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General Report —Session V: Soil Structure Interaction Under Dynamic Loading

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General Report - Session V
Soil Structure Interaction Under Dynamic Loading

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For this presentation the papers of Session V are grouped into four subgroups. Most of these papers appear in Volume I of the Proceedings. The remainder of the papers will be published in Volume II.

1. Soil-Foundation Interaction

5.02 Lumped-Parameter Model and Nonlinear DSSI Analysis by M. Luau, G. Lin and W.F. Chen

The authors consider the seismic response of nonlinear shear-type structure supported on a rigid surface foundation (no embedment) resting on an elastic half-space. The calculations are performed in the time domain after the frequency-dependent horizontal (sway) and rocking impedance functions have been approximated by 2-DOF discrete systems characterized by eight lumped parameters. Three structures corresponding to an 8-DOF frame, a nuclear power plant containment shell and a 10-story building are subjected to three earthquake ground motions corresponding to the Tianjin Hospital record during the 1976 Tangshan earthquake, the N-S 1940 El Centro record and the Taft record. The response is calculated for a rigid soil and for soil characterized by shear wave velocities of 100, 200, and 400 m/sec. The authors find that the extent of the SSI effects depend on the properties of the structure, the characteristics of the soil and the nature of the ground motion. In particular, the frequency content of the ground motion has a pronounced effect on the interaction.

5.05 Dynamics of Rigid Foundations on Fluid-Saturated Soil by A.R. Khoee and A.M. Kaynia

The authors consider the steady-state harmonic response of a three-dimensional rigid foundation resting on fluid-supported soil. A boundary element approach based on formulating the basic field equations of poroelastodynamics in terms of the soil displacement and the fluid pressure is presented. Numerical results for the vertical, rocking and horizontal compliance functions for a rigid pervious square foundation bonded to the surface of a saturated half space are presented for different values of the coefficient of permeability. These results indicate that the compliance functions for a highly permeable saturated medium are similar to those for a dry medium. The authors have also found that a relatively impermeable medium behaves similarly to a dry medium with modified elastic properties. However, it would be of interest to compare the results obtained by the authors' (u-p) model with earlier results of Halpern and Christiano (1986), Gazetas and Petrakis (1987) and Philippacopoulos (1989), all based on Biot's (u-w) model.

5.07 Efficient Evaluation of Dynamic Impedance by G. Lin and Huai-hai Chen

The authors consider the problem of calculating the harmonic response of a layered viscoelastic half-plane subjected to a uniform distributed load acting on the surface of the half-plane. This two dimensional problem has been considered in the past by Dasgupta and Chopra (1979) and Xu and Mai (1987). In the present paper the response is obtained by the numerical integration of truncated integrals over wavenumber. The integration is performed in two intervals. In the first interval the integrand is dominated by plane waves and presents strong oscillations. In this range, a dense sampling of points is used. In the second range, the integrand is dominated by surface waves, exhibits less oscillations and can be calculated using sparser sampling. To avoid the well known problems with the Haskell-Thomson formulation used by the authors, the successive calculation of transfer matrices is stopped at certain layers. It would be desirable to have more complete quantitative comparisons illustrating the relative advantage of the approach as well as more detailed tests of the validity of the approach in a multilayered case.

5.14 Improved Soil-Spring Method for Soil-Structures Interaction - Vertical Excitation by A.H. Hadjian and H.T. Tang

The authors present an improved method to obtain the vertical response of a structure in the presence of SSI effects. The procedure is tested by application to the case of the Lotung 1/4-scale containment model for three recorded earthquakes. Detailed comparisons with recorded response and with calculations by other procedures illustrate the validity of this iterative approach. At the hands of the authors, the original soil-spring method is improved to include the frequency dependency of the impedance functions and the effects of layering and embedment of the foundation. These effects are introduced in the form of corrections based on rational approximations or an exact or numerical solutions for the response of foundations on the surface or embedded in uniform or layered half-space. The authors have been able to identify and determine these corrections and to incorporate them into an iterative approach which accounts for most of the interaction effects. The major advantage of the approach, beyond its relative simplicity, resides in the insights it offers as to the extent of the various components or aspects of the complete SSI problem.

5.36 Study of Seismic Base Isolation of Bridge Considering Soil Structure Interaction by S.K. Thakkar and R. Mahashwari

The authors consider the seismic response of a single span bridge in which the girder is isolated from the piers by use of elastomeric bearings. The SSI effects on the embedded portion of the substructure are modelled by use of soil springs. Parametric studies including variations in soil stiffness, input response spectrum, water level and embedment depth are conducted. The results seem to indicate that elastomeric bearings result in reductions of forces in the substructure but that the effectiveness of the isolation mechanism is more significant for hard sites. The results of the study are suggestive but could be strengthened by use of better models for the embedded portion of the substructure. The models should include not only the stiffness provided by the surrounding soil but also the modification of the ground motion by the embedded portion of the structure.

5.43 Dynamic Interaction of an Uplifted Beam with the Supporting Soil by M.A. Haroun and A.A. El-Zetny

The authors study the uplift of unanchored thin-walled liquid storage tanks during seismic excitation. The interaction with the soil is introduced by the use of Winkler type springs which work only in compression. The nonlinearities associated with base plate contact with the foundation are examined by the use of a one dimensional strip model.

5.49 Consistent Infinitesimal Finite-Element Cell Method: In-Plane Motion by J.P. Wolf and C. Song

The authors present an approach to obtain the unit impulse response matrix for an unbounded medium by consideration of a consistent infinitesimal finite-element cell. The infinitesimal finite-element cell method relies on a finite-element representation within the cell and on the use of similarity. The approach does not require the use of a fundamental solution satisfying the radiation condition at infinity and lends itself to consideration of anisotropic media. By taking the analytical limit, as the width of the cell tends to zero the discretization in the radial direction is eliminated and the discretization is reduced to that along structure-soil interface. The approach appears promising for cases in which the condition of geometrical similarity in the radial direction applies.

5.53 Seismic Behavior of a Diaphragm Wall Tank by C.M. Gilbert, A. Laforce and M.A. Boudement

The authors study the seismic response of a buried LNG tank. Two and three dimensional finite-element models of the tank and of the surrounding soil to calculate the response for a synthetic time history prescribed at the rock outcrop. The results including the variation of earth pressure with depth indicate that a prestressed concrete ring may be required on the upper part of the tank to control tensile stresses which would tend to separate the various panels of the diaphragm wall.

5.56 Effect of Soil Properties on Foundation Settlement under Earthquake Loading by M. Tehranizadeh

The author uses a direct finite-element approach to study the effects of SSI for a seven-story building resting on mat foundation. The soil was modelled as a layer resting on rigid soil. Records obtained during the 1977 Tabas earthquake were used as prescribed motion of the underlying rock. A parametric study varying the stiffness of the soil, the thickness of the foundation mat, the weight of the structure indicates that absolute and relative settlements decrease as the stiffness of the soil or the thickness of the mat is increased. The settlements appear to increase as the weight of the structure and the number of floors is increased.

2. Soil-Pile Interaction

It is of interest to note that all five papers reported herein attempt to address the rather complex nonlinear behavior of soils in the immediate vicinity of piles. Obviously, this is a critical issue for obtaining an adequate soil-pile response under large displacements. Many of the solutions divide the soil medium into two regions: a nonlinear annulus adjacent to the pile and the elastic far field.

5.18 Cyclic Mobility Effects on Soil-Pile Interaction in Dense Sand by F. Pelli, E.J. Parker, L. Conte and M. Bosoni

The authors present a methodology to evaluate the effect of earthquake-induced cyclic mobility in dense sand on the soil-pile interaction. The cyclic mobility effects on piles arise from seismic loading in free field conditions and pile-soil interaction loading in soil surrounding piles. The numerical modeling in this analysis for single pile consists of an annular disturbed soil zone surrounding the pile and an external zone. The cyclic mobility for the external zone is evaluated based on the interpretation of consolidated-undrained cyclic triaxial test results. Concerning the disturbed zone, the analysis result of the stress distribution in this zone is utilized. The proposed method was applied to the design of three submerged-floating tunnels in the Messina Straits, Italy.

Through analyses, the authors successfully derive the stiffness reduction factors for the soil and present the lateral load-pile cap displacement curve resulting from cyclic mobility. Furthermore, they indicate that even in dense sand the foundation stiffness reduction can occur during strong motion earthquake. Concerning the analysis approaches, they also argue that in dense sand an approach based on deformations, cyclic stress ratios and number of cycles is more appropriate and easily applicable for design.

5.39 Prediction of Non-linear Pile Foundation Response to Vertical Vibration by T. Nogami and H. Chen

The authors successfully derive a method to analyze the dynamic soil-pile interaction in the vertical vibration of a nonlinear pile foundation. Soil around the pile shaft is divided into the near field and the far field. The near field represents the soil in the close vicinity of the pile shaft, where strong nonlinearity is induced by large pile shaft displacement. The far field represents the soil outside the near field soil, and the far field soil is assumed to be located at a distance from the pile far enough to behave elastically. The analysis model is a dynamic Winkler soil-pile interaction model. The dynamic stiffness for the far field soil is evaluated by Nova's procedure. On the other hand, the dynamic stiffness of the near field soil consists of a frequency independent nonlinear complex spring and a consistent mass. The model parameters are determined from the elastic soil modules and the test results of the static complex unit load transfer curves.

The proposed method was analytically verified by using the FEW-BE modeling and good agreement between both methods are shown. Furthermore, the predicted responses calculated by the proposed method are compared with those observed in the vertical forced vibration test on an in-situ pile. through this comparison, the authors confirm that the proposed method leads to reasonable response of the nonlinear pile foundation.

5.45 Evaluation of Seismic Response of Pile-Supported Structures with a 3-D Nonlinear Approach by Y.X. Can, P.L. Gold and C.S. Desai

The authors analytically evaluate the seismic response of pile supported structures. The analysis model used in this paper is a three-dimensional finite element interactive subsystem model, which consists of two subsystems. One is the structure subsystem and the other is the foundation subsystem. The two subsystems are connected at the joints between the pile heads of the foundation and the column bases of structure. The structure subsystem is idealized as spatial frame elements. The foundation subsystem comprising piles and surrounding soils, is idealized as isoparametric hexahedral elements. In order to model the constitutive law of soils more precisely, the authors applied a plasticity model named d-version of the Hierarchical Single Surface modelling derived by Dr. Wathugala in 1993. The time domain earthquake response analyses were performed for a two-story reinforced concrete spatial frame with symmetrical configuration on an end-bearing pile foundation. Ground motions from the 1989 Loma Prieta earthquake were applied as the baserock horizontal input.

Based on the analysis results, the authors point out that the dynamic internal forces of the structures obtained by the 3-D nonlinear approach deviate significantly from those obtained by the rigid ground motion model and the structures are generally subjected to three-dimensional forces and couples, despite the type of bedrock seismic excitation and the configuration of structures.

5.46 Nonlinear Dynamic Impedance of Pile Group Foundation by K. Miura, K. Masuda, T. Maeda and T. Kobori

The authors describe a Green's function based formulation for the nonlinear impedance of pile groups and present a set of numerical results for the dynamic impedances and for the distribution of forces on the pile cap for both uniform and layered media. A nonlinear zone adjacent to the pile is modelled, and the rest of the soil medium is assumed linear. Separate finite-element static analyses show that the soil strains far from the pile are limited by the nonlinearity of the zone adjacent to the pile. Plain stress condition is shown to give slightly better results than a plain strain assumption. The influence of perimetral variation of nonlinearity is also included by subdividing the nonlinear annulus region into four 90 degree segments. Additionally, strain dependency of shear modules and damping effects are incorporated using an iterative convergence procedure.

A complete set of results for a single pile and 2x2, 4x4, 6x6, and 8x8 groups of piles provide significant insights into the nonlinear behavior of pile groups. For example, as the number of piles increases, the interaction effect is reduced and the piles start to vibrate nearly independently of each other as a direct result of soil nonlinearity adjacent to the piles. Also changes in load distribution from the elastic solution occur as a result of soil nonlinearity. The load distribution tends to become more uniform from the perimeter to the center of the pile group.

5.47 Seismic Response on Full-Size Pile Group by Y.C. Hand and G.C. W. Sabin

The seismic response of pile groups is investigated by both theory and experiment. Dynamic experiments were performed on a full-scale pile group, comprising six piles in-situ. The analyses were done by using the boundary zone model with non-reflective interface. In this model, soil consists of the boundary zone near the pile shaft and the outer zone. The nonlinearity of the soil is only induced in the boundary zone. To prevent the fictitious reflection of radiation wave emitted from the pile shaft at the interface between the boundary zone and the far zone, the authors assumed that the boundary zone has the medium properties with a continuous variation as the parabolic function into the outer zone and non-zero mass.

Generating harmonic excitations by a smaller exciter on the common pile cap of the six piles group, the linear forced vibration tests were performed and the amplitudes of horizontal and rocking vibrations were observed. Predicting the linear vibration of the pile group by the proposed boundary zone model and the non-boundary zone model, the proposed approach leads to better agreement with the measured results than the non-boundary zone model. After the smaller excitation tests, the nonlinear forced vibration tests were done by using a larger exciter. The excitation forces were changed at four levels and the nonlinearity of the pile group was observed in horizontal and rocking vibration. The boundary zone model predicts well the observed nonlinear behavior of the foundation. The effect of nonlinearity on the seismic response of pile group was also examined by the proposed model. Based on this investigation, the authors conclude that the nonlinearity of the soil-pile system substantially increases the seismic response of a pile group for both horizontal and rocking displacements.

3. Experimental Methods and Results

Experimental studies in SSI reported in this section cover a whole gamut of problems: full scale tests of piers, model tests of containment structures, shake table tests and several techniques to induce ground motions for in-situ dynamic testing. A classification of the papers is given in Table 1.

5.01 Soil Investigation and FVT Analysis in Hualien LSST SSI Research by T. Ueshima, K. Kudo, T. Kokusho, T. Okamoto and Y. Tanaka

The authors present results of forced vibration tests and numerical analyses conducted as part of the Large-Scale Seismic Test Program at Hualien, Taiwan. The research project involves construction of a 1/4 scale model of a nuclear reactor building in gravelly soils to study seismic effects on nuclear structures. After model construction and before backfill (i.e. no embedment), horizontal force vibration tests (FVT) were performed on the roof and basemat of the structure. Finite element method (FEM) analyses were carried out and the "blind prediction" results based on measured in-situ soil data were within 10% of the experimental results. Further analyses were performed by varying the soil parameters until the calculated frequency response matches the measured response. The authors conclude that shear wave velocity data for analysis should be measured at the appropriate construction stage and confining pressure. The results presented in the paper are encouraging. Similar analysis and comparison of FVT results for the embedded structure (i.e. after backfill) should provide further insight into the use of FEM in soil-structure interaction analysis.

5.04 Effect of Soil Dilatancy on Vibration and Earth Pressure by Y. Ohshima and H. Watanabe

The authors carried out small-scale model tests on a shaking table to study ground vibration and dynamic earth pressure acting on an embedded structure. Vibration tests were conducted with and without the model structure (n instrumented box) embedded in dry sand. The test results indicated that horizontal excitation also produced vertical ground vibration, which caused dynamic earth pressures to act on the structure walls parallel to the direction of shaking, in addition to pressures acting on the walls perpendicular to the shaking direction. The authors postulated that these observed phenomena were due to dilatancy or volume change of the soil during yielding, which they indirectly confirmed by elasto-plastic dynamic FEM analysis. This conclusion has important implication, and a more direct confirmation of soil dilation, e.g. by displacement sensors, would have been enlightening.

5.19 Foundation Soil Influence on Seismic Response of Piers by P.O. Biotallevi and R. Poluzzi

The authors conducted horizontal forced vibration tests in Italy on two fairly similar viaduct piers founded on similar piles but in different soil conditions. The measured transfer functions of the pier in overconsolidated clays were very different from those of the pier in underconsolidated saturated clayey silt, confirming the importance of soil-structure interaction effect. Using simple damped oscillator models and results from the field tests, the authors computed the response of the two piers to four selected earthquake accelerograms. The calculated displacements for the pier on compact soil were much smaller than those for the pier on soft soil.

5.23 Settlement of Shallow Foundation on Sand Due to Cyclic Loading by B.M. Das, S.C. Yen and G. Singh

The authors conducted laboratory tests to evaluate permanent settlement of a square surface model foundation on dense sand subjected to a combination of sustained static and cyclic loading. Only one model foundation and one soil density were used in their experiment. The cyclic load was applied at 1 Hz which was well below the natural frequency of the foundation. The model test results showed that the ultimate cyclic settlement depends on the magnitudes of the static and cyclic loads. Interesting correlations between observed settlements and applied loads were presented. The laboratory experimental results, however, are for a very limited foundation/soil condition, and their practical implications are not clear.

5.28 Application of Weak Earthquake Records in Soil-Structure Interaction Analysis by E. Juhasova

The author describes the equations of motions for wave propagation through a layered medium. Because of the lack of strong motion seismic record for certain regions, the author suggested using weak earthquake records with appropriate modification of frequency content for input into ground response analysis.

5.35 Recommendations of a Workshop for a Soil-Structure Interaction Experiment by M. Celebi and J.E. Luco

The authors summarize the findings of a workshop held in 1992 to discuss the feasibility of instrumenting a building in a seismically active region of the United States to carefully study soil-structure interaction effects. The recommendations from the panel of experts at the workshop included guidelines on the selection of site, soil condition, building type and extensive instrumentation arrays for the superstructure, foundation and free-field. It is anticipated that implementation will start within 1-2 years. The experiment will be managed by the U.S. Geological Survey, The paper is informative.

5.51 RESCUE Testing of Full-Scale In-Situ Structures by P.R. Gefken and J.W. Simons

The authors present a newly developed technique for controlled dynamic testing of full-scale structures in-situ. The technique, referred to as repeatable earth shaking by controlled underground expansion (RESCUE), produces ground motions by simultaneous expanding a planar array of vertical sources buried in trenches surrounding the structure to be excited. The authors performed FEM analysis to illustrate the feasibility of using this technique to test a highway overpass to failure. The idea is innovative but its practical usefulness has yet to be demonstrated.

5.57 Tests of Buildings and Foundations with Vibrations of Ground by A.N. Tetior

The author describes three methods used in Ukraine for dynamic testing of foundations and structures. The methods are: (1) free vibration of an "inertia box" containing soil and model piles; (2) inducing ground vibrations adjacent to foundations or buildings by dropping weights from a crane; (3) forced vibration testing of a box containing soil and model structures. The common feature of all three methods is that vibration is induced in the ground to excite the foundation or structure.

4. **Miscellaneous**

5.12 Prestressed Concrete Piles Under Seismic Loading: Case History by M. Adib, W.C.B. Villet and A. Nisar

The authors describe the performance of a 14-inch prestressed concrete pile foundation during the October 17, 1989 Loma Prieta earthquake. The piles supported a 10 story hotel structure. Based on the evaluation of eight post-earthquake exposed piles the authors conclude that: a) the prestress in the piles contributed to the satisfactory performance of the piles, b) the correct load distribution to piles is important, and c) the 1988 UBC base shear values indicate shear forces in the piles within the range that would cause cracking to initiate. In view of the rather complex pile response described in Section 2, these conclusions may not be extrapolated.

5.22 Geotechnical Aspects of Seismic Design of Bridges in New York City by K. Kishore and S.K. Jaim

The paper summarizes the available geotechnical and seismological information for the earthquake resistant design of bridges in New York City which are required to comply with recent specifications of the authorities. After an introduction on the importance of seismic bridge design, the geological layout of the city is briefly described followed by a summary of the seismic activity during the past 250 years and a presentation of the consequences of an earthquake in that region. The influence of local soil conditions including liquefaction is discussed next, based on available geotechnical information. Some general suggestions for seismic retrofit of existing bridges are made and the process of ongoing work is described. In summary, the paper had only a general informative character without any new aspects on earthquake resistant design of bridges.

5.54 On Modal Analysis of 12-Story Building from Strong Earthquake Record by F. Kong

The author applies a recursive system identification technique, in the time domain, to analyze a set of acceleration response records obtained from a 12 story building on piles during the February 20, 1990 earthquake in Japan. Two identification techniques, the recursive least squares method and the prediction error method were used. The author concludes that the identification of frequencies and the associated damping values by these methods are similar and reasonable. The figures purporting to demonstrate these conclusions could have been enlarged enough to make them readable, and thus used by the reader in understanding the conclusions of the author. As they are now presented, the figures are not usable.

Table 1, A Classification of Papers in Section 3

Paper No.	First Author	Laboratory Experiment Testing	Field Experiment Testing	Theoretical Study
5.01	Ueshima		X	
5.04	Ohshima	X		
5.19	Diotallevi		X	
5.23	Das	X		
5.28	Juhasova			X
5.35	Celebi		X	
5.51	Gefken		X	
5.57	Tetior	X	X	