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NEAR-FULL SCALE TESTING AND ANALYSIS OF SATURATED SAND-PILE INTERACTION UNDER EARTHQUAKE CONDITION

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SUMMARY

Near-full scale testing and analysis of a 2x1 steel pile group shake-table experiment using the largest laminar container in the world are presented. At NIED (National Research Institute for Earth Science and Disaster Prevention), Japan, a large-scale shake-table test physically modeled the seismic interaction between a full-size pile group and liquefied sand. The large experimental database includes 570 time histories for the three shaking events. Visual analysis using web-based interactive tools (http://geotechvisual.ucsd.edu) captures essential behavior aspects than otherwise had not been detected. Saturated sand-pile interaction is significant during the stage of pore water pressure increase until reaching the zero effective stress condition. *P-y* analysis reveals agreement with previous *p-y* curves reported in the literature.

INTRODUCTION

Liquefaction of loose, saturated sandy soil under earthquake condition is a major cause of damage to piles and deep foundations. Buildings, roads, bridges, port facilities and other civil engineering works are affected. Cracking and rupture of piles and pile connections, permanent lateral and vertical movements, and rotations of pile heads and caps with impacts on the superstructure have been observed. Dobry [1] lists a number of earthquakes in the last four decades where deep foundations have been damaged by liquefaction.

Physical modeling has emerged in the US and Japan as a main tool to study the problem, understand and quantify the parameters involved, and provide guidance and calibration to both simplified engineering procedures and numerical simulation techniques. With the aid of large-scale 1g shake-table test models, it is now possible to obtain detailed measurements of soil and pile responses and to evaluate the importance of varying the earthquake characteristics (level of shaking, frequency content, and waveforms), soil profile characteristics, and pile characteristics.

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Taking advantage of the experimental facilities available in NIED, a near-full scale test of a 2x1 pile group was conducted to study its interaction with saturated sand under simulated earthquake condition. Special features of the database of experimental results include: 1) experiment conducted under 3 different levels of input motion amplitude; 2) unique opportunity of displaying near full-scale soil-pile interaction data under reliable controlled laboratory conditions; 3) high density of employed sensors deployed in the ground and pile, 190 sensors deployed for monitoring sand and pile behaviors in each test; or 570 time histories for the three shaking events; 4) high resolution documentation of salient characteristics of soil-pile interaction during the process of increase of pore water pressure leading to larger bending moments induced along the pile. However, once the pore pressure reach the maximum (zero effective stress) and the sand is completely liquefied, the induced moments substantially decrease; 5) unusual pile geometry to avoid undesired testing effects and gain further insight into pile-liquefied sand interaction; and, 6) monitoring of the sand stratum liquefaction-induced softening behavior. Three different levels of input motion (0.5, 1.0, and 1.5 m/s^2) were applied and as the amplitude of the input motion increases the depth of liquefied sand increases accordingly. The amplitude of 1.5 m/s^2 causes the entire depth of the sand stratum to liquefy. This database is a significant complement to studies mainly based on limited field evidence, laboratory testing of soil elements and scaled centrifuge experimental results.

Large scale testing of full or nearly full size structural models requires not only appropriate experimental facilities but also suitable tools to process, interpret and analyze large amounts of the collected experimental data. Data visualization appears as an important tool for these purposes; Zegal [2], Abdoun [3] and Abe [4]. Data visualization may be defined as the act or process of putting experimental data into visual form, or the generation of images from complex data sets. When visualizing data, the exact values of the data are not as important as the relationship between values. Data visualization is used to gain insight into the data set, and expose relationships between values that might not be apparent in the raw data. In this way, data visualization eases data analysis, and allows for a clear communication during data dissemination.

This paper describes this experimental program conducted at NIED aimed at studying the seismic interaction between a 2x1 pile group and liquefied sand, shows a visual analysis of experimental results using web-based data visualization tools, and conducts a static, displacement-based p-y analysis.

OVERVIEW OF EXPERIMENTAL SETUP AND ARRAYS OF INSTRUMENTATION

The experiment (Fig. 1) aimed at studying the seismic interaction between a full-size 2x1 pile group and liquefied sand. The testing program encompassed three experiments with three different amplitudes of input motion (Table 1), i.e., three shaking events were applied to the soil-pile-superstructure system. For excitation, the time history of the 1995 Kobe Earthquake record in Port Island at 28m underground was used. The shaking events were applied along the direction East-West, parallel to the longest dimension of the laminar container (Fig. 2). Table 1 also indicates the global relative density for the sand before each shaking event. For these experiments, the total height of the soil was 4.0m using just 22 out of the total 28 laminates. To make the container waterproof, a 3mm-thick composite membrane made of neoprene, Kevlar fiber and acrylic was used.

Table 1: Three Experiments with Different Shaking Amplitudes and D_r

Test No.	Max. Acc. (m/s^2)	Relative Density, D_r (%)
1	0.5	46.7
2	1.0	54.5
3	1.5	59.8

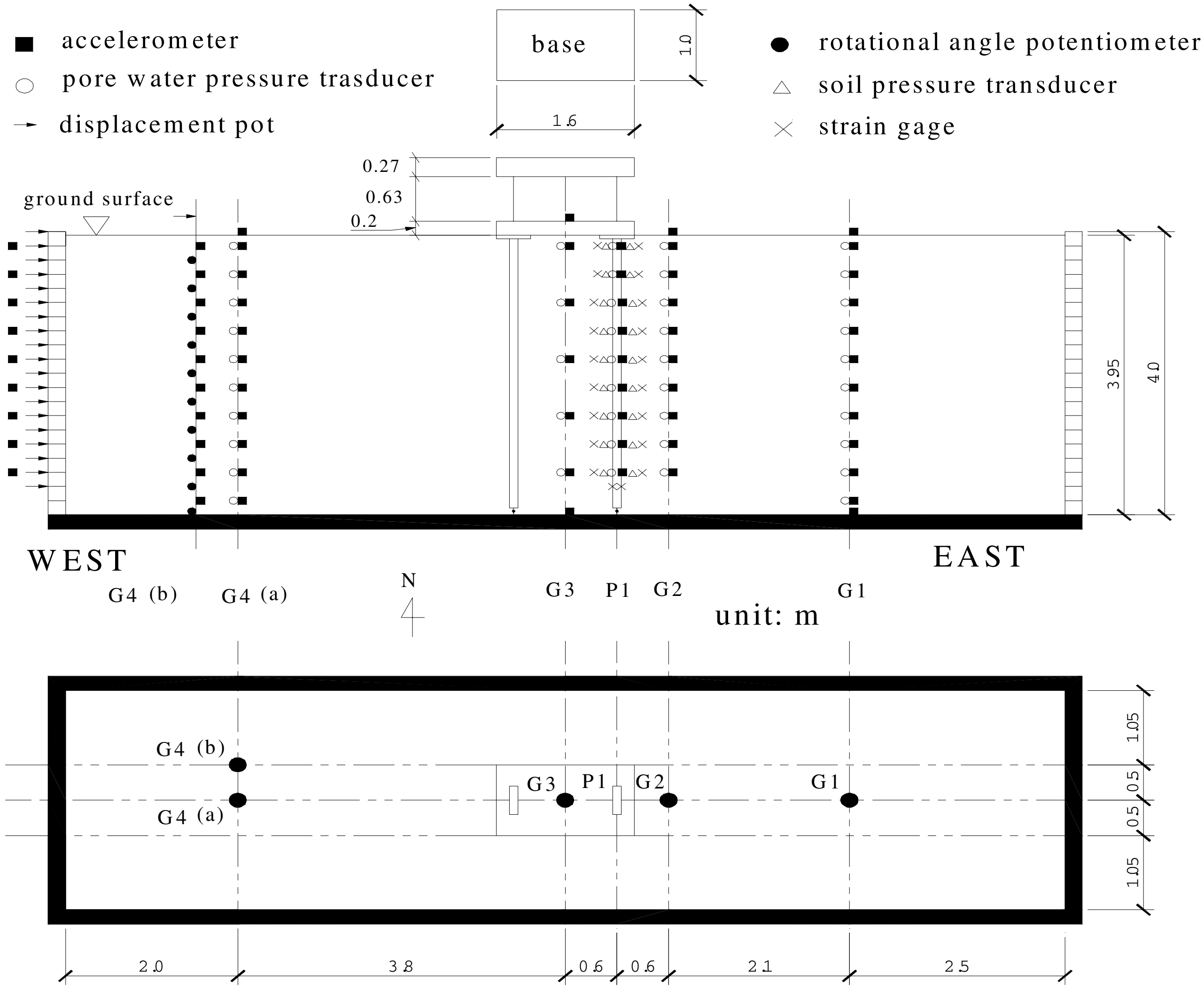

Fig. 1 Experimental setup

Fig. 2 World's largest laminar container

The material used for these experiments was the Kasumigaura-sand with average grain size D_{50} = 0.21mm, coefficient of uniformity C_u = 2.12, specific gravity G_s = 2.638, fine grain size content F_c = 5.8%, and maximum and minimum void ratios of 1.224 and 0.732 respectively. Using a large soil handling system, the sand stratum was formed using the water sedimentation method, and the degree of saturation was checked measuring P-waves. P-wave propagation speeds of 1500-1600 m/s were measured, which agree well with P-wave measurements in fully saturated sand samples in large-scale triaxial tests.

The 2x1 pile group is composed of two 3.8m-long steel piles with rectangular, solid type cross-section, 0.10m thick and 0.40m wide (Young Modulus is E=21000 MPa, and EI=700 MN-m^2) (Fig. 3). The piles have hinged supports (Fig. 4) and bear a 3.6t mass simulating a superstructure (Fig. 5). One of the two piles was heavily instrumented and the pile group was placed at the center of the soil container as shown in Fig. 1. Although the cross-section of the piles are not used in real construction, it was employed in this experimental program for the following reasons: 1) to eliminate undesirable torsional stresses and strains during shaking; 2) to ease the measurement of soil pressures and pile strains along the piles; and 3) to ease numerical modeling by assuming 2-dimensional models under unidirectional shaking.

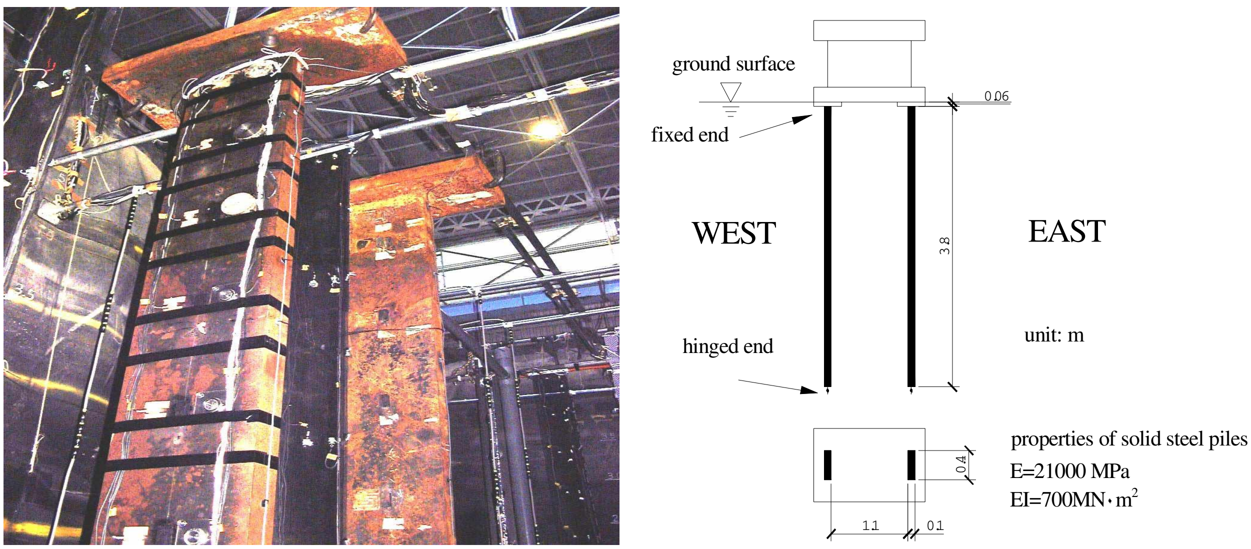

Fig. 3 Full-size 2x1 pile group

Fig. 4 Hinged supports of piles

Fig. 5 View of the 3.6t superstructure mass

Five vertical arrays of instrumentation were placed inside the ground, G1, G2, G3, G4 (a) and G4 (b) (Fig. 1). Arrays G1, G2, G3 and G4 (a) include accelerometers and pore water pressure transducers placed at different elevations. Array G4 (b), located in the west side of the soil container, includes accelerometers and rotational angle potentiometers. After making some conversions, these potentiometers provided horizontal displacements of the liquefied ground at different elevations. A strain pot to monitor the ground surface displacement at the top of array G4 (b) was placed as well (Fig. 1).

One of the piles, the one located on the east side (Fig. 3), was densely instrumented with 10 strain gauges and 9 soil pressure transducers on both sides, totaling 20 and 18 transducers respectively. In addition, 9 accelerometers and 9 pore water pressure transducers were attached to the pile (Fig. 1). A vertical array of 9 accelerometers @ 0.40m and another of 19 displacement pots @ 0.20m were placed on the west side of the laminar container to monitor the motion of the container during the experiments and assess the effects of the boundary conditions on ground and ground-pile response (Fig. 1).

The structural model on top of the pile group was instrumented with 6 accelerometers, and 5 displacement pots. Four displacement pots located at 0.05m from the edges record horizontal displacements at the four corners whereas one displacement pot is located at the center of the east side. A set of three accelerometers is located on the east and west side of the base respectively. On the east side, two accelerometers record in two mutually perpendicular horizontal directions and another accelerometer records in the vertical direction. In the same fashion, three accelerometers are placed on the west side of the base. The plan dimensions of the base are 1.6m by 1.0m.

Table 2 shows the arrays, type and number of sensors per array and the total number of sensors. It is seen that 190 sensors were deployed to monitor the soil and pile group behavior.

Table 2 Number of instruments used in the experiments (See Fig. 1)

Sensors	Arrays								Total number
	G1	G2	G3	G4(a)	G4(b)	P1	Ww	Ss	
ACC	12	10	7	11	10	9	9	6	74
PPT	10	9	5	10		9			43
PTM					10				10
DSP					1		19	5	25
SPTR						18			18
SG						20			20
Total number	22	19	12	21	21	56	28	11	190

ACC : accelerometers
PPT : pore pressure transducers
PTM: potentiometers
DSP : displacements
SPTR: soil pressure transducers
SG : strain gauges
Ww : west wall of container
Ss : superstructure

EXPERIMENTAL RESULT DATA SETS

A total of 190 time histories constitute the data set per experiment. Since three shaking events were imparted, 3 data sets totaling 570 time histories were recorded.

Figure 6 shows time histories of accelerations and Fig. 7 curvatures recorded along the instrumented pile during test N^{o}. 3. Curvature was calculated from the strain gauges placed on both sides of the pile. It is clearly observed that the amplitudes of acceleration and curvature increase as the depth decreases. Fig. 8 displays the variations of pore water pressures along the instrumented pile during test No. 3. Liquefaction of the entire sand stratum is achieved at around 1s, due to the rapid increase of pore pressure during the first second of shaking. Thereafter pore pressure remains stable during the liquefaction phase. At around 1s the sand liquefies (Fig. 8), and the accelerations – at low frequencies- increase in amplitude for about 2s and then drastically decrease. Curvatures along the pile shows that at the moment of reaching the zero effective stress condition, there is a large pulse or large induced bending moment along the pile, and thereafter the magnitude of the curvature or bending moment gradually decreases.

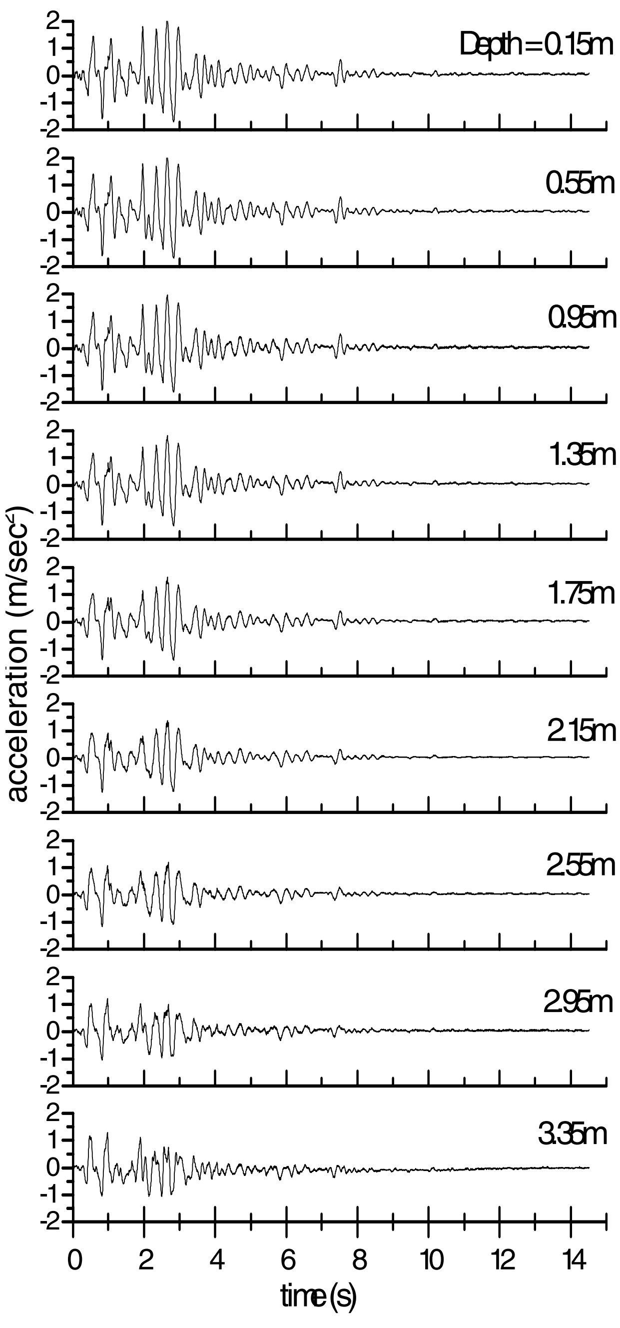

Fig. 6 Time histories of accelerations recorded along instrumented pile (array P1), Test N° 3

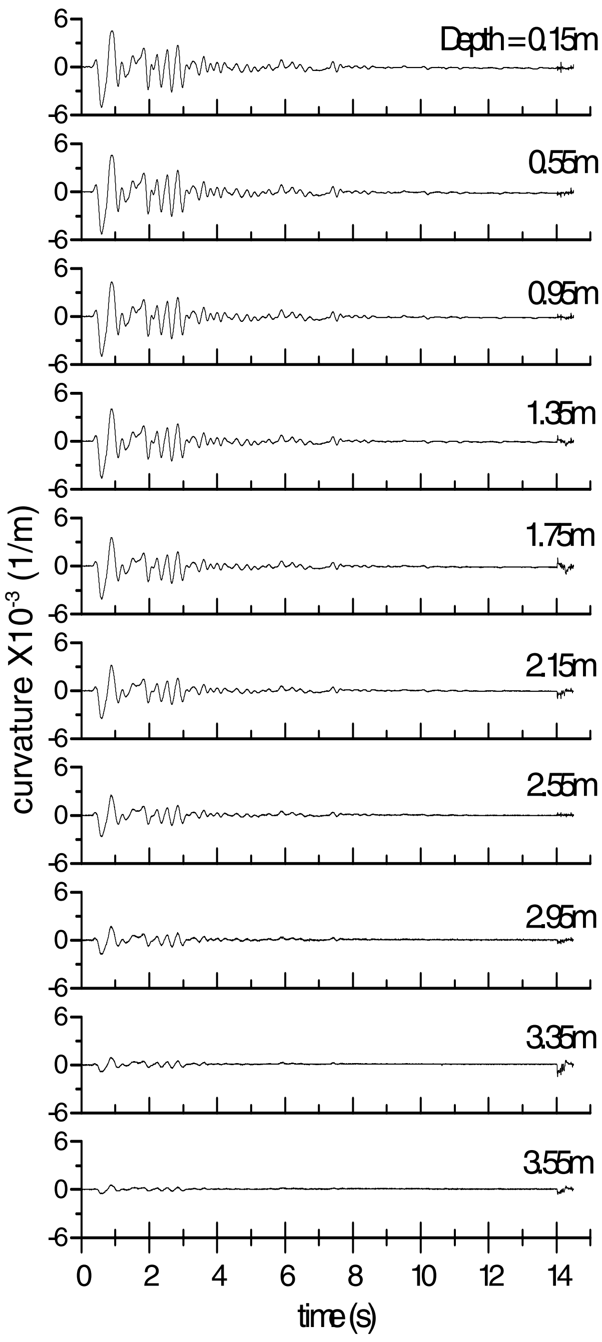

Fig. 7 Time histories of curvatures recorded along instrumented pile (array P1), Test N° 3

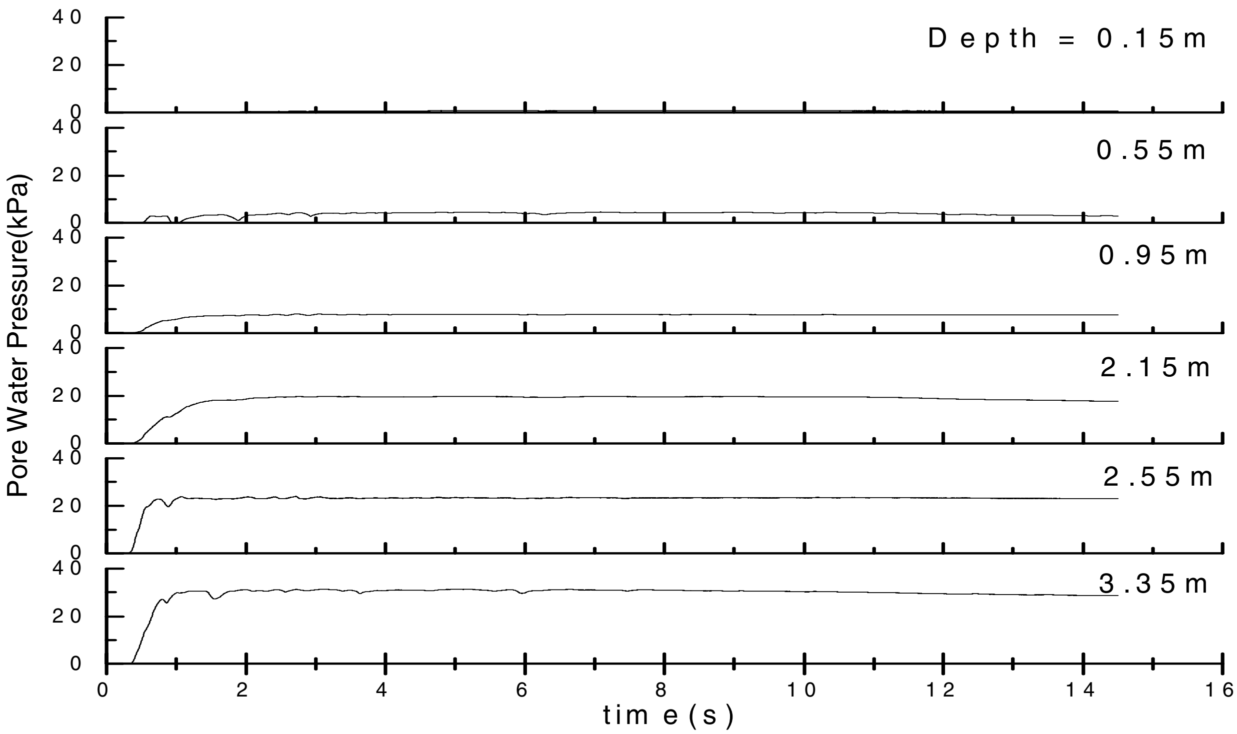

Fig. 8 Time histories of pore pressures (west side) recorded along pile (array P1), Test N^o 3

VISUAL ANALYSIS OF EXPERIMENTAL RESULTS

The visual analysis of test results has been conducted using web-based interactive tools and is presented at http://geotechvisual.ucsd.edu. The animations using interactive Java applets enable tracking and reproducing the recorded time histories of pore water pressures, accelerations, effective stresses, soil pressures, horizontal ground displacements, pile curvatures and p-y curves for each of the 3 experiments.

A typical format of interactive applet is shown in Fig. 9. This figure shows a snapshot of the variation of effective stresses along the vertical array G4 (a) for test N^o 2 (maximum acceleration of input motion is 1m/s^2). This array has 10 pore water pressure transducers, and for each transducer at different depth the time histories of effective stresses are displayed. Simultaneously the variations of effective stresses along depth are shown. An inclined line representing the initial effective stress aids to identify the thickness of liquefied sand. When the line showing the variations of effective stresses reaches and coincides with the vertical axis, the zero effective stress is achieved and hence sand liquefaction. To improve visualization of test results, interpretation of variations with time and depth, and description of the observed phenomenon of soil-pile interaction, the animations can move forward and backward in time under a controlled speed. In addition, comparison of test results of different arrays for the same experiment can be carried out. For example, by clicking on “Select Sensor Array” (Fig. 9), the effective stresses of another array or other arrays can be added to the applet and compared to each other.

Cross-experiment comparison for a particular measured quantity in a particular array can also be performed. For instance, Fig. 10 shows a snapshot of comparison of variation of pore water pressures from array G4 for the 3 experiments, indicated as “Exp.1,” “Exp.2,” and “Exp.3.” By clicking on “Change Time History Set,” time histories of the other two experiments are displayed.

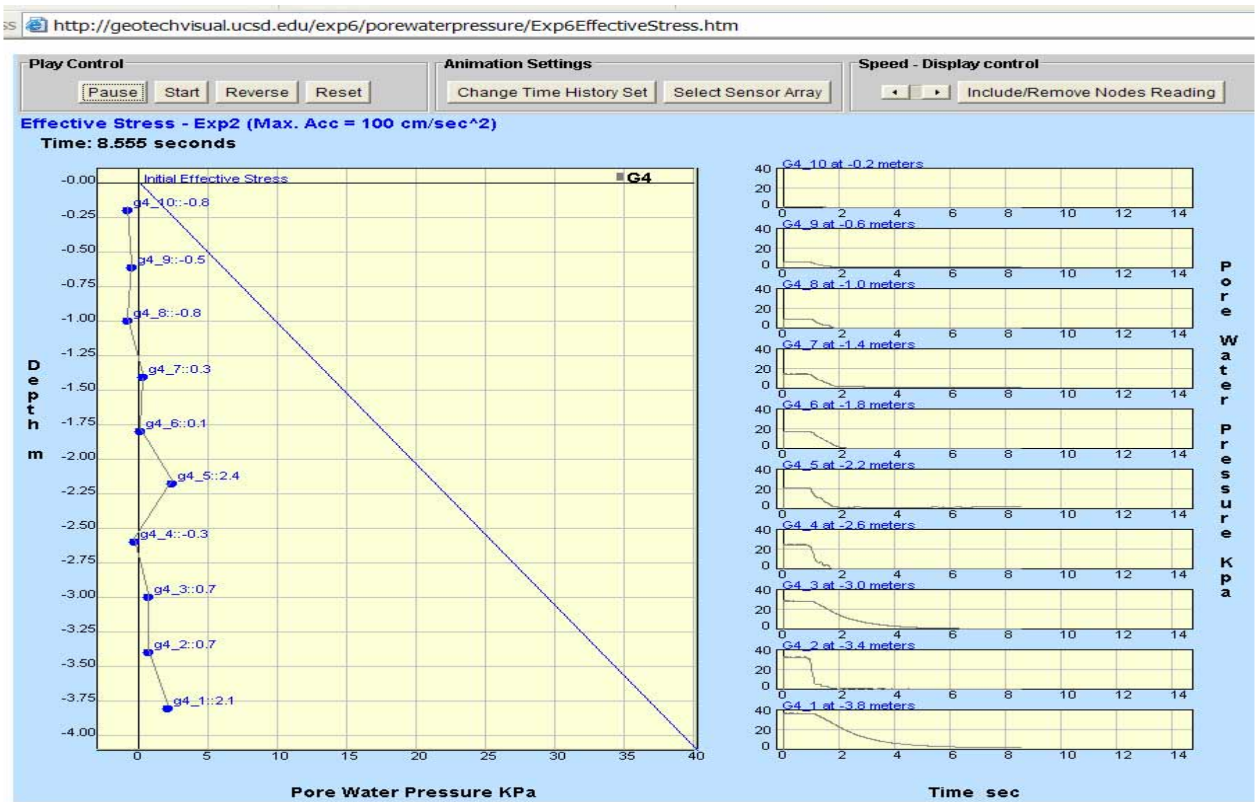

Fig. 9 Snapshot of variation of effective stresses along array G4 (a) for test N^o 2

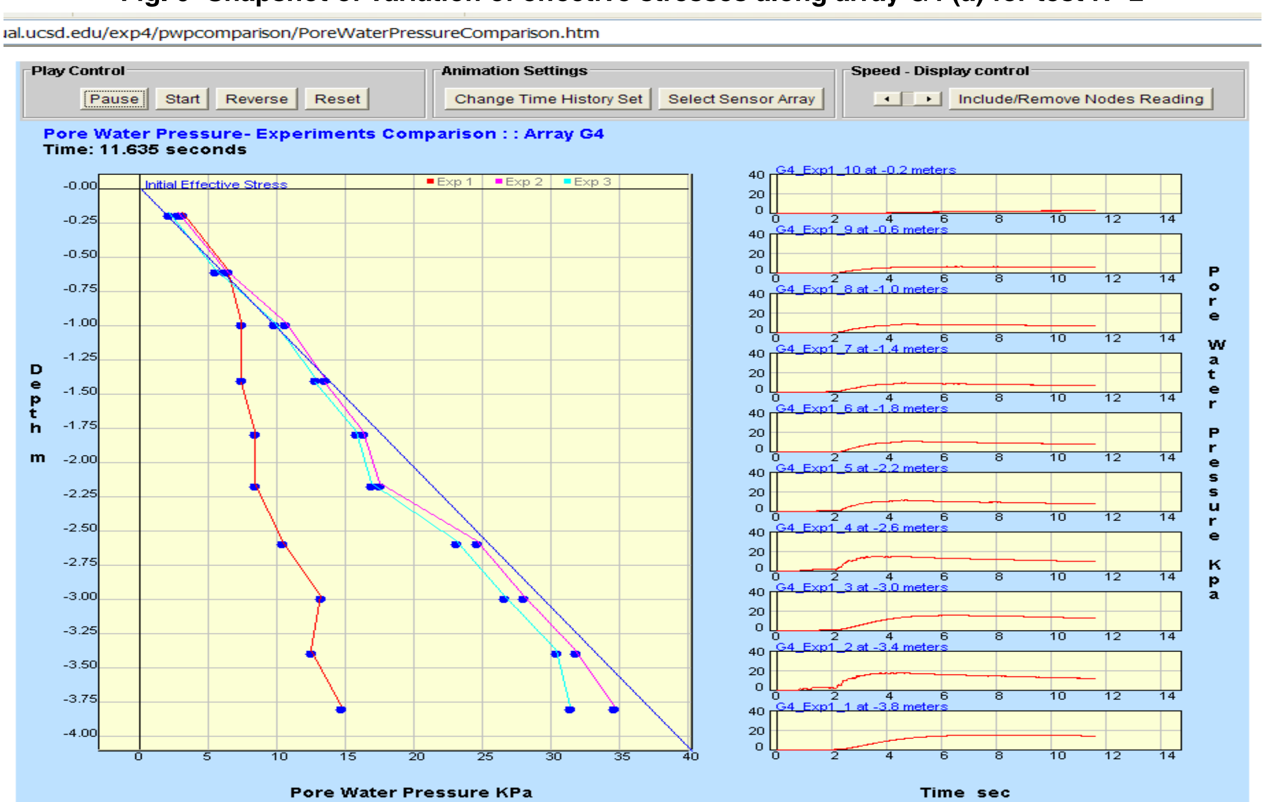

Fig. 10 Comparison of pore pressures measured in array G4 for the 3 tests

Figure 11 shows an animation of pore water distribution inside the sand deposit and distribution of bending moments along the piles. The input motion is also displayed to see the correspondence between the variations of the base excitation with pore pressure and pile moment response. This animation also has the capability of moving forward and backward to facilitate data interpretation and viewing. To improve visualization the lateral displacements of the laminar container have been amplified ten times.

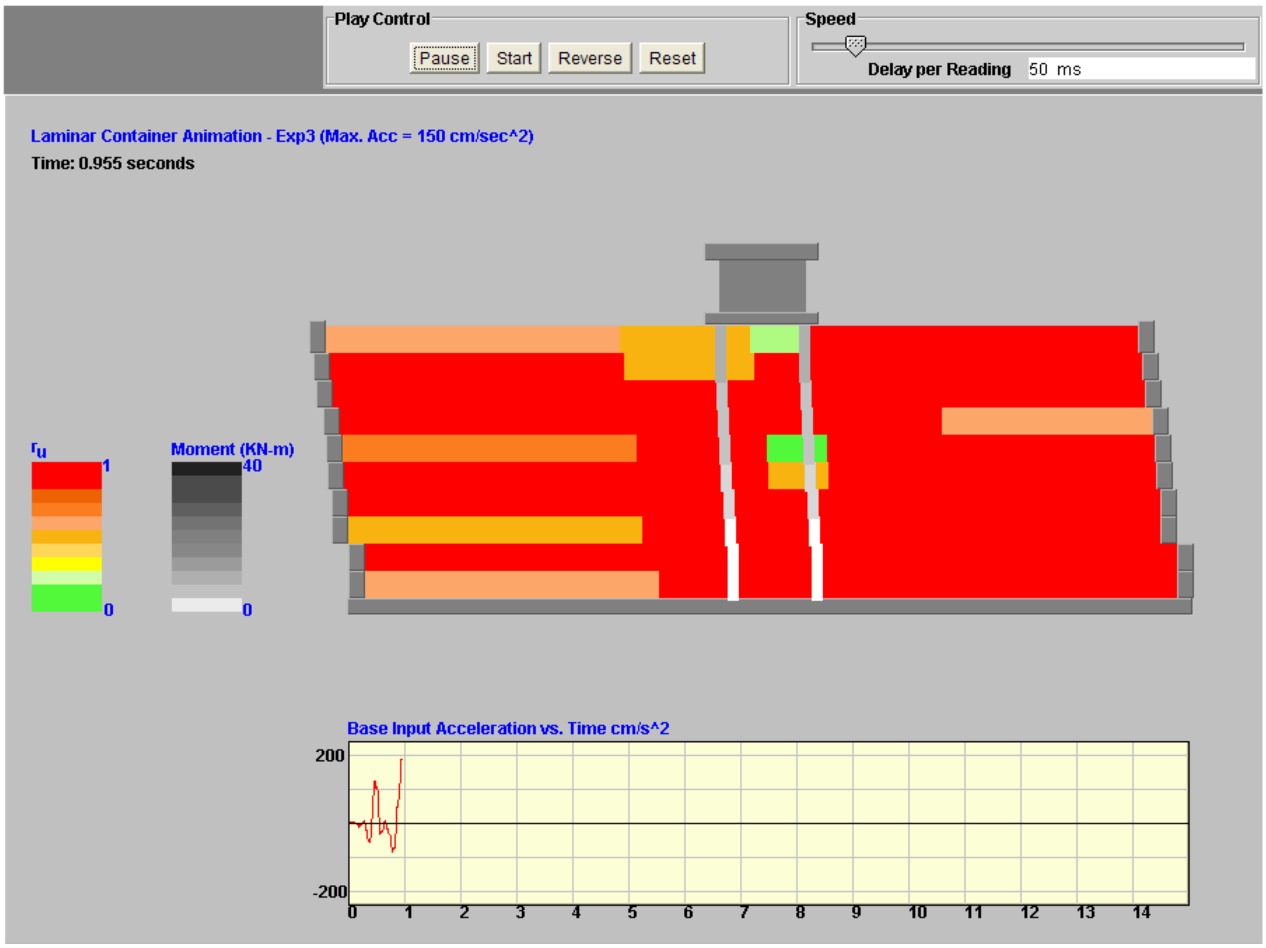

Fig. 11 Spatial and temporal distribution of pore pressures in sand deposit and bending moments in piles

Visual analysis conducted with interactive visualization tools of test results revealed: 1) The variation with depth and time of measured quantities for each of the vertical arrays of sensors in each of the experiments enabling easy identification of time of liquefaction occurrence and thickness of liquefied sand, length of pile with larger bending moments, variation of peak acceleration with depth, variation of horizontal sand displacements, and variation of soil pressure; 2) The influence of input motion amplitude on propagation of liquefaction front from ground surface downward, extent of liquefaction, and time to reach this condition. The larger the amplitude of acceleration, the larger the extent of liquefaction, and the sooner its occurrence; and, 3) The most significant part of sand-pile interaction is during the period of pore water pressure increase and immediately after reaching r_u = 1.0 (r_u = pore pressure ratio = excess pore pressure/initial effective stress). During this period, the bending moments inside the pile significantly increase. Once the sand in completely liquefied the interaction between piles and sand shows small flexural moments along the piles.

p-y ANALYSIS

A convenient way of representing soil-pile interaction by a Winkler model is by using *p-y* curves. A *p-y* curve relates the subgrade reaction or soil resistance to either the pile lateral displacement or the relative displacement between soil and pile.

The subgrade reaction *p* is obtained by two procedures. In the first procedure, *p* is obtained from double differentiation of bending moments, which are calculated from curvature values. Curvatures were calculated directly from readings of the strain gauges located along the instrumented pile. Curvature at the pile head was assumed to be the same as the one at 0.15m deep (location of top strain gauge), and curvature at the mechanical hinge connection at the bottom was assumed to be zero. In the second procedure *p* was directly obtained from the data recorded by the soil pressure transducers.

The soil displacement was obtained directly from the readings of the rotational angle potentiometers from the G4 (b) array located in the free field. Pile displacements (*ypile*) were calculated by integrating the pile rotations along the pile. Relative displacement between soil and pile is denoted as *y*.

Figure 12 displays a snapshot of an interactive applet to display the *p-y* curves (http://geotechvisual.ucsd.edu). "PY" and "P-YPile" indicate *p-y* curves based on *y* and *ypile* displacements respectively. "py1" and "py2" indicate *p* values using back-calculated and measured soil pressures respectively.

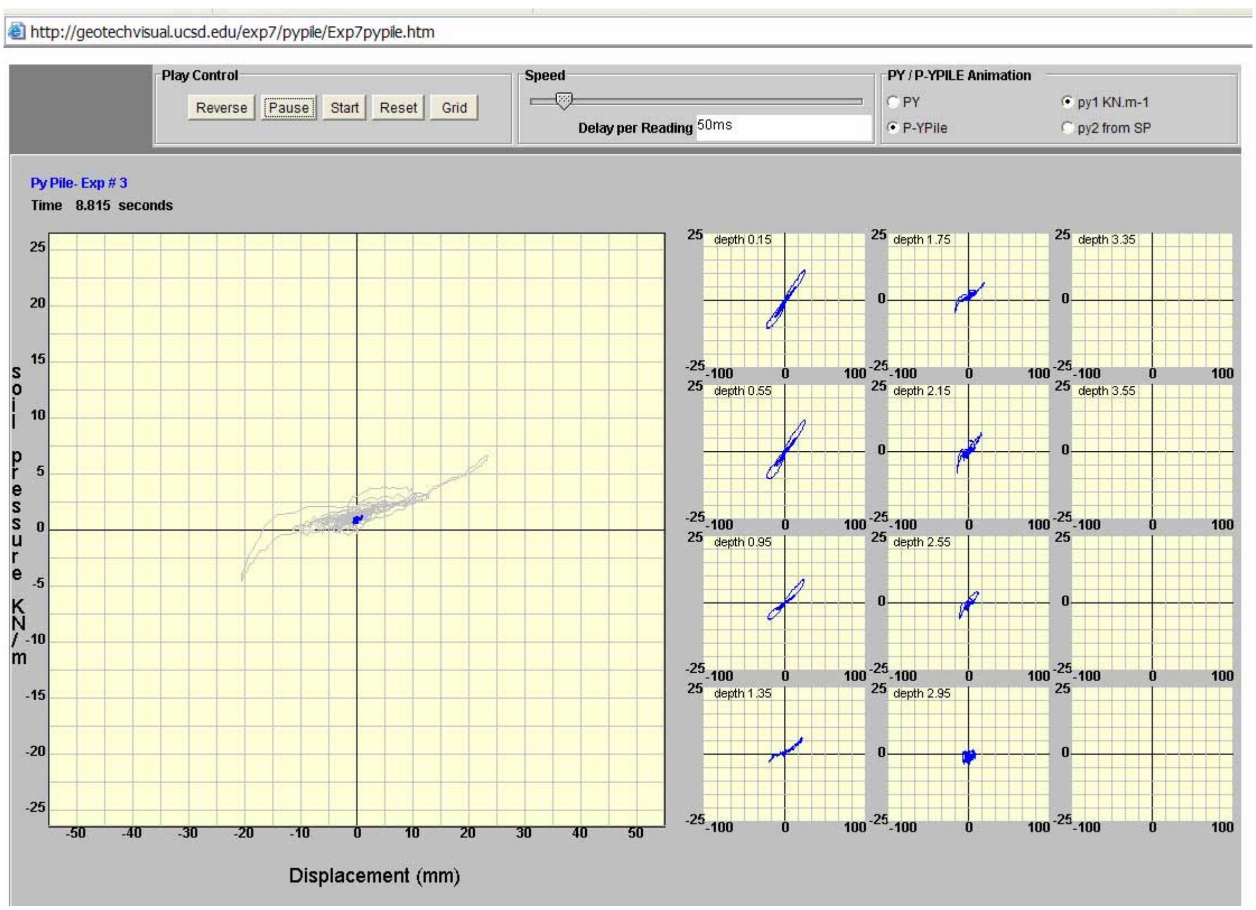

Fig. 12 Variations of *p-y* curves with time and depth (Test 3)

Visual Analysis of *p-y* curves

Figure 12 shows a typical interactive applet to simultaneously visualize *p-y* curves at 12 different depths as shown on the right-hand side of the applet. The large plot on the left-hand side shows one of the 12 *p-y* curves at a larger scale. This plot can be chosen just by clicking on any of the 12 curves at any time during viewing. The *p-y* curves can be displayed moving forward or backward in time and can be paused or frozen at any time. Also the speed of the animation can be controlled. This visualization tool allows simultaneously comparing different *p-y* curves at different depths and capturing the changes of shapes of the curves with time and depth.

The average relative density of the saturated sand for the three experiments was around 55%. Figure 12 displays *p-y* curves for test N^o 3 with maximum base acceleration of 1.5m/s^2. It is observed that *p-y* curves soften as the depth increases. At 1.75m deep, it is clearly observed the dilatant behavior at large displacements. These p-y curves are consistent with the expected behavior of saturated, medium dense sand at the level of confining stresses under earthquake condition. These observations are in good agreement with other curves for comparable conditions reported in the literature; Wilson [5], Ashford [6], and Suzuki [7].

For experiment N^o 2 (max. acc. 1.0m/s^2), Fig. 13 shows a snapshot of *p-y* curves determined from back-calculated *p*-values, and Fig. 14 shows *p-y* curves obtained from *p*-values measured from the soil pressure transducers. By comparing both sets of curves, it is observed that back-calculated *p*-values might tend to overestimate *p-y* behavior and make sand appear harder than it really is.

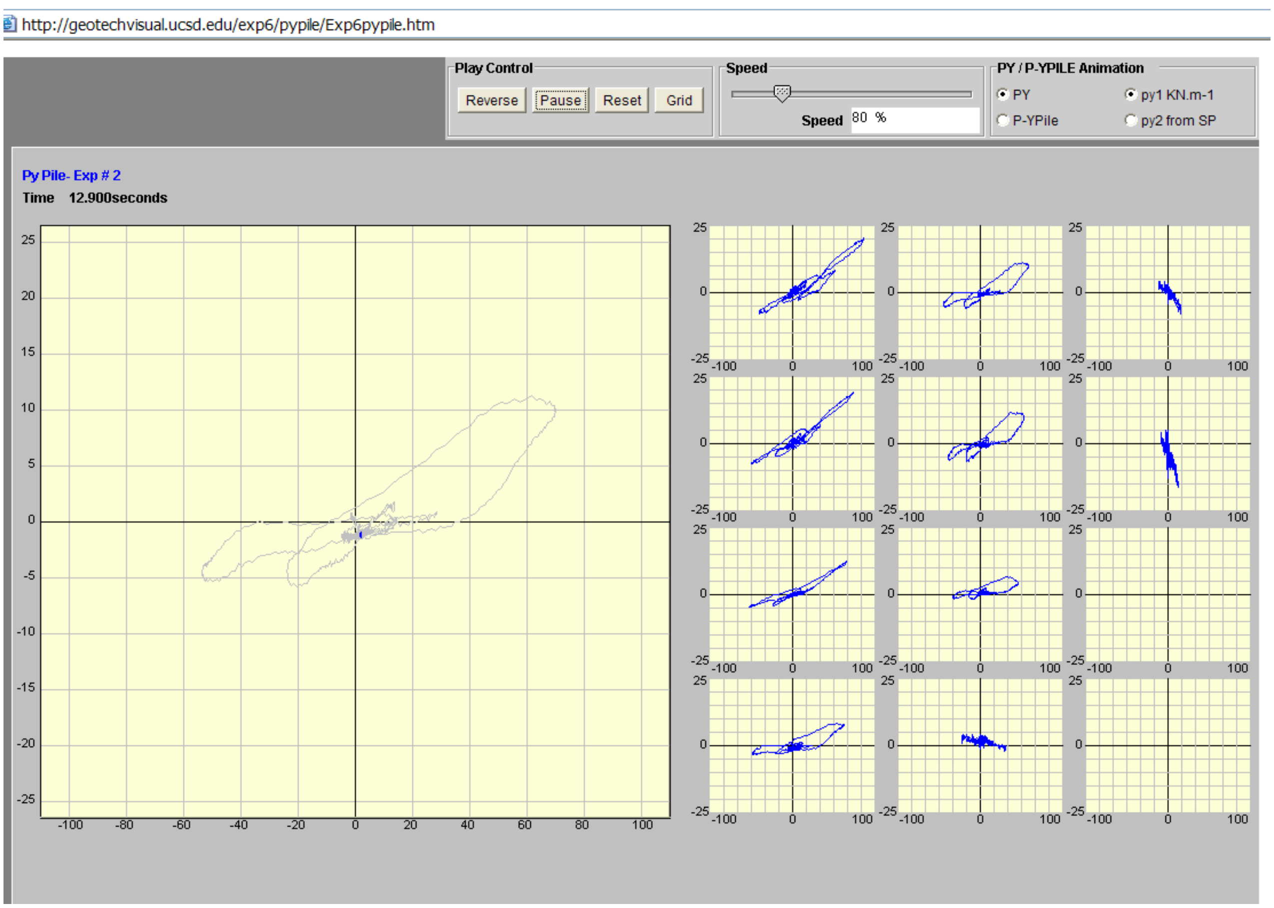

Fig. 13 Variations of *p-y* curves with time and depth (Test 2; back calculated p)

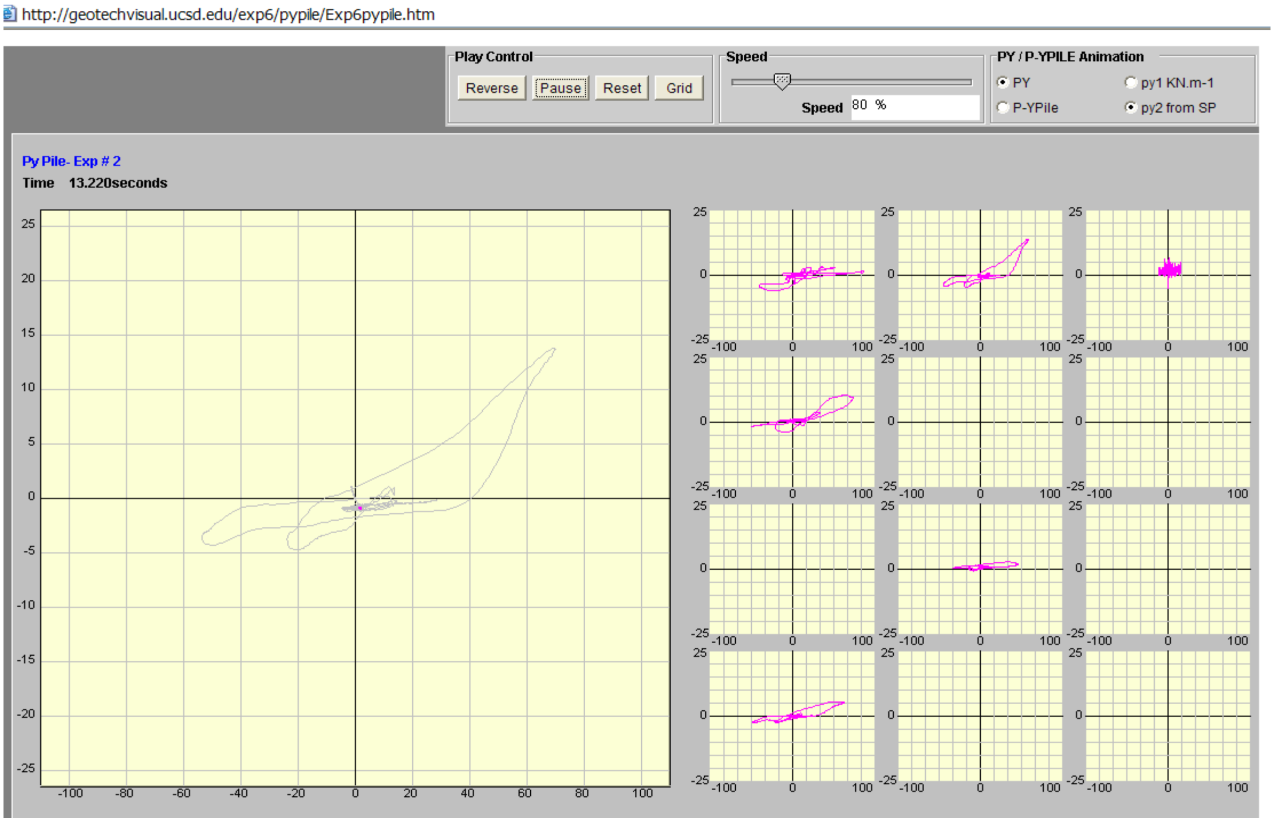

Fig. 14 Variations of *p-y* curves with time and depth (Test 2; *p* from soil pressure transducers)

CONCLUSIONS

Near-full scale testing and analysis of earthquake interaction between a 2x1 pile group and saturated sand have revealed essential features of interaction behavior. Pile geometry helped reducing undesirable torsional effects during shaking and easing measurements of soil pressures and pile strains. Visual and *p-y* analyses reveal that significant bending moments are induced to the piles until sand liquefies, and *p-y* curves are consistent with testing and soil conditions. Back-calculated *p*-values might tend to overestimate *p-y* behavior.

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