General Report — Session 6: Soil-Structure Interaction Under Dynamic Loading for Both Shallow and Deep Foundations

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INTRODUCTION

The importance of soil-structure interaction (SSI) under dynamic loads was recognized as early as in the 1960s in the design of shallow foundations for machines and mechanical equipment. Subsequently, SSI analysis received significant attention in the seismic safety evaluation of nuclear power plants. During the 1970s and 1980s major advancements were made in developing computer codes that now allow 3-dimensional SSI analysis of large, deeply embedded structures. During the past decade, the major thrust of SSI research has been targeted to the understanding of pile-supported structures to seismic waves. This has been driven primarily by the increased concern about the seismic vulnerability of bridges and bridge foundations.

This session of the conference provides an opportunity to learn of the recent developments in the field of soil-structure interaction under seismic loads. A total of 32 papers were submitted to this session. The papers were categorized into the following three general topic areas, one of which has two sub-areas.

1.	**Case Histories**	12 papers
2.	**Analytical Studies**	
	a) Shallow Foundations	7 papers
	b) Deep Foundations	9 papers
3.	**Experimental Investigations**	4 papers

This general report presents summaries of each of the 32 papers submitted to this session. The report ends with a list of issues that are raised with the intent of stimulating discussions during the soil-structure interaction session of the conference.

1. Case Histories

Twelve papers describe applications of SSI analysis to real projects. Strictly speaking, most of these examples are not case histories in the sense that they provide field measured performance data that demonstrate the effect of soil-structure interaction under dynamic loads. The examples describe the application of SSI analysis in the evaluation of the dynamic response of structures.

Amin, Joshi, and **Bhatt**. *"Structure Soil Structure Interaction Effects: Seismic Analysis of Safety Related Collocated Concrete Structures"*. The authors describe an investigation of the potential effects of structure-soil-structure interaction (SSSI) at the Savannah River Site of the U.S. Department of Energy. Three adjacent buildings were modeled and analyzed in three dimensions using the computer programs SASSI and ABAQUES. Two of the buildings (Process and Purification) were very large structures. The third building (Stack building) was a much smaller structure. SSSI as well as SSI of the individual buildings were performed and the peak accelerations, seismic loads, and floor spectra were computed and compared. The results indicated that SSSI effect between the two large structures (Process and Purification buildings) was not significant. There was some observable effect of SSSI between the large Process building and the smaller Stack building, however, only when the input earthquake motion was in the east-west direction. The forces at the base of the Stack building were slightly larger due to SSSI effect.

Han, *"Dynamic Soil-Pile-Structure Interaction"*. The author describes SSI analysis performed for a large structure supporting the largest compressor train in North America. The compressor table-top structure is founded on piles. The superstructure was modeled using finite elements, and springs and dashpots represented the soil-pile interaction. The foundation stiffness and damping coefficients were computed using DYNAN and DYNA4 programs. The SSI analysis of the system was performed using the computer program SAP2000. To evaluate the effect of foundation flexibility on the superstructure response, the SSI analysis was performed for two cases: fixed base, and flexible base with the pile foundation. In the example analysis, the peak amplitude of the vertical response of the structure on fixed base was about five times that of the flexible base structure. However, there was little difference in the horizontal responses of the fixed base and flexible based structures.

Tanaka, *"Dynamic SSI Analyses Considering Anisotropy of the Foundation Gravelly Layer in Hualien, Taiwan"*. The author describes the use of orthotropic elastic body model to represent the anisotropic behavior of gravelly soils in SSI analysis. The Hualien Large-Scale Seismic Test Program, in Taiwan, included measurement of shear wave velocities using the downhole and crosshole tests. These measured velocity values, (5m below ground surface in a gravelly layer), showed significant scatter. Shear wave velocities were also computed using one-dimensional inversion analysis of recorded earthquake motions. The velocity values thus computed for the gravelly layer showed significant dependency on the azimuth of the record. Orthotropic elastic body model was used to describe the azimuth dependency of the shear wave velocity of the gravelly soil. This model was used to analyze the SSI response of a ¼ scale building model that was subjected to a forced vibration test. The analysis was performed using the computer program ABAQUES. The results from the force vibration tests compared well with those computed from the SSI analysis using the orthotropic elastic body model. However, the observed response of the building model to an actual earthquake did not compare well with those computed analytically. This was attributed to the effect of soil non-linearity.

Zhou, Hu, and **Chi**, *"Seismic Analysis of Tunnel Surrounded by Soft Soil in Shanghai"*. The authors present results of finite element analyses of a tunnel in Shanghai. Two cross sections were analyzed, one in soft clay the other in sand. The paper briefly describes a constitutive model that provides residual pore water pressures and strains. Results from the analyses are presented with little discussion. The paper lists observations made from the analytical results.

Cubrinovski, Ishihara, and **Kijima**, *"Effects of Liquefaction on Seismic Response of Storage Tank on Pile Foundations"*. The authors describe their analysis of the seismic response of a storage tank that is located on the man-made island of Mikagehama, Japan. The tank experienced the 1995 Kobe earthquake with some damage to its pile foundation. The tank is founded on 23 m long and 45 cm in diameter concrete hallow piles. The soil profile consists of 13.6 m deposit of reclaimed gravelly soil overlying silty sands. Prior to the earthquake, to improve the site, sand compaction piles were driven around the tank foundation to a depth of 15 m. During the 1995 Kobe earthquake, there was extensive liquefaction and liquefaction-induced damage to pile foundations. The authors utilized this storage tank case history to investigate the effect of liquefaction and site improvement on the performance of the pile foundation of the storage tank. To analyze the soil-pile-tank system, a 2-D finite element model was prepared in which a fully coupled effective stress constitutive model was used to characterize the soil behavior. To evaluate the effectiveness of the soil improvement, the analysis was performed for both improved and unimproved site conditions. The results of the analyses led to the conclusion that because of ground improvement the ground deformations within the foundation, and hence, the displacements and bending moments of the piles were significantly reduced. The analysis described did not include the potential effect of liquefaction-induced lateral deformation on the foundation piles.

Luo and **Murono**, *"Seismic Analysis of Pile Foundations Damaged in January 17, 1995 South Hyogo Earthquake by Using the Seismic Deformation Method"*. The authors describe their analysis of the response of a 2x2 cast-in-place pile group to the 1995 South-Hyogo earthquake. Using a borehole camera, cracks in the piles were detected. Analytical investigations were performed to determine the adequacy of the Seismic Deformation Method (SDM) in predicted the observed pile damage. The procedure allows the inclusion of both the inertial and kinematic effects on the piles. The soil-pile system is represented though foundation springs, and the superstructure is modeled with lumped masses and springs. Using the acceleration record of Kobe University, the shear forces and bending moments in the piles were computed due to the inertial forces and ground deformations. The predicted damage to the piles and their locations along the piles matched well with those observed after the earthquake. The authors conclude that the Seismic Deformation Method is capable to predict the response of pile foundation to seismically induced ground deformations and inertial loads.

Yang, Dobry, and **Peck**, *"Foundation-Soil-inclusion Interaction Modeling for Rion-Antirion Bridge Seismic Analysis"*. The authors describe a very interesting bridge pier-foundation-soil interaction analysis. The planned Rion-Antirion Bridge in Greece will be the longest cable-stayed bridge in the world. The bridge design faces a number of challenges including high seismicity, large impact and wind loads, and a deep soil deposit of soft clay, silt, and sand. An innovative design for the foundation of the piers has been adopted in which the 90m diameter piers of the bridge will rest on a gravel ballast layer placed over the natural soil that will be reinforced with open-ended steel pipe piles referred to as inclusions. The paper describes a set of soil-structure interaction analyses of the foundation performed to validate the design. Two and three-dimensional nonlinear finite element analyses of the pier foundation were performed using the program ABAQUS. The predicted failure mechanisms were compared with observations made in centrifuge model tests and sliding tests conducted in the filed. The paper presents impressive figures of the models used and the failure mechanisms observed from the numerical analyses. The results from the various soil-structure analyses validated the base isolation effect of the gravel ballast layer, the soil reinforcing effect of the inclusions, and the adequacy of the innovative foundation design of the bridge.

Uzuoka, Kubo, Yashima, and **Zhang**, *"Numerical Study on 3-Dimensional Behavior of a Damaged Pile Foundation During the 1995 Hyogo-ken Nanbu Earthquake".* The authors present results of their investigation of the failure of the pile foundation of a building during the Hyogo-ken earthquake of 1995. The piles of the foundation of the five-story building were damaged resulting in the titling and settlement of the building. The piles were embedded in reclaimed land that experienced liquefaction-induced lateral deformations during the earthquake. Three dimensional effective stress analyses of the soil-pile-building model were performed to explain the damage to the piles and the direction of tilt of the building. The numerical model was first verified by comparing the computed free-field ground surface motions with those recorded nearby in a borehole array. The results of the 3-D effective stress analysis of the soil-pile-building model showed that the direction of the building tilt was associated with the failure directions of the piles.

Wartman, Vahdani, and **Liang**, *"Seismic Soil Structure Interaction Analyses of an Office Building in Oakland California".* The authors describe a SSI analysis of a 10-story building with three basement floors, located in Oakland, California. The purpose of the investigation was to evaluate the potential SSI effects on the response of the building, and to develop seismic input motions at the base of the building. The paper includes descriptions of two-dimensional models that were developed for the SSI analysis. Using various ground motion records, the computer program FLUSH was utilized to compute the motions at the base of the building (at ground level). The effect of SSI was evaluated by computing the ratio of the acceleration response spectrum of the motion at the base of the building and that of the free field ground surface motion. In the horizontal direction, for periods less than 0.25 sec, the motions at the base of the structure had spectral values of up to 35 % higher than the corresponding spectral values of the free field motions. In the period range of the building (1.8 sec) there was no discernable effect of SSI. In the vertical direction, SSI effects were negligible for all periods.

Takemiya, Shimabuku, Katayama, Kishida, and **Furukawa**, *" Nonlinear Response of Underground Duct Structures with due Attention to Seismic Input Ground Motions".* The authors present nonlinear 2-D finite element analysis of the seismic response of an underground structure. The maximum horizontal accelerations, shear stresses, and shear strains were computed and their intensities indicated on the mesh. It was observed that the presence of the underground structure influenced the dynamic motions and stresses within a zone of soil equal to twice the dimensions of the structure. The maximum internal structural forces occurred typically at the corners. The results from the 2-D finite element analysis were compared with those obtained from the soil deformation method in which the seismic load on the structure was induced by prescribed soil deformations computed from 1-D wave propagation analysis. The 2-D analysis yielded smaller structural forces than the soil deformation method.

Chang, Ketchum, Mok, Settgast, Wang, Waggoner, Gonnermann, and **Chin**, *"Dynamic Soil-Foundation-Structure Interaction Analyses of Large Caissons".* The authors describe a series of dynamic analyses of a bridge caisson subjected to 0.6g peak horizontal acceleration at rock outcrop. The example caisson analyzed is that of Pier W3 of the west spans of the San Francisco-Oakland Bay Bridge. The cellular concrete caisson (38.7m x 22.9m in plan) is in 33m of water and is embedded in 34m of soil. The primary purpose of the investigation was to evaluate the effects of soil yielding, gapping, slippage, caisson sliding and uplift on the seismic response of the caisson. Initially, 2-D and 3-D finite element analyses were performed using SASSI and equivalent linear soil properties. The results indicated that the 2-D model compared with the 3-D model yielded similar caisson responses. Also, the analyses showed that under the input seismic motions, the dynamic stresses along the caisson-soil side and base interfaces exceeded the static stresses, thus indicating potential gapping and uplift. To determine the effect of such gapping and uplift on the dynamic response of the caisson, 2-D linear and nonlinear analyses were performed using FLAC. In the nonlinear analyses, the soil-caisson model included interfaces to allow gapping, and sliding along the side and base of the caisson. The computed accelerations and caisson shear and moments from the 2-D FLAC linear analyses compared well with those obtained from the 2-D SASSI equivalent linear analyses, thus validating the FLAC model. The results from the 2-D FLAC nonlinear analyses showed that allowing soil gapping and caisson sliding and uplift could result in significant reduction in the motions of the caisson and in the caisson shear stresses and bending moments. However, gapping, sliding and uplift had relatively little effect on the frequency characteristics of the caisson.

Fallah, *"Assessment of the Foundation of a Near Shore Power Plant Under Earthquake Loading"*. The author describes stability analyses of a power plant located in the south of Iran. First, liquefaction analyses of the foundation soils were performed following the empirical approach commonly used in practice. Then, pseudo-static stability analysis was made of the power plant and its foundation soil profile using two-levels of horizontal seismic coefficients. Finally, a finite element analysis of a model of the power plan and its foundation was made to compute the dynamic shear stresses induced by the earthquake motion. The author concludes that the plant is stable under the design earthquake load.

2. Analytical Studies

a) Shallow Foundations

Seven papers describe analytical and numerical modeling of footings and underground structures. Specifically: 1 paper deals with soil constitutive relations, 1 paper analyzes seismic response of tunnels; 1 paper derives absorbing boundaries for FE applications, 1 paper is on pavement dynamics, and 3 papers analyze seismic response of footings.

Wagner and **Meskouris** investigate the inelastic behavior of bulk material in silos, in their paper *"Granular Material Behavior under Dynamic Excitation"*. Four different models are described the authors: (1) classical hypoplasticity theory, (2-3) two variations of hypoplasticity theory based on time history analysis, and (4) an integranular strain approach. In addition, an interface element based on Mohr-Coulomb law to simulate the interaction between silo shell and soil is described. The models are evaluated using cyclic odeometer and triaxial tests. The authors report that hypoplasticity theory modified by the energy criterion and the integranular strain approach (i.e., models 3 and 4) model adequately the cyclic soil behavior observed in the tests. It is shown that in the hypoplastic models more strain is accumulated than in the intergranular strain model. A comparison with experimental results by Schultz (1982) --- a German reference, for silo-soil interaction is presented. The silo of the experiments is 6 meters tall and 0.69 meters wide, containing sand with void ratio of 0.72 and unit weight of 15 kN/m^3. No additional information on the experimental setup is provided by the authors. A graph showing horizontal soil pressure distribution along the silo walls is provided. Theory and experiment appear to match reasonably well. In their paper, entitled *"Simplified Evaluation for Dynamic Layered Soils-Structure Interaction"*, **Zhang** and **Zhang**, present a simplified procedure for determining SSI effects in embedded structures in layered media. The method is based on 1-dimensional wave propagation to analyze soil response to vertically-propagating seismic waves in conjunction with subgrade reaction theory for soil-structure interaction. A solution to the governing equations using modal superposition and convolution integrals is presented following the procedure suggested by Sarma (1994). To this end, uniform damping for all soil layers is considered. The subgrade reaction coefficients are derived based on the solution by Zhang et al (1998) which was developed for retaining walls and plane strain conditions. Results are presented for 5 different cases involving layered soil profiles. Distributions with depth of soil accelerations and lateral soil-structure contact pressures are presented. Although no all SSI effects (e.g., radiation damping) can be modeled with this approach, the results presented by the authors are valuable.

Gomes, Oliveira and **Correia**, present an analytical finite-element study of tunnel response to earthquake loading entitled *"Seismic Response Assessment of Underground Structure Cross-Sections Using Response Spectra"*. To this end a plane-strain finite-element model of a tunnel cross section and the surrounding soil is developed. The system is subjected to vertically propagating seismic shear waves expressed though a rock response spectrum. The parameters studied by the Authors are: tunnel diameter D = 10 m, tunnel centerline depth H = 15 m, tunnel Young's Modulus E_c = 29000 MPa, and Poisson's ratio $_c$ = 0.25. A wide range of ground Young's moduli varying from 1 MPa, corresponding to soft soils, to 10000 Mpa, corresponding hard rock, are studied. The geostatic stress computation consider a soil unit weight of 19 kN/m^3, and a lateral earth pressure coefficient K_o = 0.5. A constant response spectrum with spectral acceleration of 0.5g was adopted. To assess the effects of SSI on the tunnel response, the following dimensionless parameters were utilized: (1) the standard flexibility index F (Einstein & Schwartz, 1979); (2) a dimensionless bending moment coefficient expressing the ratio of the maximum moment in the tunnel cross section to the maximum geostatic moment; (3) a corresponding axial force coefficient. Results from the parameter studies indicate that: (i) only the first two vibrational modes contribute to tunnel distress; (ii) tunnel soil-interaction tends to increase with increasing values of soil Poisson's ratio; (iii) dimensionless bending moments grow higher for higher tunnel thickness to diameter ratios, while dimensionless axial forces remain practically constant; (iv) Bending moments increase as K_o values deviate from unity; (v) for seismic loads, supports with wall thickness to radious ratios t/R = 0.25 can be considered flexible and no significant bending moments are developed. In the second part of the paper, four representative cases are analyzed with the supporting material ranging from soft soil to hard rock. It is reported that, unlike geostatic conditions where peak stresses occur at the crown, under seismic conditions maximum stresses occur close to 45 degrees from vertical. Additional analyses using strain-compatible soil properties show that peak moments are practically independent of strain level, while peak axial forces somewhat decrease with increasing soil strain.

Ismail and **Mullen** present an interesting study on computational aspects of SSI, entitled *"Computational Simulation procedure for Soil-Structure Interaction Modeling in Building Seismic Damage Response"*. The study focus on infinite elements as transmitting boundary conditions, nonlinear soil material response, and contact surfaces at the soil-foundation interface. In the first part of the paper, the authors study comparatively the performance of dashpots and infinite elements as transmitting boundaries for wave-propagation problems in 1-D, 2-D, and 3-D environments. Results indicate that: (i) in 1-D conditions, infinite elements and dashpots produce more or less the same response to an externally applied pulse; (ii) under 3-D axisymmetric conditions (Lamb problem), infinite elements reproduce the exact solution to the problem up to a radius equal to 1.7 times the far-field radius. The importance of soil/structure interface modeling is examined in the second part of the paper. The Master and Slave sub-models available in ABAQUS are briefly discussed. As an application, a spread footing representing the foundation of a building is modeled considering the master sub-model for the soil and the slave sub model for the footing. Infinite elements are used and nonlinear soil response is modeled using the cap model of ABAQUS. Results from the analysis showed that nonlinear soil response is concentrated at the interface between soil and footing. The third part of the paper presents FE modeling of a building-soil system with reference to a three-story office building located in North Mississippi. The soil under the building consists of three layers of total thickness of 100 ft and average shear wave velocity of about 900 ft/s. The mesh incorporates the main building (modeled using beam and slab elements), the foundation (modeled as a single footing), and the soil. To model radiation effects, infinite elements are placed at 450ft (1.7 r_f) from the structure. The total size of the mesh is about 11,000 elements. An alternative analysis using simple SSI springs according to NEHRP provisions is employed for comparison. Results from eigenvalue analyses indicate relatively minor changes in the first three natural periods due to SSI. The FE results show more SSI than the linear spring analysis.

Rabah and **Nadir** present an application of the Barkan Method to analyze the vibrations of a rigid surface footing. The study shows that the old Barkan method, although now largely superseded, is still being used by engineers.

In a very interesting paper, entitled *"An Effective Absorbing Boundary for 3D FEM Time Domain Analyses"*, **Kellezi** and **Takemiya** present a simple procedure for deriving wave transmitting boundaries for 3-D elastodynamic analyses of infinite media. A historical review is first presented and difficulties associated with deriving such boundaries are discussed. It is pointed out that while the rigorous boundary condition at the ends of the mesh is global in space and time and is described by integro-differential equations, it is possible to formulate the boundary conditions using approximate differential operators which are local in space and time. On the basis of the decay of waves with depth under an impulsive load acting on the surface of a homogeneous half-space a radiation criterion is formulated using a bunch of cone models. It is shown that frequency-independent springs and dashpots can be derived for both body and surface waves traveling away from the foundation. Criteria for the distance of the absorbing boundary are discussed. A parameter study is then performed involving a Hammer pulse load on a homogeneous halfspace, modeled with 1000 8-node cubic FE's. The boundaries of the model are placed at a distance 1.1 times the wavelength of S waves in the medium. It is demonstrated that the proposed boundary condition performs better than previous absorption devices (e.g, Dirichlet boundary, Tensor impedance, Extended boundary etc.) It is concluded that the formulation provides sufficient accuracy when the boundary is placed at least 1 to 1.5 wavelengths from the source of vibrations.

Wang, Ji, and **Luan** present a simplified analytical method for wave propagation in layered media, entitled *"A Simplified Method of Vibration Analysis of Layered Foundation and Applications in Pavement Parameter Identification"*. The paper considers a multi-layered viscoelastic medium subjected to a surface harmonic load uniformly distributed over a rectangular area. The lateral boundaries of the medium are placed sufficiently far away from the load, so that box effects are small. The solution scheme proposed by the authors involves a

Fourier series expansion in conjunction with a spline function representation of the displacement components in the medium. Because of the orthogonality of Fourier series, the terms of the expansion can be uncoupled and each one can be determined separately. An identification scheme is then proposed for determining the modulus and damping ratio of each layer, to be used in conjunction with Falling Weight Deflectometer (FWD) testing for pavements. The method is implements by minimizing a relative error function that quantifies the difference between the computed compliance function of the system and the experimentally-derived compliance function. In view of the ill-conditioned matrices that can be generated by the method, the singular value decomposition technique is implemented to solve the resulting equations. A numerical study is then presented involving five different layered media. Results indicate: that: (i) compared to earlier solutions the proposed method can predict surface deflections or compliance functions with a favorably-acceptable accuracy; (b) the non-homogeneity of subsoil has a considerable influence on dynamic response; (c) material damping in the soil is an important factor in governing the dynamic response of the system.

b) Deep Foundations

Nine papers describe applications of SSI analysis to deep foundations including lateral response of single piles, pile groups, and drilled shafts. Analysis approaches include beam on elastic foundation theory, finite element, and mixed finite element-boundary element numerical simulation. Emphasis varies with some papers focusing on nonlinear response of the piles or shafts using fiber models of the cross-sections subject to both static and dynamic loads, while others focus on nonlinear response of the soil subject to dynamic load. Five of the papers are restricted to frequency-dependent elastic response. Many include comparisons to experimental results from load tests. It is clear to the reporter that there is no consensus on the best way to approach the seismic response problem of deep foundations, yet each approach appears to have some merits for the applications considered, many of which are shown to predict test results well

Ashour, Norris, and **Shamsabadi**, *"Effect of the Non-Linear Behavior of Pile Material on the Response of Laterally Loaded Piles."* P-Y curves are generated numerically using nonlinear fiber cross-section beam models of a steel pipe pile and a reinforced concrete drilled shaft. A strain wedge approach is used to develop the nonlinear soil resistance in a beam on elastic foundation representation of the pile-soil system. The authors demonstrate the importance of incorporating the local softening of the effective EI along the length. Comparisons with lateral load tests in Houston and Memphis appear to substantiate their approach. Neither cyclic nor dynamic response is considered in this paper.

Ashour, Pilling, and **Norris**, *"Assessment of Pile Group Response under Lateral Load Interaction".* P-Y curves are generated in a manner similar to that described in the previous paper. In this case, however, pile group interference is modeled using the strain wedge approach. No mention is made of nonlinear modeling of the pipe piles. Comparisons with full scale single and group pile results highlight the interference effects and appear to substantiate their approach. While applications to seismic response of highway bridge foundations are envisioned, no mention is made of cyclic or dynamic response.

Cairo, Conte, and **Dente**, *"Simplified Methods for the Dynamic Analysis of Single Pile in Layered Soils".* Two simplified methods for determining the impedance functions for a single pile in layered soils are presented and compared relative to results of more detailed or computationally intensive approaches. The first makes use of previously derived discrete layer stiffness matrices for the pile-soil system, while the second uses a cone model approach. Results are restricted to harmonic axial loading.

Mylonakis and **Roumbas**, *"Lateral Impedance of Single Piles in Inhomogeneous Soil".* The authors present rigorous results for determining the impedance functions for the beam on elastic foundation representation of a single pile-soil system, where the soil is idealized with a Young's modulus that increases with depth according to a power law. An equivalent homogeneous soil for the halfspace is formulated and used to demonstrate the sensitivity of the dynamic stiffness coefficients in a swaying mode of vibration to the degree of inhomogeneity, whereas the rocking mode appears to be insensitive. Sensitivity of the damping ratios is also shown to be significant for both vibrational modes, but the variations are not sensitive to the relative pile/soil stiffness.

Koo, Chau, Yang, Wong, and **Lam**, *"A Continuum Model for Soil-Pile-Structure Interactions under Earthquake Excitation".* Dynamic amplification factors are developed for footing level elastic response of an idealized beam representation of a coupled soil-pile-building system to harmonic SH-type transverse shaking. The pile group considered has 3 piles in the transverse direction and no effect of the piles along the longitudinal direction is considered. An infinite Fourier series representation of responses is assumed for the transverse displacement and shear force at each pile as well as for the building shear force, considering all necessary boundary and compatibility conditions of the partitioned continuum. The coupling of building and foundation is made through an assumed rigid pile cap. Application of the approach is made to a 30-story building in Hong Kong designed for wind. Analysis using a 40 m deep soil layer shows a shift of the fundamental coupled system response to that of the free field response, which is nearest to the second transverse fixed base building mode. Also, the coupled system response is noticeably amplified relative to that of the free field. A parameter study for a 20-story building shows that response at the footing level increases with building stiffness, contrary to assumptions of conventional wind-based design.

Fischer, Maurial, Meskouris, Konke, and **Schube**, *"Design Concept for High Speed Railway Bridges in Regions with High Seismic Activity and Soft Soil"*. Design studies for a high-speed railway viaduct in Taiwan are presented, which are aimed at demonstrating suitability of a four-column, pile-supported pier concept in meeting two competing requirements: 1) sufficient ductility to resist damaging severe earthquakes without collapse and 2) sufficient stiffness to keep rail compressive stresses within acceptable limits under moderate earthquakes and normal operating conditions. Eigenvalue, linear response spectrum, and both linear and nonlinear time history analyses are performed on a finite element model of an isolated pier under transverse loading. Material nonlinear response in the reinforced concrete columns is obtained using a fiber model of the cross-sections. All piles are modeled using linear discrete springs. Linear time history analysis of the longitudinal response of the 11-span system of piers and simply supported, prestressed concrete girders is also performed to evaluate longitudinal response under seismic excitation for comparison with static analysis of braking and thermal expansion.

Maheshwari, Truman, and **Gould**, *"Effect of Plasticity of Soil on Seismic Response of Pile Foundation: Parametric Study"*. A finite element model of a single end bearing pile resting on bedrock and inserted in a finite volume of soil. 3D continuum elements are used for both soil and pile, and the soil is modeled using linear elastic and nonlinear plasticity constitutive laws. The pile is modeled as linear elastic. No consideration is given of the loading in the pile, the presence of the supported structure, or of radiation damping. Analyses of harmonic SH wave propagation from the bedrock elevation using direct integration in the time domain show the influence of the pile rigidity on the reduction of free field response at the pile head elevation. Results are reported to compare favorably with results in the literature for similar idealized conditions, but no direct comparisons are presented.

Kim, Lim, Kim, and **Cho**, *"Soil-Pile Interaction Analysis using FE-BE Coupling in Frequency Domain"*. Frequency domain analysis of linear elastic response of a single pile is performed using finite elements for the pile and near field soil and boundary elements for the far field (radiation damping). The model includes a mass, which rests on top of the pile. The mass is subjected to harmonic loading. A half-plane is considered for the soil with multiple layers under plane strain conditions. Linear elastic springs are used to account for loss of contact at the soil-pile interface. Results compare reasonably well with experiments using a shaker mounted on the mass and with analysis results in the literature, especially a case where perfect bonding is relaxed through a weak zone. The verified model is used to study the influence of the mass at the pile head and the slenderness of the pile, showing a tendency of increasing response amplitude and slightly decreasing fundamental frequency with increasing mass and a tendency of decreasing amplitude and dramatically increasing fundamental frequency with increasing slenderness.

Prakash and **Jadi**, *"Prediction of Lateral Dynamic Response of Single Piles Embedded in Fine Soils"*. A correction is discussed that demonstrates improvements in available theoretical predictions of lateral dynamic response of single piles in fine soils. The procedure involves arbitrarily reducing the in-situ shear modulus and three radiation damping constants such that resonant amplitudes obtained from field tests agree to some tolerance. A curve-fitted empirical relation is established between the reduction factors, which exhibit significant scatter, and the estimated shear strain at the predicted peak amplitude. The empirical relations are then used to predict response for both the original data set and a new data set. The original data set corresponds to 14 and 12.5-inch diameter steel pipe test piles in southeast Michigan. Validity was established with respect to 10.75-inch diameter concrete-filled pipe piles in high plastic clays in Houston, Texas, as well as a test performed reported by Novak and Grigg on a small pile embedded in a very fine silty sand layer. More work is recommended to further validate and refine the procedure especially using full-scale test data and to extend the procedure to pile groups.

3. Experimental Investigations

Four papers describe the results of experiments carried out to study foundation stiffness, earth pressure acting on embedded footings, p-y characteristics of pile foundations during shaking, and ground deformation or bearing capacity of a surface foundation.

Massimino, Maugeri, and **Novita,** *"Experimental, Theoretical, and Numerical Evaluation of the Stiffnesses of a Soil-Foundation Model by Shaking-Table Test".* The authors carried out some tests of a sand-shallow foundation in a six-degree-of-freedom shaking table to study the behavior of a plane-strain footing under both static and dynamic (quasi-harmonic excitation with two levels of amplitudes). The test set-up included a foundation block (0.4 m high, 0.4 m wide and 0.95 m long) with a weight of 4.2 kN embedded to a depth of 0.1 m, a super-structure consisting of three steel plates with a total weight of 30 kN, and a 1-m thick sand layer having a relative density of 48.5 %. The response of the footing was monitored by accelerometers and displacement transducers. The objective of the experiment is to compare the vertical settlement and vertical stiffness of the foundation under the static load with the results of the finite element analysis, and the horizontal displacement and stiffness and rotation and rocking stiffness under the dynamic excitation with values estimated by the theoretical solution and numerical calculations based on the push-over finite element analysis (not dynamic analysis). The authors concluded that the theoretical solutions of impedance functions provided reasonable estimates of stiffness if the loading conditions were such that no significant soil nonlinearity occurred. At a higher level of dynamic excitation in which soil nonlinearity became significant, the results of the push-over static nonlinear finite element analysis were in reasonable agreement with the experimental results.

Tamura, Miyazaki, Fujii, Tsuchiya, and **Tokimatsu,** *"Earth Pressure Acting on Embedded Footing during Soil Liquefaction by Large-Scale Shaking Table Test".* The authors performed a series of shaking table tests using a large-scale laminar shear box (6 m high, 12 m long, and 3.5 m wide) to study the effects of non-liquefied crust overlying liquefied soils on an embedded footing. The structure was founded on a footing which was supported by 2x2 steel piles. The test parameters varied in the tests included (1) models of two super-structures having different natural frequencies (Models B-S and B-L); and (2) a surface footing and an embedded footing having a depth of embedment of 0.5 m. The authors did not provide the size of the footing. However, based on the drawing on Fig. 1, it appears that the footing was 2.5 m x 2.5 m supported by steel piles. The pile tips were connected to the bottom of the laminar box by hinges and the pile heads were rigidly connected to the footing. The soil model consisted of a 1.5 m thick layer of gravel at the bottom of the box, overlain by a 4 m thick layer of saturated sand. The authors did not provide the relative density of the sand. On top of the saturated sand layer, there is a 0.5 m thick layer of unsaturated sand to the top of the simulated ground surface. The water table was at the 0.5 m depth below the ground surface.

The models were excited by an acceleration time history having a peak acceleration of 240 cm/s^2 and a duration of 30 seconds. The responses, including lateral earth pressures acting on the embedded footing, pore water pressures at 12 levels throughout the soil profile, induced strains at the pile heads, acceleration time histories of the super-structure and the ground surface were recorded during the tests. However, the authors did not described their instrumentation for the tests. The authors indicated that the soil model had a fundamental frequency of about 5 Hz and the super-structures had a natural frequency of 5.4 and 1.3 Hz, respectively, for Models B-S and B-L.

Based on the test results, the authors presented the following conclusions: (1) Before the onset of liquefaction the total earth pressure acting on the footing was induced mainly by the inertial force of the super-structure. The total earth pressure tends to be out of phase by 180 degrees with the inertial force of the super-structure. (2) The total earth pressure after liquefaction was induced mainly by the soil deformation. After liquefaction, the total earth pressure appeared to be in phase with the inertial force of the super-structure. The shear force at the pile heads is the sum of the total earth pressure and the inertial force. (3) The relation between the relative displacement (between the free-field ground surface and the footing) and the total earth pressure is linear before any significant pore water pressure development. The relation becomes nonlinear after substantial development of pore water pressure in the profile. The total earth pressure decreased with cyclic loading after liquefaction. (4) The peak value of the total earth pressure on the model with the low-frequency (i.e., 1.3 Hz) super-structure was larger than that on the model with the high-frequency super-structure (i.e., 5.4 Hz).

Tokimatsu, Suzuki, and **Suzuki,** *"Back-Calculated p-y Relation of Liquefied Soils from Large Shaking Table Tests".* The authors performed a series of shaking table tests using a large-scale laminar box (6 m high, 12 m long and 3.5 m wide). The test series included soil-pile-structure systems having various conditions including (1) two levels of shaking, (2) one surface footing and one embedded footing supported by a 2x2 pile group, (3) without a superstructure and with a superstructure having two different periods (0.2 and 0.8 seconds), and (4) three different densities of sand (i.e., loose, medium dense and dense). The objective of the tests was to evaluate p-y relationships (i.e., coefficient of subgrade reaction) as functions of pore water pressure, relative displacement between pile and free-field soil, and soil density. The results indicate that (1) the coefficient of subgrade reaction generally decreases linearly with an increase in pore pressure or a decrease in effective stress, (2) the coefficient of subgrade reaction decreases with an increase in relative displacement, and (3) the reduction in the coefficient of subgrade reaction with an increase in relative displacement is larger for a loose sand than for a dense sand.

Miyaura, Miura, Kawamura, and **Yokohama,** *"Lateral Flow Deformation Evaluation of Ground-Structure System under Various Cyclic Loading Conditions".* The authors performed a series of model tests of a footing founded on sand. The tests were conducted using a two-dimensional plane strain soil box (2 m long, 0.7 m deep, and 0.6 m wide). Test parameters included two different widths of the footing (B = 0.1 and 0.2 m), two relative densities of sand (50 and 80%), static and cyclic loading of a vertical load applied at the top of the footing with five different values of off-set or eccentricity from the centerline of the footing (e/B = 0, 0.15, 0.3, 0.4 and 0.5), and a loading condition simulating wave loading. The objective of the experiment was to evaluate soil deformation beneath the footing as functions of footing width, soil density, eccentricity of the applied load, vertical settlement, and vertical stress applied to the footing. The results indicated that (1) the bearing capacity of the footing decreases with an increase in eccentricity ratio (e/B), (2) lateral flow of sand is a function of settlement, and (3) soil volume ratio (ratio of the volume of lateral soil flow to the volume of vertical soil settlement) can be used to relate to the phenomenon of the bearing capacity failure of a footing.

SUMMARY

The papers presented in this session of the conference describe a wide variety of applications of dynamic SSI in geotechnical engineering practice. Not surprisingly, with the worldwide concern about seismic vulnerability of civil infrastructure, most of the papers focus on SSI effects under seismic loads. Only a few papers describe dynamic response of machine foundations.

From the papers, it is evident that during the past decade impressive advancements have been made in this evolving SSI field. Clearly, there is increased emphasis on improving our understanding of the performance of pile foundations under seismic loads. As more field observations are recorded, analytical tools are being developed and validated. Such developments are bound to improve the current practice of incorporating SSI in the seismic analysis of pile-supported important structures, such as bridges.

ISSUES FOR DISCUSSION

The following questions are raised with the intent of stimulating discussions during this session of the conference.

1. In what situations SSI effects are beneficial or detrimental?
2. How should analytical models and computer programs that are being developed for SSI analysis be validated and made accessible to the practitioners?
3. Typically, SSI analyses reported in geotechnical earthquake engineering literature are more soil-foundation interaction analyses without including the superstructure. What are the effects of the superstructure on the overall soil-foundation-structure interaction response? What are the potential effects of superstructure nonlinearity in SSI analysis?
4. What is an appropriate analysis procedure to account for soil-pile-structure interaction for various types of piled foundations (small piles versus large diameter piles)? Is use of static p-y curves in dynamic analysis of piled foundations appropriate for large-diameter piles (i.e., <2 m diameter drilled shafts)? How can kinematic interaction be accounted for in the dynamic analysis of a piled foundation? Is the kinematic interaction important in affecting the response of a piled foundation?