Selecting an appropriate shear plate configuration to measure elastic wave velocities

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Abstract:

The (small-strain) elastic moduli of soil can be determined from stress wave velocity measurements. Bender/extender elements are widely used in laboratory experiments; however, discussion on how to accurately determine wave velocities using this method continues. Planar piezoelectric transducers (sometimes called shear plates) are a relatively new technology, whose use is not yet widely established, that appears to offer some advantages in comparison with bender/extender elements for laboratory geophysics tests. This contribution critically assesses the use of planar piezoelectric elements experimentally and using discrete element method (DEM) simulations. Planar piezoelectric elements capable of generating and receiving either shear or compression waves were placed in the top and base caps of a triaxial apparatus. Samples of glass ballotini were used so that stress wave propagation simulations could be performed on equivalent virtual samples using DEM. The appropriate shear plate configuration to effectively measure the shear wave velocity is explored. Considering both time and frequency domain responses, it is revealed that shear plate signals are sensitive to the surface area and thickness of the piezoelectric elements and to the lateral boundary conditions. Using a shear plate with the widest possible surface area exposed to the soil specimen is recommended to increase the signal-to-noise ratio and to produce more planar shear waves, resulting in a more accurate measurement of shear wave velocity.

Introduction

The small-stain moduli of soils are important to predict ground deformation (Atkinson 2000; Clayton 2011). It is difficult to measure stiffnesses at very small strains accurately using conventional, load-deformation techniques even where local deformation transducers are used. Consequently dynamic test approaches that measure the velocity of propagation of compression (*P*-) and shear (*S*-) waves continue to be developed. These include the torsional resonant column technique (Hardin and Richart 1963), bender and extender elements (Shirley and Hampton 1978; Lings and Greening 2001), and planar piezoelectric elements (Brignoli et al. 1996; Ismail and Rammah 2005; Suwal and Kuwano 2013).

The idea of using planar piezoelectric elements to generate and detect stress waves in soil was initially explored by Lawrence (1965) who compared them with point-source bender elements. Little subsequent consideration of this technology is recorded prior to the work of Brignoli et al. (1996) and Ismail and Rammah (2005) who compared the shear wave velocity data generated using bender elements and planar piezoelectric elements (shear plates) for similar and identical specimens, respectively. Brignoli et al. (1996) concluded that use of shear plates is favoured particularly in the case of coarse-grained materials or strongly undisturbed stiff soils. Ismail and Rammah (2005) reported that for soft clay bender element signals are stronger and clearer although the arrival time can be easily distinguished using shear plates. The potential for coarse grains to damage bender/extender elements in high pressure tests lead to use of shear plates by Otsubo (2016). None of these prior studies included parametric studies to inform decisions on the optimal plate configuration.

In a point-source bender element test, *P*-wave components are also generated (Sanchez-Salinero et al. 1986; Arroyo et al. 2003); these *P*-waves propagate faster than *S*-waves and can contaminate the *S*-wave signal. Theoretically this *P*-wave contamination, which complicates data interpretation, can be removed by inputting a completely planar shear wave. Analysts using planar wave propagation do not report any *P*-wave interference (Mouraille et al. 2006). Using the discrete element method (DEM) O'Donovan (2013) highlighted the sensitivity of the transmitted signal to the material fabric close to point source transmitters. O'Donovan et al. (2016) also showed that bender elements generate compression waves that travel diagonally using a point-source excitation in their DEM analyses.

While a case has been made for use of planar piezoelectric elements, there is no consensus on the appropriate set-up. Referring to Table 1, there is some variation in the documented element size and shape: Brignoli et al. (1996) used a rectangular shear element having 12.7 × 12.7 × 6.3 mm (length × width × thickness), and a circular compression element with 8 × 2 mm (diameter s× thickness). Ismail and Rammah (2005) used a cubical-shaped shear element with dimensions 7 × 7 × 7 mm. Suwal and Kuwano (2013) placed a circular compression element (20 × 2 mm) beneath a circular shear element (20 × 5 mm).

This paper aims to clarify the following key issues regarding use of planar piezoelectric elements:

- How does the shear plate configuration adopted influence the recorded signal amplitude? (Recognizing that an increase in amplitude will increase the signal-to-noise ratio and improve the data quality)
- To what extent does use of shear plates reduce the interference of *P*-waves upon *S*-wave data?
- Do the interpreted V_S data depend on the shear plate configuration?

These issues were explored by considering configurations of either two or five piezoelectric plates embedded in the top and base caps of a triaxial cell. Spherical, borosilicate glass ballotini were used so that the physical data could be complemented by the detailed particle-scale data available from complementary DEM simulations.

Experimental study

Sample preparation

To facilitate comparison with DEM simulations using spherical particles, samples were formed of borosilicate glass ballotini with a mean particle diameter D_{mean} = 1.2 mm ($1 \leq D \leq 1.4$ mm). The ballotini shapes were quantified using a Qicpic image analysis sensor (Witt et al. 2004; Altuhafi et al. 2013); they had a sphericity of 0.94, an aspect ratio of 0.96 and a convexity of 0.99. The minimum and maximum void ratios (e_{min} and e_{max}) for the tested material of 0.524 and 0.626, respectively were measured. These measurements mostly followed JGS (2009); however, for the relatively large particle sizes used here, a larger container (64.3 mm in height and 79.9 mm in diameter) was used to reduce the effect of container size on e_{min} and e_{max} values instead of the standard container (40 mm in height and 60 mm in diameter).

Cylindrical ballotini samples, 111-112 mm in height and 50 mm in diameter, were tested in a standard triaxial apparatus; the change in sample volume was calculated using two axial displacement sensors and a radial displacement sensor placed at the specimen mid-height. The axial displacement was measured over a distance of 50 mm to reduce bedding errors. The relatively loose specimens were prepared by slow dry pluviation into a metal mould, lined with the latex membrane used in the test, using a funnel whose position was maintained just above the top of the sample. Referring to Table 2 the resulting void ratios were $0.602 \leq e \leq 0.604$ at an effective confining pressure $p' \approx 100$ kPa. The specimens were maintained dry and subjected to isotropic confinement by supplying an air pressure to the cell. The top cap was not fixed to a loading rod, and thus its mass added a vertical pressure of 1.5 kPa to the specimen. No porous stone was used so that the ballotini contacted the shear plates directly.

Shear plate configuration

Planar piezoelectric elements capable of generating and receiving either shear or compression waves were used. The compression element expanded normal to the largest planar element face, while the shear elements deformed in shearing mode so that the upper planar face translated. The piezoelectric elements used in this study comprised lead zirconate titanate (PZT) with material density ρ_{PZT} = 7800 kg/m^3 and Poisson's ratio ν_{PZT}

= 0.3. The compression elements had dimensions of 15 × 15 × 1 mm or 15 × 15 × 0.5 mm, and the shear elements had dimensions of 15 × 15 × 1 mm, 15 × 15 × 2 mm or 30 × 15 × 1 mm (Table 1). The resonant frequency for the piezoelectric element used was 1900 kHz for t = 1 mm according to the manufacturer's data sheet.

Two types of top and base caps were fabricated to accommodate either two wider elements (Fig. 1a) or five small elements (Fig. 1b). The surface of the caps was not completely flat as the recession in which the shear plates were embedded was 0.6 mm thick, so that the thin elements protruded about 0.4mm above the caps. Referring to Fig. 2, three types of design configuration were considered: 2L, 5S and 5St as detailed below:

- 2L: This configuration used two rectangular shear elements (30 × 15 × 1 mm) with polarization (and translation) parallel to the short side of the element (Figs. 1a and 2a). Each element occupied 22.9% of the top / base cap surface area.
- 5S: This configuration used five square shear elements (15 × 15 × 1 mm) all having the same polarization (Figs. 1b and 2b). Each element occupied 11.5% of the top / base cap surface area.
- 5St: The same top / base cap was used as in case 5S. The configuration included two compression elements (thickness t =1 mm), a thin compression element (t = 0.5 mm), a shear element (t = 1 mm) and a thick shear element (t = 2 mm). The polarization of the two shear elements was normal to the line connecting them (Fig. 2c).

<u>Shear plate dynamic tests</u>

The test procedure is schematically illustrated in Fig. 3a. The transmitter element generates stress waves, and the receiver element detects and records stress waves. The applied electric voltage signal input to control the movement of the transmitting piezoelectric elements had a sinusoidal shaped-pulse (single period) with a nominal frequency f_{in} = 10 kHz and a source voltage of ± 10 V (i.e. a peak to peak amplitude of 20 V). The nominal frequency of the first cycle of coherent waves received was close to the input frequency, giving a similar V_S value for both the peak-to-peak and the start-to-start methods (Yamashita et al., 2009), and the same input frequency was considered for *P*-wave propagation. The effective wavelength λ_{eff} values were calculated as $\lambda_{eff} = V_S / f_{eff}$, as considered in Jia et al. (1999), to give a value of $\lambda_{eff} \approx 33$ mm for the experimental samples where f_{eff} is the nominal frequency observed for the first cycle of arrived *S*-wave signals. The ratio of sample length to effective wavelength, L/λ_{eff}, was ≈3.3 for the experimental cases satisfying the general recommendation of that $L/\lambda_{eff} \geq 2$ to reduce the influence of near-field effects (Sanchez-Salinero et al. 1986). The peak to peak voltage applied to the transmitter was 20 V; where a maximum displacement of 7.5 nm in air for a 3-mm thick *P*-type element was observed by the authors using an accelerometer, which is slightly thicker than those reported here. When a smaller input voltage was inserted to the transmitter element, the recorded receiver response reduced proportionally, confirming the dynamic soil response is within an elastic regime. The inserted and received electric voltage signals were recorded using two oscilloscopes each having two channels. The multiple transmitter elements were wired in parallel so that they each received the same applied source voltage and so deformations should be identical.

The voltage signals recorded at each receiver element were stacked over 128 signals to reduce background noise, and they were amplified by a factor about 100 using custom-made amplifiers. When the target stress level was achieved, a pause time of minimum 1 hour was allowed for each specimen until there was no increase in wave velocity with time and when there were only negligible changes in void ratio was negligible. To interpret the arrival time of the *S*- or *P*-waves, the peak-to-peak method was adopted; this uses the time delay between the peaks at the inserted and received signals.

DEM simulation method

<u>DEM sample preparation</u>

The DEM simulations were performed using a modified version of the LAMMPS molecular dynamics code (Plimpton 1995). Referring to Fig. 3b, the samples were rectangular and comprised 155,165 spheres with dimensions of 48.5 × 48.5 × 96.7 mm. The lateral boundaries were periodic, and the rigid wall boundaries represent the top and base caps; a specified area of the wall surface was excited to model the deformation of piezo-electric plates (Fig. 4). A simplified Hertz-Mindlin contact model (Itasca Consulting Group 2007) was used to calculate the inter-particle contact forces and the contact forces that developed between particles and the rigid caps. The particle diameters and material properties matched the experiments (particle density ρ_p = 2600 kg/m^3, particle Young's modulus E_p = 70 GPa, particle Poisson's ratio ν_p = 0.2). According to the manufacturer's data sheets the ballotini had E_p = 77 GPa; however following Cavarretta et al. (2012) a slightly lower E_p value was used in the DEM simulations to account for imperfections in the manufactured product. The same E_p and ν_p values were used for the top and base caps.

Initially a non-contacting cloud of particles was generated, and isotropic compression was applied using a servo-control algorithm. The inter-particle friction used during the isotropic compression μ_{prep} was set to be 0.05 to prepare a specimen having a similar void ratio to those recorded in the experimental program. Gravity was neglected in the simulations. During compression between confining pressures of p' = 1 kPa and p' = 100 kPa viscous damping was used to remove kinetic energy and reduce vibrations. The void ratio e at p' = 100 kPa was 0.607 (Table 3). The stress wave propagation simulations considered here were performed at p' = 100 kPa.

<u>Wave propagation simulation procedure</u>

The stress-wave simulation approach adopted here broadly follows that documented in Otsubo et al. (2017), and key details are repeated here for clarity. To simulate the wave transmission, either the entire top cap or a portion of the top cap was excited horizontally (X-direction (Fig. 4)) or vertically (in the Z-direction) to generate *S*-waves or *P*-waves, respectively. In both cases the waves propagated in the longitudinal (Z-) direction. The displacement of the transmitter element was controlled to have a sinusoidal pulse shape with a nominal frequency f_{in} = 10 kHz and a double amplitude of 5 nm. Xu et al. (2015) reported that the sample response becomes inelastic and the wave velocity reduces if the excitation amplitude exceeds a threshold amplitude; a parametric study demonstrated that a double amplitude of 5 nm is sufficient to ensure an elastic sample response. The inter-particle friction coefficient was increased to μ_{wave} = 0.2 before generating the waves; this ensured an elastic response at the contacts (Magnanimo et al. 2008). Viscous damping was turned off during the wave propagation simulations; note that wave velocities are not affected by damping (Mouraille et al. 2006). For the DEM simulations, rather than considering voltage measurements to infer the stresses applied and received as in the experiments, the stress responses at the transmitter and receiver elements were directly recorded. Just as was the case for the experimental data, the DEM data were interpreted using the peak-to-peak method to determine shear wave velocity (V_S) values. For the DEM samples λ_{eff} ≈32 mm for the DEM cases so that L/λ_{eff}, was ≈3.3 which is in adherence with good practice as noted above.

Recorded data

Recorded data sets for each design configuration are presented in turn prior to discussing the main observations that emerged from the data. Table 4 summarizes the key experimental data including V_S values calculated using the peak-to-peak method. Table 5 summarizes equivalent results for DEM data set.

<u>2L configuration</u>

For the 2L configuration (Fig. 2a), as indicated in Fig. 5 the transmitter elements are denoted as T_1^{2L} and T_2^{2L} and the receiver elements are denoted R_1^{2L} and R_2^{2L}. Three scenarios of wave transmission were considered: T_1^{2L} only, T_2^{2L} only, and both T_1^{2L} and T_2^{2L}. For each scenario, signals received on R_1^{2L} and R_2^{2L} were recorded individually, and the following six combinations of travel paths are considered:

- u_{11}^{2L} (or u_{12}^{2L}): Transmission by T_1^{2L} recorded at R_1^{2L} (or R_2^{2L}) (Fig. 5a)
- u_{21}^{2L} (or u_{22}^{2L}): Transmission by T_2^{2L} recorded at R_1^{2L} (or R_2^{2L}) (Fig. 5b)
- u_{D1}^{2L} (or u_{D2}^{2L}): Simultaneous transmission by T_1^{2L} and T_2^{2L} received at R_1^{2L} (or R_2^{2L}) (Fig. 5b)

In the equivalent DEM simulations the top and base caps in the Z-direction were bisected in the X-direction to model $T_1^{2L\,DEM}$ and $T_2^{2L\,DEM}$ transmitter elements and $R_1^{2L\,DEM}$ and $R_2^{2L\,DEM}$ receiver elements (Fig. 4a). The superscript DEM is included in the notation relating to DEM simulations. The areas of the transmitter and receiver plates were varied to consider six wave paths following the experimental approach by taking one of the caps halves to represent one transmitter element and the entire cap to represent the simultaneous excitation achieved in the laboratory.

The experimental data are presented in Fig. 6, and the DEM data are presented in Fig. 7. For both datasets the time domain responses are presented so that the time scale is divided by the travel distance (L) from the centre of transmitter to the centre of receiver. For the diagonal wave paths (u_{12}^{2L}, u_{21}^{2L}, $u_{12}^{2L\,DEM}$ and $u_{21}^{2L\,DEM}$), L was taken as the centre-centre diagonal travel path. The L values are listed in Tables 4 and 5. The experimental data consider the input and recorded signals in terms of voltage, while the DEM data consider the input and recorded signals in terms of shear stress acting on the elements.

5S configuration

Amongst the many possible combinations and wave paths that could be explored using the 5S configuration, the following scenarios of vertical wave paths were considered as the response of diagonally propagated waves are discussed using the 2L configuration:

- $u_{5\to5}^{5S}$: Transmission by T_5^{5S} recorded at R_5^{5S} (Fig. 8a)
- $u_{135\to135}^{5S}$: Simultaneous transmission by T_1^{5S}, T_3^{5S} and T_5^{5S} recorded simultaneously at R_1^{5S}, R_3^{5S} and R_5^{5S} so that the received signals were superposed (Fig. 8b)
- $u_{245\to245}^{5S}$: Simultaneous transmission by T_2^{5S}, T_4^{5S} and T_5^{5S} recorded simultaneously at R_2^{5S}, R_4^{5S} and R_5^{5S} so that the received signals were superposed (Fig. 8c)
- $u_{all\to all}^{5S}$: Simultaneous transmission by all the five transmitter elements recorded simultaneously at all five receiver elements so that the received signals were superposed (Fig. 8d)

The proportions of the surface area (A_T) covered by transmitters T_5^{5S}, T_{135}^{5S} (or T_{245}^{5S}) and T_{all}^{5S} are 11.5%, 34.4% and 57.3%, respectively. Similarly, the proportions of the receiver area (A_R) for R_5^{5S}, R_{135}^{5S} (or R_{245}^{5S}) and R_{all}^{5S} are 11.5%, 34.4% and 57.3%, respectively. The time and frequency domain data are presented in Fig. 9 for the combinations listed above.

To systematically consider the influence of disk area in the DEM simulations a circular area at the centre of each cap was taken as the transmitter or receiver while the cap outside the area was not excited (Fig. 4b). Consideration of a circular shear plate is relevant as disk-shaped shear plates can be used, e.g. Suwal and Kuwano (2013). The area ratio was varied systematically from 2% to 100% where $A_T = A_R$, totalling 12 cases, where time and frequency domain responses of three distinct cases (2%, 20% and 100%) were presented in Fig. 10. The following notation was used: $u_{2\to2}^{5S\,DEM}$, $u_{20\to20}^{5S\,DEM}$ and $u_{100\to100}^{5S\,DEM}$, e.g. $u_{20\to20}^{5S\,DEM}$ stands for S-waves generated at A_T = 20% and received at A_R = 20%.

5St configuration

Using both the 5S (Fig. 2b) and 5St (Fig. 2c) configurations, the path-dependency of the system responses to P-wave and S-wave propagation was investigated considering the following wave paths (Figs. 8 and 11):

- $u_{5\to5}^{5S}$: *S*-wave transmission by T_5^{5S} recorded at R_5^{5S} (central propagation path)
- $u_{1\to1}^{5S}$: *S*-wave transmission by T_1^{5S} recorded at R_1^{5S} (propagation path close to the side with oscillation normal to boundary)
- $u_{2\to2}^{5S}$: *S*-wave transmission by T_2^{5S} recorded at R_2^{5S} (propagation path close to the side with oscillation parallel to boundary)
- $u_{5\to5}^{5StP}$: *P*-wave transmission by T_5^{5StP} recorded at R_5^{5StP} (central propagation path)
- $u_{1\to1}^{5StP}$: *P*-wave transmission by T_1^{5StP} recorded at R_1^{5StP} (propagation path close to the side)

The resultant data are presented in Fig. 12.

The effect of shear element thickness (t) on received signals was investigated using 5St configuration (Fig. 2c). Shear elements with t = 1 and 2 mm were implemented at equivalent positions (slot 2 and slot 4, respectively), on the top and base caps. Referring to Fig. 11 the following wave scenarios were compared.

- $u_{2\to2}^{5St}$: Transmission by T_2^{5St} (t = 1 mm) recorded at R_2^{5St} (t = 1 mm)
- $u_{4\to4}^{5St}$: Transmission by T_4^{5St} (t = 2 mm) recorded at R_4^{5St} (t = 2 mm)

The resultant data are presented in Fig. 13. For the same specimen, system responses for *S*-wave ($u_{2\to2}^{5St}$) and *P*-wave ($u_{1\to1}^{5StP}$) along equivalent side paths (slot 2 and slot 1, respectively) were compared in Fig. 14.

Discussion

Application of principle of superposition

Both the experimental and DEM data for the 2L configuration show that the principle of superposition holds, confirming the sample responses are linear-elastic. Fig. 6b shows that the summation of individual components u_{11}^{2L}, u_{12}^{2L}, u_{21}^{2L} and u_{22}^{2L} agrees with the summation of u_{D1}^{2L} and u_{D2}^{2L}. For the DEM data the summation of $u_{11}^{2L\,DEM}$, $u_{12}^{2L\,DEM}$, $u_{21}^{2L\,DEM}$ and $u_{22}^{2L\,DEM}$ is identical to the summation of $u_{D1}^{2L\,DEM}$ and $u_{D2}^{2L\,DEM}$ (Fig. 7b).

The frequency domain responses were determined using the Fast-Fourier-Transform (FFT) functionality in MATLAB (MathWorks 2017). The data were recorded every 2×10^{-7} s for experiments and 1×10^{-7} s for DEM simulations, and zero padding was considered when the FFTs were applied. Considering the resultant frequency domain responses, the summation of u_{11}^{2L}, u_{12}^{2L}, u_{21}^{2L} and u_{22}^{2L} (Fig. 6d), agrees with the summation of u_{D1}^{2L} and u_{D2}^{2L} in line with the time domain response (Fig. 6b), and there are local peaks observed at both 10 and 8 kHz. Qualitatively similar observations hold for the DEM data (Figs. 7c and 7d). The frequency domain response is similar for $u_{11}^{2L\,DEM}$ and $u_{22}^{2L\,DEM}$, while $u_{11}^{2L\,DEM}$ and $u_{12}^{2L\,DEM}$ disagree due to difference in wave paths as discussed below. However, the summation of individual responses is identical to the response for $u_{D1}^{2L\,DEM}$+$u_{D2}^{2L\,DEM}$ as observed in the laboratory experiments.

Path-dependency of response

The influence of the path of wave propagation on the received signals was analysed. Considering the experimental data for the 2L configuration, both time and frequency domain responses for u_{11}^{2L} and u_{22}^{2L} and for u_{12}^{2L} and u_{21}^{2L}, each of which had the same transmitter-receiver area combinations, were almost indistinguishable (Figs. 6a and 6c). Similarly, for the DEM data, the responses for $u_{11}^{2L\,DEM}$ and $u_{22}^{2L\,DEM}$ and for $u_{12}^{2L\,DEM}$ and $u_{21}^{2L\,DEM}$ were indistinguishable (Fig. 7a and 7c). However, when the signals u_{11}^{2L} and u_{12}^{2L} are compared (or u_{22}^{2L} and u_{21}^{2L}), i.e. vertical path or diagonal path (Fig. 5), there are clear differences in the frequency associated with the peak in their spectra which shifts from about 10 to 8 kHz, where the diagonal paths (u_{12}^{2L} and u_{21}^{2L}) exhibit greater spectral amplitudes for higher frequencies ($15 < f < 20$ kHz). These differences in the observed responses occur because *S*-wave excitation from a limited transmitter area produces non-planar waves. These data highlight the complexity of waves propagating in different directions. The DEM data (Fig. 7c) show a slightly different trend; the frequency at which the peak amplitude of $u_{12}^{2L\,DEM}$ occurs is higher than the frequencies associated with the peak amplitude for $u_{11}^{2L\,DEM}$; the difference in the manifestation of the path dependency for the lab and DEM data is probably due to the difference in lateral boundary conditions. The boundary effect is discussed further below.

For the experimental case of the 5S configuration path-dependency was considered by looking at the orientation of the perturbation. For $u_{135\rightarrow135}^{5S}$, the three elements were excited in the direction of their alignment (Fig. 8b), while for the path $u_{245\rightarrow245}^{5S}$ the perturbation was normal to the element alignment (Fig 8c). Comparing $u_{135\rightarrow135}^{5S}$ and $u_{245\rightarrow245}^{5S}$ in Fig. 9, the signals exhibit a greater sensitivity to the transmitter-receiver combination.

The path-dependency influences the interpreted data: referring to Table 4, for the 2L configuration, the shear wave velocity (V_S) values are found to be $V_{S,12}^{2L} \approx V_{S,21}^{2L} > V_{S,11}^{2L} \approx V_{S,22}^{2L}$, while for the 5S configuration the V_S values differ as $V_{S,245\rightarrow245}^{5S} > V_{S,135\rightarrow135}^{5S}$. In both cases, the initial low-amplitude disturbance is greater for earlier *S*-wave arrivals, e.g. $u_{245\rightarrow245}^{5S}$ is more affected by the disturbance compared with $u_{135\rightarrow135}^{5S}$ (Fig. 9a).

There are two issues to consider with path-dependency; firstly, whether a representative volume element is achieved and second whether boundary effects are coming into play. The path-independency of the DEM data indicates that a representative element volume is indeed achieved. Consequently, the path-dependency observed in the experiments must be influenced by the specimen boundary.

Effect of membrane boundary

The effect of membrane boundary on the received signals for the experimental cases was assessed by considering the lateral distance from a piezoelectric element to the membrane boundary and the direction of perturbation. Wave signals along a centre path and a side path both propagating vertically were compared (Fig. 11). Were the sample to be infinitely wide, the response should not be influenced by the location of piezoelectric elements. Referring to Figs. 12a and 12b for *S*-wave data using the 5S configuration (Fig. 2b), the centre path ($u^{5S}_{5\to5}$) and two side paths where the direction of perturbation faces normal to the membrane ($u^{5S}_{1\to1}$) and parallel to the membrane ($u^{5S}_{2\to2}$) (Fig. 2b). The overall response with time varies in each case; $V^{5S}_{S,2\to2}$ was larger than $V^{5S}_{S,5\to5}$ by 4% while $V^{5S}_{S,1\to1}$ was smaller than $V^{5S}_{S,5\to5}$ by 3.4% (Fig. 12a and Table 4). Note that $u^{5S}_{2\to2}$ and $u^{5S}_{4\to4}$ exhibit similar results, and so as $u^{5S}_{1\to1}$ and $u^{5S}_{3\to3}$, which increases confidence of the finding here. Frequency domain responses show that, in comparison with the two side paths, the centre wave path ($u^{5S}_{5\to5}$) gives larger amplitude of received signals especially at higher frequencies (Fig. 12b). The source of the discrepancy in the V_S data needs further research. However, the reduced amplitude of received signals can be explained by the difference in the acoustic impedance at the boundaries among the glass beads specimen, membrane, and air. The impedance is defined as the product of *P*-wave velocity and the density of the material where the impedance for air is very small compared to the others, indicating almost of all waves reflect at the boundary between the membrane and air. There is about 40% difference in the impedance between the membrane and tested specimen; this indicates about 7% of waves can be transmitted by the membrane and the energy does not contribute to the receiver response.

For the *P*-wave cases observed using the 5St configuration (Fig. 2c), a measurable difference was observed between the centre path ($u^{5StP}_{5\to5}$) and the side path ($u^{5StP}_{1\to1}$) (Fig. 12c). The time for the first peak was not identical for the given input frequency of 10 kHz although the time for the initial rise of the signal was in good agreement. This indicates that the *P*-wave arrival time can be determined more accurately considering the first rise of the received response as suggested by Brignoli et al. (1996). The centre path exhibits higher frequencies than the side path with a similar variation in frequency domain responses (Fig. 12d) in line with the *S*-wave cases (Fig. 12b). Note that the other side path ($u^{5St}_{3\to3}$) for *P*-waves was not included here as the thinner element (t = 0.5 mm) was damaged during the test preparation.

P-wave contamination

For the 2L configuration a low-amplitude *P*-wave interference prior to the arrival of a coherent *S*-wave signal (i.e. near-field effect, Sanchez-Salinero et al. (1986)) is observed for the four wave paths illustrated in Fig. 6a (experimental data) and the corresponding four wave paths illustrated in Fig. 7a (DEM data). For the DEM data the *P*-wave arrival time obtained by a separate simulation of planar *P*-wave propagation (indicated in Fig. 7a), confirms that the initial low-amplitude disturbance is caused by interference of *P*-wave arrival.

Experimental data for the *P*-wave and *S*-wave signals were compared using the 5St configuration (Fig. 2c). Equivalent locations were considered by analysing $u^{5StP}_{1\to1}$ for *P*-waves and $u^{5St}_{2\to2}$ for *S*-waves. Referring to Fig. 14a, *P*-waves arrive earlier than *S*-waves, and the responses had a similar amplitude of output signals. The arrival time of the *P*-wave corresponds to the time when the low-amplitude disturbance is observed prior to coherent *S*-wave arrival. The overall variation of frequency domain response is similar comparing *S*-waves and *P*-waves, while *P*-waves exhibit higher frequencies at local maxima (Fig. 14b), and greater amplitudes at higher frequencies (> 20 kHz).

For the experimental data the disturbance is also evident for the summation of the individual waves (Fig. 6b). In contrast for the DEM data, the low-amplitude *P*-wave disturbance disappears when the signals are summed (Fig. 7b). This is because pure planar *S*-waves were generated in the DEM case.

Considering the 5S configuration, the DEM data show the area-dependency of the *P*-wave contamination. Fig. 10a shows that for $u_{20\to20}^{5S\,DEM}$, the first *S*-wave peak is slightly affected by the interference, whereas $u_{2\to2}^{5S\,DEM}$ exhibits a completely different signal when compared with $u_{100\to100}^{5S\,DEM}$ (planar wave). The frequency domain responses are also affected by the surface area (Fig. 10b), where multiple local peaks are evident for a smaller area of excitation, and the higher frequency components are relatively greater for a smaller area. These features agree with the experimental data (Fig. 9b).

<u>Area-dependency of signal amplitude</u>

Considering both the experimental data (Table 4) and the DEM data (Table 5), the peak amplitude of the first cycle of the received *S*-waves was taken to be an index of signal quality (a higher peak amplitude gives a higher signal to noise ratio). The peak amplitude has a linear dependency on the product of the transmitter area and the receiver area, $A_T \times A_R$ (Figs. 15a and 15b).

Regression analyses for experimental data and DEM data confirm a good approximation using linear-fitting with the coefficients of determination greater than 0.99. The linear variation can be explained by the fact that a larger number of particles contacting with the transmitter element were excited, and a larger number of particles near the receiver element contributed to the greater amplitude of the output signal. This observation agrees with Jia et al. (1999) who compared two types of receiver diameter (12 mm and 2 mm), and the amplitude of the coherent *P*-waves was considerably larger using the wider element.

<u>Area-dependency of interpreted V_S values</u>

To examine the area-dependency of the interpreted V_S values, Fig. 16 considers normalised V_S data for the $u^{5S\,DEM}$ series and the experimental data of $u_{5\to5}^{5S}$, $u_{5\to all}^{5S}$, $u_{all\to5}^{5S}$ and $u_{all\to all}^{5S}$; the V_S values are normalised by the minimum value of V_S for each of data sets. The four experimental cases were selected as their configurations generate and receive *S*-waves propagating through the centre path of the specimen to minimize the path-dependency and boundary effects. The V_S values decrease non-linearly as the average of A_T and A_R increases (Fig. 16) to give an increase of up to 5% for the numerical case. It is the planar *S*-wave excitation ($u_{100\to100}^{5S\,DEM}$) and $u_{all\to all}^{5S}$ that give the lowest V_S value for the DEM simulations and experimental cases, respectively. While the variation in V_S is at most 5% compared to the case for planar *S*-wave propagation, these data support use of as wide a shear plate as possible.

To better understand system response during *S*-wave propagation, the particle kinetic energies in the oscillation (*X*-) direction K_X (= 0.5×mass×square of particle velocity in the *X*-direction) are illustrated in Figs. 17a-17d for planar wave excitation, i.e. A_T = 100% ($u^{5S\,DEM}_{100\to100}$), and in Figs. 17e-17h for A_T = 2% ($u^{5S\,DEM}_{2\to2}$). To insert a similar amount of the total K_X values in both cases, the input transmitter displacement for $u^{5S\,DEM}_{2\to2}$ was increased by a factor of 50 where the particle velocity increases proportionally with the increase of transmitter displacement for a given input frequency for a linear system. Snapshots taken at 0.025, 0.1, 0.175, and 0.25 ms along a middle slice of the *XZ*-plane were analysed. A planar wave front was observed when the entire cap was excited (Figs. 17a-17d). The coherent K_X component propagates with a constant speed and its front arrives at the receiver plate at around 0.3 ms. In contrast when only 2% of the platen is excited a non-planar wave front is generated (Figs. 17e-17h), in agreement with O'Donovan et al. (2012). The coherent K_X propagation speed values are similar to those of the planar *S*-wave ($u^{5S\,DEM}_{100\to100}$), while small-amplitude but non-negligible K_X values are detected at the receiver at 0.25 ms (2.59 ms/m) earlier than $u^{5S\,DEM}_{100\to100}$ (Fig. 10a).

A discrepancy between experimental and DEM results is that the experimental data for $u^{5S}_{all\to all}$ still include the low-amplitude disturbance followed by coherent *S*-wave arrival (Fig. 9a), while this disturbance was not observed in equivalent DEM data (Fig. 10a). This might be attributed to the fact that small compressional deformation is generated inevitably during shear deformation of a piezoelectric element as noted by Brignoli et al. (1996). The actual compressional deformation of *S*-type piezoelectric element used in this study was not measured. The 0.4 mm protrusion of the 1 mm thick shear plates beyond the cap surface might also introduce a deviation from a purely planar wave in the laboratory experiments. In addition, as periodic lateral boundaries were used in the DEM simulations, the complex reflection at the membrane boundary was not captured.

Sensitivity to element thickness

Figure 13a compares *S*-wave signals for $u^{5St}_{2\to2}$ (t = 1 mm) and $u^{5St}_{4\to4}$ (t = 2 mm) that propagated vertically (Fig. 11) where the time is divided by each travel distance considering the thickness of their elements. *S*-wave velocities between $V^{5St}_{s,2\to2}$ and $V^{5St}_{s,4\to4}$ are similar within 1.4% difference, while the peak amplitude of $u^{5St}_{4\to4}$ is 2.4 times greater than $u^{5St}_{4\to4}$ indicating that a thicker element produces a greater amplitude. Their frequency responses exhibit a similar variation up to *f* = 12 kHz where the peak amplitude of $u^{5St}_{4\to4}$ (t = 2 mm) is about twice as large as that for $u^{5St}_{2\to2}$ (Fig. 13b). This highlights an advantage of using a thicker piezoelectric element to increase the signal-to-noise ratio, leading to an easier detection of the arrival time. Referring to Table 4, comparing the two diagonal wave paths, i.e. $u^{5St}_{2\to4}$ (from t = 1 mm to 2 mm) and $u^{5St}_{4\to2}$ (from t = 2 mm to 1 mm), the amplitude of the received signal for $u^{5St}_{2\to4}$ is nearly twice that recorded in $u^{5St}_{4\to2}$, indicating that the thickness of the receiver plate seems more effective to increase the peak amplitude; however, this qualitative observation should be assessed in future research.

Conclusions

This contribution has discussed the effect of shear plate configuration on elastic wave measurements using planar piezoelectric plates. The samples considered comprised spherical ballotini, and the experiments were complemented by DEM simulations to improve insight. Recognizing that an increase in signal-to-noise ratio as well as reduced disturbance due to *P*-wave interference improves the data quality, for the uniformly graded spherical particles considered here, the following conclusions can be made regarding appropriate shear plate configuration:

- In a triaxial test environment, the received peak amplitude increases in proportion to the product of the transmitter area and the receiver area, giving a larger signal-to-noise ratio.
- A smaller transmitter area leads to a larger V_S. The DEM data showed that where the transmitter and receiver plates occupy only 2% of the top/base cap area, the V_S estimate is 5% larger than the value calculated using ideal planar waves. Therefore, use of wider shear plate is recommended to obtain a more reliable, more accurate measurement of V_S.
- A thicker plate gives a higher received signal amplitude; however, for the thicknesses considered here there was a negligible influence on the interpreted V_S values. This empirical finding supports using a thicker plate while taking the change in resonant frequency into consideration.
- The path-dependency of the observed responses can be partially attributed to membrane boundary effects. High frequency contents are reduced due to the interaction between membrane and specimen. However, its effect on the wave velocity needs further investigation.
- DEM simulations indicated that near-field effects are induced due to excitation of *S*-waves from a limited area, while experimental data are affected by near-field effects irrespective of surface area of shear element. This discrepancy is probably due to inevitable compressional deformation associated with shear deformation of a physical shear element.
- The principle of superposition can be applied to the data confirming that the responses are linear-elastic for the small strains induced using this measurement technique.

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Table 1 Specification of shear plate tests

	sample dimension	plate dimensions		signal type	transmitter voltage	frequency
	mm	*S*-type : mm	*P*-type : mm		V	kHz
Brignoli et al. (1996)	50-70 × 20 - 140	12.7×12.7×6.3	8×2	sinusoidal pulse	±65	1 – 50
Ismail and Rammah (2005)	*	7×7×7	-	sinusoidal pulse	±110	5 – 10
Suwal and Kuwano (2013)	75 × 150	20×5 (disk-shaped)	20×2 (disk-shaped)	sinusoidal pulse	±93	1 – 40
Current study	50 × 110	15 - 30×15×1 - 2	15×15×0.5 - 1	sinusoidal pulse	±10	10, 15

* Shear plate dynamic tests were performed in the lateral direction with distances of 110 – 150 mm

Table 2 Experimental cases

Shear plate configuration	D [mm]	e	e_{min}	e_{max}
2L (Fig. 2a)		0.604		
5S (Fig. 2b)	1-1.4	0.602	0.524	0.626
5St (Fig. 2c)		0.604		

Table 3 Material properties used in DEM simulations

D [mm]	E_p [GPa]	v_p	μ_{prep}	μ_{wave}	e
1-1.4	70	0.2	0.05	0.2	0.607

Table 4 Summary of experimental data for *S*-wave propagation

Type	wave path	A_T	A_R	$A_T \times A_R$	V_S	peak amplitude	travel distance (L)
					m/s	V	mm
2L	u_{11}^{2L}	0.229	0.229	0.053	318.3	0.132	111.4
2L	u_{12}^{2L}	0.229	0.229	0.053	322.0	0.116	112.7
2L	u_{21}^{2L}	0.229	0.229	0.053	322.0	0.102	112.7
2L	u_{22}^{2L}	0.229	0.229	0.053	319.1	0.126	111.4
2L	u_{D1}^{2L}	0.458	0.229	0.105	322.4	0.228	111.4
2L	u_{D2}^{2L}	0.458	0.229	0.105	319.1	0.240	111.4
2L	$u_{11}^{2L}+u_{12}^{2L}$	0.229	0.458	0.105	318.7	0.248	111.4
2L	$u_{21}^{2L}+u_{22}^{2L}$	0.229	0.458	0.105	318.3	0.228	111.4
2L	$u_{11}^{2L}+u_{12}^{2L}+u_{21}^{2L}+u_{22}^{2L}$	0.458	0.458	0.210	318.7	0.476	111.4
2L	$u_{D1}^{2L}+u_{D2}^{2L}$	0.458	0.458	0.210	318.7	0.468	111.4
5S	$u_{1\to1}^{5S}$	0.115	0.115	0.013	289.4	0.041	112.0
5S	$u_{2\to2}^{5S}$	0.115	0.115	0.013	311.6	0.031	112.0
5S	$u_{5\to5}^{5S}$	0.115	0.115	0.013	299.6	0.052	112.0
5S	$u_{135\to5}^{5S}$	0.344	0.115	0.039	297.4	0.104	112.0
5S	$u_{245\to5}^{5S}$	0.344	0.115	0.039	297.7	0.116	112.0
5S	$u_{5\to135}^{5S}$	0.115	0.344	0.039	294.8	0.111	112.0
5S	$u_{5\to245}^{5S}$	0.115	0.344	0.039	298.3	0.127	112.0
5S	$u_{5\to all}^{5S}$	0.115	0.573	0.066	295.5	0.188	112.0
5S	$u_{all\to5}^{5S}$	0.573	0.115	0.066	294.5	0.174	112.0
5S	$u_{135\to135}^{5S}$	0.344	0.344	0.118	290.9	0.280	112.0
5S	$u_{245\to245}^{5S}$	0.344	0.344	0.118	297.7	0.280	112.0
5S	$u_{all\to135}^{5S}$	0.573	0.344	0.197	291.5	0.460	112.0
5S	$u_{all\to245}^{5S}$	0.573	0.344	0.197	295.2	0.466	112.0
5S	$u_{135\to all}^{5S}$	0.344	0.573	0.197	292.4	0.475	112.0
5S	$u_{245\to all}^{5S}$	0.344	0.573	0.197	294.5	0.441	112.0
5S	$u_{all\to all}^{5S}$	0.573	0.573	0.328	292.4	0.744	112.0
5St	$u_{2\to2}^{5St}$	0.115	0.115	0.013	318.9	0.040	111.1
5St	$u_{4\to4}^{5St}$ (t = 2 mm)	0.115	0.115	0.013	314.5	0.086	109.1
5St	$u_{2\to4}^{5St}$	0.115	0.115	0.013	293.2	0.1528	114.3
5St	$u_{4\to2}^{5St}$	0.115	0.115	0.013	292.6	0.08	114.3

Table 5 Summary of DEM data for *S*-wave propagation

type	wave path	A$_T$	A$_R$	A$_T$ × A$_R$	V_S	peak amplitude	travel distance (L)
					m/s	kPa	mm
2L	$u_{11}^{2L\,DEM}$	0.500	0.500	0.250	328.5	0.0336	96.73
2L	$u_{12}^{2L\,DEM}$	0.500	0.500	0.250	332.8	0.0402	99.73
2L	$u_{21}^{2L\,DEM}$	0.500	0.500	0.250	333.2	0.0408	99.73
2L	$u_{22}^{2L\,DEM}$	0.500	0.500	0.250	329.1	0.0325	96.73
2L	$u_{D1}^{2L\,DEM}$	1.000	0.500	0.500	325.2	0.0734	96.73
2L	$u_{D2}^{2L\,DEM}$	1.000	0.500	0.500	325.2	0.0712	96.73
2L	$u_{11}^{2L\,DEM}+u_{12}^{2L\,DEM}$	0.500	1.000	0.500	325.3	0.0727	96.73
2L	$u_{21}^{2L\,DEM}+u_{22}^{2L\,DEM}$	0.500	1.000	0.500	325.7	0.0721	96.73
2L	$u_{11}^{2L\,DEM}+u_{12}^{2L\,DEM}+u_{21}^{2L\,DEM}+u_{22}^{2L\,DEM}$	1.000	1.000	1.000	325.5	0.1448	96.73
2L	$u_{D1}^{2L\,DEM}+u_{D2}^{2L\,DEM}$	1.000	1.000	1.000	325.2	0.1445	96.73
5S	$u_{2\to2}^{5S\,DEM}$	0.115	0.115	0.013	341.3	0.00183	96.73
5S	$u_{3\to3}^{5S\,DEM}$	0.115	0.115	0.013	339.5	0.00307	96.73
5S	$u_{5\to5}^{5S\,DEM}$	0.115	0.115	0.013	338.7	0.00522	96.73
5S	$u_{7\to7}^{5S\,DEM}$	0.344	0.344	0.118	337.4	0.00786	96.73
5S	$u_{10\to10}^{5S\,DEM}$	0.344	0.344	0.118	335.9	0.0107	96.73
5S	$u_{15\to15}^{5S\,DEM}$	0.344	0.115	0.039	334.0	0.0160	96.73
5S	$u_{20\to20}^{5S\,DEM}$	0.344	0.115	0.039	332.0	0.0218	96.73
5S	$u_{25\to25}^{5S\,DEM}$	0.115	0.344	0.039	330.3	0.0300	96.73
5S	$u_{35\to35}^{5S\,DEM}$	0.115	0.344	0.039	328.3	0.0454	96.73
5S	$u_{50\to50}^{5S\,DEM}$	0.573	0.344	0.197	326.6	0.0689	96.73
5S	$u_{70\to70}^{5S\,DEM}$	0.573	0.344	0.197	325.5	0.1070	96.73
5S	$u_{100\to100}^{5S\,DEM}$	0.344	0.573	0.197	325.2	0.1445	96.73

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Figure 1 Design of shear plates embedded in base pedestal. (a) 2L-configuration (b) 5S-configuration.

Figure 2 Schematic of shear plate configurations (S stands for shearing mode and P stands for compression mode) (a) 2L-type (b) 5S-type (c) 5St-type.

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Figure 16 Sensitivity of *S*-wave velocity (V_S) with area ratio (V_S is normalised by the lowest value of V_S for laboratory and DEM data sets, respectively).

Figure 17 DEM data for propagation of particle kinetic energy in X-direction for (a-d) planar *S*-wave (e-h) *S*-wave excited at 2% area of transmitter wall at (a&e) 0.025 ms (b&f) 0.1 ms (c&g) 0.175 ms (d&h) 0.25 ms. Dashed lines indicate the coherent wave front observed for planar *S*-waves.