Cyclic behavior of sand under non-uniform shear stress waves

Mohamed A. ElGhoraiby[1*] and Majid T. Manzari [1]

Abstract

During an earthquake, soil deposits are often subjected to complex stress/strain time histories that are quite different from the simplified ones used in laboratory tests for evaluation of the stress-strain-strength of these soils. To mimic the stress/strain time histories experienced at different depths of a mildly sloping soil deposit, a series of direct simple shear tests were conducted on Ottawa F65 sand specimens. The trends observed in these experiments were then used to estimate the lateral spreading of mildly sloping saturated deposits of the same sand subjected to various base motion time histories measured in the centrifuge tests conducted as part of an international research project (Liquefaction Experiment and Analysis Project, LEAP-2015 and LEAP-2017).

In each CDSS test, after imposing the initial stress state, the specimen was subjected to non-uniform stress waves that resembled the shear stress time histories expected likely to develop in the LEAP-2015 and LEAP-2017 centrifuge specimens. A total of 17 CDSS tests were performed on specimens with relative densities of approximately 66%. Initial vertical and shear stresses were imposed on each soil specimen to correspond to the state of stress in a mildly sloping soil layer at two depths of about 4m and 3m. A ramped sinusoidal shear stress wave similar to the ramped sinusoidal base motion used in the LEAP centrifuge experiments was employed. The test results displayed a consistent trend between the peak cyclic stress ratio and the permanent shear strain that developed in the soil. The effects of overburden stress on the magnitude of permanent deformations were observed. Smaller initial vertical stress resulted in a more dilative response and smaller permanent shear strain. The observed permanent shear strain vs. peak cyclic stress ratio curves were then used to predict the lateral spreading of mildly sloping deposits tested in the LEAP-2015 and LEAP-2017 centrifuge experiments. Reasonably close correlation between the predicted and measured displacements were obtained. The developed dataset can be used for calibration, evaluation, and further development of constitutive models for liquefiable soils.

1 Department of Civil and Environmental Engineering, George Washington University, Washington, DC, USA.

* Corresponding Author, ghoraiby@gwu.edu.

1. Introduction

The testing of soils in a controlled environment and under simplified boundary conditions have been used to understand the effects of various factors (e.g. density, confining stress, static shear stress, etc.) on the stress-strain-strength response of soil, and have shed light on many complex phenomena such as liquefaction and its effects such as lateral spreading.

In this paper the stress-strain response of soil elements in a gently sloping ground subjected to ramped sinusoidal motions are physically modelled through a series of cyclic direct simple shear (CDSS) tests. The experiments are performed on K_0-consolidated specimens of Ottawa F65 sand with the initial stresses similar to those at different soil depths of a sloping ground. These specimens are then sheared using an input shear stress which mimics the stress waves imposed on the centrifuge soil specimens in the tests conducted as part of the Liquefaction Experiments and Analysis Project (LEAP). The goal of these tests is to observe the permanent shear strain generated at different depths of the soil layer and to make a direct comparison with the magnitude of the lateral displacements observed in LEAP centrifuge experiments.

Over the past three decades, many centrifuge tests have been conducted to study the effect of liquefaction on the lateral spreading of mildly sloping grounds. During the VELACS project [1], the lateral spreading of a sand layer with a slope of 2 degrees was modelled in the centrifuge tests performed at RPI, Caltech, and UC Davis [2]. These tests were used in the evaluation of the state-of-the-art constitutive models available at that time. The centrifuge tests at RPI were performed on Nevada sand in a laminar box [3]. These tests studied the effects of the ground slope on the pore pressure build up, acceleration time histories, and lateral displacements over the soil depths. The tests conducted at Cambridge University showed that the lateral spreading profile over the layer is nonlinear and the majority of the displacement occurs at higher depth while very little displacement occurs at shallower depth [4]. The effects of lateral spreading on piles were studied through a series of centrifuge experiments by Abdoun et al. [5].

More recently, the LEAP 2015, 2017 and 2019 projects studied the lateral spreading of mildly sloping ground through an extensive testing program conducted at several centrifuge testing facilities across the world [6–8]. The LEAP experiments modelled a 4 meters layer of medium dense Ottawa F65 sand with a slope of 5 degrees. The input motion was a ramped sinusoidal motion with a 1Hz frequency with a duration of 16 seconds. The amplitude of the base motion reaches a peak ground acceleration (PGA) at 8 seconds then gradually decreases to zero during the remaining time. LEAP 2015 focused on modelling the same tests across different facilities. LEAP 2017 focused on the sensitivity of the slope response to variations in PGA and soil initial density, while the goals of LEAP 2019 was on the validation of the generalized scaling law. The centrifuge experiments conducted for these three projects resulted in an extensive database, where a trend between the lateral spreading magnitude, the base motion intensity and soil density was clearly observed [7]. These experiments also aided in the assessment and validation of a number of current state-of-the-art numerical simulation tools [9,10]. In addition to deterministic numerical simulations, series of stochastic finite analyses were performed to consider the variability of soil density within the centrifuge specimen and the variation in the base motions achieved in the centrifuge tests, and to assess the validity of a constitutive model and a numerical modelling platform to capture the response of a mildly sloping ground for a relatively broad range of densities and base excitations [11].

Zeghal et al. [12] compared the stress-strain response of the LEAP 2015 centrifuge experiments with the results reported by the modellers in the LEAP-2015 prediction exercise. The stress and strain time histories were numerically computed from the measurements obtained from the middle arrays of pore pressure transducers and accelerometers along the depth of the soil layer. The results showed good comparisons between the experiments and simulations and highlighted the limitations caused by the quality of measured responses and the complexity of the boundary value problem.

The laboratory element tests could play a role in providing complementary insights on the response observed in the centrifuge experiments. Cyclic triaxial, cyclic direct simple shear (CDSS) and hollow cylinder torsional shear tests have already played an important role in our current understanding the liquefaction triggering and post-liquefaction response of soils. However, in the majority of these tests, the soil specimen is subjected to cycles of shear stress/strain with constant maximum amplitude. Such conventional tests have been extensively used in the development of the empirical procedures for evaluation of liquefaction resistance [13,14]. Empirical procedures for estimation of liquefaction-induced settlements are also based on the results of element tests such as those reported by Ishihara and Yoshimine [15]. The results of the latter tests have also been used in the development of other empirical procedures [16].

Faced by the random nature of an earthquake time history, the empirical procedures often treat a given earthquake record as a uniform sinusoidal motion with "an equivalent number of cycles" [17]. This simplification has made it feasible to compare the response of the soil in the field to the liquefaction strength curves obtained from the conventional element tests. This concept was originally used in the study of fatigue in metal where the duration of motion is very long. Earthquakes occur over much shorter duration and might result in large plastic strains. Therefore, the use of equivalent number of cycles involve high level of uncertainty [18].

To better understand the effects of the non-uniform nature of earthquake, several researchers have conducted element tests on liquefiable soils subjected to irregular (non-uniform) shear stress time histories [19–22]. Ishihara and Nagase [19] used a bi-directional direct simple shear device to investigate the response of Fuji river sand under irregular and multi-directional input motions. Pan and Yang [20] conducted element tests to model the soil response under wave loading. The common take from these studies is that the liquefaction strength of the soil is affected by the stress history and that the irregular nature of earthquakes should be considered in the element tests.

Motivated by the need to investigate the effects of the non-uniform nature of the shear stress time-history and inspired by the large database of centrifuge experiments conducted during the LEAP projects, a CDSS testing program was devised to consider non-uniform shear stress waves. The main goal of this program was to obtain an insight onto the magnitude of the permanent shear strain that develop along the depth of a mildly sloping liquefiable ground. Further observations are drawn by comparing the results obtained in these tests with the results obtained from the LEAP centrifuge experiments.

As previously mentioned, the designated soil used in the LEAP projects is Ottawa F65 sand. Several laboratory experimental studies were conducted on the soil to determine the soil properties [23–28]. In addition to these tests, cyclic triaxial [23,26–29], direct simple shear [25,26] and torsional shear [30] tests were performed to determine the liquefaction strength of the soil. The tests provided significant information on the effects of soil density, overburden stress, and stress anisotropy on the liquefaction strength of Ottawa F65 sand. In all of these test uniform sinusoidal motion was used until a liquefaction criteria was met.

In this paper, a new set of cyclic direct simple shear tests is presented. These new tests focus on the effects of overburden stress on the permanent deformation that develops due to non-uniform shear stress history that mimics the base motion imposed in the LEAP centrifuge experiments. The tests are intended to model the stress-strain response of the soil at different depths of the centrifuge experiments. In the following sections, first some key properties of Ottawa F65 sand and its liquefaction strength obtained from uniform CDSS tests are discussed. Then, the experiment setup is outlined followed by a presentation of the results. Afterwards, the data obtained from the CDSS tests are used to predict the lateral displacements of the centrifuge experiments conducted during LEAP 2015 and 2017 projects. Finally, conclusions drawn from this study are listed.

2. Properties of Ottawa F65 Sand

Ottawa F65 sand is a clean poorly graded soil produced by US Silica, in Ottawa, Illinois. It consists of over 99% silica and less than 1% fines content. The particles shape is sub-rounded and it has a specific gravity of 2.65. The hydraulic conductivity of Ottawa F65 sand ranges from 0.008 to 0.015 cm/sec depending on the achieved soil density in the range 1500 to 1795 kg/m^3. LEAP researchers have adopted the values of 0.78 and 0.51 for maximum and minimum void ratios of this soil, respectively [31]. As mentioned in the previous section, extensive testing has been done to characterize the physical and mechanical properties of this soil (See the references cited in introduction).

2.1 Liquefaction strength under uniform cyclic loading

Prior to the following study, a series of uniform cyclic direct simple shear tests were performed to determine the stress-strain behaviour and liquefaction strength of Ottawa F65 sand. Two sets of CDSS tests were conducted on samples with similar relative densities (67.5% and 66.2 %) subjected to overburden stresses of 100 kPa and 40 kPa. The shear wave velocity V_s measurements for the 100 kPa and 40 kPa had a mean and coefficient of variation (COV) of 159.23 (m/sec) and 145.98 (m/sec), and 1.75% and 3.79%, respectively. The mean elastic shear modulus computed from these measurements are 41.7 MPa and 35.15 MPa for the 100 and 40 kPa tests, respectively. Figure 1 shows the results of a typical test conducted on a sample subjected to 100 kPa vertical stress and a cyclic shear stress ratio (CSR) of 0.15. Figures 1a to 1d show the effective stress path and shear stress vs shear strain during cyclic loading as well as the vertical stress vs. shear strain and the time history of excess pore pressure ratio r_u, respectively. Figure 2 shows the liquefaction strength curves obtained from these two sets of tests. The criteria used for liquefaction strength is the number of cycles it takes to reach a double amplitude shear strain of 7.5%. Additional details on these tests can be obtained in ElGhoraiby[32]; Elghoraiby et al. [26].

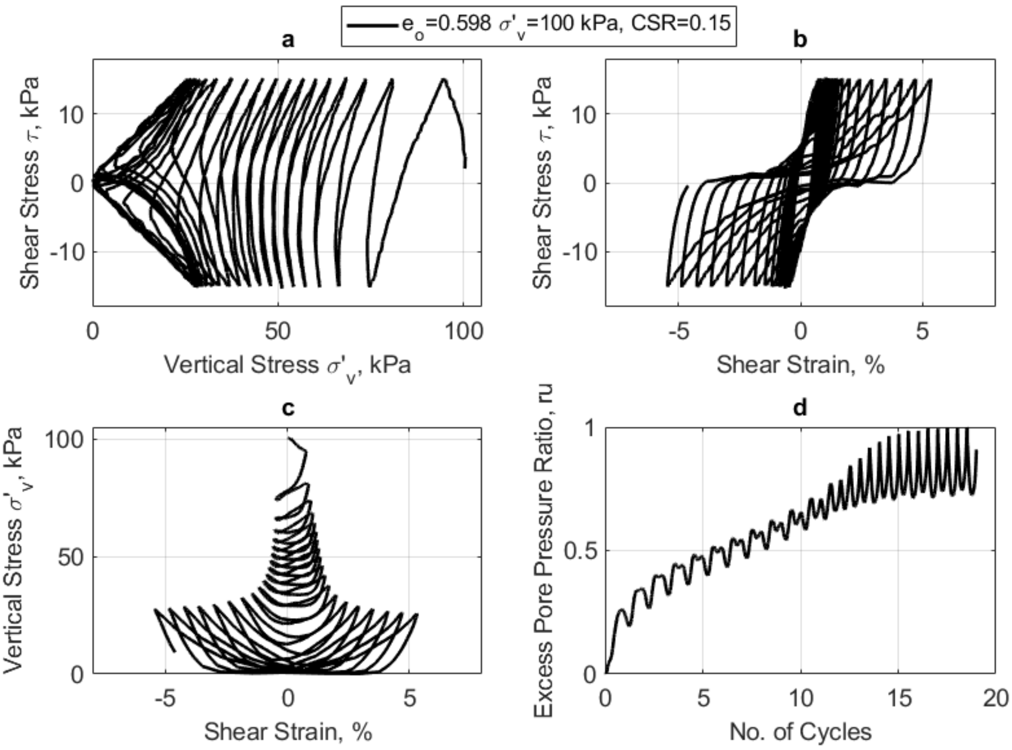

Figure 1. Uniform CDSS experiment of Ottawa F65 sand specimen subjected to vertical stress of 100 kPa and CSR 0.15

3. Non-Uniform CDSS Test Setup

Figure 3. LEAP Centrifuge ExperimentFigure 3 shows the baseline schematics for the centrifuge experiments conducted during the LEAP 2015/2017 projects. The main phenomenon studied in these projects is the lateral spreading of mildly sloping liquefiable ground. The setup consists of a medium dense soil layer (D_r=65% Ottawa F65 sand), with a depth of 4 meters at the mid-length of the soil slope, a total length of 20 meters and a width of at least 8 meters in the prototype scale. The centrifuge model is subject to a ramped sinusoidal motion (Figure 2. Liquefaction strength curves of Uniform CDSS tests

) with a frequency of 1 Hz and a duration of 16 seconds. A target peak ground acceleration (PGA) of 0.15g was initially planned. The effects of soil density and PGA on the seismic response of the slope were studied in the LEAP 2017 project. More details on the centrifuge experiments could be obtained from the LEAP 2017 summary papers [7,33].

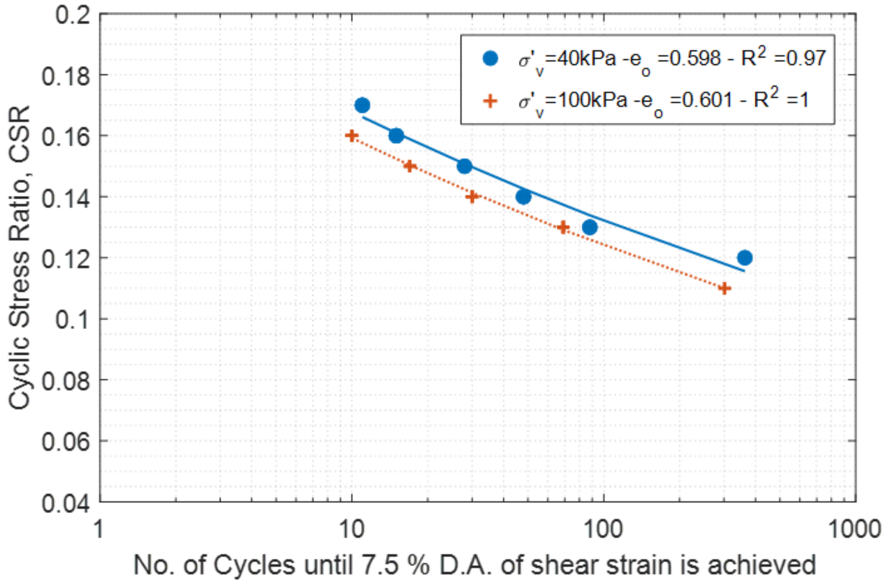

Figure 2. Liquefaction strength curves of Uniform CDSS tests

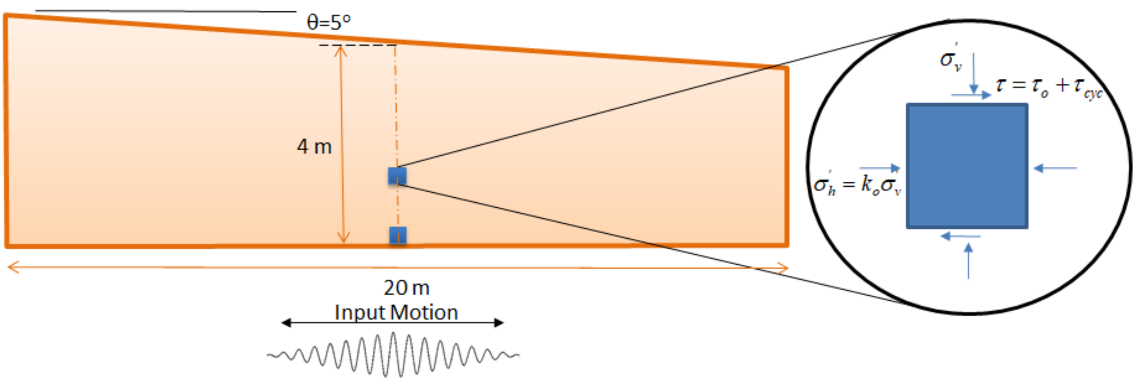

Figure 3. LEAP Centrifuge Experiment

In order to gain a better understanding of the permanent shear strains that develop at different depths of the soil slope, the experimental study presented here was devised to model the soil response by using direct simple shear experiments. The direct simple shear device used in this study is a Norwegian Geotechnical Institute (NGI) type, where the sample is confined in a rubber membrane surrounded by Teflon coated rings for lateral constraint. The typical specimen size is approximately 23 mm thick and a diameter of 64 mm. A constant volume condition is maintained by restraining the vertical displacement of the top cap. The top and bottom caps are equipped with bender elements to measure the shear wave velocity of the soil. Samples of different densities could be prepared using a constant height dry pluviation technique [32].

The state of stress of the soil in the centrifuge experiment are mimicked in the direct simple shear test. As shown in Figure 3, the soil at a given depth within the sloping ground experiences an overburden stress, σ'_v, due to the overlying soil. The horizontal stress, σ'_h, of the soil is defined by assuming a Ko-condition, while static shear stress, τ_o, is due to the ground slope. During a seismic event, in addition to the initial static shear stress, the soil is subjected to cyclic shear stress τ_{cyc}. In the following sections, two sets of experimental data are presented that model the soil response at the depth of 4 and 3 meters.

4. Experimental Results

Two series of cyclic direct simple shear tests were conducted. In these tests, the soil is first consolidated under different vertical overburden stresses and then subjected to a specific static shear stress. Afterwards, cyclic shear stress of non-uniform amplitude is applied. The vertical stresses applied are 40 and 30 kPa and a slope of 5 degrees is assumed. These tests mimic the setting of the centrifuge experiment performed in LEAP as shown in Figure 3. A ramped sinusoidal shear stress loading is applied to correspond to the base motion used in the LEAP centrifuge experiments. Each cycle had a period of 10 seconds.

Tables 1 and 2 list the tests performed on the samples subjected to 40 kPa and 30 kPa vertical stress, respectively. The tables show the achieved void ratio and relative density of each specimen after consolidation, the applied vertical and static shear stresses, the applied peak cyclic stress ratio and the permanent shear strain obtained in each test.

Table 1. CDSS ramped motion tests e_o=0.583 - σ'_v=40 kPa

e_o=0.602- cov=1.387% - D_r=66% - σ'_v =40 kPa - Ramped						
Test No	e_o	Dr (%)	σ'_v (kPa)	τ_o (kPa)	max CSR	Permanent Shear Strain (%)
1	0.587	71.6	40	3.5	0.38	15.69
2	0.604	65.1	40	3.5	0.35	11.77
3	0.601	66.2	40	3.5	0.34	10.32
4	0.609	63.5	40	3.5	0.306	7.31
5	0.613	62.0	40	3.5	0.3	6.65
6	0.600	66.7	40	3.5	0.25	3.60
7	0.594	68.8	40	3.5	0.24	2.68
8	0.607	64.1	40	3.5	0.22	0.26

Table 2. CDSS ramped motion tests e_o=0.583 - σ'_v=30 kPa

e_o=0.597 - cov=1.07% - Dr=67.6% - sigv=30 kPa - Ramped						
Test No	e_o	D_r (%)	σ'_v	τ_o	max CSR	Permanent Shear Strain (%)
1	0.603	65.5	30	2.6	0.42	9.66
2	0.597	67.6	30	2.6	0.41	9.5
3	0.595	68.6	30	2.6	0.38	8.98
4	0.600	66.5	30	2.6	0.34	6.4
5	0.595	68.4	30	2.6	0.36	5.98
6	0.593	69.2	30	2.6	0.32	5.36
7	0.607	64.0	30	2.6	0.28	3.34
8	0.601	66.5	30	2.6	0.3	2.81
9	0.591	69.8	30	2.6	0.25	0.85

The shear wave velocity measurements and the corresponding elastic shear moduli for these series of tests are listed in Table 3. The variation of elastic shear moduli with the applied overburden stress that are obtained in this study along with the data obtained from the 100 kPa series in the uniform CDSS tests conducted earlier are presented in

Figure 4. A power law correlation between the applied vertical stress and the mean elastic shear modulus can be obtained from these results.

Table 3. Shear wave velocity measurements and computed shear modulus

σ'_v (kPa)	Shear Wave Velocity, V_s		Shear Modulus, G	
	Mean (m/sec)	COV (%)	Mean (MPa)	COV (%)
40	141.71	5	33.1	10.2
30	140.14	6.7	32.6	13.1

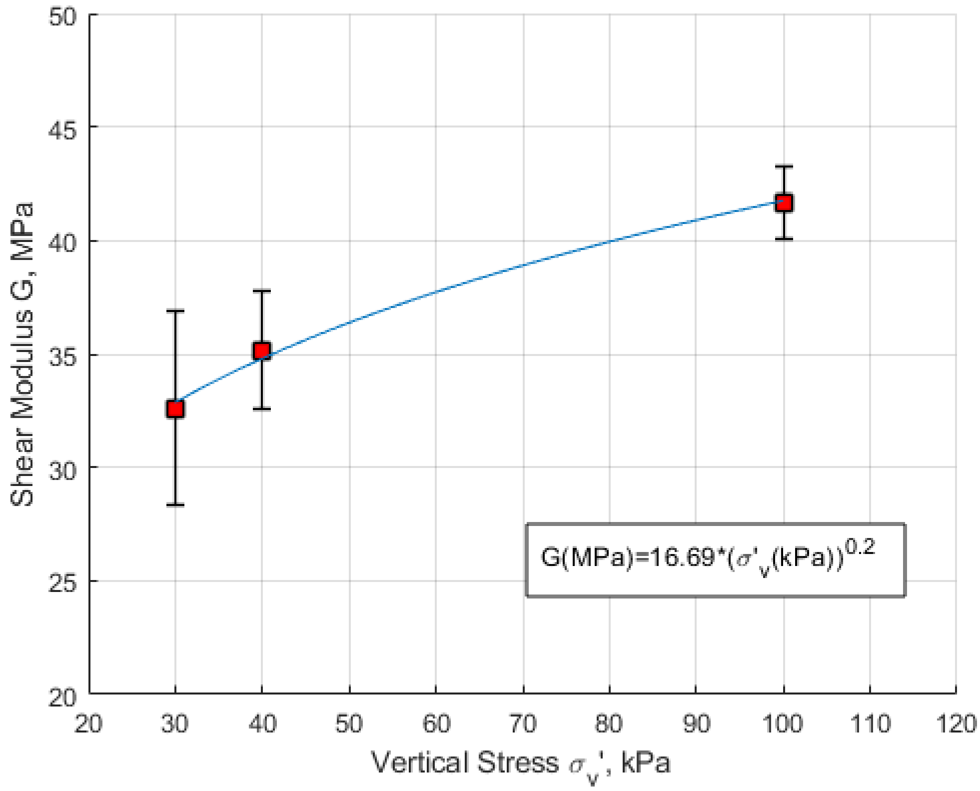

Figure 4. Elastic shear modulus based on shear wave velocity measurements

Figure 5 shows the results of one of the tests performed. The soil specimen was subjected to a vertical stress of 40 kPa and subjected to a ramped sinusoidal motion with a peak CSR of 0.25. As the results show, the specimen has experienced a permanent shear strain of 3.6%. The peak cyclic stress ratio was varied in different tests to obtain a general trend.

Figure 6 compares the effect of the maximum CSR on the magnitude of the permanent shear strain. The plots show the results obtained from tests performed on the samples subjected to vertical stress of 30 kPa and CSRs of 0.38, 0.32 and 0.25. Figure 7 shows a similar comparison for samples subjected to a vertical stress of 40 kPa and CSRs of 0.3, 0.25 and 0.22. Figures 8 and 9 compare the effects of different vertical overburden stresses on the accumulated permanent shear strain for samples sheared at CSR of 0.3 and 0.34, respectively. It is observed that as the confining stress decreases the soil has a more dilative tendency. The effect of the overburden stress on the liquefaction resistance of soil has been documented by the literature and was accounted in for in design [34]. The observations made here are in agreement with what is documented in the literature. The observed response is also consistent with the critical state concept. For a given relative density, a soil element subjected to a higher confining stress has a larger state parameter and hence exhibits a more contractive response [35].

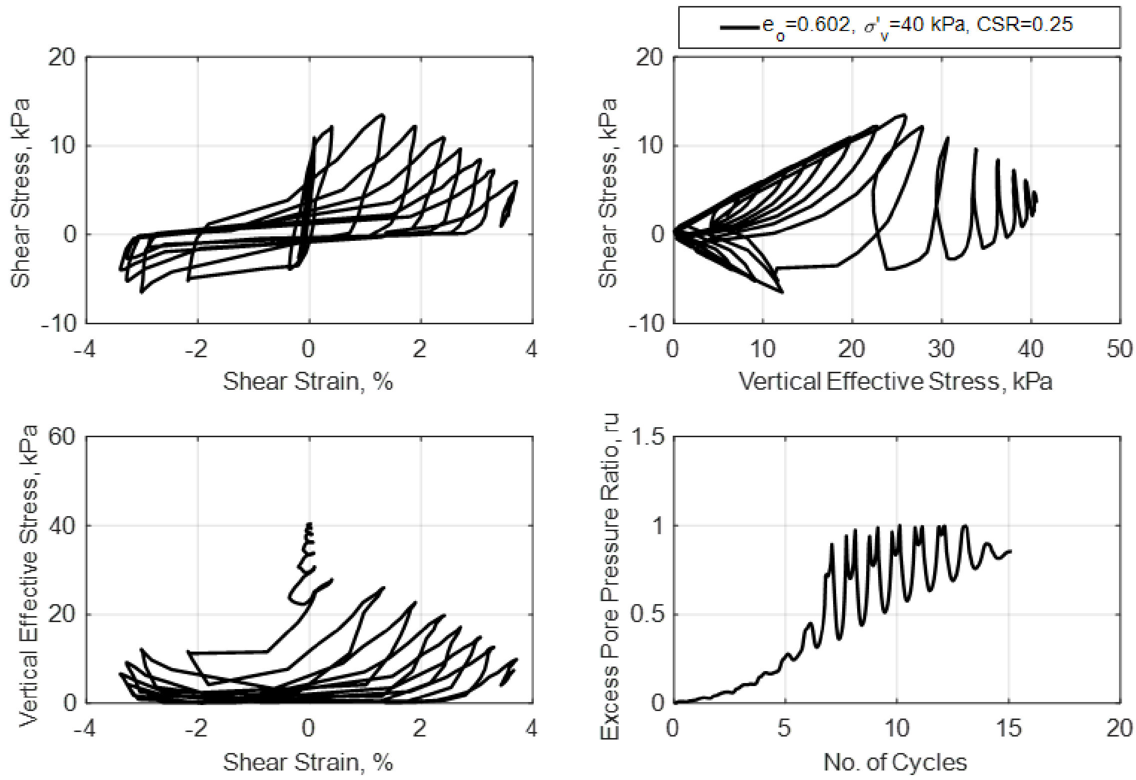

Figure 5. CDSS Test on a sample subjected to a ramped sinusoidal motion

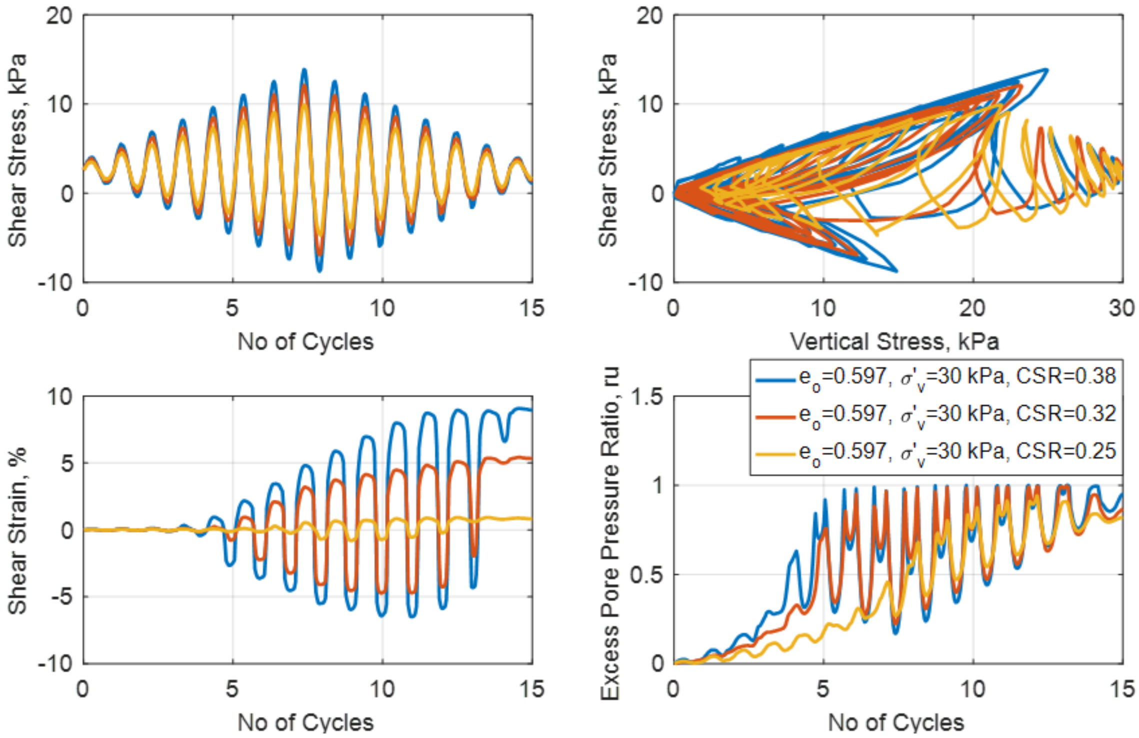

Figure 6. The effect of different CSRs on the generated permanent shear strain for samples under 30 kPa vertical stress

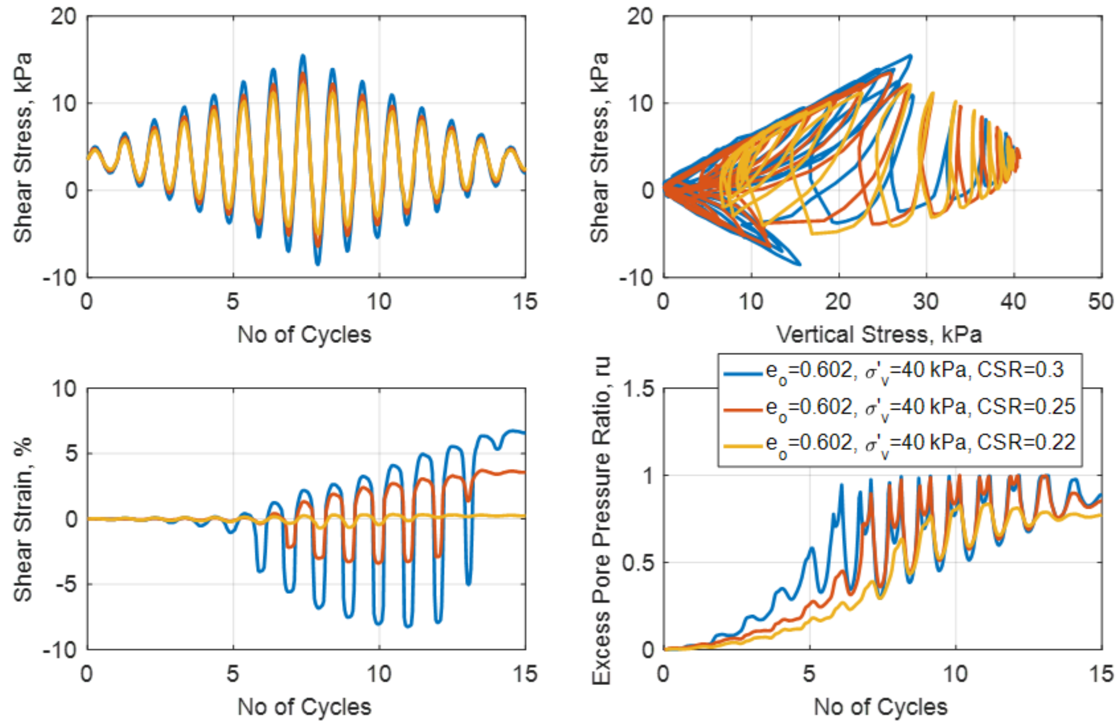

Figure 7. The effect of different CSRs on the generated permanent shear strain for samples under 40 kPa vertical stress

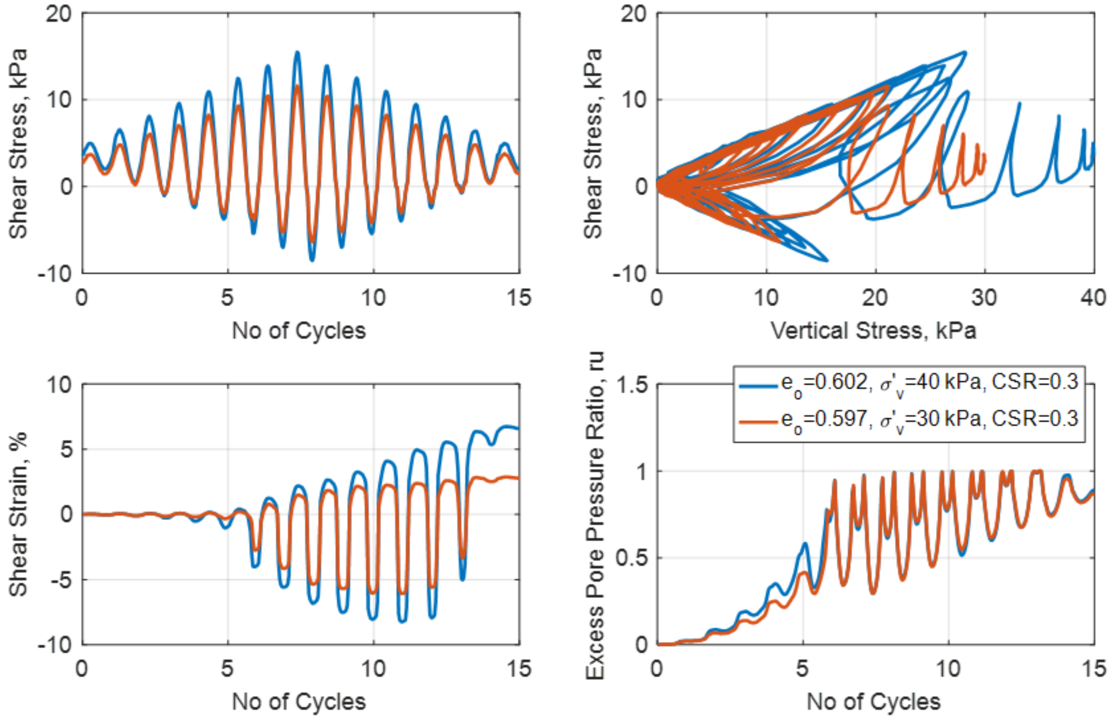

Figure 8. The effects of overburden stress on the response of specimens sheared at CSR of 0.3

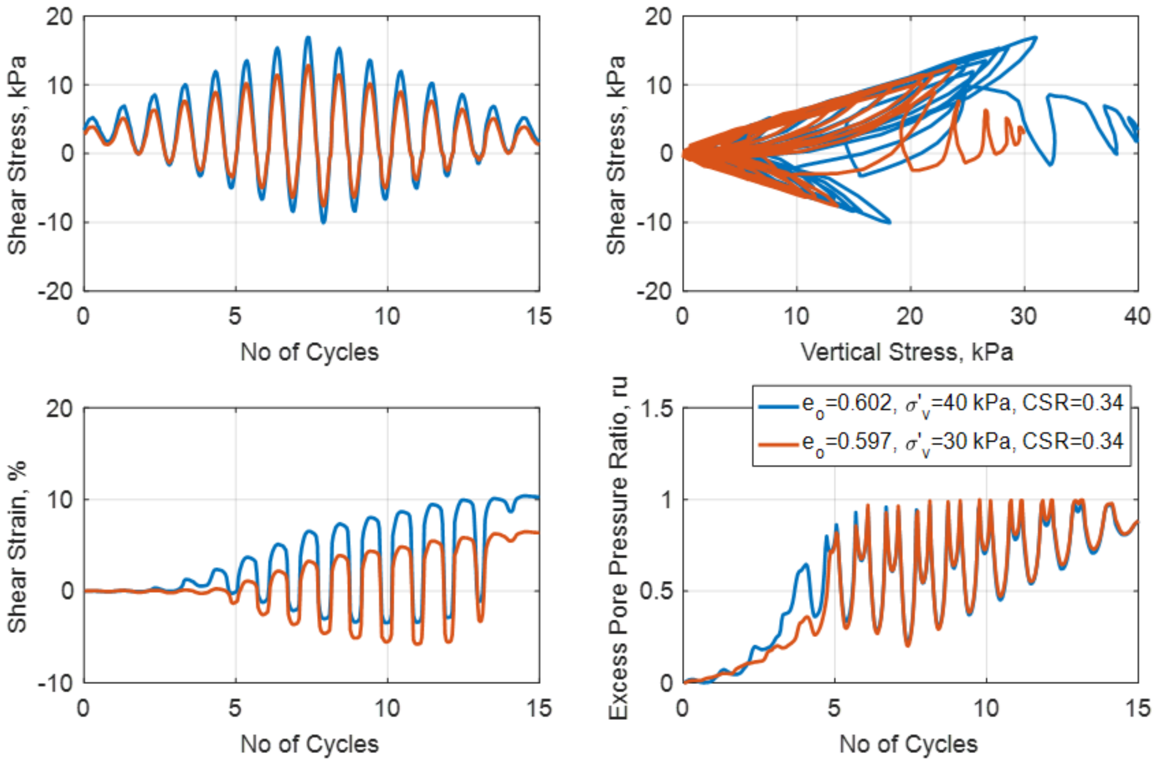

Figure 9. The effects of overburden stress on the response of specimens sheared at CSR of 0.34

Figure 10 shows a plot of the accumulated permanent shear strain versus the maximum applied CSR. Two curves were obtained for the tests conducted on the samples subjected to vertical stress of 40 and 30 kPa. The results clearly show the significance of the magnitude of the overburden pressures on the response of the soil. For the soil specimen subjected to CSR of 0.35, a sample with vertical stress of 40 kPa produces about twice as much permanent shear strain as a sample with vertical stress of 30 kPa.

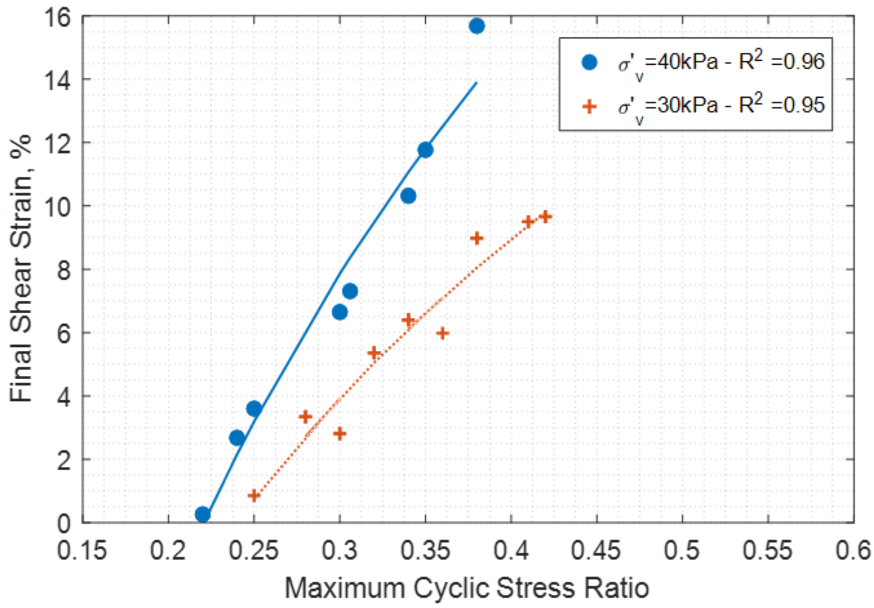

Figure 10. Final shear strain vs maximum CSR curves

5. Estimation of the Magnitude of Lateral Spreading Using the CDSS Test Results

The results presented in the previous section provide some insights on the stress-strain response of the soil during liquefaction-induced lateral spreading. By comparing the results of the tests with two different levels of vertical stress, It can be seen that a soil with higher confining stress is more contractive and yields higher shear deformation than the more dilative soil with smaller confining stress. This observation suggests that the magnitude of lateral strain is likely to be larger at larger depths and the profile of lateral displacement should be non-linear along the depth of soil layer. Higher lateral strains would occur at the bottom of the soil layer while relatively small strains would occur near the surface of the soil. This observation is supported by the observations made in the centrifuge experiments conducted for a similar boundary value problem [4]. Figure 11 shows the results obtained from one of the experiments conducted at Cambridge University. The figure shows the movement of the marker line at the end of centrifuge experiment. The test conducted composed of a sloping liquefiable soil layer with a slope of 6 degrees and a prototype thickness of 5 meters. The soil layer is underlain by a dense (non-liquefiable) base to maintain the thickness of the liquefiable layer across the length of the model. The figure shows the marker line movements, where pre-earthquake configuration is shown in black and post-earthquake is shown in red. The axis show the scale in mm at model scale. The post liquefaction lateral displacement profile obtained in this centrifuge test is consistent with the observations made from the results of the CDSS tests.

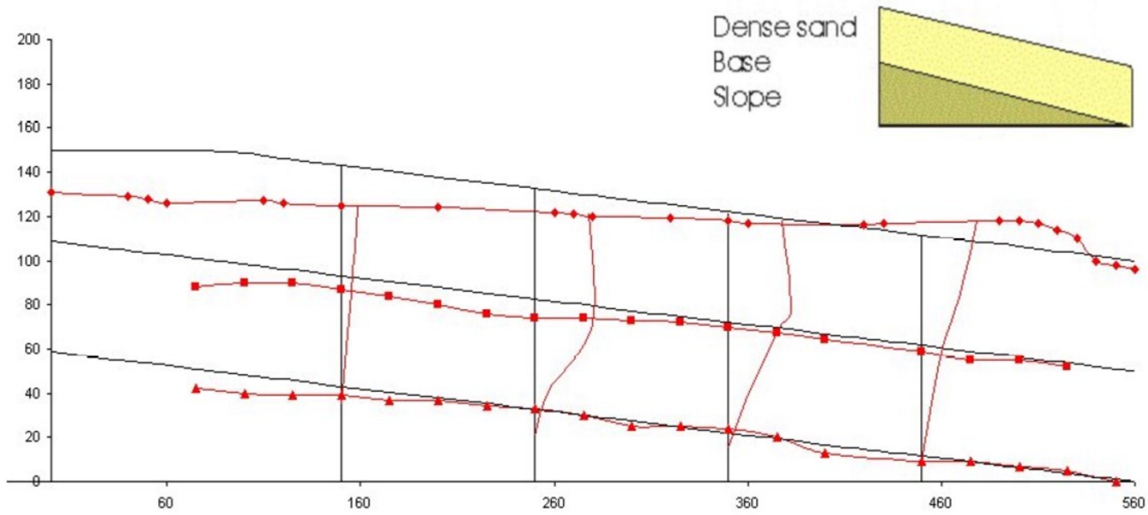

Figure 11. Cambridge University centrifuge experiment lateral displacement profiles [4]

The centrifuge experiments conducted as part of the LEAP projects provide an opportunity to conduct a direct comparison between the centrifuge and the CDSS tests and to assess the potential use of the latter tests to provide an estimate of the observed lateral spreading in the centrifuge tests. In the following sections, first the methodology used to compute the lateral displacement is discussed followed by a comparison of the results.

5.1 Methodology

The main objective is to utilize Figure 10 in estimating the magnitude of the shear strain that is expected to develop. To that end, the maximum cyclic stress ratio for each centrifuge experiment needs to be computed. This value could be obtained by assuming that the cyclic shear stress experienced by the soil in the centrifuge experiment could be estimated using the formula presented (Eq. 1) by Seed and Idriss, [13]:

$$\tau_{cyc} = 0.65 \frac{a_{\max}}{g} \sigma_v r_d \qquad (1)$$

Where τ_{cyc} is the cyclic shear stress, $a_{\max}$ is the maximum acceleration at the ground surface, g is the acceleration due to gravity, σ_v is the total vertical stress and r_d is the stress reduction factor that is assumed to be 1.0 due to the shallow depth of the soil layer.

Typically, the maximum acceleration at the ground surface is obtained from a site response analysis. However, in this case since the displacement time histories are available at the ground surface, the maximum value of surface acceleration is obtained from the measured time histories. As an example, Figure 12 shows that the lateral displacement time history taken at soil surface of the RPI 2015 using high speed camera tracking of markers on the slope surface [36]. From this time history, the acceleration time history is computed through second order numerical derivation. In order to reduce the noise and high frequency content of the motion that may not be contributing to the lateral displacement of the soil, a moving average smoothing was applied to the computed velocity time history before the acceleration was computed. Figure 13 shows the resulting acceleration time history. While other more advance noise-filtration techniques are available, this method is found most suitable as it ensures that the acceleration time history when double integrated, results in a back-calculated lateral displacement time history that matches the measured one as shown in Figure 14.

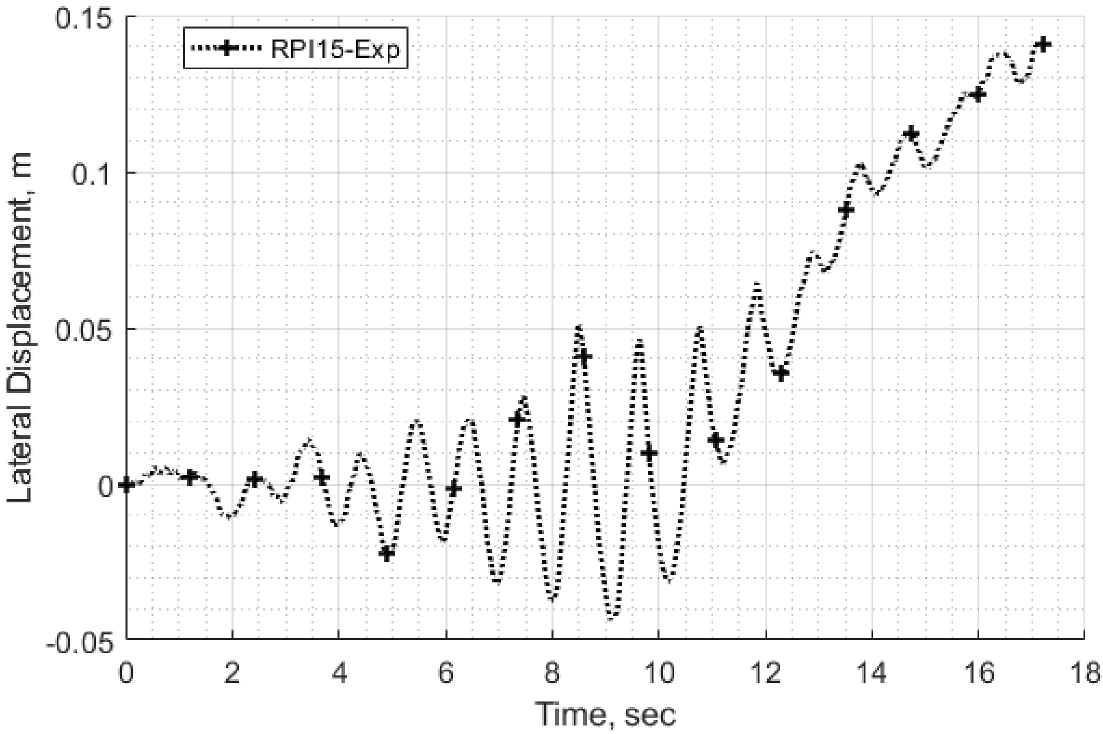

Figure 12. Lateral displacement time history for RPI 2015 experiment [36]

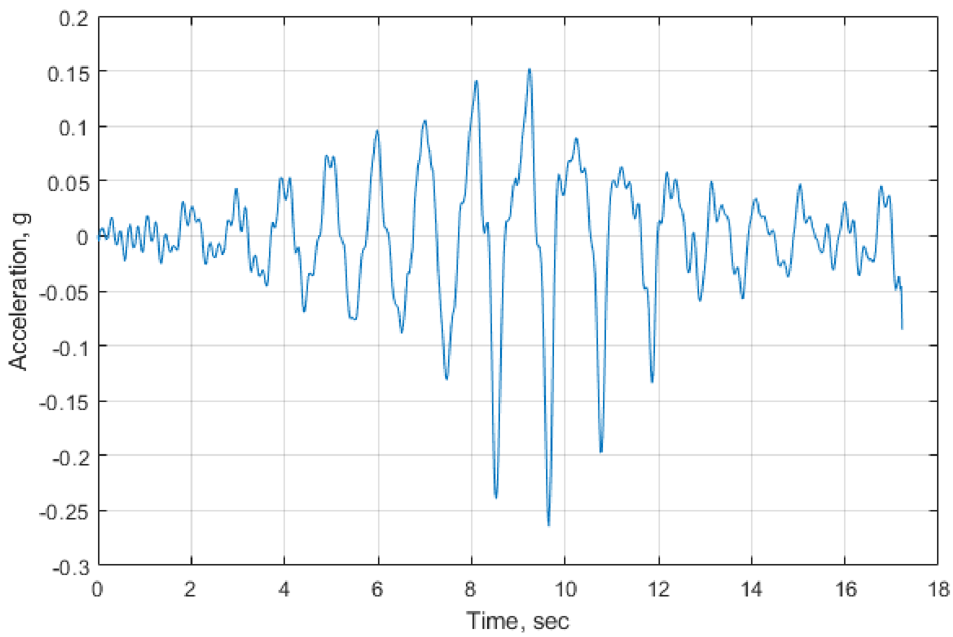

Figure 13. Acceleration time history at the ground surface for the RPI 2015 experiment

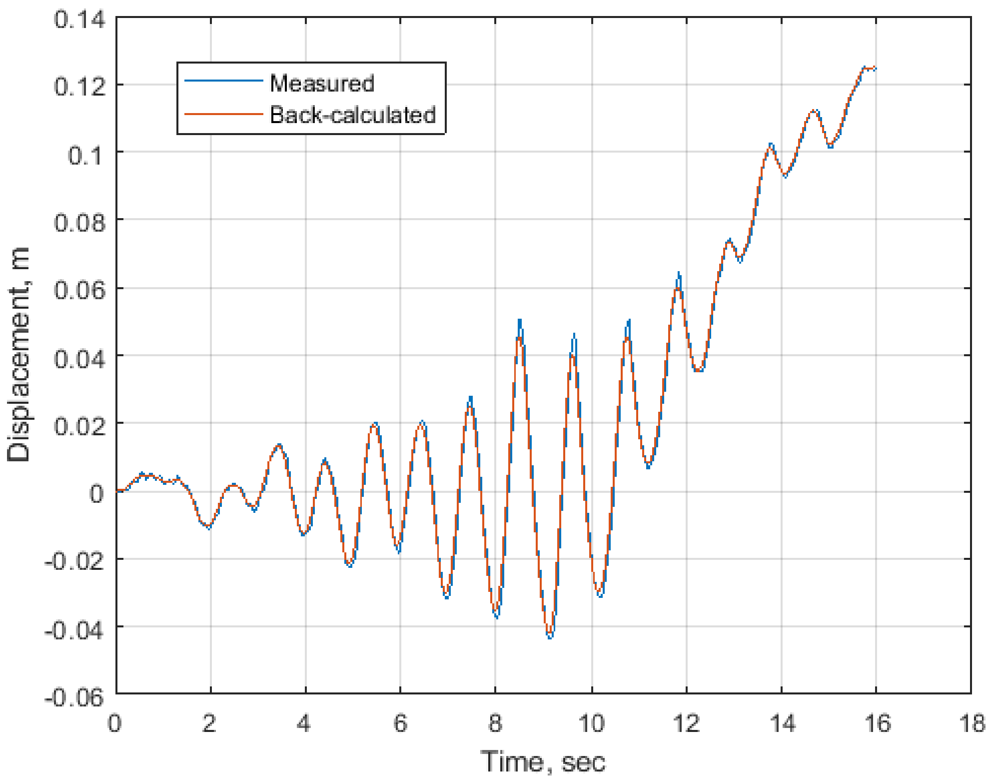

Figure 14. RPI 2015 lateral displacement time history: measured vs. back-calculated

The maximum acceleration time history could be obtained from the computed acceleration time history. Using this value, the maximum cyclic stress ration (CSR_{max}) could be obtained from Eq. 1. Using the computed maximum CSRs, the permanent shear strain could be obtained from Figure 10 for both the 40 kPa and the 30 kPa. As discussed earlier, the majority of the lateral displacement on the ground surface is due to shear strain developing at the bottom of the soil layer. In this case, for the 4.0 m soil layer, it is assumed that the average shear strain over the soil profile would occur at the bottom 2.0 m of the soil layer. Based on this is assumption, the shear strain obtained from the 30 kPa dataset is integrated over the tributary width of 2.0 meter to obtain an estimate of the permanent lateral displacement.

5.2 Comparison of Results

Following the previously described methodology, an estimate of the permanent lateral displacement is obtained for several of the LEAP centrifuge experiments conducted during LEAP 2015 and 2017 projects. First, considering the RPI 2015 example that was discussed in the previous section, the maximum acceleration at the ground surface is obtained to be 0.265 g as shown in Figure 13. With the computed a_{max}, Eq. 1 yields a cyclic stress ratio (τ_{cyc}/σ'_v) of 0.344. From Figure 10, for a CSR level of 0.344 and at the depth of 3 meters, an expected shear strain of 6.4% is expected. Assuming that the majority of the lateral strains would occur in the bottom 2 meters, the expected displacement is estimated as 0.128 meters. In comparison to the obtained lateral displacement from the centrifuge experiment, the CDSS tests provided a reasonable estimation for the amount of expected lateral displacement.

To further assess the validity of the previous observations, additional tests conducted as part of LEAP 2017 project are also investigated. The tests were conducted at three different centrifuge research facilities (RPI, KAIST and NCU) are considered [37–40]. The tests performed by RPI were conducted by different researchers and the results showed a high level of repeatability and consistency when compared to the LEAP 2015 test. These tests were also able to closely match the target input motion. The results of the tests performed at RPI were the only ones where time history of surface displacement was recorded in-flight using a high speed camera. Moreover, in these tests the achieved density of soil specimen was based on direct measurements and were not inferred from the calibration tests conducted during the sample preparation set up. Therefore these tests are considered the tests with the highest level of fidelity and the main focus of our comparisons. For the tests conducted by KAIST and NCU, the final displacements were recorded at the end of the tests and the time history was computed from the accelerometer closest to the surface. In addition, the reported achieved densities were inferred from the calibration procedure done during the sample preparation set up. Therefore, higher level of error is expected from these experiments. Nonetheless, these tests provide a valuable resource for comparison, especially for the NCU tests which were conducted at a higher PGA than the main 0.15g base motion.

Experiment	PGA (g)	Achieved Density, kg/m3	a_{max} (g) (comp)	CSR (comp)	Measured disp. (m)	CDSS shear strain (%)	disp. (m) (comp)	Error (%)
RPI15	0.167	1652	0.267	0.347	0.141	6.460	0.129	8.17
RPI17-1	0.155	1650	0.278	0.362	0.124	7.196	0.144	-16.05
RPI17-2	0.144	1659	0.266	0.346	0.155	6.414	0.128	17.12
RPI17-3	0.170	1623	0.268	0.349	0.142	6.540	0.131	7.56
KAIST17-2	0.184	1593	0.274	0.356	0.150	6.919	0.138	7.67
NCU17-1	0.260	1652	0.441	0.573	0.259	15.213	0.304	-17.72
NCU17-2	0.193	1652	0.446	0.579	0.251	15.406	0.308	-22.55
NCU17-3	0.204	1652	0.344	0.448	0.281	10.903	0.218	22.33

shows a bar chart comparing the measured versus estimated lateral displacements for several of the LEAP 2015/2017 centrifuge tests. The blue bars show the measured while the red bars show the estimates. It can be seen that the estimated values are reasonably close to the measured results. Table 4 lists the results obtained for the comparison between the measured displacement for each centrifuge experiment and the computed displacement from the CDSS tests following the previously presented procedure. The table shows the PGA, the achieved density and the measured displacement for each tests. It is also important to note that for the RPI17-2 tests, base motion had an additional 3Hz component added to the 1Hz for its frequency. The remainder of the table shows the computed maximum surface acceleration a_{max}, the computed CSR (Eq. 1), the expected level of shear strain from the CDSS tests presented herein (Figure 10) and the expected displacement from the shear strain assuming it occurs over the bottom 2 meters of the soil layer. The table shows the error between measured and computed displacements. The computed displacements estimated the measured lateral displacement with an error that is less than 23%.

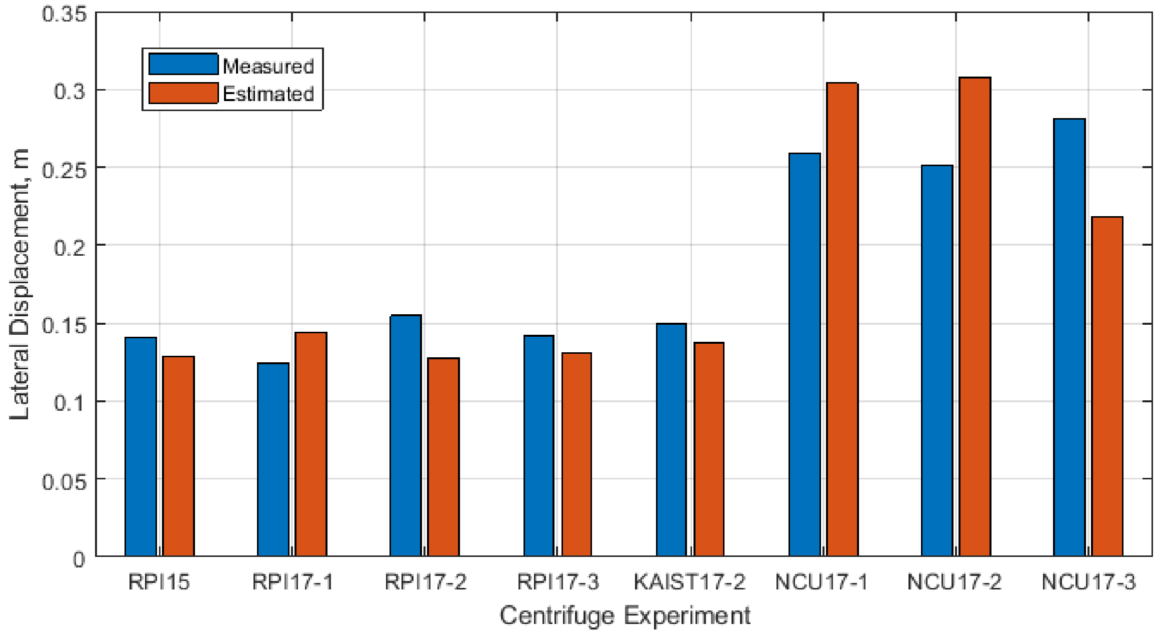

Figure 15. Measured vs. estimated lateral displacement for LEAP 2015/2017 centrifuge experiments

Table 4. Comparison between the measured displacements in the centrifuge experiments and the predicted displacement from the CDSS Tests

Experiment	PGA (g)	Achieved Density, kg/m3	a_{max} (g) (comp)	CSR (comp)	Measured disp. (m)	CDSS shear strain (%)	disp. (m) (comp)	Error (%)
RPI15	0.167	1652	0.267	0.347	0.141	6.460	0.129	8.17
RPI17-1	0.155	1650	0.278	0.362	0.124	7.196	0.144	-16.05
RPI17-2	0.144	1659	0.266	0.346	0.155	6.414	0.128	17.12
RPI17-3	0.170	1623	0.268	0.349	0.142	6.540	0.131	7.56
KAIST17-2	0.184	1593	0.274	0.356	0.150	6.919	0.138	7.67
NCU17-1	0.260	1652	0.441	0.573	0.259	15.213	0.304	-17.72
NCU17-2	0.193	1652	0.446	0.579	0.251	15.406	0.308	-22.55
NCU17-3	0.204	1652	0.344	0.448	0.281	10.903	0.218	22.33

Different sources of errors might have influenced the accuracy of the predictions. First, while the shear stress time history applied in the CDSS followed the target acceleration, the acceleration time history at the ground surface is not exactly matching that form. Also as previously mentioned, besides RPI15 which closely matched the target input motion, each of the remaining centrifuge tests input motions exhibited a degree of noise or higher frequency content that was not modelled in the CDSS tests. In addition, the exact density measurement for the soil density was not taken for all of the centrifuge tests, therefore the soil density was assumed in the cases of KAIST and NCU tests. All these in addition to the sources of uncertainty the maybe present in the CDSS tests and the estimation method may have contributed to the variation in the results. However, even though there are a large uncertainty in the input variability, the quality of the estimated displacements computed for these tests appears to be quite reasonable.

6. Conclusions

The paper presents an experimental study on the effect of overburden stress on the permanent lateral deformations of liquefiable sloping grounds. The experiments were inspired by the LEAP centrifuge experiments conducted during 2015 and 2017. A total of 17 tests were performed on samples prepared at a relative density of 66-67% and subjected to a vertical confining stress of 40 and 30 kPa. The experimental results demonstrated the effect of low overburden stresses on the more dilative response of the soil. Conforming to the principles of critical state soil mechanics theory, the sample with smaller confining stress exhibited a more dilative response and generated smaller permanent shear strains. The data produced in this study provides an additional resource for the constitutive modellers to evaluate the performance of their constitutive models and possibly find ways to improve the model performance. Moreover, the data obtained in this study was used to evaluate the capability of the CDSS tests to estimate the magnitude of the lateral spreading observed in the LEAP centrifuge tests. A comparison between the CDSS tests and the centrifuge tests conducted during LEAP 2015 and 2017 projects shows that using a simple method the magnitude of lateral spreading could be estimated within relatively small margin of error.

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