Real Time Simulation of Soil-Structure Interaction Effects on Shaking Tables

Kazuo KONAGAI[1)], Osamu UEMURA[2)], Takeyasu SUZUKI [3)]and Tota KATSUKAWA[4)]

1) Professor, Institute of Industrial Science, University of Tokyo, Dr. Eng.
2) Japan Highway Public Corporation
3) Group Manager, Earthquake Engrg. Research Group, Technical Research & Development Inst., Kumagai Gumi, Co., Ltd., Dr.Eng.
4) Earthquake Engineering Research Group, Technical Research and Development Inst., Kumagai Gumi, Co., Ltd.

SUMMARY

A new method to simulate soil-structure interaction effects in shaking table tests has been presented recently by the authors. In the method, analog circuits or digital signal processors are used to produce soil-foundation interaction motions in real time. Their expressions of soil-structure interaction motions are based on published rigorous formulations of impulse response functions of foundations resting on or embedded in homogeneous or layered soils of semi-infinite extents. This paper introduces in its first half the method for simulating soil-structure interaction effects in shaking table tests and some pieces of contrivance for better control of shaking tables. The latter half then describes a simple example of soil-structure interaction simulations using the present method.

1. INTRODUCTION

Such devastating events as Sounth-Hyogo Earthquake of 1995 seem to have stimulated a sharp rise in demand for huge shaking tables that allow models weighing for example more than thousand tons to be tested. Shaking tables are usually so driven by servo-hydraulic actuators that they follow closely input seismic motions. However, a shaking table, when heavily loaded with a structure model to be tested, interacts with the model, and this interaction often causes the table's motion to deviate from the intended time history. Recent advances in signal-processing technology have certainly enhanced controllability of shaking tables to a great extent, and yet, the motions of a table are often required to be adjusted, through iterative trials, to the intended base motions by modifying the input time histories. Generally, the larger a table is, the more difficult it is for the table to be controlled at will.

A large table with improved performance is certainly a necessity in many earthquake-related researches. However, faithful reproduction of free-field ground motions on the table may not necessarily be adequate, because actual structures interact with their foundations and the surrounding soils in real earthquakes, causing the ground motions at the structures' bases to deviate from the free-field ground motions. This dynamic interaction is a phenomenon associated with the influx and efflux of energy which is generated by the earthquake excitation and transmitted through the soil-structure interface. It is noted that the difference between the influx and efflux is exactly the energy stored up within a structure, and thus, is closely related to the extent of damage to the structure. If this interaction effects are rationally simulated in shaking table tests, one will obtain necessary pieces of information for interpreting failure processes of prototype structures in terms of energy.

Konagai and Nogami (1997-1998b) have recently developed a method to produce soil-structure interaction effects in a shaking table test on a structure model, without using physical ground model. In their method, soil-structure interaction effects are simulated by adding appropriate soil-structure interaction motions to the free-field ground motions at the shaking table. Their expressions of soil-structure interaction motions are based on published rigorous formulations of flexibility functions and/or impulse response functions of foundations resting on or embedded in homogeneous or layered soils of semi-infinite extents. In general, radiation damping will cause the total damping of a soil-structure system to be greater than that of the structure itself. Thus, incorporation of soil-structure interaction effects in a shaking table test will lead to reducing the demands on the capacity of the shake table, and the structure model may not necessarily be shaken too forcibly. However, real-time adjustment of the shaking table's motion is definitely a prerequisite for the present method, and one can not do it through iterative trials.

This paper introduces in its first half the method for simulating soil-structure interaction effects in shaking table tests

2/14

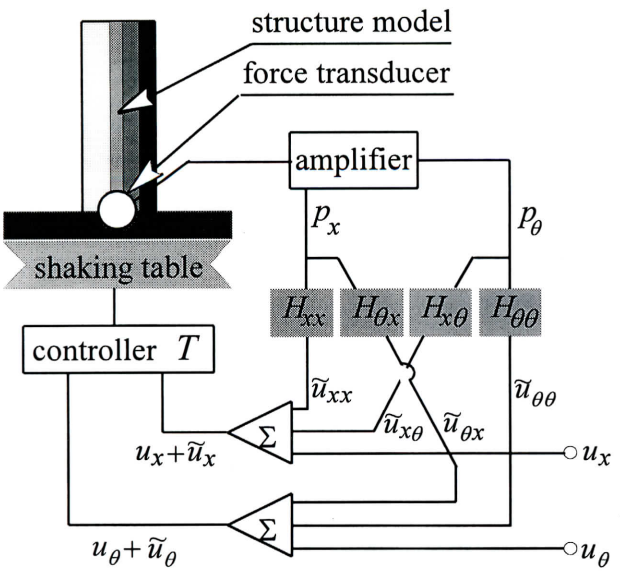


Figure 1 Simulation of soil-structure interaction on a shaking table

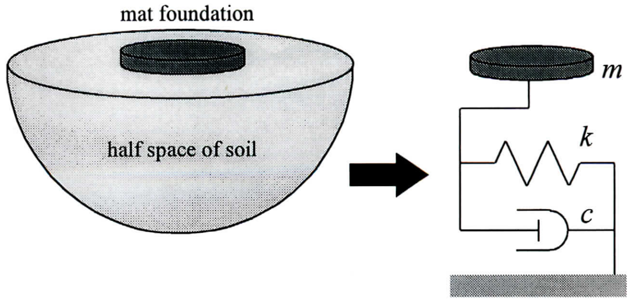


Figure 2 Equivalent spring-damper system supporting a rigid mat foundation

and some pieces of contrivance for better control of shaking tables. The latter half then describes a simple example of soil-structure interaction simulations using the present method.

2. PRESENT METHOD

In the present method, a shaking table's motion is controlled directly following the actual process of soil-structure interaction. **Figure 1** shows a schematic view of the set-up in a shaking table test for earthquake simulation, in which a superstructure model is placed directly on the table without a physical ground model. Only sway and rocking motions of the table are considered herein just for the sake of simple explanation. The soil-structure interaction effects are simulated by adding appropriate soil-structure interaction motions to the free-field ground motions at the shaking table. In the simulation, first, the transducers at the base of the foundation pick up the signals of the base forces p_x and p_θ in sway and rocking motions, respectively. These two amplified signals are then applied to a pair of signal converters $H_{x,x}$ and $H_{x,\theta}$ to produce the signal corresponding to the sway motion $\tilde{u}_x$ induced by the dynamic response of the structure model itself. Simultaneously, the other pair of converters $H_{\theta,x}$ and $H_{\theta,\theta}$ produces output corresponding to the rocking motion, $\tilde{u}_\theta$. The output signals $\tilde{u}_x$ and $\tilde{u}_\theta$ are then added to the signals of free-field motions, u_x and u_θ, to produce the signals of foundation motions, $u_x+\tilde{u}_x$ and $u_\theta+\tilde{u}_\theta$. The signals are finally translated into the shaking table motions by the shaking table controller T.

The signal converters $H_{x,x}$, $H_{x,\theta}$, $H_{\theta,x}$ and $H_{\theta,\theta}$ are essential in the present method. It is noted here that the impulse response functions for sway and rocking motions of a foundation resting on or embedded in a soil medium are closely approximated by linear combinations of exponentially decaying sine and/or cosine functions; the fact has been proved in some published works (Veletsos, A. S. and Verbic, B. 1974, Meek and Wolf 1992a-1993b, Konagai and Nogami 1997-1998b). Since these basic functions and/or their linear combinations are easily generated by both **analog circuits** and **digital signal processors** (**DSP**), these devices can be used as the signal converters.

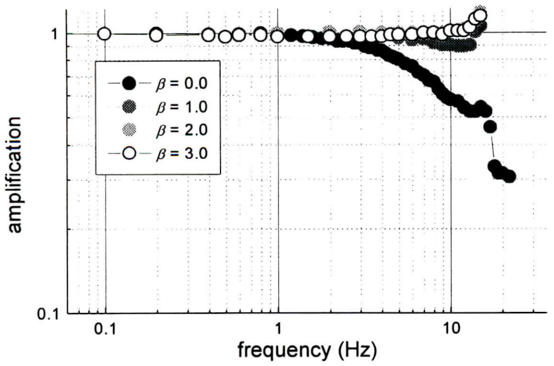
Real-time adjustment of a shaking table's sway and rocking motions respectively to $u_x+\tilde{u}_x$ and $u_\theta+\tilde{u}_\theta$ is definitely a prerequisite for the present method. Shaking tables, however, do not follow closely the intended time histories. In general, the transfer function, T, of a shaking table system permits the transmission of signals with frequencies below a certain cutoff value with little attenuation. But even below this limit of frequency, a signal is delayed approximately a certain time Δt. The effect of this time delay can be compensated, in principle, just by multiplying all the transfer functions of the above-mentioned converters $H_{x,x}$, $H_{x,\theta}$, $H_{\theta,x}$ and $H_{\theta,\theta}$ by T^{-1}. This manipulation, however, sometimes causes the present system to be conditionally unstable. In order to provide a clear perspective of the effect of this delay Δt, the flexibility function $H_{x,x}$ of a rigid foundation m resting on an elastic semi-infinite half space of soil (**Figure 2**) is examined. According to Meek and Wolf (1992a), the rigorous soil stiffness for sway motion of this foundation is closely approximated by the stiffness of a simple spring-damper system (Voigt model) as illustrated in **Figure 2**. The flexibility of the foundation thus can be described in the frequency domain as:

$$H_{x,x} \cong \frac{1}{k-\omega^2 m + i\omega c} \tag{1}$$

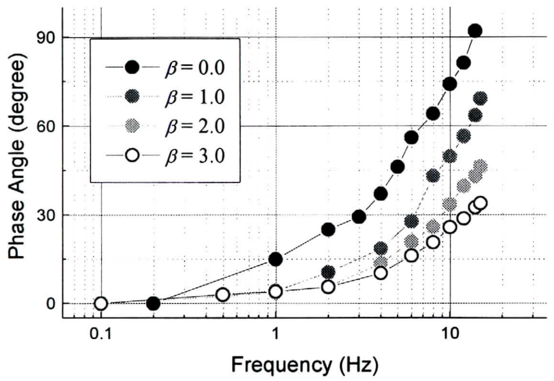
where, k and c = equivalent spring and damping constants of the soil stiffness, respectively, $i=\sqrt{-1}$, and ω = circular frequency.

Below the cutoff frequency, the transfer function $T(\omega)$ of the shaking table system is simply approximated as:

$$T = e^{-i\omega \cdot \Delta t} \tag{2}$$



(**a**) absolute values of T



(b) phase lag of T

Figure 3 Transfer function of a shaking table

The compensation of the effect of T can be made by modifying $H_{x,x}$ to $H_{x,x} \cdot T^{-1}$, which is written as:

$$H_{x,x} \cdot T^{-1} = \frac{e^{i\omega \cdot \Delta t}}{k - \omega^2 m + i\omega c} \quad (3)$$

and is approximated for smaller values of Δt and ω as:

$$H_{x,x} \cdot T^{-1} \cong \frac{1}{k - \omega^2 (m - \Delta m) + i\omega(c - \Delta c)} \quad (4)$$

where, $\Delta m \cong c \cdot \Delta t$ and $\Delta c \cong k \cdot \Delta t$ (5a), (5b)

Equation (4) clearly shows that the above-mentioned manipulation of $H_{x,x}$ leads to subtraction of Δm and Δc from the mass m and damping constant c of the soil-foundation system respectively. In order for the signal converter $H_{x,x} \cdot T^{-1}$ to produce a stable signal, Δm and Δc should be smaller than m and c, and this calls for:

$$\frac{\Delta m}{m} = 4\pi^2 \frac{t_c \Delta t}{t_0^2} < 1 \text{, and } \frac{\Delta c}{c} = \frac{\Delta t}{t_c} < 1 \quad (6a), (6b)$$

with $t_c = c / k$ and $t_0 = 2\pi\sqrt{m / k}$ (6c), (6d)

The parameter t_c is referred to as "time constant" that describes the decaying rate of a damped oscillation, and t_0 is the period of the oscillation. In many cases of soil-structure interaction realities, the conditions described by inequalities (6a) and (6b) are satisfied, and thus, the present method can be used without causing any serious troubles.

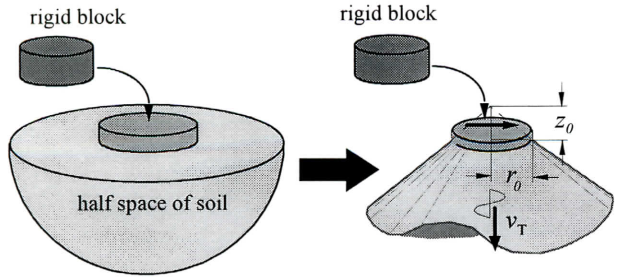
However, time delay Δt must be minimized to some possible extent when inequalities (6a) and (6b) are not satisfied. One possible way is to increase the gain of a servo-amplifier that produces compensatory signal for deviation from the intended time history of the shaking table's motion. **Figure 3** shows one typical performance of a servo-amplifier. This servo-amplifier was installed in an existing shaking table system whose transfer function T has a noticeably low limit of frequency transmission. Below this cut-off frequency, the time delay Δt is about 0.04 s (phase lag $\cong$ 15° at 1Hz) as indicated by the curve connecting solid circles labeled "$\beta = 0$" in the legend of this figure. The parameter β designates the gain of the servo-amplifier, and thus, **Figure 3** clearly demonstrates the effectiveness of increasing the gain β in both increasing the cut-off frequency and decreasing the time delay. This manipulation, however, narrows the margin for the table's unstable cluttering caused by the fluctuation of the signal that echoes through the closed loop for the servo-control.

3. EXAMPLE OF SIMULATIONS OF SOIL-STRUCTURE INTERACTION EFFECT

In order to provide a proper perspective on the usefulness of the present method, a simple example of simulations of soil-structure interaction effects is introduced herein. A rigid cylindrical block is assumed to be put on a rigid and circular mat foundation resting on a semi-infinite half medium of soil (**Figure 4a**). The dimensions of both the prototype block and foundation are listed in **Table 1**, whereas **Table 2** shows the parameters for the soil medium. The coefficient of friction between the block and the foundation is set at 0.2. According to the approach by Meek and Wolf (1992a-1993b), the soil supporting a circular mat foundation is idealized for each degree of freedom as a truncated semi-infinite cone (**Figure 4b**) with its own apex height z_0. The apex ratio z_0 / r_0, or the opening angle of the cone is determined by equating the static stiffness coefficient of the disk on the semi-infinite soil half-space to that of the corresponding cone: whereas the wave propagating through the cone with the velocity v dominates the stiffness within the considerably high frequency range. For a translational cone, the velocity v is found identical to the shear wave velocity v_T, and the unit impulse response function $h_{x,x}(t)$ is obtained as:

$$h_{xx}(t) = \begin{cases} \dfrac{1}{k} \dfrac{k}{c} e^{-\frac{c}{k}t} & t > 0 \\ 0 & t < 0 \end{cases} \quad (7)$$

where, $k = \dfrac{\rho_s v_T^2 \cdot \pi r_0^2}{z_0}$, $\dfrac{k}{c} = \dfrac{v_T}{z_0}$ and



a Rigid block on mat foundation **b** translational cone

Figure 4 Rigid block put on a rigid mat foundation resting on a semi-infinite soil medium

TABLE 1 DIMENSIONS OF BLOCK AND FOUNDATION

(a) block

mass	radius	height
7.1×10^5 kg	7 m	2 m

(b) mat foundation

mass	radius	height
1.4×10^6 kg	11 m	1.6 m

TABLE 2 MECHANICAL PROPERTIES OF SOIL

density	shear wave velocity	Poisson's ratio
1.6×10^3 kg/m^3	100 m/s	0.5

$$\frac{z_0}{r_0} = \frac{\pi}{8}(2-\nu) \qquad \text{(8a), (8b), (8c)}$$

with ν = Poisson's ratio. Equation (7) is noticed to be identical to the unit-impulse response function of a simple spring-damper system in **Figure 2**. A model of the soil-structure system is then prepared by reducing the parameters, m, k and c to the uniform scale of 1 to 10^5. Since the ratio of these parameters is kept unchanged, the time scale is not changed at all.

Figure 5 shows the model put on a shaking table. The steel block in the middle is the model of the rigid block, and the shaking table itself virtually represents the motion of the mat foundation on the semi-infinite soil half-space. The block is put not directly on the shaking table but on a flat steel plate supported by four stiff upright legs with strain gages pasted on them. These gages pick up the base shear force from the block. The surface of the steel plate is covered up with a sheet of teflon that reduces frictional resistance to the intended extent. An impulse which is shown later in **Figure 6** is given to the shaking table as an input motion u_x. The test was also conducted for the above block model put on the rigid base. **Figure 6** shows time histories of both the displacement of the shaking table and the distance that the block has slipped. Dotted lines in this figure show the motions without the interaction effect being taken into account, whereas thick lines show the motions affected by the soil-structure (foundation-block) interaction.

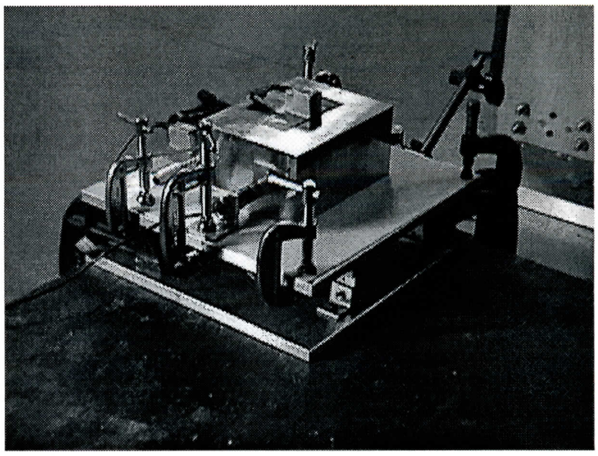


Figure 5 Block model on shaking table

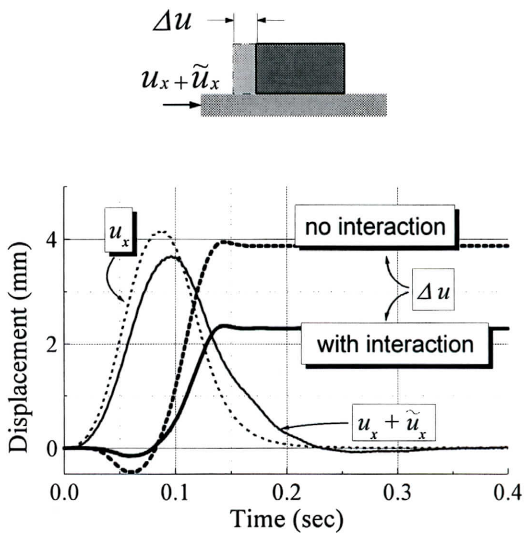


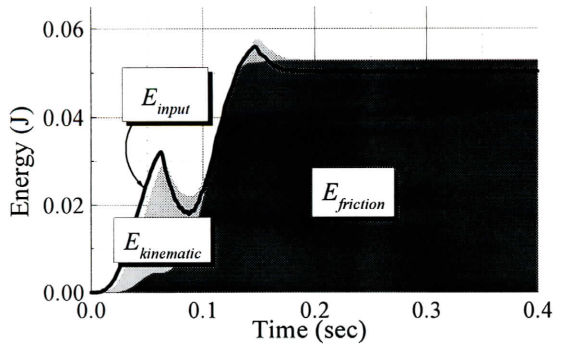
Figure 6 Displacement of shaking table and distance that block has slipped

Incorporation of the soil-structure interaction leads to slight increase in the duration of the base motion and drastic decrease of the distance that the block has slipped. The mass of the block is the direct cause of the increase in the duration of the base motion, and the decrease of the sliding distance is closely linked with the increase of the energy that has dissipated as outwardly propagating waves into the virtually spreading soil medium. The present method allows both influx E_{input} and efflux $E_{dissipated}$ of energy through the foundation to be measured in real time. These two kinds of energy are respectively:

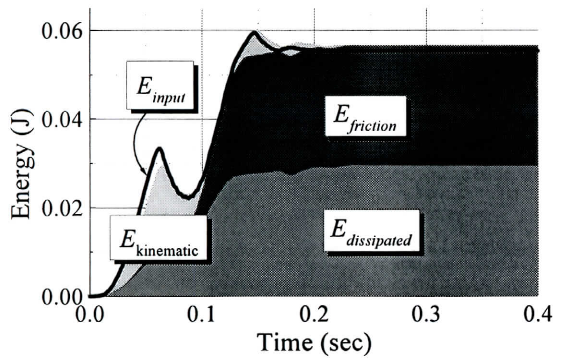
$$E_{input} = \int_0^t \left(p_x \dot{u}_x + p_\theta \dot{u}_\theta\right)\cdot dt \qquad \text{(9a)}$$

$$E_{dissipaed} = \int_0^t \left(-p_x \dot{\tilde{u}}_x - p_\theta \dot{\tilde{u}}_\theta\right)\cdot dt \qquad \text{(9b)}$$

The energy, $E_{consumed}$, used up within the model on the shaking table is then obtained as:



(**a**) no interaction



(**b**) with interaction

Figure 7 Influx, efflux and consumption of energy

$$E_{consumed} = E_{input} - E_{dissipated} \tag{9c}$$

Figure 7a shows the variations of these energies with time where the interaction effects are ignored, and thus, the cumulative loss of energy through friction ends up to be the same amount as the energy influx. On the other hand, **Figure 7b**, in which soil-structure interaction effects are incorporated, shows that a part of influx energy dissipates away and just the remainder is used up through friction.

4. CONCLUSIONS

A new method for a model experiment on a shaking table has been presented. The present method allows us to simulate soil-structure interaction effects in real time on shaking tables. The conclusions of this study are summarized as follows:

(1) In the present method, soil-structure interaction effects are simulated by adding appropriate soil-structure interaction motions to the free-field ground motions at the shaking table. It has been proved in the authors' previous works that the impulse response functions for sway and rocking motions of a foundation resting on or embedded in a soil medium are closely approximated by linear combinations of exponentially decaying sine and/or cosine functions. Thus either analog circuits or digital signal processors (DSP) can be used to produce soil-structure interaction motions.

(2) In general, the transfer function of a shaking table system permits the transmission of signals with frequencies below a certain cutoff value with little attenuation. But even below this limit of frequency, a signal is delayed a certain time. This delay leads to the virtual increases in both mass and damping constant of a soil-foundation system. This error must be compensated by modifying the signals corresponding to soil-structure interaction motions.

(3) In order to provide a proper perspective on the usefulness of the present method, a simple experiment was conducted on a shaking table. A steel block was put on a shaking table that virtually represents the sway motion of a rigid circular mat foundation on a semi-infinite half space of soil. An impulsive displacement was then given to the shaking table as an input free-field motion, and both the displacement of shaking table and the distance that the block slipped were measured. Incorporation of the soil-structure interaction led to slight increase in the duration of the base motion and noticeable decrease of the distance that the block slipped.

ACKNOWLEDGMENT

Partial financial support for this study has been provided by the Ministry of Education, Science and Culture (Grant in Aid for Scientific Research, No. 09875109). Grateful acknowledgment is made to Dr. Toyoaki Nogami, Professor, Dept., Civil and Environmental Engineering, University of Cincinnati, for his kind advice and help throughout the course of our study. The authors are indebted to Mr. Toshihiko Katagiri, IIS, Univ. of Tokyo, for his help throughout the experiments.

REFERENCES

Konagai, K. and Nogami, T. (1997). "Subgrade model for transient response analysis of multiple embedded bodies," *Earthquake Eng. Struct. Dyn.* **23**, 1097-1114.

Konagai, K. and Katsukawa, T. (1997). "Real time control of a shaking table for soil-flexible structure interaction," *Bull., Earthquake Resistant Structure Research Center*, IIS, Univ. of Tokyo, **30**.

Konagai, K. and Nogami, T. (1997). "Simulation of Soil-Structure Interaction on a Shaking Table," Numerical and Physical Modeling for Dynamic Soil/Structure Interaction Phenomenon, *Geotechnical Special Technical Publication, ASCE*, **64**, 91-106.

Konagai, K. and Nogami, T. (1998a): Analog Circuits for Simulating Soil-Structure Interaction on a Shaking Table, *Intrn. Jour., Soil Dynamics and Earthquake Engineering*, in press.

Konagai, K., A. Mikami and T. Nogami (1998b): Simulation of Soil-Structure Interaction Effects in Shaking Table Tests, *Geotechnical Earthquake Engineering and Soil Dynamics 1998*, Seattle, Geotechnical Special Publication, ASCE, in press.

Meek, J. W. and Wolf, J. P. (1992a). "Cone Models for Homogeneous Soil," *J. Geotechnical Eng., ASCE*, **118(5)**, 667-685.

Meek, J. W. and Wolf, J. P. (1992b). 'Cone Models for Embedded Foundation', *J. Geotechnical Eng., ASCE*, **120(1)**, 60-80, (1992c).

Meek, J. W. and Wolf, J. P. (1993a). "Cone Models for Nearly Incompressible Soil," *Earthquake Eng. Struct. Dyn.*, **22**, 649-663.

Meek, J. W. and Wolf, J. P. (1993b). "Why cone models can represent the elastic half space," *Earthquake Eng. Struct. Dyn.*, **22**, 759-771.

Veletsos, A. S. and Verbic, B. (1974), "Basic Response Functions for Elastic Foundations," *J. Eng. Mech. ASCE*, **100(2)**, 189-201.