Closure to “Discussion of ‘Measurement of Stiffness Anisotropy in Kaolinite Using Bender Element Tests in a Floating Wall Consolidometer’ by X. Kang, G.-C. Kang, and B. Bate” by Coffman, Salazar and Zhao
DISCUSSION

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Reference

ABSTRACT
The authors appreciate the interest of the discussers in this paper. The main arguments of the discussers were: (1) comparing the back-pressure saturated, constant-rate-of-strain consolidation device that incorporated bender elements (BP-CRS-BE device) developed by the discussers to the floating wall consolidometer based bender element testing system in the original paper (Kang, X., Kang, G.-C., and Bate, B., 2014, “Shear Wave Velocity Anisotropy of Kaolinite Using a Floating Wall Consolidometer-Type Bender Element Testing System,” Geotech. Test. J., Vol. 37, No. 5, pp. 869–883. [DOI: 10.1520/GTJ20120205]); (2) requesting the quantification of both the system lag and the machine deflection; (3) suggesting the authors use cross correlation method to determine the first arrival time because Vs values obtained by time domain method are “only approximate,” while the latter was the only method used by the discussers in their referenced work (Salazar, S. E. and Coffman, R. A., 2014, “Design and Fabrication of End Platens for Acquisition of Small-Strain Piezoelectric Measurements during Large-Strain Triaxial Extension and Triaxial Compression Testing,” Geotech. Test. J., Vol. 43, No. 2. pp. 1–11. [DOI: 10.1520/GTJ20140057]); and (4) making misleading arguments regarding the compression and shear waves measurements. In this closure, the authors first briefly compared the BP-CRS-BE device to the floating wall consolidometer based bender element testing system, and pointed out that (1) the well-documented wavelength ratio (Rd ratio) consideration in designing a bender element device and the seemingly unsatisfaction of such consideration in the BP-CRS-BE device, and that
(2) both the lack of details in B-value checking to examine saturation and the lack of shear wave velocity resulted from the BP-CRS-BE device to substantiate the arguments of the discussers. Then the authors provided the requested quantifications of both system lag and machine deflection to address some postulations by the discussers. The authors disagreed with Arguments 3 and 4 made by the discussers, and respond accordingly.

**Keywords**
bender element, shear wave velocity, system lag, machine deflection, anisotropy

### Questions Regarding Wavelength Ratio \((R_d)\) Consideration, B-Value Checking, and Results of the BP-CSR-BE Device

The discussers presented the BP-CRS-BE device, which primarily installed a pair of bender elements in the CRS consolidometer in order to utilize the benefits of CRS consolidometer, such as rapid consolidation time, direct usage of Shelby tube samples, ability to back-saturate the sample in a triaxial chamber, and higher applied stress due to smaller sample size (diameter 0.071 m) than the floating wall consolidometer sample (diameter 0.114 m) in Kang et al. (2014) given the same load frame capacity. Even if functioning as designed, the BP-CRS-BE device can only measure \(V_s\) in the \(hV\) direction due to near field effect limitation (details in the next paragraph), while the floating wall consolidometer based bender element testing system developed by the authors (Kang et al. 2014) measured \(V_s\) of a single sample in all three orthogonal directions \((hv, hh, vh)\) with full consideration of the near field effect (Kang and Bate 2016). Therefore, the designs of the two devices are different in measuring capability. Nevertheless, if functioning as designed, the BP-CRS-BE device can still contribute to the geotechnical literature. However, there are severe concerns not addressed by the discussers, namely, the wavelength ratio \((R_d)\) consideration, B-value checking, and lack of actual experimental \(V_s\) results to substantiate the functionality of the proposed device. Those concerns will be elaborated upon as follows.

The BP-CRS-BE device is subject to near field effect not only for \(V_s\) measurement in \(hh\) and \(vh\) directions; as admitted by the discussers, "Horizontally propagating shear waves with vertical particle motion \((hv)\) were transmitted and received within the BP-CRS-BE device (as the device was currently fabricated). However, the BP-CRS-BE device can also be further modified to enable generation of other wave and particle motions but was not, at this time, because of the potential for near-field effects (specifically for \(vh\) waves)," but also for \(V_s\) measurement in \(hv\) directions as elaborated upon as follows. The geometry of the floating wall consolidometer system in Kang et al. (2014) was determined by considering the wavelength ratio \((R_d)\) requirement. As elaborated in Kang et al. (2014), the wavelength ratio, \(R_d\), should be greater than or equal to 2 in order to avoid the near-field effect (Marjanovic and Germaine 2013; Sanchez-Salerino et al. 1986; Pennington et al. 2001; Wang et al. 2007) and to obtain accurate \(V_s\) results. An example was even provided in Kang et al. (2014) to elaborate on the limitation of 0.071 m (2.8 in.) diameter sample: "The tip-to-tip distance of a horizontally transmitting S-wave is limited by the diameter of a triaxial sample (usually 0.071 m or 2.8 in.), which is smaller than twice the wavelength (0.04 m) of an S-wave (typical frequency of 5000 Hz) traveling in kaolinite under 100 kPa applied vertical stress \((V_s\) of 200 m/s) (Fam and Santamaria 1997)." Unfortunately, the sample diameter in the device at Coffman et al. (2014) was even smaller (0.0635 m) than that of a standard triaxial sample (0.071 m), which is likely to subject \(V_s\) measurements in both \(hv\) and \(hh\) directions to the detrimental near-field effect due to low wavelength ratio \((R_d < 2)\). Furthermore, the sample height (0.0254 m) in Coffman et al. (2014) is even shorter than the diameter, which renders more severe near-field effect for \(V_s\) measurement in \(vh\) direction.

The discussers claimed that "the back-pressure saturation component of the BP–CRS–BE device allowed for unsaturated soil samples to become saturated, through the use of a pressurized triaxial chamber." However, based on the experience of the authors, back-pressure in a conventional triaxial cell (normally rated 1034 kPa) may not be enough to saturate an initially unsaturated clay sample. Moreover, the detailed setup and procedures of the BP-CRS-BE device for B-value checking were also missing for saturation examination.

Given the above-mentioned reasons, the functionality of the BP-CSR-BE device is in doubt. The discussers claimed that kaolinite samples were tested in this BP-CSR-BE device. However, no shear wave velocity result measured by this device, either directly in the Discussion or referenced in a related work done by the discussers, was presented to verify its functionality. The only other work referenced by the discussers is Salasar and Coffman (2014), where a modified triaxial test with bender element and bender disk, not BP-CSR-BE device with bender element, was used. In the authors’ opinion, it is premature to compare this BO-CSR-BE device to other bender element device without such experimental results.
System Lag

System time delay (or system lag) in a bender element test, originating from electrical system and mechanical parts, should be quantified (Dyvik and Madshus 1985; Montoya et al. 2012; Yamashita et al. 2009). The time delay in the electrical system originates from the circuit of generator, receiver, amplifier, filter, and the connectors, whereas the time delay in the mechanical parts of the bender element is due to the time for wave transmission through multiple layers of coatings of the bender element unit.

A simple setup utilizing a triaxial cell was developed to quantify the system lag (Fig. 1a). Tips of a pair of bender elements, aligning along the center piston of the triaxial cell, were in direct contact. External loads were applied by the weights on the top plate of the piston to examine the time delay when the testing system subjected to different loads. The measured lag time ranges from 6–11 \( \mu \)s (Fig. 1b), which agrees well with previous studies: 0–5 \( \mu \)s (Gajo et al. 1997), 0–15 \( \mu \)s (Yamashita et al. 2009), or 9 \( \mu \)s (Brandenberg et al. 2008). The time lag did not show significant change as the applied stresses (assuming the cross-section of contact area is width \( \times \) thickness of the bender element) increased from 6 to 1195 kPa. It is worth noting that system lag becomes more severe as travel distance decreases. As a result, there is a benefit of using a large (0.114 m diameter) sample in Kang et al. (2014) than using a triaxial sample (usually 0.071 m in diameter) to reduce the system lag error (e.g., by 43 \% given: soil \( V_s \) of 200 m/s and system lag of 10 \( \mu \)s).

Machine Deflection Quantification

The machine deflection due to load piston, U-shaped steel, caps and fabric cloth was quantified by the testing setup in Fig. 2a. The resulting deflection at the highest vertical applied pressure, 800 kPa, was 0.77 mm. The \( e-log r' \) curves of kaolinite samples in 0.005 and 1 mol/l NaCl solutions with deflection correction is plotted in Fig. 2b. The influence of machine deflection on void ratio change is at most (at 800 kPa vertical stress) 1.0 and 3.0 %.
for 0.005 and 1 mol/l NaCl solutions, respectively. Besides, the likelihood of inducing additional deformation due to cable ties, as speculated by the discussers, is low as no visible movement of the cable ties and the bender elements were observed.

Methods for First-Arrival Time Determination

The discussers argued that “the use of time domain selection of travel times should not be utilized for determination of shear wave velocity because the obtained values of shear wave velocity are only approximate” and postulated that “the shear wave velocity values (in Kang et al. 2014) were less than the published values because of improper selection of the travel times.” The authors found above argument and postulation groundless. Coffman et al. (2014) also recommended “signal cross correlation methods (Viggiani and Atkinson 1995) be employed to determine the shear wave travel times.” Contradictorily, instead of the cross correlation method, the discussers only used the time domain method in their referenced work (Salazar and Coffman 2014). Different methods of first arrival time determination have been studied extensively (Lee and Santamarina 2005; Viggiani and Atkinson 1995; Wang et al. 2007; Yamashita et al. 2009). It is not the scope of this work to re-evaluate these different methods. The authors, however, would like to refer to the international parallel test using bender element on measuring the elastic shear modulus ($G_{\text{max}}$) of sand samples by the TC29 (Stress-Strain and Strength Testing of Geomaterials) committee of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) to clarify the method comparison (Yamashita et al. 2009). Reports of the test results obtained from 23 institutions from 11 countries suggested that at least 18 institutions used time domain determination method, while only 5 institutions used cross correlation method (Yamashita et al. 2009). Furthermore, that study concluded that (1) the scatter by time domain method, especially by start-to-start method, is small as compared with other methods (including the cross correlation method), and (2) no specific method was recommended between time domain method and cross correlation method.

Compression and Shear Waves Measurement

The discussers stated “Kang et al. (2014) negated the importance of the compression wave in an attempt to enhance the shear wave response by changing the excitation frequency and reducing the near-field effect. For instance, no compression waves are observed in the signal presented in Figs. 4 or 8 of the Kang et al. (2014) article.” This mistakenly suggested that compression wave is desirable in the received signals in a bender element test, contrary to the general consensus that compression wave is to be avoided in shear wave velocity determination by a single pair of bender elements (Lee and Santamarina 2005; Leong et al. 2009). The discussers also argued that, “as discussed in Salazar and Coffman (2014), proper identification of the first arrival of the compression wave and the shear wave may lead to the determination of Poisson’s ratio values and constrained modulus values. Thus, both compression and shear waves should be collected and analyzed.” Above arguments are also imprecise and could mislead the readers. Identification of both compression and shear waves in a laboratory sample is desirable, but is often measured with two separate pairs, such as two bender/extender pairs (Leong et al. 2009; Lings and Greening 2001), or a hybrid bender element-ultrasonic system (Cheng and Leong 2014). In the work, the discussers referred to (Salazar and Coffman 2014), two separate pairs were also used as clearly stated that “two types of transducers were incorporated into the apparatus, bender elements and bender disks, used to measure wave velocity and compression wave velocities, respectively.” Furthermore, measurement of both compression and shear waves with a single pair of disk shaped piezoceramic transducers was reported, but was performed separately in time (Suwal and Kuwano 2013).

Clarification and Figure Updates

The authors would like to clarify that the bender elements in a fixed wall consolidometer setup (Bate et al. 2013; Choo et al. 2015) were not damaged due to the low stress (applied vertical stress $\leq 200\, \text{kPa}$) used, but were prone to damage under higher stress.

References


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