LARGE SCALE SHAKING TABLE TESTS OF SEISMIC SOIL-PILE INTERACTION IN SOFT CLAY

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SUMMARY

Seismic soil-pile-superstructure interaction (SSPSI) is an important problem currently attracting considerable attention around the world. The lack of well-documented and well-instrumented full-scale case history data from actual earthquakes has motivated researchers to perform scale-model physical testing. Large-scale SSPSI model tests have been performed on the 6.1 m x 6.1 m U.C. Berkeley/PEER Center multi-directional shaking table, using a unique system that overcomes many of the problems associated with previous efforts. This paper focuses initially on the development of the 1-g scale model testing program. Secondly, the paper presents results obtained from single piles with different inertial loading conditions, which illustrate the potential for both kinematic and inertial response. Finally, a comparison of the model's measured site response to the anticipated free field response confirms that the modeling system is performing as intended.

INTRODUCTION

The coincidence of major pile-supported structures sited on soft soils in areas of earthquake hazard results in significant demands on these deep foundations. Possible resonance effects between longer period soft soil sites, which may amplify ground motions, and large structures can exacerbate the problem. Liquefaction and/or strain-softening potential in these soft soils can impose additional demands on pile foundation systems. Historically, it has been common seismic design practice to ignore or simplify the influence of pile foundations on the ground motions applied to the structure. This is generally accepted as a conservative design assumption for a spectral analysis approach, as the flexible pile foundation results in period lengthening and increased damping, and consequent decreased structural forces relative to a fixed base case. It is somewhat more common to evaluate pile integrity during seismic loading, though this too is accomplished with simplified and non-standardized analysis methods. However, in observations of pile performance during earthquakes, two principal facts emerge: pile foundations do affect the ground motions the superstructure experiences, and piles can suffer extreme damage and failure under earthquake loading..

Unfortunately, there is a lack of well-documented seismic soil-pile response case histories, and of these cases very few include piles that have been instrumented to record dynamic response. This limited database of measured pile performance during earthquakes does not provide a good basis for calibration and validation of the available analytical methods developed for seismic soil-pile-superstructure interaction problems. Centrifuge and shaking table model tests have therefore been used to augment the field case histories with laboratory data obtained under controlled conditions. The vast majority of centrifuge and shaking table model tests have studied soil-pile seismic response in cohesionless soils with liquefaction potential. But many pile foundations for critical structures are sited on soft clays, which have the potential for cyclic strength degradation during seismic loading. The San Francisco-Oakland Bay Bridge sited on San Francisco Bay Mud is a prime example.

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Therefore a strong need exists to examine SSPSI in strain-sensitive cohesive soils. Shaking table experiments provide an excellent opportunity to augment the limited database of SSPSI in soft clays, and afford the ability to do so under controlled and varied conditions. Importantly, such experiments can be designed to simulate the fully-coupled behavior of the soil-pile-superstructure system, and fully-coupled analytical methods can be applied to the results.

PHYSICAL MODELING

The principal objectives of the shaking table test program were to gain insight into modes of SSPSI and to generate a suite of case histories with which to calibrate an advanced numerical code for SSPSI analysis being developed at U.C. Berkeley. The shaking table tests were performed at the U.C. Berkeley/PEER Center Earthquake Simulator Laboratory, the largest facility of its kind in the United States. This shaking table is 6.1 m x 6.1 m, has a payload capacity of 580 kN, a bandwidth of 0 - 20 Hz, and has recently been upgraded to have six controlled degrees of freedom.

Testing Parameters

The shaking table tests consisted of a series of models of soil with embedded piles, in single and group arrays, joined by pile caps supporting lumped masses on flexible columns. This design allowed the complete SSPSI problem to be physically modeled, without uncoupling the superstructure and foundation response. The model tests were configured to gain insight into particular SSPSI problems, including superstructure frequency response, multidirectional shaking, kinematic vs. inertial response, cap embedment, group effects, etc.

Multiple piles and pile groups were positioned in the test container so as to minimize interaction, and were tested simultaneously. Instrumentation included 35 accelerometers deployed in downhole vertical arrays in the soil and attached to the pile caps and superstructures, and 7 pairs of strain gages fixed to each of up to 12 model piles in a given test. Wire potentiometers measuring superstructure deflections increased the number of data acquisition channels to 144. Sine sweeps and earthquake time histories, reflecting a range of magnitudes and frequency content, were scaled to peak horizontal accelerations of 0.05 to 1.0 g and applied to the model in 1-D and 2-D loading. Each test setup was shaken at progressively higher acceleration levels, until significant soil degradation occurred.

Dimensional analysis was the framework for scale model similitude in the test program. By defining scale factors for length, density, and acceleration, the scaling properties of the three fundamental measures of length, force, and time are determined, and all prototype properties can be expressed in dimensional form for appropriate scaling. The principal model similitude parameters are defined in terms of the geometric scaling factor λ and are summarized in Table 1. A geometric scaling factor of 8 was adopted for these tests.

Table 1. Prototype:Model Scaling Factors

Mass Density	1	Length	λ
Force	λ^3	Stress	λ
Stiffness	λ^2	Strain	1
Modulus	λ	EI	λ^5
Acceleration	1	Time	$\lambda^{1/2}$
Velocity	$\lambda^{1/2}$	Frequency	$\lambda^{-1/2}$

Model Container Design

Geotechnical scale modeling in the laboratory requires the use of a container to support the model soil, which imposes boundary conditions that do not exist in the prototype field case. A successful container design minimizes the influence of these boundary conditions on the overall system response and allows the model to closely replicate the seismic response of level ground (i.e. free field) conditions. Several containers were modeled numerically and a laterally flexible but radially stiff cylindrical design was identified as achieving quasi-free field response [Riemer and Meymand, 1996]. This design extends centrifuge testing laminar box concepts to allow for multi-directional shaking.

The model container confines a soil column 2.3 m in diameter and up to 2.0 m in height, and is shown in Figure 1 mounted on the shaking table. The top steel ring is supported by four extra-heavy wall steel pipes with connecting heavy-duty universal joints, providing the ring with full translational freedom, but preventing overturning rotations. A neoprene rubber membrane is hung from the top ring and clamped at the base, and woven Kevlar straps are arrayed in circumferential bands around the exterior of the membrane. The combination of the rubber membrane and Kevlar bands provide the desired container properties of lateral flexibility in simple shear and radial stiffness. Internal shear strips arrayed vertically around the circumference are included to transfer complementary shear stresses developed in the soil.

Figure 1. Model container on shaking table and filled with model soil

Model Soil and Model Piles

A model soil with appropriately scaled stiffness and strength properties was developed for the project, and consisted of 72% kaolinite, 24% bentonite, and 4% type C fly ash (by weight). The model soil has a unit weight of 14.8 kN/m3, a plasticity index of 75, an undrained shear strength of 4.8 kPa and a shear wave velocity of approximately 32 m/second (the last two parameters measured at a water content of 130% and cure time of 5 days). Bender element and cyclic triaxial laboratory tests were performed to characterize the modulus degradation and damping curves of the model soil. Meymand et al. [1998] provide a more detailed discussion of the model soil development.

From standard Caltrans design, a 410 mm diameter x 12.7 mm wall concrete-filled steel pipe pile was selected as the target prototype. Scaling constraints dictated a maximum prototype pile length of 12.8 m, which provided a

L/d ratio of 32, acceptable for a slender pile. The fixity conditions of the pile, known to be significant in lateral response, were established as fixed against rotation at the head, and fixed against (relative) translation at the tip. This corresponds to a pile driven into a firm strata at the base, and cast into the pile cap. The flexural rigidity of the prototype pile was computed as 79,120 kN-m2. Accordingly, the model piles were fabricated using 50.8 mm diameter 6061 T-6 aluminum tubing with a wall thickness of 0.71 mm, which provided the correctly scaled flexural rigidity (EI).

SHAKING TABLE TEST RESULTS

The work presented here focuses on the results of a shaking table experiment referred to as Test 1.15. The layout of this test is shown in Figure 2 (the arrow indicates the primary axis of shaking) and consisted of four single piles with head masses ranging from 4.5 to 72.7 kg. embedded in 2.0 m of model soil. The vertical arrays of accelerometers were located within 0.5 m of the piles, but were out of the line of shaking. T-bar pullout and hammer blow tests were performed to determine the test-specific soil strength and shear wave velocity profiles. The shear strength profile corresponded to a lightly overconsolidated soft to medium stiff clay, overlying a hard clay bearing layer.

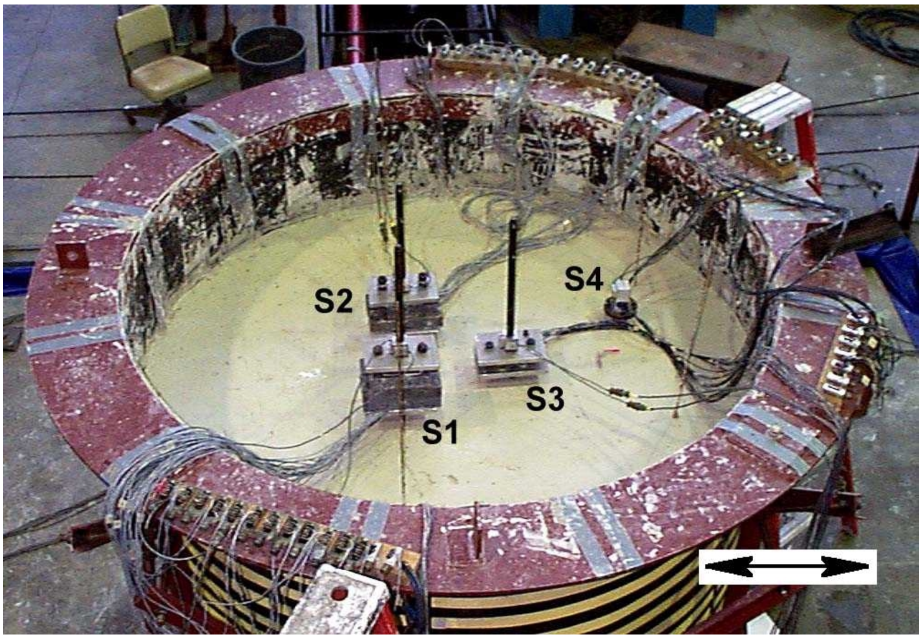

Figure 2. Configuration of shaking table Test 1.15

The model was subjected to a series of seismic events including sine sweeps and earthquake records. A scaled version (a_{max} = 0.20g) of the motion recorded at Yerba Buena Island during the Loma Prieta earthquake was used as the shaking table command signal for the test analyzed herein. The pile bending moment envelopes from this test are shown in Figure 3, illustrating that inertial interaction dominated the response of the more heavily loaded piles S1, S2, and S3, and kinematic interaction significantly influenced lightly-loaded pile S4. The pile head to free field transfer functions depicted in Figure 4 for piles S1 and S4 reinforce this point.

P-y curves were derived from the strain gage test data for pile S1 for the time window shown in Figure 5a, and are depicted in Figure 5b. A method of so-called "weighted residuals" originated by Wilson [1998] was utilized for double differentiation of pile bending moments to obtain "p", and straightforward double integration of bending moments was performed to obtain "y". Rigorous treatment of boundary conditions and data visualization animations in Matlab were essential to obtaining the p-y results. These experimental p-y curves are plotted against the backbone cyclic p-y curve specified for soft clay by Matlock [1970] and codified by the American Petroleum Institute [1993]. The experimental p-y curves illustrate hysteretic and degrading behavior, and are in very good agreement with the reference Matlock/API curves. This result suggests that the p-y method provides a reasonable description of the nonlinear soil-pile interaction in these model tests, and is a suitable model for analytic simulations.

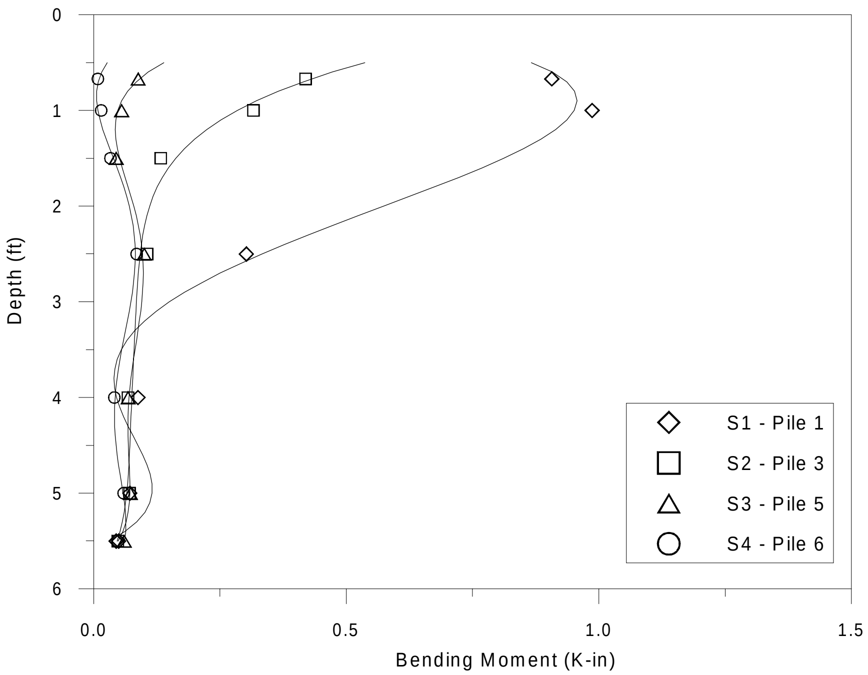

Figure 3. Test 1.15 pile bending moment envelopes

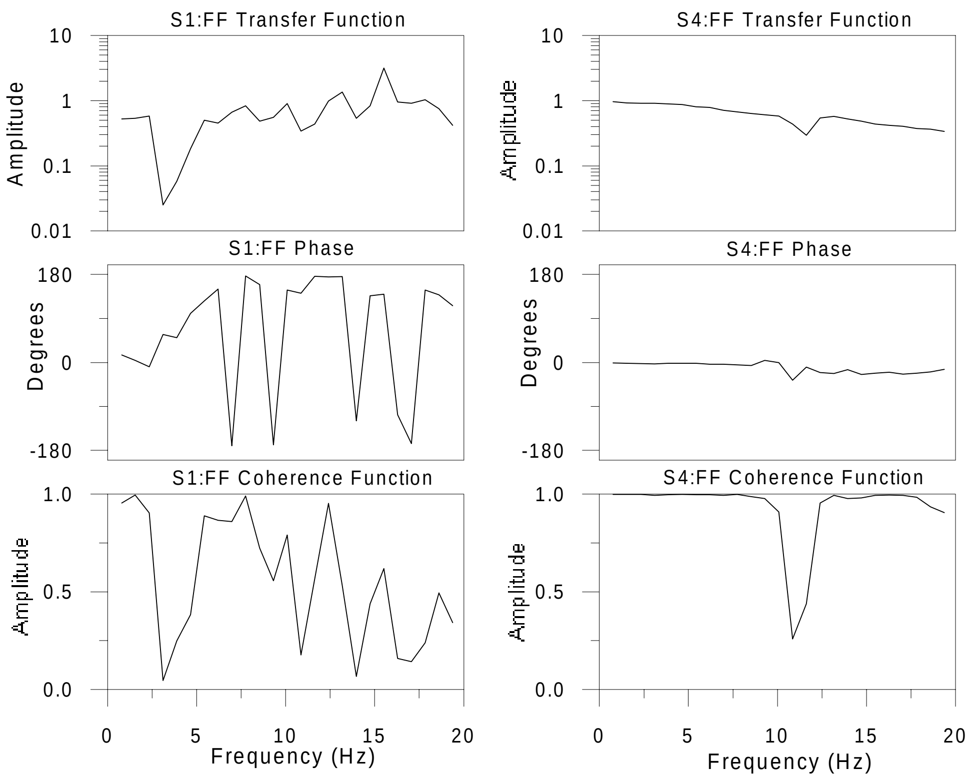

Figure 4. Pile Head:Free Field transfer functions from Test 1.15

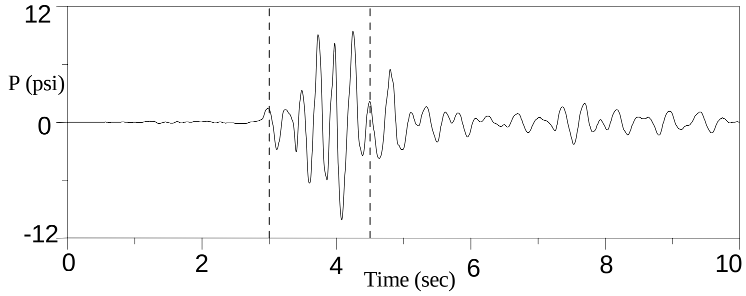

Figure 5a. Test 1.15, Pile 1, p-y analysis time window

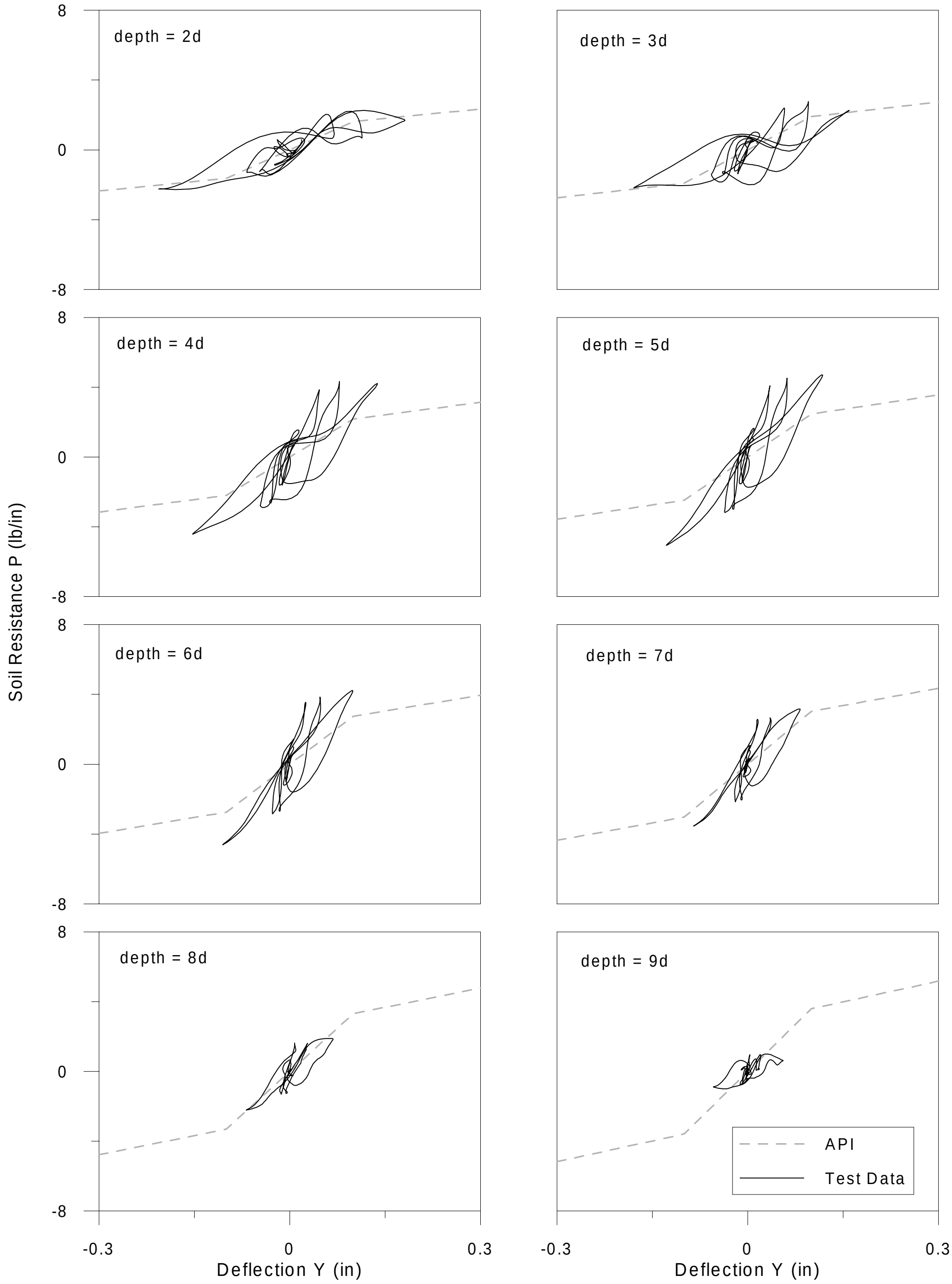

Figure 5b. Test 1.15, Pile 1, experimental vs. API cyclic p-y curves

SIMULATION OF FREE-FIELD SHAKING

The effectiveness of the model container in allowing "free field" response of the model soil column was evaluated by comparing soil accelerations recorded at the surface and at depth with those numerically simulated by SHAKE 91 (Idriss and Sun, 1992). Test 2.24 is studied here as it offers a denser vertical array of accelerometers for comparison. An advanced cyclic triaxial testing device was utilized to obtain modulus degradation and damping curves for the model soil, and a test-specific shear wave velocity profile was developed using the methods described above. Figure 6 shows good agreement between the observed (solid lines) and computed (dashed lines) 5% damped acceleration response spectra, indicating the model successfully responded in a free field mode. These results were consistently obtained for the suite of tests which included different ground motions, a range of shaking intensities, and two-dimensional shaking. This agreement represents an important validation of the model container technology, as it indicates that model boundary conditions were sufficiently suppressed to effectively simulate free field conditions in the soil.

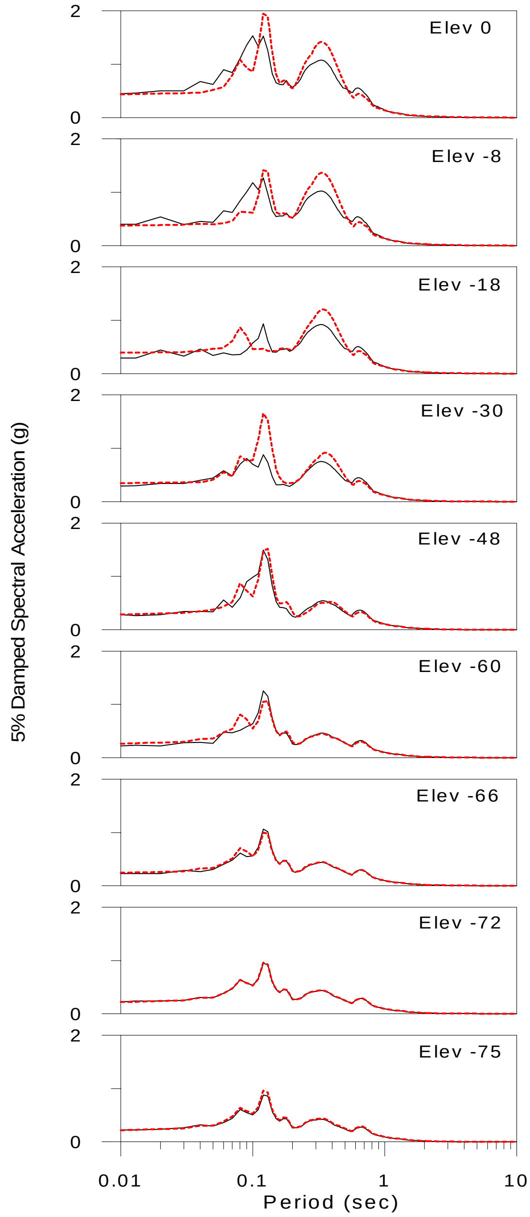

Figure 6. Test 2.24 site response (solid lines) vs. predicted (dashed lines) 5% damped acceleration response spectra (elevations in inches, relative to ground surface).

CONCLUSIONS

Recent experimental research at the University of California, Berkeley regarding seismic response of pile foundations has been briefly described.. Dimensional analysis techniques have been used to identify scale modeling criteria and to develop properly-scaled model soil and simple pile-supported structures. A unique model container has been designed to allow multi-directional simple shear deformation, minimize boundary effects, and to replicate free field site response. Site response data from accelerometers at multiple depths suggest the container is successful in applying the appropriate boundary conditions. The effects of kinematic and inertial interaction were demonstrated for a test involving single piles. The derivation of p-y curves from the test data was shown to provide a suitable basis for analytical simulation of the test data. While limited space has precluded its presentation in this paper, additional testing has focused on the relevance of conventional static and cyclic pile head loading tests to the prediction of seismic response, comparisons of single piles with pile groups of various sizes, the effects of pile cap embedment, and initial investigations into the effects of two-dimensional shaking. Further information about this research project is available online at *www.eerc.berkeley.edu/meymand.*

The overall project includes both physical and numerical modeling. The data set developed during the testing program is the subject of ongoing analysis at U.C. Berkeley, including the analysis of dynamic pile response using the finite element computer code GeoFEAP [Lok et al., 1998]. This fully-coupled formulation is capable of accurately describing the dynamic response of a relatively complex soil-pile-superstructure system, with the advantage of solving the SSPSI problem in a single step.

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