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DISCUSSION

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Discussion "Measuring Shear Wave Velocity Using Bender Elements" By Leong, E. C., Yeo, S. H., and Rahardjo, H.

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Installation

The authors present a valuable summary of common bender element installations and data interpretation approaches, including new data on input signal effects (wave form, amplitude, and frequency). The purpose of this discussion is to contribute complementary information gathered through our own experience which is directly related to bender element installation and measurements. Wave propagation phenomena such as geometry dispersion, material dispersion, relative scale effects, and low-pass Brillouin filtering are discussed in Santamarina et al. (2001).

We agree with the authors on the difficulty in parallel connections, which leads to the more common use of series connection. However, there is an important advantage in parallel connection besides its enhanced motor response: the parallel connection grounds the outside electrodes and the source bender element becomes a self-shielded transducer. This configuration prevents crosstalk, particularly in soils with high electrical conductivity such as marine sediments and wet clayey soils. When two series bender elements are used, the bender elements need to be electrically insulated first (e.g., with a thin layer of polyurethane or epoxy) and then coated with conductive paint and grounded to avoid crosstalk.

Calculation of First Arrival

A bender element installation is a series system: signal generator $\rightarrow$ power amplifier $\rightarrow$ bender element $\rightarrow$ soil $\rightarrow$ bender element $\rightarrow$ amplifier/filter $\rightarrow$ A/D card or oscilloscope. Each component adds its own impulse response. Therefore, the signal coming out of each component is equal to the signal going in convolved with the component's impulse response.

This system view of bender element installations has several implications. First, one should minimize the use of peripheral electronics and select their operating frequency to have minimal impact on the signal spectrum. For example, we place more emphasis on signal stacking than on filters and amplifiers to improve the signal-to-noise-ratio. Second, one should avoid spectral techniques to calculate travel time, unless we can compare signals of the "same nature" or remove the effect of all series components (see details and examples in Brocanelli and Rinaldi 1998; Blewett et al. 2000; Arroyo et al. 2003; Lee and Santamarina 2005). For example, the cross-correlation between input and output signals is inherently biased by the system frequency response.

A clear example of using signals of the same nature is the analysis of multiple reflections. Consider a short wave train sent from the source bender element in the bottom plate. The wave train reaches the top plate, reflects back to the bottom plate, and once again towards the top plate. A receiver bender element housed on the top plate detects the first and second passes. When spectral techniques are used to compare the first and second signals detected by the receiver, the frequency responses of all peripheral components cancel out, and only the soil response remains. Mathematically, this is a self-healing measurement.

An alternative approach to first arrival time detection and spectral techniques consists of matching the complete signal, taking into consideration not only the frequency response of the system but near field effects as well (Cruse and Rizzo 1968; Aki and Richards 1980; Sanchez-Salinero 1986). The match of a measured signal is shown in Fig. 1 (emphasis is placed on matching the earlier part of the signal). The value of V_s is directly extracted from the signal matching technique (details in Lee and Santamarina 2005).

Input Signal

The authors elaborate on the implications of bender element size and installation. An additional important implication of size and installation is the corresponding impulse response. This is readily seen in the signals shown in Figs. 2 and 3, which were captured with square and single-cycle sinusoid input signals (bender elements installed with stiff anchoring).

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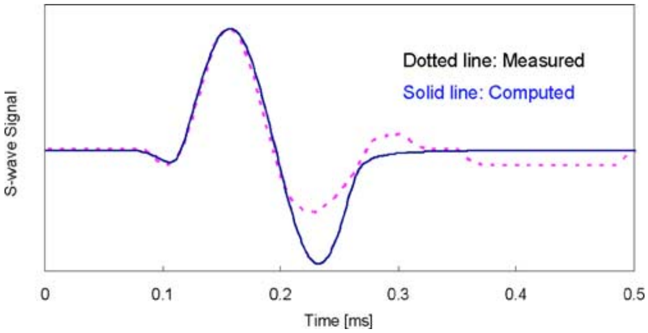

FIG. 1—*Signal matching technique for the estimation of S-wave velocity in the presence of near-field effects.*

When the duration of the square input is much longer than the characteristic time scale in the system, the output signal has two arrivals (consider the 3 ms duration square signal in Fig. 2): one caused by the positive step at the beginning of the square wave, and the other with opposite polarity caused by the negative step at the end of the square wave. The response to the positive and the negative steps begin to overlap when the duration of the square wave is shorter than ~0.5 ms. As the duration of the input square wave decreases further, the input energy decreases as well, and virtually no signal is detected when the duration of the square wave becomes 1 μs. The received signals have a characteristic period of ~0.23 ms; therefore, the resonant frequency of the system is ~4.4 kHz.

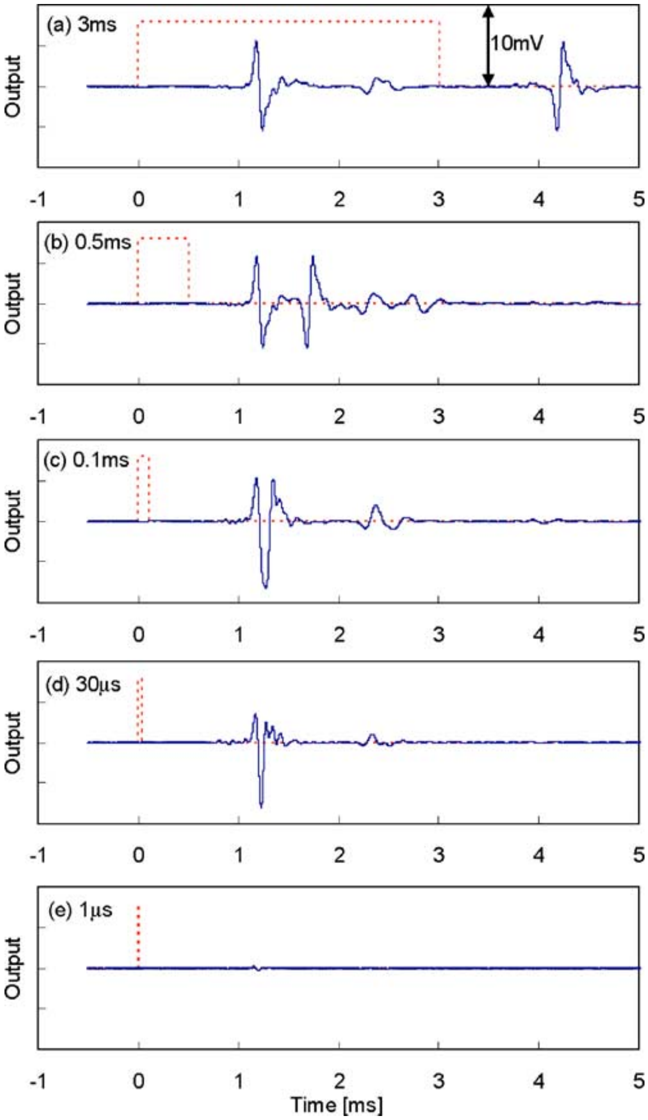

FIG. 2—*Input signal effects: Square signal. Dotted line: Input signal* (*1.0* V).

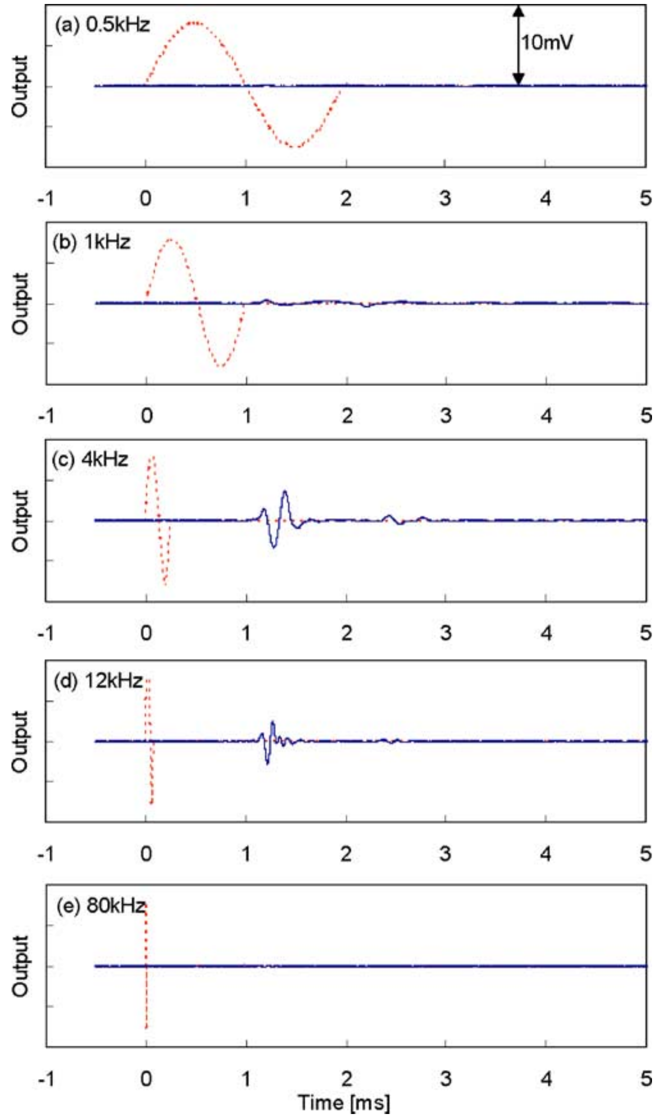

FIG. 3—*Input signal effects: Single-cycle sinusoid. Dotted line: Input signal* (*1.0 V*).

Similar results are observed when the single-cycle sinusoid is used as the input signal. The results are represented in Fig. 3. No signal is detected when the frequency of the sinusoid is either 0.5 or 1 kHz. The strongest output is detected when the input sinusoid is at 4 kHz, which is the approximate resonant frequency of this system. The amplitude of the received signal decreases for higher input frequencies. These results confirm that the optimal frequency for a single-cycle sinusoidal input is the one near the resonant frequency of the system.

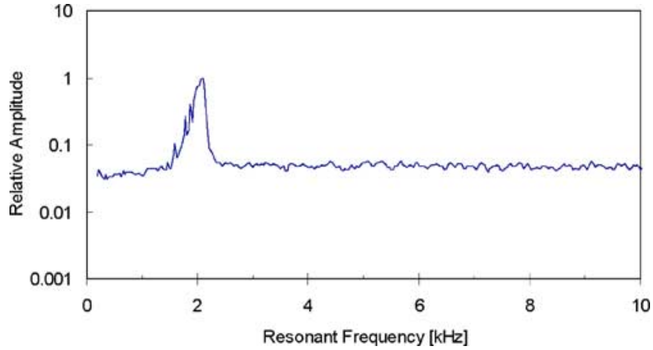

FIG. 4—*Resonant frequency of anchored bender element in air* (*no soil around it*). *Cantilever length: 8.70 mm.*

Resonant Frequency

The resonant frequency of bender element installations determines the near field and affects travel time determinations. It is important to note that the resonant frequency of the system is not constant. The resonant frequency of a mounted bender elements in air (no soil around) is similar to the value predicted by the analytical solution for a cantilever beam, and it is affected by anchor conditions (Lee 2003). However, the resonant frequency of the mounted bender element surrounded by soil under compression depends on the cantilever beam properties, anchoring conditions and both the soil density and stiffness; therefore, the resonant frequency of bender element installations varies with effective stresses. Figure 4 shows the frequency response of the mounted bender element used in this study when subjected to step excitation in air (impact). The resonant frequency in air is ~2 kHz, while the resonant frequency in the sand with 160 m/s shear wave velocity is ~5 kHz, as discussed above (Lee and Santamarina 2005).

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