Missouri University of Science and Technology
Scholars' Mine

International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

04 Apr 1995, 2:30 pm - 3:30 pm

Earthquake Input Motions for Physical Model Tests

Gregg L. Fiegel
University of California, Davis, CA

I. M. Idriss
University of California, Davis, CA

Bruce L. Kutter
University of California, Davis, CA

Follow this and additional works at: https://scholarsmine.mst.edu/icrageesd

Part of the Geotechnical Engineering Commons

Recommended Citation

Fiegel, Gregg L.; Idriss, I. M.; and Kutter, Bruce L., "Earthquake Input Motions for Physical Model Tests" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 4.
https://scholarsmine.mst.edu/icrageesd/03icrageesd/session02/4

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

Earthquake Input Motions for Physical Model Tests

Paper No. 2.06

Gregg L. Fiegel, I.M. Idriss, and Bruce L. Kutter
Department of Civil and Environmental Engineering, University of California, Davis, CA

SYNOPSIS: The results from several dynamic centrifuge experiments are presented in this paper; the experiments were performed as part of a study to assess the influence of local site conditions on earthquake ground motions. Medium dense dry sand and saturated soft clay models were subjected to the accelerogram recorded at Santa Cruz during the 1989 Loma Prieta Earthquake. Scaled versions of the input motion were used to shake the soil models; in addition, different time steps were used in order to study the effects of frequency content of the input motion. The results confirm that the characteristics of the input motion and the soil model combine to have important effects on soil response. This fact must be recognized when selecting input motions for physical model tests.

INTRODUCTION

Dynamic geotechnical centrifuge modeling is being used increasingly to study site response, liquefaction, soil-structure interaction, and other geotechnical problems. In recent years, the development of more sophisticated shake tables for use in dynamic geotechnical centrifuge modeling has enabled researchers to subject soil models to a wide range of simulated earthquake loadings.

It has long been recognized that different earthquakes can produce markedly different ground motions at a soil site. Analytical site response studies have shown that calculated ground motions for soil sites are primarily affected by the intensity and the frequency content of the input rock motion (e.g. Idriss 1991). Since the response of a soil site is highly dependent on the input earthquake rock motion, the input motion or motions applied during a dynamic centrifuge test must be considered carefully. A wide range of possible input motions should be used covering the probable range of motions that may occur in the prototype. This is especially important when examining failure mechanisms using the centrifuge because the dynamic response of the soil model is not necessarily known *a priori.*

This paper summarizes the results from several centrifuge experiments that were performed as part of a study to assess the influence the local site conditions on earthquake ground motions. Each model was subjected to several earthquakes. The intensity and frequency content of the earthquakes were varied to evaluate the response of level ground soil models.

CENTRIFUGE EXPERIMENTS

Each experiment was performed at a centrifugal acceleration of 50 *g* using the 1 m radius centrifuge at the University of California, Davis. The centrifuge is equipped with a shaking table driven by a servo-hydraulic actuator which is capable of approximately reproducing earthquake time histories.

Soil models were tested in the "hinged-plate" model container described by Fiegel et al. (1994). Guidelines presented in previously published research (e.g. Whitman and Lambe 1986; Campbell et al. 1991; Schofield and Zeng 1992) were followed in designing the hinged-plate container so that it would simulate one-dimensional vertical propagation of shear waves. The container consists of four rectangular aluminum frames and has the following inside dimensions: 38.1 cm long, 21 cm wide, and 22.9 cm deep. As shown in Fig. 1, the side and end plates of the rectangular frames are composed of two angles and a square tube. The side plates rest on steel balls which are supported by an external rail and column system; therefore, each level of the container is free to move back-and-forth in the direction of shaking. The end plates of the container are connected to the side plates with a bearing type joint which allows each end plate to rotate. Confinement or continuity along an end wall is provided by a hinge between the end plates of each level. A thin roughened aluminum sheet lies next to each end wall. This shear sheet, which is fixed to the base of the model container, accounts for dynamic complementary shear stresses that occur during shaking (Schofield and Zeng 1992).

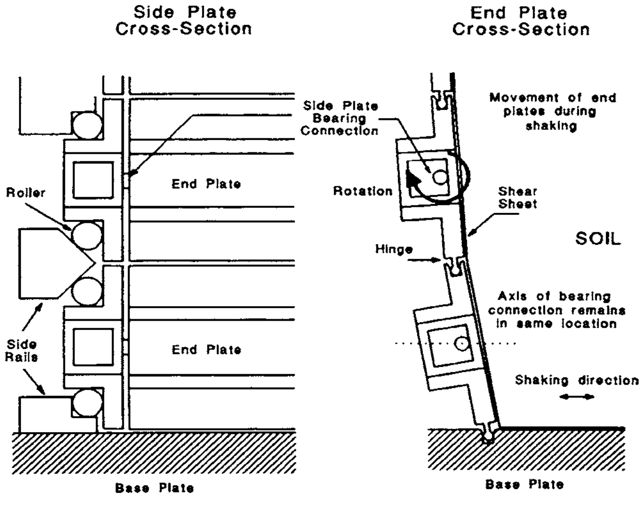

Fig. 1 The concept of the hinged-plate container design (from Fiegel et al. 1994)

Medium dense dry sand and saturated soft clay models were examined using the hinged-plate model container. The sand models consisted of 12.5 cm and 19 cm high deposits placed at 60% relative density. The sand was uniformly graded with a coefficient of uniformity of 2 and a mean grain size of 0.13 mm. The clay models consisted of approximately 20 cm of normally consolidated clay overlain by 1 cm of dense sand; the average water content of the clay was approximately 52%. The clay had a liquid limit of 56% and a plasticity index of 28%.

Accelerometers were placed within each model; pore pressure transducers were included in the clay models. In addition, a displacement transducer was used to measure settlement at the surface of each model, and small linear potentiometers were located on the outside of the hinged-plate model container to measure relative horizontal displacement at different elevations during shaking. The potentiometers allowed for the determination of shear strain time histories for the soil model.

During the sand experiments, earthquakes were applied to the models within a few minutes after the proper centrifuge speed was achieved; the smallest amplitude earthquakes were applied first followed by successively larger amplitude earthquakes. During the clay experiments, pore-water pressure within the clay and settlement at the surface were continuously monitored. Initially, each model was spun until the pore pressures and settlement exhibited negligible change with time; this indicated that primary consolidation was essentially complete. The clay models were shaken within a few minutes after primary consolidation. As with the sand models, the smallest amplitude earthquakes were applied first followed by successively larger amplitude earthquakes. After each earthquake, the model was allowed to spin without further shaking until earthquake-induced excess pore-water pressures had dissipated.

EARTHQUAKE INPUT MOTIONS

Typically an actual earthquake accelerogram is chosen for use as the input motion in a centrifuge experiment. It should be noted, however, that the accelerogram measured at the base of the model container during a centrifuge experiment will not be identical to the original earthquake input motion; in dynamic centrifuge model experiments the original input motion is influenced by the shaker-model system.
The accelerogram recorded at Santa Cruz during the 1989 Loma Prieta Earthquake was utilized in this study. Shown in Fig. 2 are acceleration response spectra calculated for the Santa Cruz motion input to the shaker-model system and the actual motion measured at the base of the model container. As indicated, the shapes of the two spectra are similar; however, for this experiment the high frequency components of the original motion were attenuated while the low frequency components were amplified.

Three sets of earthquake input motions were derived from the Santa Cruz accelerogram. The time step (DT) of the original Santa Cruz recording was 0.02 s. In order to study the effects of loading frequency on soil response, the original time step was halved and doubled thus creating a total of three input motions. Fig. 3 shows the three input motions (scaled to prototype values) that were recorded at the model base during an experiment. As indicated, the prototype peak acceleration for each motion shown in Fig. 3 is approximately 0.3 *g*. As part of this study, each Santa Cruz earthquake input motion was scaled to produce input motions with prototype peak accelerations of 0.1 *g*, 0.3 *g*, and 0.6 *g*; thus, up to nine Santa Cruz earthquake motions could be used to shake the sand and clay models.

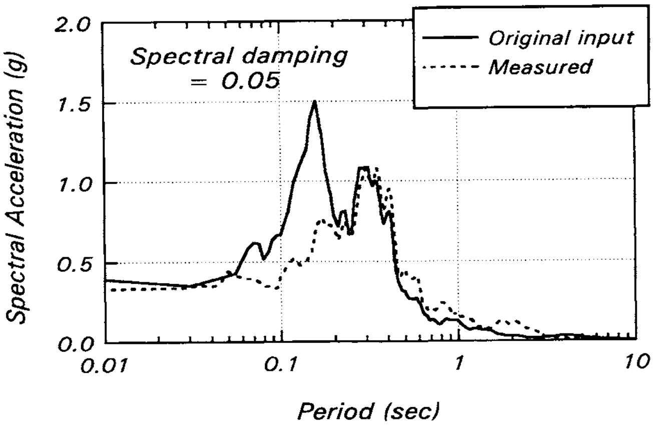

Fig. 2 Comparison of acceleration response spectra for input and measured Santa Cruz motions.

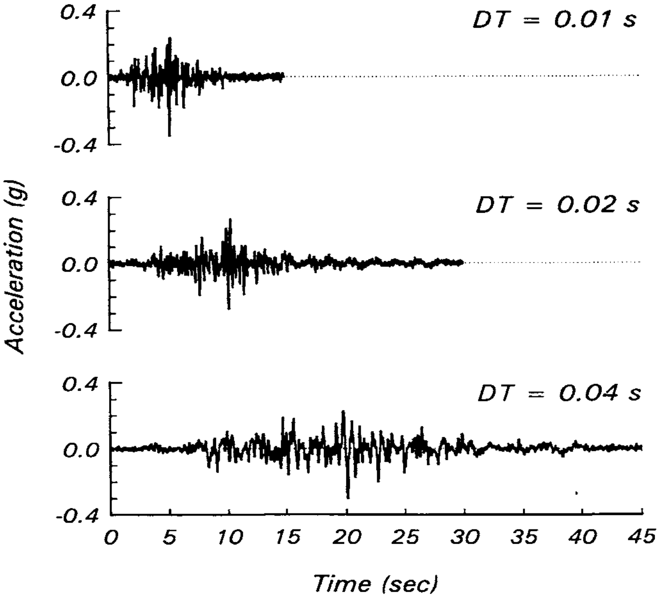

Fig. 3 Santa Cruz acceleration time histories

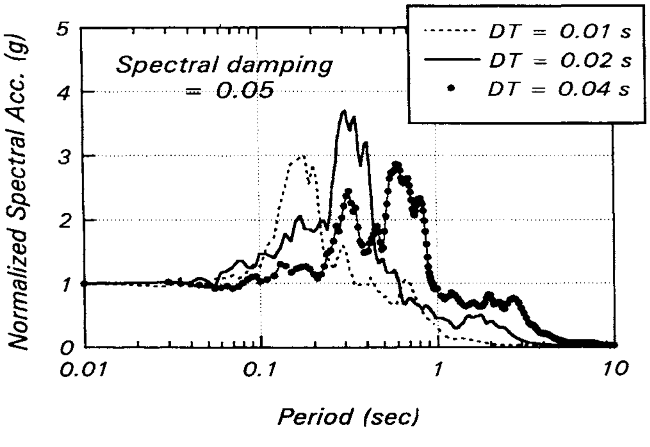

Fig. 4 Plots of normalized spectral acceleration for the three Santa Cruz motions

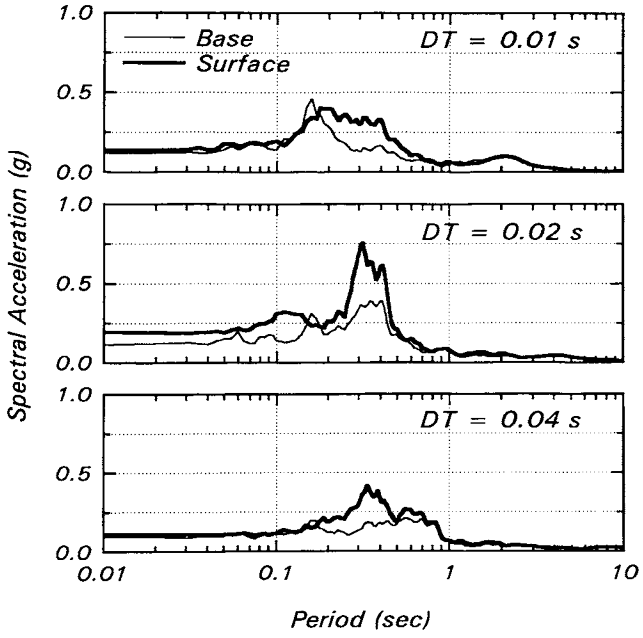

Fig. 5 Base and surface prototype acceleration response spectra for three 0.1 g shaking events (sand model); spectral damping = 0.05

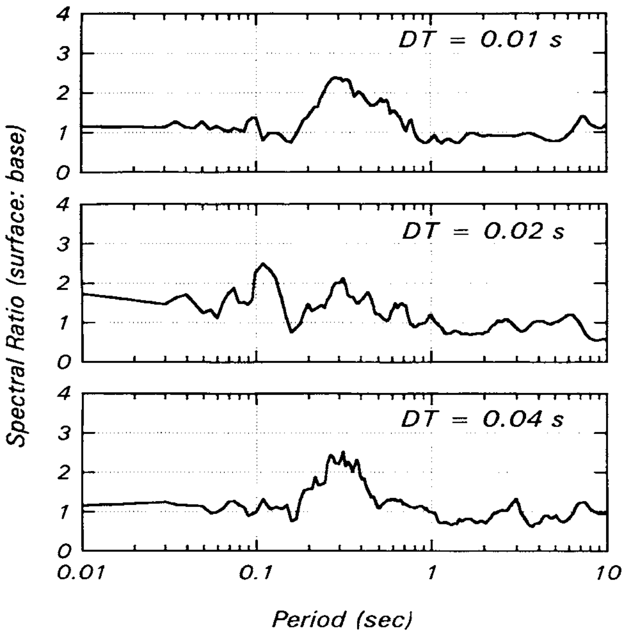

Fig. 6 Spectral ratios found for the three 0.1g shaking events (sand model)

Normalized acceleration response spectra or spectral shapes for the three motions in Fig. 3 are shown Fig. 4. These spectral shapes show that the predominant periods for the DT = 0.01, 0.02, and 0.04 s earthquakes are approximately 0.15, 0.30, and 0.60 s, respectively.

RESULTS OF CENTRIFUGE EXPERIMENTS

Sand Experiments

Initial experiments were conducted with a medium dense dry sand model approximately 12.5 cm high. This model was subjected to a total of six Santa Cruz earthquakes. Shown in Fig. 5 are base and surface prototype acceleration response spectra for three 0.1 *g* shaking events; Fig. 6 includes spectral ratios for each event. Spectral ratio is defined as the ratio of the surface acceleration response spectrum to the base acceleration response spectrum.

Response of the sand layer was greatest for the DT = 0.02 s shaking event. Peaks evident on the spectral ratio plots in Fig. 6 indicate that the natural period of the sand layer was approximately 0.3 s. This helps to explain why the response of the sand layer was greatest for the DT = 0.02 s event. As shown, the input base motions measured for the DT = 0.01 s and DT = 0.04 s events have a majority of their shaking energy below and above the natural period of the sand layer; however, the DT = 0.02 s event has a predominant period comparable with the natural period of the sand layer. A plot of peak acceleration at the soil surface versus peak acceleration measured at the model base is shown in Fig. 7 for two sand models. The plot shows that the response of the sand layer was also greatest for the DT = 0.02 s event for higher levels of shaking.

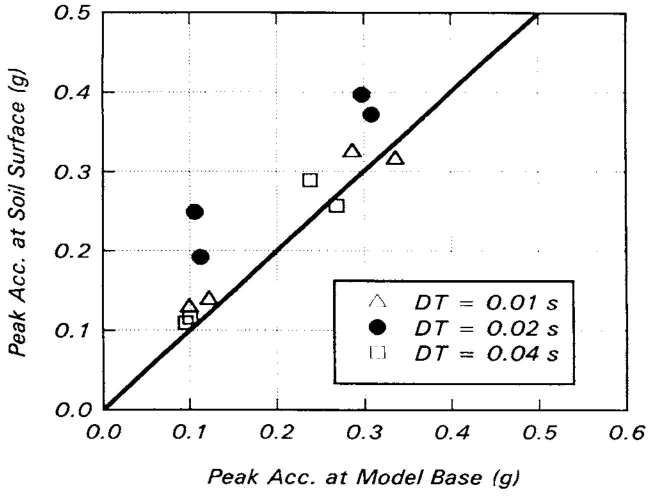

Fig. 7 Peak accelerations measured at the base and at the surface of a sand model

Another suite of dry sand experiments was performed using a model that was approximately 19 cm in height. In these experiments the model was subjected to three DT = 0.02 s earthquakes with prototype peak accelerations of 0.1 *g*, 0.3 *g*, and 0.6 *g*, respectively. Spectral ratios for one test are shown in Fig. 8. Results from the 0.1 *g* shaking event indicate that the natural period of the sand layer was about 0.45 s; as expected, this period was greater than the period found for the shorter 12.5 cm model. Values of spectral ratio for higher levels of shaking were lower than those found for the 0.1 *g* event; in addition, with increased shaking levels the apparent natural period of the sand layer shifted slightly toward higher periods.

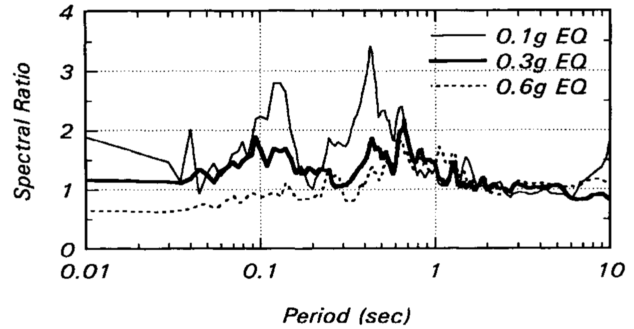

Fig. 8 Spectral ratios found for a sand model subjected to a DT = 0.02 s Santa Cruz event scaled to produce three levels of intensity

Clay Experiments

The clay models were subjected to up to nine earthquake motions. As indicated previously, the nine earthquake motions were derived from the Santa Cruz accelerogram recorded during the Loma Prieta Earthquake.

Shown in Fig. 9 are base and surface prototype acceleration response spectra for the 0.1 *g* shaking events of one experiment; shown in Fig. 10 are corresponding spectral ratios. The results from the DT = 0.02 s and DT = 0.04 s events show that significant amplification occurred at periods that were coincident with high energy components of the base motion. However, significant amplification for the DT = 0.01 s event occurred at periods that were much higher than the 0.15 s base motion predominant period. As indicated in Fig. 10, the peak spectral ratios for the three shaking events occurred between periods of 0.6 and 0.9 s; the amplification of the base motion was largest for the DT = 0.01 s event and smallest for the DT = 0.04 s event.

Shown in Figs. 11 and 12 are prototype acceleration response spectra and spectral ratios for the 0.3 *g* shaking events of the same clay experiment. For this level of shaking the peak spectral ratios for the three events occurred between periods of 0.8 and 1.1 s. The amplification of the base motion was largest for the DT = 0.01 s event. Significant amplification for this event again occurred at higher periods where the shaking energy was relatively low. The peak spectral ratio was similar to the value calculated for the 0.1 *g* event; thus, it appears that the shaking energy for periods greater than about 0.3 s was again small enough to generate near linear response for this event. In contrast, the spectral ratios in Fig. 12 corresponding to the DT = 0.02 s and DT = 0.04 s 0.3 *g* shaking events were smaller than those found for the 0.1 *g* events. These lower spectral ratios indicate that the level of shaking for these 0.3 *g* events was strong enough to cause some nonlinear soil response.

Spectral ratios for the three DT = 0.02 s earthquake input motions are plotted together in Fig. 13. The plot shows that spectral ratios were greater for the smaller shaking events for periods less than about 1.3 s; however, this trend was reversed for longer periods. As indicated, the peak spectral ratios occurred at longer periods as the level of shaking was increased.

Observations Regarding Soil Nonlinearity

Maximum shear strains were measured at the center or mid-depth of the model for the soft clay experiment described above. Values of maximum shear strain are plotted in Fig. 14 versus peak acceleration measured at the model base for each Santa Cruz event; also plotted are results from earthquakes performed as part of two other clay model experiments. The results presented in the figure show that a wide range of shear strains were measured for similar shaking levels; in addition, the results show that shear strains were larger as the level of shaking was increased.

The dashed lines drawn in the Fig. 14 illustrate trends in the data for each of the three Santa Cruz input motions. Maximum shear strain is approximately proportional to peak base acceleration for the DT = 0.01 s motion; however, maximum shear strain is not proportional to peak base acceleration for the DT = 0.02 s and DT = 0.04 s motions. As indicated, the relationship between maximum shear strain and peak base acceleration for the DT = 0.02 s and DT = 0.04 s motions is nonlinear; further, the trends for these two motions indicate that a limiting value of shear strain exists for high levels of shaking. Overall, the trends illustrated in Fig. 14 indicate that the maximum shear strain for this particular model soil deposit was affected by both the level of shaking and the frequency content of the input motion.

To further check on whether the behavior of the soft clay model was nonlinear or not, the predominant period of the model was estimated using the spectral ratios discussed earlier. If a smooth curve is approximated for a spectral ratio plot, then a peak spectral ratio and corresponding predominant period can be estimated for each level of shaking. For example, "average' predominant periods for the 0.1 *g*, 0.3 *g*, and 0.6 *g* shaking events shown in Fig. 13 were found to be approximately 0.6 s, 0.9 s, and 1.9 s, respectively. These three periods are plotted in Fig. 15 as a function of peak base acceleration; in addition, points corresponding to other shaking events and other model tests are plotted in this figure. The nonlinear trend illustrated by the dashed lines in Fig. 15 is similar to the trend shown in Fig. 14. Overall, the plot shows that there was a definite increase in the period of maximum spectral amplification (predominant period) as the level of shaking was increased.

DISCUSSION

The results presented in this paper illustrate the effects that different earthquake input motions can have on the response of a soil layer. Soil response can vary depending on whether the input motion has a predominant period similar to the natural period of the soil deposit; this was clearly evident for the sand experiments as well as for the clay experiments. In these experiments, measured soil response was markedly different for earthquake motions with similar intensity but different frequency content.

Earthquake input motions with similar frequency content but varying intensity also affected soil response. The intensity of an earthquake is one of the primary factors controlling the degree of soil nonlinearity that a model will experience. The results from the sand experiments showed that increasing earthquake intensity caused smaller amplification of response at periods shorter than about 1 s; at larger periods similar amplification was obtained for all the intensity levels used. The results from the clay experiments showed that the amplification of response decreased for periods shorter than 1.3 s as the earthquake intensity was increased. The opposite effect was observed for periods larger than 1.3 s emphasizing the nonlinear behavior of the clay tested in these experiments.

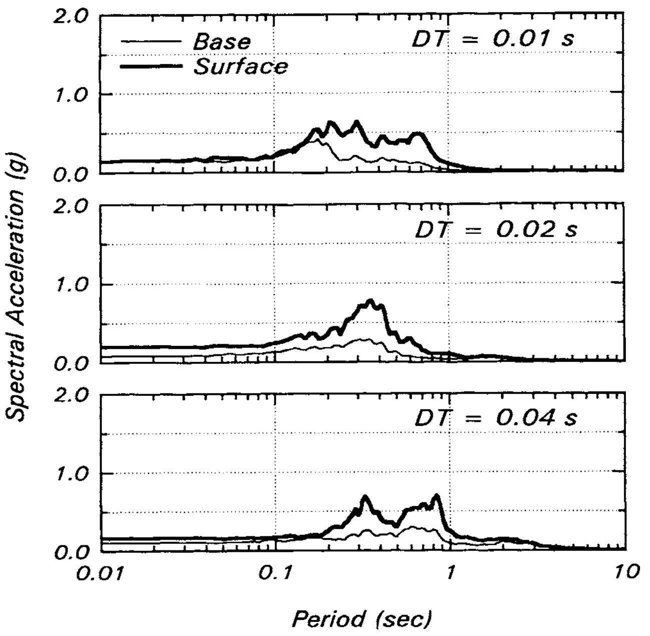

Fig. 9 Base and surface prototype acceleration response spectra for three 0.1 g shaking events (clay model); spectral damping = 0.05

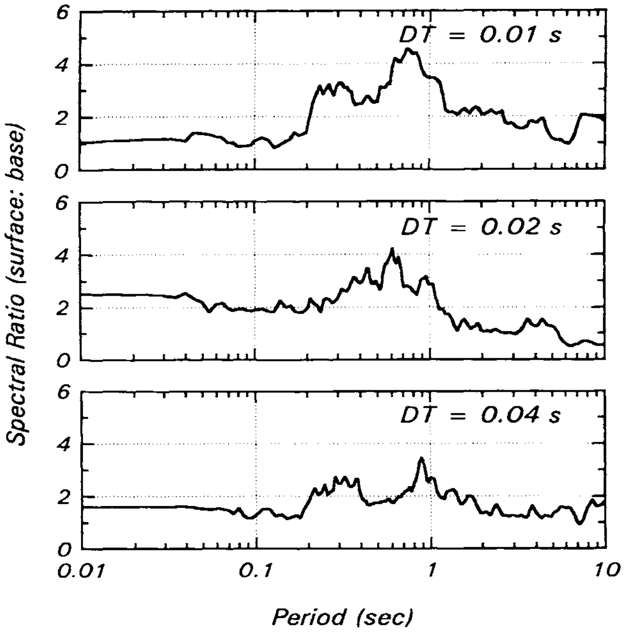

Fig. 10 Spectral ratios found for the three 0.1 g shaking events (clay model)

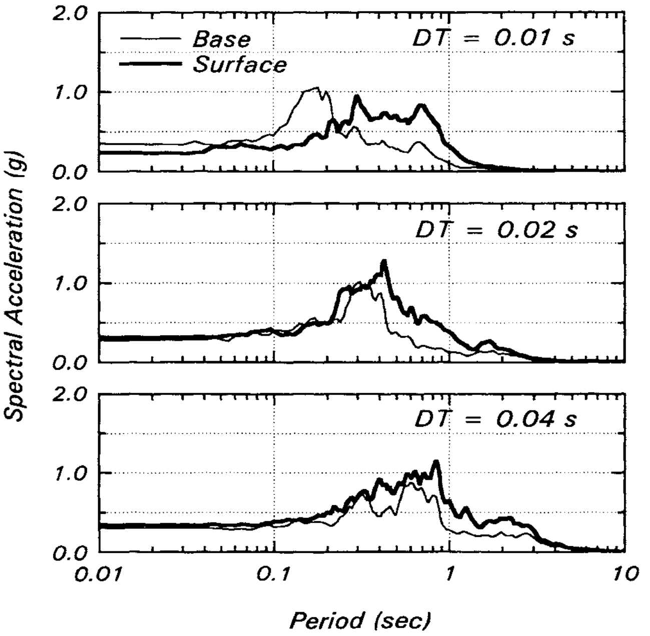

Fig. 11 Base and surface prototype acceleration response spectra for three 0.3 g shaking events (clay model); spectral damping = 0.05

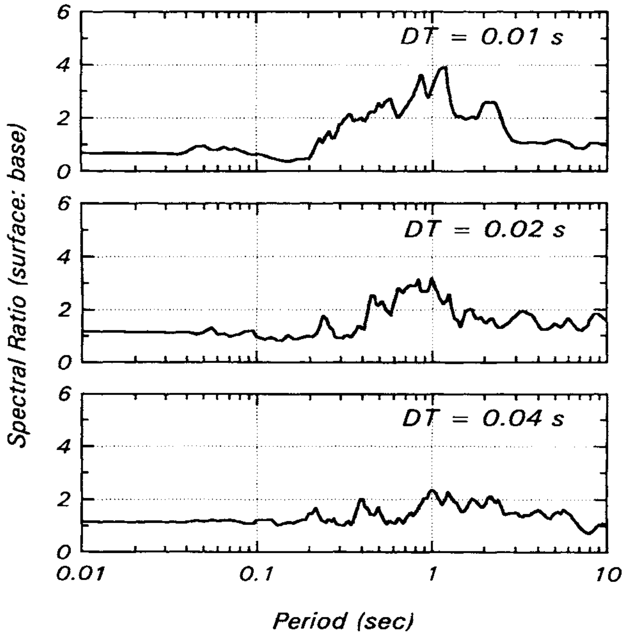

Fig. 12 Spectral ratios found for the three 0.3 g shaking events (clay model)

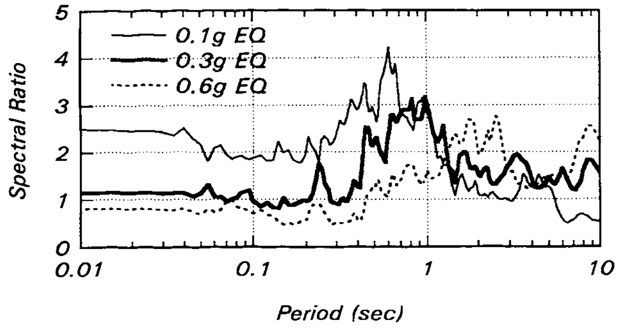

Fig. 13 Spectral ratios found for a clay model subjected to a DT = 0.02 s Santa Cruz event scaled to produce three levels of intensity

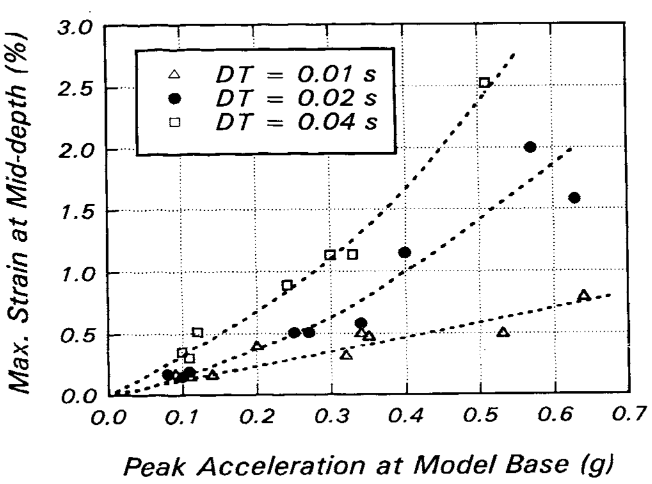

Fig. 14 Maximum strain measured at mid-depth plotted versus peak base acceleration for several clay models subjected to the Santa Cruz event

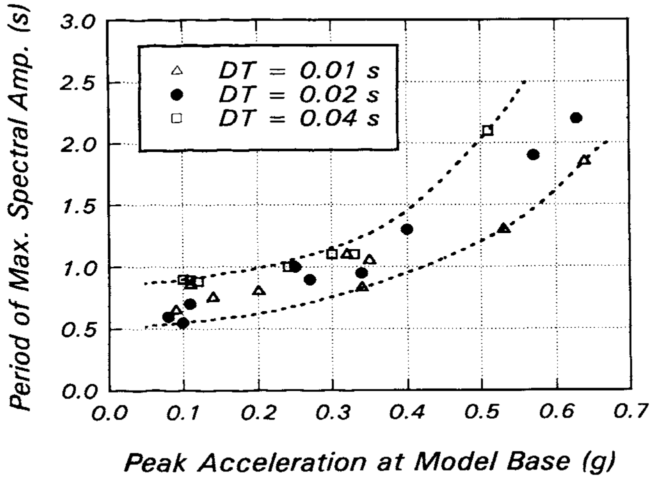

Fig. 15 Period of maximum spectral amplification plotted versus peak base acceleration for several clay models subjected to the Santa Cruz event

CONCLUSION

The results presented in this paper highlight the importance of understanding the dynamic characteristics of a centrifuge soil model. These characteristics should be known prior to conducting a centrifuge experiment so that proper earthquake input motions can be selected; the same is true when utilizing other experimental techniques and analytical procedures. If a single earthquake motion is chosen for use in a series of experiments without regard for the dynamic characteristics of the soil model, then incomplete conclusions can be drawn regarding the phenomenon being evaluated.

The authors have found that the following procedure can be effective when conducting dynamic model experiments:

1.) Estimate the natural frequency of the soil model using basic calculations or analytical procedures.

2.) Construct a model identical to the soil model being tested. Subject this model to a series of low intensity sinusoidal motions of varying frequency content in order to understand the dynamic characteristics of the soil-container system.

3.) Compare the calculated natural frequency with the natural frequency found for the model. A large discrepancy between the two must be addressed when interpreting the experimental results.

4.) Choose a motion or series of motions for use in the research program that will address the phenomenon being investigated as completely as possible. The intensity and frequency content of these motions should be similar to those expected in the prototype.

ACKNOWLEDGEMENT

The test results included in this paper are part of a research program sponsored by the California Department of Transportation (Caltrans) under Contract RTA59T342 A/2; Mr. James Moese is the contract monitor. This support is gratefully acknowledged.

REFERENCES

Campbell, D., Cheney, J., and Kutter, B.L. (1991). "Boundary effects in dynamic centrifuge model tests." *Proc., Centrifuge 91*, Boulder, Colorado, A.A. Balkema Publishers, 441-448.

Fiegel, G.L., Hudson, M., Idriss, I.M., Kutter, B.L., Zeng, X. (1994). "Effect of model containers on dynamic soil response." *Proc., Centrifuge 94*, Singapore, A.A. Balkema Publishers.

Idriss, I.M. (1991). "Earthquake ground motions at soft soil sites." *Proc., Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Vol. 3*, St. Louis, Missouri, 2265-2272.

Schofield, A.N. and Zeng, X. (1992). "Design and performance of an equivalent-shear-beam container for earthquake centrifuge modeling." *Cambridge Report: CUED/DSOILS/TR245.*

Whitman, R.V. and Lambe, P.C. (1986). "Effect of boundary conditions upon centrifuge experiments using ground motion simulation." *Geotechnical Testing Journal*, ASTM, 9(2), 61-71.