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Performance of Improved Ground

Elizabeth A. Hausler and Nicholas Sitar
University of California, Berkeley

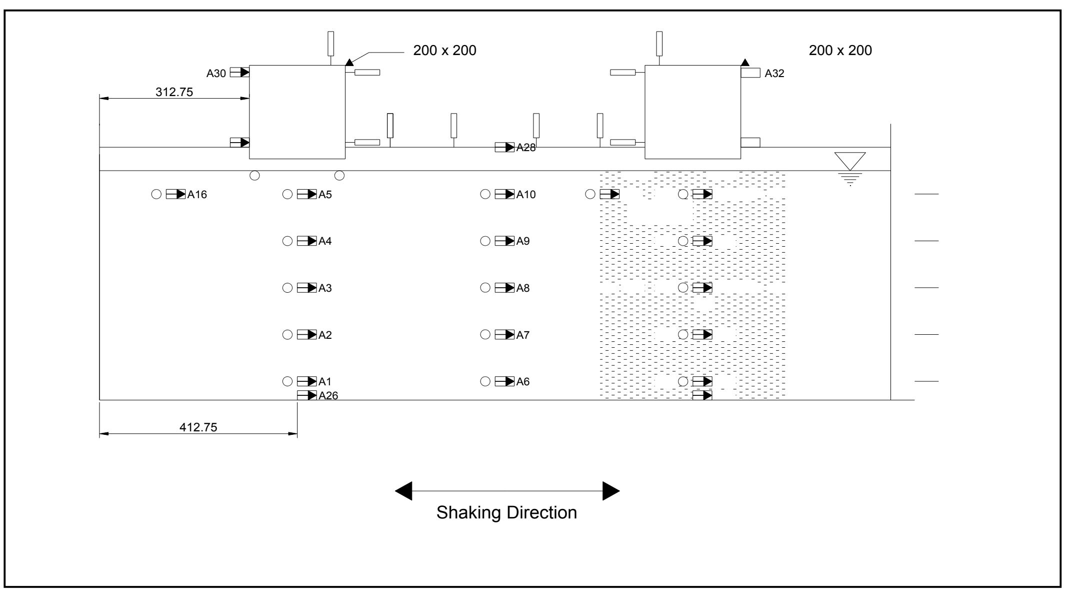
Abstract. Liquefaction-induced foundation displacement during earthquakes continues to be a major cause of damage to all types of structures, including buildings, bridges, dikes, levees, and seawalls. However, historical evidence from events as far back as the 1964 Niigata earthquake and most recently the devastating 1995 Hyogoken Nanbu (Kobe), Japan, and 1999 Kocaeli, Turkey, earthquakes indicates improved sites suffer less ground deformation and subsidence than nearby unimproved areas. The field case histories, however, lack sufficient quantitative information on building settlement, vertical ground strain, and the level, depth, and lateral extent of ground improvement. Therefore, a series of dynamic centrifuge tests designed to explore the influence of remediation zone geometry on foundation displacement and soil deformation is has recently been completed. Measurements of acceleration, excess pore water pressure, and soil deformations and the response of a rigid structure on an embedded mat foundation are used to evaluate the relative performance of improved and unimproved zones.

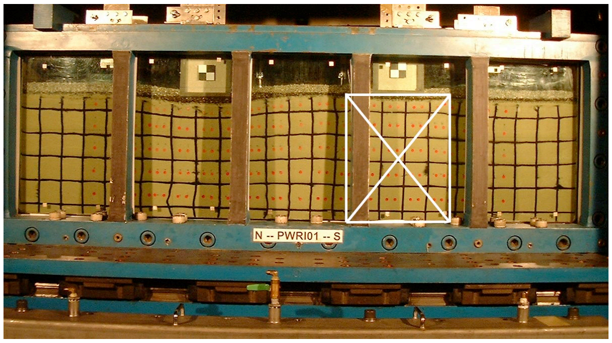
Vision and Objectives. The objective is to establish guidelines for determining the geometry of a remediation zone required to meet a desired performance level for various types of structures, including buildings, levees, and dams. In the U.S., the depth of improvement is usually based on a conventional deterministic liquefaction triggering assessment, or in some cases, by a sophisticated site response analysis using finite element or finite difference modeling software. In Japan, similar procedures are used, and the Japanese Road and Bridge code specifies a maximum required depth of improvement of 20m, but in some cases, the potentially liquefiable zone may be deeper. The required lateral distance or width of soil improvement outside the perimeter of the structure is limited to the area that controls the stability of the structure, even if the surface effects of liquefaction are more widespread, but determination of this distance is difficult. In a broader, performance-based design context, the ability to accurately predict the performance of the foundation elements, including improved ground, is paramount, and in this research project we are striving to quantify the range of deformations possible and their likelihood under different seismic loading scenarios.

Research and Achievements. The first phase of the study was to collect field case histories for sites with ground improvement as countermeasure against liquefaction that have been shaken by an earthquake. Over 100 case histories on the performance of improved sites from 15 earthquakes in Japan, Taiwan, Turkey, and the United States have been compiled. The field case histories cover a wide range of improvement methods, from conventional densification methods like sand compaction piles to less common lateral restraint-based methods such as sheet pile walls or deep soil mixing grids. The collected data indicate that improved sites generally performed well. About 10 percent of the surveyed sites required significant post-earthquake remediation, repair or demolition. Unacceptable performance designations resulted most often for excessive ground deformations in the presence of a severe lateral spreading hazard or because of an insufficient remediation zone depth. See the project web site, www.ce.berkeley.edu/~hausler/casehistories.html and Hausler and Sitar (2001).

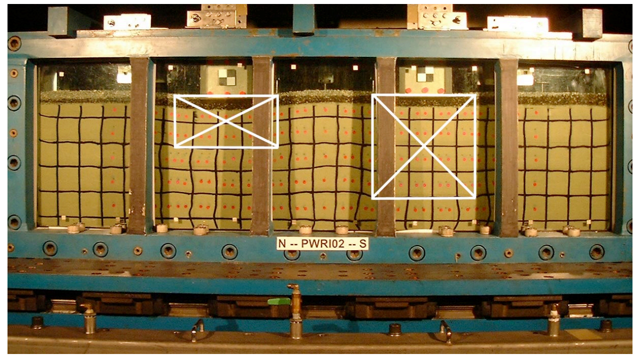
The second phase of the study was to compile a database of published centrifuge and 1g shaking table test data on various aspects of the performance of improved ground under seismic loading. The majority of studies concentrated on measurement of pore pressures and good quantitative data on the distribution of deformations and the influence of the geometry of the improved zone is rare.

The third and most substantial phase of this research project is the dynamic geotechnical centrifuge testing program. Four tests have been performed at UC Davis and two of them repeated at the Public Works Research Institute (PWRI) in Japan. An example model configuration for a UC Davis test is shown in section view below. Two distinct zones with square, rigid Plexiglas structures are present, each with a bearing pressure of 96 kPa (2ksf). In prototype scale, the model consists of 20m of potentially liquefiable (D_r = 30 - 35%) material. In the case shown below, the improved block (D_r = 85%) in the south half of the model extends down to the bottom of the container, through the full liquefiable thickness. No improvement is present under the north structure. In the second model test case, the improved zone under the north structure extends down through 30% of the potentially liquefiable thickness, and the improved zone under the south structure extends down through 70% of the potentially liquefiable thickness. The third model test case is identical to the second except that the relative density of the potentially liquefiable soil has been increased to D_r = 50%. The fourth model was a repeat of the third, intended to explore the effect of an equipment malfunction during the third test. All models were saturated with a viscous pore fluid. The models were shaken with small (0.16g) and large (0.75g)scaled versions of the ground motion recorded at 83m depth at Port Island in the 1995 Kobe earthquake. As shown below, acceleration, pore pressure, and displacement were measured.





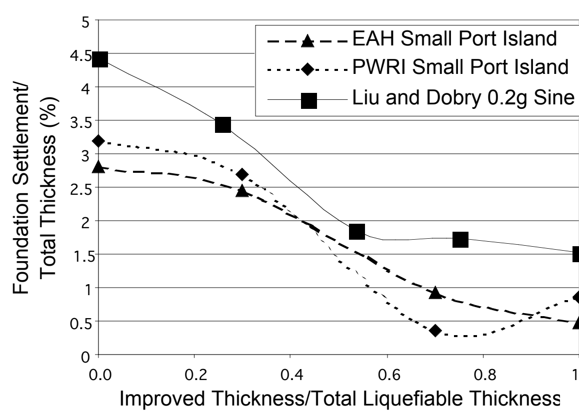
Section view of PWRI test, 0% and 100% improved depth cases, improved zones shown in boxes



Section view of PWRI test, 30% and 70% improved depth cases, improved zones shown in boxes

Preliminary Findings. The most important findings pertain to the influence of the depth of improvement on soil deformation and the settlement of the structure. The photographs of the post-test deformed soil profiles for the PWRI test series illustrate that the greatest deformation occurs in the area immediately beneath the improved zone and at the bottom of the soil profile. The figure shown here relates normalized foundation settlement (total settlement divided by the pre-improvement potentially liquefiable thickness) to the normalized improved depth (ratio of improved depth to the potentially liquefiable thickness). For low levels of shaking (approximately 0.16g PGA), the results are consistent between the two test series and with an independent centrifuge test series performed by Liu and Dobry (1995).

Observations related to acceleration and attenuation of motion:



(1) Attenuation of the input motion is clearly present in the unimproved zones.
(2) The largest shear strains develop in the zone immediately beneath the improved zones and at the deepest layers of the soil model for the large shaking events.
(3) The most energy transmission to the structure occurs for the case of improvement through the full liquefiable thickness.
(4) Within a test series, less energy is transmitted through the soil layer for the large shaking event.
(5) Acceleration spikes commonly associated with the cyclic mobility of dense sand are present in the unimproved ground recordings near the interface with the improved ground zone.
(6) Although the input motion was repeated quite well from test to test on the same shaker, the motion used at the CGM was not repeated exactly at PWRI. The PWRI motion has a higher frequency component and longer duration.

Observations related to excess pore water pressure generation:

(1) The rise in excess pore water pressure is most rapid in the unimproved zones away from the structures.
(2) Excess pore water pressure generation is inhibited by the presence of the structures and dissipation is prolonged directly beneath the structures.
(3) The most dilative soil response (spikes of negative excess pore water pressure) is recorded in the deep instruments in the model with improvement through the full liquefiable thickness.
(4) Increasing the relative density of the unimproved soil (from $D_{r,initial}$ = 30% to 50%) reduces the excess pore water pressure generation slightly.

Publications and References

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Acknowledgements

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Keywords

Centrifuge modeling, liquefaction, ground improvement, shallow foundations, settlement