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Liquefaction-Induced Settlement Assessment in Laboratory

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ABSTRACT

The estimation of ground deformation induced by liquefaction is a significant aspect of earthquake engineering due to its incorporation in structural design standards. Many research studies are in fact trying to produce standard charts based on some case studies in which it would be capable to predict the associated settlement. Several works were based on in-situ investigation methods like Standard Penetration Test (SPT) and Cone Penetration Test (CPT), where correlations are made with some loading and soil physical parameters to determine the ground deformation. However, these studies include several limitation and restrictions and they are being subjected far away from understanding the true dynamic behavior of specific soil deposit. Nowadays, the need for an accurate evaluation of soil response in the laboratory is considered one of the most important features toward producing a complete seismic and post-seismic soil model. In an attempt to estimate the post-liquefaction settlement of soils, series of undrained cyclic strain controlled tests are performed on Ottawa F65 soil via Triaxial Simple Shear Apparatus (TxSS) followed by dissipation tests. This paper provides a detailed experimental methodology to perform seismic and post-seismic analysis in laboratory. It is shown that along with the effect of cyclic amplitude and relative density, the dissipated energy can highly influence the determination of the volumetric strain induced by liquefaction. This paper proves the correlation present between the volumetric strain and the energy dissipated by analyzing 32 testing results performed at several conditions. On the other hand, the paper highlights the influence of the shear wave velocity as a controlling factor in determining the volumetric strain. This approach ensures that the sufficiency of the application of two laboratory testing, such as TxSS and piezoelectric ring-actuator technique (P-RAT) to determine the post-seismic behavior and shear wave velocity respectively, can simply lead to liquefaction-induced settlement assessment.

Keywords: Dynamic behavior, volumetric strain, settlement, dissipated energy, shear wave velocity, TxSS, P-RAT

INTRODUCTION

Seismic shaking of a granular soil leads to the loss of the inter-particle which leads to the rearrangement of the soil particles. In the sense that this shaking can occur in a rapid rate and on a specific soil density and permeability, then the conditions are considered as undrained conditions. As a result, pore pressure will build up causing the shear strength reduction leading to liquefaction. Post-liquefaction phase is identified when the pore pressure starts to dissipates, which is usually takes place during or at the end of the shaking. The dissipation usually accompanied by re-increase of soil's effective stress and reconsolidation of the loose sand (Ishihara and Yoshimine 1992), which is termed as liquefaction-induced settlement or seismic settlement. The importance of predicting ground deformation in loose, saturated granular soils has been widely recognized for a reliable evaluation of liquefaction damage. The previous well-known methods of settlement analysis for undrained seismic shaking are those established by Tokimatsu and Seed (1987) and Ishihara and Yoshimine (1992). These methods have been successively modified and refined (e.g., Shamoto et al. 1996, 1998; Zhang et al. 2002; Wu and Seed 2004; Lee 2007; Cetin et al. 2009; Juang et al. 2013). These methods where mostly relied on clean or uniform sand deposits, where the estimation of the volumetric change was based on several laboratory testing (Cyclic Triaxial, hollow cylindrical and Simple Shear test) and a number of field case studies for method validation necessities. The study that is done by Ishihara and Yoshimini (1992) is considered the most used in the evaluation of the seismic settlement, due to the versatility of the obtained chart in determining the volumetric strain. It is enough to determine the volumetric strain by knowing the relative density, cyclic amplitude and safety factor for liquefaction to occur. However, despite the applicability of this chart in several case studies, the settlement determined from such chart can be just an estimation due to the inaccuracy evolved from relying on uniform soil deposit. On the other hand, in the addressed chart, the correlation is found to be dependent on one loading parameter (cyclic amplitude) and one soil physical parameter (relative density). Consequently, this can lead to questioning the importance of having different influencing or controlling parameters in which they combine both physical and loading conditions like the energy dissipated from seismic activity. Several field tests are commonly used for the evaluation of liquefaction resistance of sandy soils, including the cone penetration test (CPT), the standard penetration test (SPT) and shear-wave velocity measurement (Vs). However, until now, the use of the Vs is so limited. Some has proved that it is possible to attain directly the volumetric strain from the Vs measurement just by performing the required transformation of the standard penetration number to the corresponding compatible Vs value (Yi, 2010). In this paper, the focus will be more on understanding the correlation between volumetric strain and the dissipated energy, which is defined as the energy needed to liquefy a soil specimen. Especially that, lately, the energy methods have been widely used in determining the liquefaction potential for soils due to its dependency on the cyclic amplitude and cyclic stress. It is found to better understand this influence; it is easier to control the relative density and the cyclic amplitude while varying the number of cycles. On the other hand, preparing several granular soil samples in laboratory under the same relative density for series of testing would not always lead to similar relative density among all specimens. In fact, such a control can be done by determining the shear wave velocity of each tested specimen on the TxSS and by testing it using the P-RAT. Then, different categories of soil state in the addressed study will be tackled. For this reason, series of undrained strained-controlled cyclic tests were performed on Ottawa-F65 using TxSS apparatus, in which dissipation of the generated pore pressure can be performed easily after the cyclic testing takes place. Series of Vs testing is performed on loose and dense state of Ottawa-F65 using the P-RAT. A Chart is obtained showing the correlation between the volumetric strain along with the accompanied dissipated energy based on the calculated and measured Vs.

EXPERIMENTAL WORK

Experimental Setup

Cyclic triaxial simple shear test (TxSS) apparatus, used in this study, was designed by IREQ in a collaboration with Université de Sherbrooke to provide confining pressure to the soil specimen during simple shearing by a non-uniform waveform. The ability to rotate principle stresses, ability to simulate the three dimensional in situ conditions of the soil and the ability to apply confining pressure to the soil samples are all in the combined triaxial simple shear (T_xSS) (Chekired et al. 2015). Comparing this test to other cyclic tests, TxSS will give direct measurement of pore pressure rather than the pressure deduction method, which leads to inaccurate results most of the time. Cyclic undrained testing at certain specified conditions mentioned in the next section is performed using the TxSS to shear the soil specimen and evaluate its resistance and accompanied increase in excess pore pressure. Dissipation of the generated excess pore pressure is permitted in drained testing after the cyclic test in order to study the post-cyclic behavior. In which the flow rate is measured via a flowmeter and the dissipated water volume can be determined precisely.

On the other hand, the shear wave velocity for the tested sand has been measured using the Piezoelectric Ring Actuator technique (P-RAT). This technique has been developed in the geotechnical laboratory at the Université de Sherbrooke (Gamal El-Dean 2007, Ethier 2009, Karray et al. 2015, Mhenni et al. 2015, Mhenni et al. 2016 …). This technique has been incorporated into oedometer apparatus, where two piezoelectric ring sensors are attached to the base (emitter) and top (receiver) of the oedometer. When the piezoelectric ring sensor is excited, a radial shearing is generated, resulting in S-wave propagation. The P-RAT is accompanied with a special software that is characterized by its ease and objectivity in signal processing and interpretation (Karray et al. 2015, Mhenni et al. 2016) which allows the determination of the reliable shear wave velocity at each void ratio during the oedometric testing.

Specimen Preparation and Experimental Methodology

Uniform Ottawa F-65 sand with the grain size distribution curve shown in Figure 1 and the physical properties mentioned in Table 1 was used in this study. Wet tamped preparation method was used to prepare reconstituted soil specimens in unreinforced rubber membrane where the specimen was set to be between a manufactured porous cap and base (Bayoumi et al. 2018). Moist sand was placed in three layers and every layer was compacted to reach the desired density. Soil samples had been prepared for testing on two different dry densities; 1500, 1580 and 1650 Kg/m3. After the soil specimen was subjected to saturation, with a Skempton's B value greater or equal to 0.97, it was isotropically consolidated to an initial stress ratio of ko = (σ'h/σ'v) = 1, where σ'v and σ'h are the effective vertical and horizontal stresses respectively (Chekired et al. 2015). Soil samples of height 22 mm and diameter to height ratio equals to 0.28 had been carried out at the same initial effective confining pressure equals to 100 kPa. The samples were also subjected to the same loading frequency of 1 Hz. A series of undrained cyclic strain-controlled tests under isotropic stress conditions and at different values of cyclic strain γ_{cyc} were conducted until initial liquefaction occurs. After liquefaction takes place, drainage was permitted and the volume change was recorded via a flowmeter. Excess pore pressure generation and dissipation were recorded throughout cyclic and dissipation processes. From the analysis of the stress path resulted, the energy dissipated in the soil specimen is determined by integrating the area bound by stress–strain hysteresis loops as suggested by Green et al. (2000). This analysis allows the determination of initial shear modulus and the shear wave velocity of the soil specimen prior to testing. P-RAT is used to determine the shear wave velocity as a function of the varying void ratio in an oedometer. As a result, several soil specimens were prepared in three layers at several initial dry densities; 1350, 1500 and 1650 Kg/m3. In fact, the shear wave velocity is measured at every loading and reloading state of the soil specimen, in which it will be possible to know the corresponding shear wave velocity for each void ratio.

Table 1. Parameters of Ottawa F-65

Parameters	Ottawa F-65
D_{50}(mm)	0.217
Cu	1.68
Cc	1.28
e_{min}	0.53
e_{max}	0.82
Gs	2.668

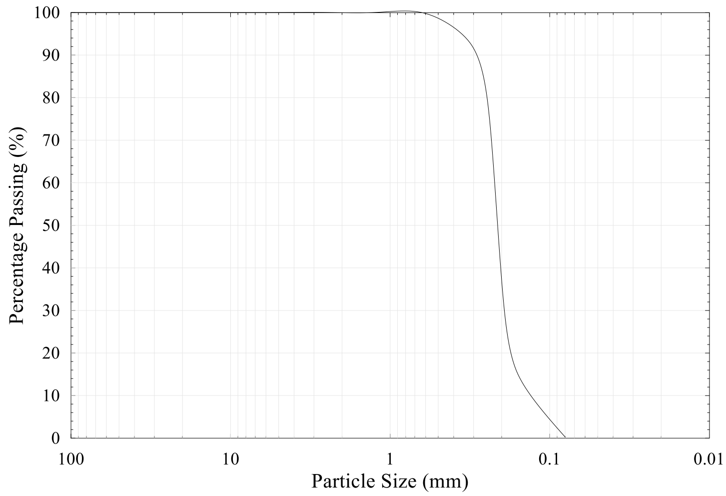

Figure 1. Grain size distribution of Ottawa F-65.

RESULTS AND DISCUSSIONS

Table 2 summarizes the results of 32 tests according to their corresponding cyclic amplitude, number of cycles, excess pore pressure generation ratio (Ru= u/σ'_c), dissipated energy ($\sqrt{W}$), dissipated water volume and normalized shear wave velocity (Vs_1= Vs $(\sigma'_c/100)^{0.25}$). Where u is the residual pore water pressure generated and σ'_c is the confinement effective stress. An example of the buildup pressure during the cyclic test on Ottawa sand F-65 under a cyclic shear strain of γ_{cyc}=0.94 is shown in Figure 2. Initial liquefaction is defined throughout this study as the excess pore pressure, Ru of 0.9 to 1. It is well demonstrated that liquefaction is reached in sample of relative density 91% of Ottawa Sand after approximately 10 cycles. Figure 2 reveals the variation of CSR (Cyclic stress ratio) as a function of the distortion of cyclic strain in the form of a hysteresis loops.

Since the beginning of the energy methods developments, the mechanism of energy in the seismic behavior of soil can be described in three aspects. First, certain amount of dissipated energy density δW is needed to change the void ratio of drained soil from e to e+δe. Second, this required amount of energy increases as the void ratio approaches the minimum void ratio e_{min}. The third observation is the tendency to increase the pore pressure instead of decrease of void ratio if soil is saturated and undrained. The increase of pore pressure causes a decrease of intergranular forces and soil stiffness and thus incremental energy δW decreases with increasing pore water pressure (Lenart, 2008). The latter finding about relationship between incremental dissipated energy and stiffness of a soil led to the idea that the dissipated energy required for pore water pressure changes during cyclic loading can be determined per unit volume from the hysteresis loops. Therefore, dissipated energy is defined as the area bounded by hysteresis loops of the stress-strain curve in case of results from laboratory cyclic loaded tests as suggested by Green et al. (2000). Based on the obtained results, the volumetric strain (ε_v), which is determined in the post-cyclic phase increases as the dissipated energy ($\sqrt{W}$) increases. Consequently, the variation of volumetric strain is proportional with the variation of the dissipated energy for several soil states and relative densities as shown in figure 3. It can be deduced that the volumetric strain-dissipated energy relation highly depends on the state of the soil. Previously, it was studied that the volumetric strain is influenced by the relative density and cyclic amplitude. However, the relative density of uniform sand is not easy to determine precisely, and shear wave velocity has played an important role in the identification of the accurate relative density range for the categories specified in the presented chart. The normalized shear wave velocity for every test presented in figure 3 is estimated from a calibrated model that allow from the hysteresis loops of the cyclic test to determine the corresponding shear modulus and shear wave velocity as shown in figure 2 (SIG4 model). According to figure 3, the performed tests are divided into four different shear wave velocity ranges; less than 140 m/s, between 140 m/s and 165 m/s, between 170 m/s and 185 m/s and between 200 m/s and 230 m/s. The dissipated energy in the soil samples, which are with high shear wave velocity,

is set to be more compared to that of a soil sample with low shear wave velocity, since a dense soil requires more energy to liquefy. It is important to mention that there are some tests due to experimental errors can deviate from its estimated shear wave velocity category. Some of the tests shown in table 2 differ in the number of cycles and cyclic amplitude, so this causes some differences in the energy and volumetric strain resulted. The amount of energy dissipated in a sample and volumetric strain induced by cyclic loading will increase as the number of cycles increase. This increase can be clearly shown in tests 11 and 13 at the same cyclic amplitude and different number of cycles. In addition, the cyclic amplitude has the same influence; the dissipated energy will increase with higher strain. It can be barely shown here, but it is important to note that for same sample, for liquefaction to occur, less energy is needed when higher cyclic amplitude is applied (Bayoumi et al., 2017). This can be seen clearly by comparing the tests at the same conditions and varying amplitude like test 28 and 29 at 1580 kg/m^3.
On the other hand, the estimated normalized shear wave velocity from the calibrated model of TxSS is plotted with the adequate initial void ratio of soil sample before being tested in figure 4. Furthermore, in order to verify the accurate void ratio or relative density corresponding to each test, P-RAT measurement has been performed. Normalized shear wave velocity obtained from the P-RAT measurement is shown in bolded and bordered diamonds in the plot of figure 4. The last latter confirm the compatibility of the measured shear wave velocity with the estimated shear wave velocities.

Table 2. Results of TxSS tests on Ottawa-F65

Density (kg/m3)	**Test**	**Number of cycles -Ncyc**	**Number of cycles to liquefaction-Nliq**	**Cyclic Amplitude-γ (%)**	**Ru**	**Dissipated Energy-√W**	**Volumetric Strain- εv (%)**	**Normalized shear wave velocity-Vs1 (m/s)**
1500	**1**	8	Not liquefied	0.295	0.61	0.553	0.51	133
	2	18	Not liquefied	0.275	0.78	0.736	0.51	135
	3	12	Not liquefied	0.295	0.78	0.622	0.65	135
	4	18	11	0.44	0.93	1.061	1.56	138
	5	12	Not liquefied	0.29	0.63	0.662	0.28	143
	6	18	18	0.44	0.9	1.086	0.71	144
	7	29	21	0.43	0.91	1.31	1.39	145
	8	3	Not liquefied	0.275	0.21	0.365	0.17	145
	9	3	Not liquefied	0.265	0.29	0.335	0.19	149
	10	15	Not liquefied	0.29	0.45	0.8	0.28	151
	11	15	Not liquefied	0.255	0.38	0.656	0.19	151
	12	4	Not liquefied	0.275	0.27	0.453	0.21	154
	13	2	Not liquefied	0.256	0.14	0.302	0.05	162
	14	2	Not liquefied	0.53	0.27	0.55	0.17	163
	15	2	Not liquefied	0.17	0.2	0.3	0.12	153
1650	**16**	110	Not liquefied	0.5	0.91	3.33	0.71	212
	17	240	Not liquefied	0.3	0.57	3.03	0.24	213
	18	12	Not liquefied	0.56	0.61	1.775	0.31	224
	19	16	Not liquefied	0.2	0.21	1.022	0.13	216
	20	24	Not liquefied	0.34	0.35	1.196	0.16	207
	21	59	Not liquefied	0.24	0.63	1.776	0.27	201
1580	**22**	20	Not liquefied	0.55	0.79	1.39	0.56	158
	23	8	Not liquefied	0.55	0.73	0.969	0.41	171
	24	4	Not liquefied	0.41	0.41	0.627	0.24	178
	25	6	Not liquefied	0.4	0.4	0.791	0.16	182
	26	24	10	0.52	0.94	1.78	0.86	182
	27	15	Not liquefied	0.55	0.81	1.43	0.47	185
	28	18	9	0.57	0.97	1.604	0.94	177
	29	18	15	0.61	0.92	1.465	1.01	176
	30	79	79	61	0.96	1.651	0.98	173
	31	8	Not liquefied	0.55	0.61	0.981	0.35	178
	32	10	Not liquefied	0.4	0.59	1.05	0.31	185

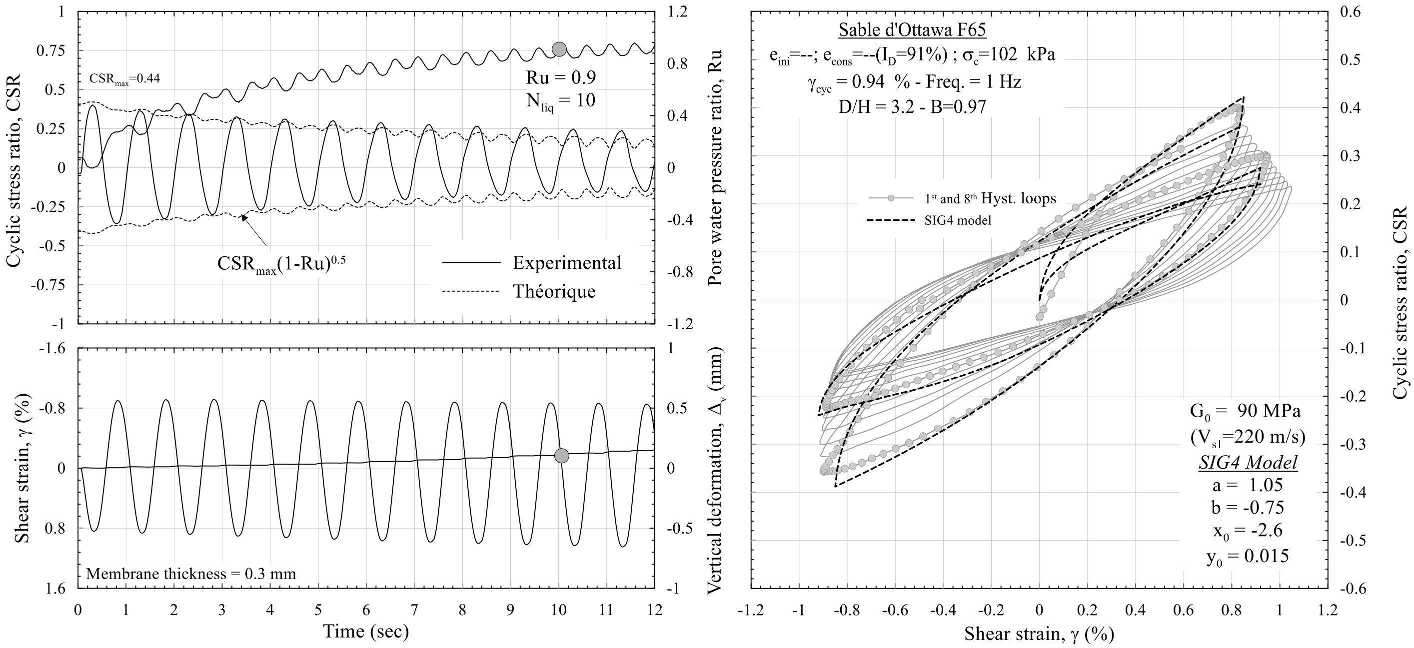

Figure 2. TxSS Records of CSR variation and pore pressure generation of Ottawa F-65

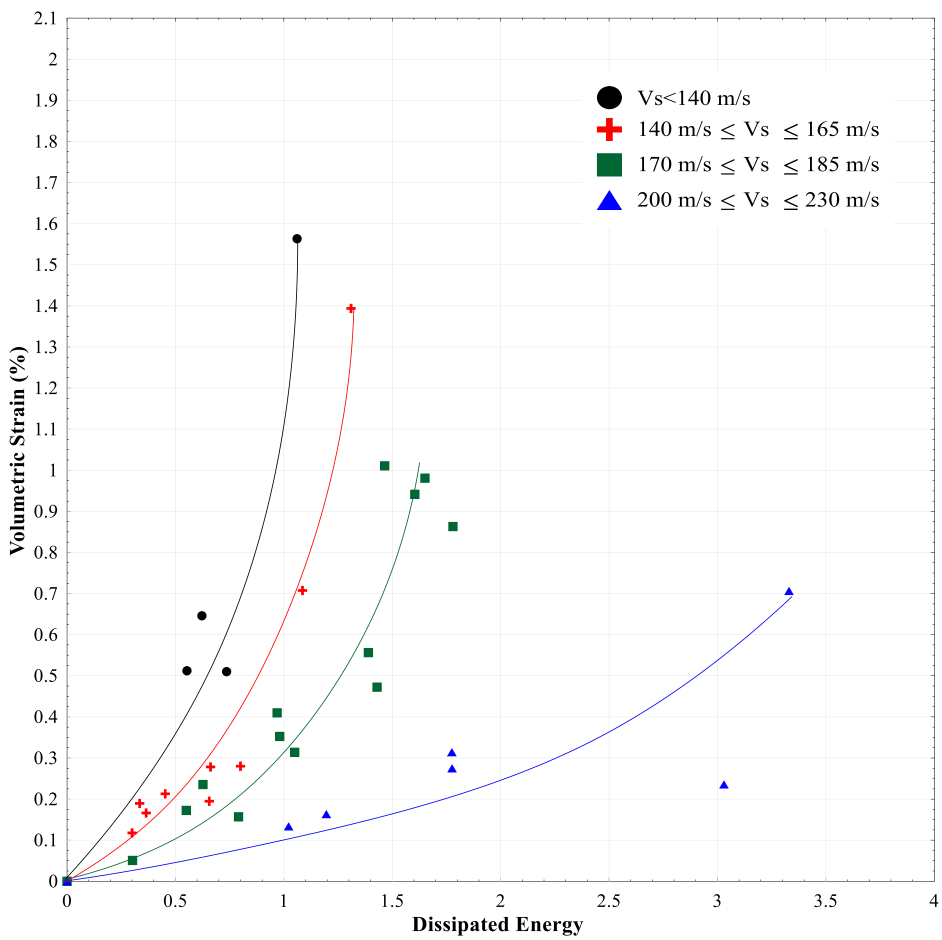

Figure 3. Variation of the volumetric strain as a function of the dissipated energy for the 34 tests.

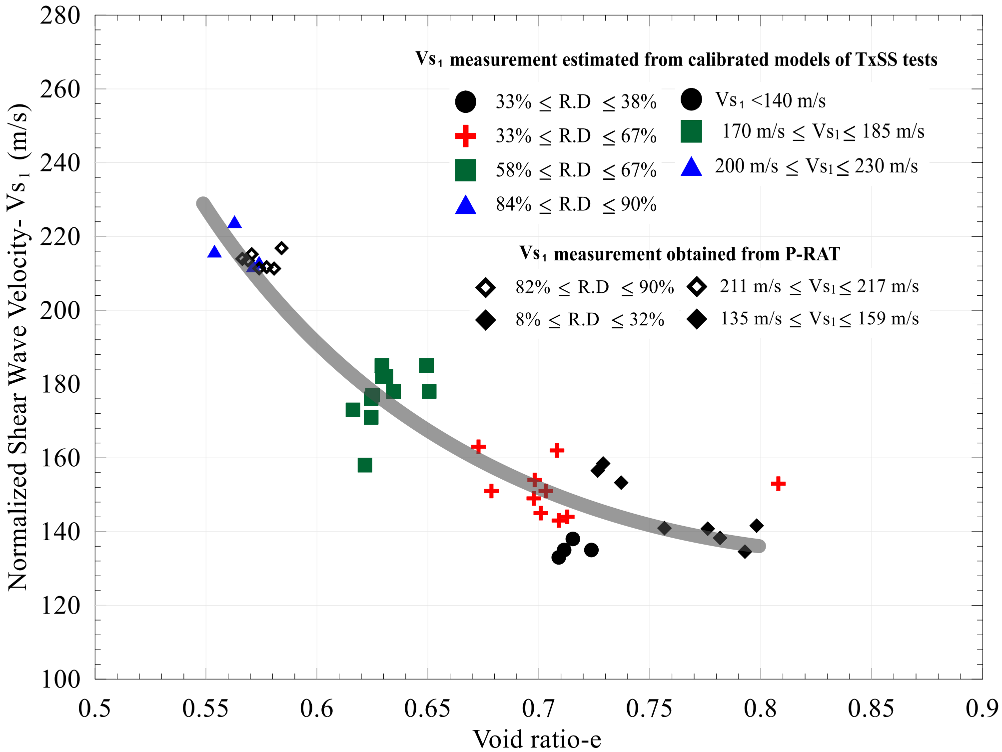

Figure 4. Variation of the shear wave velocity as a function of the void ratio from tests performed by TxSS and P-RAT

CONCLUSIONS

The paper introduces an approach of liquefaction induced-settlement assessment based on identifying the volumetric strain from the dissipated energy. The obtained variation of the volumetric strain as a function of the dissipated energy leads to promising approach despite its formation on 32 cyclic tests performed using the Triaxial Seismic Simulator the TxSS. The addressed correlation is influenced by several loading and physical soil parameters, especially the cyclic amplitude and the relative density. Due to the importance and the lack of accuracy in determining the corresponding initial relative density, it is shown that counting on the shear wave velocity can be a reliable controlling mechanical parameter of the tested soil. The results obtained has been characterized according to four different normalized shear wave velocity ranges which have been estimated based on a calibrated model from the TxSS cyclic results. For further verification of the estimated shear wave velocity and the corresponding relative density, measurements of this parameter were performed by the piezoelectric ring actuator technique (P-RAT). The use of such a technique in an oedometric cell eases the determination of the measured shear wave velocity at the soil's corresponding void ratio, which can verify the estimated shear wave velocity and its associated void ratio. As a conclusion, the liquefaction induced settlement assessment can be attained by the correlation of volumetric strain-dissipated energy. Nevertheless, this requires performing several cyclic tests on many soil types. In order to establish a good correlation, further analysis should be done on varying loading and soil physical and mechanical properties (cyclic amplitude, frequency, relative density, shear wave velocity…). In fact, the application of two laboratory testing, such as TxSS and piezoelectric ring-actuator technique (P-RAT) to determine the post-seismic behavior and shear wave velocity respectively, can simply lead to liquefaction-induced settlement assessment in laboratory.

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