



Performance of Retrofitted pile foundations subjected to Seismically Induced Lateral Spreading

T. Abdoun,

Rensselaer Polytechnic Institute, Troy, NY, USA.

Y. Wang

Mueser Rutledge Consulting Engineers, New York City, NY, USA.

ABSTRACT: Experiences from earthquakes and centrifuge models have shown the great importance of the shallow nonliquefiable soil in increasing the forces and moments imposed on the pile cap and pile foundation subjected to liquefaction-induced lateral spreading. This paper focuses on evaluating retrofitting strategies, with emphasis on the placement of a soft or frangible material near the foundation in the shallow nonliquefiable layer. While this shallow soft material reduces the stiffness and the strength of the pile foundation with respect to the superstructure inertia forces, it constitutes an extremely effective way to mitigate the effect of lateral spreading cases in which the resistance to inertia is provided by other foundation elements are one area of application of the proposed retrofitting strategies. Results of three centrifuge tests, Models 2, 2r1 and 2r2, are presented to illustrate the effectiveness of the implemented retrofitting method.

The experimental results for each of the centrifuge pile models are reviewed and compared. After implementing the proposed retrofitting strategies, a dramatic reduction in the maximum bending moment is observed at the upper boundary of the liquefied layer (2 m depth). A reduction of up to 35% in the measured maximum bending moment is also observed at the lower boundary of the liquefied layer (8 m depth). These significant reductions in measured pile maximum bending moments in Model 2r, together with the associated reduction of up to 50% in the measured pile head displacement, demonstrate the effectiveness of the implemented retrofitting method

1. INTRODUCTION

Earthquakes are major natural hazards worldwide. Case histories indicate that in most large earthquakes soil liquefaction-related failures have occurred. For instance, the 1971 San Fernando, California earthquake caused more than five hundred million dollars in damage (NRC 1982). In 1976, the Tangshan, China earthquake resulted in collapse and severe damage of many buildings and in the death of several hundred thousand people (NRC 1982). The 1995 HyogoKen Nanbu earthquake in Kobe, Japan, caused more than one hundred billion dollars in total damage. The recent Turkey, Taiwan and Greece 1999 earthquakes also caused tremendous destruction. In all these earthquakes, much of the damage was related to liquefaction and associated induced lateral spreading.

Evaluation of case histories and physical models reveal the significance of several factors influencing the deformation of deep foundations, as well as bending moments and cracking of damaged piles. These factors include: free-field permanent lateral ground displacement; thicknesses and properties of soil strata penetrated by the piles; and the geometry and properties of the pile foundation. The observed damage and cracking to the piles is often concentrated at the upper and lower boundaries of the liquefied sand layer where there is a sudden change in soil properties (Hamada 1992; Yokoyama et al.

1997; Tokimatsu 1999, Abdoun and Dobry 2002; Abdoun et al. 2002 and Dobry et al. 2002), or at the connections between pile and pile cap (e.g., Hamada 1992 and Hamada 2000).

A series of centrifuge tests were conducted earlier to study the great importance of the shallow nonliquefiable soil in increasing the bending response of the pile foundation (Abdoun and Dobry 2002; Abdoun et al. 2002 and Dobry et al. 2002). This paper presents a promising rehabilitation approach of existing foundations; to replace the shallow soil in a trench around piles and pile cap by a soft material that will yield under constant lateral soil forces (Figs. 1b & 1c). This would decrease both bending moments and foundation deformations while allowing the ground lateral spreading to take place without interference from the foundation. As this retrofitting scheme also decreases the lateral resistance of the foundation to inertial loading, a desired material should remain resilient under the transient inertial loading while yielding to static force. In this study, the trench surrounding the foundation will be filled with soft clay. Trenches may be located directly around the foundation (Fig. 1b) or may be located at some distance from the foundation so as to increase the resistance to inertial loading (Fig. 1c).

This paper presents the results of three centrifuge experiments performed to study lateral spreading and its effect on single pile foundations for retrofitted and non-retrofitted piles (Fig. 1). The objectives of this study are accomplished mainly using the centrifuge experiments and corresponding interpretations and comparisons. These objectives can be summarized as follows: i) study the three-layer lateral spreading soil response in the free field during earthquake shaking including the magnitude and profile with depth of the maximum induced lateral displacement; and ii) study the soil-pile interaction in three-layer soil system during liquefaction and lateral spreading, with and without the implementation of retrofitting strategies.

2. DESCRIPTION OF CENTRIFUGE MODELS

Sketches of RPI's laminar box (0.25 m (W) \times 0.46 m (L) \times 0.25 m (H), in model units) including the instrumentation used for all the centrifuge models are presented in Figure. 1. The laminar box consists of a stack of up to 39 rectangular rings separated by linear roller bearings, arranged to permit relative movement between rings in the long direction with minimal friction. A relative displacement of up to 0.006 m between adjacent rings is possible, and the design permits an overall shear strain up to 20%. The laminar box is optimized to accommodate and accurately measure a wide range of cyclic and permanent lateral strains occurring in the soil model. More detailed information on RPI laminar box used in this study is presented by Van Laak et al. (1994) and www.cee.rpi.edu/centrifuge.

The prototype being simulated in Model 2 (Fig. 1a) involves a single solid pile of diameter 0.60 m, length 10 m and $EI = 8000 \text{ kN}\cdot\text{m}^2$, with a pile cap embedded in the top cemented sand layer. An Aluminum pile cap was rigidly clamped to the top of the pile model. The pile cap has dimensions of 2 m (W) \times 2.5 m (L) \times 0.5 m (H), in prototype units. In model units, the model height is approximately 0.20 m, simulating a 10 m prototype soil deposit and pile length at 50g. The prototype profile includes a bottom layer of 2.0 m slightly cemented sand, topped by a 6.0 m layer of uniform Nevada sand placed at a relative density of about 40%, topped by a 2.0 m layer of the same slightly cemented sand. At 50g, the $D_r = 40\%$ fine Nevada sand layer in the model simulates a liquefiable, $D_r = 40\%$ coarse Nevada sand layer in the prototype. The soil profile is fully saturated with water, inclined 2° to the horizontal corresponding to 4.8° inclination in the field after the instrumental correction (Taboada 1995), and spun at a centrifuge acceleration of 50g.

The model was excited by 40 cycles of a 100 Hz sinusoidal input parallel to the base of the laminar box, with uniform acceleration amplitude of about 15g. For the 50g centrifuge acceleration of the test, this corresponds respectively, to a frequency of 2 Hz and peak acceleration of 0.3g in prototype units. The horizontal accelerations outside the laminar box and in the soil, excess pore water pressures in the liquefiable sand layer, lateral displacements of the rings, and bending moments along the pile were measured.

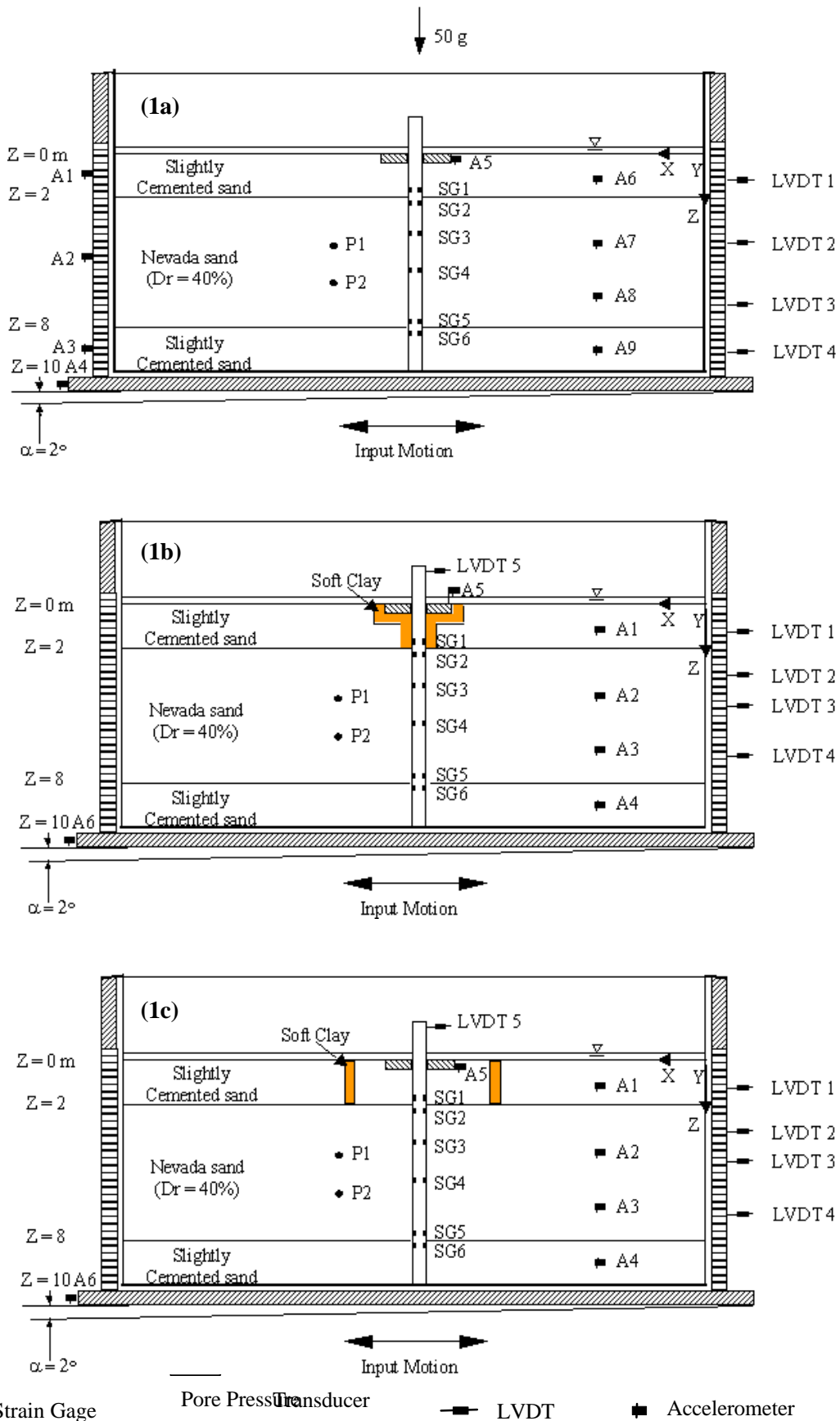


Figure 1: Setups and instrument locations of six centrifuge models; Model 2 (1a), Model 2r1 (1b) and Model 2r2 (1c)

The proposed rehabilitation approach of existing foundations will require replacing the shallow soil in a trench around piles and pile cap by a soft material that will yield under constant lateral soil forces (Figs. 1b and 1c). Models 2r1 and 2r2 shown in Figs. 1b and 1c, respectively, represent the two strategies used in retrofitting existing single piles with pile cap embedded in a three layer soil system. In Model 2r1 (Strategy 1), the slightly cemented sand directly surrounding the pile cap is replaced by 1m width of a slurry wall made by bentonite and water mixture. The depth of the slurry wall is about 1 m. A 1 m width ring of clay wall is directly surrounding the pile from 1m below the slightly cemented sand surface to the boundary of the cemented sand layer and liquefiable sand layer. In Model 2r2 (Strategy 2), a slurry wall made by bentonite and water mixture was placed around the foundation about 1 m away from the pile cap. The slurry wall has dimensions of 1 m width and 2m depth.

3. SUMMARY OF CENTRIFUGE TESTS FREE FIELD MEASUREMENTS

It is important to analyze the free field experimental results measured away from the piles to verify tests repeatability. A comparison between excess pore pressure profiles and soil lateral displacement profiles for all models presented in Fig. 1, at different times during shaking are presented respectively in Figs. 2 and 3. These free field records are very similar, confirming that the presence of the pile did not affect the free field soil response, and also validating the good repeatability of these centrifuge tests. In all models the lateral displacement occurred essentially within the 6.0 m thickness of the liquefiable sand layer (Fig. 3). The permanent ground surface lateral displacements at the end of shaking for all models are listed in Table 1. A similar good comparison, not presented in this paper, was also obtained between the recorded acceleration time histories for the seven centrifuge models (Wang 2001).

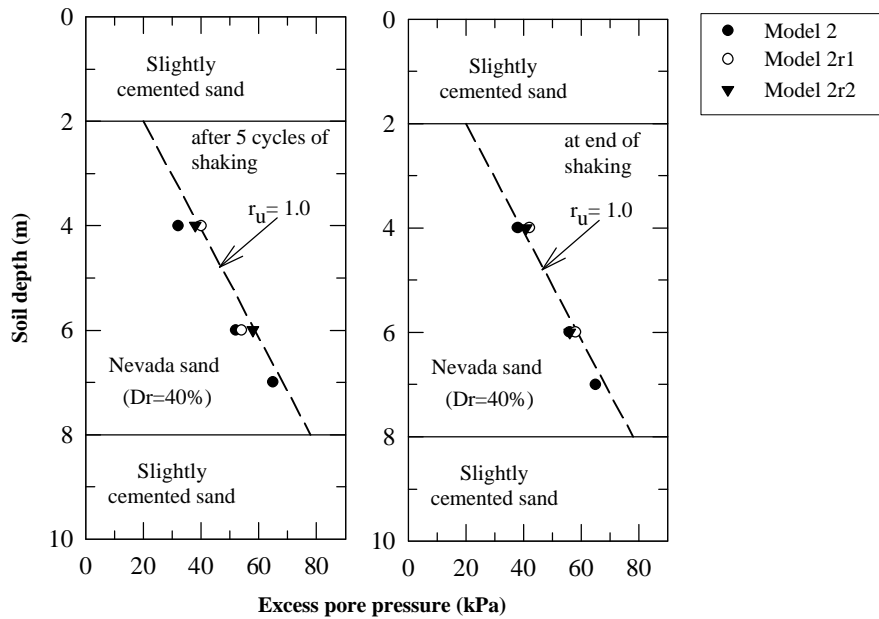


Figure 2: Profiles of free field excess pore pressures measured during and at the end of shaking

4. COMPARISON OF RESULTS MEASURED IN MODELS 2, 2R1 AND 2R2; PILE RETROFITTING WITH NO INERTIAL EFFECTS

Lateral Displacement: Figure 3 shows the recorded lateral displacements of the soil system at various elevations. The permanent prototype lateral displacements of the ground surface after shaking were about 0.70, 0.74 and 0.78 m for Models 2, 2r1 and 2r2, respectively (Table 1).

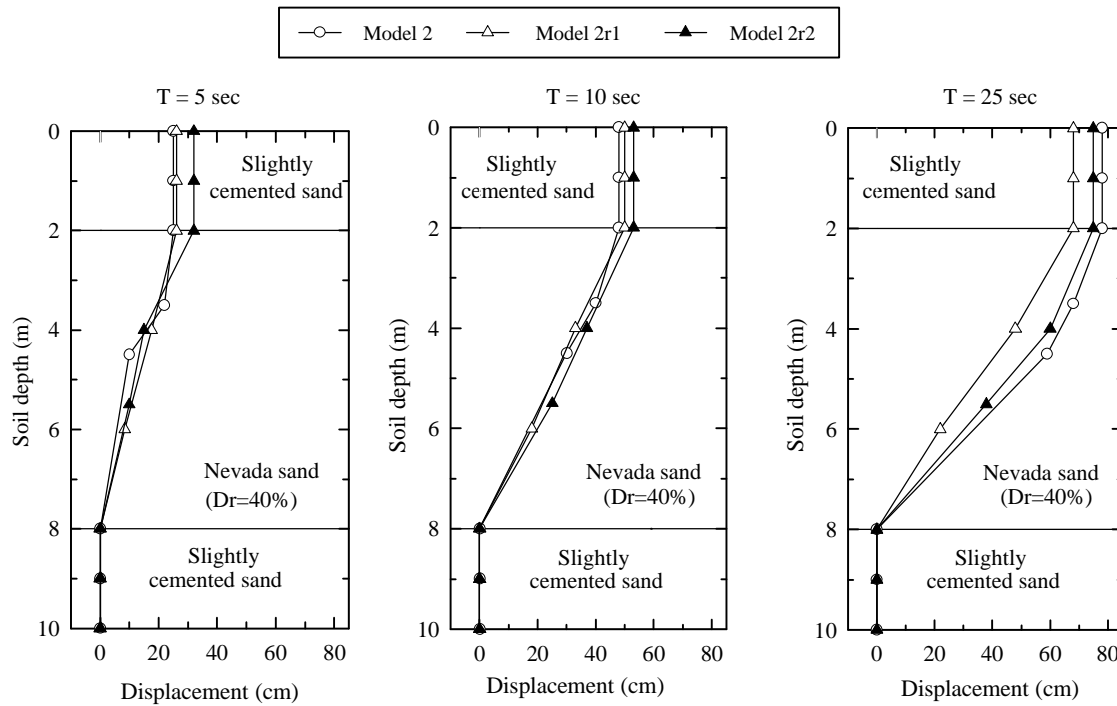


Figure 3: Lateral displacement profiles at different times during shaking, Models 2, 2r1 and 2r2

Table 2: Summary of single pile foundation characteristics and measurements during centrifuge tests ($D_r = 40\%$ in all the tests for the liquefiable layer)

Model No.	No. of soil layers	Pile Cap	Mass	Retrofitting strategy	Measurements on piles			Free field ground surface lateral displacement (m)
					Bending moment, M_{max} (kN-m)		Pile deflection, D_{pmax} (m)	
					Upper boundary	Lower boundary		
2	3	Yes	No	No	270	305	0.85	0.70
2r1	3	Yes	No	Strategy 1	0	220	0.42	0.74
2r2	3	Yes	No	Strategy 2	30	290	0.60	0.78

A comparison of soil and pile lateral displacement profiles of Models 2, 2r1 and 2r2 is presented in Figure 4. Smaller pile head displacements were measured in Models 2r1 and 2r2 than those measured in Model 2. This indicates that the implemented remediation did decrease the pile lateral displacement. Figure 5 presents photos of soil condition around the pile cap after the test of Model 2r1. The pictures indicate that the implemented remediation did decrease the pile lateral displacement as the clay in the upslope of the pile cap was crushed while a gap was left on the downslope side of the cap. The permanent prototype lateral displacements of the pile head at the end of shaking were about 0.85, 0.42 and 0.60 m for Models 2, 2r1 and 2r2, respectively (Table 1).

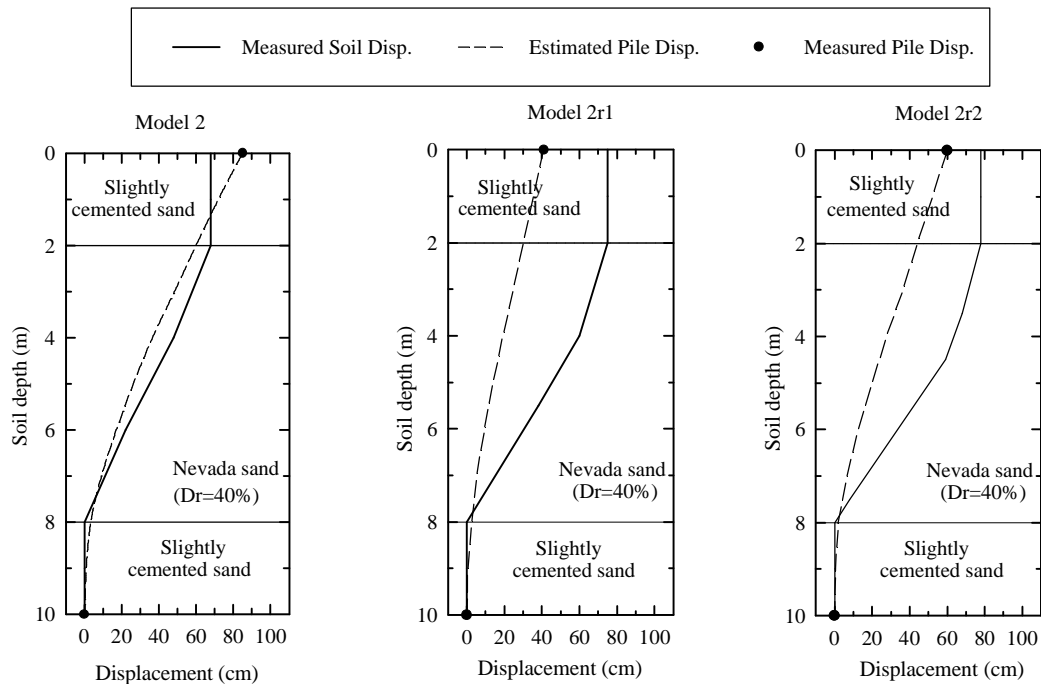


Figure 4: Pile and soil lateral displacement profiles at the end of shaking, Models 2, 2r1 and 2r2, estimated pile displacements were calculated using Beam-on-Winkler springs (BWS)



Direction of free field lateral displacement

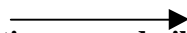


Figure 5: Photos of soil condition around pile cap after the test, Model 2r1

Bending Moments: The effect of the remediation can be best seen in the comparison of the bending moments. Figure 6 shows the bending moment measured along the pile in Models 2, 2r1 and 2r2 plotted at different times during shaking as the ground surfaces lateral displacement (D_H) was increasing. Before remediation, the measured moments at the interface of the top cemented layer and the liquefiable layer is about 200 kN-m in prototype units. After remediation, it drops to almost zero in Model 2r1 and only 20 kN-m in Model 2r2. Before remediation, the maximum bending moment between the bottom layer and the liquefied layer is about 305 kN-m. It drops to about 200 kN-m in Model 2r1 and drops to about 250 kN-m in Model 2r2.

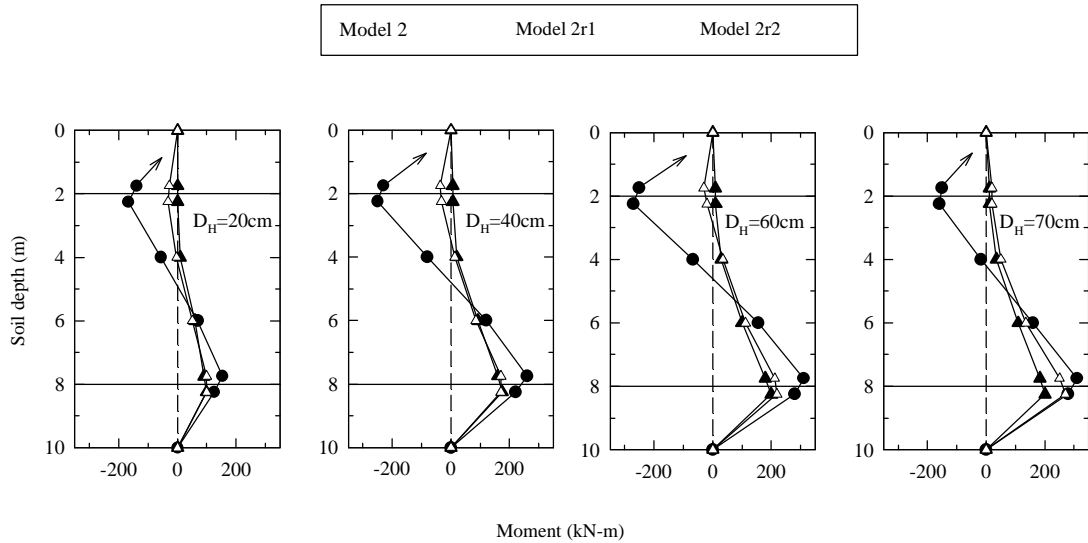


Figure 6: Bending Moments Along the Pile in Model 2, Model 2r1 and Model 2r2

5. CONCLUSIONS

The results from three centrifuge model tests of sand liquefaction with and without retrofitting strategies for the single pile foundation are reported in this paper, with detailed data interpretations and discussions. Some major conclusions may be drawn from these results as follows:

- 1 This work demonstrates that centrifuge modeling of soil-pile interaction during liquefaction is both realistic and useful. Consistent results were obtained from all centrifuge model tests, which provided detailed information on bending moment response of single pile foundations subjected to lateral spreading with or without retrofitting.
- 2 As expected, the maximum bending moment was still measured at the lower boundary between liquefied and nonliquefied soil, while the bending moment at the upper boundaries between liquefied and nonliquefied soil was greatly reduced after retrofitting.
- 3 Test results indicate that the lateral pressure, exerted by the shallow nonliquefied soil layer controls the bending moments developed along the pile.
- 4 In the absence of inertia force, a significant reduction of the measured maximum bending moment is achieved by the implementation of the two proposed retrofitting strategies aimed at reducing the lateral pressures exerted by the shallow nonliquefied layer.

6. ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to Professor Ricardo Dobry for his help in the planning and interpretation of test results. The work reported herein was partially supported by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) and the National Science Foundation (NSF). This support is gratefully acknowledged.

7. REFERENCES

- Abdoun, T. and R. Dobry 2002. Evaluation of pile foundation response to lateral spreading, *Soil Dynamics and Earthquake Engineering Journal*. (in print)
- Abdoun, T., R. Dobry, T. D. O'Rourke and S.H. Goh 2002. Pile Response To Lateral Spreads: Centrifuge Modeling, *ASCE Journal of Geotechnical and Geoenvironmental Engineering* (in print).
- Arulmoli, K., Muraleetharan, K. K., Hossain, M. M., and Fruth, L. S. 1992. Verification of Liquefaction Analysis by Centrifuge Studies Laboratory Testing Program Soil Data, *Technical Report, The Earth Technology Corporation, Irvine, California, March, 404p*.
- Dobry, R., T. Abdoun, T. D. O'Rourke, and S.H. Goh 2002. Piles in Lateral Spreading: Field Bending Moment

- Evaluation, *ASCE Journal of Geotechnical and Geoenvironmental Engineering* (in print).
- Hamada, M. 1992. Large Ground Deformations and their Effects on Lifelines: 1964 Niigata Earthquake, *Ch. 3 of Hamada and O'Rourke*, 3-1 to 3-123.
- Hamada, M. 2000. Performances of Foundations Against Liquefaction-Induced Permanent Ground Displacement, *Proc. 12th World Conf. On Earthquake Engineering*, Paper 1754.
- NRC 1982. Earthquake Engineering Research - 1982, Overview and Recommendations, *Report by The Committee on Earthquake Engineering, National Research Council*, National Academy Press. Washington, DC.
- Taboada, V. 1995. Centrifuge Modeling of Earthquake-Induced Lateral Spreading in Sand Using a Laminar Box, *Ph.D. thesis*, Rensselaer Polytechnic Institute, Troy, NY.
- Tokimatsu, K. 1999. Performance of Pile Foundations in Laterally Spreading Soils, *Proc. Second Intl. Conf. on Earthquake Geotechnical Engineering (P. Seco e Pinto, ed.)*, Lisbon, Portugal, June 21-25, Vol. 3, pp. 957-964.
- Van Laak, P., Taboada, V., Dobry, R., and Elgamal, A. W., 1994. Earthquake Centrifuge Modeling Using a Laminar Box, *Dynamic Geotechnical Testing: Second volume, ASTM STP 1213, Ronald J. Ebelhar and Vincent P. Drnevich, and Bruce L. Kutter, eds., American Society for Testing and Materials*, Philadelphia.
- Yokoyama, K., Tamura, K. and Matsuo, O. 1997. Design Methods of Bridge Foundations Against Soil Liquefaction and Liquefaction-Induced Ground Flow, *2nd Italy-Japan Workshop on Seismic Design and Retrofit of Bridges Rome*, Italy, February 27-28, pp. 109-131.
- Wang, Y., 2001. Evaluation of pile foundation retrofitting against lateral spreading and inertial effects during liquefaction using centrifuge models. *MS Thesis, Dept. of Civil Engineering*, Rensselaer Polytechnic Institute, Troy, NY.