Theme Report on Topic 4
FOUNDATION AND SOIL-STRUCTURE INTERACTION

by

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In recent years, there has been a remarkable increase of interest in the dynamics of foundations and soil-structure interaction. It is, therefore, not surprising that over fifty contributions were accepted for the session dealing with this subject. The contributions were prepared by researchers as well as practising engineers and hence, reflect the current trends in research and the practical experience of the profession. The papers cover individual aspects of the subject or approach the problem in its entirety and can perhaps be grouped as follows:

Soil properties;
Rigid footings;
Pile foundations;
Soil-structure interaction;
Special problems (the problem of two bodies, underground structures etc.).

This report will attempt to summarize the main ideas, observations and experiences as far as they can be extracted from the contributions and condensed into a brief presentation. This task is rather difficult because of the huge body of information provided on one hand and the extreme brevity of some reports on the other. It is for this reason that not every name and contribution can be mentioned.

Soil Properties

The growth of knowledge of dynamic soil properties is fundamental but appears to be lagging behind the rapid development of analytical facilities. Yet, very few contributions in this session deal with soil properties.

It has been recognized that dynamic soil properties of a particular soil vary with confining pressure, the level of strain its history and the character of the loading and its duration. Variations of soil stiffness and material damping with these parameters are of particular practical interest. However, the study of additional characteristics needed for the description of nonlinear , viscoelastic and transient phenomena is also needed. The contributions made only deal with some of the aspects mentioned.

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Aramaki and Koga conducted experiments with poor soils that are particularly important from the viewpoint of soil-structure interaction. They found that both stiffness and damping of poor soil decrease with increasing displacement. This indicates that an increase in material damping with increasing level of strain found or assumed by most researchers need not always materialize.

Lastrico et al. observed a peculiar nonlinearity of naturally cemented silty fine to medium sands utilized in the foundation of a nuclear power station in the eastern United States. The sand studied has markedly different properties at small and large strains. The difference observed is due to the destruction of the calcite cement bonding between the particles and is caused by strains of about one percent.

Rigid Foundations

Rigid foundations were studied theoretically and experimentally by a few contributors. The theoretical studies treated both aspects of rigid footings, namely their impedance functions and direct excitation by seismic waves.

The impedance functions define the relationship between the forces and displacements. Their real and imaginary parts describe the frequency variable stiffness and damping of the foundation.

Hadjian and Luco report significant progress in refining the impedance functions for rigid foundations, by the inclusion of soil layering and viscosity. Substantial differences from half-space solutions are worth noting particularly the sharp reduction of damping. They found that a layer can be approximated by a half-space if the layer thickness is larger than six times the radius of the foundation. The properties of the top shallow layers are most decisive.

These observations are amplified by Westermo and Wong who present a very illustrative comparison of three basic models used in analysis (Fig. 1): (A) - a half space, (B) - a layer and (C) - an enclosed medium. Model B produces very sharp resonances if material damping is small. The enclosed medium (Model C) is sometimes used in laboratory experiments and finite element models. The boundaries do not allow the dissipation of progressive waves and therefore, the energy of vibration is trapped within the rigid boundaries. The resulting standing waves manifest themselves by a number of resonances, stiffness peaks or zero stiffnesses. It appears that these dramatic variations in stiffness and damping cannot be eliminated by any realistic value of material damping, or by any increase in the size of the model.

Direct excitation of a rigid footing by seismic waves was studied by Luco and Wong who investigated theoretically the response of a rectangular foundation to Rayleigh wave excitation. The effect of incident Rayleigh waves was found to be completely different from the effect of the vertically incident shear waves. This finding contradicts the assumption often used in the direct finite element analyses of soil-structure systems.

Experimental research into the dynamics of rigid foundations leads to significant observations also. A few researchers conducted field experiments with exceptionally large bodies whose dimensions were equal or close to those of the prototypes. Seismic excitation and forced oscillations were applied. Such large scale field experiments are very useful as they provide the best verification of the theories used.

Tajimi et al. investigated vibration characteristics and seismic response of the foundations of a large shaking table. The foundation studied is rigid and the total area of its base is 39 x 25 m^2 with an embedment depth of 8.2 m (Fig. 2). The footing was subjected to forced vibration tests and its seismic response to a few earthquakes was also registered. All measurements were compared with theoretical predictions based on finite element analysis. The results of their unique study are very encouraging because, on the whole, they found very good agreement between the experimental and theoretical responses. It is important to note that nonlinearity, usually strong with small footings, did not show in any appreciable degree.

Hamada and Kudoh conducted experiments with a huge concrete mat having dimensions 68 m x 68 m x 5 m but refer to them only briefly. It would be useful if they could give more information on their experiment.

Arya et al. also report tests with very large partly embedded bodies but more details concerning the comparison with theory are desirable.

Petrovski conducted about 200 dynamic field tests with rigid embedded foundations exposed to harmonic excitation. The measured response was compared with analytical predictions. Typical dimensions of the test bodies were 1 x 2 x 2 m^3. The response curves measured feature a typical nonlinearity observed in similar experiments (Fig. 3). Despite that, excellent agreement between the theoretical and experimental resonant frequencies was found. The theoretical resonant amplitudes exceeded the measured amplitudes by a few hundred percent. It appears that this discrepancy could be closed by the inclusion of material damping. It was found in other experiments that this is needed for realistic estimates of horizontal response of surface footings or with shallow embedment. Deep embedment is a powerful source of energy dissipation through wave propagation and consequently, the effect of material damping is much less.

Laboratory experiments with very small embedded bodies are also reported but these results cannot be generalized. The reason for this is that soil stiffness and consequently the effectiveness of embedment depends on confining pressure which is extremely small in the laboratory experiment and as a result of it, the conditions of physical similarity are violated. In addition, wave reflection from the boundaries may distort the geometric damping as previously discussed.

The difficulty caused by the lack of confining pressure can be circumvented if the laboratory experiments are conducted in a centrifuge.

Scott et al. conducted such laboratory experiments using a centrifuge to study the dynamic behavior of a rather stiff embedded pile. Experiments of this kind can eliminate the considerable difficulties associated with full scale field experiments but are not easy to conduct. Also, the limited size of the test box may call for special measures to alleviate the box effect already mentioned.

Pile Foundations

Another group of papers is devoted to the dynamic behavior of pile foundations, the response of which depends on interaction between the soil and an elastic pile. For off-shore drilling platforms, interaction between the piles and water is also included. Results of theoretical as well as experimental studies are reported.

Three kinds of theoretical models are used. The first approach represents soil as a continuum. The continuum approach is limited by the standard assumptions of linear elasticity or viscoelasticity and the invariability of soil properties but has a few advantages: It correctly represents geometric damping as well as soil layer resonances, and yields explicit formulae for the impedance functions of the soil-pile system. Also, it facilitates extensive parametric studies at negligible computing costs and offers a fundamental insight into soil-pile interaction. Nonlinearity can be accounted for only very approximately by choosing an equivalent linear modulus of the soil according to the expected level of strain.

The second approach represents the soil-pile system by a set of discrete (lumped) masses, springs and dashpots. This model can incorporate variations of soil properties with depth and even nonlinearity in more detail but depends very much on the definition of local soil stiffness and geometric damping.

The third approach is the finite element method. It has the advantage of representing the soil, piles, water (if present) and the structure by compatible elements in a unified way with a great deal of flexibility in the variation of soil properties.

However, there are several complications that are difficult to tackle by any method. These are the time variable separation of the pile from soil that can appear at large displacements and low confining pressure, nonlinearity, variation of soil modulus with local state of stress and wave scattering among piles in a group. These aspects are difficult to incorporate even in the finite element method and some of them would call for a truly three-dimensional nonlinear approach. (Kamil et al. report some progress in that direction). For these reasons a certain degree of physical inaccuracy has to be accepted in any approach to pile dynamics.

Despite these difficulties, a comparison of experiments with theoretical predictions indicate that the theory can yield a reasonable estimate of pile stiffness, damping and dynamic response if the variation of soil properties with depth and the possible lack of fixity of the pile tip are accounted for at least approximately.

Some of the contributions presented deal with individual problems of pile dynamics, others aim at developing a more general approach. The paper by Kamil et al. is an example of the latter.

The report by Novak describes some results obtained by the continuum approach. Two methods were used. A more rigorous one that models the soil as a viscoelastic layer, similar to the method used by Tajimi, and a simpler one in which the soil reactions are taken from a plane strain solution. The results of the two methods approach each other as the frequency increases. The theories offer an insight into the complicated nature of soil-pile interaction, illuminate the effect of the governing dimensionless parameters, yield the impedance functions of embedded piles and provide local stiffness and damping for the discrete approaches. The relaxation of the pile tip, typical of floating piles, was found to be very important, because it reduces stiffness and increases damping (Fig. 4). Experiments with pile foundations confirmed that it is the upper layer of soil which affects the response most.

Bielak extended Novak's approach and conducted an extensive theoretical study of the response of buildings supported by end bearing piles and excited by harmonic motion of the ground. He concluded that tall flexible structures may be often treated as if they had rigid foundations but low structures can be affected by pile foundations to a high degree.

Important questions of this kind were studied experimentally in the field by a few researchers. These studies were conducted in Japan whose high seismic activity made it possible to monitor the response of soil, piles and structures to a number of earthquakes in several years. Fig. 5 shows the elevation of the structures studied by Kawamura et al., Sugimura and Hagio et al. (Goto investigated pile foundations of bridge piers.)

These authors monitored the free field motion of the soil at different depths, the motion of the piles and the response of the structures. Well over a hundred earthquakes were observed with magnitudes in most cases below 6.0.

At differing sites some similar observations were made. For example, it was observed that the motion of the piles does not differ significantly from the free field motion with the exception of the uppermost layer of soil. At the surface, marked magnification of the motion of the soil occurs (Fig. 6); however, this magnification is not followed by the pile cap whose response is smaller than that of soil at the same level. This difference is indicative of the interaction effects resulting from the inertia of the structure and of the bending moments generated in piles. The low level of soil-pile interaction at greater depths is very favorable from the practical point of view because it reduces the importance of exact modeling of the tip condition and soil properties of the lower layers.

Other observations concerned the response of the pile supported structures, modal damping and frequency distribution of the measured accelerations. All of the measurements are very useful and are likely to be used for checking different theories in the future. Generalization of the experimental observations for other input motions is, however, difficult as the frequency distribution of the ground shaking depends on the distance of the epicenter and the strength of the earthquake. The power spectral densities established by Sugimura indicate that far and/or large-scale earthquakes carry most energy in the low frequency range which need not be the case with other earthquakes.

The next large group of papers deals with soil-structure interaction with the main emphasis being placed on the behavior of the structure.

Soil-Structure Interaction

Soil-structure interaction occurs if the ground motion results in relative displacements (including rotations) between the footing of the structure and the surrounding soil. If the absolute motion of the footing follows exactly the free field motion of the soil, no interaction takes place. In general, the stiffer the structure and the weaker the soil the more pronounced the interaction can be. The effect of this interaction is to modify the stiffness as well as the damping of the structure and its response to ground motion. However, the ground motion itself also depends on the properties of the soil deposit as the seismic tremor is modified by its passage through the soft soil and perturbated by the presence of a region with different stiffness introduced by the structure. Thus, a soft soil deposit may affect the structure in three closely related but different ways. An understanding of the individual factors is needed but from the practical point of view, their joint result is most important.

A number of contributions is devoted to various aspects of soil-structure interaction.

Kanai and Shimosaka studied the damping of actual buildings caused by dissipation of vibrational energy through seismic waves into the ground. They applied their approach to a number of buildings monitored during the San Fernando Valley earthquake and achieved a remarkably good agreement between theory and experiments.

Herrera and Bielak formulate the dynamic soil-structure interaction as a diffraction problem. In particular, they study the effect that a region with different mechanical properties, representing the structure, has on the overall motion. They conclude that the analysis should use as input the motion that would appear at the bottom of the excavation before the structure is present.

Abdel-Ghafar and Trifunac investigate the effect of plane harmonic SH-waves on a multi-span bridge (Fig. 7). Their analysis tackles the problem in three typical steps: analysis of input motions, the force displacement relationship for the foundations (the impedance functions) and the dynamic analysis of the structure. Their simplified model illuminates the effects of the angle of incidence, the rigidity of the girders, the mass ratios and the ratio of the span lengths. The effect of shielding of one foundation by another is also very illustrative.

Response of a long structure to an obliquely incident earthquake motion was also analyzed by Oguchi. He studied the little understood behavior of an elastic plate under three-dimensional conditions. He finds that the response of an elastic plate can be completely different from that of a rigid one.

Studies of the seismic response of extensive structures such as long bridges, pipelines or elastic slabs are useful but very difficult. It appears that the potentials of a purely statistical approach to the response of such extensive structures would be worth examining. The seismic input can be viewed as a three-dimensional random motion of soil fully defined by power spectral densities, covariances and coherence functions. The latter functions are well suited to describe the diminishing correlation of the ground motion with frequency and distance. The structural response to an input defined in this manner can be solved in terms closely following those commonly used in the statistical theory of turbulence.

A general evaluation of the existing methods used in practice to analyze soil-structure interaction is presented by Gutierrez and Chopra. They evaluate the effectiveness and applicability of three groups of approaches. These are, in their terminology, the simple substructure method, the direct finite element method and the general substructure method. This division appears suitable to follow.

The simple substructure method (also called the impedance method) is the rather standard approach in which the structure is idealized as a one-dimensional system supported by a rigid plate which is attached to the ground. The ground stiffness and damping are defined by the complex impedance functions. The response of the structure is solved by means of Fourier transformation, modal analysis or some other method. The most serious limitation of this method stems from the assumptions of linear elasticity, invariability of soil properties and other assumptions usually adopted in the derivation of the impedance functions. But the approach is simple, fundamentally correct, and the computing costs are most often negligible. Despite its approximations, this approach makes it usually possible to recognize to which degree the soil-structure interaction is important. Another advantage is, that it can also be used, at least in an approximate way, with pile foundations.

The direct finite element method is very popular because the computer programs are readily available and the method routinely handles non-homogeneous soil properties, embedment and the structure combined with the soil in one model. However, even with the advent of the transmitting boundaries (Waas 1972) some serious limitations are inherent in this method too.

Most models used are two-dimensional and as such, depend very much on the existence of rigid horizontal bedrock that can naturally determine the vertical extent of the model and provide the needed rigid horizontal boundary. If essentially similar soils extend to a great depth, the rigid boundary is not accessible and the direct finite element method can lead to unacceptably large errors if the depth usually recommended and equal to the width of the base of the structure is used.

These problems were studied by Gutierrez and Chopra and a few others. Lee and Reddy conducted an extensive parametric study of a two-dimensional finite element model of a power plant site. They found that the energy-absorbing boundary applied at the base not only absorbed the energy radiating from the structure but also reduced the energy of seismic waves propagating along the base. Therefore, they suggest that the depth of the finite element mesh should be at least two thirds of the length of the mesh and that its lower boundary should be left free.

Another complication is associated with the seismic input. The direct finite element method introduces the earthquake motion at the base of the mesh. Because the input motion is specified for the surface where it is monitored, the motion of the base is obtained by deconvolution of the surface motion. This process assumes that the surface motions were produced exclusively by vertically propagating shear waves and excludes surface waves as well as non-vertically incident body waves. These assumptions can lead to the omission of torsion and to other errors as shown by Luco and Wong and discussed earlier.

Significant errors may also result from the application of a two-dimensional finite element model to the analysis of an isolated structure. The essential difference in responses produced by a concentrated load in a half-space and in a half plane can exemplify this point.

Nevertheless, the finite element method is a powerful tool of great flexibility. A good example of this is presented by Smith, Vaish and Porter who describe the extension of the two-dimensional finite element method to include new problems associated with seismic loading of floating nuclear power plants. These authors report on the analysis of a nuclear power generating facility to be built off the coast of New Jersey and featuring two 1,150 megawatt nuclear plants (Fig. 8). These plants will be constructed on floating barges moored to caissons that are protected by a breakwater. To include the hydrodynamic effects of the ocean water the authors refined the fluid finite element. They also formulated a "split-modelling" procedure using two different models for low and high frequencies, respectively. Considering the complexity of such models it is obvious that floating nuclear power plants call for a significant extension of the concepts of soil-structure interaction and open new vistas for challenging research. Some of the directions of this research were initiated by the development of off-shore towers (Dungar, Eldred).

Another example of the application of the two-dimensional finite element technique to the more traditional problems is the study by Ukaji, Höeg and Shah. Their model simulates the dynamic behavior of a system consisting of a plane frame, a rigid embedded foundation and a horizontally layered soil deposit. They utilize a partial viscous side boundary to increase the accuracy of the finite element model and incorporate an equivalent linear and elasto-plastic stress-strain relationship.

Returning now to the adopted classification of the approaches to soil-structure interaction, it remains to discuss the last group, the general substructure method.

This approach was developed by Gutierrez and Chopra in an attempt to overcome the limitations of the direct finite element method. This method can analyze the structure as a finite element system and the soil region as either a continuum or as a separate finite element system. The free-field earthquake motion is introduced directly eliminating the deconvolution calculations and the associated assumptions made in the direct method. The concept of the foundation impedance is generalized in order to avoid the restrictions of a rigid base usually adopted in the impedance approaches. They formulated the foundation impedance matrix for a deformable interface between the structure and soil (Fig. 9). To that goal, the soil region is idealized as a finite element system or as a viscoelastic half plane. The greatest advantage of the general substructure method is that it is computationally very efficient. The reason for this efficiency is twofold: the method works with two separate smaller systems and it takes advantage of the modal analysis limited to just a few first modes of vibration of the structure. Combining the advantages of both preceding methods, the simple substructure method and modal analysis, the general substructure method provides a very effective tool.

The final verification of the validity of any theory can be established only by field experiments. In addition to the experiments already mentioned, the tests by Osawa, Kitagawa and Irie can be considered suitable for such comparisons. (Fig. 10) Their test structure is simple for analysis and large enough to be representative of real structures as its reinforced concrete mat had dimensions 4 x 4 x 1 m^3.

Having discussed the individual aspects of soil-structure interaction, the attention should be turned to the question of the practical implications of their joint effect on different structures supported by different foundations. The answer to this question is essential for rational design.

The research done by Minami and Sakurai aims at the formulation of general recommendations for design. These writers simulate the soil-foundation-building system by a cyclic truss type model (Fig. 11). The soil is supposed to consist of three layers overlying the firm base. Four soil types are assumed ranging from rock to fill and characterized by predominant vibration periods and damping being smallest for rock (3 and 5%). The soil model is cyclic (repetitive) in order to eliminate the side boundary conditions. The foundations included piles, piers and basements. The structural damping ratio of 3% was assigned to all buildings. The 1940 El Centro and 1952 Taft earthquakes were used as input.

Hundreds of computer simulations were performed and the results compiled into multiple spectra curves presented in Fig. 12. The graphs yield the base shear coefficient depending on the type of soil and the natural period of the soil-foundation-building system which in turn is determined depending on the number of stories, type of soil and type of foundation.

It can be seen that the base shear coefficient markedly depends on the type of soil; it increases with frequency and for a specific frequency increases with decreasing stiffness of the soil. The trend emerging indicates that the seismic loading is largest for low stiff buildings on hard soil and least for the filled ground. The amplitudes of the response vary with all the parameters involved but diminish with increasing soil damping. The multiple spectra appear to reflect the experience that low stiff buildings built on stiff soil often suffer serious damage.

A similar study has been conducted under the auspices of the Applied Technology Council of the U.S.A. but the approach is different. The earthquake input spectra were derived from a number of observations made on different soils and the impedance function approach was used to describe the structural properties, the response and the base shear. Despite the different approaches and possible different numerical outcome for specific situations, the general trends of both methods appear similar.

Obviously further improvements and refinements of this integral approach to soil-structure interaction are most desirable as it can lead to a better understanding of the working of the whole system and provide rational guidance for design.

Special Problems

In this paragraph a few additional subjects are briefly discussed.

Cross-interaction between two structures. - It has been observed in several earthquakes that damage can also result from the interaction of two adjoining buildings. This problem was treated by Kobori, Minai and Kusakabe who analyzed theoretically and experimentally the interaction between two rigid bodies and by Aydinoglu and Cakiroglu who used a discretized model.

Underground structures. - Seismic response of underground structures is encountered in underground nuclear reactors, tanks, tunnels etc. Progress in the development of analytical techniques for such structures is reported (Reddy et al., Chowchuvech and Wen and others). Earthquake observations of a cylindrical underground tank were made by Hamada and Sato and used to refine an analytical method.

A theoretical and experimental study of the response of a submerged tunnel was conducted by Hamada, Akimoto and Izumi. For this little researched but important structure they made a number of useful observations.

Conclusions

Significant progress has been made in the theoretical and experimental aspects of soil-structure interaction.

Analytical and numerical methods were refined to better model real situations.

Experiments with large models and prototypes were conducted in the field and used for the verification of the theories. The results of these comparisons support the validity of the theories used.

Practical guidelines for rational design of structures affected by soil-structure interaction are being completed. They contribute to a better understanding of the working of the soil-foundation-structure system as well as to safer and more economical design.

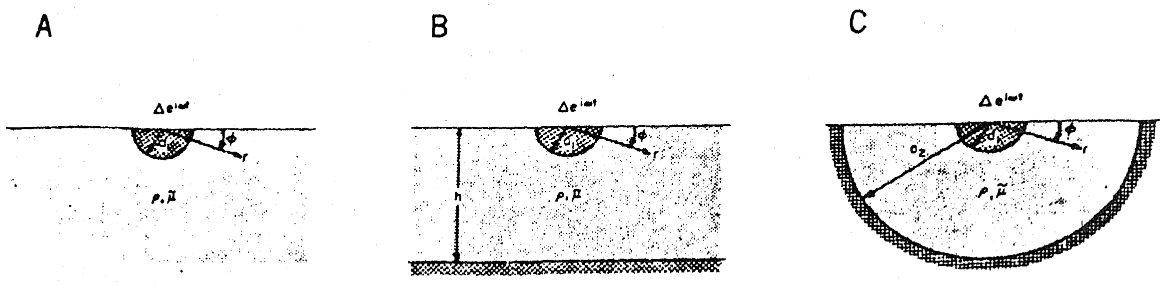


Fig. 1 Three Basic Models (Westermo, Wong)

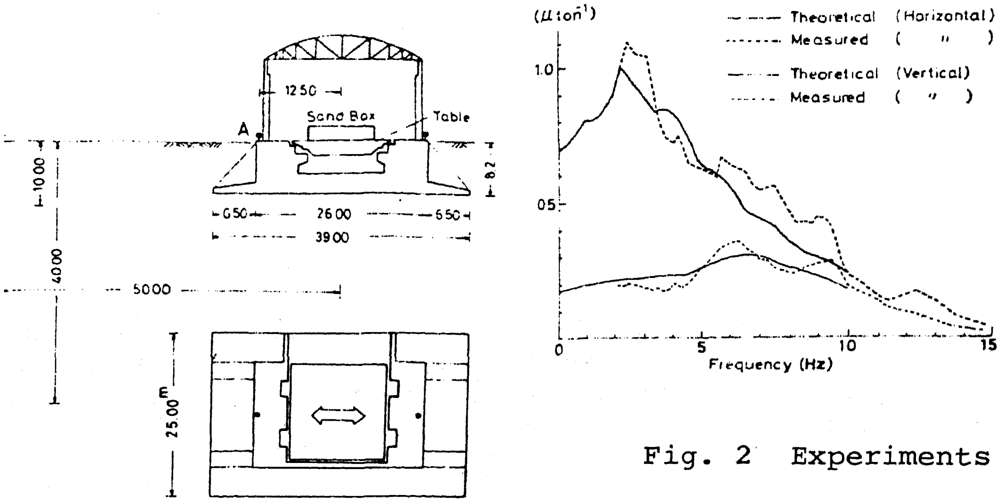


Fig. 2 Experiments by Tajimi

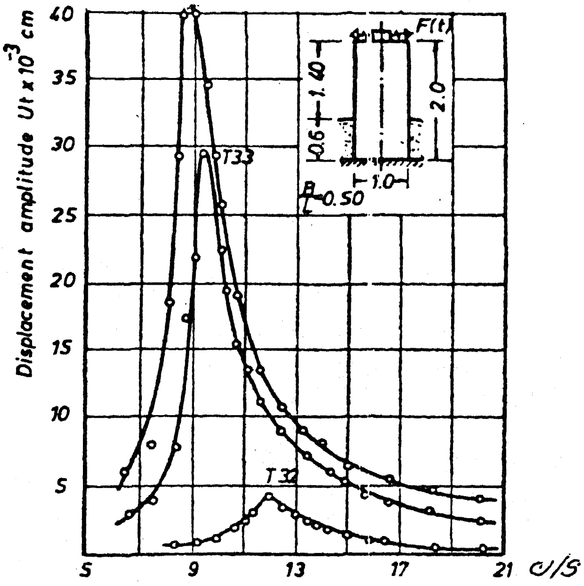


Fig. 3 Typical Nonlinearity (Petrovski)

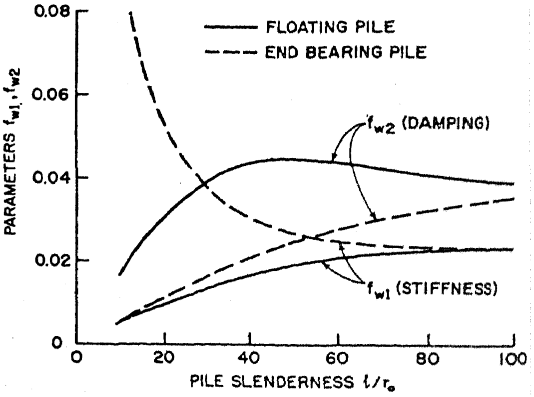
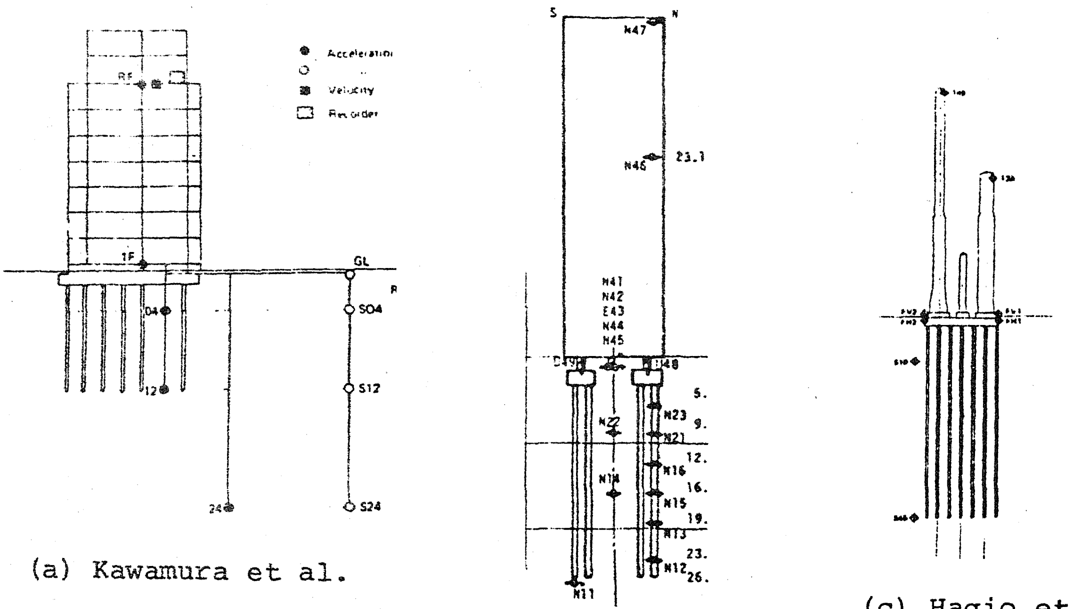


Fig. 4 Stiffness and Damping
Floating Piles (Novak)



(a) Kawamura et al.

(b) Sugimura

(c) Hagio et al.

Fig. 5 Experiments With Pile Supported Structures

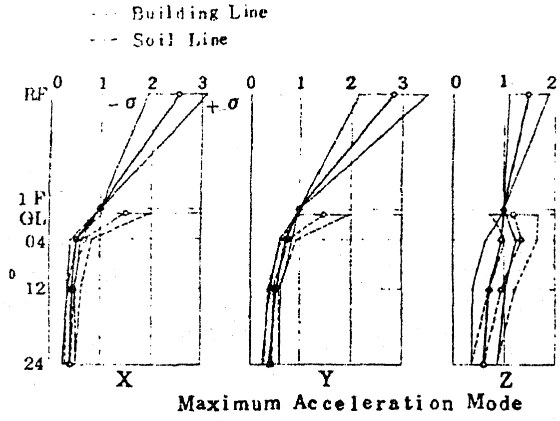


Fig. 6 Acceleration of Soil, Piles and Structure (Kawamura et al.)

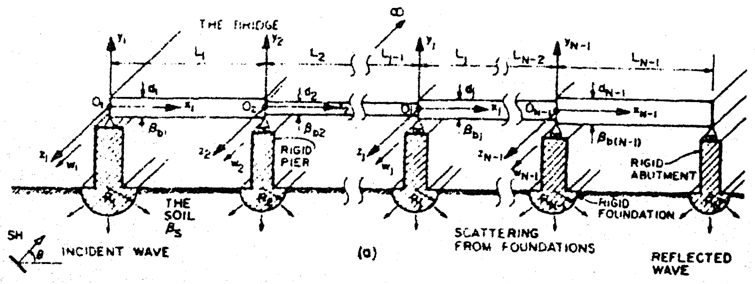


Fig. 7 Effect of Incident SH Wave on Bridge (Abdel-Ghaffar and Trifunac)

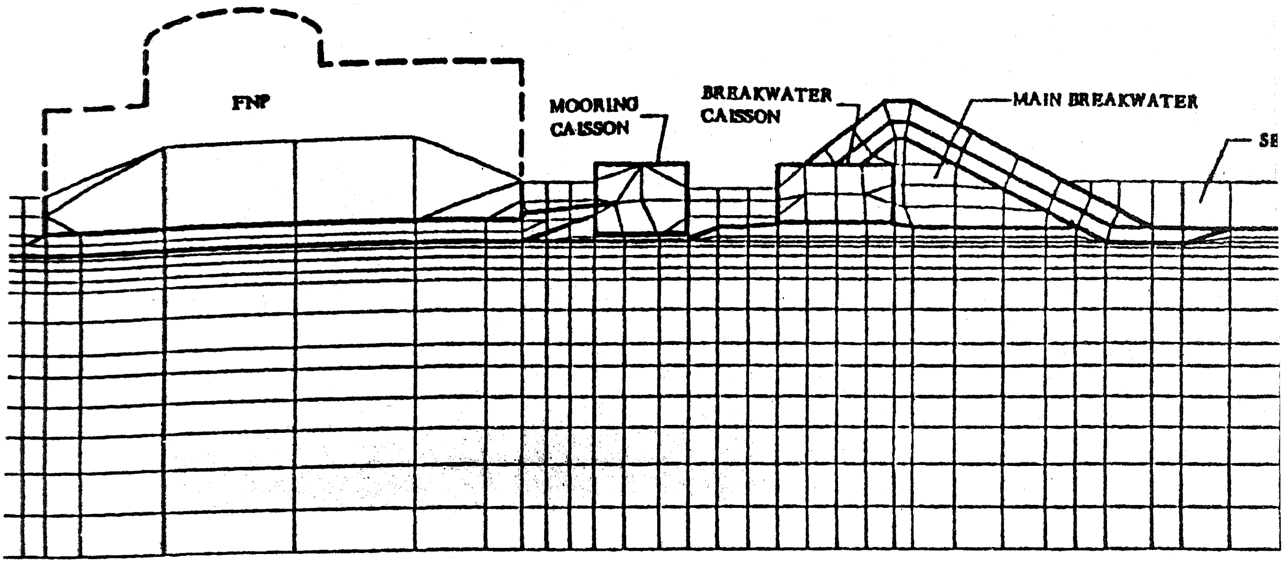


Fig. 8 FEM Model of Floating Nuclear Power Plant (Smith, Vaish and Porter)

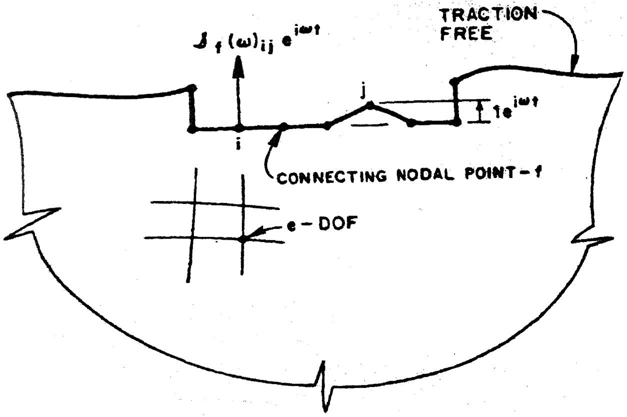


Fig. 9 Physical Interpretation of Foundation Stiffness Matrix (Gutierres, Chopra)

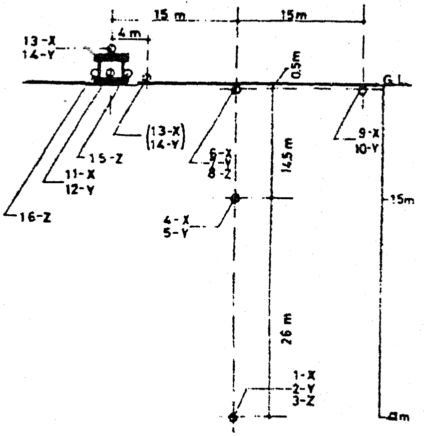


Fig. 10 Outline of Experimen by Osawa, Kitagawa and Irie

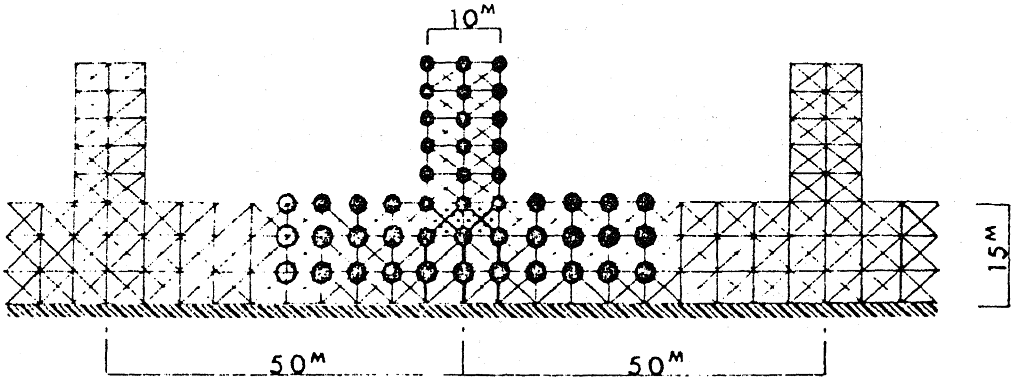


Fig. 11 Cyclic Truss Type Model of Minami and Sakurai

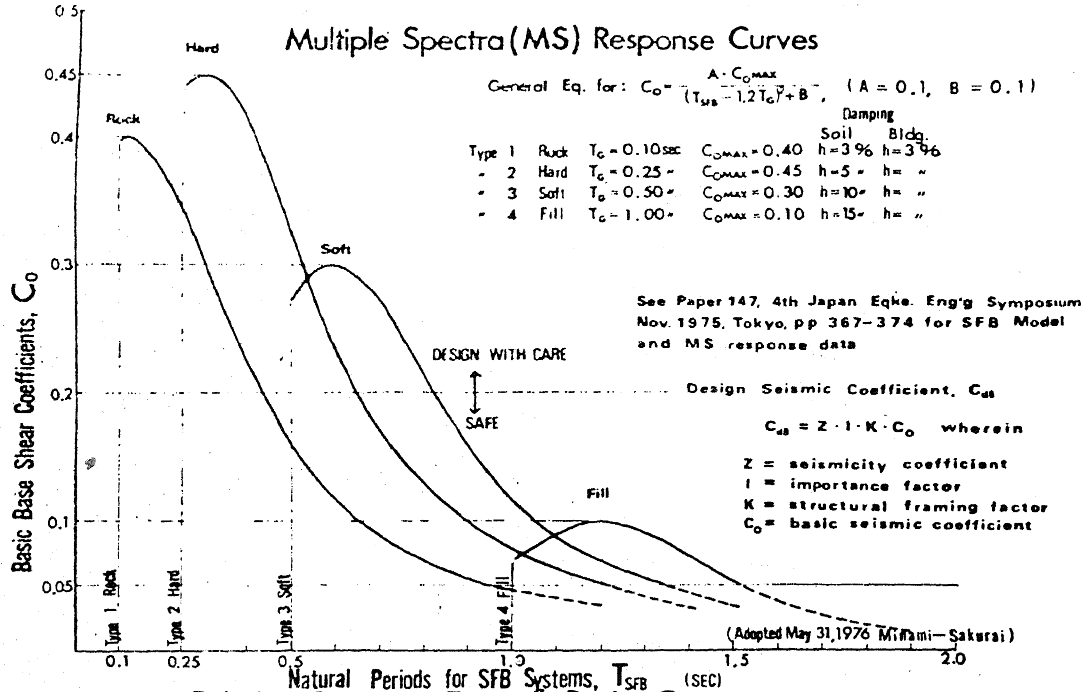


Fig. 12 Multiple Spectra for Basic Shear Coefficients (Minami and Sakurai)

Contributions to Topic #4

Abdel-Ghaffar, A.M. and M.D. Trifunac. "Antiplane Dynamic Soil-Bridge Interaction for Incident Plane SH-Waves".

Aramaki, G. and K. Koga. "An Experimental Study of the Characteristics of the Subgrade Reaction in the Poor Subsoil".(See Theme 6 ; paper No. 47)

Arya, A.S., S.K. Thakker, V.K. Puri and R. Prakash. "Response of Foundation Wells of Bridges During Earthquake".

Aydinoglu, M.N. and A. Cakiroglu. "Dynamic Interaction Between Soil and a Group of Buildings".

Bielak, J. and V.J. Palencia. "Dynamic Behavior of Structures With Pile-Supported Foundations".

Chowchuvech, P. and R.K. Wen. "Dynamic Analysis of Underground Cylinders Subjected to Earthquake Excitations". (See Theme 3 ; Paper No. 85)

Ciongradi, I. and N. Ungureanu. "A Dynamic Model For the Soil-Foundation-Structure Interaction in the Earthquake Analysis of Framed Structures".

Dungar, R. and P.J.L. Eldred. "The Effect of Earthquakes on the Foundation Stability of Gravity Oil Platforms".

Flores-Berrones, R. "A Theoretical Approach for Computing Radiation Damping in End Bearing Pile Foundations".

Goto, Y. "Studies on Practical Idealization of Soil-Pile-Group System Concerning Dynamic Interaction".

Gupta, Y.P. and A.K. Basak. "Effect of Various Fill Materials by the Side of Foundation Block on its Vibration Characteristics".

Gutierrez, J.A. and A.K. Chopra. "Evaluation of Methods for Earthquake Analysis of Structure-Soil Interaction".

Hadjian, A.H. and J.E. Luco. "On the Importance of Layering on The Impedance Functions".

Hagio, K., A. Suenaga, T. Yamada and S. Kawamura. "Earthquake Motion Measurement of Plant Towers on Soft Subsoil."

Hamada, M. and S. Sato. "Behavior of Underground Tank During Earthquakes".

Hamada, M., T. Akimoto and H. Izumi. "Dynamic Stress of a Submerged Tunnel During Earthquakes".

Hanada, K. and T. Kudoh. "Analysis on Dynamic Behaviours of Semi-Infinite Ground and Structure Systems".

Herrera, I. and J. Bielak. "Soil-Structure Interaction as a Diffraction Problem".

Iguchi, M. "A Basic Study on the Behaviour of Long Dimensional Size Buildings During Earthquakes".

Ilyichev, V. and V.G. Taranov. "The Experimental Method for Prediction of Soil-Structure Interaction Under Seismic Vibrations".

Kamil, H., G. Kost and A. Gantayat. "Soil-Pile-Structure-Fluid Interaction Under Seismic Loads".

Kanai, K. and S. Shimosaka. "On the Seismic Damping of Actual Buildings".

Kaufman, B.D., O.A. Savinov, A.M. Uzdin and S.G. Shulman. "On Structure-Foundation Interaction During Earthquakes".

Kawamura, S., H. Umemura and Y. Osawa. "Earthquake Motion Measurement of a Pile-Supported Building on Reclaimed Ground".

Kobori, T., R. Minai and K. Kusakabe. "Dynamic Cross-Interaction Between Two Foundations".

Kuribayashi, E. and Y. Iida. "An Application of Finite Element Method to Soil-Foundation Interaction Analyses".

Lastrico, R.M., S.K. Saxena, J.A. Fischer and T.M. Gates. "Static and Dynamic Properties of a Naturally Cemented Sand". (See Theme 6 ; Paper No. 42)

Lee, Y.C. and D.P. Reddy. "A Study of Boundary Effects in the Analysis of Nuclear Power Plant Structures".

Luco, J.E. and H.L. Wong. "Dynamic Response of Rectangular Foundations for Rayleigh Wave Excitation".

Margason, E. and D.M. Holloway. "Pile Bending During Earthquakes"

Medvedeva, S.V. "The Influence of the Overground and Underground Parts of Construction Heights Correlation on the Intensity of Seismic Effect".

Minami, J.K. and J, Sakurai. "Earthquake Response Spectra for Soil-Foundation-Building Systems".

Munirudrappa, N., B.K. Ramiah and B.C. Rajanna. "Response of Embedded Footings and Structures Under Earthquake Motion".

Niccum, M.R., L.S. Cluff, F. Chamorro and L.A. Wyllie, Jr. "Banco Central de Nicaragua: A Case History of a High-Rise Building that Survived Surface Fault Rupture". (See Theme 7 ; Paper 2)

Novak, M. "Soil-Pile Interaction".

Osawa, Y., Y. Kitagawa and Y. Irie. "Evaluation of Various Parameters on Response Analysis of Earthquake Motions Including Soil-Building System".

Petrovski, J. "Prediction of Dynamic Response of Embedded Foundations".

Petrovski, J. and D. Jurukovski. "Influence of Soil-Structure Interaction on Dynamic Response of Structures".

Prater, E.G. "Response of an Earth Dam Founded on a Soil Deposit to Travelling Seismic Waves".

Rashidov, T.R., G.Kh. Khozhmetov, A.A. Ishankhodzhaev, V.A. Omelyanenko and A. Kh. Matkarimov. "Investigations of Earthquake Resistance of Constructions Interacting With Soil".

Reddy, D.V., O.E. Moselhi and S.A.E. Sheha. "Dynamic Structure - Medium Interaction of Underground Nuclear Reactor Containments".

Scott, R.F., H.P. Liu and J. Ting. "Dynamic Pile Tests by Centrifuge Modelling."

Sharda, S.C., A.S. Arya and S. Prakash. "Tests on Well Foundation Models Under Horizontal Dynamic Loads".

Shikhiev, F.M. and P.I. Jakovlev. "Calculation of Bearing Capacity for the Foundations Subjected to Seismic Loads".

Smith, P.D., A.K. Vaish and F.L. Porter. "Site-Structure Interaction for a Floating Nuclear Plant Under Seismic Loading".

Sugimura, Y. "Earthquake Observation and Dynamic Analysis of a Building Supported on Long Piles".

Tajimi, H., C. Minowa and Y. Shimomura. "Dynamic Response of a Large-Scale Shaking Table Foundation and Its Surrounding Ground".

Takeuchi, M., K. Kotoda and S. Kazama. "Analytical Method of Determining the Spring Constants Available for Various Types of Foundations".

Tetior, A.N., Yu.A. Shepljakov and A.A. Rubel. "Investigation of Breast-Wall Shell Constructions on Effect of Seismic Load".

Ukaji, K., K. Höeg and H.C. Shah. "Elastic-Plastic Dynamic Analysis of Soil-Foundation-Structure Interaction".

Ungureanu, N. and I. Ciongradi. "Dynamic and Earthquake Analysis of Some Shear Wall Structures With Openings and Wall Diaphragm Frames Considering the Unequal Settlements Effect of Foundation Soil".

Westermo, B.D. and H.L. Wong. "On the Fundamental Differences of Three Basic Soil-Structure Interaction Models".

Wyllie, Jr. L.A., F. Chamorro, L. Cluff and M.R. Niccum. "Performance of Banco Central Related to Faulting". (See Theme 7 ; Paper No. 1)

DISCUSSIONS ON "THEME REPORT"

K.G. Bhatia (India)

In an industrial complex, the influence of soil structure interaction on the response of single structure can be computed by known techniques, it would like to know how much would be the variation in response if two or more structures are considered at the same time so that the effect of coupling can be considered. Also, with what level of confidence we can adopt the results of a single structure for its design without considering the coupling effect between various structure existing at the same site.

Many investigators have used different approaches for studying the effect of soil-structure interaction and made conclusions based on the specific approaches used by them, e.g. (i) replacing soil by suitable spring and dash pot, (ii) replacing soil by mass and spring to give time period which would be same as that of ground, (iii) wave propagation technique, (iv) direct FEM method, (v) sub-structure method etc.

As the discussor understands each method considers same of the parameters for the soil media and ignores some other parameters depending upon the limitation of the method. The discussor would like to know that the conclusions derived by using one approach would remain same or different and if so what could be the expected difference ?

What is Dr. Novak's recommendation regarding use of specific methods for the particular type of problem, of course, keeping in view the computational limitations, errors involved and the level of confidence by which we can use the same for design.

For the soil structure interaction problem, soil data is obtained from experiments. It is obvious that soil at a specified depth is under the influence of a known surcharge. During the process of excavation and construction in stages, the surcharge variation on the layer is experienced. Also under earthquake condition the soil is subjected to time dependent loads.

The discussor feels that the soil properties as obtained by the test earlier will undergo certain changes under earthquake ? How far the results obtained by using the initial soil properties shall vary from the response of the actual structure assuming it is subjected to same motion. It would like Dr. Novak to throw some light in this area and also to suggest how the variation in soil properties can be taken into account in the analysis.

A.R. Chandrasekaran (India)

In situations where it is convenient to use frequency independent springs and dashpots for embedded structures, number of persons including the discussor have been using Prof. Novak's analogy. There is a slight lacuna in the expressions as they are independent of cross-sectional dimensions of the structure. Will Prof. Novak like to comment ?

M.V. Ratnam (India)

Other factors like economy, time etc. being more or less the same, the discussor would like to know, from a satisfactory seismic behaviour point of view, whether one should prefer (a) bearing pile foundation or (b) friction pile foundation if both offer a possible and feasible solution.

The discussor would specifically likes to have the comment from the preference point of view (satisfactory performance) of the client.

S.C. Gupta (India)

It is stated that soil structure interaction consideration is very important while undertaking design of buildings, However a practical designer while designing a not so important structure is usually under financial restraint due to costs and time involved in such analysis, assumes a fixed base condition for his model. The discussor requests Prof. Novak to enlighten me if such an assumption would be on conservative side as far as strength design of the building is considered, or not ?

Shamsher Prakash (India)

1) It is a matter of general observation that the developments in "material property" determination lags behind the "application" of sophisticated tools for analysis. The following questions need be examined:

(i) Triaxial versus plane strain test results.

(ii) Triaxial versus "stress path dependent" stress strain properties.

These and similar questions have been discussed over and over again at meetings like this one, but the proper answers are still far.

2) As a consequence of the lack of information as listed above, the question of a suitable "constitutive law" for definition of stress-strain under "static" and "dynamic" loading is still more difficult to answer.

In my opinion, these are two very important questions, which our session may discuss and give suitable directions for future work.

3) Non-Linearity of soils : The results of large size foundations show that non-linearity did not show to any appreciable degree. In one investigation of a hammer foundation, it had been observed that there were hardly any residual settlements. It is, therefore, necessary to define problems or questions in which nonlinearity of soils may not be considered. The definition of "stress-strain" for such cases is far more easier than if non-linearity is considered.

4) We at Roorkee University are concerned with analysis of piles and "pile supported" structures and subjected to static and "earthquake type" lateral loads. A comprehensive study on "soil-pile" system indicated that piles are excited in several modes of vibrations and the contributions of II and III modes of vibrations in the overall motion to a typical ground motion are appreciable.

However if the "soil pile-superstructure" interaction is considered, only the first mode of vibrations of piles is important. This is due to coupling effects. What the discussor wishes to emphasize is that the interaction effects may alter the picture and the final results significantly.

5) Application in practice : After all, our results are to be used in practice and recommendations have to final place in the codes of practices. We have therefore to see how much of the material of this important session theme 4 serves us to that end.

Author's Closure

The answer of M. Novak to K.G. Bhatia

When two or more structures are close to each other they interact. This effect is called structure-soil-structure interaction or the problem of two bodies. The degree of this interaction depends primarily on the distance between the bodies, their mass ratio, depth of embedment and of the deposit and frequency. There are a few analytical and finite element solutions to this problem. One of them is being presented by Kobori, Minai and Kusakabe to this session. There are indications that the interaction effects can be quite severe for very close, partly embedded structures The solutions mentioned offer an estimate of the error committed by considering just one structure.

The second question concerns the differences that may exist between the solutions obtained by different methods. If the different methods use exactly the same assumptions and are applied correctly, they should yield the same results. This is so, particularly with surface structures. With embedded structures, different results are obtained if one of the methods ignores either the embedment or the kinematic interaction (modification of the seismic input by the presence of the body). Unfortunately, really objective comparisons are still missing.

The choice of the method depends on the importance and type of the project, the desired degree of detail of representing the soil properties such as heterogeneity or nonlinearity and the expected significance of soil-structure interaction. E.g., with slender structures on stiff soil, the effect of soil-structure interaction may be negligible or slightly favourable and a simple impedance function approach will do. On the other hand, if strong nonlinearity and heterogeneity are important for a significant rigid structure, the finite element method is the most suitable one to use.

As far as the soil properties are concerned, their description remains rather inaccurate and more research is needed.

The answer of M. Novak to A.R. Chandrasekaran

The formulas used in the approach referred to are mathematically accurate for plane strain conditions, i.e. for an infinitely long cylinder underoing uniform harmonic vibration. The soil reaction to such a motion has a real part (true stiffness) and an imaginary (out-of-phase) part describing the damping. With frequency independent parameters, the real part is independent of the dimension of the body, r_0, for translations in the axial (vertical) and lateral (horizontal) directions. This is a consequence of the plane strain assumption and analogous results are obtained in other situations described by plane strain. However, the out-of-phase part of the soil reaction is proportional to r_0. The complete reaction (its absolute value) is composed of both parts and therefore, does depend on the dimensions of the body. The predominance of the out-of-phase component at higher r_0 or frequencies indicates a strong viscous effect of the medium. For non zero frequencies, the results are close to those of other solutions, including the finite element method.

For vibration modes involving rotations such as torsion and rocking, both static and dynamic stiffnesses depend on the dimension of the body.

The answer of M. Novak to M.V. Ratnam

The theory mentioned in my paper indicates that in vertical direction, friction piles offer higher damping but lower stiffness than end bearing piles. In horizontal direction, the difference in the performance of both types should be much less marked. The rocking mode (the second mode of the coupled response) depends also on the vertical stiffness of the piles and thus, on their type.

The choice between the two types depends on the stiffness and damping desirable in each particular situation.

The answer of M. Novak to S.C. Gupta

The answer to this question depends very much on what kind of soil-structure interaction the designer has in mind. If the ground motion is given by a certain pseudo velocity spectrum assumed to be valid for the level of the footing then the assumption of rigid foundation is usually conservative for ordinary buildings; the inclusion of soil-structure interaction reduces the natural frequencies and increases the total damping and the seismic response (loading) of the building decreases.

If, however, the seismic motion is given for the level of the bedrock, the analysis should also include the modification of the seismic motion by the overlying layer of soil and by the presence of the footing representing a zone with higher stiffness. There are indications that this modification tends to flatten the peak of the spectrum and shift it into the region of lower frequencies. In such a case, the interaction effects may be quite different. A useful insight into the total result of soil-structure interaction can be obtained from the paper by Minami and Sakurai presented to this session.

The following is the closure for paper on page 1555

The answer of M. Novak to R.K.M. Bhandari

The effect of liquefaction on buckling stability of piles is an important question. If the soil liquefied the lateral support of the piles would diminish. However, the possibility of pile buckling depends on conditions particularly on the diameter of the piles, their loading and the extent of the liquefied zone which in turn depends on the overburden, depth of the basement and other factors. Opinions on this question differ widely. Piles suffered extensive damage in earthquakes that occurred in Japan and Alaska but the reasons for their failure might have been other than buckling.

Laboratory experiments conducted without proper modeling of confining pressure may exaggerate the danger because a very shallow layer of sand readily liquefies along the whole length of the pile. Nevertheless, some consultants prefer to refrain from piles if the danger of liquefaction exists or even replace the soil. Another precaution may be to choose larger diameter piles and a deep basement.

More research and practical experience are needed before reliable criteria are found.

The answer of M. Novak to S.L. Agarwal

The methods of determining the stiffness and damping coefficients are described in detail in the references. They are all dynamical methods. The mass of the soil need not be separately included because the soil reactions contain it as they were derived from the equations of continuum.

One of the methods was recently extended to consider layering of the soil or any variation of soil properties with depth. This is often a very important factor, particularly if the soil stiffness diminishes towards the surface due to diminishing confining pressure. The theories reported assumed linearity and are therefore limited to small amplitudes. Large amplitudes and associated nonlinearity can be considered only very approximately by using reduced values of the shear modulus of soil.

The answer of M. Novak to M. Venkata Ratnam

Horizontal stiffness of a pile depends more on the stiffness of the upper layer of soil than on that of the lower layer because the upper part of the pile undergoes large displacements while the lower part of a slender pile remains almost motionless. The depth of the most important upper layer is a few pile diameters if the layer has any meaningful stiffness. This is, however, difficult to estimate in general. For this reason those theories are preferable that make it possible to consider variation of soil properties with depth and particularly the diminishing of soil stiffness towards the surface. Otherwise, the horizontal stiffness of the pile may be considerably overestimated. A method considering layering has been recently completed by the author.