# NHERI@UTexas Proof-of-Capability Testing Workshop: In-Situ Liquefaction Tests of Columbia-River Sand and Silt Deposits

## Draft Report

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# INTRODUCTION

Natural Hazards Engineering Research Infrastructure Equipment Facility at the University of Texas at Austin (NHERI@UTexas) hosted a two-day workshop (June 23rd and June 24th, 2016) on in-situ liquefaction testing at Portland, OR. The workshop started at 3 pm on June 23th at the Residence Inn by Marriott Portland Airport with presentations from Professors Kenneth H. Stokoe, II and Brady R. Cox from NHERI@UTexas and Professor Armin W. Stuedlein from Oregon State University. The lectures provide an overview of our NHERI@UTexas equipment, explore research opportunities and challenges, discuss specific details toward developing proposals for the NSF Engineering for Natural Hazards (ENH) program, and the geology of the Willamette and Columbia River Valleys. A field demonstration of an in-situ, proof-of-capability liquefaction test was held in the morning of June 24th at the Port of Longview at Longview, WA. One of the large-mobile-hydraulic NHERI@UTexas shakers, named T-Rex, was utilized to generate dynamic horizontal loading on the ground surface, while the subsurface response of silty soils were monitored with push-in vibration and pore pressure sensors. The objective of the workshop was to showcase the capability of NHERI@UTexas equipment in situ the liquefaction susceptibility of naturally-occurring silty soils in the Willamette and Columbia River Valleys. The site is located immediately north of the Columbia River at the Port of Longview. The approximate locations of the geotechnical site investigations at test Sites OSU-1 and OSU-5 are shown in **Figure 1**.

Geotechnical site investigations at the project site include: (1) ten Cone Penetration Test (CPT) soundings to identify site layering and to develop two, perpendicular site cross-sections, (2) two shallow geoprobe borings to recover soil samples for visual-manual classification and index testing, (3) three direct-push crosshole seismic tests to develop constrained compression wave velocity ($V_P$) and shear wave velocity ($V_S$) depth profiles, and (4) two large-scale, in-situ shaking tests with the vibroseis T-Rex to evaluate the


**Figure 1.** Location of NHERI Workshop at Sites OSU-1 and OSU-5.

relationships between cyclic shear strain and the generation of excess pore water pressure of the natural soils. Results from these investigations are discussed below.

## PRELIMINARY GEOTECHNICAL INVESTIGATIONS

### CPT Soundings and Site Layering

Initial site layering was developed from ten CPT soundings. OSU-1 through OSU-7 were pushed in a linear array roughly parallel to the Columbia River and OSU-8 through OSU-10 were pushed in a linear array approximately perpendicular to the first array. The cross-sections developed from the normalized soil behavior type show an uppermost layer of silty sand to sandy silt ranging in thickness from 3.0 to 4.5 m, underlain by a layer of clayey silt to clay that extends at least to a depth of 12.0 m. Nearby deep explorations indicate that this layer of clayey silt extends to 30 m and deeper in some cases. The CPT soundings performed for this demonstration were all pushed to a depth of 12 m below the ground surface.

The results from the two most relevant CPTs, OSU-1 and OSU-5, are shown in **Figure 2** and **Figure 3**. The figures show the corrected cone tip resistance ($q_t$), sleeve friction resistance ($f_s$), and normalized soil behavior type ($I_c$) over the range of depths 0.0 to 12.0 meters.

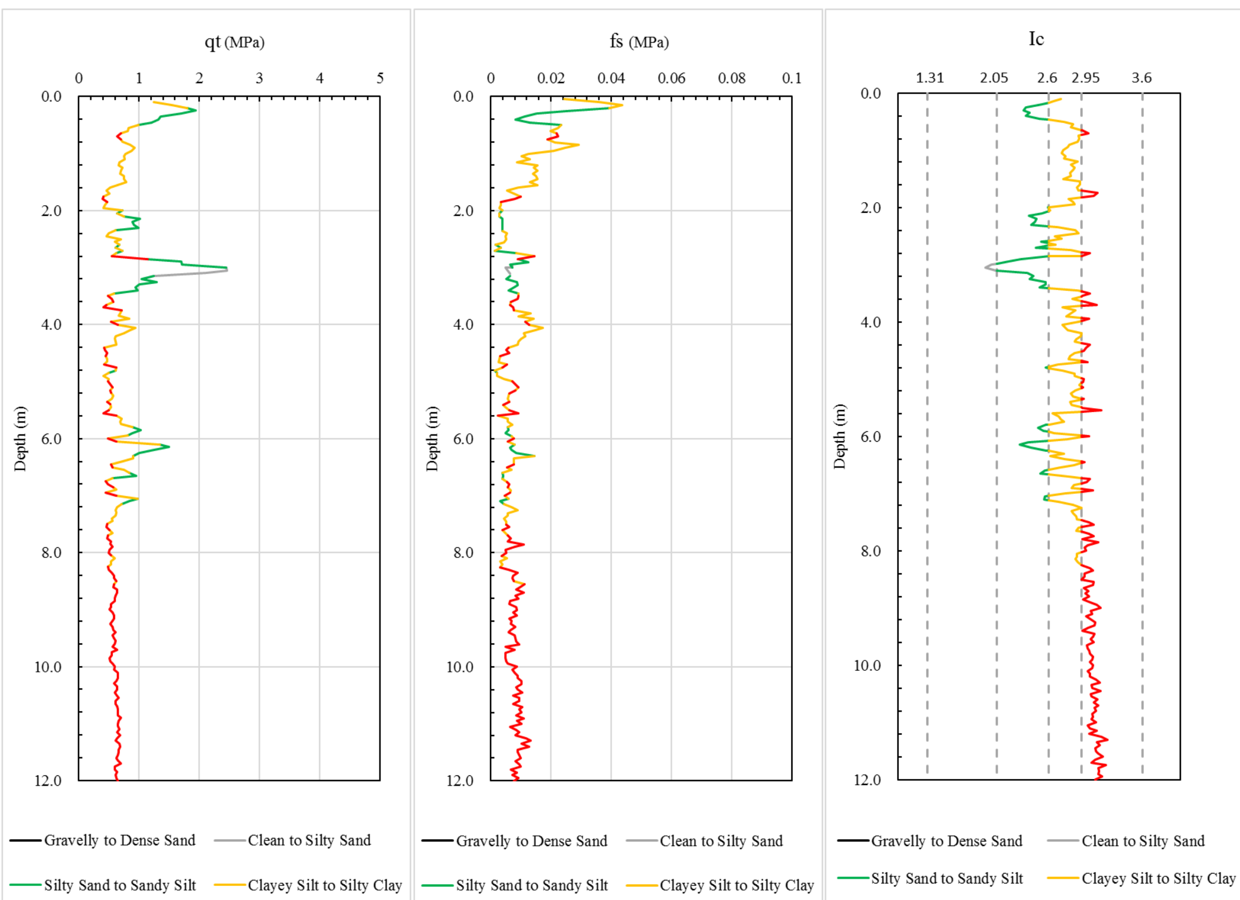


**Figure 2.** Corrected cone tip resistance ($q_t$), sleeve friction resistance ($f_s$), and normalized soil behavior type ($I_C$) for sounding OSU-1.

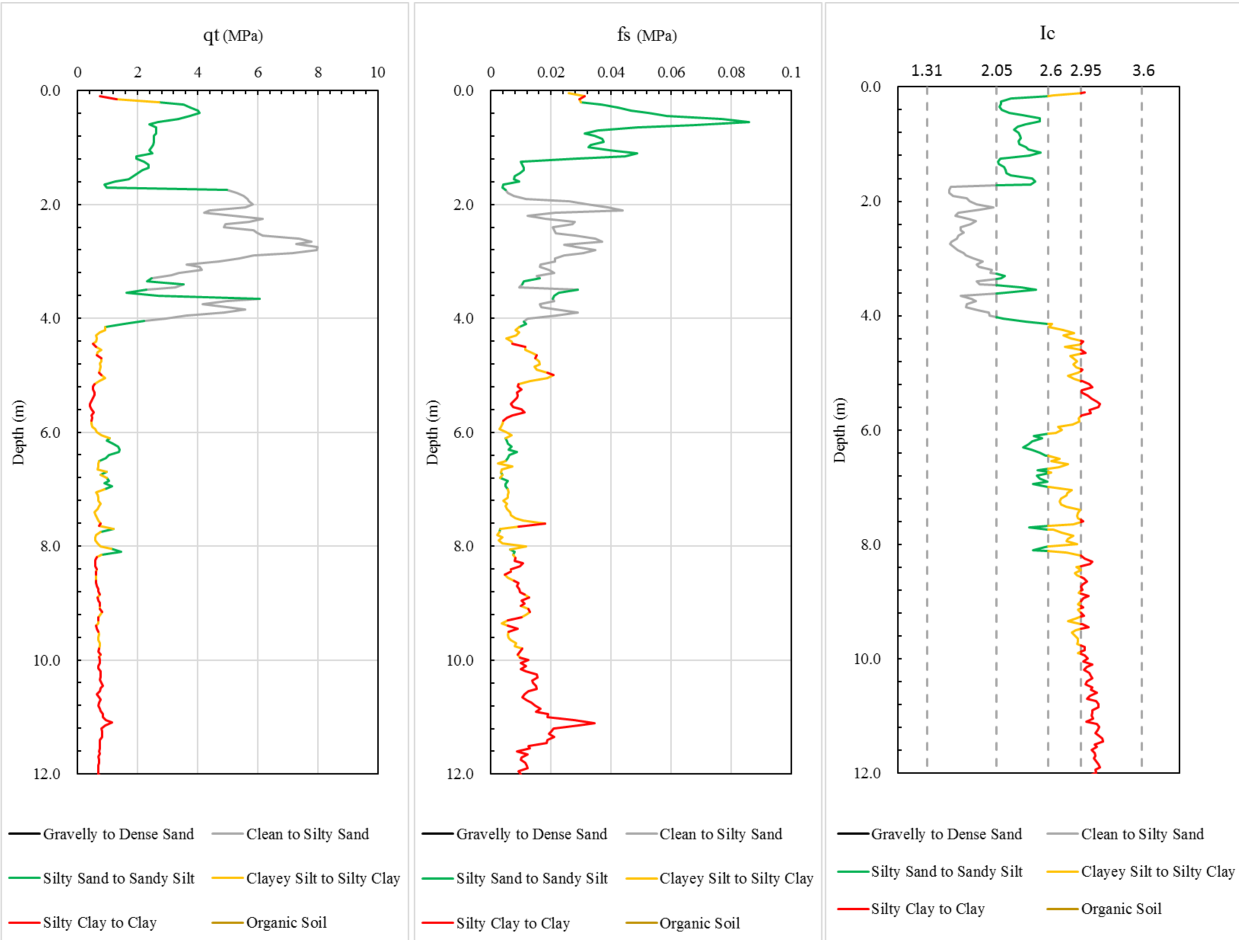


**Figure 3.** Corrected cone tip resistance ($q_t$), sleeve friction resistance ($f_s$), and normalized soil behavior type ($I_C$) for sounding OSU-5.

## Direct-Push Crosshole Seismic Testing

*Test Overview*

Direct-push crosshole (XH) seismic testing was performed at three locations adjacent to soundings OSU-1 and OSU-5. The objective of crosshole testing was to determine the depth to 100 % saturation based on the $V_P$ values and to develop a soil stiffness profile based on the $V_S$ values. The crosshole test involved pushing two instrumented cones into the ground using a hydraulic ram located on the back of T-Rex from 0.4 to 5 meters below the ground surface. Tilt sensors in the instrumented cones were used to track the deviation from vertical as the cones were pushed into the ground, allowing corrections to the length of horizontal travel path between cones. The crosshole testing schematic is shown in **Figure 4** for the plan view and cross section.

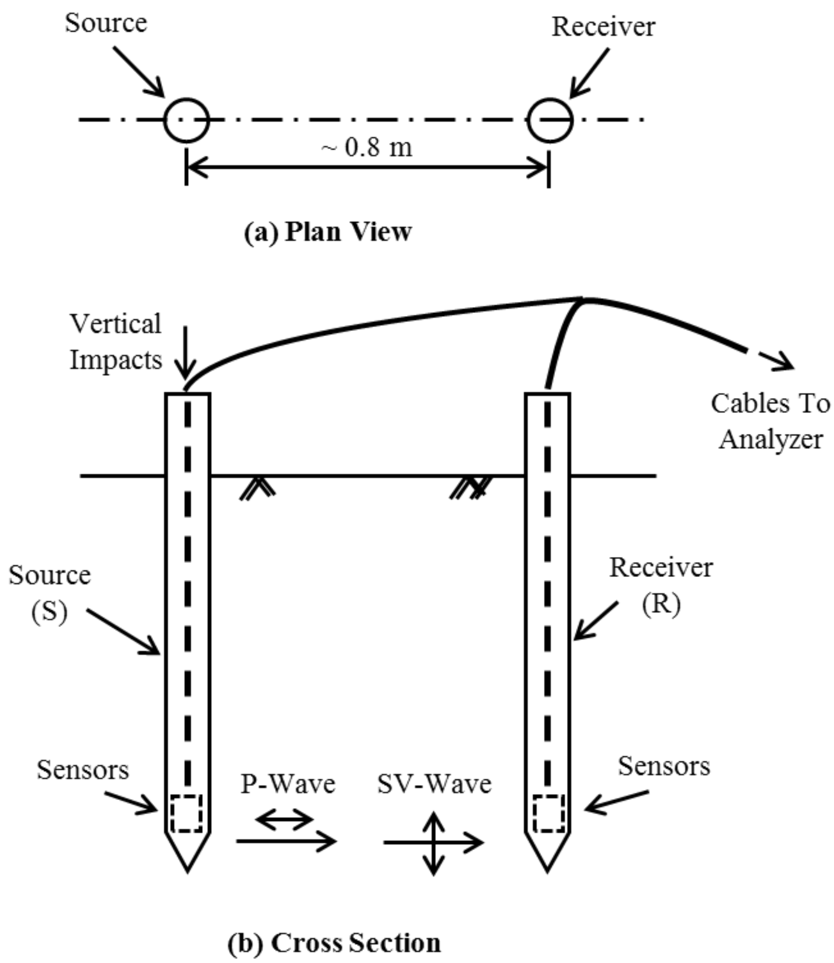


**Figure 4.** Test schematic for direct-push crosshole seismic testing in the plan view and cross-section configurations

*P-Wave Velocities*

The P-wave velocities from XH 1 and XH 5 show that the depth to 100 % saturation is in the range of 2.8 to 3.6 meters below the ground surface. This compares to the depth ofthe water table of 1.4 meters below the ground surface as determined from pore pressure transducers (PPTs) and water level indicators. Zones of 100 % saturation are identified by $V_P \geq$ 1,500 m/s and a high-frequency signature in the P-wave arrival time record. While the minimum degree of saturation required for liquefaction triggering is not known, it is believed that values of degree of saturation (Sr) $\geq$ 98.5 % are sufficient. These values of Sr $\geq$ 98.5 % correspond to values of $V_P$ greater than 600 m/s in sands.

*S-Wave Velocities*

The S-wave velocities from XH 1 and XH 5 show $V_S$ values less than 150 m/s over the top five meters from the ground surface. The crosshole test XH 1 was performed at a relatively uniform silty site (OSU-1) while XH 5 was performed at a silty site with sandy layers (OSU-5). The S-wave velocity profile shows that the silty site, Site OSU-1, is considerably softer than the site with sandy layers (Site OSU-5).

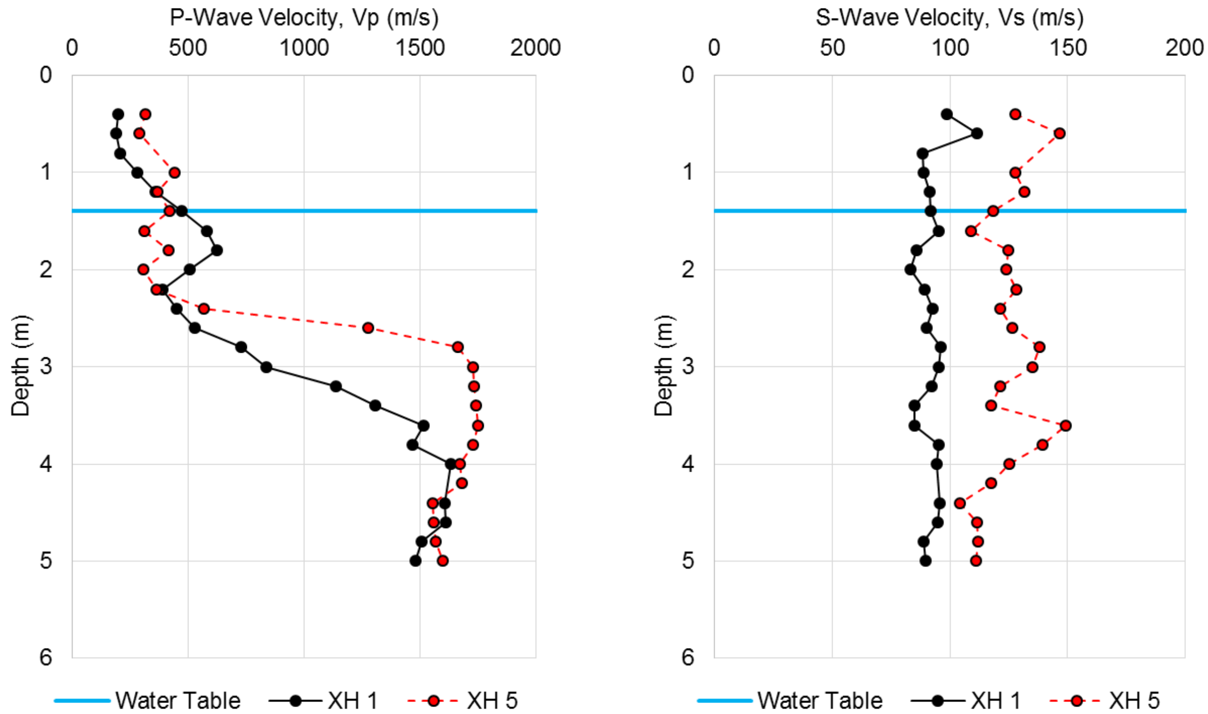


**Figure 5.** P-wave and S-wave velocity profiles from sites OSU-1 and OSU-5.

# Shake Testing

## Instrumentation Arrays

Shake testing with T-Rex was performed at two test sites: Site OSU-1 and Site OSU-5. At both locations, six ground motion sensors and four pore pressure transducers were installed at depth to measure the dynamic response of the soil to staged shaking. The test panels also included three source rods for crosshole testing, using the installed ground motion sensors as the receivers. The instrumentation array at Site OSU-1 and OSU-5 are shown in plan view and cross-section view in **Figure 6** and **Figure 7**.

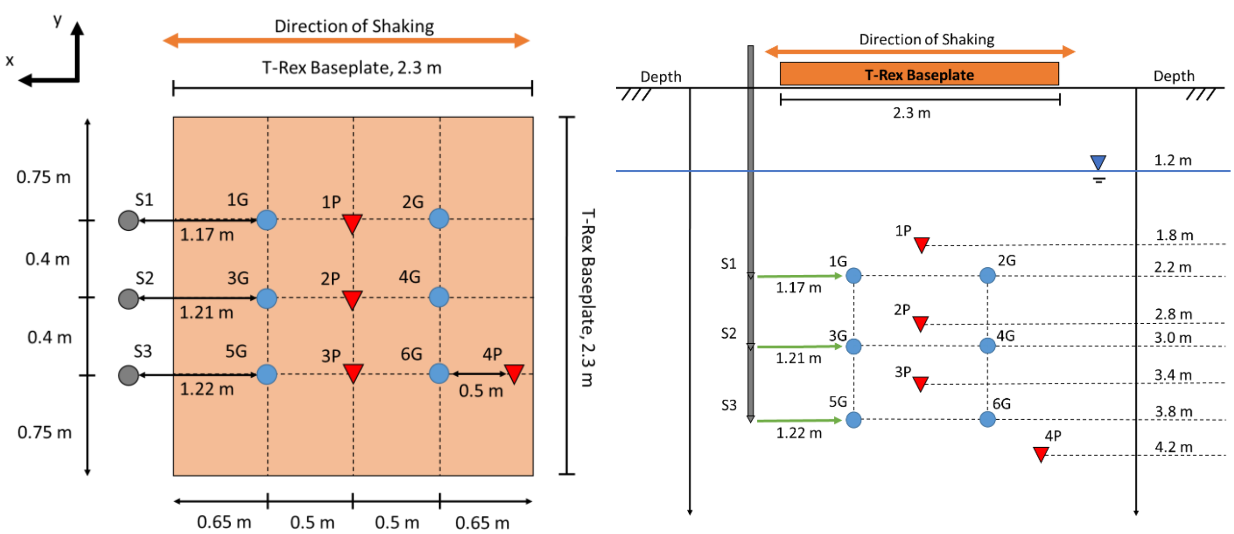


**Figure 7.** Plan view and cross section of test panel OSU-1 for shake testing

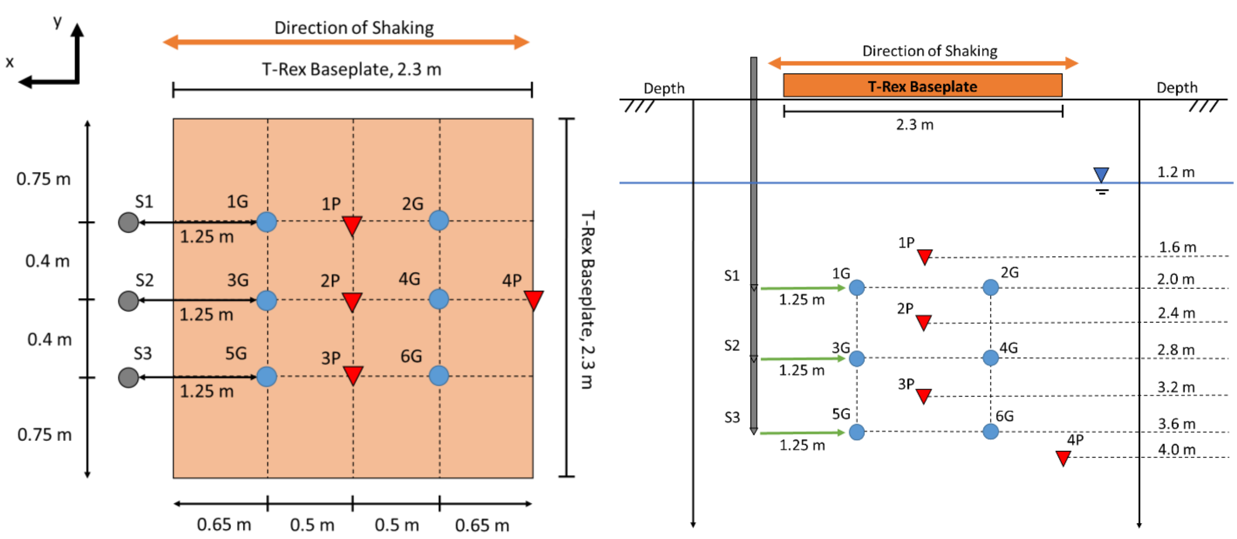


**Figure 6.** Plan view and cross section of test panel OSU5 for shake testing

## Custom-Built Sensors

Custom-built sensors were used for shake testing. The majority of the ground motion sensors used in testing include three 28-Hz geophones (installed orthogonally to measure particle velocity along the x, y, and z axes) and a two-dimensional tilt accelerometer (see **Figure 8**). The tilt accelerometer was used only during installation to measure the deviation in the x-y plane as the sensor was pushed into the ground. The three 28-Hz geophones were used for shake testing as well as crosshole and downhole testing. All sensor components were epoxied in a 1.5-inch polycarbonate cone-tipped cylindrical casing.

**Figure 8.** Ground motion sensor with two 28-Hz geophones.

Water pressure was measured during the shaking tests using GE Druck PDCR 1830 pore pressure transducers (PPTs) that were epoxied in 1.5-inch polycarbonate cone-tipped cylindrical casings (see **Figure 9**). Water flow to the membrane of the PPT was protected using two bronze filters to keep out soil particles. The PPTs were saturated prior to installation and covered with a membrane to maintain saturation until the PPT was pushed below the water table.

**Figure 9.** GE Druck PDCR 1830 Pore Pressure Transducer encased in a polycarbonate housing.

## Crosshole and Downhole Testing

Crosshole and downhole testing is performed before and after each stage of shake testing. The objective of these tests is to observe the effect that changes in effective stress due to pore pressure generation have on the stiffness of the soil, as measured by changes in the value of $V_S$ over the course of testing.

In crosshole testing, each source rod terminates at the same depth as and in line with a pair of ground motion sensors, as shown in **Figure 6** and **Figure 7**. The shallowest crosshole pair consists of S1, 1G, and 2G; the middle crosshole pair consists of S2, 3G, and 4G; the deepest crosshole pair consists of S3, 5G, and 6G. By tapping on the top of the steel source rod, a compression wave propagates down the length of the rod and then radiates P- and S-waves from the cone tip of the steel source rod. The arrival of the P- and S-waves are captured on an analyzer that records the inline and vertical geophone components of the ground motion sensors. The $V_P$ and $V_S$ of the soil between ground motion sensors at each depth is estimated using the interval travel time and known distance between sensors. At Site OSU-1, crosshole testing is performed at depths 2.2 m, 3.0 m, and 3.8 m. At Site OSU-5, crosshole testing is performed at depths 2.0 m, 2.8 m, and 3.6 m.

Downhole testing is similarly performed using the baseplate of T-Rex as the source and the six ground motion sensors as the receivers. In this test configuration, the baseplate of T-Rex is hit with a sledgehammer to generate a small-strain, vertically-propagating shear wave with the same polarization as the waves generated in shake testing. The left-side of the array forms one set of sensors for downhole testing (1G, 3G, and 5G) while the right-side of the array forms another set (2G, 4G, and 6G). As with crosshole testing, the inline and vertical geophone components of the ground motion sensors are recorded on an analyzer. The $V_S$ of the vertically-propagating shear wave is estimated using the interval travel time and known distance between sensors.

## Excess Pore Pressure Ratio vs. Shear Strain

The medium-strain behavior of the in situ soil was studied using controlled, staged-loading with T-Rex. The cyclic loading at each test site was: 1) staged, horizontal loading applied at the ground surface resulting in a downward propagating shear wave, 2) sinusoidal loading typically applied at 10 Hz for 100 cycles (N), and 3) loading performed in stages with increasing force levels ranging from a minimum of $\pm$ 13 kN to a maximum of $\pm$ 133 kN.

The induced shear strain at each PPT was evaluated using a 4-node, displacement-based shear strain calculation method (Chang, 2002). The instrumentation array is designed to create two, 4-node elements using the ground motion sensors as corners. The shallow array is created by sensors 1G, 2G, 3G, and 4G and the deeper array is created by sensors 3G, 4G, 5G, and 6G.

The excess pore pressure ratio, $r_u$, is calculated assuming a total unit weight above the water table of 15.7 $kN/m^3$ and a saturated unit weight below the water table of 17.3 $kN/m^3$ for the soil. As stated above, the water table is located approximately 1.4 m below the ground surface. A vertical stress of 50.5 kPa from the weight of T-Rex is included in the initial vertical stress calculation and is distributed as a function of space below the baseplate of T-Rex using a Boussinesq bulb distribution. The baseplate of T-Rex measures 2.3 by 2.3 $m^2$ in plan view. Additional details and discussions regarding shake testing and its analysis procedures are available in Roberts (2014).

The results of shake testing at OSU1 and OSU5 are shown in **Figure 10** and **Figure 11**. The values of shear strain refer to the average cyclic shear strain over 100 cycles of shaking. The values of $r_u$ correspond to the value that was measured on the $100^{th}$ cycle of shaking.

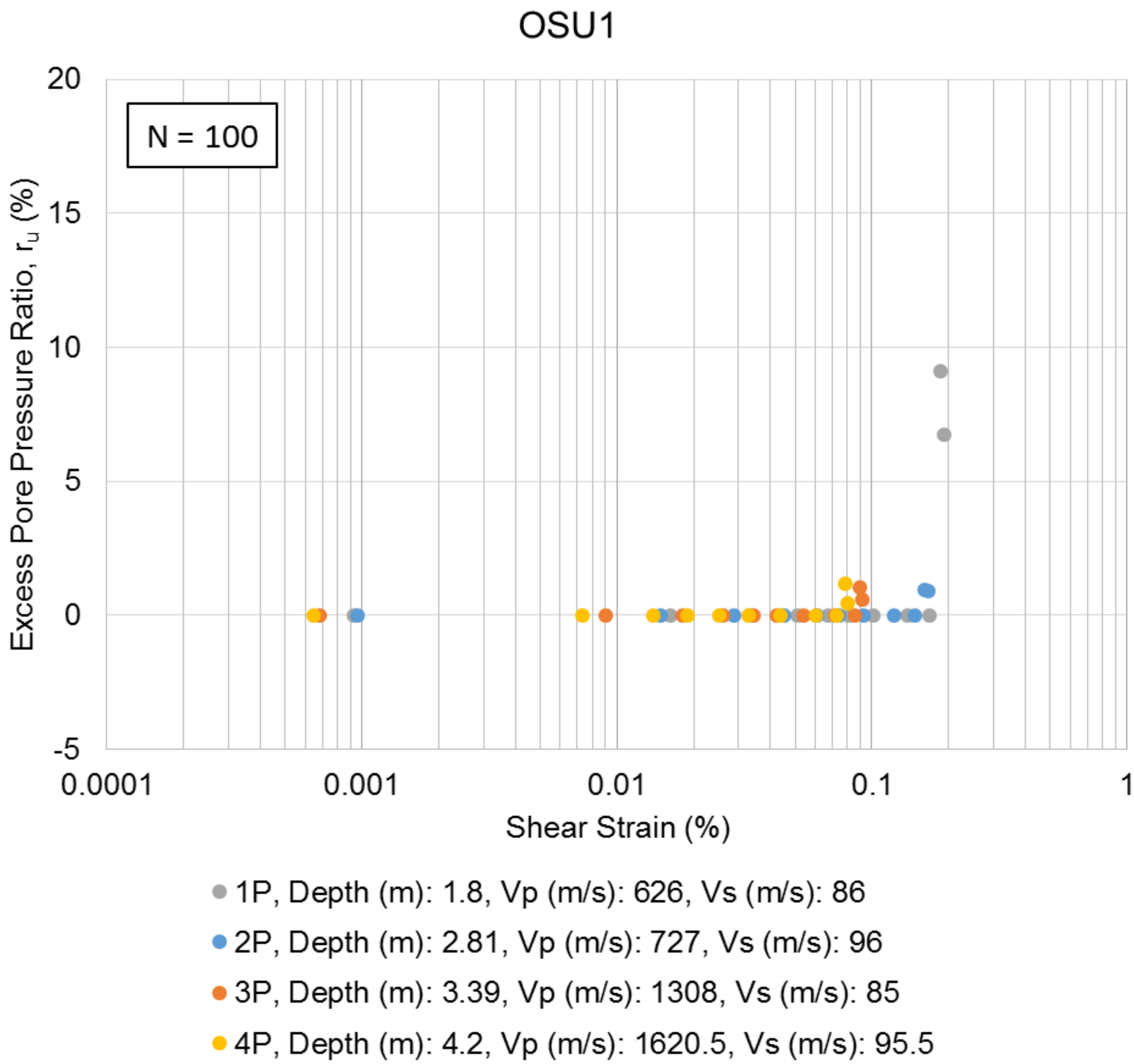


**Figure 10.** Excess pore pressure ratio versus shear strain results from shake testing at Site OSU-1 after 100 cycles

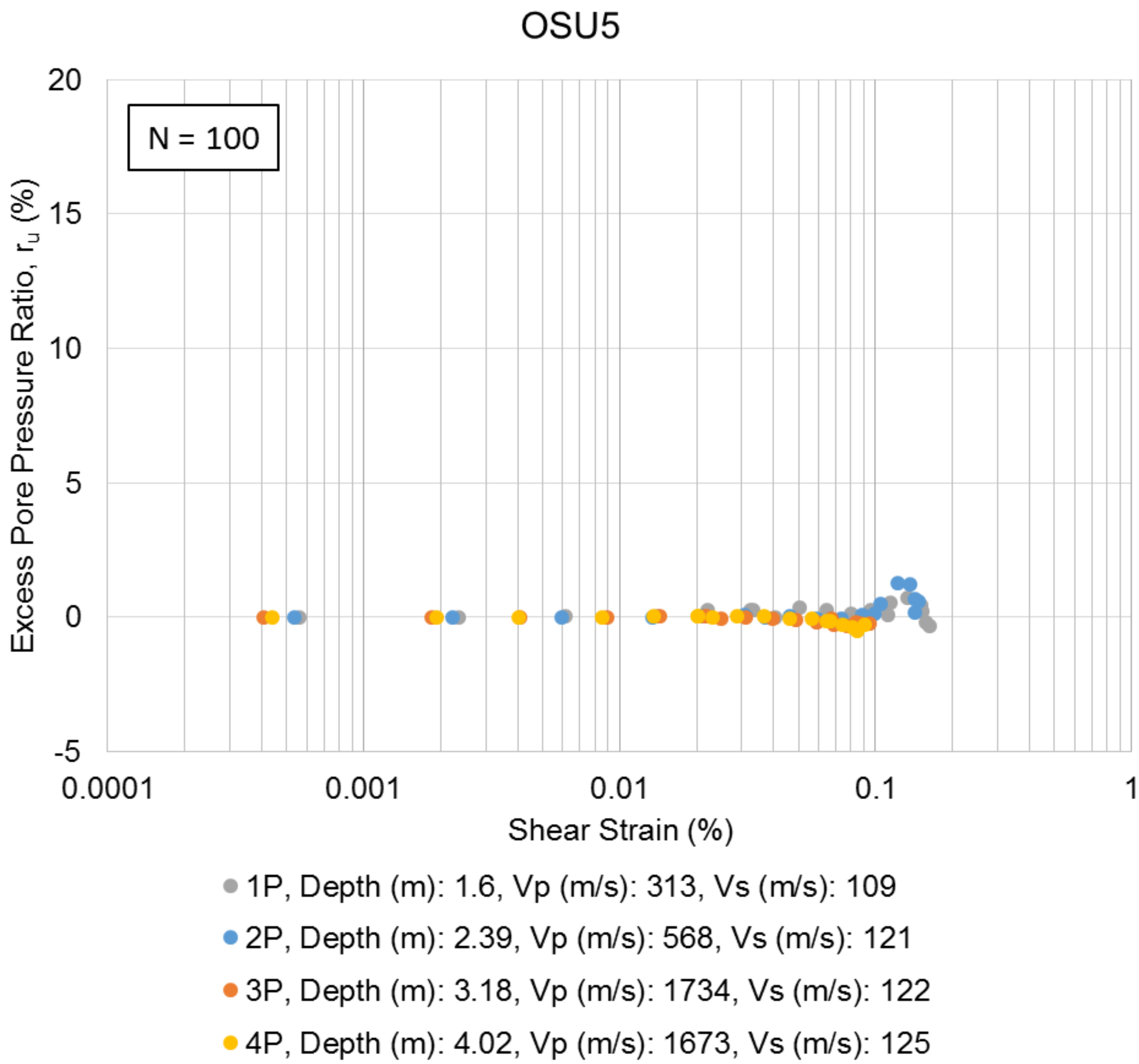


**Figure 11.** Excess pore pressure ratio versus shear strain results from shake testing at Site OSU-5 after 100 cycles

## Long-term Pore Pressure Records

Each of the PPTs were recorded for several minutes after each shaking stage to observe the continued increase and subsequent dissipation of pore pressure due to shaking. In several cases, the pore pressure was shown to continue increasing substantially after the end of shaking, hinting at a complex hydraulic gradient in the soil. The time record in **Figure 12** shows the excess pore pressure ratio at each of the four PPTs before, during, and after loading Stage 9 at OSU1. This stage loaded the ground for 100 cycles at 10 Hz and approximately 100 kN.

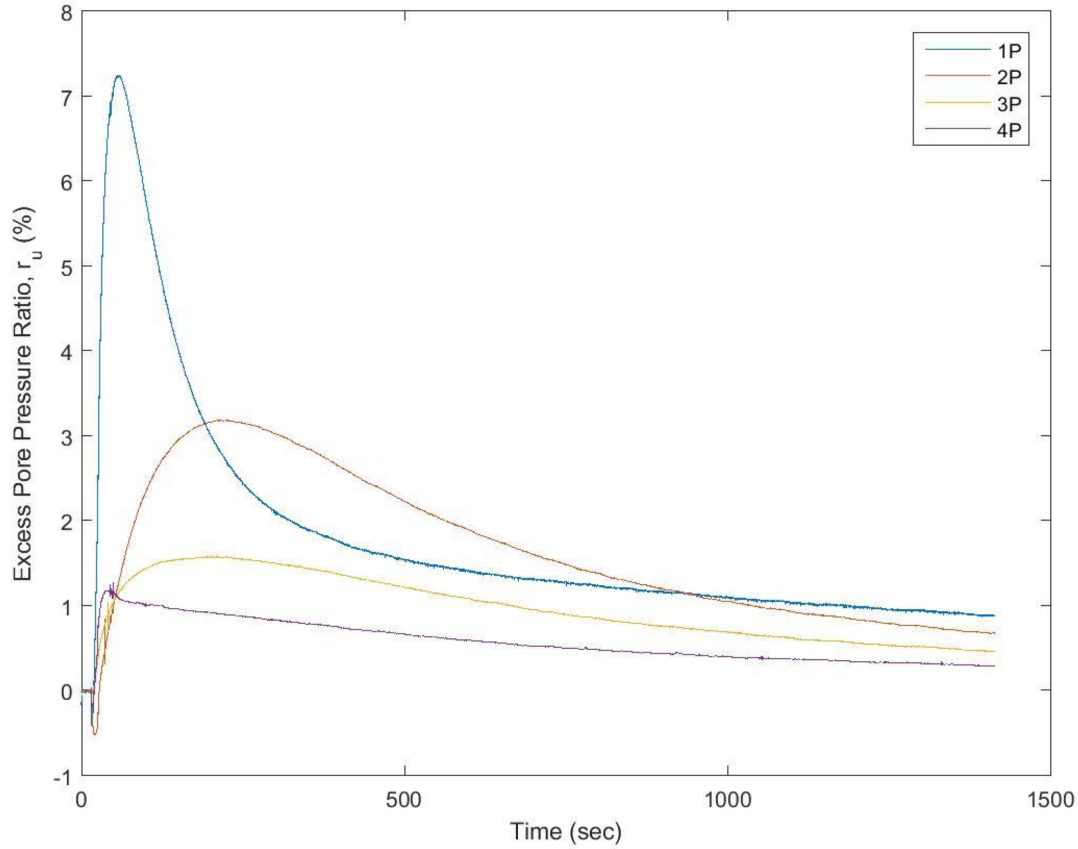


**Figure 12.** Excess pore pressure ratio time records at OSU1 following loading Stage 9. End of loading is approximately 15 seconds into the time record.

## CONCLUSION

The objective of the workshop was to evaluate the liquefaction susceptibility of silty soils using a variety of in-situ geotechnical investigation techniques. Preliminary results from CPT showed the subsurface layering by soil behavior type, indicating the presence of primarily sandy silts and silty sands near the surface in the test region. The depth to 100 % saturation ranges from 2.8 to 3.6 m below the ground surface as identified by the $V_P$ values evaluated from direct-push crosshole seismic testing.

Large-scale shake testing was performed at two locations at the demonstration site, Site OSU-1 and Site OSU-5. The preliminary results indicate a large variability in responses within each location as well as between locations. The variability includes 1) the generation of negative vs. positive pore pressure and 2) continued increase in excess pore pressure after shaking has ceased vs. immediate dissipation in excess pore pressure after shaking has ceased. At this time, it is believed that the main factors influencing the variable responses include variations in 1) soil type and fines content, 2) degree of saturation, 3) soil skeleton stiffness, and 4) relative density. Additional analysis of the data is currently ongoing.

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