A bender element system for measuring shear wave velocities in centrifuge models

Physical Modelling in Geotechnnics
6th ICPMG 2006
Ng, Zhang and Wang (Eds)
pp. 165-170

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ABSTRACT: A multi-source, multi-receiver bender element system was developed to measure shear wave velocities in centrifuge models. Up to eight source benders can be excited by a high-voltage power supply while up to sixteen receiver bender elements can be used to detect the transmitted signal. Analog band-pass filters are used to remove unwanted signals prior to amplification. Phase distortion caused by the analog filters is corrected by a digital transfer function that reverses the filter effects. Ambient vibrations during spinning of the centrifuge are further reduced by digital filtering and signal stacking. The resulting signals are of high enough quality for accurate determination of travel time. A stacking algorithm to improve the signal to noise ratio is described.

1 INTRODUCTION

A bender element is a piezoelectric transducer composed of two conductive outer electrodes, two ceramic plates and a conductive metal shim at the center (Fig. 1). The ceramic plates are polarized and made piezoelectric. When a bender element is deformed, the lattice distorts the dipole moment of the crystal and a voltage is generated. Conversely applying a voltage potential causes a bender element to deform. Hence bender elements can be used as either shear wave sources or receivers. Bender elements couple well with the soil, and mechanically similar benders operate in the same frequency range and are therefore "tuned" to each other.

Shear wave velocity of the soil can be obtained by measuring the time required for the wave to travel between two bender elements. Small strain shear modulus can be computed from shear wave velocity and mass density as $G_{max} = \rho \cdot V_s^2$, where G_{max} is small strain shear modulus, ρ is mass density and V_s is shear wave velocity. Measurements of travel times between arrays of bender elements can be used to create a two- or three-dimensional image of the small-strain shear modulus within a mass of soil. Inversion of travel time measurements is called shear wave tomography (e.g. Santamarina and Fratta 1998).

Bender elements have been used extensively in small laboratory samples such as triaxial specimens (Dyvik and Madshus 1985), where the small signals generated by the source bender can be easily identified through the receiver bender at the other end of the specimen. Gohl and Finn (1987) and Lei et al. (2004) have demonstrated the use of bender elements on geotechnical centrifuges. In the work of Lei et al, the benders had a tip to tip distance of 100 mm. Lee and Santamarina (2005) presented results of bender element studies of small-scale laboratory specimens and identified several important issues that influence the performance of bender elements, including electromagnetic coupling, directivity, resonant frequency, detection of first arrival and near field effects. Distance between bender elements was 60 mm tip-to-tip in their study.

Adaptation of bender elements for large centrifuge specimens is complicated by 1. attenuation of the shear waves across the larger specimens (e.g., model container FSB2 at UC Davis is about 800 mm wide and 1650 mm long), and 2. mechanical vibrations on the centrifuge are superimposed with the bender signals. Bender elements generate small-amplitude shear waves and the amplitude of received signals decreases with distance from the source. Obtaining sufficient signal quality is more difficult over the moderate distances desired in the centrifuge models than in the smaller distance in other laboratory applications. Vibrations caused by the mechanical components of the centrifuge can have larger amplitude than the shear waves generated by the bender elements, which can obscure the bender signal.

This paper presents a bender element system implemented on the 9-m radius centrifuge at the Center for Geotechnical Modeling at UC Davis. Implementation on the centrifuge follows development of instrumentation and inversion algorithms, and proof-of-concept studies at Georgia Tech (Lee 2003). The goal of the project is to measure the three-dimensional spatial distribution of small strain shear modulus by scanning the interior of the models using elastic waves.

A number of components were developed specifically for measuring shear wave velocities on the centrifuge. A high-voltage power supply was implemented to excite source benders with small-strain shear waves with larger amplitude than typical laboratory implementations to increase the distance of wave propagation so that the elastic waves can reach receiver benders across the width of the container. Signal conditioning hardware was developed to maximize the received signals of interest while minimizing extraneous signals. Data processing algorithms were developed to correct for phase lag caused by analog filters in the amplifiers for the receiver benders, and to further maximize the signal-to-noise ratio. Data is presented for a trial run in a centrifuge model at 1-g (not spinning) and at 20-g during spinning. Ongoing and future work is discussed.

2 HARDWARE

This section presents the hardware implemented in the system, including the bender elements, bender driver, receiver amplifiers, and computer components. Typical bender elements are shown in Figure 1, and all the components in the system are presented in Figure 2. Note that everything shown in Figure 2 is mounted on the centrifuge to avoid transmission of high frequency source or receiver signals through slip rings. Additional information about the bender element hardware can be found on the Center for Geotechnical Modeling website (http://nees.ucdavis.edu).

2.1 *Bender elements*

Figure 1 shows bender element schematics, and photos of benders that have been used in the UC Davis centrifuge. The bender elements used in this study were product no. T226-A4 sheets cut 12.7 mm by 8 mm, purchased from Piezo Systems, Inc., Cambridge MA (http://www.piezo.com). The bender sheets were Y-poled for parallel operation. The capacitance of these benders is proportional to their size, and is approximately 0.1 nF/mm^2, hence the capacitance of an individual bender is about 10 nF.

Voltage signals are sent to, or read from the bender elements by shielded coaxial cables that connect to the benders. Series benders involve piezoceramic crystals with opposite direction of polarization and voltage across to the outer electrodes. Parallel benders involve piezoceramic crystals with the same direction of polarization and the voltage wire is connected to the conductive metal shim while the outer electrodes are grounded. For the same applied voltage, the parallel connection provides twice the displacement of the series connection, and therefore is better as a source. For a given displacement, the series connection provides twice the voltage of the parallel connection, and therefore is better as a receiver.

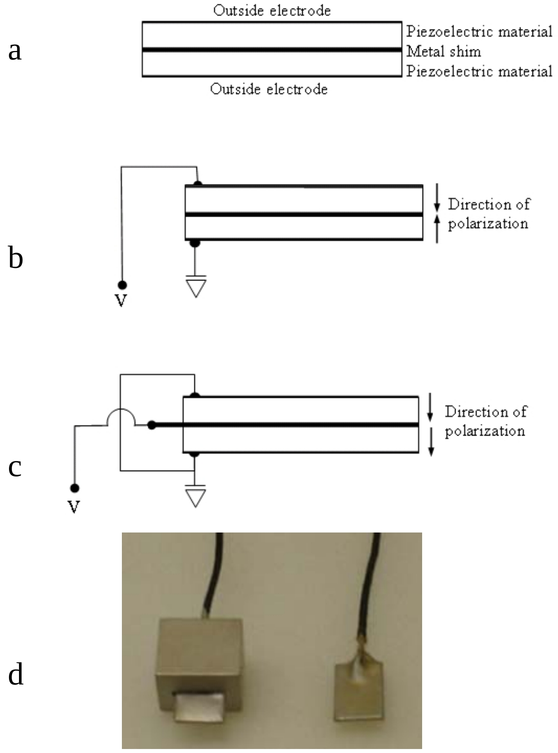

Figure 1: (a) schematic representation of bender element components. Bender elements connected with (b) a series-type electrical connection and (c) a parallel type electrical connection, and (d) photos of fixed bender element and (left) and free bender element (right). [a – c after Lee and Santamarina (2005)]

Previous studies have used bender elements mounted as cantilevers to a block or a frame in centrifuge models (Lei et al. 2004) or to the end platens of laboratory specimens (e.g., Dyvik and Madshus 1985). In the present study we have demonstrated that “free benders” (see Figure 1) embedded in the soil without a mounting block can also act as effective transmitters and receivers. Free benders have the advantage of minimizing the mass of the element and eliminate the need for mounting frames that can influence the dynamic behavior of the centrifuge model.

2.2 *Bender driver*

A high-voltage (± 90 VDC) bender driver induces an wave with larger amplitude than common laboratory implementations [e.g. ± 10 VDC was used by Lei et al. (2004)], though still in the elastic range of soil behavior. 90 Volts was chosen because this is the

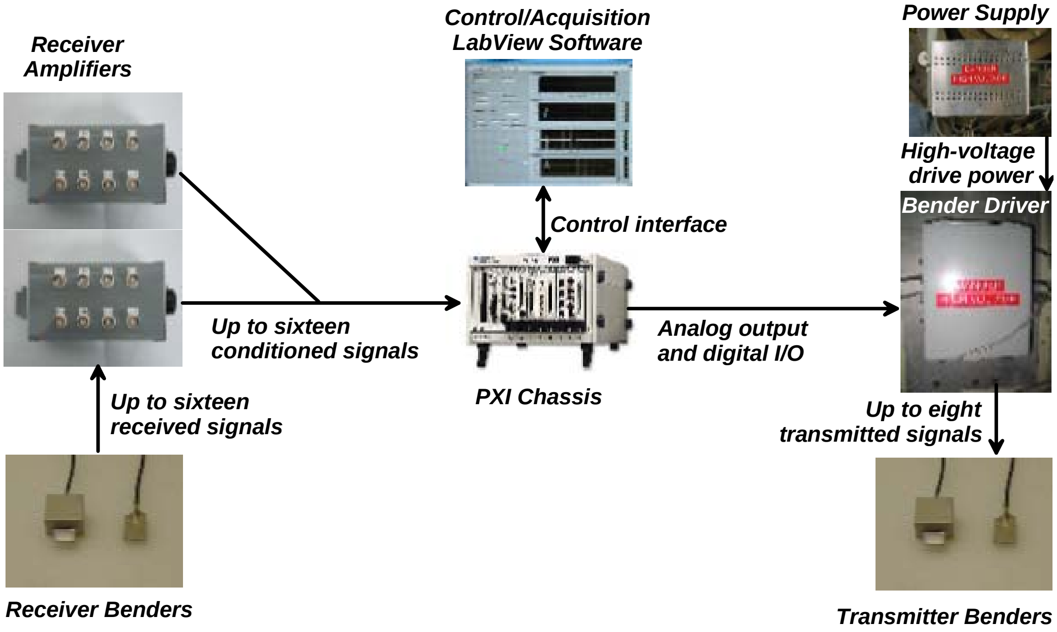

Figure 2: Component schematic of the multi-transmitter, multi-receiver bender element system.

largest voltage that is recommended by the supplier Piezo Systems Inc.; larger voltage sources could cause damage to the bender elements. Maximizing the amplitude of the elastic waves was desired to maximize the signal to noise ratio and to increase the distance the elastic waves would propagate.

The bender driver has one analog input for generation of the command signal, and has 8 analog outputs that can direct the analog input to different transmitter bender elements. Any one bender can be excited independently, or all elements can be excited simultaneously using this bender driver.

The bender driver is powered by a high-voltage power supply (input: 110 VAC; output: 90 VDC, 200 mA max) that is enabled only during shear wave measurements. This safety feature will enable the bender driver to receive high-voltage power only when commanded rather than during an entire centrifuge spin. Specifications for the bender driver and high-voltage power supply are provided in Table 1.

The rise time of voltage supplied to an individual bender can be approximated as $c\cdot\Delta V/i$, where c is the capacitance of an individual bender, ΔV is the change in voltage and i is the output current. Hence, exciting a single transmitter bender with an instantaneous change in voltage from -90 to +90 VDC is associated with a rise time of approximately 9 μs ($c = 10$ nF, $\Delta V = 180$ VDC, $i = 200$ mA). Rise time increases in direct proportion to the number of transmitter benders that are simultaneously excited. Command voltages are transmitted quickly to the bender elements, which is important for accurate source-to-receiver measurements of travel time.

Table 1. Specifications of bender driver and high-voltage power supply.

Bender driver	
Analog inputs	1
Analog outputs	8 (selectable for individual or simultaneous excitation)
Input power voltage	+ 24 VDC
Output voltage	± 96 VDC
Function input	waveform up to ± 9 VDC amplitude
Rise time of output	~9 μs for a single transmitter bender
High-voltage power supply	
Input power	110 VAC
Output voltage	± 90 VDC (max. 200 mA)
Analog voltage switch	+3 to +32 VDC

2.3 *Receiver amplifiers*

Custom amplifiers for the bender receivers were designed and manufactured for optimal performance in the UC Davis centrifuge environment. Currently, sixteen receiver bender elements can be accommodated by two separate eight-channel amplifier modules. Differential input signals are filtered by a 1^{st} order band-pass filter with corner frequencies of 1 kHz and 100 kHz, and subsequently amplified by a gain of 100. The signals must be filtered to prevent saturating the amplifiers due to output of the bender elements caused by mechanical noise on the centrifuge. These filters affect the phase of the signal, but since the filter properties are known, compensation for their effect is accomplished by post-processing of the digital signals as described later. The amplifiers are powered by +24 VDC. Specifications of the receiver amplifiers are provided in Table 2.

Table 2. Specifications of receiver amplifiers.

Manufacturer	Voler Systems, Inc.
Amplifier modules	2
Analog inputs	16 differential (8 per module)
Analog outputs	1 EDAC connector per module with 8 twisted pair wires.
Input power voltage	+ 24 VDC
Amplifier gain	100
Low pass filter	1st order, $f_c = 100$ kHz
High pass filter	1st order, $f_c = 1$ kHz

2.4 *Computer components*

Data acquisition is performed using the RESDAQ-AUX computer mounted at the center of the centrifuge connected to an 8-slot PXI chassis by National Instruments (NI PXI-1042) mounted near the end of the arm. Data is transmitted and received simultaneously using a NI PXI-6259 data acquisition card with 16 differential analog inputs, 48 digital I/O channels, 4 analog outputs, and maximum sampling rate of 1.00 MS/s.

3 SOFTWARE AND SIGNAL PROCESSING

Software written in LabView is used to control the data acquisition system and process the acquired signals. The software is configured to allow up to eight source benders to be excited with an analog waveform using the analog output from the PXI-6259 card, and the source benders are selected using digital logic. The software permits up to sixteen waveforms from receiver benders to be acquired simultaneously using the 16-channel 16-bit analog input multiplexer on the PXI-6259 card.

The various data acquisition components distort the phase of the acquired signals in the frequency band of interest (i.e. near 5 kHz), but the high-pass filter in the Voler amplifier modules is the dominant source of phase distortion. The phase distortion is associated with an undesired time shift in the signal that must be considered. The transfer function for the high-pass filter is given by Equation 1:

$$H_1 = \frac{\frac{f}{f_c}}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} \qquad (1)$$

where f_c is the corner frequency. The phase distortion induced by the high-pass filter is recovered by applying the inverse of Equation 1 to the Fourier transform of the recorded signal. The reconstructed waveform is subsequently band-pass filtered by applying the transfer function given by Equation 2:

$$H_2 = \frac{1}{\sqrt{1+\left(\frac{f_{c1}}{f}\right)^{2\cdot order_1}}} \cdot \frac{1}{\sqrt{1+\left(\frac{f}{f_{c2}}\right)^{2\cdot order_2}}} \qquad (2)$$

where f_{c1} is the high-pass corner frequency, f_{c2} is the low-pass corner frequency, and order controls the slope of the filters. The Butterworth transfer function given by Equation 2 is applied only to the amplitude portion of the Fourier transform of the signal, while the phase portion of the signal is retained to prevent phase distortion. The influence of phase distortion in source-to-receiver shear wave velocity measurements decreases as the spacing between benders increases, and is believed to be small for the large spacing used in the centrifuge models.

Signal to noise ratio was further improved by stacking the acquired signals. Time between wave pulses was sufficient to permit reflections to attenuate so they did not superimpose with first arrivals of subsequent waves. Signal quality increased with the number of signals stacked (stacking number), and was deemed sufficient for travel time measurement at a stacking number of about 300. The increase in signal quality obtained by high stacking numbers is a desired effect, but data processing time increases, which is an undesired consequence. Future improvements to the stacking algorithm are discussed later.

4 RESULTS

This section presents data acquired from bender elements embedded in a centrifuge model while the model was not spinning (i.e. 1-g) and while the model was spinning at 20-g. The model consisted of a 0.20-m thick deposit of dense dry Nevada sand (D_r = 80%). Tip-to-tip spacing between transmitter and receiver benders was 60 mm and the length of the benders was 12.7 mm. The signals were sampled at 90 kHz.

4.1 *1-g test*

The 1-g test was performed to observe the signal quality without the ambient vibrations induced by spinning the centrifuge. Figure 3 shows the recorded signal from the receiver bender, and the square wave command signal that was sent to the bender driver. The ±9V amplitude of the square wave command was amplified by 10 in the bender driver, sending a ±90V signal to the transmitter benders. The stacking number for the recorded signal was 300. The desired shear wave signals are clearly identifiable shortly after the change in voltage in the command signal. The recorded signal was subsequently post-processed to correct the phase distortion and eliminate data on frequency bands outside of the bender signal. The influence of this post-processing was negligible because of the lack of ambient vibrations at 1-g in the absence of centrifuge spinning.

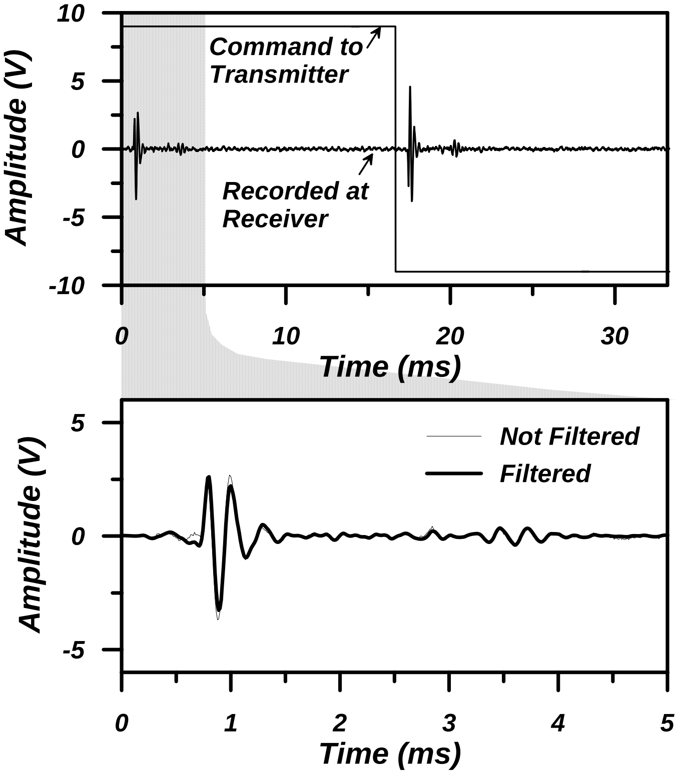

Figure 3: From 1-g test in centrifuge model (a) command square wave and acquired signals and (b) acquired signals with and without band-pass digital filtering.

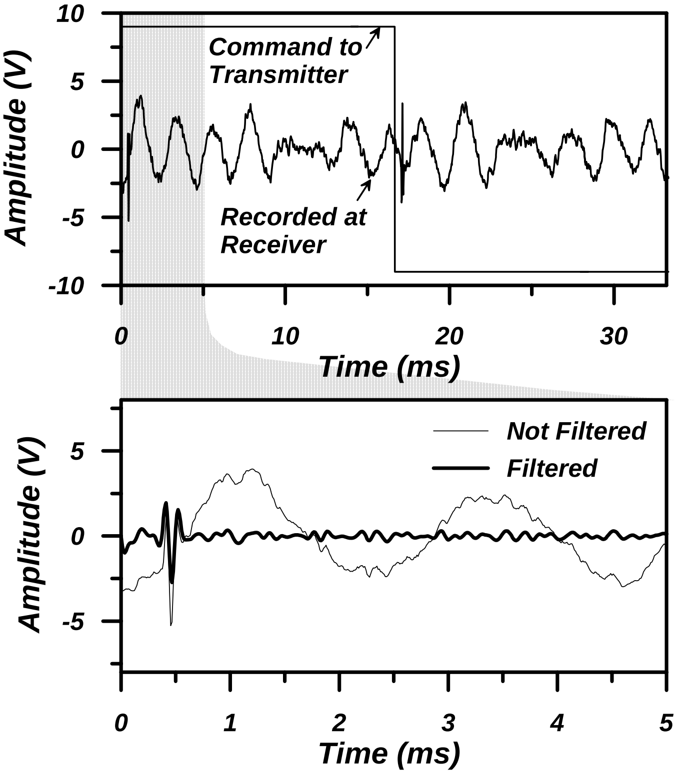

Figure 4: From 20-g test in centrifuge model (a) command square wave and acquired signals and (b) acquired signals with and without band-pass digital filtering.

4.2 *20-g test*

The centrifuge was spun to 20-g to perform testing, and data were acquired from the same bender element configuration as for the 1-g test. Figure 4 shows the recorded signals from the receiver bender, and the square wave command signal that was sent to the bender driver. The stacking number for the recorded signal was 300. Stacking amplifies the desired bender signal, while the ambient vibrations do not stack. However, the amplitude of the ambient vibrations caused by mechanical equipment mounted on the centrifuge is much larger than the amplitude of the bender signal, and the ambient vibration component is significant even after 300 stacks. The signal was post-processed the same way as in the 1-g test, and the filtered signal quality resembles the quality of the signal collected at 1-g. The influence of ambient vibrations was effectively eliminated by the signal processing methods, allowing travel time to be clearly determined.

The quality of the processed signals is similar at 1-g and 20-g, but the two signals are not identical; travel time is smaller, and predominant frequency of the shear wave pulse is higher at 20-g than at 1-g. Both of these differences were anticipated because of the increase in the stiffness of the sand associated with the increase in effective confining stress at 20-g compared with 1-g.

5 FUTURE WORK

Arrays of bender elements will be installed in the centrifuge model containers to obtain two-dimensional and/or three-dimensional images of shear wave velocity of the soils in the models. Ideally, the bender elements will provide shear wave velocity measurements quickly enough to monitor changes in soil properties after shaking, for example as excess pore pressures dissipate following liquefaction. Another application is to identify changes in effective stress in the soils beneath shallow foundations after earthquake loading or during cyclic loading since shear wave velocity depends on pressure.

An improved stacking algorithm is being developed to obtain quality signals over larger distances and at faster intervals than provided by the current data processing techniques and signal stacking approach. In the current approach, time intervals between transmitted signals are sufficient to permit attenuation of the various wave reflections. This approach prevents reflections from one transmitted wave from superimposing upon the first arrival of a subsequent wave, which could potentially be detrimental to wave quality. However, the time required to execute this approach may preclude characterization of soil stiffness over a desired short time interval, particularly when the bender elements are spaced further apart and require larger stacking numbers.

The improved stacking algorithm utilizes variations in the frequency of the command signal to cause reflections to superimpose on varying portions of the base signal. The influence of these reflections becomes smaller as stacking progresses, while the base signal continues to increase in amplitude. Hence, the frequency of the command signal may be increased significantly, thereby permitting quality signals to be obtained over smaller time intervals.

Another benefit of varying the command signal frequency is that the influence of periodic noise or ambient vibrations is reduced. Without varying the command frequency, there is the possibility that periodic noise with the same frequency as the command frequency could add up during stacking, thereby reducing the quality of the acquired signal. By varying the command frequency this periodic noise decreases in amplitude as stacking progresses.

Post-processing of the acquired signals will be performed during stacking in the improved stacking algorithm by applying a pulse of command square waves, buffering the acquired waveforms, applying the transfer functions, and quantifying the signal quality. This process will be repeated until signal quality is deemed sufficient. For the waveforms presented in this paper, transfer functions were imposed only after a sufficient number of stacks were performed to visually verify signal quality. High-amplitude portions of the waveform on frequency bands outside of the predominant bender signal frequency obscured the signal, thereby necessitating large stacking numbers for signal quality verification. By applying the transfer functions incrementally as stacking progresses, the required stacking number will decrease because the bender signal will not be obscured by large amplitude vibrations on frequency bands outside that of the bender signal.

The fast stacking algorithm was applied to a dry sand sample in a centrifuge model container at 1-g, and the results are promising. High frequency square wave command signals (i.e. over 1000 Hz) have been sent to the transmitter benders, and random noise and reflections were effectively canceled as the received signals were stacked. Furthermore, the interval between the transmitter bender and receiver bender was 800 mm, which is the desired distance for measurements of shear waves across the width of the container. Future investigations are required to verify the fast stacking algorithm on the centrifuge during spinning.

6 CONCLUSION

A bender element system was developed for measuring shear wave velocities on the centrifuge at UC Davis. The system hardware was optimized to operate in the centrifuge environment, with waves traveling over relatively large distances in the presence of ambient mechanical vibrations. A high-voltage power supply is used to maximize the amplitude of up to eight transmitted bender signals. Up to sixteen bender elements can receive the signals generated by the transmitters.

Stacking was used to increase signal to noise ratio in the bender signals. Subsequently, a transfer function was applied to recover phase distortion caused by the analog filters in the receiver amplifiers, and noise was reduced by applying a zero-phase digital band-pass filter. Ambient vibrations during centrifuge spinning were effectively eliminated using this data processing scheme.

Tests of the bender element system were performed in a centrifuge model at 1-g (without centrifuge spinning) and at 20-g during spinning. The 1-g test showed that clean bender signals were transmitted through soils with no ambient vibrations. The 20-g test showed how ambient vibrations during spinning can cloud the underlying bender signal, but the signal can be recovered by signal processing.

A fast stacking algorithm is being developed to will permit rapid determination of shear wave velocities, though data is not yet available to sufficiently explain the algorithm.

7 ACKNOWLEDGEMENTS

The development and implementation of the bender element system was funded by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) under NSF Award No. CMS-0086566.

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