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# CENTRIFUGE MODEL TESTS TO IDENTIFY DYNAMIC PROPERTIES OF DENSE SAND FOR SITE RESPONSE CALCULATIONS

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## ABSTRACT

Four centrifuge models, tested on the large centrifuge at UC Davis, are described in this paper. These four experiments involved dense profiles of Nevada Sand ($D_r$ = 90 to 100%) tested in two different model containers. The purpose of the experiments was to evaluate numerical site response procedures by comparison with model test data. In this paper we focus on determining basic material properties of one of the models by using in-flight measurements of shear wave velocity and calculations of stress-strain relationships using data from an extensive array of accelerometers. Shear wave velocity profiles were measured at centrifuge accelerations of approximately 10, 20, and 40 g; and before, during, and after the models were subject to base shaking using the servo-hydraulic shaker in an attempt to identify any influence of shaking history on shear wave velocity. The base shaking included realistic earthquake time histories scaled in frequency and amplitude to simulate motions with low, medium, and high intensity, and motions that included sinusoidal sweeps of different frequencies. A new windowing procedure to compute shear modulus and shear strain amplitude time histories from accelerometer array data is briefly described.

## INTRODUCTION

In January 1998, a workshop, organized by Dr. Edward Field, was convened at the University of Southern California with aim to document how nonlinear seismic soil response (unrelated to liquefaction) is perceived by the seismological and geotechnical engineering communities. The workshop revealed that some seismologists feel nonlinear or even equivalent linear analyses may not be necessary; that linear site response calculations may be adequate. Geotechnical engineers generally recommend that if ground response analysis is to be carried out to predict the response to strong shaking, then the nonlinearity needs to be taken into account by equivalent linear or fully nonlinear analysis procedures. One goal of this project is to help establish guidelines as to when nonlinear site response analyses are called for and when linear or equivalent-linear analyses can adequately predict the near-surface accelerations with appropriate accuracy.

This project is a collaborative effort between UC Davis and UC San Diego (UCSD). The UC Davis team has thus far focused on performing and documenting highly instrumented, repeatable, physical model tests to determine the linear and nonlinear behavior of stiff soil sites during small and large earthquakes. The team from UCSD has focused on numerical simulations of the centrifuge model site configurations. A sister paper from the UCSD team in this conference [Elgamal et al. (2000)] presents site response calculations compared to some of these test results.

This paper presents shear modulus data deduced from in-flight shear (S-) wave velocity measurements and shear modulus and degradation behavior obtained by back-analysis of accelerometer data. A procedure for computing a time-history of shear modulus is introduced. The documentation from the experiments, including the data files and model descriptions, are available to interested researchers over the Internet through the web server of the Center for Geotechnical Modeling at http://cgm.engr.ucdavis.edu.

## CENTRIFUGE MODEL CONFIGURATIONS

Four level-ground sand models (numbered DKS02 to DKS05) were constructed of Nevada Sand and tested on the large servo-hydraulic shaking table mounted on the large centrifuge at UC Davis (Kutter et al. 1994). The model configurations are shown in some detail in Fig. 1. Two models (DKS02 and DKS04) were tested in a "flexible shear beam" container. The other two were tested in a stiff walled container. Three of the models had a depth of about 0.5 m, and the other (DKS05) had a smaller depth (0.245 m). In DKS05, the sand was placed in a

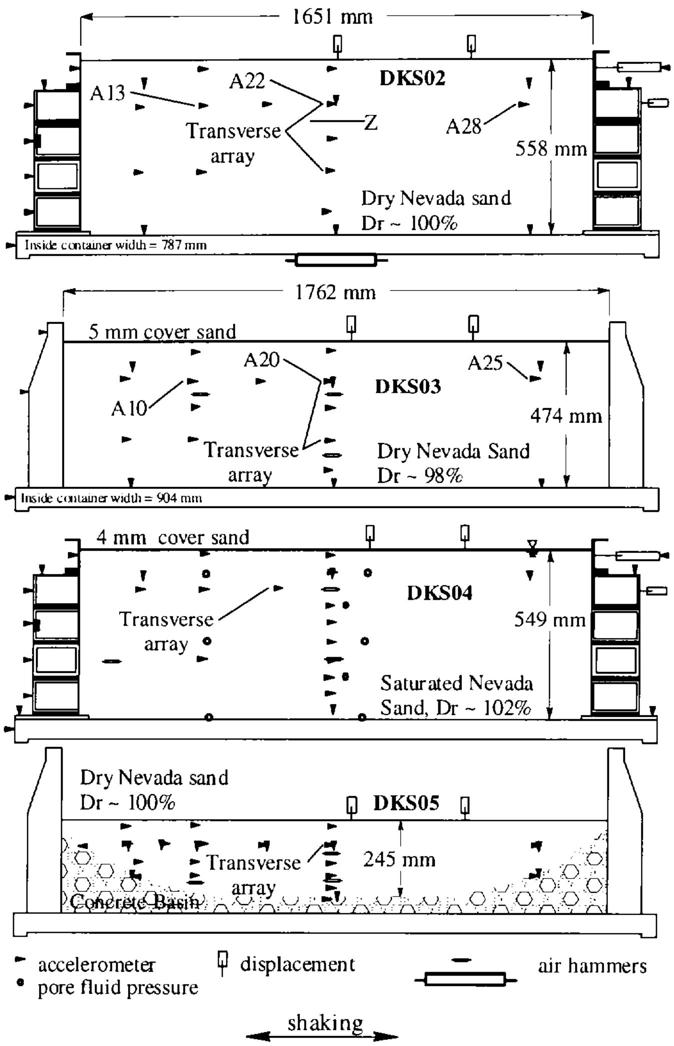


*Fig. 1. Model profiles as tested*

smoothly curving basin formed by casting concrete in the stiff-walled container, and was instrumented in an attempt to document basin effects. Model DKS04 was saturated with a viscous pore fluid (hydroxypropyl methylcellulose dissolved in water), but all other models consisted of dry sand.

Each model was instrumented with extensive horizontal and vertical arrays of accelerometers, as shown in Fig. 1. Instruments for which data are presented in this paper are labelled with instrument numbers. Longitudinal horizontal arrays (in a row along the direction of shaking) were included to enable quantification of end effects. Transverse arrays, also noted in Fig. 1, were included to be sensitive to side effects and torsional response of the model. Vertical accelerometers were included in each model to record accelerations due to cyclic dilatancy, basin effects, and undesired rocking of the container/centrifuge bucket.

Different prototype soil depths were simulated by shaking each model while spinning at centrifuge accelerations of 10, 20, and 40 g. Air hammers were used as S-wave sources to measure S-wave velocity profiles at various stages of the centrifuge tests.

## SHEAR WAVE VELOCITY MEASUREMENTS

Bender elements have been used by others as S-wave sources for laboratory tests, but in the centrifuge environment models are fairly large and ambient vibrations produce mechanical noise that tends to overwhelm the small waves produced by bender elements. To resolve this problem, air hammers have been developed as simple alternative S-wave sources. An air-hammer consists of a small-diameter metal tube with a Teflon piston. Regulated air pressure is ported to either side of the piston through a four-way valve. Firing the hammer involves pressurizing one side of the chamber and venting the opposite side, which shoots the piston from one end of the chamber to the other. The piston hitting the end of the chamber imparts a P-wave off the end of the chamber and S-waves propagating radially away from the longitudinal chamber walls. The S-wave particle vibration is thus parallel to the chamber length. An external air hammer was developed and attached to the bottom of the base plate at the centerline in DKS02 as shown in Fig. 1. The source waves, though useful, were not as clean as desired. In later tests, internal mini-air hammers (Arulnathan et al. 2000) were used as S-wave sources, as indicated in Fig. 1.

Fig. 2 shows the high quality S-wave propagation data produced by internal mini-air hammer tests in the central vertical array of test DKS03. The "***hit***" labels in Fig. 2 show the location and time at which hammer impact occurred. The first hit occurred for the hammer located at a depth of about 15 m at a time of approximately 0.04 s. The S-wave can be tracked up through the soil profile, and reflecting off the container base and back up through the soil profile. The second hit (at a time of approximately 0.26 s, due to a bounce of the same hammer) produces a similar signature. The hit at a time of 0.38 s was from a shallower hammer at a depth of about 7 m.

Each model included over 75 hammer hits to measure S-wave velocities in various locations. Some data was interpreted by hand, as indicated in Fig. 2, but this was time consuming. A more automated procedure using cross-correlation functions was developed to determine the time lag between instruments. The velocities from all air hammer tests on model DKS03 are plotted as a function of the vertical effective stress in Fig. 3. The velocities are normalized by the velocity of a compression wave in water (1550 m/s) and stresses are normalized by atmospheric pressure (101.3 kPa). The data are broken into "set 1" and "set 2". Set 1 data includes only normally consolidated soil profiles, before the models were subject to large (greater than 0.1 g prototype) base shaking events. Thus set 2 includes effects of overconsolidation and seismic history on the shear modulus. As expected, seismic history and overconsolidation increase (albeit slightly) the S-wave velocity. Changes in lateral earth pressure could be the predominant factor causing the increase in shear modulus. The

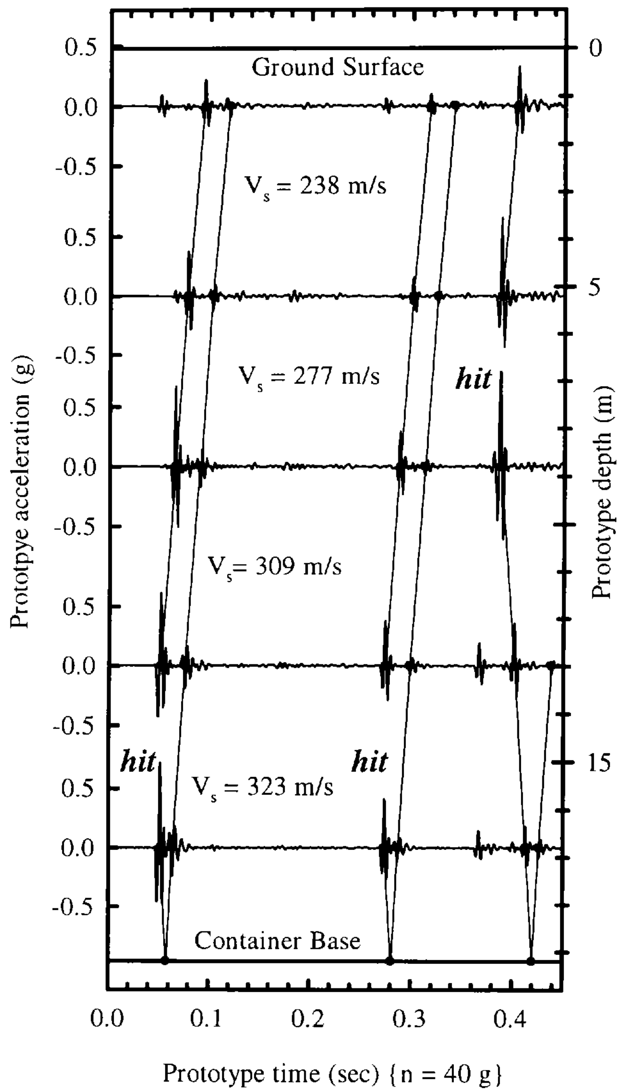


*Fig. 2. Air hammer time histories from DKS03 recorded prior to seismic shaking.*

soil is initially very dense; thus we would not expect (and indeed, did not observe) significant densification due to seismic history.

A linear regression was fit to the set 1 data from each model. These results are also presented in Fig. 3 for reference. The data reports and electronic data from all S-wave velocity measurements are available for download on the Internet at http://cgm.engr.ucdavis.edu.

## GROUND MOTION SIMULATION

A wide variety of ground motion time histories (sine sweeps, and realistic earthquake motions) were imposed on each model at each centrifuge acceleration. The earthquake motions were obtained by scaling the amplitude and frequency content of the recording at UC Santa Cruz during the 1989 Loma Prieta Earthquake. The reference prototype event was considered to occur at 20 g centrifuge acceleration. The time step of original event was scaled according to the centrifuge scaling laws: $\Delta t = \Delta t_e / 20$ ($\Delta t_e$ is the time step corresponding to the recording of the prototype record). A second model event was constructed by increasing the frequency content by approximately a factor of two by reducing $\Delta t$ to $\Delta t_e/40$. A third was made by decreasing frequency content by a factor of two by increasing the time step to $\Delta t_e/10$. These scaled events simulate the reference prototype event at 40 g and 10 g, respectively (with the amplitudes scaled accordingly). Each model was subject to each of these three motions while the centrifuge spun at 20 g. The amplitude of the motions was also varied. The same suite of motions was also applied to the models at 10 g and 40 g. Thus, the higher frequency motion represented the same prototype earthquake with a deeper soil deposit (20 m) for the 40 g test and the lower frequency motion represented the same prototype earthquake on a shallower soil deposit (5 m) when the model was subject to 10 g centrifugal acceleration.

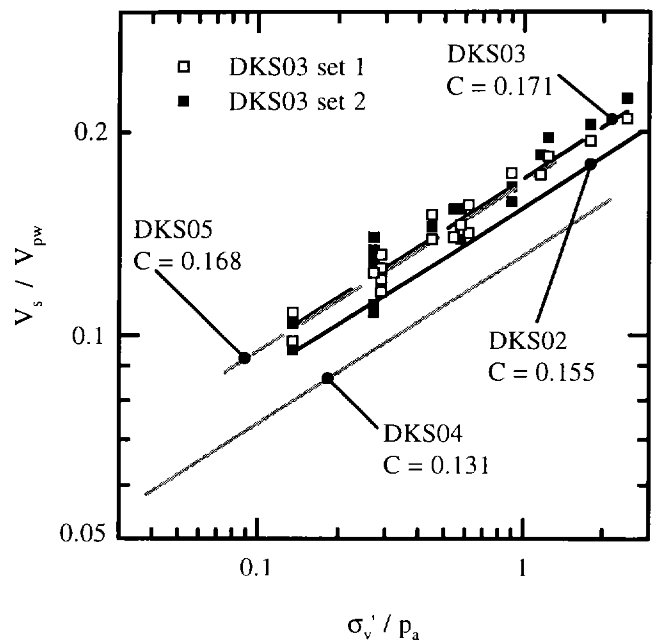


*Fig. 3. Normalized set 1 shear wave velocity versus normalized vertical effective stress for the four DKS models. For all tests* $V_s / V_{pw} = C\,(\sigma_v' / p_a)^{0.25}$.

The sine sweep motions consisted of fifteen wave packets, with fifteen cycles of constant frequency waves within each packet. Successive wave packets had a frequency 1.0676 times greater than that in the previous packet so frequency in the $n^{th}$ packet can be calculated from the equation:

$$f_n = f_1 \cdot 1.0676^{n-1} \qquad (1)$$

With the coefficient 1.0676, the ratio of the highest and lowest frequencies in an event with n = 15 is 2.5. Fig. 4 shows some data from three accelerometers (A13, A22, and A28 in Fig. 1)

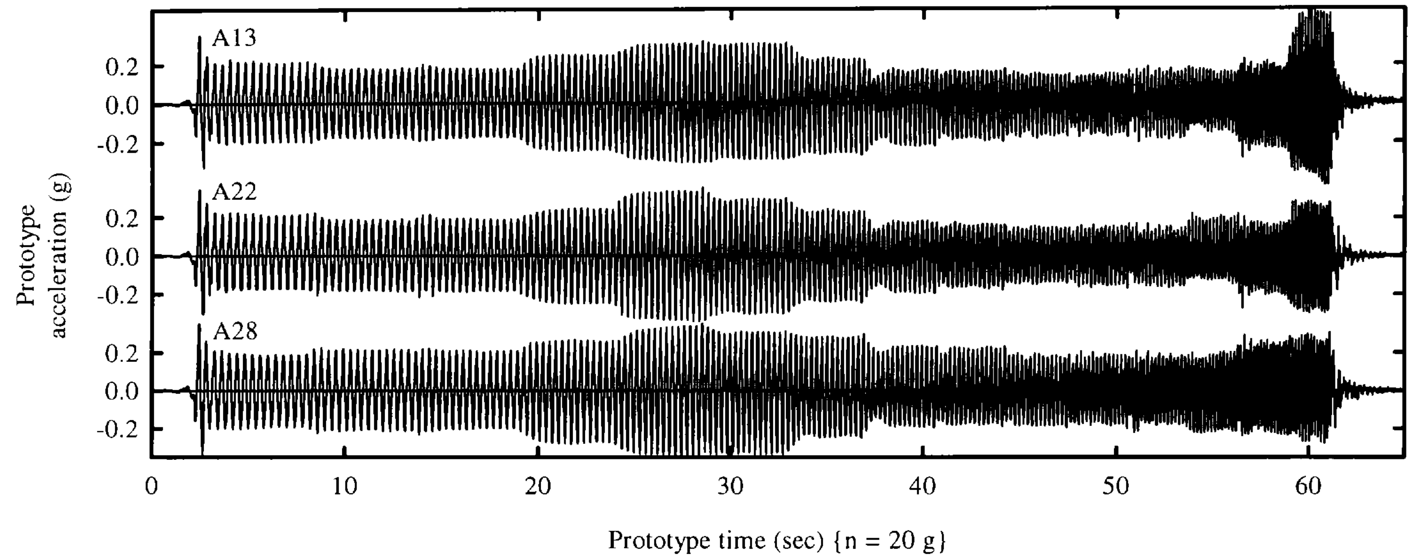


*Fig. 4. Acceleration time histories in longitudinal array from DKS02 event BG. See Fig. 1 for instrument key.*

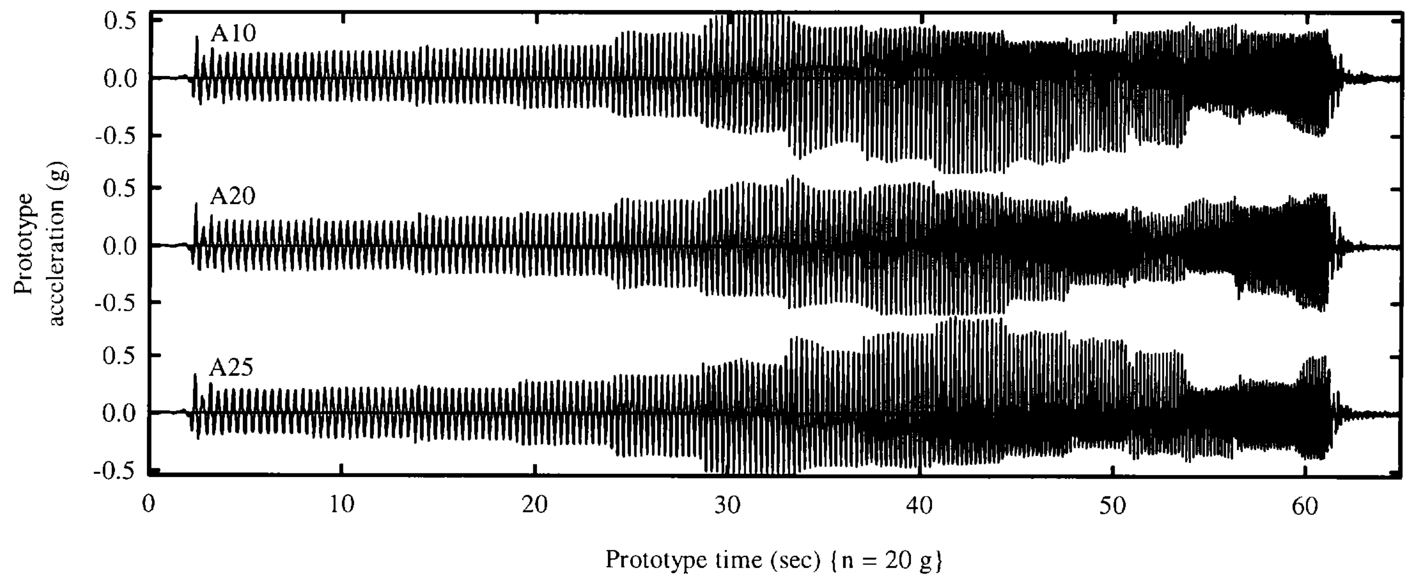


*Fig. 5. Acceleration time histories in longitudinal array from DKS03 event 59. See Fig. 1 for instrument key.*

in the longitudinal array of accelerometers at a model depth of about 140 mm in model DKS02 obtained while the centrifuge spun at 20 g. The initial frequency was 2.5 Hz (prototype) and the highest frequency in this event is 6.25 Hz (50 Hz and 125 Hz in the model). The total duration of prototype shaking in this sine sweep motion was 60 seconds. Noticeable steps in amplitude can be noticed at transitions from one packet to the next. These steps are caused by amplification of motions in the soil as well as in the servo-hydraulic system. The first packet contains 15 pulses of 2.5 Hz prototype shaking from approximately t = 2 s to t = 8 s (prototype time). The last packet contains 15 pulses of 6.25 Hz and runs from approximately t = 59 s to t = 61 s.

The data in Fig. 4 also indicate that the model response is fairly uniform along the length of the flexible container. On the other hand, Fig. 5 shows similar data obtained in the stiff walled model container. Here the asymmetry of the response due to the effects of the rigid container is apparent.

## SHEAR MODULI FROM SHAKING EVENTS

The data from each central vertical array of accelerometers has been processed to compute a moving average of the shear modulus and shear strain as described below. The concept for the shear modulus and strain calculations is similar to that

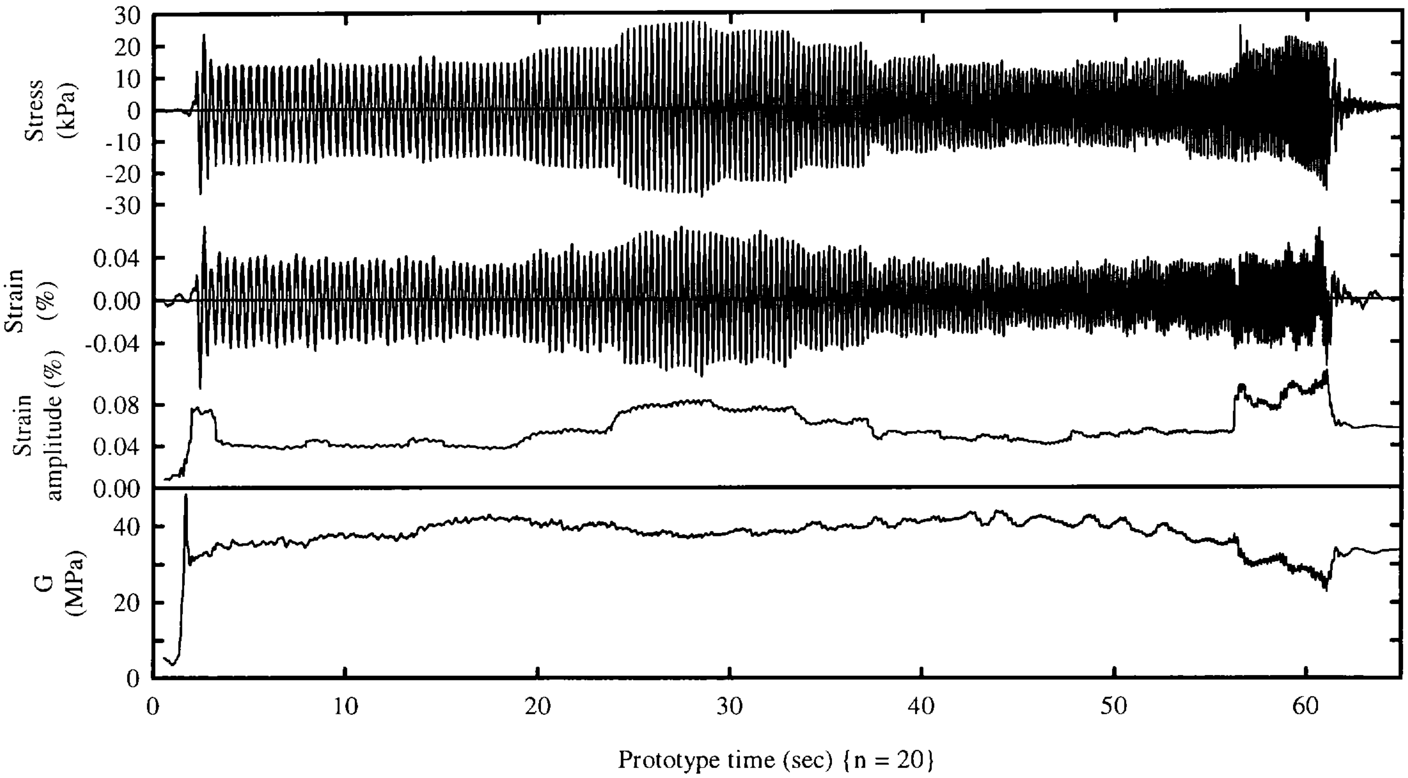


*Fig. 6. Back-calculated shear stress, shear strain, strain amplitude, and shear modulus at depth 3.9 m (Z from Fig. 1) for DKS02 event BG {n = 20 g}.*

described by Zeghal et al. (1995). A linear variation of acceleration is assumed between accelerometer locations and the mass x acceleration of soil layers is integrated from the ground surface to the depth of interest (the midpoint between two selected accelerometers) to obtain a time history of shear stress at the depth of interest. A shear strain time history is obtained by double integration of the difference between the two accelerometers and dividing this by the distance between the accelerometers. The top two traces in Fig. 6 present shear stress and shear strain time histories for event BG in test DKS02.

To obtain a shear modulus and strain amplitude time history, the procedure developed by Narayanan (1999) was adopted. In this method, a time window of stress and strain are plotted against each other. A linear regression of this data defines the shear modulus for that window. The reference shear strain for this window is obtained by dividing the maximum shear stress in the window by shear modulus. Once the shear modulus and damping are determined for the first window, the time is incremented and the next window of data is analyzed. The results are found to be somewhat sensitive to the window size, so the window size needs to be selected with care. We have chosen a window size equal to 3 complete sine wave cycles. The window size was automatically adjusted depending on the frequency of the sine wave at the midpoint of the window.

The shear modulus and strain amplitude data from Fig. 6 is plotted in the familiar modulus reduction format in Fig. 7. A value of $G_{max} \approx 93.8$ MPa, calculated from Fig. 3, was used to normalize G. The results fall within the upper and lower bound sand lines defined by Seed and Idriss (1970). Data from other depths and events are currently being examined similarly.

## SUMMARY AND CONCLUSIONS

This paper provides an introduction to a recent series of experiments that have been performed on the large centrifuge at UC Davis. A small portion of the data can be presented in a six page conference paper, but complete data reports [for example, Stevens et al (1999)] describing each experiment can be downloaded from the UC Davis Center for Geotechnical Modeling web site. The reports include a complete chronology of each test, describe the models in detail, and include electronic data from every shaking event.

In-flight S-wave velocity measurements have been presented to determine the maximum shear modulus. Data from selected shaking events has also been processed by a new procedure to produce shear modulus and shear strain time histories using a moving window technique. The modulus and strain amplitude data from a single shaking event were normalized by the maximum shear modulus derived from shear wave velocity tests of the model in flight. The resulting modulus reduction data is consistent with the modulus reduction curves typically used in site response analyses.

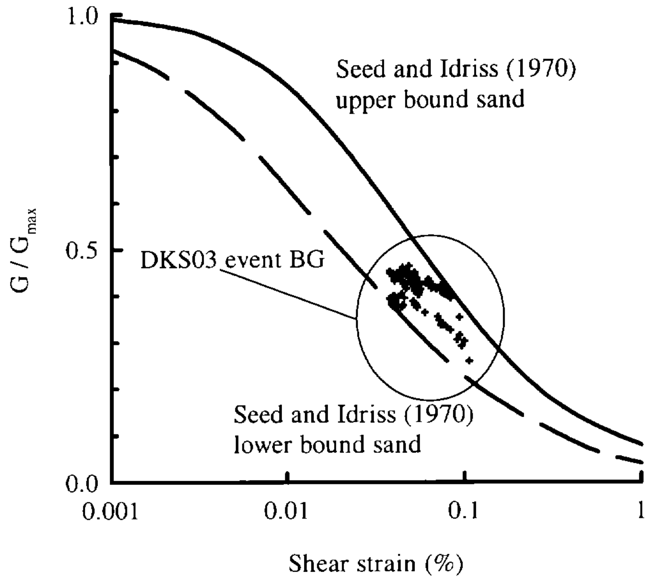


*Fig. 7. Normalized shear modulus versus shear strain at a depth of 3.9 m (Z from Fig. 1) for DKS02 event BG.*

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REFERENCES

Arulnathan, R., R. W. Boulanger, B. L. Kutter, and W. Sluis. (2000) A new tool for Vs measurements in model tests. *Geotechnical Testing Journal, GTJODJ*, ASTM, in press.

Kutter, B.L., I.M. Idriss, T. Khonke, J. Lakeland, X.S. Li, W. Sluis, X. Zeng, R. C. Tauscher, Y. Goto, and I. Kubodera, (1994) Design of a Large Earthquake Simulator at UC Davis. Proc. Int. Conf., *Centrifuge 94*, Singapore, pp. 169-175.

Narayanan, K. (1999) *Modeling the seismic response of stratified soil.* MS Thesis, Department of Civil and Environmental Engineering, UC Davis

Seed, H.B., and Idriss, I. M. (1970) Soil Moduli and Damping Factors for Dynamic Response Analyses. *Report EERC-70-10*, Earthquake Engineering Research Center, Berkeley, CA.

Stevens, D.K., D.W. Wilson, and B.L. Kutter (1999) Comprehensive investigation of nonlinear site response - centrifuge data report for DKS03. Report No. UCD/CGMDR-99/03, Center for Geotechnical Modeling, University of California, Davis. Available on Internet at http://cgm.engr.ucdavis.edu/reports.html.

Zeghal, M., Elgamal, A.W., Tang, H.T., and Stepp, J. C. 1995. Lotung downhole array. II: Evaluation of soil nonlinear properties. *J. Geotech. Engrg.*, ASCE, 121(4), 363-378.