Effectiveness of Vertical Drains for Liquefaction Mitigation Based on Large-Scale Laminar Shear Box Testing

L'efficacité des Drains Verticaux d'Atténuer la Liquéfaction Basé sur des Essais à Grande Echelle Utilisant une Boîte de Cisaillement Laminaire

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ABSTRACT: Although small-scale testing suggests that vertical drains can be effective in mitigating liquefaction induced pore pressure and displacements, no full-scale drain installation has been subjected to an earthquake. This lack of performance data under full-scale conditions is an impediment to expanding the use of this technique. To address this problem, full-scale tests with vertical drains were conducted in loose liquefiable sand using a 6 m high laminar shear box and high-speed actuator system. Tests involved 75 mm diameter slotted plastic drain piles at 0.9 m center-to-center spacing. The sand was deposited by water pluviation to a relative density between 35 to 45%. Base input motions consisted of 15 sinusoidal cycles with peak accelerations increasing from 0.05g, to 0.10g, to 0.20g. This series of three tests was repeated three times. In contrast to tests with untreated sand, which liquefied completely after only a few cycles, the drains were successful in increasing the number of cycles to liquefaction. In addition, pore pressure dissipation at the end of shaking was markedly increased. While liquefaction was not prevented in all cases, the ground surface settlement was reduced by 40 to 60% relative to that for the untreated sand case. This result is in agreement with centrifuge tests.

RÉSUMÉ: Bien que des essais à petite échelle suggèrent que les drains verticaux peuvent être efficaces pour atténuer liquéfaction induite par déplacements et de pression interstitielle, aucune installation de drains à grande échelle n'a été soumise à un séisme. Cette carence en données de rendement sous des conditions de grandes échelles constitue un obstacle à l'expansion de cette technique. Afin de résoudre ce problème, utilisant, des drains verticaux, des essais à grande échelle, ont été menés dans le sable liquéfiable lâche à l'aide d'une forte boîte de 6 m de cisaillement laminaire et un système de vérins à grande vitesse. Des essais inclus 75 mm de diamètre de pieux de drains en plastique fendue, placés à 0.9 m d'équidistance. Le sable a été déposé par précipitation aquatique à une densité relative comprise entre 35 et 45%. Des mouvements de base inserée se composaient de 15 cycles sinusoïdaux avec des accélérations de crête passant de 0.05 g, à 0.10 g, 0.20 g. Cette série de trois essais a été répétée trois fois. Contrairement aux testes avec du sable non traité, qui se sont complètement liquéfiés juste après quelques cycles, les drains ont réussi à augmenter le nombre de cycles à la liquéfaction. En outre, la dissipation de la pression interstitielle en fin de secousses a nettement augmenté. Bien que la liquéfaction n'ait pas été prévenue dans tous les cas, le tassement de la surface du sol a été réduit de 40 à 60% par rapport à celui du sable non traité. Ce résultat affirme les essais de centrifugation.

KEYWORDS: Liquefaction, Vertical Drains, Laminar Shear Box tests, Liquefaction hazard mitigation,

1 INTRODUCTION

Liquefaction of loose saturated sand results in significant damage to infrastructure in nearly every major 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 earthquke, $99 million damage in the 1989 Loma Prieta earthquake, and over $11.8 billion in damage just to ports and wharf facilities in the 1995 Kobe earthquake (Rollins et al, 2004), and damage to 51,000 properties in the Christchurch earthquake sequence (S. van Balleagooy, personal communciation, 2016). The loss of these major port facilities subsequently led to significant indirect economic losses.

Typically, liquefaction hazards have been mitigated by densifying the soil in-situ using techniques such as vibrocompaction, stone columns, compaction grouting, 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 (R_u = excess pore pressure divided by the vertical effective stress) must normally be kept below 0.4 to prevent excessive settlement due to increases in compressibility (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). Vertical drains can relieve these pressures, prevent the formation of a water interlayer, and reduce the potential for lateral spreading and slope instability.

Unfortunately, no field performance data is available to show how vertical drains actually perform when subjected to earthquake motions. This lack of performance data under full-scale conditions is an impediment to expanding the use of this technique. In the absence of earthquake performance data, investigators have used a number of methods to investigate the effectiveness of vertical drains. These methods include: field tests involving controlled blasting or vibrations to induced pore pressure (Rollins et al. 2004, Chang et al. (2004), centrifuge testing with scaled models that are accelerated to simulate the stress levels existing under field conditions (Howell et al. 2012), and numerical methods (Vytiniotis et al. 2013). While each of these methods can be used to obtain useful information, a full scale test is desirable to validate the results found in the other tests which are only analogues of the actual field conditions. To address this problem, full-scale tests with vertical drains were conducted in loose liquefiable sand using the 6-m high laminar shear box and high-speed actuator system at George E. Brown, Jr. NEES facility at the Univ. at Buffalo in New York. This paper describes the testing details, the basic test results, and the conclusion reached in this study.

2 TEST LAYOUT & INSTRUMENTATION

Plan and profile views of the laminar shear box are presented in Figure 1. The laminar box consists of 40 stacked rectangular rings with dimensions as shown in Figure 1. Each ring is 15 cm tall and is supported by a series of roller bearings which allows each ring to move independently in the horizontal direction so that the movement was largely controlled by the mass of the soil inside the box. Therefore, the soil had the potential to respond as it might in the field during earthquake shaking. Two flexible rubber membrane liners were placed inside the laminar box to allow the sand to be saturated and undrained during the cyclic loading. Acceleration time histories can be imposed on the bottom of the laminar box using two high-speed hydraulic actuators using a hydraulic accumulator system.

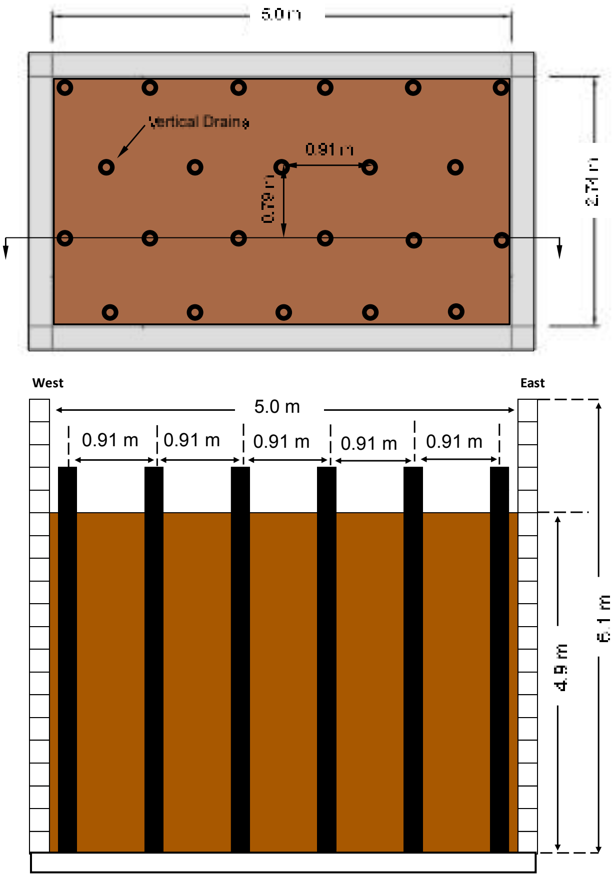

Figure 1. Plan and profile views of the laminar shear box with vertical drains in triangular pattern spaced at 0.9 m on centers.

The sand in the laminar shear box was deposited by water pluviation to a depth of about 5 m. The sand was pumped from containers in a saturated state and deposited into standing water at a height of about one meter using the spreader. The sand was a poorly graded clean sand (Ottowa F55) with a mean grain size of 0.23 mm and a coefficient uniformity of 1.52. Small buckets placed in the sand during deposition indicated that the relative density was typically between 40 and 50%. Downhole permeability tests indicated that the horizontal hydraulic conductivity in the sand ranged from 0.03 to 0.05 cm/sec with a slight decrease with depth.

Prior to sand deposition, vertical drains were hung from a frame above the box and tied to a PVC grid at the bottom. As shown in Figure 1, the drains were placed in a triangular pattern with a spacing of 0.9 m on centers. Therefore, there was no densification associated with drain installation as would be the case for drains in the field which are installed using a vibratory mandrel. The drains were 75 mm diameter corrugated plastic pipes with an outside diameter of approximately 94 mm which was surrounded by a filter fabric sock to prevent infiltration of sand. The drains were cut-off about 40 mm above the ground to allow free drainage.

Nine shaking tests were performed on the laminar shear box. Tests were performed in three rounds with peak accelerations of 0.05g, 0.10g, and 0.20g for each round. A peak acceleration of 0.20g was the highest acceleration permitted by the NEES@UB lab. Figure 2 provides plots of the planned input base time histories. All motions were intended to consist of 15 cycles of sinusoidal motions with a frequency of 2 Hz. Typically, 15 cycles of motion are associated with a Magnitude 7.5 earthquake, which is often used as the base magnitude for liquefaction studies. A ramp-up and ramp-down period was used to be consistent with previous testing at the site.

Excess pore pressure was measured with three vertical arrays of pore pressure transducers spaced at approximately 1.5 m depth intervals. These arrays were located at mid-points between drains where the drainage effect would be lowest. Sand settlement was measured by string potentiometers anchored to the ground along with Sondex "profilometers" which gave settlement versus depth profiles with measurements at 60 cm depth intervals. In addition, total ground settlement was computed by dividing the water volume expelled in each test divided by the surface area.

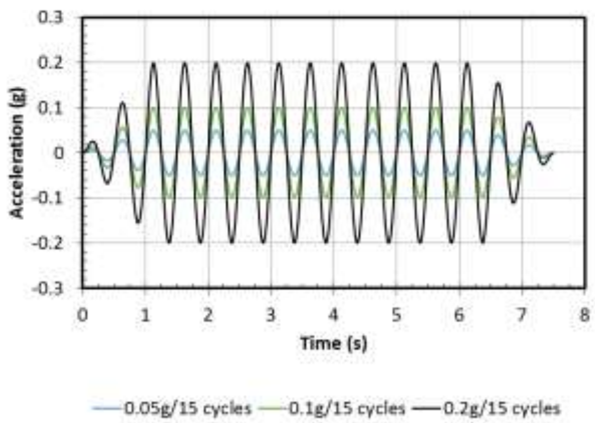

Figure 2. Base input motions for each round of shaking.

3 TEST RESULTS

Shortly after shaking began in each test, water begain erupting from each drain pipe and continued to flow for a few seconds after the completion of shaking. Average flow volume per drain with full drainage area was 5.5 to 8.2 liters/s for the first round of testing and decreased by about 40% for each round of testing. In contrast to other tests without drains, there were no sand boils at the surface and the majority of flow appeared to be coming from the drains themselves.

3.1 *Excess pore pressure behavior.*

Previous laminar shear box testing, with the sand at a similar relative density but without drains, showed that the sand would liquefy within four cycles of loading with a peak acceleration of 0.05 g (Bethapudi, 2008). In addition, after shaking, excess pore pressure ratios, remained near 100% for 20 to 90 seconds and then required 60 to 120 seconds more to dissipate below 20%.

Excess pore pressure ratio time histories are provided at three depths for the second round test subjected to a peak acceleration of 0.10g in Figure 3. With drains in place, excess pore pressure ratios did not typically reach 100%, particularly at greater depths. In contrast to the tests without drains, the excess pore pressure ratios immediately decreased at the completion of shaking and excess pore pressure ratios were typically less than 20% within a few seconds after the end of shaking.These results demonstrate that the drains are significantly decreasing the rate of pore pressure generation and increasing the rate of dissipation.

The peak excess pore pressure ratio, R_u, is plotted as a function of depth for each shaking test (namely, 0.05, 0.1, and 0.2g) for each round of testing in Figure 4. Of course, ratios closer to the drains would likely have been lower. Typically, the

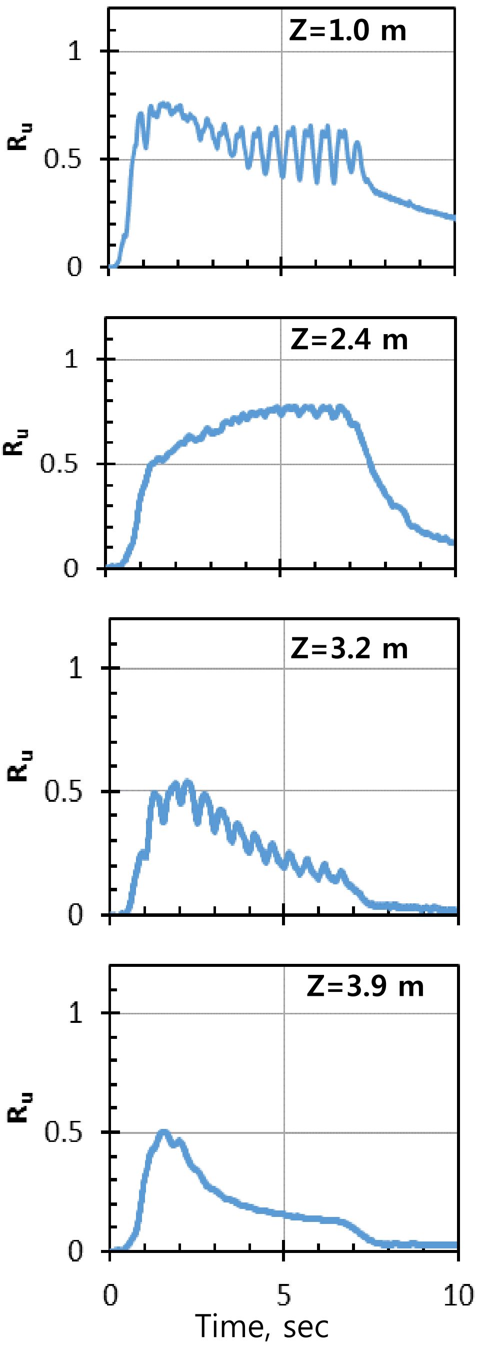

Figure 3 Excess pore pressure ratio time histories measured by pore pressure transducers located at 1.0, 2.4, 3.2, and 3.9 m below the ground surface for the 0.1g peak acceleration motion during round 1 testing.

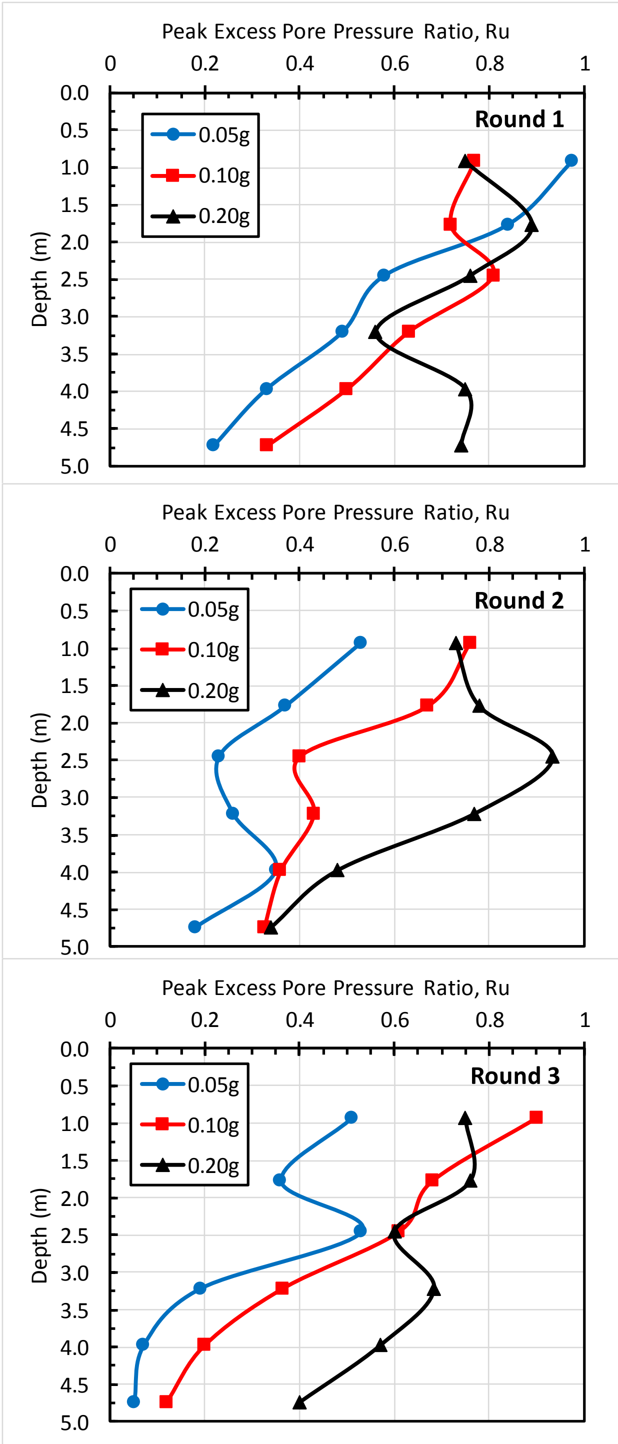

Figure 4 Peak excess pore pressure ratio for three arrays vs. depth plots for round 1, 2, and 3 test with 0.05, 0.10, and 0.20g base input motions per round. Peak values are averages at each depth for three transducers.

peak R_u decreases with depth despite the fact that in a similar test without drains, the entire sand layer liquefied within just a few cycles at 0.05g acceleration. This result indicates that the drains are being effective in reducing excess pore pressure; however, they are increasingly effective with depth. This confirms results observed in centrifuge tests with drains (Howell, et al. 2012). Thefore, some combination of surface densification and drainage might provide an optimum solution. In this regard, the densification produced by drain insertion in field applications could be particularly beneficial.

With each progressive round of testing, the peak excess pore pressure ratio generally decreased. Although this effect may be partially attributable to increasing density, analyses of the development of pore presure with respect to induced shear strain suggest that this a beneficial effect of drainage. At low relatively densities, the drains may not have sufficient capacity to prevent liquefaction, but their effect may become more significant as density increases.

3.2 *Settlement behavior*

With drains, about 80% of the ground settlement occured during shaking and 95% occurred after 5 seconds of additional pore pressure dissipation. Within each round settlment generally increased with acceleration, while settlement decreased with each round of testing ast the sand compacted.

Figure 5 provides a comparison of the cumulative settlement as a function of the number of tests for the first set of nine tests with drains spaced at 0.9 m, PVD-2 Test, in comparison with previous studies without drains. All settlement has been scaled to match a soil depth of 4.9 m. The LG1 test involves repeated tests with a peak acceleration of 0.1g with an untreated sand layer 4.9 m deep (Thevanayagam, Personal Communication, 2015). The IPS1 test result involved testing with induced partial saturation treatment in a 3-m thick layer of the total 4.9 m thickness (Thevanayagam et al. 2015). Settlement has been scaled up proportionally based on measurements showing that the untreated sand was responsible for the vast majority of the settlement. In the IPS1 testing, the sand was subjected to 0.1g acceleration for six tests and 0.2g acceleration for two tests. Significantly more settlement was observed for tests where 0.2g accelerations were applied.

Although the comparisons are not perfect nor completely direct because of differing acceleration levels, using 0.05g, 0.1g, and 0.2g accelerations in PVD-1, it is clear that the cumulative settlement curve for the profile with vertical drains is significantly lower than without. In many cases the settlement is only 60 to 70 percent of the settlement for the untreated sand. Considering that the untreated test curves are generally for 0.1g, while the treated sand experienced three 0.2g cycles, the reduction produced by the drains may be even greater than represented in Figure 5.

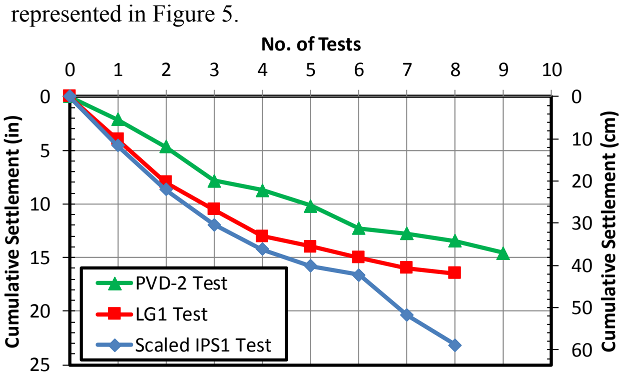

Figure 5. Cumulative settlement versus number of shaking tests in laminar box with drains (PVD-2 Test) in comparison with laminar box without drains (LG-1 and IPS1 Test).

4 SUMMARY AND CONCLUSIONS

A series of shaking tests were performed with a 6-m tall laminar shear box in which 75 mm diameter vertical drains were placed in a triangular arrangement with a center-to-center spacing of 0.9 m. Shaking consisted of 15 cycles of loading with peak acceleraitons of 0.05, 0.10, and 0.2g. Tests were performed to evaluate the abiltiy of the drains to reduce pore pressure and settelement in comparison to sand without drains. The sand in the box was initially at a relative density of 40 to 50%.

Based on the results of the laminar shear box testing the follwing conclusions can been made;

1. Vertical drains were effective in reduing the peak excess pore pressure ratios relative to tests without drains. The drains were more effective at greater depths.

2. The drains carried large volumes of water to the surface and eliminated sand boils observed in tests without drains. The rate of pore pressure dissipation was significantly increased with drains and excess pore pressure ratios typically dropped below 0.2 within a few seconds after the end of shaking.

3. Although the drains did not eliminate pore pressure induced settlement, the settlement was reduced by about 30 to 40% of the settlement without drains. This reduction is similar to that observed in centrifuge testing with vertial drains (Howell et al 2012).

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