10% to almost 100%. Figure 3 depicts natural w versus liquid limit (L.L.) from the SPT samples taken below the ground water table against the Chinese criteria (Perlea, 2000). The result showed that in most cases the SPT samples had their w higher than the corresponding L.L. and fell in the potentially liquefiable criteria. Another implication is that the soil tends to be sensitive and difficult to sample with a regular tube or piston sampler. The SCPTU profiles (SCPTU-a to SCPTU-c) shown in Fig. 4 include q_c, friction ratio (R_f), pore pressure measurement behind the cone face (U_2), V_s and soil behavior index (I_C). Both the SPT and SCPTU showed loose or soft soil layers

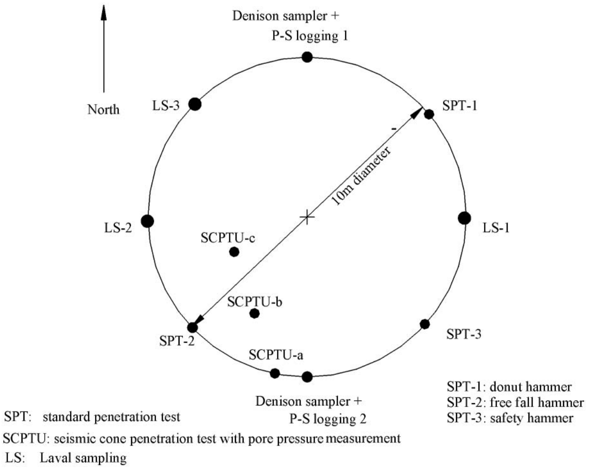


Fig. 1. **Distribution of boreholes and test locations at Yuan Lin test site**

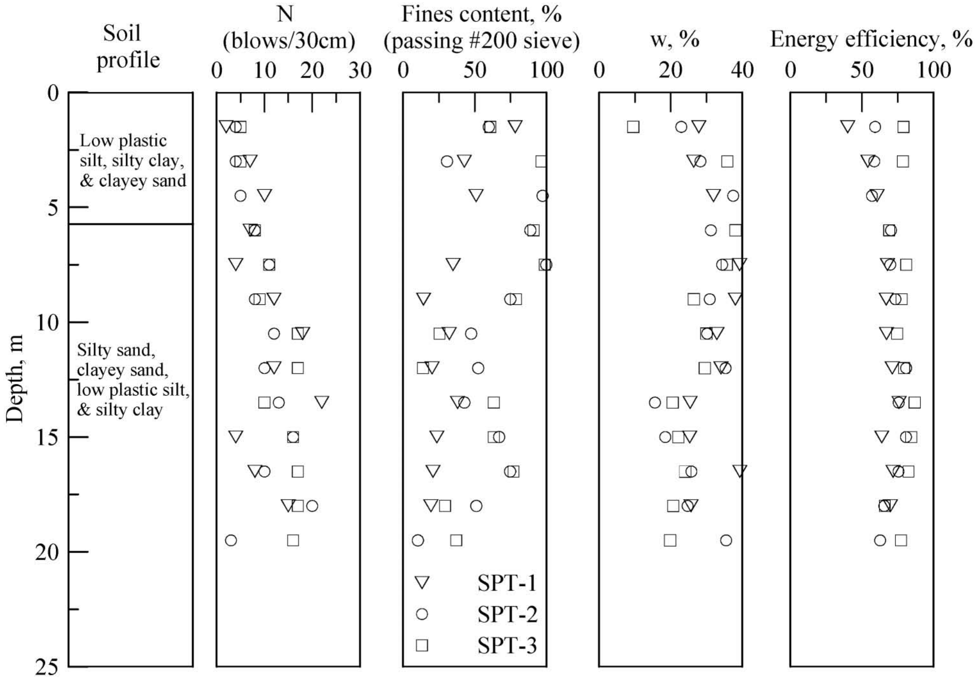


Fig. 2. Soil profile and SPT test results from the Yuan Lin test site

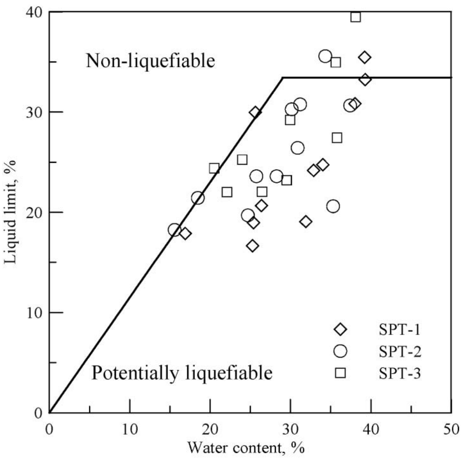


Fig. 3. Water content comparison with the Chinese criteria

within 10 m depth. Following the in situ penetration tests and sieve analysis on the split spoon samples, the depths of Lava samples were selected in three boreholes (LS-1 to LS-3) in an attempt to retrieve samples with three different levels of fines contents as previously described. The depth selections of the Laval samples are summarized in Table 1. The fines content, plastic limit (P.L.), L.L. and group symbol in Table 1 are according to tests on the Laval samples.

The original plan also included taking 70 mm diameter Denison samples, but was not successful. The Denison sample boreholes were then extended to 20 m deep, and lined with a plastic casing where in situ V_s measurements were made using a P-S logging device (*see* Fig. 1).

LAVAL SAMPLING AND FIELD PACKAGING PROCEDURE

A Longyear 38 drill rig was used to prepare the borehole and operate the Laval sampler. The boreholes were extended by a 330 mm diameter fishtail device. The soil cuttings were removed with a mud flow that consisted of a mixture of bentonite and barite. The density of the drill mud was maintained between 1.1 and 1.3 times that of water. After reaching the sampling depth, the fishtail device was removed from the borehole to give room for the Laval sampler. The Laval sampler as schematically described in Fig. 5 was developed at Laval University (La Rochelle et al., 1981), originally for taking high quality samples in sensitive clay. The sampler is made of two main parts; a sampling tube and an overcoring tube. To take a sample, the drill rig pushes the sampling tube into the bottom of the borehole while rotating the overcoring tube. The steel teeth and cutters were located at 20 mm behind the bottom of the sampling tube. During penetration, the head valve was kept open to allow drill mud circulation and thus removal of soil cuttings. The Laval sample can be 450 to 550 mm long. After a waiting period of 5 to 30 minutes, the head valve was closed and the bottom of the sample sheared by rotating the inner rod. The sample was then retrieved to the ground surface.

Samples taken from soil layers expected to have medium or high fines contents (sample numbers 1 and 2 in Table 1) were extruded on site. The sample was cut with a wire saw into 120 to 180 mm long segments and placed on a pre-waxed wooden board. The sample along with the wooden board was then wrapped in three layers of wax and two layers of plastic film. The sealed samples were kept in a moisturized container during transportation and

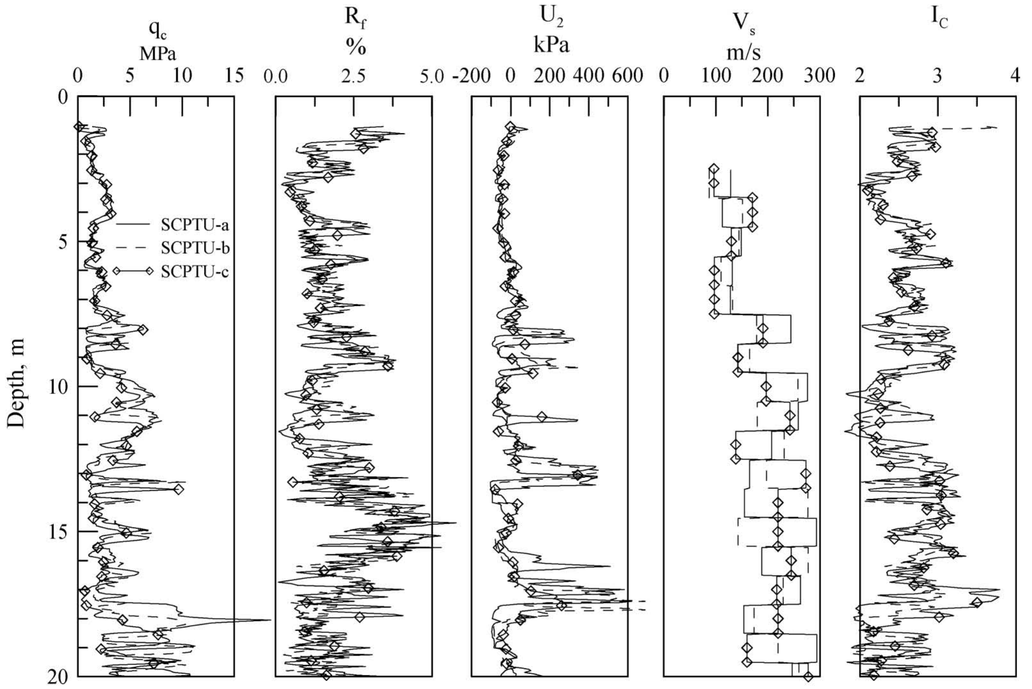


Fig. 4. Profiles of SCPTU at the Yuan Lin test site

Table 1. Summary of Laval samples

Bore hole number	LS-1			LS-2			LS-3		
Sample number	1	2	3	1	2	3	1	2	3
Depth, m	3.32–3.80	6.05–6.29	10.80–11.25	3.51–4.05	9.00–9.46	10.85–11.38	3.62–4.13	5.90–6.41	10.98–11.40
Fines content, %	43	91	20	31	75	48	43	89	18
L.L.	21	40	25	24	26	22	21	31	25
P.L.	14	28	14	12	16	8	14	19	14
Group symbol	SM-SC	ML	SC	SC	CL	SC	SM-SC	CL	SC

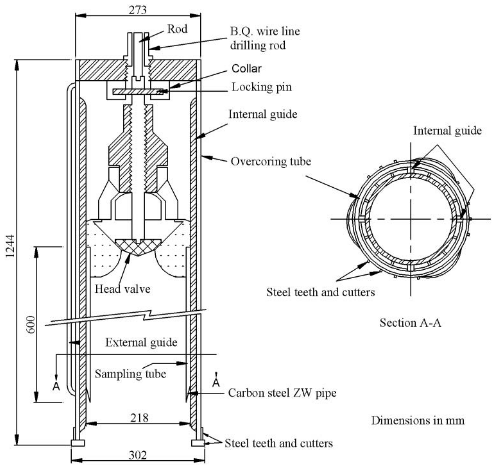


Fig. 5. Schematic view of the Laval sampler (after La Rochelle et al., 1981)

laboratory storage.

The samples taken from soil layers expected to have low fines contents (sample number 3 in Table 1) remained in the sampling tube and kept vertical until it was completely frozen. A procedure referred to as the unidirectional freezing reported by Konrad et al. (1995) was followed to solidify the sample without causing volume change. The soil along with the sampling tube was placed in a Styrofoam lined wooden box and gradually frozen from top of the sample by dry ice at −80°C. A backpressure equal to the water head within the sample was applied by means of a nylon tubing connected to the bottom of the sample to ensure that no water can drain under gravity. The bottom drainage and backpressure assured pore water drainage only due to water volume expansion during freezing. The amount of expelled water and temperature at the bottom of the soil sample were monitored as the freezing progressed. The freezing process took 15 to 24 hours, upon which the temperature at the bottom reached below 0°C. Figure 6 depicts a record of time ver-

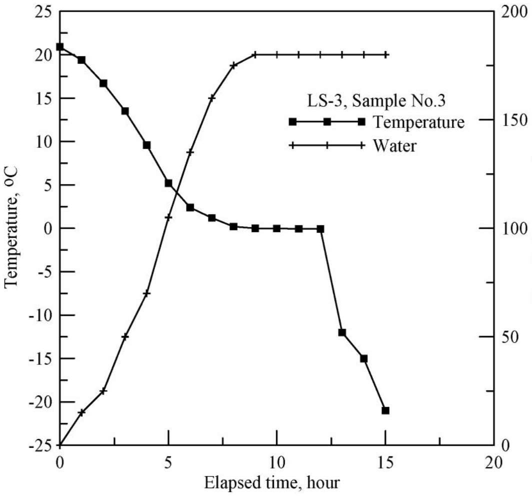
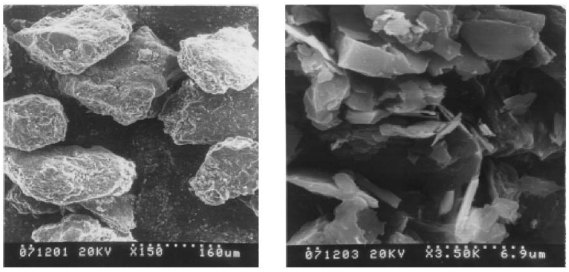


Fig. 6. Water volume expelled and temperature variation with time



Coarse (retained on #200 sieve) Fine (passing #200 sieve)

Fig. 7. SEM photos of the YLS particles

Table 2. Physical properties of the selected Laval samples

Borehole	Sample No.	Depth, m	G_s	FC, %	Sample	e_{min}	e_{max}
LS-1	1	3.32–3.80	2.73	43	LS	0.86	1.27
					WS		
					MT		
LS-3	2	5.90–6.41	2.75	89	LS	1.01	1.69
					WS		
					MT		
LS-3	3	10.98–11.40	2.71	18	LS	0.85	1.29
					WS		
					MT		

LS : Laval sample
MT: Reconstituted specimen by moist tamping
WS: Reconstituted specimen by water sedimentation

sus expelled water volume and temperature measured at the bottom of soil sample No. 3 of LS-3. The same sample was later used for the tests to be reported in this paper. The frozen samples were stored in a freezer during shipping and laboratory storage until the time of shearing test.

GEOLOGICAL ORIGIN AND PHYSICAL PROPERTIES OF YUAN LIN SOIL

The soil deposits in Yuan Lin area are of Holocene age originated from the central mountain range that lied on the east side of Taiwan. Weathered sedimentary and metamorphic rocks on steep slopes were eroded by rainfall and transported by rapidly flowing streams before deposition on the west plain, to a thickness of several hundred meters. The process of transportation ground the fractured rock into soil particles. The scanning electron microscope (SEM) photos depicted in Fig. 7 show that Yuan Lin soil particles were mostly sub-angular, and the fines were flaky.

Because of its large volume, a single Laval sample could provide at least eight, 70 mm diameter and 150 mm high specimens. The number of specimens was sufficient for the cyclic and monotonic triaxial tests involved in the study. Upon shearing tests of all the specimens, the soil originated from the same Laval sample was mixed together to perform other related physical property tests and to make reconstituted specimens. Out of the nine Laval samples shown in Table 1, three of them were used for detailed physical property and shearing tests. These samples were selected to cover the range of fines contents (FC) intended for the study and had void ratios in a rather narrow range. The selected Laval samples and their basic physical properties which include specific gravity (G_s), reference void ratios (maximum and minimum void ratios, e_{max} and e_{min}) are summarized in Table 2. Other related physical properties of the Laval samples can be found in Table 1. The procedure to determine e_{max} and e_{min} will be described later. The grain size distribution curves according to soil trimmed from the three Laval samples are depicted in Fig. 8. The soil particles were analyzed for their mineral composition. The course particles (retained on #200 sieve) were analyzed according to images taken with a polarized microscope. The fines (particles passing #200 sieve) were analyzed using the X-ray refraction tests. The results as shown in Table 3 had distinct differences in mineral contents between coarse and fine particles. The coarse particles had much higher contents of quartz. The fines were predominantly muscovite, a form of mica and clinochlore.

The reference void ratios of the three Laval samples with three different fines contents were determined following the related ASTM standards. The e_{min} was determined according to ASTM D4253 method 1A using a standard 152.4 mm inside diameter compaction mold (total volume = 2830 cm^3). The dry sand placed in the compaction mold was subjected to a surcharge of 14 kPa, and then electromagnetically vibrated under a 60 Hz frequency for 8 minutes. The e_{max} was obtained according to ASTM D4254 method C, using a 2000 mL glass graduated cylinder. Approximate 1000 g of dry sand was placed in the glass cylinder and then plugged with a stopper. The total volume under the loosest state was determined according to the height of the sand after swiftly tipping the

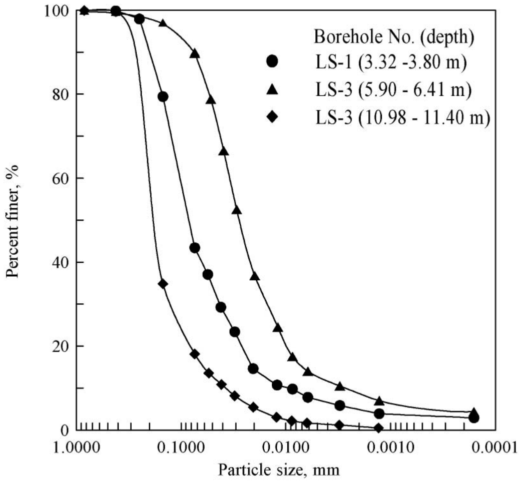


Fig. 8. Grain size distribution curves of the three Laval samples

Table 3. Mineral contents of the selected Laval samples

Mineral	FC = 18%		FC = 43%		FC = 89%	
	Coarse, %	Fine, %	Coarse, %	Fine, %	Coarse, %	Fine, %
Quartz	62.28	19.15	69.83	27.93	66.38	11.78
Clinochlore	15.76	37.98	14.65	27.90	13.01	36.38
Muscovite	14.43	39.28	12.09	39.98	12.06	50.77
Feldspar	7.52	3.59	3.43	4.19	8.55	1.06

cylinder upside down twice. It should be noted that none of the above ASTM standards were applicable for sand with fines in excess of 15%. The ASTM standard used dry sand for the determination of $e_{\min}$ and $e_{\max}$. Because of the compressible nature of the Yuan Lin sand as will be described later, even the soft and contractive specimens can have relative densities in the range from 80 to over 100%, upon saturation and consolidation. The use of relative density can thus be misleading as a density index for these soil specimens. In presenting the test data herein, the density states will be in reference to void ratios rather than relative density.

LABORATORY SPECIMEN PREPARATION

A series of static and cyclic triaxial tests were performed on Laval samples retrieved from the Yuan Lin test site. The frozen Laval samples were kept in a freezer under $-20°C$. Cutting of the frozen sample by sawing and coring could induce enough heat to thaw the sample and cause significant disturbance. To minimize disturbance, the frozen sample was first surrounded by dry ice in the freezer to lower the sample temperature to $-50°C$. The frozen Laval sample was then cut to obtain two, 170 mm long sections using a band saw, while surrounding the sample with dry ice. Four, 70 mm diameter specimens were cored from the 170 mm long section. The coring device as shown in Fig. 9 had its cutter teeth slightly smaller than the tube to create a gap between the specimen and the tube during coring. The holes drilled on the side of the tube facilitate venting of the soil cuttings generated by the coring. These measures helped to maintain solidity of the frozen sample and minimize the chance of disturbance during specimen preparation. Upon coring the specimen height was trimmed down to 140 mm by a hand saw. A small slot of 1.5 mm in width, 12 mm in length and 5 mm in depth was cut at the top and bottom of the trimmed specimen to give room for the insertion of bender element. The specimen was kept frozen during this preparation stage. Thawing took place after the specimen was seated in the triaxial cell following the general procedure reported by Hofmann (1997). The specimen was subjected a confining stress of 20 kPa and a cell water temperature of 5°C. The pore water under a controlled temperature of 8 to 10°C was forced to enter the specimen from the bottom under a back pressure of 10 kPa. The thawing process lasted approximately 1 hour. The amount of water absorbed by the specimen and the change of specimen height were monitored during the thawing process.

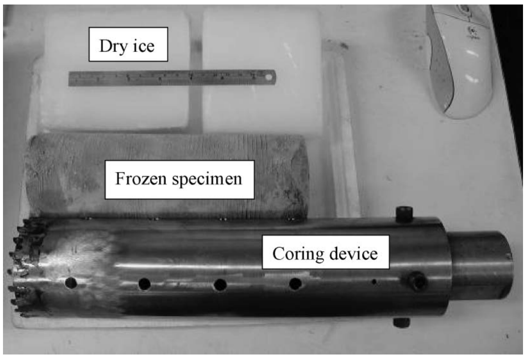


Fig. 9. The coring device for cutting frozen samples

For the non-frozen LS, the 170 mm sections were cut by a wire saw. Four, 70 mm diameter and 140 mm high triaxial specimens were trimmed by hand using a wire saw and a knife, from each section. Slots on top and bottom of the specimens were cut to give room for the bender elements.

The triaxial specimen taken from Laval samples was saturated under a back pressure of 500 kPa. Pore pressure parameter B values obtained after saturation had a minimum value of 0.99. Upon saturation, the specimens were isotropically consolidated under an effective confining stress (σ'_c) of 100 kPa. Because of the relatively high compressibility of the soil specimens and absorption of water in the thawing process (for the frozen specimens), the amounts of pore fluid coming in and out of the specimens were recorded. At the end of triaxial test, the whole specimen was used to determine the water content. The post consolidation water content or void ratio (e), to be used in the analysis of test data, was back calculated from the end-of-the-test water content measurement.

Upon triaxial tests on undisturbed specimens, soil specimens cut from the same Laval sample (i.e., same borehole and depth) were dismantled, fully mixed and oven dried to make reconstituted specimens. The reconstituted specimens were prepared using the moist tamping (MT) and water sedimentation (WS) methods. The MT specimens were created in five equal layers. The soil was mixed under a *w* of 8% and then placed in a 70 mm inside diameter and 140 mm high split mold and compacted to the desired density. Because of capillarity, there was no need to apply vacuum when removing the split mold.

A 70 mm inside diameter and 170 mm high tube shaped mold with a porous stone placed at the bottom was used to make the WS specimens. The bottom of the mold was wrapped with a plastic film to prevent drainage of water. The WS specimen was made in five equal layers. The mold was filled with deaired water to maintain a minimum of 20 mm of water above the soil. Dry soil was deposited into the mold from immediately above the water surface. Slight tapping on the side of the mold was applied when necessary to even the soil surface and reach the desired density. Upon placement of the top soil layer, the plastic film was removed to allow drainage of water from the bottom of the specimen. The time required for full drainage of water ranged from hours to as much as three days as the fines contents increased from 18% to 89 %. After drainage of water, the specimen had sufficient stability to be extruded from the mold and placed in the triaxial cell without the assistance of vacuum.

The MT specimen was permeated with CO_2 and flushed with deaired water. All reconstituted specimens were saturated under a back-pressure of 500 kPa and had a minimum *B* of 0.95. The MT and WS specimens were made in an attempt to match the void ratio of the corresponding Laval samples. In most cases, however, the reconstituted specimens had void ratios lower than those of the Laval samples.

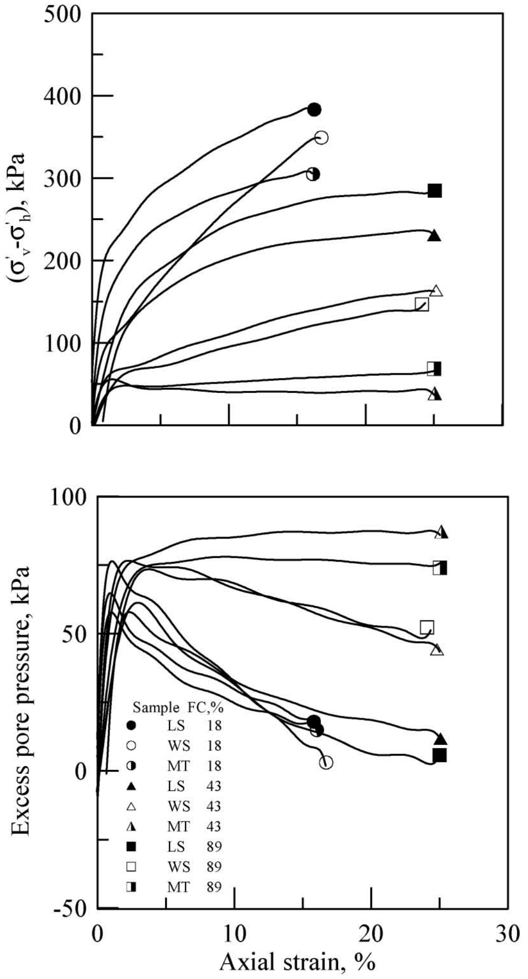


Fig. 10. **Stress-strain and excess pore pressure relationship**

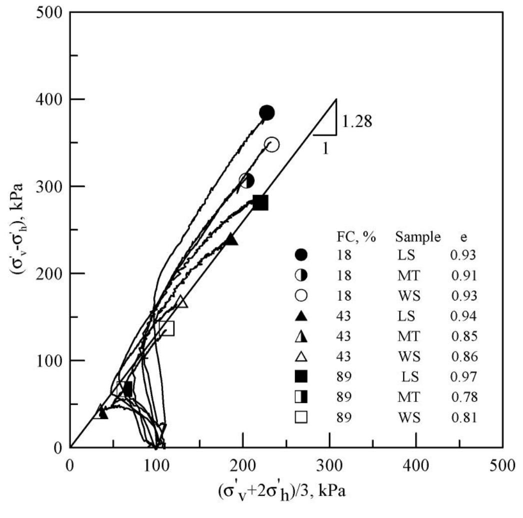


Fig. 11. **Effective stress paths**

MONOTONIC TRIAXIAL SHEARING TESTS

A Wykeham-Farrance triaxial apparatus was used in the monotonic consolidation and triaxial shearing tests. An internal load cell was used to monitor the axial force imposed on the specimen and an externally mounted LVDT was used to measure the axial deformation. All specimens were isotropically consolidated under 100 kPa effective confining stress. In order to reach or be close to the steady state, the specimens were sheared monotonically in an undrained condition by axial compression to strains as much as 25%. The relationships among deviator stress, excess pore pressure and axial strain, as well as the effective stress paths in terms of $q(=(\sigma'_v\text{-}\sigma'_h)$ versus $p'(=(\sigma'_v+2\sigma'_h)/3)$ from all the consolidated undrained triaxial tests are depicted in Fig. 10 and 11. For the range of applied axial strains in the triaxial tests, all specimens developed positive excess pore pressure during shearing. A comparison between the void ratios of the triaxial specimens (included in Fig. 11) and the e_{min}/e_{max} values in Table 2 shows that the triaxial specimens have relative densities well over 80%. For reconstituted specimens with FC equal to 43 and 89%, the relative densities are over 100%. For clean quartz sand with comparable relative densities and σ'_c of 100 kPa would most likely have a dilatant behavior with significant negative excess pore pressure development. The results shown in Fig. 10 indicate that the Yuan Lin soil has a rather contractive behavior.

For specimens with the same fines content, the LS specimens had the highest undrained peak deviator stress even when their void ratios were higher than those of MT and WS specimens. Among the reconstituted specimens, the MT specimens generally had the lowest peak deviator stress. A distinct strain softening behavior was noticed in MT reconstituted specimens with FC equal to 43 and 89% whereas all the other tests showed a strain hardening behavior. This is consistent with earlier findings (Vaid et al., 1999; Høeg et al., 2000). Regardless of the specimen preparation method, the peak deviator stress decreased significantly when FC changed from 18 to 43%. The difference in peak deviator stress was much less significant for specimens of FC equal to 43 and 89%. For the case of FC equal to 43 and 89%, tests on reconstituted specimens showed much wider spread than LS specimens in excess pore pressure development due to differences in FC.

A straight line was fitted to the data set of (p', q) that corresponded to more or less the steady state of the triaxial tests (when axial strain reached 25% in Fig. 10). The slope of this single fitted line referred to as $M_s(=6 \sin \phi'_s/(3-\sin \phi'_s))$ was approximately 1.28. This M_s should correspond to an interparticle friction angle (ϕ'_s) of 31.8°. The ϕ'_s is comparable to those of Mai Liao soil (Huang et al., 2004) with similar mineral content and origin.

SHEAR WAVE VELOCITY MEASUREMENTS AND CYCLIC TRIAXIAL TESTS

Bender elements of the type described by Dyvik and Madshus (1985) were installed in the top and bottom platens of the cyclic triaxial cell, each projecting 3 mm into the soil specimen. All cyclic triaxial test specimens were consolidated to an isotropic stress of 100 kPa. The shear wave velocity, V_s was measured using the bender elements after the specimen was consolidated, prior to the cyclic triaxial test. A single sinusoidal pulse with a frequency of 7 to 10 kHz and amplitude of ± 10 V was applied in the bender element tests. The determination of the shear wave travel time followed a procedure suggested by Kawaguchi et al. (2001).

Figure 12 shows a comparison of V_s taken from the cyclic triaxial test specimens and those from different field measurements, normalized with respect to the effective overburden stress (σ'_v) or V_{s1}. V_{s1} is computed as described by Andrus and Stokoe (2000) where

$$V_{s1}=V_s\left(\frac{p_a}{\sigma'_v}\right)^{0.25} \tag{1}$$

p_a is a reference pressure of 100 kPa. The depths of the V_{s1} from Laval samples are in reference to those where the samples were taken. For laboratory measurements using bender elements, $V_s=V_{s1}$ as the specimens were under an effective confining stress (σ'_c) of 100 kPa, which is also isotropic ($\sigma'_c=\sigma'_v$). Although there were some scattering among the field measurements, the laboratory V_{s1} values are comparable to those of field measurements. The discrepancies of V_{s1} values from different sources may well be due to differences in shearing modes and applied lateral stress for the case of bender element tests.

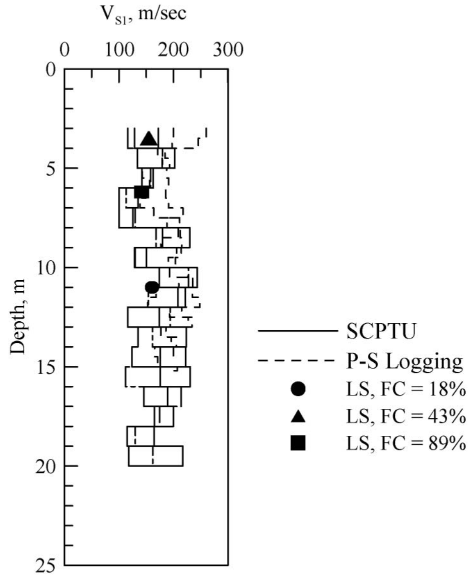


Fig. 12. Comparison of laboratory and field V_{s1} measurements in YLS

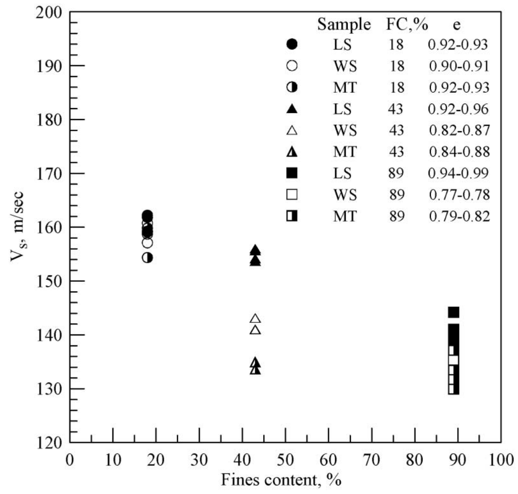


Fig. 13. Relationship between fines content and V_s

Figure 13 compiles V_s values from specimens of various preparation methods and fines contents. The void ratios were similar only in the case of LS specimens. Because of the sensitivity as above described, the void ratios of reconstituted specimens for FC equal to 43 and 89% were significantly lower than those of FC equal to 18% or LS specimens. According to Fig. 13, the V_s of LS specimens decreases by approximate 15% as the fines contents change from 18 to 89%. Apparently the fine grains of the Yuan Lin soil are softer under small strains. The decrease in V_s with fines content was more significant for the reconstituted specimens even with the discrepancies in void ratios. Had the void ratios of the reconstituted specimens with FC equal to 43 and 89% could be made as high as those of 18%, the fines content effects are expected to be even more significant. The V_s in MT specimens were

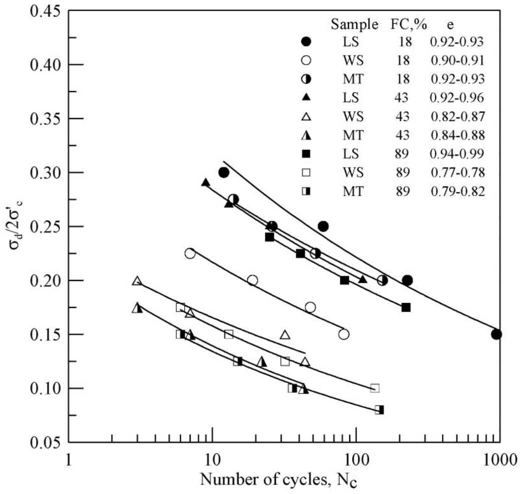


Fig. 14. Cyclic resistance of YLS

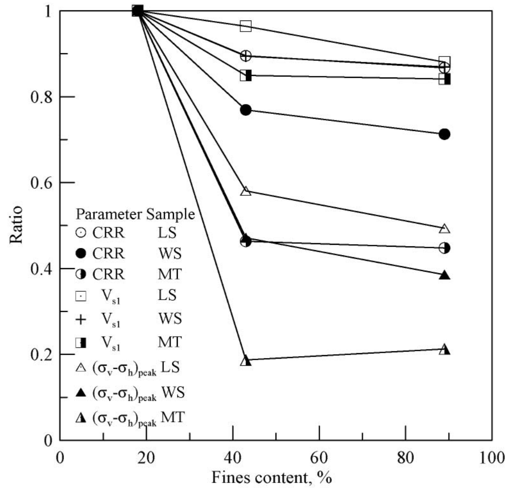


Fig. 15. Relative values as a function of FC

more sensitive to fines contents than that of WS specimens.

For the case of FC equal to 43 and 89%, the reconstituted specimens had lower V_s than those of the Laval samples even when the reconstituted specimens had much lower void ratios than the corresponding Laval samples. Among the reconstitute specimens, those made by MT had the lowest V_s. The V_s values shown in Fig. 13 are at least 30% lower than that of Ottawa sand with similar void ratio and under 100 kPa confining stress, as reported by Hardin and Richart (1963).

Upon V_s measurement, the soil specimen was then subjected to a cyclic deviator stress, σ_d in axial direction at 0.1 Hz. Three to five cyclic triaxial tests were performed using a uniform sinusoidal loading condition with various $\sigma_d/2\sigma'_c$ ratios. Figure 14 depicts the cyclic triaxial test results in terms of the $\sigma_d/2\sigma'_c$ versus the number of cycles (N_c) that produces an axial strain of 5% in double amplitude. For comparison purpose, a cyclic resistance ratio (CRR) is defined as the interpolated $\sigma_d/2\sigma'_c$ that corresponds to N_c of 20. For the LS specimens, the CRR decreased by 13% as the FC increased from 18 to 89%. In the case of WS and MT specimens, the decrease of CRR was 29 and 55%, respectively as the FC increased from 18 to 89%. The reconstituted specimens had lower CRR than that of the corresponding LS specimens. For FC equal to 18%, the CRR of MT specimens was higher than that of WS specimens. This trend is reversed as the FC equal to 43 and 89%.

Some of the earlier studies on artificial silty sand specimens, mostly of silica in nature, have indicated that there is a threshold FC, generally ranged from 25 to 45% (Koester, 1994; Polito, 1999; Xenaki and Athanasopoulos, 2003). For silty sands under the same void ratio, and FC below the threshold value, CRR decreases with FC. This trend is reversed when FC exceeds the threshold. In this study however, the CRR consistently decreases with FC without reversal for both the LS and reconstituted specimens.

Figure 15 compiles the relative values of CRR, V_{s1} and peak deviator stress ($(\sigma_v\text{-}\sigma_h)_{peak}$) taken from tests reported above, as a function of fines content for specimens prepared by different methods. The relative values are presented as ratios of the parameter normalized with respect to the same parameter from tests using 18% fines content specimens. The results show that for the three types of parameters compared, LS specimens had the least sensitivity to fines contents. The most exaggeration of the effects of fines came from the MT specimens. The discrepancies among specimen preparation methods existed even with the significant differences in void ratios among the reconstituted specimens. The fines content effects for non-LS specimens may be even more significant, had the void ratios of the reconstituted specimens with FC equal to 43 and 89% could be made as high as those of 18%.

CONCLUDING REMARKS

The Laval samples may not be truly undisturbed, but the laboratory shearing test results have demonstrated that the sampling and field packaging process should have substantially preserved its fabric as existed in situ. Among the available Laval samples taken from a test site, the authors were able to select three of them with similar void ratios but drastically different fines contents. The large sample volumes allow multiple triaxial specimens be cored or trimmed from a single Laval sample. Upon shearing tests on undisturbed specimens, the same soil was mixed again to make reconstituted specimens by MT and WS methods. This arrangement allowed the effects of fines content on static and dynamic shear strength of the YLS be evaluated with undisturbed as well as reconstituted specimens. Because of the tedious nature of taking high quality Laval samples and procedures of specimen preparation for laboratory testing, it was not possible to cover a wide range of density and stress states as well as fines contents in the experimental program. For the limited number of tests performed and the soil samples tested, the following conclusions can be drawn:

The study reported herein serves as yet another testimony to the statement by Ishihara (1993) that emphasizes the importance of mineral contents to the monotonic or cyclic behavior of sands that contain fines. Apparently the muscovite in YLS, a soft mineral was responsible for the lack of dilatancy during shear. For this reason, the mechanical behavior of YLS under monotonic and cyclic loading conditions, including shear wave velocity may be significantly different from what we have learned from tests on uniformly graded quartz sand.

The tests confirm earlier findings that in comparison with the corresponding reconstituted specimens, the undisturbed specimens have significantly higher undrained peak strength, CRR and shear wave velocity. This comparison remains even when the reconstituted specimens had lower void ratios. Previous studies have indicated that MT method has a tendency to create specimens with a less stable soil structure. For the two reconstitution methods applied by the authors, there was no definite trend as to which one tends to create weaker specimens. This phenomenon may again be related to the mineral content of YLS.

For the conditions applied, the CRR of YLS consistently decreases as FC changed from 18 to 89% for both the LS and reconstituted specimens and did not show a reversal of this trend beyond a threshold FC as some of the earlier studies have indicated. This study provides an evidence to demonstrate that the threshold FC may not be universal for all types of sand-silt mixtures.

The experiments on YLS presented herein seem to indicate that at least for CRR, V_{s1} and peak deviator stress, the effects of fines may be overly exaggerated by tests on reconstituted specimens. The MT method appears to create specimens that show more exaggeration than WS method. This finding raises questions as to the validity of conducting tests on reconstituted silty sand specimens even for relative comparison purposes.

With the significant drawbacks in reconstituted specimens, it is imperative that we obtain geotechnical design parameters from tests on undisturbed specimens for silty sands. With proper techniques, it is possible to obtain high quality silty sand samples, below ground water table, without trenching or in situ ground freezing. The cost of taking high quality silty sand samples can thus be substantially lower than that of ground freezing. For sands with FC in excess of 30%, no above-ground freezing is required to preserve the soil sample as it was the case in this study. These arrangements can make the sampling and testing on undisturbed silty sand or silt specimens relatively practical.

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