

## Liquefaction resistance of sand-silt mixtures using laboratory-based shear wave velocity

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Received: January 2010, Revised: December 2010, Accepted: January 2011

### Abstract

Laboratory data, which relate the liquefaction resistance of Firoozkooh sand and non-plastic silt mixtures to shear wave velocity are presented and compared to liquefaction criteria derived from seismic field measurements by Andrus and Stokoe [1]. In the work described herein, cyclic triaxial and resonant column tests were conducted on specimens of clean sand and sand-silt mixtures with silt content up to 60%, prepared at different densities. Cyclic undrained strength and small strain shear wave velocity were determined for identical specimens formed by undercompaction method. It was found that silt content affects cyclic resistance and shear wave velocity. In addition, the laboratory results indicated that using the existing field-based correlations will overestimate the cyclic resistance of the Firoozkooh sand-silt mixtures when silt content is 60%. For clean sand and the specimens containing up to 30% fines, results of this study on cyclic resistance are fairly consistent with Andrus and Stokoe correlations. These findings suggest the need for further evaluation of the effects of non-plastic fines content upon liquefaction criteria derived from seismic field measurements.

**Keywords:** Non-plastic fines, Liquefaction resistance, Shear wave velocity, Field performance data, Cyclic triaxial test, Resonant column test

### 1. Introduction

Predicting the liquefaction resistance of soils is an important aspect of geotechnical earthquake engineering practice. Several types of evaluating procedures have evolved over the past three decades since simplified method was pioneered by Seed and Idriss [2]. Although penetration-based methods (i.e., SPT and CPT) are well developed [3; 4], penetration tests may be impractical or unreliable at some sites. Meanwhile, shear wave velocity ( $V_s$ ) offers engineers a promising alternative and supplementary tool to evaluate liquefaction resistance of soils. The use of  $V_s$  as an index of liquefaction resistance is soundly based because both  $V_s$  and liquefaction resistance are similarly but not proportionally influenced by many of the same factors (e.g., void ratio, state stress, stress history, and geologic age), the advantages of a  $V_s$ -based method have been discussed by

many researchers [1; 3] (Fig.1). Over the past years, the  $V_s$ -based procedure for liquefaction assessment has attracted numerous studies and progressed significantly with improved correlations and more complete data bases Andrus and Stokoe [1]. The most prevailing approach nowadays is in-situ  $V_s$  measurements at sites shaken by earthquakes [5; 6; 7; 8], which follows the framework of the Seed and Idriss [2] simplified procedure and correlates the overburden stress-corrected shear wave velocity ( $V_{s1}$ ) to the magnitude-scaled cyclic stress ratio (CSR) induced by earthquakes. However, these in-situ  $V_s$ -based methods are still less well defined mainly due to the lack of field performance data [9]. Most of the measured soil parameters for in-situ  $V_s$  testing are post earthquake properties and do not exactly reflect the initial soil states before earthquakes. Thus despite their great practical importance, the field CRR- $V_{s1}$  correlations do not furnish insight into the fundamental behavior of liquefiable soils. As point out by Seed and Idriss [2], with field seismic conditions being properly simulated the controlled laboratory studies could be used to broaden the applicability of liquefaction criteria, especially for the conditions where little to no field performance data is available.

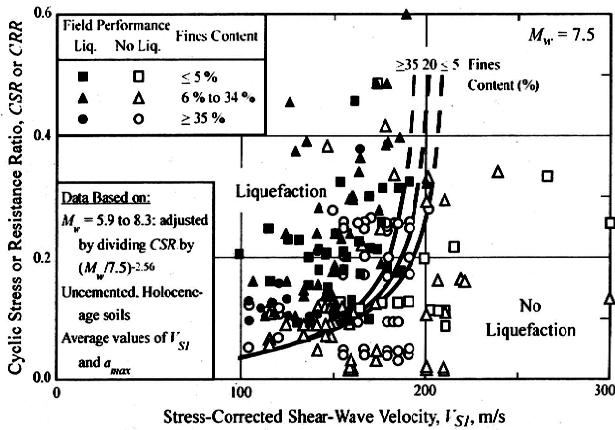
Thereafter many studies have been focusing on this subject on clean sands and sand-silt mixtures [10-19]. These studies demonstrated the validity of laboratory  $V_s$ -based methods and The  $CRR_{field}$ - $V_{s1}$  correlations developed in the laboratory and

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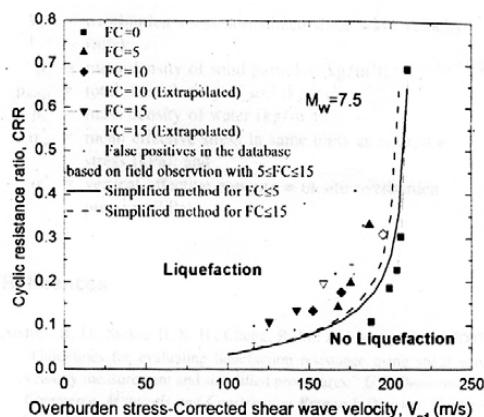
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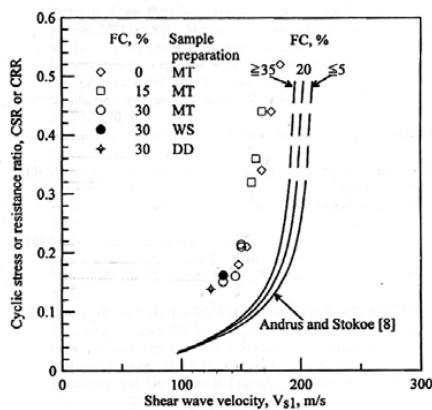
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**Fig. 1.** Relationship between  $V_{s1}$  and CRR for uncemented Holocene age soils with different fines content for  $M_w=7.5$  presented by Andrus and Stokoe [1]



**Fig. 2.** Comparison of the  $CRR_{field}$ - $V_{s1}$  correlations developed in the laboratory with the field-based correlations of Andrus and Stokoe [13]



**Fig. 3.** Comparison of the  $CRR_{field}$ - $V_{s1}$  correlations developed in the laboratory with the field-based correlations of Andrus and Stokoe [14]

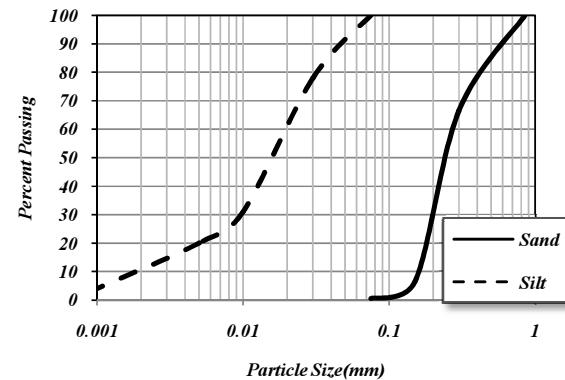
have been compared with the field-based correlations of Andrus and Stokoe [1]. For example, Ning liu et al. [13] and Huang et al. [14] research results are shown in Figures 2 and 3. In this study, cyclic triaxial and resonant column tests were conducted on reconstituted specimens of clean sand and sand-silt mixtures prepared at different densities. In this way, liquefaction resistance and shear wave velocity were measured in identical laboratory specimens and then the data obtained from this study along with other existing data were transferred to the field and compared to the field performance curves proposed by Andrus and Stokoe [1]. The experimental investigations were focused on clean sand and sand containing up to 60% non-plastic silt. High silt content samples were tested to overcome the shortage of the laboratory data in this region.

## 2. Testing material and procedure

### 2.1. Soils tested

The sand used in the study was Firoozkoh sand (No.161), commercially available material from Firoozkoh mine in north-east of Tehran. It is uniformly graded sand (SP) with a mean grain size of 0.25 mm. Its grains are subangular to subrounded in shape. The non-plastic silt used in the testing program was derived from the fine-grained portion of the Firoozkoh silty sand. Figure 4 shows grain size distributions of the soils used in this study.

Clean sand with three mixtures of sand-silt was used in this study. The mixtures were obtained by mixing respectively 15, 30, and 60% of silt with sand. The specimens were prepared to achieve the after-consolidation relative densities of 15, 30, 60 and 75%. The global void ratios ( $e$ ) and the intergrain void ratios ( $e_s$  = Sand skeleton void ratio is one that exists in a silty sand if all of the silt particle were removed, leaving only the sand grains and voids to form the skeleton) for the mixtures are



**Fig. 4.** Grain size distribution for soils used in this study

**Table 1.** Values of  $e$  and  $e_s$  for different mixtures

Type of materials	Dr=15%		Dr=30%		Dr=60%		Dr=75%	
	$e$	$e_s$	$e$	$e_s$	$e$	$e_s$	$e$	$e_s$
Sand	0.83	0.83	0.78	0.78	0.69	0.69	0.65	0.65
Sand+15%Silt	0.76	1.08	0.7	1	0.58	0.86	0.51	0.57
Sand+30%Silt	0.77	1.52	0.69	1.41	0.53	1.185	0.45	1.07
Sand+60%Silt	1.124	-	0.99	-	0.72	-	0.58	-

presented in Table 1.

There is no applicable ASTM procedure for determining minimum void ratio,  $e_{min}$  over the entire range of silt contents investigated. The vibratory table method ASTM D4253 is limited to a maximum fines content of 15%, while Proctor tests do not always produce accurate, repeatable results for clean sands. Therefore, vibratory table and modified Proctor test were all performed upon each soil mixture. Herein, for clean sand and sand with 15% silt content, vibratory table test results were considered for determination of  $e_{min}$ . Meanwhile, for sand with 30 and 60% silt content modified Proctor ASTM D1557 test results were used. Similarity, there is no applicable ASTM procedure for determining maximum void ratio,  $e_{max}$  over the entire range of silt contents investigated. The minimum density method ASTM D4254 is limited to a maximum fine content 15%. Despite this limitation,  $e_{max}$  for each soil mixture was determined in general accordance with the specifications of ASTM D4254. Figure 5 presents the variation of  $e_{max}$  and  $e_{min}$  in terms of silt content.

## 2.2. Method of sample preparation

There are three kinds of procedures widely used for preparing samples of sand for laboratory testing; moist tamping, dry deposition and water sedimentation. The basic requirements for any of the methods are firstly to obtain homogeneous samples with uniform distribution of void ratio and secondly to be able to prepare samples having the lowest possible density. The second requirement is needed to cover a wide range of density in the sample reconstituted by an identical method. It has been known that different methods of sample reconstitution create different fabrics, thereby yielding different responses to load application. Numerous researches [20; 21 and 22] have shown that the method of sample preparation has a large effect upon the cyclic resistance measured. Early studies found that moist tamping method produced a cyclic resistance that is higher than that produced by pluviation through either air or water [20]. Recent research [21] however, has shown that for specimens prepared to identical void ratios, moist tamping may produce a collapsible fabric and thus more susceptible to liquefaction, while water pluviation may produce a fabric that is dilative and thus less susceptible to liquefaction when sheared monotonically. Amini and Qi-2000

[24] found that the liquefaction resistance of stratified silty sand specimens formed by pluviating silty sand through water did not differ significantly from the resistance of uniform specimens produced by moist tamping. While pluviation more closely mimics natural depositional processes, due to segregation of fines it is not a practical method of specimen preparation for a study in which fines content and density are the main parameters being studied. While, the moist tamping method of sample preparation does not mimics the natural deposition processes of silty sands, this method was selected by Polito et al. 2001 [22] because of the high level control over fines content distribution and specimen density.

In this research, for obtaining a uniform density throughout the specimen, moist tamping method using an undercompaction procedure was used [25]. The undercompaction method consists of placing each layer at a density slightly greater than the density of the layer below it in order to account for the decrease in volume and increase in density that occurs in the lower layers when the new layer is placed. In this study, with different from Ladd [25] method process, the compaction was performed with placement of weights (700-2500gr) on soil layers, and the Plexiglas mold was impacted by hammer from besides. The specimens were made in six layers with an undercompaction value of 5%, so that the relative density was varied by 1% per layer. In this study, the specimens were made in six layers with an undercompaction value of 5%, so that relative density was varied by 1% per layer. To ensure the uniformity of density throughout the specimen height, the void ratio distribution within the specimen was obtained by solidifying specimen using a gelatin solution [26]. The solidified specimen was then sliced into sections and the distribution of void ratio within the test specimen was determined. Measurements revealed that the relative error in achieving the required density throughout the specimens was successfully less than 5% for each layer. In addition, the specimens were prepared in a Plexiglas mold to have better control over the layer's thickness (Figure 6). During sample preparation, it was found that test on low density specimens with high silt content (i.e. 60%) materials was impossible, because of excessive collapse during saturation. Thus, high silt content specimens were prepared at high relative densities of 60 and 75%, meanwhile other specimens were prepared at densities of 15, 30 and 60%.

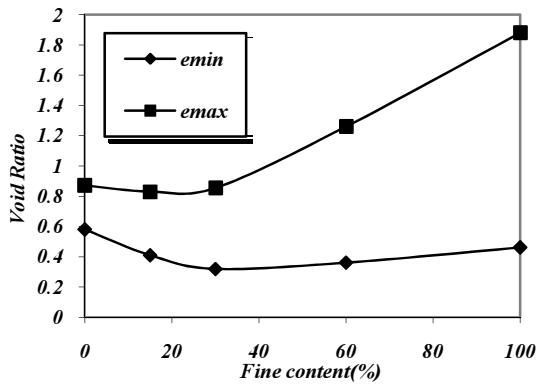


Fig. 5. Variation of  $e_{max}$  and  $e_{min}$  in terms of silt content

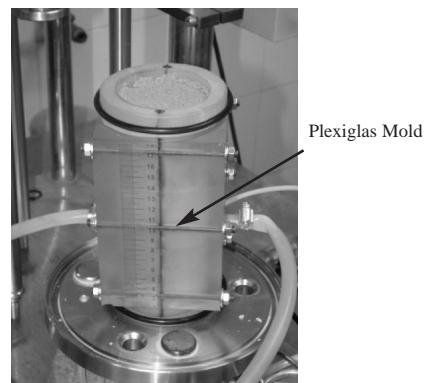


Fig. 6. controlling layer's thickness in Plexiglas mold in triaxial apparatus

### 2.3. Test procedure

The CRR values were measured using an automated stress-controlled cyclic triaxial apparatus. The specimens were tested with a typical diameter of 70 mm and a height of 150 mm. Small strain shear wave velocity,  $V_s$  was also measured using a fixed-free type, torsional resonant column apparatus. The tested specimens were typically 70 mm in diameter and 100 mm in height. The specimens were saturated with a Skempton B-value in excess of 98 %. To facilitate saturation process carbon dioxide ( $\text{CO}_2$ ) was first percolated through the specimens, then de-aired water flushed into the specimens. Finally a back pressure of 100 kPa was incrementally applied to accelerate saturation rate. Then specimens were isotropically consolidated under an effective confining stress of 100 kPa. All relative density reported herein are based on the after-consolidation void ratios. In the cyclic triaxial tests, the specimens were loaded sinusoidally at a frequency of 0.1 Hz ASTM D5311 varying deviator stress at the appropriate cyclic stress ratio until they liquefied. Resonant frequencies and amplitude of vibration measured in the resonant column tests, along with a system calibration, were also used to determine  $V_s$ .

### 3. Test results and discussion

In this study, liquefaction was defined and evaluated at initial liquefaction; when the pore pressure in the specimen first equaled the initial confining stress or the specimen reached 5% double amplitude axial strain, whichever occurred first. Cyclic resistance was also defined as the cyclic stress ratio required causing initial liquefaction in 15 cycles of loading [27]. Results of cyclic triaxial tests for this study are presented in Tables 2, 3, 4 and 5.

**Table 2.** Test data for sand

Type of Material	$\sigma_d$ , kPa	CSR	N	Dr
Sand	25.2	0.126	1	0.15
	22.6	0.113	3	0.15
	15.6	0.078	114	0.15
	30	0.15	4	0.30
	26	0.13	16	0.30
	24	0.12	44	0.30
	62	0.31	2	0.60
	48	0.24	24	0.60
	42	0.21	68	0.60

**Table 3.** Test data for sand+15% silt

Type of Material	$\sigma_d$ , kPa	CSR	N	Dr
Sand+15% Silt	24	0.124	7	0.15
	22	0.11	20	0.15
	15	0.075	350	0.15
	36	0.18	2	0.30
	30	0.15	10	0.30
	28	0.14	17	0.30
	44	0.22	17	0.60
	42	0.21	24	0.60
	36	0.18	76	0.60

**Table 4.** Test data for sand+30% silt

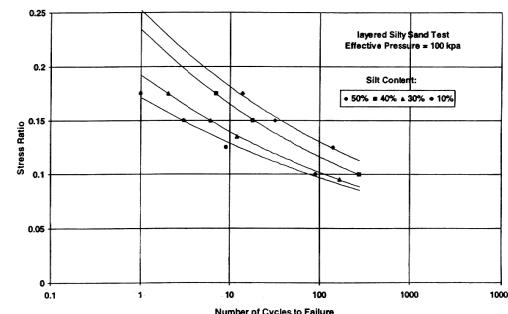
Type of Material	$\sigma_d$ , kPa	CSR	N	Dr
Sand+30% Silt	18.2	0.091	1	0.15
	14.4	0.072	5	0.15
	12	0.06	18	0.15
	22	0.11	7	0.30
	17	0.085	34	0.30
	15.8	0.079	58	0.30
	42	0.24	8	0.60
	44	0.22	13	0.60
	36	0.18	48	0.60

**Table 5.** Test data for sand+60% silt

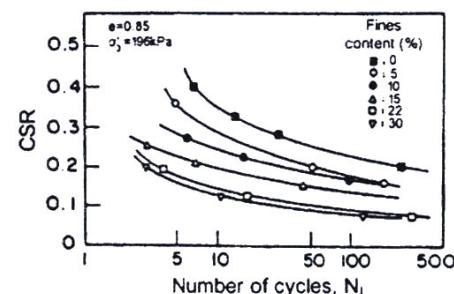
Type of Material	$\sigma_d$ , kPa	CSR	N	Dr
Sand+60% Silt	12	0.06	6	0.60
	9	0.045	11	0.60
	2	0.01	426	0.60
	48	0.24	2	0.75
	30	0.15	5	0.75
	10	0.05	40	0.75

#### 3.1. Effect of non-plastic fines on the cyclic resistance

Many studies have investigated influence of fines on the cyclic resistance of sands, and no clear consensus has been reached on their effects. As shown in Figure 7, some researchers concluded that fines increase the liquefaction resistance [24; 28; 29; 30; 31], While others indicated that the fines decrease the liquefaction resistance [32-37] (Figure 8).



**Fig.7.** Effect of silt content on liquefaction resistance of silty sands [24]



**Fig.8.** Effect of silt content on liquefaction resistance of silty sands [31]

Other studies have found that the sand's resistance to liquefaction will initially decrease as the silt content increases until some minimum resistance is reached, and then increase as the silt content continues to increase [23; 38; 39; 40; 41]. Some results of such researches are presented in Figures 9 and 10. These seemingly contradictory conclusions may from factor that include: (1) using different deposition methods for specimen preparation; (2) testing different sand with different silt contents and densities; (3) testing specimens under different confining stresses and loading conditions; and (4) using different criteria to define liquefaction and cyclic shear resistance.

Figure 11 shows results of cyclic triaxial tests in desired relative densities (i.e.  $Dr=15, 30, 60$  and  $75$  percent) expressed as cyclic stress ratio against number of loading cycles for various combinations of sand with silt content from 0 to 60%. Also, for verifying the results of this study, results of the present study are compared with that of The Polito et al. [23] on the effects of sampling method, sample size and grain size distribution of materials were compared in the same effective confining pressures.

As shown in Figs. 11(a) and (b), in very loose and medium dense materials (i.e.  $Dr=15$  and  $30\%$ ), the cyclic resistance of Firoozkoh sand first, slightly increases with fines content up to  $15\%$ , followed by a decrease beyond this value. Similar trend is shown by Polito et al in Yates sand [23].

As seen in Fig. 11 (c), in dense samples (i.e.  $Dr=60\%$ ), the cyclic resistance of Firoozkoh sand continuously decreases with silt content. This trend is also seen in Yates sand. The

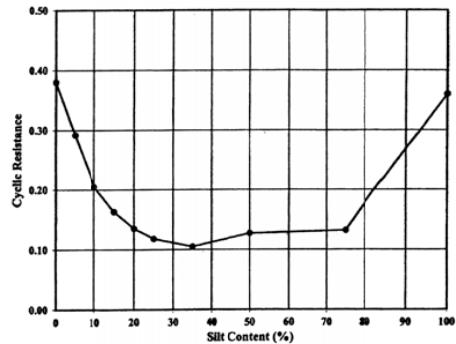


Fig. 9. Effect of silt content on liquefaction resistance of silty sands [23]

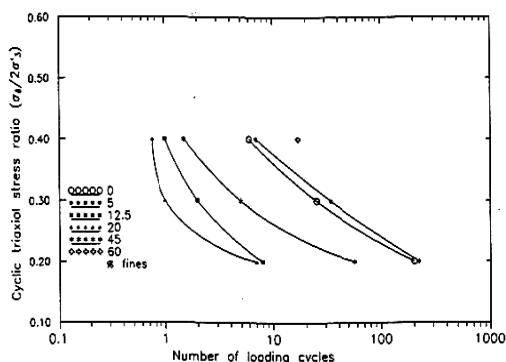


Fig. 10. Effect of silt content on liquefaction resistance of silty sands [39]

cyclic resistance of the specimens containing 60% silt with  $Dr=75\%$  is also shown on Fig. 11(d). As seen, a fairly good agreement exists between this study with that of Polito et al. [23].

Cyclic Resistance Ratios ( $CRR$ ) of different sand-silt mixtures is plotted against sand skeleton void ratios ( $e_s$ ), as shown in Fig. 12. As seen, no clear trend exists in terms of  $e_s$  for loose to medium dense specimens and cyclic resistance ratio increases with increase of sand skeleton void ratio for mixtures having 0 to 15% silt and decreases with further increase of the silt content. In dense specimens (i.e.  $Dr=60\%$ )  $CRR$  continually decreases with increase of sand skeleton void ratio.

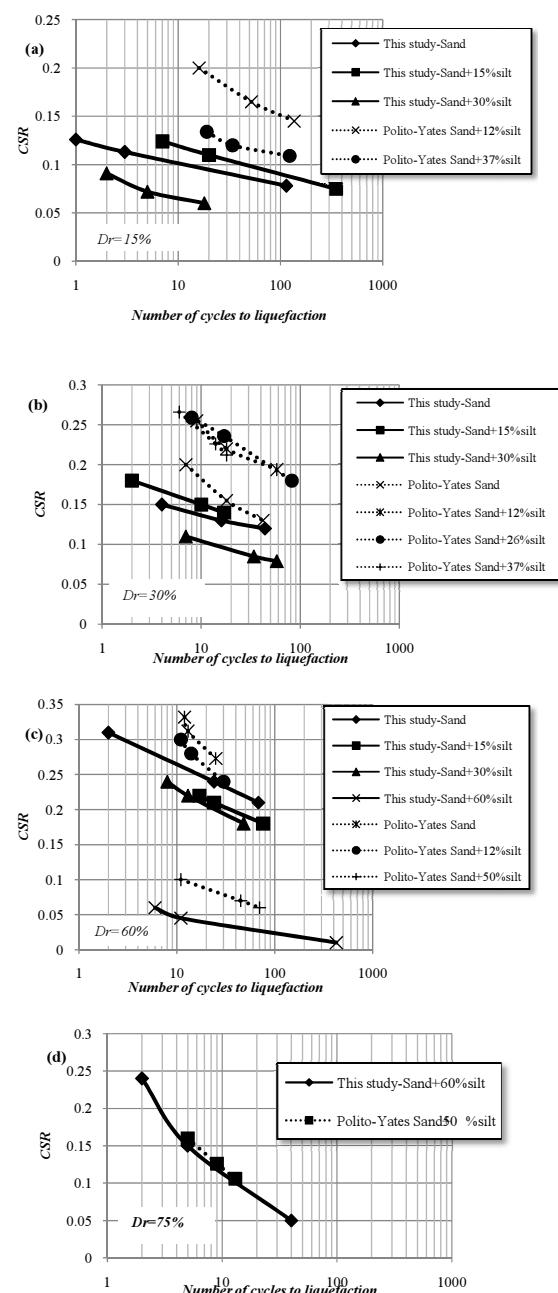


Fig. 11. Results of cyclic triaxial tests for the various mixtures of The Firoozkoh sand with silt (a)  $Dr=15\%$  (b)  $Dr=30\%$  (c)  $Dr=60\%$  and (d)  $Dr=75\%$  and Comparison of the present research results with those of Polito et al

### 3.2. Effect of non-plastic fines on the shear wave velocity

The effect of fines on the shear wave velocity have been less completely studied and understood. Resonant column tests conducted by Iwasaki and Tatsuoka [42] and bender element tests performed by Salgado et al. [43] and Huang et al. [14] showed that the small strain-shear modulus,  $G_{max}$  and therefore  $V_s$  decreased with increase in non-plastic fine content.

As mentioned above, the fixed-free type torsional resonant column device was used to measure the small strain shear wave velocity. The tested specimens were typically 70 mm in diameter and 100 mm in height. The specimens were saturated with a Skempton B-value in excess of 98 %. To facilitate saturation process carbon dioxide ( $CO_2$ ) was first percolated through the specimens, then de-aired water flushed into the specimens. Finally a back pressure of 100 kPa was incrementally applied to accelerate saturation rate. After that, specimens were isotropically consolidated under an effective confining stress of 100 kPa. All relative density reported herein are based on the after-consolidation void ratios. Resonant frequencies and amplitude of vibration measured in the resonant column tests, along with a system calibration, were also used to determine  $V_s$ . Results of resonant column test are presented in Table 6. As can be seen,  $V_s$  in clean sand and sand-silt mixtures increases with increase of relative density. On the other hand,  $V_s$  decreases with increase of silt content.

Shear wave velocity of different sand-silt mixtures is plotted against sand skeleton void ratios ( $e_s$ ), as shown in Fig.13 As

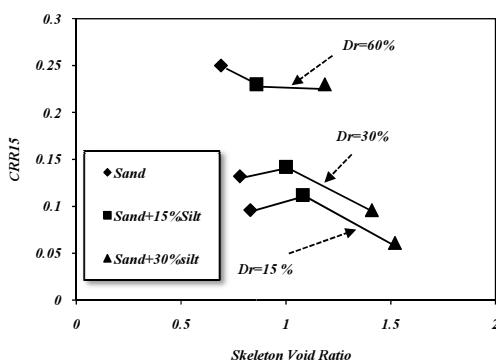


Fig. 12. Variation in  $CRR_{15}$  with sand skeleton void ratio for sand-silt mixtures specimens,  $\sigma'_3=100$  kPa

Table 6. Resonant column test results

Type of Material	Relative Density	$V_s$ (m/s)
Sand	0.15	182
	0.30	193
	0.60	201
	0.15	169
Sand+15%Silt	0.30	181
	0.60	202
	0.15	157
Sand+30%Silt	0.30	168
	0.60	189
	0.60	164
Sand+60%Silt	0.75	175

seen,  $V_s$  has a meaningful relationship with  $e_s$ , and  $V_s$  continuously decreases with sand skeleton void ratio for all mixture.

### 3.3. Conversion of laboratory data to field condition

It is of great importance to point out, however, that both of the liquefaction resistance ( $CRR$ ) and shear wave velocity ( $V_s$ ) were obtained in undrained cyclic triaxial and resonant column tests under isotropic consolidation conditions, which are usually different from the in-situ conditions required to be evaluated for design purpose. Therefore, some considerations should be included in applying the laboratory test-based  $CRR-V_s$  correlation to in situ conditions. It is common to correct  $CRR$  to in situ  $CRR$  (i.e.  $CRR_{field}$ ) in approximate manner as follows [44]:

$$CRR_{field} = \alpha \cdot \beta \cdot CRR_{triaxial} \quad (1)$$

Where  $\alpha, \beta$  = correction factors, Constant  $\alpha$  can be presented by many equations, as follows:

$$\alpha = K_0 \quad (2)$$

$$\alpha = \frac{1 + 2K_0}{3} \quad (3)$$

$$\alpha = \frac{1 + K_0}{2} \quad (4)$$

$$\alpha = \frac{2(1 + 2K_0)}{3\sqrt{3}} \quad (5)$$

in which  $K_0$  is effective earth pressure ratio at rest. Eqs. (2) And (3) were proposed by Seed and Peacock [44] and Eqs. (4) and (5) by Finn et al. [45] and Castro [46] respectively. Coefficient  $K_0$  was also taken equal to  $(1 - \sin\varphi')$  where  $\varphi'$  is angle of shearing resistance.  $\varphi'$  was determined for each mixture at desired relative density using monotonic undrained triaxial tests conducted under initial confining stresses of 100, 200 and 300 kPa (Table 7). Finally, by averaging over the  $\alpha$  values from Eqs.(2) to (5), the desired value of constant  $\alpha$  was determined (i.e.  $\alpha_{mean}$  in Table 7).

Constant  $\beta$  is a function of relative density [47] and is defined as:

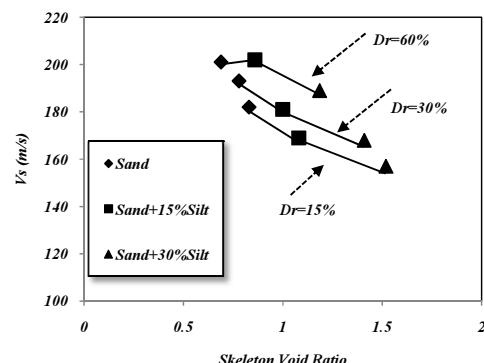


Fig. 13. Variation in  $V_s$  with sand skeleton void ratio for sand-silt mixtures specimens,  $\sigma'_3=100$  kPa

**Table 7.** A summary of test results

Type of Material	Dr	$\phi'(^{\circ})$	CRR <sub>triaxial</sub>	V <sub>s</sub> (m/s)	$\alpha_{mean}$	$\beta$	CRR <sub>field</sub>	V <sub>s1</sub> (m/s)
Sand	0.15	20	0.096	182	0.788	1.15	0.087	170.6
	0.30	29	0.132	193	0.68	1.15	0.103	174.8
	0.60	34	0.25	201	0.63	1.3	0.201	178
Sand+15%Silt	0.15	17	0.112	169	0.83	1.15	0.106	160
	0.30	23	0.142	181	0.752	1.15	0.123	167
	0.60	32	0.23	202	0.65	1.3	0.194	181
Sand+30%Silt	0.15	16.2	0.061	157	0.832	1.15	0.058	149
	0.30	19	0.096	168	0.796	1.15	0.088	157
	0.60	29	0.23	189	0.68	1.3	0.203	171
Sand+60%Silt	0.60	28	0.033	164	0.69	1.3	0.03	149
	0.75	31	0.093	175	0.66	1.45	0.088	157

$$Dr \leq 45\% \Rightarrow \beta = 1.15$$

$$Dr > 45\% \Rightarrow \beta = 0.01Dr + 0.7 \quad (6)$$

Table 7 presents the value of  $\beta$  along with  $CRR_{field}$  for different mixtures.

On the other hand, the measured  $V_s$  require adjustment allowing for the different stress states. As  $V_s$  was widely observed to depend equally on principal stresses in the direction of wave propagation and particle motion [48],  $V_s$  can be expressed as:

$$V_{sf} = V_s \left( \frac{1+2K_0}{3} \right)^{0.25} \quad (7)$$

Where  $V_{sf}$  = the equivalent field value of laboratory measured  $V_s$ . According to common practice [1; 5] the  $V_{sf}$  in Eq.(7) should be further corrected in terms of the in-situ effective overburden stress ( $\sigma'_v$ ) as follows:

$$V_{s1} = V_{sf} \left( \frac{P_a}{\sigma'_m} \right)^{0.25} = V_s \left( \frac{1+2K_0}{3} \right)^{0.25} \left( \frac{P_a}{\sigma'_m} \right)^{0.25} \quad (8)$$

Where  $V_{s1}$  = overburden stress-corrected velocity;  $P_a$  = atmosphere pressure; and  $\sigma'_m$  = mean effective stress in the laboratory. Table 7 presents the value of  $V_{s1}$  for each mixture.

Can be derived from Table 7, it is defined as the cyclic stress ratio (CSR) causing liquefaction in 15 cycles of loading. Figure 14 presents the values of  $CRR_{Field}$  for different mixtures versus relative densities.

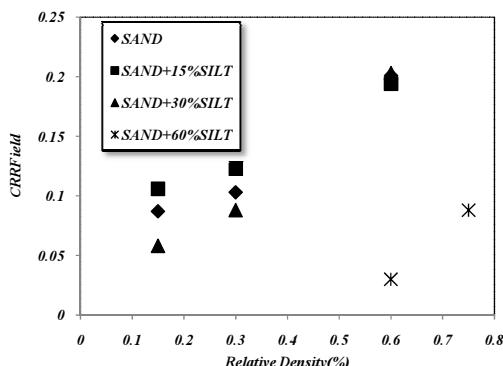
It is seen that values of  $CRR_{Field}$  increases as the silt content increases up to 15%, with further increase in silt content up to

30%, cyclic resistance ratio decreases in lower relative densities ( $Dr=15\%, 30\%$ ). As the silt content increases up to 60%, the  $CRR$  is decreased in dense relative density ( $Dr=60\%$ ) and with increase of relative density from 60% up to 75%, the  $CRR$  is increased.

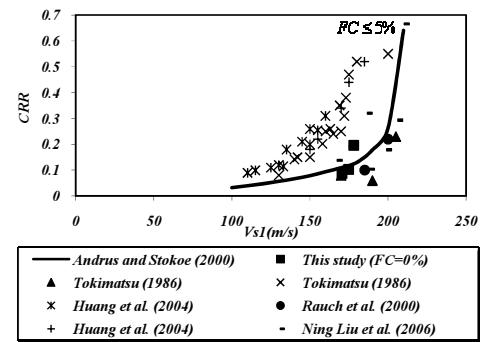
### 3.4. Comparison of CRR in converted laboratory results and in situ $V_s$ tests

The  $CRR_{field}$ - $V_{s1}$  correlations developed in the laboratory for this study and other studies are compared to the field-based correlations of Andrus and Stokoe [1] for different ranges of fines content (FC) as: (1) the laboratory-based correlations for clean sands ( $FC \leq 5\%$ ) that are based on the data from this study, Tokimatsu et al.[49]; Rouch et al. [13]; Huang et al. [14]; Ning Liu et al.[17] (Fig.15), (2) the laboratory-based correlations for silty sands with  $5\% < FC < 30\%$  that are based on the data from this study, Rouch et al. [13]; Huang et al. [14] Ning Liu et al.[17] (Fig.16), and (3) the laboratory-based correlations for sand-silt mixtures ( $FC \geq 35\%$ ) that are based on the data from this study, Huang et al. [14] and Baxter et al. [19] (Fig.17).

Fig.15 shows that the  $CRR_{field}$ - $V_{s1}$  correlation for the clean sand used in this study lie to the right of but close to the semi-empirical curve proposed in the simplified procedure for fines content less than 5%. Similarly, the trends in the laboratory data on sands with 15% fines content is found to be consist with the liquefaction boundary curves developed by Andrus and Stokoe -2000 for  $FC=20\%$  from field performance data



**Fig. 14.** Effects of nonplastic fine content on cyclic resistance ratio (CRR) vs. relative densities



**Fig. 15.** Comparison between converted  $CRR_{field}$ - $V_{s1}$  data based on the laboratory data from clean sand ( $FC \leq 5\%$ ) and the existing field-based correlation of Andrus and Stokoe [1]

(Fig.16). As shown in Fig.17, the laboratory-based correlations from this study for  $FC=30$  and 60% plot well below the field-based curve for  $FC \geq 30\%$ . Therefore, using the field-based correlation would overestimate the liquefaction resistance of these sand-silt mixtures.

As seen in Figs.15 to 17, significant difference may exist between laboratory-based correlations and field performance data of Andrus and Stokoe [1]. Although Baxter et al. [19] believe that the correlation between cyclic resistance and shear wave velocity is soil specific, the difference may originates from inherent uncertainties in the interpretation of laboratory results and field performance data. According to Rauch et al. [13], the uncertainties in laboratory data include: (1) Techniques used for forming test specimens in the laboratory significantly affect the measured cyclic resistance and shear wave velocity; (2) the cyclic stress path generated by uniform cycles of axial stress in a triaxial test only approximately models an earthquake loading on a soil deposit; (3) the uncertainties of the relationship between laboratory and field conditions are only approximately accounted for in the correction of cyclic triaxial strength ( $CRR_{triaxial}$ ) to in situ cyclic resistance ratios ( $CRR_{field}$ ); and (4) the measurement of cyclic strength and shear wave velocity in separate soil specimens also introduces a potential source of error. On the other hand, the uncertainties in field performance data may originates from: (1) the uncertainties in the plasticity of the fines in the in situ soils; (2) using post earthquake properties that do not exactly reflect the initial soil states before earthquakes; and (3) the assumption that  $CRR_{field}$  is equal to  $CSR$  obtained from Seed and Idriss [2] well known equation. This may result in significant overestimation of  $CRR_{field}$  when factor of safety is less than 1.

#### 4. Summary and Conclusions

Previous laboratory studies on sand-silt mixtures have shown that shear wave velocity can be correlated to liquefaction resistance. Therefore, a new correlation between cyclic resistance ratio and shear wave velocity ( $V_s$ ) was developed for the mixtures of Firoozkoh sand and non-plastic silt, with silt content varied from 0 to 60%. The specimens prepared at different relative densities (from 15 to 75%) were tested in

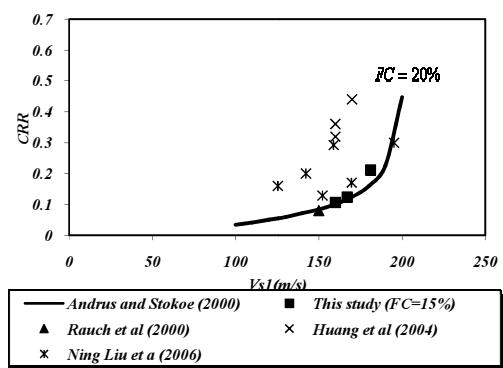
cyclic triaxial and resonant column apparatus. Data from previous laboratory studies on sands and silty sands along with the laboratory data generated as the part of this study were compared to field based  $CRR-V_s$  curves prepared by Andrus and Stokoe [1]. The following conclusions, regarding the effects of nonplastic fines on the liquefaction susceptibility, based on shear wave velocity of sands can be drawn from this study:

- In very loose to medium dense materials (i.e.  $Dr=15, 30$  and 60%), the  $CRR$  of Firoozkoh sand first, slightly increases with fines content up to 15%, followed by a decrease beyond this value and the cyclic resistance ratio of Firoozkoh sand continuously decreases with increase of silt content. These results are different from simplified procedure those proposed by Seed and Idriss [2].

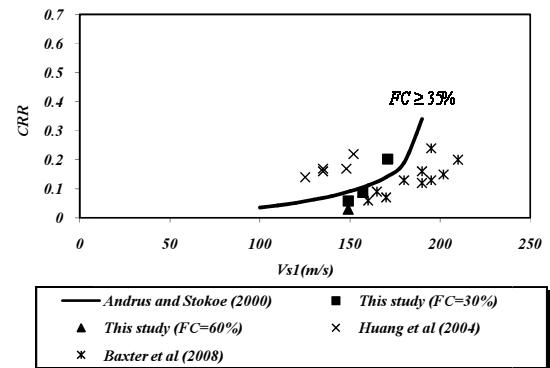
- Resonant column test results show that  $V_s$  in clean sand and sand-silt mixtures increases with relative density. However,  $V_s$  decreases with increase of silt content and sand skeleton void ratio.

- In general, when fines content is raised, the stability of the mixture fabric is reduced. Data obtained on the cyclic resistance and shear wave velocity of the mixtures evidently show that, generally, increase in fines content leads to less cyclic strength and less shear wave velocity.

- In Conversion of laboratory data to field condition, results show that the  $CRR_{field}-V_s$  correlation for the clean sand (in lower relative density  $Dr=15$  and 30%) is close to the semi-empirical curve proposed in the simplified procedure proposed by Andrus and Stokoe [1] for fines content less than 5%. Also, this trend is observed in the laboratory data on sands with 15% fines content which is found to be consist with the liquefaction boundary curves developed by Andrus and Stokoe [1] for  $FC=20\%$  from field performance data. The  $CRR_{field}-V_s$  values for  $FC=30$  and 60% are below the field-based curve for  $FC \geq 35\%$ , mean that field-based correlation would overestimate the liquefaction resistance of these sand-silt mixtures in comparison to laboratory based data. This significant difference may originate from the inherent uncertainties in laboratory and field performance data. The limited data generated in this study are not sufficient to modify the field correlations between  $V_s$  and liquefaction resistance. It would be very beneficial to have more data of this kind from



**Fig. 16.** Comparison between converted  $CRR_{field}-V_s$  data based on the laboratory data from silty sands ( $5\% < FC < 30\%$ ) and the existing field-based correlation of Andrus and Stokoe [1]



**Fig. 17.** Comparison between converted  $CRR_{field}-V_s$  data based on the laboratory data from sand-silt mixtures ( $FC \geq 35\%$ ) and the existing field-based correlation of Andrus and Stokoe [1]

laboratory tests on a wide variety of soils, particularly for fines content more than 30% for better investigation of the liquefaction criteria developed from the field-performance data.

## Acknowledgements

This research was conducted in and supported by the International Institute of Earthquake Engineering and Seismology (IIEES) under the Contract No.6712. This support is gratefully appreciated.

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