The effect of fines type on correlation between shear wave velocity and liquefaction resistance of sand containing fines

L'effet du type amendes sur la corrélation entre la vitesse des ondes de cisaillement et de résistance à la liquéfaction du sable contenant des amendes

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ABSTRACT: The use of shear wave velocity (V_s) measurements as an in-situ test for evaluation of liquefaction potential has increased substantially due to its advantages. Relatively large numbers of studies have been performed to establish the correlation between V_s and liquefaction resistance (CRR) of clean sands. Usually natural sands contain silt and/or clay and previous studies have shown that both the amount of fines and their nature influence the CRR and V_s as well. Therefore, the V_s-CRR correlations may also be affected by fines content and type of sandy soils, but these effects are less studied so far. Cyclic triaxial and bender element tests were conducted on samples of sand containing various amounts of different fines. Using this experimental data, and a proposed semi empirical method, CRR-V_s correlation was developed and the effect of fines type on the correlation is investigated. Based on the results, the CRR-V_s correlation is affected by both the amount and plasticity of the fines present in the sand and this issue should be considered in evaluating the liquefaction resistance of sands containing fines.

RÉSUMÉ : L'utilisation de la vitesse des ondes de cisaillement (V_s) de mesure comme un test in-situ pour l'évaluation du potentiel de liquéfaction a considérablement augmenté en raison de ses avantages. Un nombre relativement important d'études ont été réalisées afin d'établir la corrélation entre V_s et résistance à la liquéfaction (CRR) de sable propre. Habituellement les sables naturels contiennent limon et/ou de l'argile et des études antérieures ont montré que le montant des amendes et leur nature influencent le CRR et aussi V_s. Par conséquent, les corrélations V_s-CRR peut également être affectée par la teneur en fines et le type de sols sableux, mais ces effets sont peu étudiés jusqu'à présent. Cyclique essais triaxiaux et bender éléments ont été effectuées sur des échantillons de sable contenant diverses quantités d'amendes différentes. A partir de ces données expérimentales, et un projet de méthode semi-empirique, le CRR-V_s corrélation a été développé et l'effet du type amendes sur la corrélation est étudiée. D'après les résultats, la corrélation CRR-V_s est affectée à la fois par la quantité et la plasticité des fines présentes dans le sable et cette question devrait être pris en compte dans l'évaluation de la résistance à la liquéfaction des sables contenant des amendes.

KEYWORDS: Liquefaction resistance, Shear wave velocity, Fines type, Fines content

1 INTRODUCTION

Simplified procedure developed initially by Seed and Idriss in 1971 is widely used for evaluating the liquefaction resistance of soils from in-situ tests such as standard penetration test (SPT), cone penetration test (CPT) and shear wave velocity (V_s) measurements. Compared with other indexes, V_s offers geotechnical engineers a promising alternative and a supplementary tool toward the penetration-based methods (SPT or CPT) to evaluate liquefaction resistance of sandy soils (Andrus and Stokoe 2000). In recent years, the use of V_s for evaluation of liquefaction potential has increased substantially due to its advantages especially for liquefaction potential microzonation. Relatively large numbers of studies have been performed to establish the correlation between V_s and cyclic resistance ratio (CRR: which is the cyclic liquefaction resistance normalized by initial overburden effective stress). So, different CRR-V_s correlation curves for separating liquefaction and nonliquefaction occurrences have been proposed by different researchers (Zhou and Chen, 2007; Andrus and Stokoe, 2000; Tokimatsu and Uchida, 1990).

Previous studies have shown that both V_s and liquefaction resistance are affected by fines content (FC) and fines nature. Therefore, the V_s-CRR correlations may also be affected by these parameters. Given that usually natural soils contains silt and/or clay, the effect of FC and fines type of sandy soils on the correlation between V_s and CRR should be investigated, but these effects are less studied so far. It is interesting to note that, in the separated V_s-CRR correlation curves for FC≤5% and other FCs proposed by Andrus and Stokoe (2000), the fines type is not considered. These well known curves are recommended by NCEER and are used widely.

In this study, in order to clarify the effects of fines type on V_s-CRR correlations, laboratory measurements of V_s using bender elements and cyclic triaxial tests have been conducted on clean silica sand and sand containing up to 15% of different fines including non-plastic, low-plastic and highly plastic fines. A simple method based on theoretical considerations and laboratory data is presented and used to develop the CRR-V_s correlation. Using the developed CRR-V_s correlations, the effect of fines type on the correlation is investigated. The results are then compared with the procedure of Andrus and Stokoe (2000).

2 LABORATORY TESTS AND RESULTS

2.1 *Tested materials*

Standard Firoozkooh No.161 sand was used as the host sand. This sand is of crushed silica type with angular grains and is commonly used in Iran as the standard sand in geotechnical testing. The fine part of the soil consisted of three types: Firoozkooh micronized powder from the same mine of the host sand as the non-plastic fine (silt), Kaolin clay as the low-plastic fine and Bentonite clay as the highly-plastic fine. The physical properties of these materials are summarized in Table 1 together with the corresponding grain size distribution curves in Figure 1. Soil specimens of clean sand and also sand-fines mixture with 5 and 15% fines contents were considered in this study (Table 2). These samples were tested with different void ratios.

Table 1. Physical properties of the mixtures constituents

Material	Unified Classification	D_{50}	C_u	LL	PI	G_s
Firoozkooh sand	SP	0.23	1.32	-	-	2.65
Firoozkooh silt	ML	0.02	-	26	2	2.66
Kaolin clay	CL	0.003	-	43	18	2.69
Bentonite clay	CH	-	-	160	116	2.75

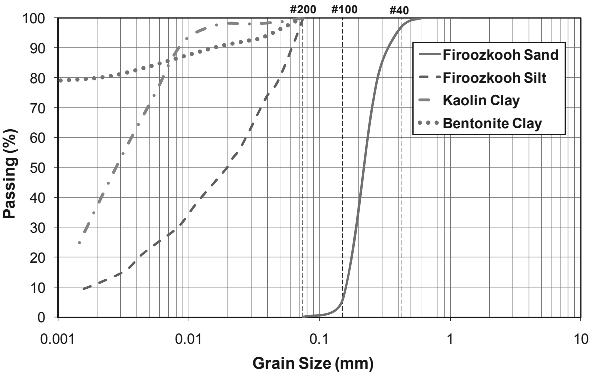

Figure 1. Grain size distribution curves of the mixtures constituents

2.2 Cyclic triaxial tests

The cyclic resistance of the sands tested was determined using undrained stress-controlled cyclic triaxial tests performed on reconstituted specimens according to ASTM D5311 standard testing procedure. The tested specimens were 70 mm in diameter and 140 mm in height.

In view of the diversity of the specimen reconstitution techniques (dry and water pluviation, moist tamping, slurry deposition, etc.), obtaining homogeneous samples in terms of void ratio distribution and consistency as well as covering a wide range of void ratios are the basic requirements. Huang et al. (2004) showed that specimen preparation method does not affect the liquefaction resistance-V_s correlations; moreover, it gives the widest range in void ratio among others (Ishihara, 1993). Therefore, moist tamping method of sample reconstitution was utilized to prepare the samples in the present study. In order to obtain a uniform density, the specimens were made in seven layers and the under-compaction method was used.

To facilitate the saturation process, carbon dioxide (CO_2) was first passed through the samples. Subsequently deaired water was allowed to flow in the specimens. Samples were then saturated by applying proper back pressure in successive steps. Samples were considered to be saturated if Skempton pore pressure parameter (B) value was greater than 0.95.

Saturated samples were then consistently consolidated uniformly in steps of 10 to 30 kPa. The consolidation process continued until the effective confining stress reached a value of 200 kPa. The void ratio of the samples after consolidation was determined by accurately measuring the moisture content at the end of the experiment.

At the end of the consolidation process, a sinusoidal loading with frequency of 1 Hz was applied to the sample having a specified cyclic stress ratio (CSR: which is the ratio of cyclic deviator stress to twice the initial consolidation stress). At least 3 cyclic tests were performed to obtain the cyclic resistance of a soil sample having a specified void ratio. All parameters except CSR were kept constant in these tests. The cyclic resistance (CRR_{tx}) is defined as the applied CSR required reaching 5% double amplitude strain in 15 loading cycles (representing an earthquake magnitude of 7.5). Generally, 110 cyclic triaxial tests have been conducted in this study on 7 different combinations of sand and fines with different void ratios.

Tests results, in the form of CRR_{tx} versus void ratio (e) for tested material are shown in Figure 2. As expected, the liquefaction resistance decreases as the void ratio increases. A power curve with the following expression can be fitted to these points for each soil.

$$CRR_{tx} = \alpha . e^{\beta} \quad (1)$$

where α and β are constants for a given material and can be obtained by fitting the obtained results; these values are presented in Table 2.

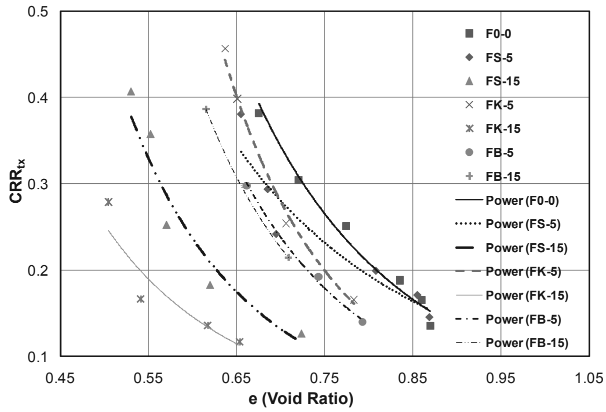

Figure 2. The CRR_{tx} versus void ratio for tested materials

2.3 Bender elements tests

In order to measure the V_s and CRR_{tx} on a single sample, the bender elements were installed in a cyclic triaxial apparatus at the top and bottom pedestal of the triaxial cell.

Immediately after the end of each consolidation stage (ranging from 30 to 200 kPa), V_s was measured using bender elements. V_s can be obtained from measuring the travel time from the source to the receiver (t) and dividing the sample length (L) to it. The value of "L" is assumed the tip-to-tip distance of the bender elements (Lee and Santamarina, 2005). In order to obtain the "t" value, the method of first arrival time was used. First arrival time refers to the time interval between the start of the source signal and the start of the major cycle of the received signal by ignoring the initial portion of the weak signal (Lee and Santamarina, 2005). In all the conducted bender element tests, a single sinusoidal pulse having a frequency of 5 kHz and amplitude of ±10 V was used as the transmitted signal. Sample result of a bender element test is represented in Figure 3 in which the first arrival time is shown.

The void ratio as well as the height of the samples changes in each consolidation stage as the confinement stress increases. To calculate the changes in the void ratio, the amount of water expelled from the specimen during consolidation stage was measured. Also, the water content of the samples was measured carefully at the end of the experiment. As the sample is already saturated prior to the consolidation phase, the void ratios at the earlier stages of consolidation can be back-calculated from these measured values. The settlement of the sample was also measured during the saturation and consolidation phase and the change in the height of the samples was accordingly used in calculating the V_s. Thus, from the bender element tests performed on a certain sample, for different void ratios and confinement effective stresses at successive stages of consolidation, the shear wave velocity is conveniently achieved. A total number of 1220 bender element tests were carried out on 110 different samples.

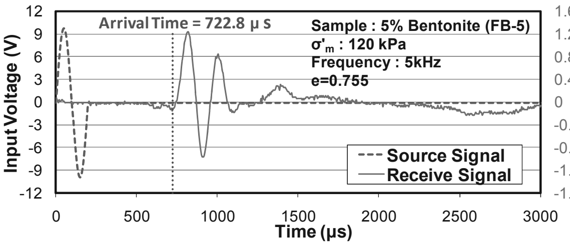

Figure 3. Representative result of bender element tests

The small-strain shear modulus (G_0) can be determined from shear wave velocity, according to the theory of elasticity, using Equation 2. In this equation ρ is the total density of the soil.

$$G_0 = \rho V_s^2 \tag{2}$$

G_0 of a granular soil is a function of its void ratio and effective confining stress, and can be obtained from the empirical equation developed by Jamiolkowski et al. (1991), as introduced in the following equation.

$$G_0 = C_g P_A^{1-n_g} e^{a_g} \sigma'^{n_g}_m \quad , \sigma'_m = [(1+2K_0)/3]\sigma'_v \tag{3}$$

where P_A is a reference stress equal to 100 kPa, σ'_m is mean effective stress, σ'_v is vertical effective stress, K_0 is the ratio of effective horizontal stress to effective vertical stress and a_g, n_g and C_g are intrinsic parameters associated with each type of soil material.

The intrinsic parameters of Equation 3 for tested materials were obtained by fitting the results of the bender element tests obtained for different consolidation stresses and void ratios and are listed in Table 2. The values of correlation coefficient, R^2, for all tested materials are very close to 1.0, indicating that the correlation is satisfactory. Using the Equation 3 and these intrinsic parameters, G_0 versus void ratio in isotropic consolidation stress of 100 kPa are presented in Figure 4.

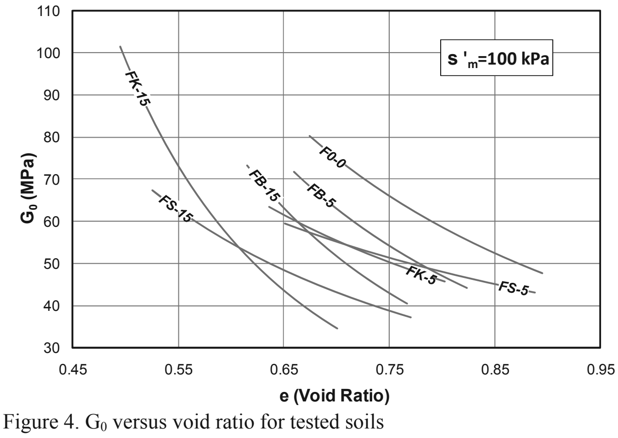

Figure 4. G_0 versus void ratio for tested soils

3 CONVERSION OF LABORATORY DATA TO FIELD CONDITIONS

Both the cyclic resistance and the V_s values measured in the laboratory must be corrected to represent the field conditions.

In a triaxial test, K_0 is equal to 1, but for saturated normally consolidated sand in the field, K_0 is generally between 0.4 and 0.5. In addition, seismic excitations in the field are multi-directional, while in a cyclic triaxial test, the cyclic load is applied in only one direction. Therefore, to account for these differences, the liquefaction resistance of the soil obtained from cyclic triaxial tests should be corrected. Several equations have been suggested in the literature regarding such corrections. In this study, the widely accepted Equation 4 proposed by Seed (1979) was used in this respect.

$$CRR = 0.9[(1+2K_0)/3]CRR_{tx} \tag{4}$$

where CRR is the actual liquefaction resistance in the field. On the other hand, according to Equations 3, the actual on-site small-strain shear modulus (G_{0field}) can be modified by the following equation to consider the effects of K_0.

$$G_{01} = [(1+2K_0)/3]^{n_g} G_{01tx} \tag{5}$$

where G_{01} is the small-strain shear modulus at a vertical effective stress of 100 kPa in the field, and G_{01tx} is the small-strain shear modulus obtained in the laboratory at an effective confinement stress of 100 kPa.

4 CORRELATION BETWEEN LIQUEFACTION RESISTANCE AND SHEAR WAVE VELOCITY

Using Equations 1 to 5, and eliminating the void ratio, the correlation between the field V_s at vertical effective stress of 100 kPa (V_{s1}) and the field liquefaction resistance (CRR) can be established:

$$CRR = (K_c P_A^{-1} G_{01})^{n_c} = (K_c P_A^{-1} \rho V_{s1}^2)^{n_c} \tag{6}$$

All parameters in Equation 6, except K_c and n_c have been defined previously. These parameters are defined as:

$$K_c = (0.9\alpha)^{\frac{a_g}{\beta}} \cdot \left(\frac{1}{C_g}\right) \cdot \left(\frac{1+2K_0}{3}\right)^{\frac{a_g}{\beta}-n_g} \tag{7}$$

$$n_c = \beta / a_g \tag{8}$$

Using Equation 6 and having the required values of intrinsic parameters for G_0 (a_g, n_g and C_g) and for liquefaction resistance ratio (α and β), the intrinsic parameters for CRR-V_{s1} correlation (K_c and n_c) can be obtained for any soil type. Assuming K_0 to be 0.5, the CRR-V_{s1} correlation intrinsic parameters were obtained and are presented in Table 2.

Like CPT- and SPT-based methods, a minimum CSR is considered as a threshold for the beginning of pore pressure build up. In this study, for conservatism, Equation 6 can be used for CSR>0.03 and below this value, independent of V_{s1}, soil is considered non-liquefiable. The developed CRR-V_{s1} curves using Equation 6 are plotted separately for sand with FC≤5% and FC=15% in Figure 5 and 6, respectively. The data obtained from experiments (modified for field conditions) are also presented in these figures. It can be seen that there is a good correlation between V_s and liquefaction resistance for a specified soil. For a constant fines content, CRR-V_{s1} curves vary depending on the plasticity of fines. Therefore, it can be concluded that the CRR-V_{s1} correlation depends on fines nature in addition to fines content.

In Figure 5 and 6, the curves proposed by Andrus and Stokoe (2000) are also presented for comparison. It worth noting that, the procedure developed by Andrus and Stokoe (2000) is based on field performance data and in situ V_s measurements.

Table 2. The intrinsic parameters that characterize liquefaction resistance, G_0 and V_{s1}-CRR correlation for tested materials

Tested Material	Fines Type and Content (FC)			Intrinsic Values for Eq. (1)			Intrinsic Values for Eq. (3)				Intrinsic Values for Eq. (6)	
	Silt	Kaolin	Bentonite	$a\times10^{-2}$	b	R^2	C_g	n_g	a_g	R^2	$K_c\times10^{-4}$	n_c
F0-0	0	0	0	9.02	-3.75	0.97	389	0.48	-1.84	0.95	7.48	2.04
FS-5	5%	0	0	10.44	-2.77	0.92	380	0.49	-1.05	0.97	11.25	2.64
FS-15	15%	0	0	3.39	-3.80	0.94	249	0.51	-1.55	0.96	10.10	2.45
FK-5	0	5%	0	4.87	-4.90	0.99	335	0.48	-1.41	0.97	13.10	3.47
FK-15	0	15%	0	3.12	-3.01	0.89	115	0.36	-3.10	0.97	1.68	0.97
FB-5	0	0	5%	5.44	-4.14	0.99	290	0.46	-2.18	0.97	6.85	1.90
FB-15	0	0	15%	5.12	-4.16	1.00	197	0.43	-2.70	0.99	6.30	1.54

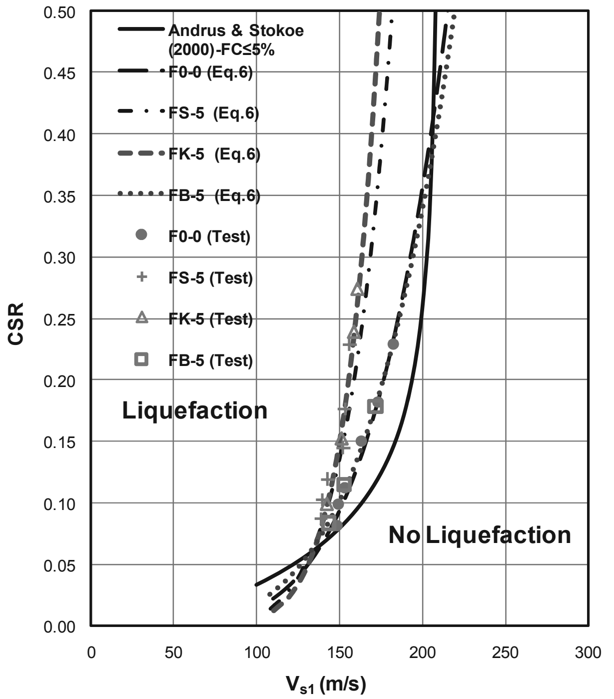

Figure 5. Correlation between CRR and V_{s1} for sand with FC≤5%

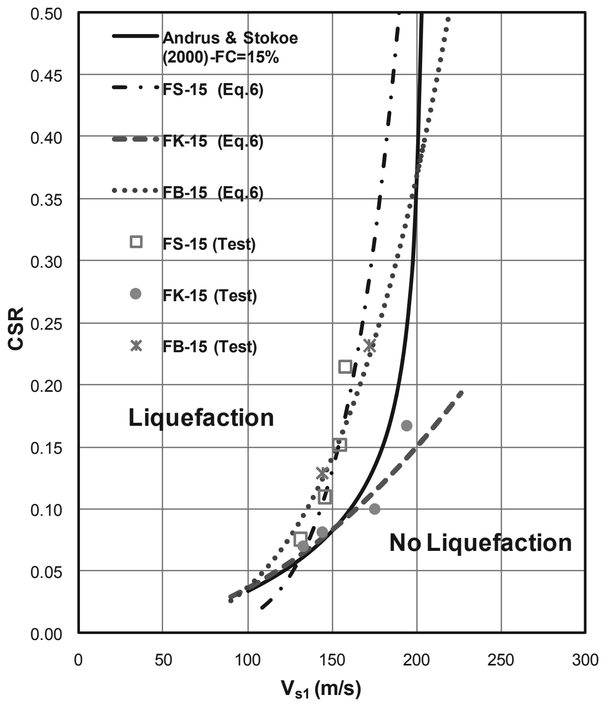

Figure 6. Correlation between CRR and V_{s1} for sand with FC=15%

Based on Figure 5, there is a relatively good agreement between the existing method proposed by Andrus and Stoke (2000) and results of this experiment for clean sand and sand containing 5% Bentonite clay. However, for sand containing 5% of silt or Kaolin clay, using the existing curves leads to conservative results. According to Figure 6, for 15% of fines content, the existing method may overestimate or underestimate the liquefaction resistance depending on the fines type.

In general based on the presented results, one can say that the correlation between CRR and V_{s1} is soil specific. It suggests the need for development of soil-specific correlations from laboratory tests for a specified soil.

5 CONCLUSIONS

In this paper, cyclic triaxial and bender elements tests were performed on clean sand and sand containing 5 and 15% non-plastic, low-plastic and highly-plastic fines to investigate the effect of fines type on the CRR-V_{s1} correlation. A semi empirical equation is established to correlate the CRR and V_{s1}.

According to the developed CRR-V_{s1} correlations for tested materials, it is found that the correlation depends on fines nature in addition to fines content. Therefore, the correlation between CRR and V_{s1} must be considered soil specific. The curves of Andrus and Stokoe (2000) may either underestimate or overestimate the liquefaction resistance of sand-fines mixtures.

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