Shaking Table Testing to Evaluate Effectiveness of Vertical Drains for Liquefaction Mitigation

A pooled-fund proposal by

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PROEJCT SUMMARY

The objective of this study is to determine the viability of large diameter (4 inch) prefabricated vertical drains for preventing liquefaction and associated settlements or lateral spreading under full-scale conditions. Although limited blast liquefaction testing, vibration testing, and centrifuge testing suggest that vertical drains can be effective, no full-scale drain installation has been subjected to earthquake induced ground motions. This lack of performance data under full-scale conditions is a major impediment to expanding the use of this technique as engineers are reluctant to take the risk of employing an untested system. To remedy this problem we propose to conduct full-scale tests with vertical drains in liquefiable sand using the 20 ft high laminar shear box and shaking table system at NEES-Univ. of Buffalo. Tests will involve both level ground and sloping ground (2º slope) and will be integrated with a previously funded NEESR study currently underway so that the control tests without drains will already be available. We will use the same sand installation techniques, as well as the same instrumentation plan and shaking protocols which have already been developed and proven successful. This collaborative approach will significantly reduce the cost of the study in comparison to a completely independent study. In addition, it will provide a comparison between the performance of the soil profile with drains relative to subsequent tests where piles will be involved. Furthermore, an FHWA pooled-fund study will provide additional support to carefully analyze the results and compare with predictive equations and numerical methods.

The broader merit of the study is that if full-scale tests prove the effectiveness of the drainage technique, significant time and costs savings can be achieved in mitigating liquefactions hazards for both new construction and retrofit situations relative to conventional densification approaches. Drains can often be installed at 25% to 40% of the cost of stone columns. In addition, drains can be installed in about one-third to one-half of the time required for stone columns. Finally, if densification is not required, the time and cost associated with post-treatment in-situ testing to evaluate improvement produced by densification may not be required with drains. In an era when construction budgets are becoming increasingly tight and projects are increasingly placed on fast-track schedules, innovative alternative solutions are required to deal with liquefaction hazards. Finally, the data from the tests will be archived on the NEES data repository for use by other analysts.

PROJECT DESCRIPTION

Significance of the Study

Liquefaction of loose saturated sand results in significant damage to transportation systems in nearly every earthquake event. Liquefaction and the resulting loss of shear strength can lead to landslides, lateral spreading of bridge abutments and wharfs, loss of vertical and lateral bearing support for foundations, and excessive foundation settlement and rotation. Liquefaction resulted in nearly $1 billion worth of damage during the 1964 Niigata Japan earthquake (NRC, 1985), $99 million damage in the 1989 Loma Prieta earthquake (Holzer, 1998), and over $11.8 billion in damage just to ports and wharf facilities in the 1995 Kobe earthquake (EQE,1995). The loss of these major port facilities subsequently led to significant indirect economic losses. The port facilities in Oakland, Los Angeles and Seattle are vulnerable to similar losses.

Typically, liquefaction hazards have been mitigated by densifying the soil in-situ using techniques such as stone columns, deep soil mixing, dynamic compaction, or explosives. An alternative to densifying the sand is to provide drainage so that the excess pore water pressures generated by the earthquake shaking are rapidly dissipated, thereby preventing liquefaction. The excess pore pressure ratio must normally be kept below 0.4 to prevent excessive settlement due to increases in compressibility (Albaisa and Lee 1974, Seed and Booker, 1977) Vertical drains allow for pore pressure dissipation through horizontal flow which significantly decreases the drainage path length. This feature becomes particularly important when drainage is impeded by a horizontal silt or clay layer and a water interlayer forms further increasing the potential for sliding (Kulasingam et al. 2004). As shown in Fig. 1 vertical drains can relieve these pressures, prevent the formation of a water interlayer and reduce the potential for lateral spreading and slope instability.

The concept of using vertical gravel drains for liquefaction mitigation was pioneered by Seed and Booker (1977). They developed design charts that could be used to determine drain diameter and spacing. Improved curves which account for head losses were developed by Onoue (1988). Although gravel drains or stone columns have been utilized at many sites for liquefaction mitigation, most designers have relied on the densification provided by the stone column installation rather than the drainage. Some investigators suspect that significant settlement might still occur even if drainage prevents liquefaction. In addition, investigators have found that sand infiltration can reduce the hydraulic conductivity and flow capacity of gravel drains in practice relative to lab values (Boulanger et al. 1997).

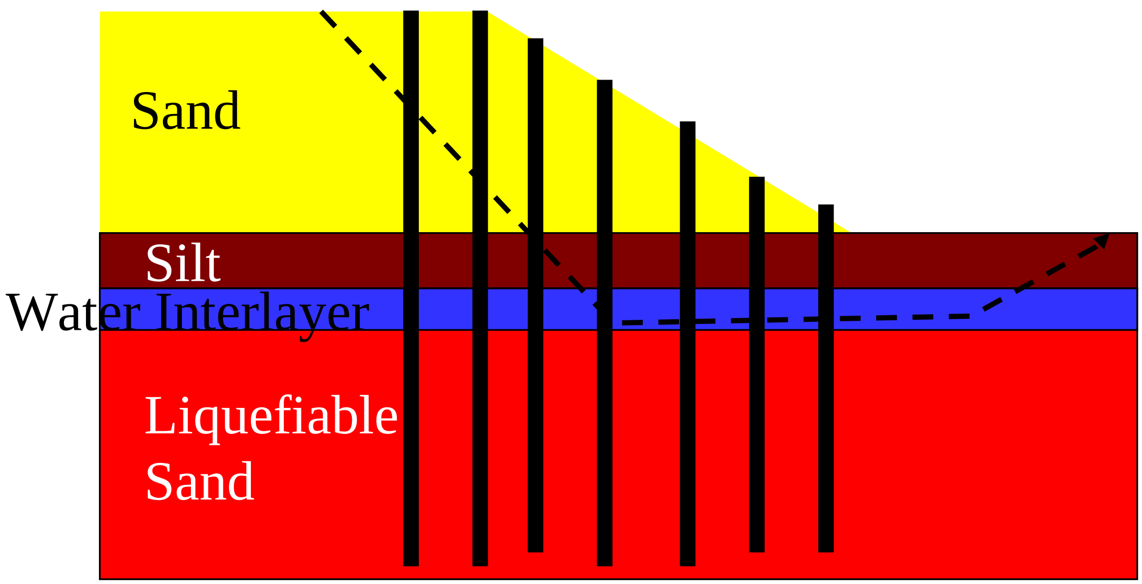

Fig. 1 Schematic drawing showing the potential for vertical drains to relieve pore pressures and intercept water interlayers which may form below a low permeability silt layer thereby reducing the potential for slope instability and lateral spreading.

One recent innovation for providing drainage is the geo-composite drain (Rollins 2003). As shown in Fig. 2, geo-composite drains are vertical, slotted plastic drain pipes also known as "EQ drains" which are typically 75 to 150 mm in diameter. These drains are installed with a vibrating steel mandrel in much the same way that smaller pre-fabricated vertical drains (PVDs) are installed for consolidation of clays. The geocomposite drains are typically placed in a triangular grid pattern at center-to-center spacings of 1 to 2 m depending on the permeability of the treated soil. In contrast to conventional PVDs, which have limited flow capacity (2.83×10^{-5} m^3/sec, for a gradient of 0.25), a 100 mm diameter drain can theoretically carry very large flow volumes (0.093 m^3/sec) with the potential to relieve water pressure in sands. This flow volume is more than 10 times greater than that provided by a typical 1 m diameter stone column

($6.51x10^{-3}$ m^3/sec). Filter fabric sleeves are placed around the drains to prevent infiltration of sand

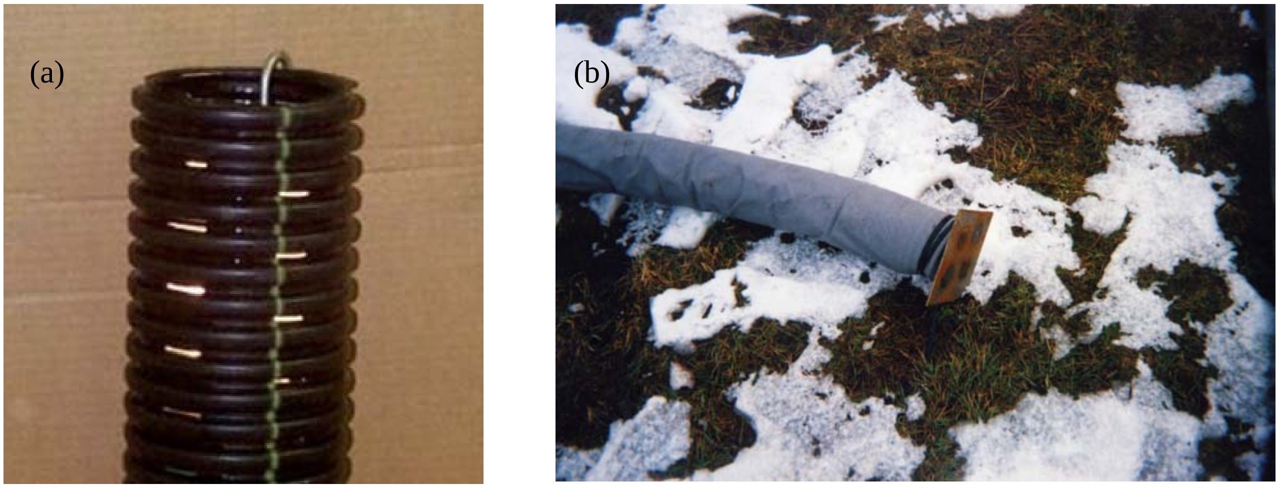

Fig. 2 (a) EQ Drain without filter fabric showing slots illuminated by light inside pipe and (b) EQ Drain with filter fabric and anchor plate at the end.

Previous Testing

Blast liquefaction tests (Rollins et al 2003, 2044) indicate that the drains allow excess pore pressures to dissipate faster than untreated soil, but the rate of loading was so rapid that liquefaction was not prevented. Chang et al. (2004) performed field tests on a volume of reconstituted, saturated sand measuring 1.2 m x 1.2 m x 1.2 m, surrounded by an impervious membrane. Tests were conducted with and without an EQ drain in the center of the test volume. Without a drain, liquefaction was produced during the application of 60 stress cycles (3 second total duration), while the excess pore pressure ratio did not exceed 25% for the test volume with a drain subjected to the same vibrations. Volumetric strain decreased from 2.1% without a drain to less than 0.5% with a drain in place. While the EQ drain successfully prevented liquefaction for this shallow soil layer, drainage of a thicker layer would be more difficult. In addition, the applied strain amplitude was relatively small and a more severe motion could produce different results.

Recently, Marinucci et al. (2008) conducted centrifuge testing to investigate the ability of vertical drains to prevent lateral spreading (Marinucci et al. 2008). esting was performed to compare performance of a 3 degree slope with and without earthquake drains. At acceleration levels between 0.11g and 0.15g full liquefaction and some soil deformations occurred on the untreated slope while smaller pore pressures and less deformation occurred on the slope with the vertical drains. As acceleration levels increased to between 0.5g and 0.8g, there was extensive liquefaction and deformation of the untreated slopes. The slope treated with vertical drains also experienced high pore pressures, but the drains limited the slope deformations to small and potentially acceptable values (Cardno, 2007). These results suggest the value of vertical drains for mitigating liquefaction-induced slope instability even if high pore pressures are not entirely eliminated

Desired Testing Conditions for Future Studies

While the previous studies clearly highlight the potential effectiveness of earthquake drains, they are all limited in one way or another. Moreover, these limitations represent a major impediment to the implementation of drainage as a more routine mitigation strategy. Most engineers are simply unwilling to take the risk of employing this approach unless more compelling full-scale test data. To provide a more convincing demonstration of the efficacy of vertical drains in preventing liquefaction, it would be desirable to observe drain performance in a 15- to 20-ft thick layer of liquefiable sand under full-scale conditions when subjected to realistic earthquake ground motions. Ideally, this would be observed at an instrumented field site, but this would require the expense of instrumentating and continuously monitoring a field site and then being fortunate enough to have an earthquake occur in a reasonable time frame while the site was still operational.

The next best alternative would involve the use of a large laminar shear box mounted on a large shaking table. Fortunately, this capability is available through the NEES@Buffalo site. Tests with and without drains can be conducted in a laminar shear box which can contain a sand volume 20 ft tall x 16 ft long x 10 ft wide which can be subjected to cyclic ground shaking with accelerations of up to 0.4g. Photographs of the laminar box are provided in Figure 3. In addition, plan view and profile views of the laminar shear box and shaking table are provided in Fig. 4. As part of a previously funded NEESR study, Prof. Thevanayangam of the Univ. of Buffalo is scheduled to be conduct tests on loose sand ($D_r \approx 45\%$) in the laminar shear box on level ground and on a 2º slope. The sand box will be subjected to progressively higher levels of acceleration up to 0.3g. Subsequent tests will involve piles within the liquefied sand. We

Fig. 3. Photographs of the stacked ring laminar shear box (24 ft high, 9 ft wide and

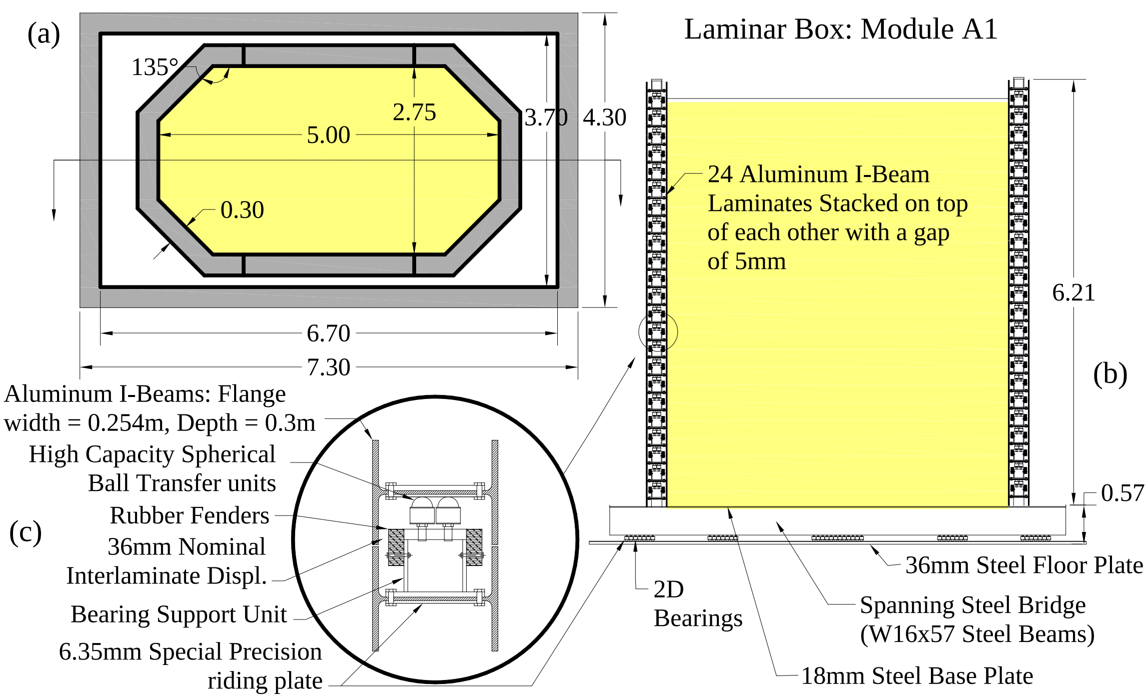

Fig. 4 (a) Plan view and (b) profile view of the laminar shear box and shaking table with dimensions along with (c) a detail drawing of the bearings between the stacked rings.

propose to piggy-back on this study and conduct supplemental tests in the same box, with the same sand, subjected to the same ground motions, but with earthquake drains in place.

Work Plan

1. Level ground shaking table tests.

As indicated previously, testing would be performed using the large-scale earthquaksimulator at the NEES@Buffalo site. Researchers at the University of Buffalo have developed hydraulic filling techniques for producing saturated sand with a relatively uniform relative density. Initially, a new flexible impervious membrane is placed within the stacked ring assembly prior to placing the sand for each test. This liner prevents leakage and ensures that the sand remains saturated. Sand for the tests is contained in storage tanks filled within de-aired water. Pumps are attached to the tanks and used to hydraulically fill the laminar shear box, layer by layer with a specified drop height for the outlet. The density of the sand fill is defined throughout the process using large steel buckets. In addition, CPT soundings are made following placement to define the tip resistance and friction ratio profiles and thereby evaluate the uniformity of the sand with depth. Although some variations are observed, the results from previous testing indicate that a relatively uniform volume of sand is produced with a relative density of about 45% ± 5%. Shear wave velocity measurements are also made. At the conclusion of a test, the sand within the stacked rings is vacuumed back into the storage tanks to be reused for subsequent testing.

Level ground tests without drains are scheduled to be performed in July 2010 as part of a previously funded NEESR study on the lateral respon. Tests with drains would be performed in the summer of 2010. While this would require us to empty the box and refill it with sand, additional cost and effort associated with assembling and dismantling the box would be eliminated.

Plan and profile views showing the laminar shear box along with the layout of the instrumentation are provided in Figs. 5 and 6, respectively. The instrumentation types and the symbols associated with each are summarized in Table 1. The locations of the drains are also shown in the plan view drawing (Fig. 5). The instrumentation will generally be placed in the same locations for the tests with and without drains so that comparisons can easily be made with respect to displacements and induced pore pressures. The drains would be placed in a triangular pattern with a center to center spacing of 1.22 m (4 ft). Although the drains are typically installed using a vibratory mandrel which can increase the relative density by 5 to 10 percentage points (Rollins et al. 2008), limited headroom at the test site prevents us from installing the drains in this manner. Therefore, the drains will simply be hung from supports at the top of the box and anchored in place at the base during sand filling. This approach, while differing somewhat from the field installation process, will allow us to isolate the benefits produced by drainage from any benefits produced by densification.

The drains consist of corrugated drain pipe with an inside diameter of 102 mm and a flow area of 81.7 cm^2. The corrugations on the drains are 9.5 mm deep, so the outside diameter is 120 mm. Three horizontal slots, approximately 25 mm long, are cut into each corrugation. The drain pipes are wrapped with a geosynthetic fabric (model SB-252) manufactured by Synthetic Industries. The fabric is a polypropylene spunbond material with an apparent opening size (AOS) of 50 microns and a permittivity of 0.47/sec. The fabric will be folded over and stapled at the base to prevent infiltration of sand.

Pore pressure generation and dissipation will be monitored using 20 piezometers in four vertical arrays as shown in Fig. 5. For the test with drains, two of the vertical arrays will be located close to a drain while two arrays will be near the mid-points between drains. In addition, four more piezometers will be positioned at different depths within one drain itself to define the pressure profile within the drain relative to the surrounding sand. Vertical acceleration time histories will be provided at 3 depth intervals within the sand mass as shown in Fig. 10. These recordings can also be used to obtain velocity and displacement time histories. Horizontal and vertical acceleration time histories will be recorded at nine levels on the stacked rings. In addition, the horizontal displacement of the rings will also be measured by potentiometers at these same levels as shown in Fig. 6.

Horizontal accelerations will also be measured at the same nine depth levels on the opposite side of the stacked ring assembly to confirm that the rings are moving as a unit and provide redundant measurements of horizontal acceleration. The total ground surface settlement will be measured by three potentiometers at the surface of the sand. In addition, vertical displacement within the sand mass will be computed using vertical accelerometers at three depths within the profile. Five horizontal accelerometers will be placed in a vertical array within the sand as shown in Fig. 6. In addition to the acceleration time histories which they will provide, these records can be double integrated to obtain time histories of displacement. Two shape accelerometer arrays, developed by Measurand, Inc., will also be embedded within the sand mass during testing at locations shown in Fig. 6. These arrays consist of flexible tubing with chip-based tri-axial accelerometers spaced at 0.15 m (0.5 ft) intervals within the water-proof tubing. In addition to providing acceleration time histories in the three coordinate axes at each node, they also provide velocity and displacement time histories in the three coordinate axes.

The tests with and without drains will also be subjected to the same acceleration time history shown in Fig. 7. The accelerations are produced by hydraulic actuators attached to the base of the earthquake simulator. Initially, five seconds of “non-destructive” motion with a peak acceleration of 0.01 g is produced. The peak acceleration is then progressively increased from 0.05g, to 0.15g, to 0.3g. At each peak acceleration level, 20 cycles of motion are applied at a frequency of 2 Hz. While the actuators apply motion in one direction only, measurements indicate that transverse accelerations also develop; however, they are typically only 3 to 10% of the accelerations in the longitudinal direction.

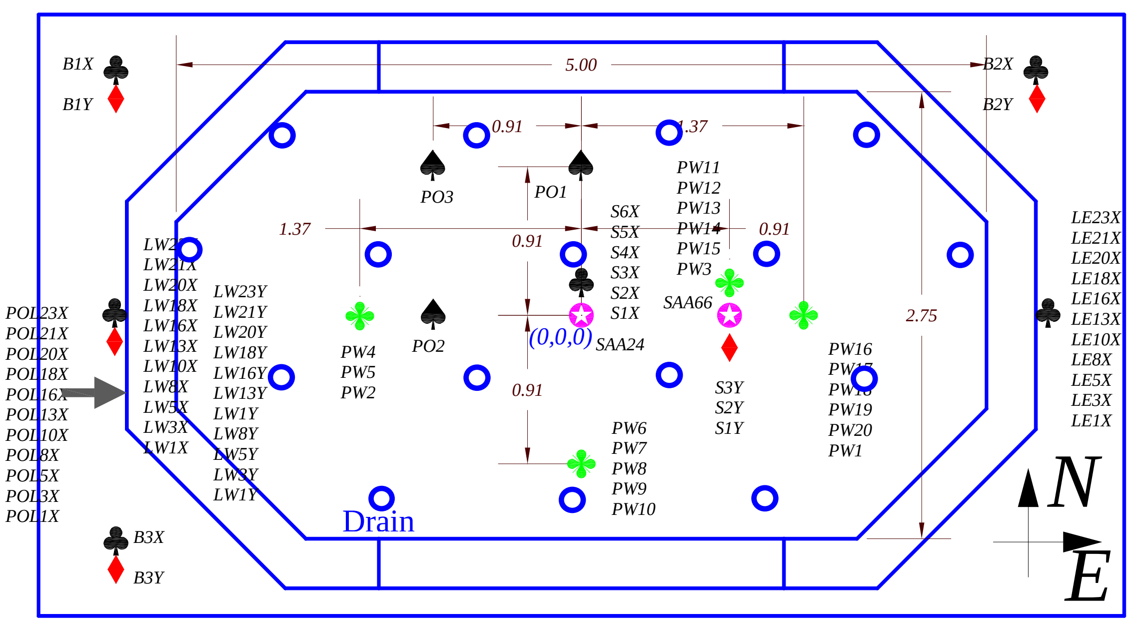

Fig. 5 Plan view of laminar shear box for level ground tests showing layout of instrumentation (Dimensions in meters).

Table 1. instrumentation for each test with symbols representing the instrumentation type.

Instruments	Quantity		Model
	LG-0	SG-1	
✪3D – SAA	2 tubes (288 channels)	2 tubes (315 channels)	Measurand Corp.
✤Piezometers	13	20	GE Druck Model PDCR 81
♣X-Acc (Ring and Base)	21	25	Sensotec 10G
♦ Y-acc (Ring and Base)	12	14	
♣ Soil-Acc-x	5	6	
♦ Soil-Acc-y	3	3	
➔X-Potentiometers	9	11	MTS Temposonic Displacement Transducers
♠Z-Potentiometers	3	3	
✖ Video camera	4	4	

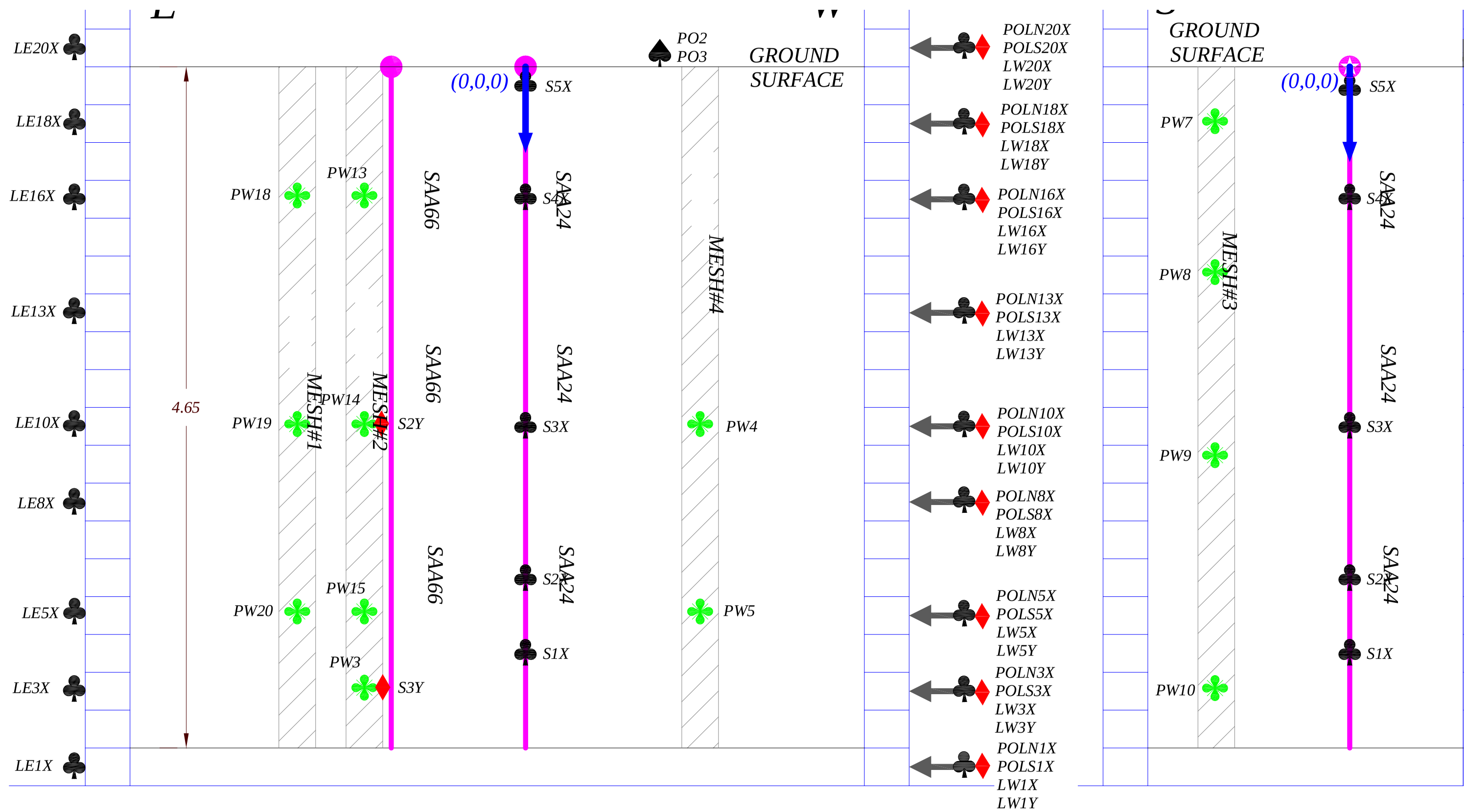

Fig. 6 Profile views of the laminar shear box with locations of instrumentation.

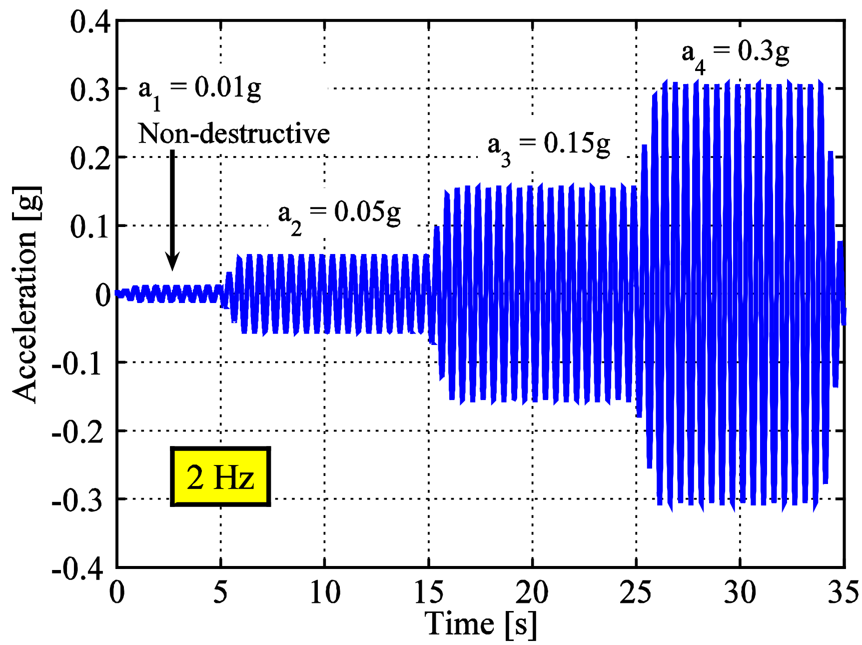

Fig. 7 Sequence of accelerations imposed at the base of the stacked ring assembly.

2. Sloping ground shaking table test.

This test will evaluate the ability of the EQ drains to reduce lateral spread displacements in addition to reducing pore pressures. After the completion of the testing under level ground conditions, the sand will be vacuumed out of test box into storage bins. The base of the box will then be inclined at an angle of 2º and sand will be re-deposited in the laminar shear box using the same procedure described previously. A test without drains will have been completed in previously by Univ. of Buffalo researchers which can be used for comparisons. The test in this study will employ the same drain and instrumentation layout as that for the test on level ground shown in Figures 5 and 6. In addition, the same progressively increasing acceleration time history will be employed up to a peak acceleration level of 0.3 g as described for the test on level ground.

3. Data reduction and data analysis

The data from the shaking table tests will be reduced to obtain the following plots:

- Pore pressure ratio versus time (or cycle) for each piezometer
- Peak pore pressure ratio versus depth for each cycle for selected profiles
- Acceleration time histories for each accelerometer
- Peak acceleration versus depth for each cycle for selected profiles from individual accelerometers as well as shape arrays.
- Settlement time histories for each accelerometer
- Settlement versus depth profiles for each cycle for selected profiles
- Lateral displacement time histories for each LVDT and accelerometer
- Lateral displacement versus depth for each cycle for selected profiles
- Volumetric strain versus pore pressure ratio

Comparisons between response with and without drains will be provided as appropriate. In many cases it may be helpful to use visualization software to understand the development of pore pressure with ground settlement and lateral displacement. Contour plots and video clips will be developed to facilitate this visualization process.

4. Evaluation of predictive methods

The finite element computer program FEQDrain, developed by Pestana et al (1997), will be used to compute the performance of the EQ drains. This program has the ability to compute pore pressure generation and dissipation along with the accompanying settlement versus time. The soil parameters in the model (liquefaction resistance, permeability, and compressibility) will be calibrated based on the tests involving sand without drains. The drains will then be inserted into the model to evaluate the ability of the model to provide agreement with the measured response observed in the tests involving drains.

Simplified approaches for computing settlement (e.g. Tokimatsu and Seed (1987), Ishihara and Yoshimine (1992), and Robertson et al (2005)) will also be evaluated along with simplified methods for predicting lateral spread displacement (e.g. Youd et al. (2005)). Pore pressure variations produced by drainage will also be compared with simplified methods proposed by Seed and Booker (1977) and Onoue (1988).

5. Preparation of final report

A final report will be prepared at the conclusion of this study. The report will provide a detailed summary of the characteristics of the test models, the instrumentation, and the acceleration time histories. The report will then provide basic test results regarding pore pressure, settlement and lateral displacement as a function of time for the various points throughout the model. These data points will also be used to produce contour plots and videos of pore pressure, settlement and lateral displacement. Next, comparisons between response with and without drains will be provided for the various parameters throughout the model.

6. Dissemination Results

The final report and appropriate annual reports will be provided to NSF and accompanying digital files will be located on Dr. Rollins' web site. In addition, all the digital data from the testing will be available through the NEES data archive system since this will be a shared-use project. Technical papers will be prepared for publication in appropriate engineering journals and conferences. We anticipate that presentations will be made at ASCE meetings and the TRB annual meeting.

REFERENCES

Boulanger, D.P., Hashish, Y. and Schmidt, B. (1997). "Drainage capacity of stone columns or gravel drains for mitigating liquefaction." 2nd Geotechnical Earthquake Engineering and Soil Dynamics Conference, Seattle, Vol. I, 678-690.

Cardno (2007). ASCE Magazine

Chang, W, Rathje, E.M., Stokoe, K.H., and Cox, B.R. (2004). "Direct evaluation of effectiveness of prefabricated vertical drains in liquefiable sand." Soil Dynamics and Earthquake Engineering, Vol. 24, Issues 9-10,723-731.

EQE (1995). "The January 17, 1995 Kobe Earthquake" Summary Report, www.eqe.com/publications/kobe/economic.htm

Holzer, TL. (1998). "Introduction". The Loma Prieta, California, Earthquake of October 17, 1989-Liquefaction, U.S. Geological Survey Professional Paper 1551-B, U.S. Government Printing Office, B1-B8.

Holzer, TL., Tinsley, JC., Bennett, MJ., Mueller, CS. (1992). "Observed and predicted ground deformation-Millter Farm lateral spread, Watsonville, California," Procs. 5th US-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Snowbird Utah, MCEER, Tech. Report NCEER-94-0026, p. 79-99.

Ishihara, K. and Yoshimine, M. (1992). "Evaluation of settlements in sand deposits following earthquakes," Soils and Foundations, JSSMFE, v. 32, no. 1, p. 1-22.

Knappett, J.A. and Madabhushi, S.P.G. (2008). Liquefaction-Induced Settlement of Pile Groups in Liquefiable and Laterally Spreading Soils." J. Geotech. and Geoenv. Engrg. 134(11), 1609-1618.

Kulasingam, R., Malvick, E.J., Boulanger, R.W. and Kutter, B.L. (2004). "Strength loss and localization at silt interlayers in slopes of liquefied sand." J. Geotech. and Geoenv. Engrg. ASCE, 130(11) 1192-1202
Lee, K.L. and Albaisa, A. (1974). "Earthquake induced settlements in saturated sands," J. of Geotechnical Engineering, ASCE, v. 100 no. GT4, p. 387-406.

Marinucci, A., Rathje, E., Kano, S. Kamai, R., Conlee, C., Howell, R., Boulanger, R., and Gallagher, P. (2008). "Centrifuge testing of prefabricated vertical drains for liquefaction remediation." Soil Dynamic s and Earthquake Engineering, Geotechnical Special Publication 181, ASCE, p. 1-10.

National Research Council (1985). Liquefaction of Soils During Earthquakes, National Academy Press, 240 p.

Onoue, A. (1988), "Diagrams Considering Well Resistance for Designing Spacing Ratio of Gravel Drains," *Soils and Foundations*, Japanese Soc. of Soil Mechanics and Foundation Engineering, 28(No. 3), 160-168.

Pestana, J.M., Hunt, C.E. and Goughnour, R.R. (1997). "FEQDrain: A Finite Element Computer Program for the Analysis of the Earthquake Generation and Dissipation of Pore Water Pressure in Layered Sand Deposits with Vertical Drains," *Report No. EERC 97-17*, Earthquake Engineering Research Ctr., Univ. of Calif., Berkeley, CA

Rollins, K.M. Joshua K.S. Anderson, McCain, A.K., Goughnour, R.R. (2003). "Vertical composite drains for mitigating liquefaction hazard." 13th Intl. Conference on Offshore and Polar Engineering, Intl. Society for Offshore and Polar Engineering, paper 2003-SAK-01, 8. pp.

Rollins, K.M., Goughnour, R.R., Anderson J.K.S. and McCain, A. (2004). "Liquefaction hazard mitigation using vertical composite drains." Procs. 13th World Conf. on earthquake Engineering, EERI, Vancouver

Rollins, K.M. and Anderson, J.K.S. (2008). "Cone penetration resistance variation with time after blast liquefaction testing." Procs. Geotechnical Earthquake Engineering and Soil Dynamics-IV, Geotechnical Special Publication 181, ASCE, 10 p, CD-ROM.

Seed, H.B., and Booker, J.R. (1977). "Stabilization of Potentially Liquefiable Sand Deposits Using Gravel Drains," J. Geotech Engrg. Div., ASCE, 103(GT7), 757-768.

Tokimatsu, K. and Seed, HB. (1987). "Evaluation of settlements in sands due to earthquake shaking," J. Geotechnical Engrg., ASCE, v. 11, no. 12, p. 1425-1445.

Youd, T.L., Hansen, C.M., and Bartlett, S.F. (2002). "Revised multilinear regression equations for prediction of lateral spread displacement, J. Geotech. and Geoenviron. Engrg., ASCE, 128(12) 1007-1017.

Zhang, G., Robertson, P.K., and Brachman, R.W.I. (2002) "Estimating liquefaction-induced ground settlements from CPT for level ground" Canadian Geotechnical Journal, Canadian National Research Council, 39(5): 1168-1180.

Yang, D., Naesgaard, E., Byrne, P.M., Adalier, K., and Abdoun, T. (2004). "Numerical model verification and calibration of George Massey tunnel using centrifuge models." Can Geotech. J. NRC Canada, 41(5): 921-942.

SCHEDULE

	2010								2011							
Work Task	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Planning for Tests	■															
Level Ground Test		■														
Sloping Ground Test			■													
Data Reduction				■	■	■	■									
Comparison of Response								■	■							
Predictive Methods										■	■	■				
Final Report													■	■	■	■

BUDGET

This project will be designated a "shared-use" project so that the UB-NEES facility will not charge rental fees or technician charges for the use facility. This represents a significant reduction in the overall cost of the project. In addition, BYU has agreed to reduce overhead charges to 10% (normally 50%) for research projects administered by the Utah Dept. of Transportation.

Faculty Salary (1.25 summer months @ $15,000/month) $18,750

Centrifuge Testing (0.5 summer months @ $15,000/month) $7500
Analysis/Report (0.75 summer months @ $15,000/month) $11,250

Student Wages (2 grad. students, 184 days each @ $120/day) $40,800

Centrifuge Testing (140 days @ $120/day) $16,800
Analysis/Report (200 days @ $120/day) $24,000

Fringe Benefits (19.9% of faculty salary, 0% for students) $3731

Travel Expenses (1.25 summer months @ $15,000/month) $8250

Faculty Travel (2 round trips to Buffalo) $2550
($500 airfare, 5 nights hotel @ $120/night, 5 days meals @ $35/day)

Student Travel (1 round trip each) $500
($500 airfare)
Student Housing (4 summer months @ $400/month) $3200

Conference Presentation $1500

Equipment $28500

Rubber membrane $25,000
Drain pipe, filter fabric and miscellaneous supplies $3500

Total Direct Costs $101531

Indirect Costs (10%) $10,153

Total Cost $111,684