The Validity Assesment of Laboratory Shear Modolus Using In-Situ Seismic Piezocone Test Results

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Abstract: Seismic piezocone device (SCPTu) together with Resonant Column and Cyclic Triaxial test apparatus are employed to measure small strain shear modulus (G0) of carbonate sandy and clayey soils of southern coasts of Iran. A large area of southern regions of Iran is formed from clay, silt and sand. In this study, maximum shear modulus that is derived from both field (by seismic piezocone) and laboratory (by Resonant Column and Cyclic Triaxial) tests on soil samples from the southern region, indicated a meaningful effect of sample disturbance. Results show that in laboratory tests, loose samples tend to become denser and therefore exhibit greater stiffness whereas dense samples tend to become looser, showing a reduction in stiffness. According to the results of the present study, there are narrow limits of soils shear moduli for which the laboratory tests and the field measurements yield approximately the same amounts. This limit of shear moduli is about 30-50(MPa) for clay deposits and 70-100 (MPa) for sandy deposits. Since the shear moduli of soils in small strains can also be computed from the shear wave velocity, also correlations based on parameters derived from SCPTu test for shear wave velocity determination of sandy and clayey soils of the studied area are presented. This study shows that shear wave velocity can be related to both corrected tip resistance and total normal stress. The measurements of the damping ratio and shear module, because of a great disturbance of stiff deposits during the sampling process and also due to considerable differences between the laboratory and field results, by the laboratory approaches are not reliable and advised.

Keywords: *Maximum Shear Modulus, Shear Wave Velocity (Vs), Seismic Piezocone Test (SCPTu), Resonant Column Test.*

1. Introduction

The capability and advantages of the cone penetration test device, comparing with standard penetration and other in-situ testing equipments, in measuring the soil strength parameters particularly fine materials have been widely investigated and discussed (Baziar & Ziaie-Moayed ,2006 [1] and Naeini & Ziaie-Moayed ,2007 [2])so far.

The seismic piezocone test device (SCPTu), among the large number of in-situ devices, represents the most versatile tool currently available for soil exploration (Lunne et al., 2002) [3]. The piezocone test provides continuous sounding capability and good repeatability. It can also be run very cost- effectively. By developing piezocone, many researches were carried out using its advantages. Pore pressure dissipation behavior is investigated by Burns & Mayne (1999) [4]. Liao & Mayne (2005) [5] and Liao et al. (2002) [6] work on seismic hazard by application of seismic piezocone.

Many researchers have worked on shear wave velocity on various soils (Lin et al., 2002 [7], Gomberg et al., 2003[8], and Mayne and Rix, 1995[9]). Despite the fact that the shear wave velocity (V_s) and the cone tip resistance (q_c or q_T) reflect the soil behavior at the opposite extremes of its highly nonlinear stress-strain-strength relationship, the two parameters can be interrelated because they are both influenced by effective confining stress level, anisotropic K_0-stress state, mineralogy, aging, bonding, and other factors (Mayne & Rix, 1995[9]). Research using resonant column testing (Hardin, 1978) [10] suggested that Vs depends on such variables

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as mean effective stress, void ratio and over consolidation ratio. Cone tip resistance is also controlled by the effective geostatic stress state given by the magnitudes of σ'_v and σ'_h (Crooks et al., 1988) [11], therefore it is possible to relate V_s and q_T or q_C empirically.

In this paper, the results of SCPTu and some cyclic laboratory tests (Resonant Column and Cyclic Triaxial) are considered and maximum shear modulus (G_0) determined by these results is evaluated for the determination of sample disturbance effects. Finally, since the small strain shear moduli of soils can be estimated using the shear wave velocity, new expressions for the shear wave velocity in terms of in-situ CPTu test results are also presented.

2. Description of Area Under Study

Two sites are selected and concentrated in the present study, both of them on the Persian Gulf Northern Coasts (Figure 1). Site "A" is located near Bandar Abbas Port near Hormorz strait and on the northern coasts of Persian Gulf. Site "B" is located in Tombak near Assaluyeh Petrochemical Port. Site "A" is constructed in an onshore environment, while the other one is a near shore environment where water depth is always below 25 meters. In particular, existence of carbonate soils in this area requires special attention. Since the area is a seismically active, determination of dynamic soil parameters are of great importance.

Sequence of layers at site A is plotted in Figure 2.

In site "A", the ultimate depth that seismic piezocone tests were performed was 20m. At depths from 0.0 to 3m, there is an overburden layer which includes silty sand with gravel. Medium dense silty and clayey sand was observed at depths from 3m to 10m. Soft to firm silty clay was encountered at depths from 10m to 20m. Soil classification based on grain size analysis and other conventional physical tests (ASTM D2487 & ASTM D422) [12 & 13] showed that the soil types for these three layers are SM, ML and CL respectively. Chemical carbonate tests performed in accordance with ASTM D4373 [14] showed more than 70 percent of $CaCo_3$ content in this site. In site "B", the ultimate depth that piezocone tests were performed was about 14m. Water depth varied from 8m to 20m. For depth from 0.0 to 10m, there is a layer of soft to medium stiff sandy silt with trace of shale. Stiff silty clay with trace of shale was observed from 10m to 14m depth. Soil classification based on grain size analysis and other conventional physical tests (ASTM D2487 & ASTM D422) [12 &13] showed that the soil types for these two layers are ML and CL; respectively. Chemical carbonate tests performed in accordance with ASTM D4373 [14] showed more than 80 percent of $CaCo_3$ content in this site. Seismic Piezocone, Resonant Column and Cyclic Triaxial tests were performed on selected undisturbed samples obtained from this site.

3. The Research Method and Approaches

The Cyclic Triaxial and Resonant Column tests are selected in this study and their results are compared to Piezocone test results. Detailed reviews of laboratory and field methods for the measurement of G_o are given by Woods (1994) [15] and Companella (1994) [16], respectively.

The Resonant Column test is the most commonly used laboratory test for measuring the

Fig. 1. The location of sites under study

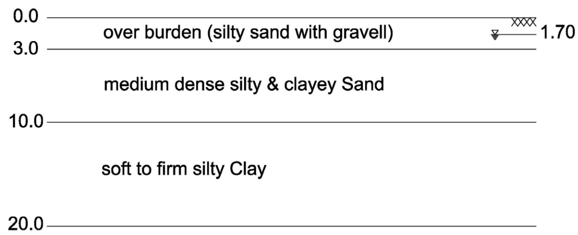

Fig. 2. Stratagraphy of sub-surface (Site A)

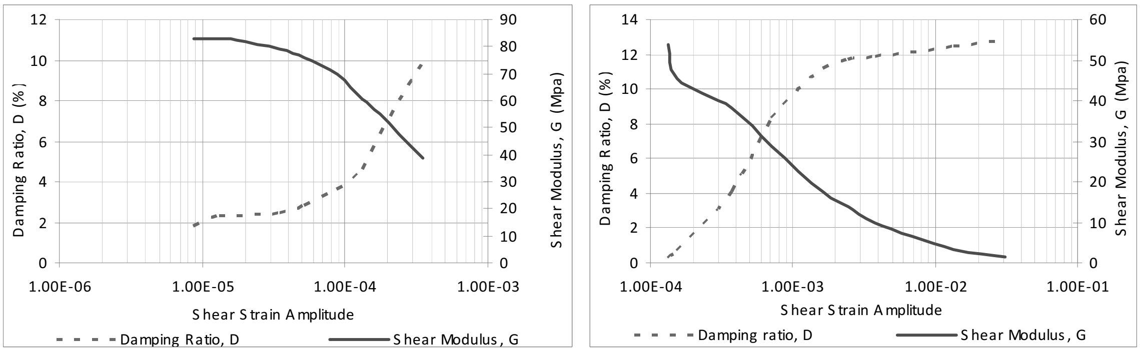

Fig. 3. Typical results of resonant column (left) and Cyclic Triaxial (right) tests

low-strain properties of soils (Kramer, 1996) [17]. The range of shear strain is less than (Ishihara, 1996) [18]. In spite of developing and using different methods to measure the soil damping directly in the field (Haddad & Shafabakhsh, 2007) [19], but still the resonant column test allows stiffness and damping characteristics of soil samples to be measured under more accurate and controlled conditions. The effects of effective confining pressure, strain amplitude, and time can readily be investigated. However measurement of pore water pressure is difficult and the material properties are usually measured at frequencies above those occur in most earthquake motions. Figure 3 shows typical test results obtained from resonant column tests. In this study, 22 undisturbed samples were tested according to the ASTM D4015 standard [20].

After the resonant column specimen has been prepared and consolidated, cyclic loading is applied. The loading frequency is initially set at a low value and is then gradually increased until the response (strain amplitude) reaches to a maximum level. The lowest frequency at which the response is locally maximized is the fundamental frequency of the specimen. The fundamental frequency is a function of the low-strain stiffness of the soil, the geometry of the specimen, and certain characteristics of the resonant column apparatus.

The Cyclic Triaxial test apparatus has been widely used for testing cohesionless soils in the laboratory under cyclic loading conditions (Ishihara, 1996) [18]. In this study, all 12 samples used in the Cyclic Triaxial tests were undisturbed. The results of Cyclic Triaxial tests were modified for low-strain based on methods presented by Seed & Idriss (1970) [21] and Vucetic & Dobry (1991) [22]. The results are used to compare with Piezocone results. The test procedure in this series is also conducted based on ASTM D3999 [23]. Figure 3 shows typical test results obtained from Cyclic Triaxial tests.

Cone penetration Testing (CPT) is conducted in accordance with ASTM D5778 [24]. A schematic diagram with the layout of the standard technique using a seismic cone and the operation of the conducted tests is shown in Figure 4. The shear wave is generated by hitting the beam-ends horizontally with the hammer in the direction of the longitudinal axis. Normally the seismic cone penetrometer is pushed into the ground and penetration is stopped at 1m intervals (Lunne et al., 2002) [3]. During the pause in penetration, a shear wave is generated at the ground surface and the time required for the shear wave to reach the seismometer in the cone penetrometer is

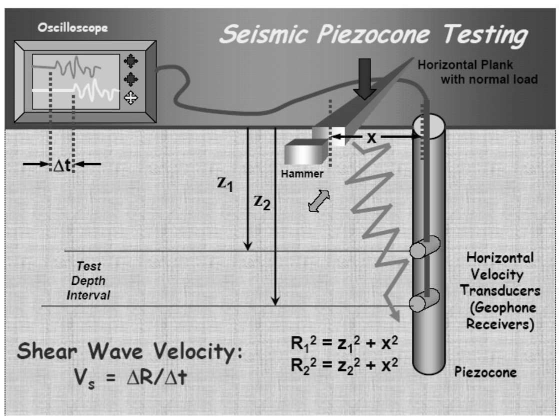

Fig. 4. Principles of the seismic cone survey technique

Table 1. Type and number of Tests performed in each site

	TEST DESCRIPTION	NO. OF TESTS IN SITE A	NO. OF TESTS IN SITE B
1	CPTU	35	30
2	SCPTU	40	30
3	RESONANT COLUMN	10	10
4	CYCLIC TRIAXIAL	10	10
5	CLASSIFICATION	200	200

recorded. Using the measured data, shear wave velocity can be calculated. Elastic theory relates the small strain shear modulus (G_0) and shear wave velocity V_s as below:

$$G_0 = \rho (V_s)^2 \tag{1}$$

Where, ρ is the mass density of the soil.

Extensive research has shown that the value of G_0 in soils is the same for both static (monotonic) and dynamic loading conditions (Jamiolkowski et al. 1994, and Tatsouka et al., 1997) [25 &26]. The magnitude of G_0 is also independent of drainage because the strains are too small to cause excessive pore water pressure, and thus applies to both drained and undrained conditions (Mayne, 2000) [27].

According to the above explanations a series of seismic tests were carried out on carbonate soils in both sites of the selected area. The No. and the type of the whole performed tests are given in table 1.

4. Comparison of Laboratory and In-Situ Shear Modulus

Small strain shear modulus obtained from Seismic Piezocone tests (SCPTu) and laboratory tests are presented and compared in this part. Furthermore, data from the current study is compared with those presented by Yasuda & Yamaguchi (1985)[28] who compiled a profusion of test data to provide diagrams in which the ratio between the laboratory-determined and in-situ measured shear moduli are plotted versus the shear modulus determined from the in-situ velocity logging. Figure 5 is a similar plot that represents the data of this study together with those of Yasuda & Yamaguchi (1985) [28]. The data in this figure present only for silty sand (SM) soil. Figure 5 shows a general tendency of the ratio of laboratory-obtained to field measured shear moduli to decrease as the stiffness of the sand becomes greater. From Figure 5, the Yasuda & Yamaguchi [28] curve for lower range of in-situ G_0 (30-50 MPa) or V_s (150-160 m/sec), the ratio of G_{0L}/G_{0F} is greater than one (where G_{0F} and G_{0L} indicate the shear moduli determined in the field and in the laboratory tests, respectively). This shows that for the soil with lower stiffness, G_{0L} is greater than G_{0F}. One of the most possible causes would be the disturbance of samples during sampling and handling (Ishihara, 1996) [18]. As it can be seen in Figure 6 for stiffer soil, sample disturbance could cause reduction in G_{0L} obtained from laboratory tests. It is interesting that the changing point of the ratio of G_{0L}/G_{0F} for the data of the current study is about 70-100 MPa. In general, loose samples tend to become denser thereby exhibiting greater stiffness and dense samples become looser showing a reduction in stiffness (Ishihara, 1996) [18].

For the studied SM soil, it seems that, there are more disturbances compared with those of Yasuda & Yamaguchi's soil (1985) [28]. The greater the disturbance, the larger the difference in the ratio of G_{0L}/G_{0F} in the range of stiffness which is small or large, reflecting the potential of volume increase or decrease due to the dilatancy (Ishihara, 1996) [18].

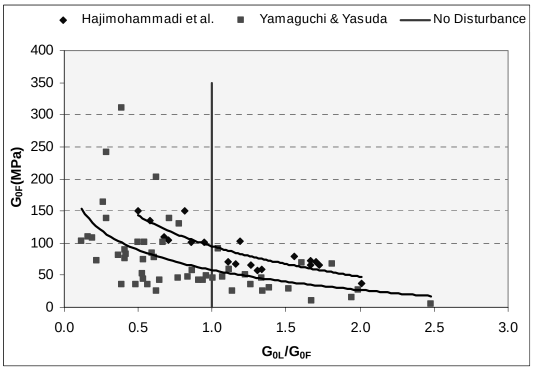

Fig. 5. Comparison of Yasuda & Yamaguchi (1985) [28] with our results for sands

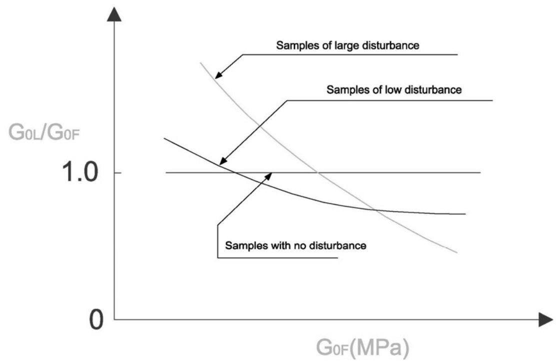

Fig. 6. Degree of sample disturbance influencing the ratio of shear moduli from laboratory tests to those from in situ tests (Ishihara, 1996) [18]

The effect of sample disturbance may be illustrated schematically in Figure 6. The other reason that may be considered is that the soil of this area is more sensitive than the soil tested by Yasuda & Yamaguchi (1985) [28].

In another set of data, Yokota and Konno (1985) [29] presented their results for silty and clay deposits as shown in Figure 7. This Figure shows a comparison of shear moduli obtained from in-situ and laboratory tests in clayey and sandy soils.

According to Figure 7, for soils with small shear moduli, it may be seen that the laboratory tests tend to yield approximately the modulus values as those obtained in the field by the use of SCPTu test. This limit is about 40 MPa for clayey deposits and 60 MPa for sandy deposits.

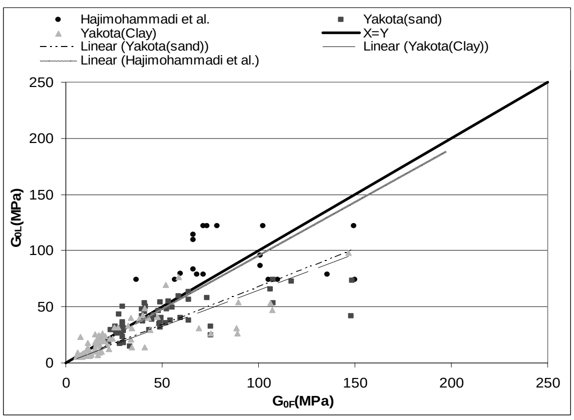

Fig. 7. Comparison between shear modulus obtained from present study and those obtained by Yokota & Kanno (1985) [29]

5. Shear Wave Velocity Experssions

One of the application and advantages of the cone penetration test data is to develop appropriate expressions to determine directly the shear modulus or shear wave velocity in a specific site empirically. Expressions have been developed for both sandy and clayey soils from either field measurements (Cross-Hole and Down-Hole testing) or calibration chamber testing (Maher et al., 2002) [30]. However, in this study we have presented new expressions for both carbonate sandy and clayey soils from seismic piezocone test data.

Hajimohammadi et al. (2007, 2008) [31&32] based on seismic piezocone results in a silty sand soils presented the following equation:

$$V_s = 250(\sigma'_V)^{0.15}(q_T)^{0.09} \tag{2}$$

Based on the results of SCPTu tests done in southern coasts of Iran (adjacent to Persian Gulf, Figure 1), new expressions for carbonate sandy silt, silty sand and sand was presented as below:

$$V_s = 630\,(\sigma_V)^{0.23}(q_T)^{0.4} \tag{3}$$

Where,

V_S: Shear wave velocity (m/sec), q_T: Corrected cone tip resistance (MPa) and σ_V: Total overburden pressure (MPa).

The main difference between Equation 2 (presented by Hajimohammadi et al. 2007,2008) [31&32] with Equation 3 is the substitution of effective normal stress by total normal stress that

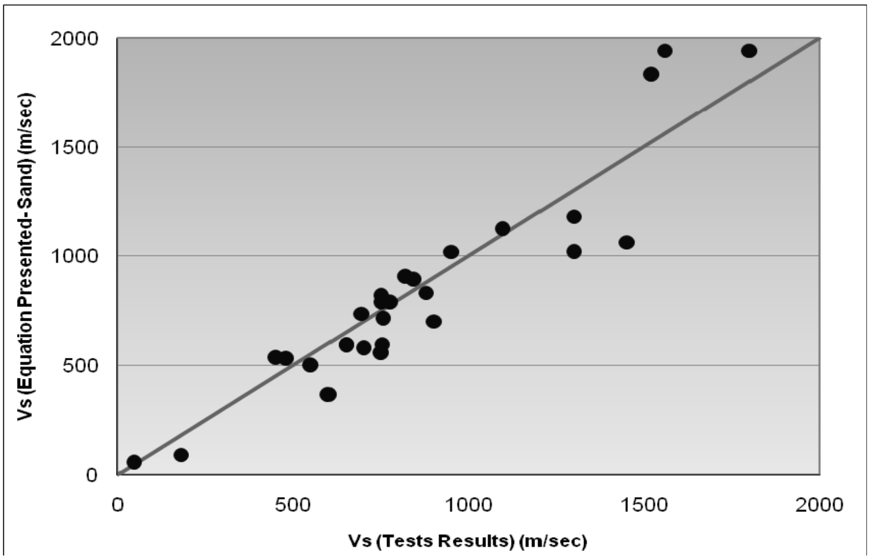

Fig. 8. The shear wave velocities for sandy soils based on the field data and the suggested equation

shows better adjustment with existed results.

Hajimohammadi et al. (2007, 2008) [31&32] based on seismic piezocone results in silty clay soils presented the following equation:

$$V_s = 11.128(q_C)^{0.4074} \quad (4)$$

Utilizing the seismic piezocone (SCPTu), a new expression is presented for carbonate clayey silts, silty clays and clays as below:

$$V_s = 199\,(\sigma_V)^{0.043}(q_T)^{0.18} \quad (5)$$

Where:

V_S: Shear wave velocity (m/sec), q_T: Corrected cone tip resistance (MPa) and : Total overburden pressure (MPa).

Comparison between the data measured directly in the sites and those obtained from Equation 5 shows that the term of q_T is a more suitable factor and gives more reliable results.

6. Conclusions

Four recordable in-situ data at two sites in Southern coast of Iran, near the Persian Gulf

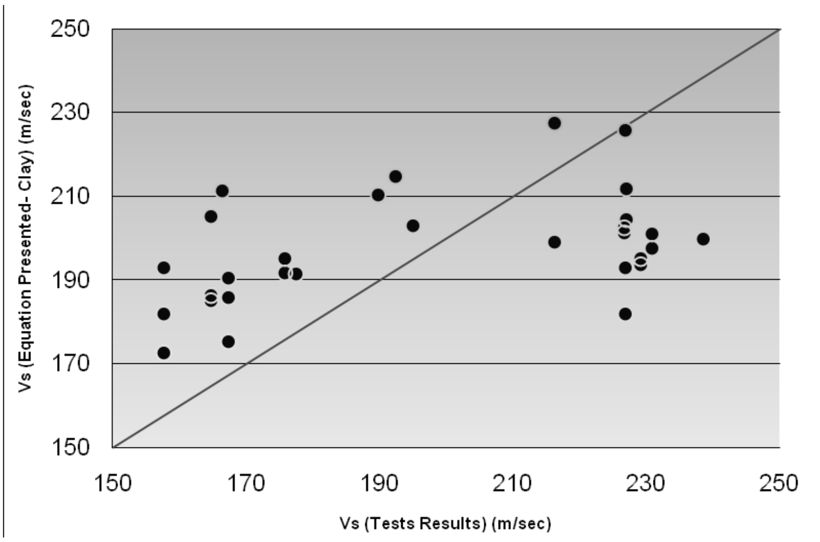

Fig. 9. The shear wave velocities for clayey soils based on the field data and the suggested equation

were measured and evaluated by using the seismic piezocone testing apparatus (SCPTu). The main purpose of the study was to assess the validity of the laboratory testing in measuring the most important dynamic soil parameters of shear modulus and damping ratio from undisturbed samples. Also obtaining simple and adequate equations for calculating the shear wave velocity of soils without the time and money consuming in-situ seismic geophysical tests has been another aim of the present study.

According to the results obtained, there is a specific limit for shear modulus of each soil, below which the samples tend to contract when subjected to shear stresses in the laboratory and show greater results than the field. While, for the soil samples with shear modulus beyond that, the dilation happens and the laboratory results are observed to be less than the field. However, for specimens having the shear modulus within the above limit, both laboratory and field measurements yield approximately the same results.

This limit could be defined in the ranges of 30-50 (MPa.) for clay and silty soils as reported by Yasuda and Yamaguchi during their extensive studies in the field and laboratory on undisturbed soil samples. Nevertheless, in the present study on the two selected sites having different and relatively coarser soils, the above limit was obtained in the ranges of 70-100 (MPa.). The deviations of the shear modulus and damping ratios measured in the laboratory from those obtained in field measurements can be attributed to the disturbance potential of undisturbed samples having the densification except the critical void ratio. The shear modulus corresponding to this state of grain packing depends on the soil type and nature and also the constraint conditions, as is the case for the critical void ratio.

It is concluded that for clayey deposits and sandy deposits, the dynamic parameters of shear module and the damping ratio measured in the laboratory on undisturbed samples are reliable when the shear modulus are in the ranges of 30-50 (MPa.), and 70-100 (MPa.) respectively.

In addition to these observations, for carbonate sands and clays of the Persian Gulf area (southern coasts of Iran), two empirical equations are presented for shear wave velocity estimation only in this region. Having the tip resistance of a simple cone penetration test and the total overburden pressure the shear wave velocity can be estimated relatively accurately. Nevertheless, if the soil deposits are saturated and the pore pressure is measured by means of a simple piezocone device, the other expression can be used based on the effective overburden stresses. The developed expressions obtained from the measured and collected data during the present study in the selected area may well define and characterize the dynamic soil parameters in this region. Nevertheless, their utilizations in other regions may need some new and extra in-situ data for calibration and verification.

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