Correlation of shear wave velocity with liquefaction resistance for silty sand based on laboratory study

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ABSTRACT

Several methods have been used for the evaluation of liquefaction potential, among which the simplified method is mostly used. In this method, which is mainly based on standard penetration test (SPT), cone penetration test (CPT) and shear wave velocity \( V_s \) measurement, a boundary curve is provided to separate the liquefiable and non-liquefiable soil zones. \( V_s \) measurement is a good alternative method of penetration-based methods (SPT and CPT). This is especially true in micro-zonation of liquefaction potential. Although relatively large studies have been carried out to establish the correlation between \( V_s \) and liquefaction resistance for sands; there are uncertainties about the effects of non-plastic fines on the correlation. The objective of this research is to study the effects of fines on the correlation of \( V_s \) and liquefaction resistance. In this regard, the cyclic triaxial and bender elements tests have been performed, and \( V_s \) and liquefaction resistance of a clean sand and four combinations of this sand with non-plastic fines up to 25% have been measured. A simple, semi-empirical, semi-analytical method is proposed to establish a correlation between \( V_s \) and liquefaction resistance. The effects of non-plastic fines on \( V_s \) and liquefaction resistance of silty sands have been examined in this study, and the effects of non-plastic fines on the correlations between these two parameters are considered. The results in this study show that an increase in the ratio of silt to sand will result in a decrease in \( V_s \) and liquefaction resistance. Based on these results, it is argued that the correlation between \( V_s \) and liquefaction resistance of various combinations of sand and non-plastic fines are soil specific. Also based on the results of this study, it is found that the existing methods of liquefaction potential evaluation which are based on \( V_s \) may underestimate or overestimate the liquefaction resistance of silty sands.

Keywords: liquefaction resistance, shear wave velocity, non-plastic fines, bender element tests, cyclic triaxial tests

1 INTRODUCTION

Over the past three decades, a methodology termed the “simplified procedure”, developed by Seed and Idriss (1971), has evolved as a standard of practice for evaluating the liquefaction resistance of soils (Youd et al. 2001). Compared with other indexes, shear wave velocity \( V_s \) offers geotechnical engineers a promising alternative and a supplementary tool toward the penetration-based methods, such as standard penetration test (SPT) and cone penetration test (CPT), to evaluate liquefaction resistance of sandy soils (Andrus and Stokoe 2000).

Many factors such as relative density, soil structure, strain and previous earthquakes can change the liquefaction resistance and \( V_s \) in the same direction (Tokimatsu and Uchida 1990). Given this, the idea of using shear wave velocity to evaluate the liquefaction resistance has been developed.

The effects of fines on \( V_s \) are less completely studied and understood (Liu and Mitchell 2006). Iwasaki and Tatsuoka (1977) showed that the small-strain shear modulus \( G_0 \), and therefore \( V_s \), decrease rapidly with increase in non-plastic fines content. A significant reduction in \( G_0 \) with the addition of silts was also reported by Randolph et al. (1994).

Many studies have investigated the influence of fines on the Cyclic Resistance Ratio (CRR) of sands. CRR is defined as the cyclic liquefaction resistance normalized with initial overhead effective stress. Review of the literature shows that there is no clear consensus as to what effect an increase in non-plastic fines content has upon CRR of sand (Polito and Martin 2001).

Relatively large numbers of studies have been performed to establish the correlation between shear wave velocity and liquefaction resistance of clean sands, but given the ambiguity and uncertainty about the effect of fines content on liquefaction resistance and also on shear wave velocity, the CRR-\( V_s \) correlation for sands with fines content is not fully clear. On the other
hand, it has recently been determined that the CRR-V_s correlation is soil specific and the existing field curves significantly overestimate or underestimate the liquefaction resistance (Zhou et al. 2010). Therefore it is necessary to study the effect of fines content on CRR-V_s correlation.

In this study, laboratory measurements of V_s using bender elements and cyclic triaxial tests have been conducted using clean sand and sand containing up to 25% non-plastic silt by weight. A new simple method based on theoretical considerations and laboratory data is presented to develop the CRR-V_s correlation. The results of this study are then compared with the simplified well known and widely used procedure of Andrus and Stokoe (2000).

2 TESTING PROGRAM

2.1 Soils Tested

Tested soil generally consists of standard Firoozkooeh #161, crushed silica sand with uniform grain size distribution, and Firoozkooeh micronized powders as fine part. Specific gravity of the sand and silt are equal to 2.65 and 2.66, respectively. The non-plastic silt has liquid limit of 26 and plastic Index of 2. Grain size distributions of the sand and the silt are shown in Figure 1.

Fig. 1. Grain size distributions of tested sand and silt

Five combinations of sand and silt were tested using sand, with fines contents of 0, 3%, 5%, 15% and 25% at different void ratios (f). A plot of the maximum and minimum index void ratios versus fines content is also presented in Figure 2.

2.2 Cyclic Triaxial Tests

Cyclic resistance of the soils was determined using undrained load controlled cyclic triaxial tests performed on reconstituted specimens. The specimens tested were 70 mm in diameter and 140 mm in height. Moist tamping method with 5% water content was used to prepare the homogeneous samples. In order to obtain a uniform density, the specimens were made in seven layers and the undercompaction method proposed by Ladd (1978) was used. ASTM D 5311 standard test method was used to perform the cyclic tests.

Fig. 2. Variation in maximum and minimum void ratios with fines content

To facilitate saturation process, carbon dioxide (CO_2) was first passed through the sample, then de-aired water was allowed to flow the specimens. At the end, using proper back pressure in successive steps the sample was saturated. The degree of saturation was controlled by means of Skempton’s pore pressure parameter, B. According to ASTM D 5311 standard, test samples are considered to be fully saturated if B is greater than 0.95. Saturated samples have consistently consolidated uniformly in steps of 10 to 30 kPa up to 200 kPa. In each different consolidation stress, V_s was measured using bender elements. After the consolidation phase, cyclic loading was performed sinusoidally at a frequency of 1 Hz according to specified cyclic shear stress ratio (CSR: Cyclic Stress Ratio which is the ratio of deviator stress to twice the initial consolidation stress).

The number of cycles required for initial liquefaction, when water pressure firstly reaches the initial consolidation stress, has been identified. The void ratio of the samples after consolidation stages was determined by accurate measurements of the moisture content at the end of the experiment. To obtain the liquefaction resistance of a sample of soil with a specified void ratio, at least 3 cyclic triaxial tests have been conducted. In these tests, all conditions except the CSR were kept constant. Generally 98 cyclic triaxial tests have been conducted. In this paper, CRR_{tx} (Liquefaction resistance from triaxial test) is considered CSR for initial liquefaction in 15 cycles. CRR_{tx} for different sand-silt mixtures, with different void ratios are presented in Figure 3. A power curve can be fitted to these points with following expression:

\[
CRR_{tx} = \alpha e^\beta
\]  

(1)

Where, e is the void ratio and \( \alpha \) and \( \beta \) are constants for a given soil material. According to Figure 3, the values of \( \alpha \) and \( \beta \) can be obtained; these values are presented in Table 1.
density of the soil.

\[ G_0 = \rho V_s^2 \]  \hspace{1cm} (2)

\( G_0 \) for granular soils is a function of void ratio and effective confining stresses (Hardin and Richart 1963). According to research conducted by Jamiołkowski et al. (1991), the small strain shear modulus can be obtained from Equation 3.

\[ G_0 = C_p \rho \sigma'_m \] \hspace{1cm} (3)

\[ \sigma'_m = \frac{1 + 2K_0}{3} \sigma' \] \hspace{1cm} (4)

Where, \( P_A \) is a reference stress equal to 100 kPa, \( \sigma'_m \) is mean effective stress, \( \sigma' \) is vertical effective stress, \( K_0 \) is ratio of horizontal effective stress to vertical effective stress and \( a_\rho, n_\rho \) and \( C_p \) are intrinsic parameters associated with each type of soil material.

### 2.3 Bender Elements Tests

In order to measure the shear wave velocity and liquefaction resistance on the same sample, the bender elements were assembled on the triaxial apparatus and the bender elements were installed at the top and bottom pedestals of the triaxial cell.

As mentioned, shear wave velocity was measured in each consolidation step up to 200 kPa in the consolidation phase by using the bender elements. The void ratio and the height of samples change with increasing the effective stress due to consolidation; this variation was considered in the shear wave velocity calculations.

In these tests, a single sinusoidal wave impulse with frequency of 5 kHz and amplitude of ±10 Volts was used as input. The shear wave velocity was calculated using the tip-to-tip distance (Lee and Santamarina 2005) and the travel time of the wave. To calculate the travel time of the wave, the first arrival time method was used. This time refers to the time between the start of the source signal and the start of the major cycle of the receiver signal by ignoring the initial portion of the weak signal. This weak signal indicates the presence of the near field effect (Lee and Santamarina 2005).

An example of the bender elements test result is presented in Figure 4. In this research a total of 990 bender elements tests were carried out on 98 different samples.

The small strain shear modulus \( (G_0) \) can be obtained from \( V_s \) by Equation 2. In this equation \( \rho \) is the total density of the soil.

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### Table 1. Liquefaction resistance parameters for different percentage of fines content

| Fine Content (F.C.) | Liquefaction Resistance Parameters | \( \sigma'_m \) | \( \sigma'_v \) | \( G_0 \) |
|---------------------|-----------------------------------|----------------|----------------|---------|
| 0%                  | 0.09                              | -3.80          | 0.97           |         |
| 3%                  | 0.09                              | -3.40          | 0.99           |         |
| 5%                  | 0.10                              | -2.81          | 0.92           |         |
| 15%                 | 0.04                              | -3.75          | 0.93           |         |
| 25%                 | 0.02                              | -3.82          | 0.97           |         |

### Table 2. Intrinsic values for small-strain shear modulus Evaluation for different percentage of fines content

| \( C_p \) | \( a_\rho \) | \( n_\rho \) | \( R^2 \) |
|----------|-------------|-------------|---------|
| 389      | 0.48        | -1.84       | 0.95    |
| 404      | 0.50        | -0.94       | 0.99    |
| 380      | 0.49        | -1.05       | 0.97    |
| 250      | 0.51        | -1.53       | 0.96    |
| 150      | 0.51        | -2.14       | 0.94    |

The small-strain shear modulus versus void ratio for combinations of silt and sand in isotropic consolidation stress of 100 kPa are presented in Figure 5.

### 3 CRR-VsL CORRELATION

Both the cyclic resistance and the shear wave velocity measured in the laboratory must be corrected to represent the field conditions. In the cyclic triaxial test, \( K_0 \) is equal to 1, but for saturated sandy soil in the field conditions, this value is generally between 0.4 and
0.5. In addition, the real earthquake vibration is multi-directional, while the cyclic triaxial test is one-directional. Therefore, the liquefaction resistance of the soil obtained from cyclic triaxial tests should be modified. For this modification, there are different relationships. Equation 5 is one of the most common methods provided by Seed et al. (1979), and is used in this study.

\[
\text{CRR} = 0.9 \left(1 + \frac{2K_0}{3}\right) \frac{\text{CRR}_{\text{field}}}{\text{CRR}_{\text{ref}}} \quad (5)
\]

Where, CRR is actual liquefaction resistance in the field. 0.9 is a factor to account for strength loss in multidirectional shaking in a real earthquake, compared with unidirectional laboratory testing.

![Fig. 5. G_0 versus void ratio for different percentage of fines content in consolidation stress=100 kPa](image)

Using Equation 1 to 5, the correlation between the field shear wave velocity in the vertical effective stress of 100 kPa (\(V_{s1}\)) and the field resistance to liquefaction (CRR) can be established (Equation 6). In this Equation, shear wave velocity is in meters per second and soil density is in tones per cubic meter.

\[
\text{CRR} = C_c (\rho V_{s1}^2)^{\gamma c} \quad (6)
\]

\[
C_c = 0.9a_c \left(\frac{1}{P_A C_g} \right) \left(1 + \frac{2K_0}{3}\right) \frac{a_g}{a_{eq}} \quad (7)
\]

\[
n_c = \frac{\beta}{a_g} \quad (8)
\]

\(V_{s1}\) is obtained by in situ shear wave velocity measurements (\(V_{s1,\text{field}}\)) should be corrected for overburden pressure using Equation 9.

\[
V_{s1} = V_{s1,\text{field}} \left(\frac{P_A}{\sigma_v}\right)^{0.25} \quad (9)
\]

If \(a, \beta, a_{eq}, n_c, \text{ and } C_g\) from the tests results are substituted in Equation 6, and also \(K_0\) is assumed to be 0.5, then the CRR-\(V_{s1}\) correlation coefficients (\(C_c, n_c\) and \(m_c\)) will be obtained (Table 3).

CRR-\(V_{s1}\) curves obtained using Equation 6 and Table 3 together with the data obtained from experiments (modified for field conditions) are presented in Figure 6. As can be seen, there is a good correlation between shear wave velocity and liquefaction resistance. By adding small amount of fines (3%), CRR values increase rapidly for constant \(V_{s1}\) values. Figure 6 also shows that adding more non-plastic fines up to 15% will not cause significant changes in CRR-\(V_{s1}\) curve, but CRR will decrease by increasing the fines content up to 25% and it will reach the clean sand CRR-\(V_{s1}\) curve.

Table 3. CRR-\(V_{s1}\) correlation coefficients for different percentage of fines content

| Fine Content (F.C.) | \(C_c\) | \(n_c\) | \(m_c\) |
|---------------------|--------|--------|--------|
| 0%                  | 2.53E-11 | 2.07   | 4.14   |
| 3%                  | 2.29E-18 | 3.62   | 7.25   |
| 5%                  | 5.28E-14 | 2.69   | 5.37   |
| 15%                 | 6.17E-13 | 2.45   | 4.89   |
| 25%                 | 5.20E-10 | 1.79   | 3.57   |

![Fig. 6. The CRR–\(V_{s1}\) correlation for different percentage of fines content](image)

4 COMPARISON WITH PREVIOUS STUDIES

The procedure developed by Andrus and Stokoe (2000) is based on field performance data and in situ \(V_s\) measurements. It follows the framework of the Seed-Idriss simplified procedure and is widely used.
The CRR-\(V_{s1}\) curves obtained in the present study and those from Andrus and Stokoe (2000), separated for different fines content are provided in Figure 7 to 9. According to this figure, the existing method may overestimate or underestimate the liquefaction resistance obtained from shear wave velocity. It confirms the hypothesis that the CRR-\(V_{s1}\) correlation is soil specific.

According to Figure 7 to 9, there is also a relatively good agreement between the existing method (Andrus and Stokoe 2000) and results of this experiment for clean sand and silty sand with 25% of fines content. However at low percentages of fines content (i.e. 3% to 15%), using the existing curves for evaluating liquefaction resistance from shear wave velocity, leads to very conservative results.

5 CONCLUSION

In this paper, cyclic triaxial tests and bender elements tests were performed on clean and silty sand with 0% to 25% fines content to study the effect of fines content on the CRR-\(V_{s1}\) correlation and also to investigate the accuracy of the simplified method for evaluating liquefaction potential from shear wave velocity. A new semi empirical equation is established to correlate the CRR and \(V_{s1}\).

The direct results of this study show that adding a small amount of non-plastic fines (3%) will increase CRR values rapidly for constant \(V_{s1}\) values. Adding more fines up to 15%, will not cause significant changes in CRR, but CRR will decrease by increasing the fines content up to 25% and it will reach the clean sand curve. Also there is a relatively good agreement between the existing method and results of this experiment for clean sand and silty sand with 25% of fines content. However for low percentages of fines content (3% to 15%), using the existing CRR-\(V_{s1}\) curves, leads to very conservative results.

The results of this and previous studies show that also there is a good correlation between shear wave velocity and liquefaction resistance, this correlation is...
soil specific and the existing simplified method may underestimate or overestimate the liquefaction potential of silty sands.

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