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Identification of Small Strain Dynamic Properties of Dense Sand

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ABSTRACT

System identification techniques are employed to characterize the stiffness and damping characteristics of a dense sand stratum at low dynamic excitation conditions. The identification process utilizes a large database of input-output accelerations recorded in a highly instrumented centrifuge experimental program conducted by researchers at the University of California at Davis. This paper presents a computational effort based on the recorded small shaking events, where the peak ground surface acceleration ranges from $0.05g$ to $0.196g$ in amplitude. The dynamic behavior of the prototype stiff soil site near its first resonance is modeled by that of a one-dimensional shear beam. An employed system identification process attempts to define the shear wave velocity profile and damping that provide a best match to the experimental dynamic soil response near the first resonance, along a central downhole accelerometer array. Both linear viscous and hysteretic soil models are utilized in this identification study. The identified properties are found to be consistent among the investigated events, and are in good agreement with other laboratory estimates. The calibrated (via system identification) shear beam predications were found to be an excellent match to those recorded at all central downhole accelerometer locations around the first resonance.

INTRODUCTION

A highly instrumented centrifuge test was conducted to study the linear and nonlinear behavior of stiff soil sites during earthquakes at the University of California at Davis (UCD). The experiment employed a Flexible Shear Beam (FSB) container mounted on the $9m$-radius geotechnical centrifuge at UCD (Kutter *et al.* 1994). The FSB container dimensions are $1.651m \times 0.787m \times 0.584m$ in length, width and height respectively. Nevada sand at about 100% relative density was used to represent the stiff soil. Numerous accelerometers were installed to document the horizontal and vertical responses of the model (Fig. 1). The configuration of the FSB container and locations of the installed accelerometers are illustrated in Fig. 1.

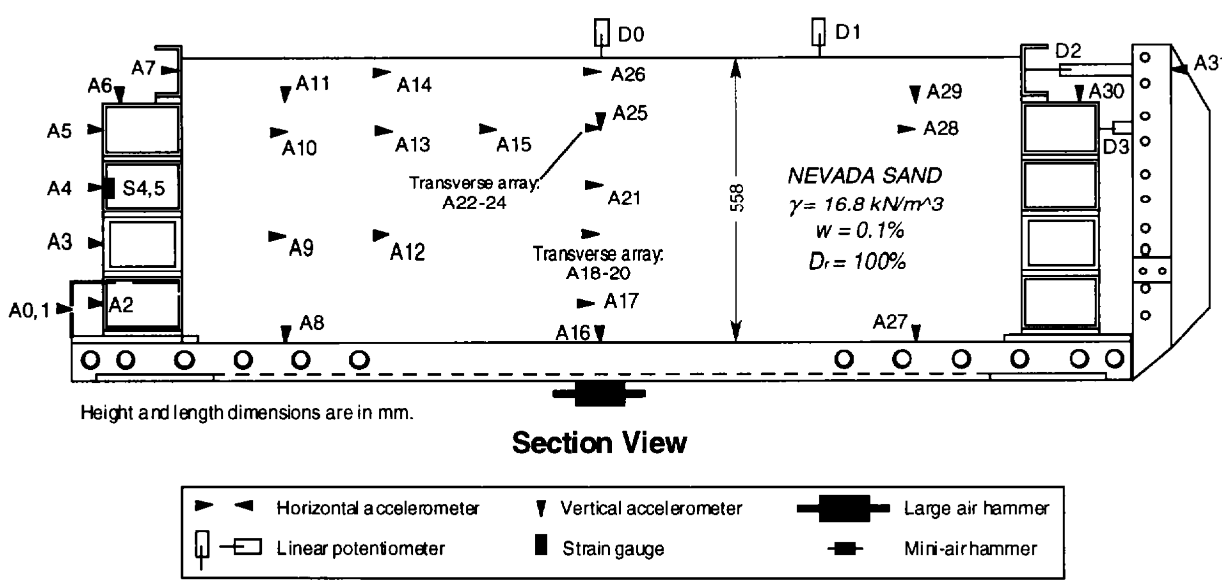

Fig. 1: Model Configuration of the DKS02 FSB Container (after Stevens et al. 1999)

Various tests, including earthquake-like excitations and frequency sweeps, were conducted under centrifugal accelerations of 10*g*, 20*g* and 40*g* respectively (Stevens *et al.* 1999). This paper presents a computational system-identification of the dynamic responses of 4.75*m*-, 9.5*m*- and 19*m*-depth dense sand sites based on recorded small shaking events at 10*g*, 20*g* and 40*g*, respectively. Surface peak ground acceleration during the selected events ranges from 0.05*g* to 0.196*g* in amplitude. The dynamic behavior of the stiff soil site near its first resonance is modeled as a 1D shear beam. The employed system identification process attempts to define the values of the two most influential but unknown properties (i.e., shear wave velocity profile and damping) that provide a best match to the experimental dynamic soil response near the first resonance, at all central downhole accelerometer locations. Both linear viscous (SBEAM) and hysteretic (SHAKE, Schnabel *et al.* 1972) soil models were utilized in this identification study. A sister publication in this conference (Stevens *et al.* 2001) also utilizes the recorded set of data (Stevens *et al.* 1999) to identify site properties and reports findings consistent with the work reported herein.

PROTOTYPE SITES

Tests at centrifugal accelerations of 10*g*, 20*g* and 40*g* represent a prototype site of 4.75*m*-, 9.5*m*- and 19*m*-depth respectively. Figure 2 illustrates the dimensions of the prototype site under various centrifugal acceleration levels with the locations of central accelerometers. It is noted that the location of input motion in our numerical model (Fig. 2) was set at **A17** instead of the actual aluminium container base as shown in Fig. 1. This modification was made in order to avoid potential relative slip movement between the container base and the overlying soil.

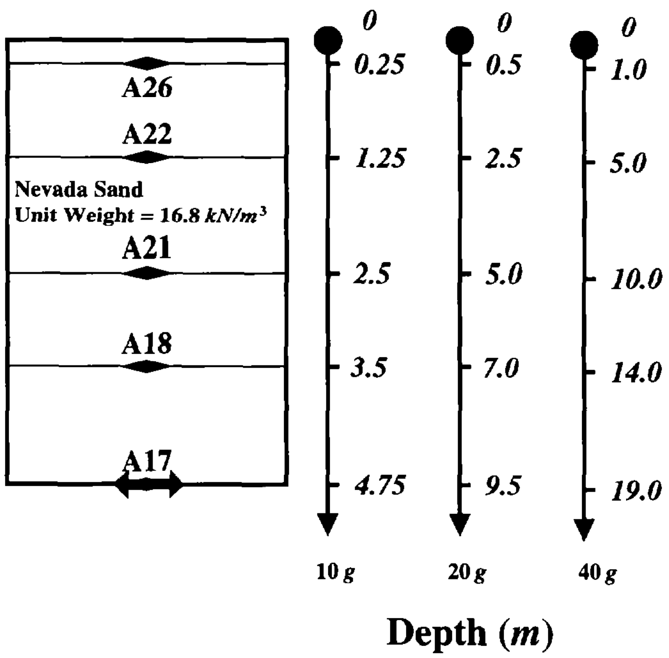

Fig. 2: Prototype Site Illustration and Locations of Central Array Accelerometers.

EVENTS SELECTED FOR THIS STUDY

Several small shaking events of the comprehensive centrifugal experimental program (Stevens *et al.* 1999) were selected for this preliminary system identification study. Table 1 lists 8 events studied along with recorded peak accelerations and centrifugal acceleration *g* levels. Surface peak ground acceleration ranges from 0.05*g* to 0.196*g* in prototype scale.

No.	Event ID	PGA at **A26**, *g*	Acceleration *g* Level
1	DKS02_c	0.073	10
2	DKS02_e	0.071	10
3	DKS02_ae	0.173	10
4	DKS02_n	0.093	20
5	DKS02_aa	0.107	20
6	DKS02_v	0.052	40
7	DKS02_bk	0.117	40
8	DKS02_bv	0.196	40

Table 1: Small Shaking Events Utilized in this Study.

IDENTIFICATION OF DYNAMIC PROPERTIES

Spectral Analyses

Spectral analyses were conducted to assess the essential features of this stiff cohesionless site. Transfer functions of Fourier spectrum amplitudes were calculated considering the base motions (**A17**) as input and the near surface motions (**A26**) as output. The average (of the Table 1 events) spectral amplitudes (Fig. 3) consistently showed a fundamental frequency of about 7.63*Hz*, 4.66*Hz* and 2.79*Hz* for the prototype site under centrifugal accelerations of 10*g*, 20*g* and 40*g* respectively. It may be seen that the fundamental frequency of the stiff site is relatively isolated from the subsequent higher resonance. A conducted preliminary 3D eigenvalue study confirmed this observation, with the first mode of the 3D configuration being similar to the first mode of a 1D shear beam. As such, the dynamic behavior of the stiff soil site near its first resonant frequency is modeled as a 1D shear beam.

Parametric System Identification

System identification studies in earthquake geotechnical engineering have been pioneered by Abdel-Ghaffar and Scott (1978 and 1979) and Zeghal (1990). Herein, the system identification process (Gill *et al.* 1997) attempts to define values of the two most influential but unknown properties (i.e., shear wave velocity profile and damping) that provide a best match to the experimental dynamic soil response near the first resonant frequency, at all central downhole accelerometer locations. Both the linear viscous (SBEAM) and hysteretic (SHAKE) soil models were utilized in this pattern-recognition identification study. These codes were employed in a linear soil properties mode (i.e., no dependence on shear strain amplitude). In order to effectively study stiff site response near the first resonant frequency by a 1D shear beam model, the objective function was defined as a least square difference of acceleration Fourier amplitude ratio with respect to the motion at **A17** between the recorded and computed accelerations at all central downhole accelerometer locations (i.e., **A26**, **A22**, **A21** and **A18**). Frequency windows (*Hz*) of [0, 11], [0, 6.5] and [0, 4] were applied in computing the objective function for the events under centrifugal accelerations of 10*g*, 20*g* and 40*g* respectively to include the first resonance only.

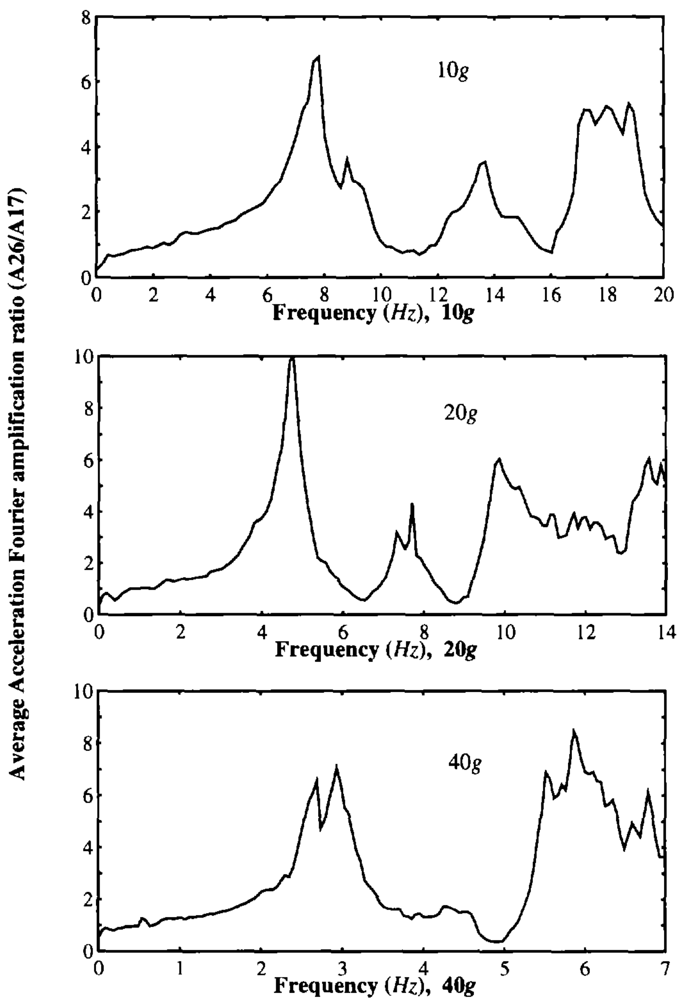

Fig. 3: Acceleration Fourier Amplification Ratio Spectra (A26/A17) for the Stiff Site.

The identified shear wave velocity profiles were consistent among all 8 events in both the viscoelastic (SBEAM) and the hysteretic (SHAKE) material models. Figure 4 illustrates the identified shear wave velocity profiles of sand (the identified system identification profiles were increased by 15% as shown in Fig. 4 due to the approximately 30% added mass of FSB container). The 4.75*m*, 9.5*m* and 19*m* profiles in Fig. 4 correspond to the 10*g*, 20*g* and 40*g* events respectively. The soil profile defined by Steven *et al.* (2001) was estimated through hammer tests during this FSB experiment. Data of Arulmoli *et al.* (1992) corresponds to an average derived from laboratory monotonic triaxial test results on Nevada sand at 60% relative density approximately. The variation of the identified shear wave velocity profiles among the different events may be partially influenced by possible small changes of soil properties during/after each shaking event.

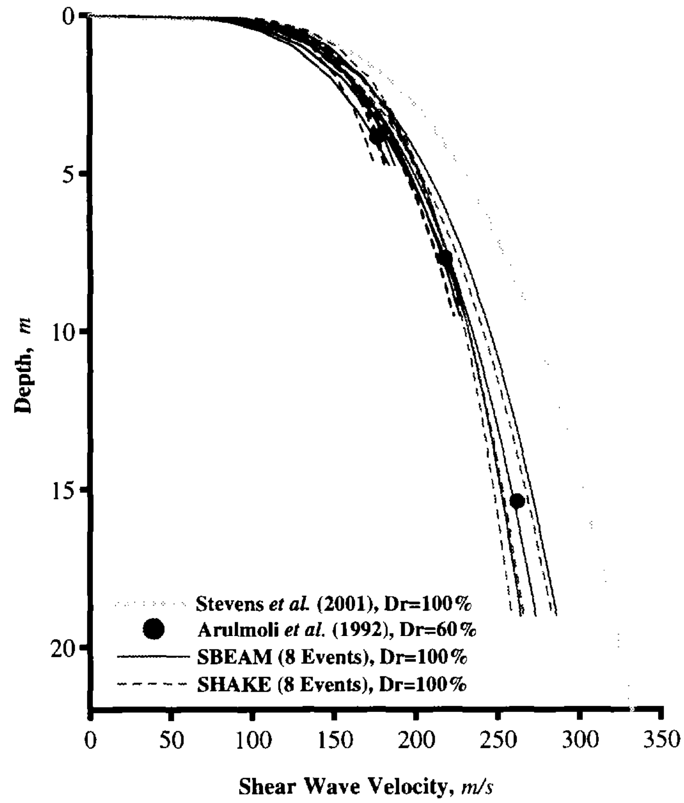

Fig. 4: Identified Shear Wave Velocity Profiles.

The identified shear wave velocity profiles resulted in excellent resonant frequency estimates (Table 2), where the measured frequencies were estimated from the recorded acceleration Fourier amplitude ratio spectra (**A26/A17**), and the frequencies of SBEAM and SHAKE were calculated through an eigenvalue analysis using the corresponding identified shear wave velocity profile. In general, the maximum difference between the measured and identified frequency is about 2%.

No.	Event ID	Measured	SBEAM	SHAKE
1	DKS02_c	7.80	7.90	7.82
2	DKS02_e	7.70	7.83	7.74
3	DKS02_ae	7.40	7.49	7.44
4	DKS02_n	4.68	4.67	4.62
5	DKS02_aa	4.65	4.68	4.63
6	DKS02_v	2.78	2.80	2.76
7	DKS02_bk	2.90	2.93	2.88
8	DKS02_bv	2.70	2.75	2.72

Table 2: Measured and Identified Fundamental Frequency (Hz).

The identified damping is presented together with the lower and upper bounds of damping curves for sand as recommended by Seed and Idriss (1970). As shown in Fig. 5, the identified damping falls mostly in the range of recommended values. The shear strain level in both SBEAM and SHAKE refers to its maximum value during each shaking event. The viscous (SBEAM) and hysteretic (SHAKE) material models yield almost identical damping values for each individual event at the first resonant frequency.

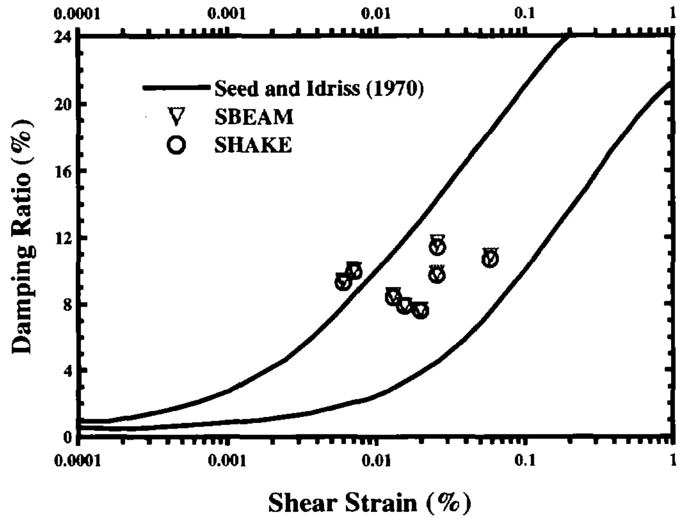

Fig. 5: Identified Damping Values.

COMPUTATIONAL SIMULATION

In order to check the resulting time-domain response, the identified properties were utilized to reproduce the site dynamic response. Almost identical responses were obtained from the SBEAM and SHAKE computation in all 8 events. A remarkable match was obtained between the recorded and computed responses as well at all central accelerometer locations for all 8 events. Figures 6 and 7 show excellent matches of recorded and computed (SHAKE) acceleration time histories for the events DKS02_c and DKS02_bv respectively. Since this preliminary study was focused on system identification at the fundamental resonance, both recorded and computed accelerations presented in Figs. 6 and 7 were filtered accordingly for the purpose of comparison. A similar match for all other locations and events was observed as well.

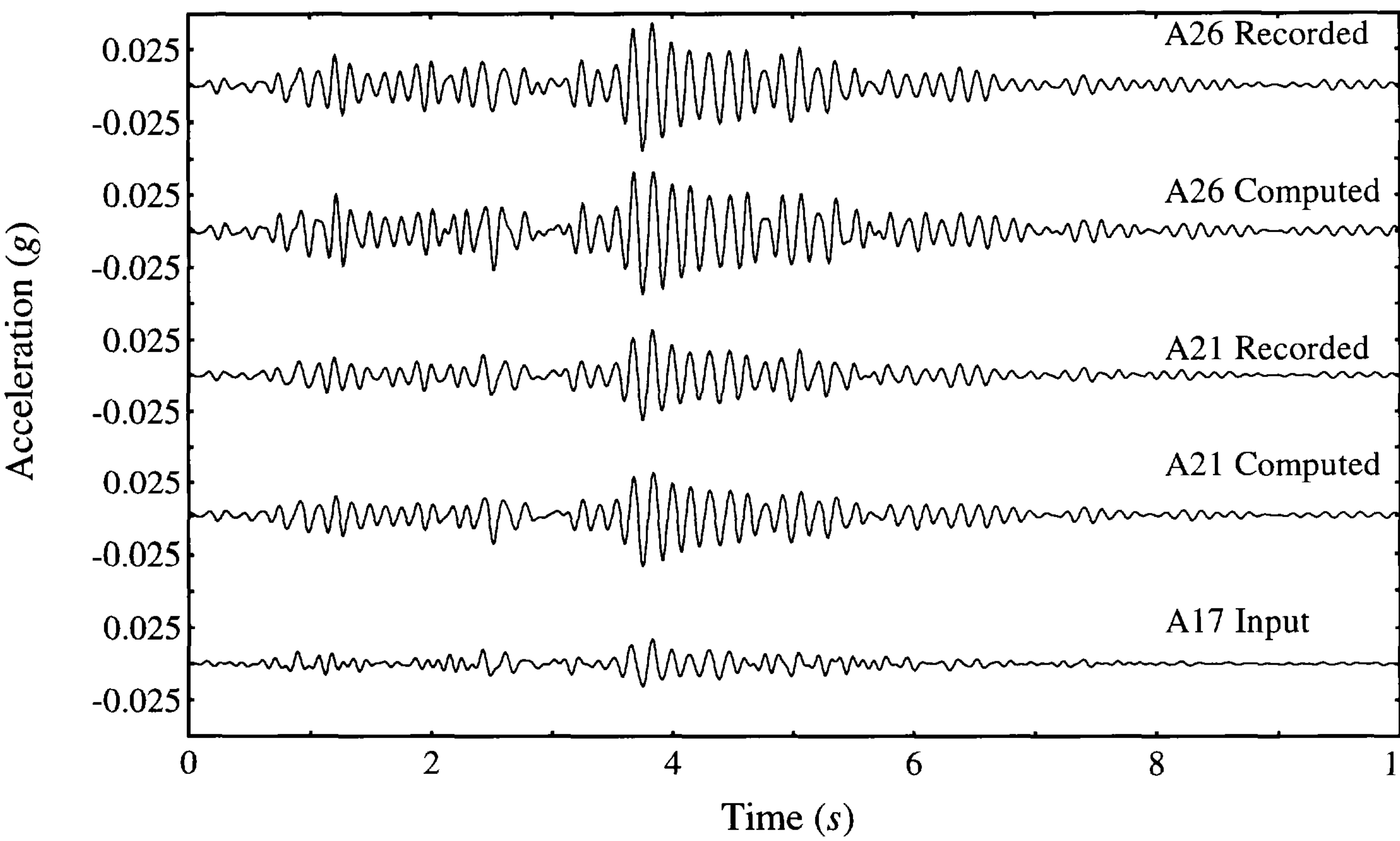

Fig. 6: Filtered ([0, 11]Hz) Computed (SHAKE) and Recorded Accelerations (Locations A26 *and* A21*) during Event DKS02_c (10g).*

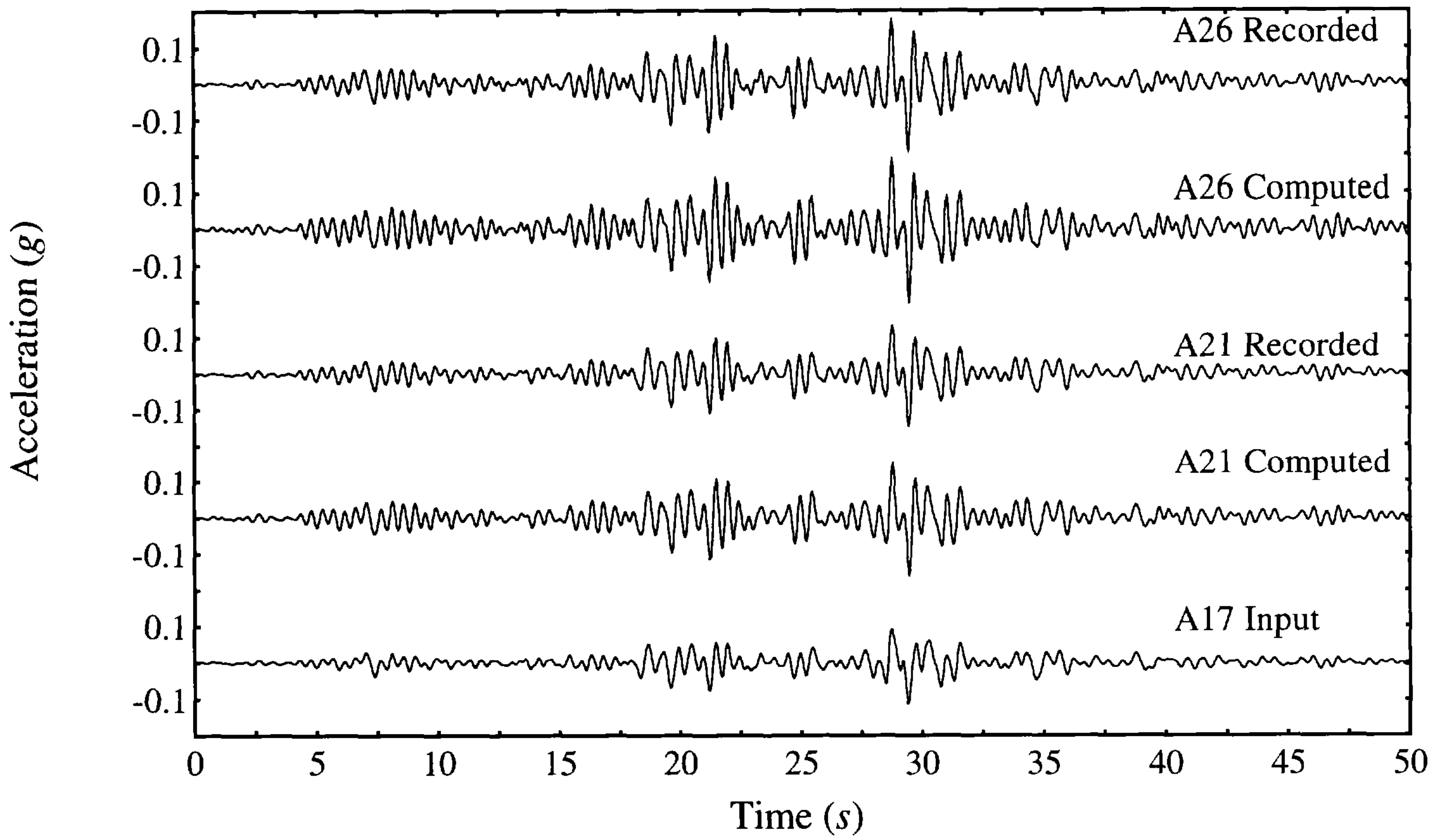

Fig. 7: Filtered ([0, 4]Hz) Computed (SHAKE) and Recorded Accelerations (Locations A26 *and* A21*) during Event DKS02_bv (40g).*

SUMMARY AND CONCLUSIONS

System identification techniques were employed to characterize the damping and stiffness characteristics of dense sand under small and moderate strain conditions. The identification process is based on a large database of input-output accelerations recorded in a highly instrumented centrifuge experimental program conducted by researchers at the University of California at Davis (UCD). The experiment employed a Flexible Shear Beam (FSB) container mounted on the $9m$-radius geotechnical centrifuge at UCD. Shaking tests were conducted under centrifugal accelerations of $10g$, $20g$ and $40g$ respectively. This paper presents an initial pattern-recognition system identification effort based on the recorded small events at $10g$, $20g$ and $40g$. The data set as analyzed represents the dynamic responses of $4.75m$-, $9.5m$- and $19m$-depth dense sand sites, respectively. Surface peak ground acceleration among the selected events ranges from $0.05g$ to $0.196g$ in amplitude. The centrifuge experimental data provided a broad range of dynamic responses (frequency content and amplitude), and allowed for a comprehensive system identification study.

The dynamic behavior of the stiff soil site near its first resonance is modeled as a 1D shear beam in this preliminary study. The system identification process attempted to define values of the two most influential but unknown properties (i.e., shear wave velocity profile and damping) that provide a best match to the experimental dynamic soil response near the first resonance, at all central downhole accelerometer locations. Both viscoelastic and hysteretic linear soil models were utilized in this identification study.

The identified properties are found to be consistent among the events considered. The computed responses were found to be an excellent match to those recorded at all central downhole accelerometer locations near the first resonance. In the next phase of research, soil nonlinearity will be included. The change in shear modulus and damping with shear strain amplitude will be defined using the above-described system identification approach.

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