Parametric Study on Liquefaction-Induced Building Settlements using 1-g Shake Table Experiments

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ABSTRACT
Liquefaction-induced ground failure has accounted for major damage in structures and lifelines for several decades (e.g. the 1989 Loma Prieta earthquake among others). Well-documented case histories have provided valuable insight into the mechanisms of this phenomenon. Recent earthquakes such as the 2010-2011 Canterbury earthquake sequence in New Zealand and the 2011 Great Tohoku earthquake in Japan have documented that settlement of buildings over liquefiable soils can be much greater than predicted using semi-empirical procedures in common practice to date.
A large number of low-story structures sustained significant damage resulting from liquefaction-induced settlements in the recent seismic events and reconnaissance of the affected areas has documented extensive damage to buildings with shallow foundations within liquefaction-prone areas.

The estimation of liquefaction-induced settlement is based on semi-empirical correlations that evaluate settlement in the free-field conditions whereas observations have shown that the liquefaction-induced settlement under buildings can be considerably larger.

In this study, an extensive series of 1-g scaled shake table experiments were carried out to reproduce liquefaction-induced building settlements which included comprehensive parametric study to establish the effects of several parameters on the free-field and building settlements such as building dimensions, ground motion duration, and the liquefiable soil relative density.

Results of this experimental study are compared to recent centrifuge tests and field measurements and provide valuable insight into the effects of abovementioned parameters on the liquefaction-induced settlement for both free-field and under building conditions. The scaled model experiments were fully instrumented using accelerometers, LVDTs, and pore-water pressure sensors to quantify these effects.

1 INTRODUCTION

Settlement of foundations subjected to the effects of liquefaction have been known to cause severe damage. This damage has been documented extensively in recent case histories and has provided valuable insight into the mechanisms controlling the behavior of liquefaction. 1-g shake table testing was performed to evaluate the performance of circular rigid shallow foundations over liquefiable soils. Each experiment focused on the influence of specific parameters (foundation width, ground motion duration and relative density of liquefiable soil) in regards to liquefaction-induced settlement. Liquefaction settlement was considered for both free-field and building foundation conditions. Results of this comprehensive parametric study are presented in this paper.

2 BACKGROUND

Recent earthquakes in Japan and New Zealand generated significant liquefaction resulting in a large number of low-story structures on shallow foundations sustaining significant damage. Figure 1 presents the liquefaction-induced settlement experienced by shallow foundations during a field reconnaissance after the 2011 Tohoku earthquake. The low-story building in the background is supported on a rigid shallow foundation while the building in the foreground is supported on a pile foundation. The rigid shallow foundation was documented to have experienced roughly 70cm of total settlement and the pile-supported foundation did not experience any settlement (Ashford et al. 2011, Bray 2016).

Through field observations and experimental research, it has been concluded that current engineering design practices in estimating seismic building settlements do not capture the mechanisms that largely control liquefaction settlement. Liquefaction-induced settlement uses semi-empirical procedures that predict post-liquefaction, one-dimensional, consolidation settlement for free-field conditions (Dashti et al. 2010a, 2010b, Bray et al. 2014, Bray 2016). Post-liquefaction settlement predictions for the free-field, such as those proposed by Tokimatsu and Seed (1987) and Ishihara and Yoshimine (1992), largely relate the cyclic stress ratio and soil relative density to estimate a volumetric strain. Tokimatsu and Seed (1987) further state that this procedure has an associated error ranging from 25-50% and acknowledges that liquefaction conditions are more complex than accounted for in their prediction.

Seismic induced building settlements observed during field reconnaissance from the 1964 Niigata, 1990 Luzon, 2010-2011 Canterbury and 2011 Tohoku earthquakes have been documented to be much greater than those predicted for free-field conditions. Dashti et al. (2010a and 2010b), identified that liquefaction-induced settlement for shallow foundations are effected by factors such as shaking intensity, liquefiable soil relative density and thickness as well as building weight and width. In addition, the majority of settlement was observed to occur during strong motion and not in post-liquefaction as predicted using current practices. These observations by Dashti et al. (2010a and 2010b) and Bray and Dashti (2014) suggest the current standard of practice could benefit by incorporating the shaking intensity rate, captured by the Arias intensity, as well as shear-induced and localized volumetric-induced deformations for foundations over liquefiable soils.

Figure 1. Observed Liquefaction-Induced Settlements after 2011 Tohoku Earthquake (Ashford et al. 2011, Bray 2016).

3 1-G SHAKE TABLE EXPERIMENTS

A series of 1-g shake table experiments were conducted to reproduce liquefaction-induced settlements using scaled model buildings founded over clean, saturated liquefiable sands. The experiments also included parametric study to establish the effects of parameters on free-field and building settlements. These factors included building dimensions, ground motion duration and relative density of liquefiable soil.

The experiment configuration was developed using a geotechnical project located in Stateline, Nevada (USA) for the case study. The project consist of a seismic retrofit of shallow foundations on potentially liquefiable soils up to approximately 3.0 meters in thickness.

3.1 Soil Box

Each experiment utilized a transparent soil box fitting the approximate dimensions of 2.04 x 0.64 x 0.82 m (length x width x height). Construction of the box consisted of Lexan glass of 2.5-cm thickness and reinforced using a rigid steel frame as presented in the following Figure 1. Two drains installed along the base of the soil box assist with saturation and draining of the soil used during experimentation. The soil box implemented 7.6-cm thick high-density foam padding at each end to reduce rigid boundary effects during model excitation. Lombardi et al. (2015) conducted a series of tests to evaluate the performance of foam used as a method in minimizing boundary effects created by the confinement in rigid model soil containers. They demonstrated that rigid soil containers that incorporated foam at the end boundaries were characterized to effectively reduce reflection of body waves from the rigid boundaries of the container. The implementation of duxseal and other means of dampening boundary effects has been extensively studied by other researchers such as Pak et al. (1996), Coe et al. (1985), Cheney et al. (1990), Lenke et al. (1991), Campbell et al. (1991), Weisman and Prevost (1991), Chazalas et al. (2001), Chakrabortyy et al. (2008), Pitilakisa et al. (2008), Murillo et al. (2009), and Cilingir and Madabhushi (2010).

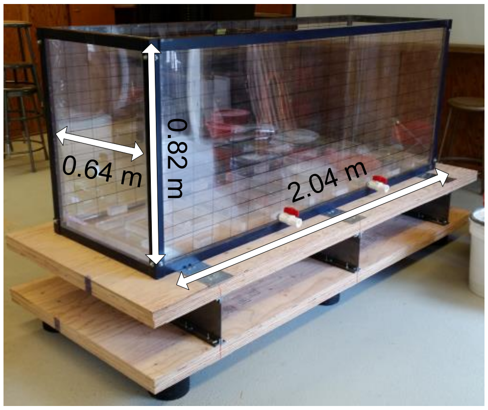

Figure 2. Soil Box Dimensions used in This Study.

3.2 Soil Properties

Shake table testing was performed using a fine to medium, poorly graded Sierra Silica #60 mesh (S.S. #60) sand ($D_{50} \approx 0.32$ mm, $C_u \approx 1.75$, $C_c \approx 1.04$, $e_{min} \approx 0.73$, $e_{max} \approx 1.01$). Liquefiable layers were prepared to approximate relative densities and saturated unit weights as presented in Table 1. All non-liquefiable layers were prepared using an approximate relative density (D_r) of 70%.

Table 1. Summary of Relative Densities and Unit Weights Utilized in Model Configuration.

Relative Density (%)	Saturated Unit Weight (kN/m^3)
25	18.15
35	18.27
45	18.40
55	18.53
70	18.73

3.3 1-g Model Configuration and Preparation

Soil model configuration consisted of a non-liquefiable layer overlain by a liquefiable layer of equal thickness (30.5 cm). The standard model configuration used in each experiment is presented in Figure 3 and includes the typical configuration of instrumentation used in experimentation. The groundwater table is located at the surface of the soil profile.

The non-liquefiable layer was conditioned to 5% moisture content before placement and hand compaction within the soil box. Saturation of the non-liquefiable layer was achieved by slowly introducing water using the drains at the base of the soil box. The liquefiable layer was constructed by means of pluviation through water. Instrumentation was installed concurrently during construction of each model layer.

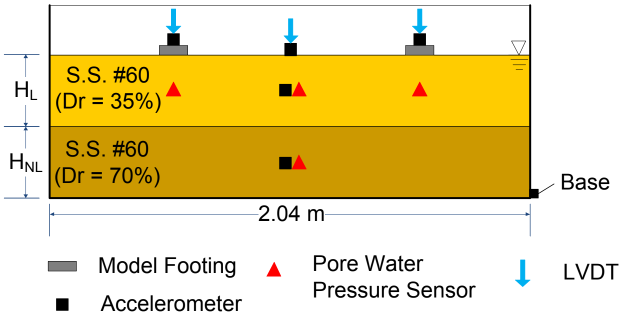

Figure 3. Parametric Study Model Configuration.

3.4 Ground Motions

Input ground motions were implemented by manually applying a horizontal force on the soil container for a specified duration and ranged from 2 to 8 seconds. Measured base ground accelerations had an average peak of about 0.25g and an average frequency of 3.0 Hz.

3.5 Rigid Mat Foundations

Model foundations consisted of circular concrete footings and assumed an approximate contact pressure of 5.9kPa in prototype. Model contact pressures were based on the average loading combinations for a single-family residence of approximately 5.9kPa (Perko 2009). Model foundations ranged in diameter from 7.6 to 25.4 centimeters and are presented below in Figure 4.

Figure 4. Model Building Foundations.

3.6 Model Similitude

The liquefaction model was configured using similitude laws for 1-g shake table testing as presented by Iai (1989). Each experiment assumed a scaled factor of similitude equal to 10. The following laws recommended by Iai (1989) are presented in Table 2.

Table 2. Summary of 1-g Shake Table Experiments.

Quantity	Model	Prototype
Length	1/λ	1
Density of Soil/Water	1	1
Strain of Soil	$1/\lambda^{0.5}$	1
Total and Effective Stress	1/λ	1
Pore-Water Pressure	1/λ	1
Acceleration	1	1

Note: λ=10, scaling ratio in this study

4 EXPERIMENTAL RESULTS

Table 3 presents a summary of the model parameters used in the parametric study for Tests #38 through #46 and #50 through #52. Each test considered the influence of parameters such as model foundation diameter, soil relative density and ground motion duration on liquefaction settlement. Tests #38 through #43 focused on the influence of foundation diameter on liquefaction settlement. Tests #44 through #46 focused on the influence of relative density of liquefiable layer. Tests #50 through #52 focused on ground motion duration.

Table 3. Summary of 1-g Shake Table Experiments.

Test No.*	Relative Density** (%)	Input Motion Duration (sec)	Foundation Diameter (cm)
38	35	6	15.2
39	35	6	20.3
40	35	6	7.6
41	35	6	11.4
42	35	6	20.3
43	35	6	25.4
44	25	6	15.2
45	45	6	15.2
46	55	6	15.2
50	35	2	***15.2 / 25.4
51	35	4	***15.2 / 25.4
52	35	8	***15.2 / 25.4

*Liquefiable and Non-Liquefiable Layer Thicknesses of 30.5 cm
** Liquefiable Layer. Non-liquefiable layer = 70%
***Experiments included two unsupported model foundations

Figure 4 presents the typical output recorded by accelerometers, pore-water pressure sensors and LVDT captured in each experiment. Ground accelerations are presented for the conditions of input, midpoint of liquefiable layer and model surface (free-field and model foundation). Excess pore-water pressure is presented for midpoint of the liquefiable layer below the model foundation. Observed settlements are also presented for the free-field and model foundation. It is observed within the output, that liquefaction develops shortly after ground input motion develops. Additionally, this is correlated to an immediate increase in the generation of excess pore-water pressure. Liquefaction occurs when the excess pore-water pressure equals the vertical effective stress within the soil model. Settlements in free-field and model foundation are observed to commence at approximately the same instant that the excess pore-water pressure reaches the present vertical effective stress at the midpoint of the liquefiable layer.

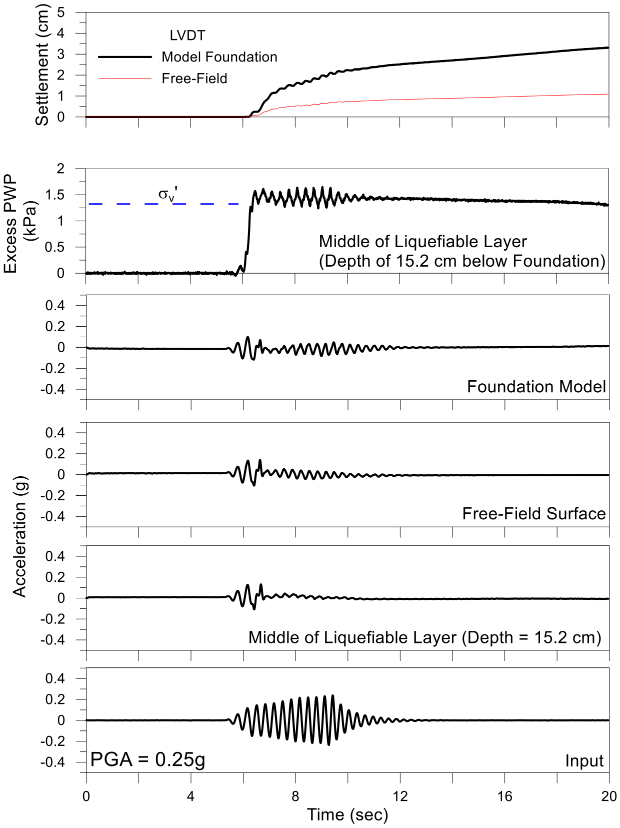

Figure 5. Typical Results of Experiment for Parametric Study.

Figures 5 through 7 present the results of the parametric study based on the influence of model foundation dimensions, ground motion duration and relative density of liquefiable soil.

The results presented in Figure 6 indicate that liquefaction-induced building settlement decreases with an increase in foundation diameter.

The results presented in Figure 7 indicate that liquefaction-induced settlement increases over longer ground motion durations. The tests presented in the plot were performed using a case scenario that included a liquefiable layer thickness of 30.5 cm with relative density of 35% and model foundation diameter of 15.2 cm. The rate of settlement for the Model Foundation case is larger than that of the Free-Field condition.

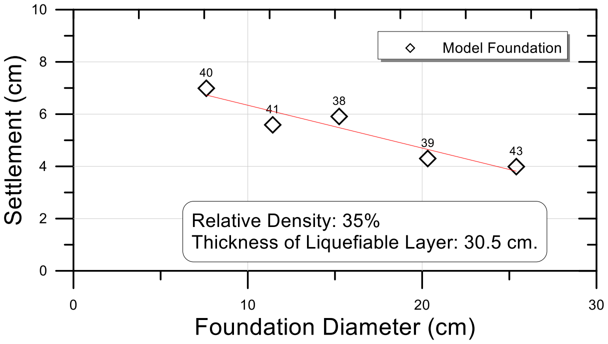

Figure 6. Influence of Foundation Dimensions.

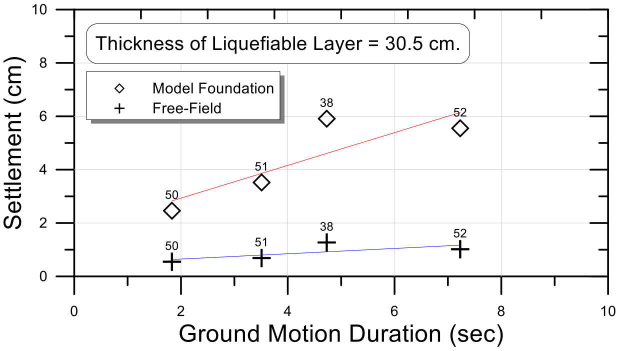

Figure 7. Influence of Ground Motion Duration.

The results presented in Figure 8 suggest that liquefaction-induced settlement decreases, for both cases of Free-Field and Model Foundation, with an increase in relative density of liquefiable layer. The tests presented in the plot were performed using a case scenario that included a liquefiable layer thickness of 30.5 cm with ground motion duration of 6 seconds and model foundation diameter of 15.2 cm. The Model Foundation condition shows a greater rate in reduction of settlement.

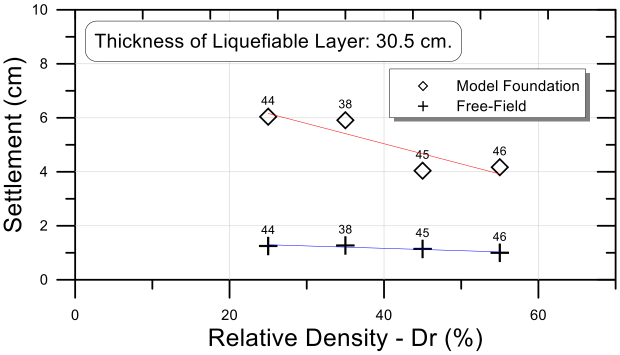

Figure 8. Influence of Relative Density

Results of our parametric study illustrate the effects of several parameters on liquefaction-induced settlements. Among the studied parameters, the model building settlement seems to be inversely proportional to the foundation diameter and liquefiable layer relative density. Furthermore, the ground motion duration appears to be directly proportional to the observed settlements. In all of the experiments, we observed larger model building settlements compared to the free-field settlements. In addition, the results from this study were compared to the previous case histories where liquefaction-induced building settlement was evaluated during field-reconnaissance for two earthquakes. The 1964 Niigata and 1990 Luzon earthquake each evaluated liquefaction-induced settlement of lightly loaded single story structures. Results of the observations for both events are presented in the following Figure 9 adopted from Liu and Dobry (1997). The range of normalized liquefaction-induced settlements are further defined by upper and lower bounds. Results of the parametric study are compared to the upper and lower bounds in the figure and are presented in Figure 10. Our parametric results from Tests #38 through #46 and #50 through #52 show good agreement with the upper and lower bounds. It should be noted here that in our experimental study the model foundation widths did not exceed the thickness of the liquefiable layer, hence all of our data points in Figure 10 fell to the left side of ratio 1.0. Additional tests with larger foundation width is needed to extend the breadth of the data in Figure 10.

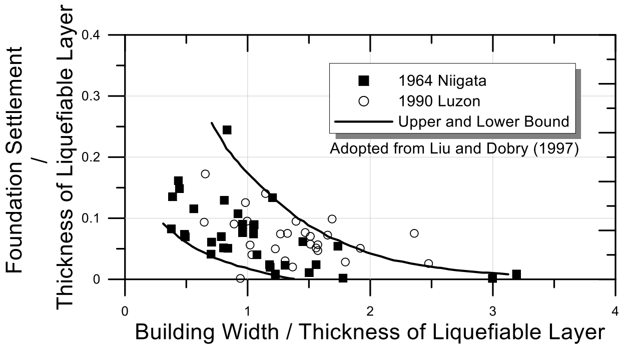

Figure 9. Comparison of Normalized Building Dimensions to Observed Foundation Settlement (Adapted from Liu and Dobry, 1997).

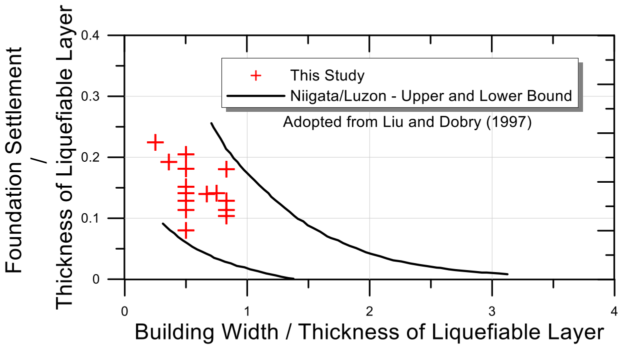

Figure 10. Comparison of Results of Parametric Study to Previous Case Histories.

5 SUMMARY AND CONCLUSIONS

Well-documented case histories have provided valuable insight into the mechanisms of liquefaction-induced building settlement. Field reconnaissance of recent earthquake events (2010-2011 Canterbury Earthquake sequence, 2011 Tohoku Earthquake) have documented that settlement of buildings over liquefiable soils can be much greater than those predicted using semi-empirical procedures in estimating liquefaction settlement such as those proposed by Tokimatsu and Seed (1987) and Ishihara and Yoshimine (1992).

Experimental research has identified that the majority of liquefaction settlement occurs during strong motion and not during post-liquefaction and reconsolidation. Additionally, semi-empirical predictions are based in the free-field and do not account for the influence of foundations during liquefaction. The mechanisms controlling liquefaction settlement under loading from building foundations are not well understood. Dashti et al. (2010a, 201b) and Bray and Dashti (2014) indicate that the shaking intensity, captured by the slope of the arias intensity curve should be accounted for in the semi-empirical predictions to improve the estimation of liquefaction-induced building settlement.

Comprehensive parametric study was conducted to observe the influence of foundation width, relative density of liquefiable layer and ground motion duration on liquefaction settlement in the field-field and under model building foundation. Results of the parametric study have concluded the following for seismic induced settlement in both free-field and building environments. (1) Settlement decreases with increasing foundation width, (2) Settlement increases with increasing ground motion duration and (3) Settlement decreases with increasing relative density of the liquefiable layer.

Results of our parametric study are compared to previous field reconnaissance observations from previous earthquake events that evaluated degree of settlement of shallow foundations damaged by liquefaction during the 1964 Niigata and 1990 Luzon events. Our results fit within the range of data observed during those events.

6 ACKNOWLEDGEMENTS

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