Assessment of elastic wave velocities through granular soils during monotonic loading

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ABSTRACT

The precise estimation of the wave velocities and stiffness of geomaterials is essential for the accurate design of structures as well as reliable geotechnical characterization of sediments. In the present study, disk-shaped piezo-ceramic transducers are utilized to determine shear wave and compression wave velocities at both isotropic and anisotropic stress states. Silica sand specimens were first isotropically consolidated to confining pressure of 100 kPa and elastic wave velocities were measured at different excitation frequencies. Samples were then monotonically sheared at a low strain rate while keeping the cell pressure constant, and wave measurements were performed at various strain levels during the shearing process. It is observed that wave velocities of specimens prepared at different void ratios tend to converge at a large axial strain similar to the stress-strain relationship. The increment of normal stress component has a significant influence on compression wave velocity as compared to shear wave velocity.

Keywords: disk transducers; wave measurement; Poisson's ratio; stress anisotropy; silica sand

1 INTRODUCTION

The precise estimation of wave velocities and stiffness of geomaterials is an essential prerequisite for the accurate design of structures as well as authentic geotechnical characterization of sediments. Measurement of elastic waves by means of piezo-ceramic elements has been popularized by Shirley and Hampton (1978), when they developed bender elements to detect shear waves in sediments. The bender element technique has been widely adopted to determine the wave velocities through geo-materials (Dyvik and Madshus 1985; Viggiani and Atkinson 1995; Kuwano and Jardine 2002). However, the bender element technique has limitations; it causes remarkable disturbance near the place of insertion, and it is not suitable for undisturbed or cemented specimens. To overcome the limitations, disk-shaped transducers have been adopted and installed at the boundaries of the specimen (Brignoli et al. 1996; Ismail and Rammah; 2005; Suwal and Kuwano 2013; Otsubo and O'Sullivan 2018). Due to its flat shape, disk transducers can generate more planar waves compared to bender elements for both compression (P-) and shear (S-) waves, and they can be simultaneously recorded. However, utilization of flat shaped transducers still needs more experiences before applying it to in-situ measurements. In the present study, wave velocities are measured using disk transducers at both isotropic and subsequent monotonic loading in a conventional triaxial apparatus. This study aims to estimate and monitor the soil properties during triaxial shearing including stiffness using the disk-shaped transducer.

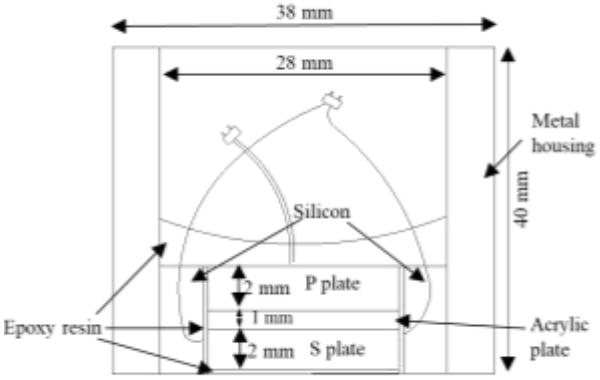
2 DEVELOPMENT OF DISK TRANSDUCERS

The disk transducers were developed by properly merging both P- and S-type elements on either side of an acrylic plate using epoxy resin. Fig. 1(a) presents a schematic design of the disk transducers. The merged P- and S-type elements are placed inside a metal housing and are supported using silicon and epoxy resin. The metal housing with the disk transducers at the center is then carefully inserted inside the top cap and bottom pedestal of the triaxial apparatus (Fig. 1(b)). In the developed disk transducers, the S-type element was kept at the top (i.e. nearer to the specimen), and the P-type element was kept at the bottom. A thin layer of epoxy resin was gently applied to coat the surface of both the P- and S-type plates to prevent damage due to water and abrasion caused by the angular sand particles.

3 MATERIAL AND SAMPLE PREPARATION

Referring to Fig. 2, an angular silica sand with diameters ranging from 1.4 to 2 mm was used (specific gravity = 2.64, the max. and min. void ratios = 0.983 and 0.681, respectively according to JGS (2000)), although a larger container (80×60 mm) was used.

Cylindrical sand specimens of size 75×150 mm were prepared using a split mold and side tapping method was adopted to obtain the desired void ratios. Three types of specimens were discussed in the present study: (1) loose specimen having an initial void ratio (e_o) of 0.921 at a mean isotropic confining pressure (p') of 100 kPa, and a relative density (D_r) of 21%, (2) medium dense specimen having e_o = 0.835 and D_r = 49%, (3) dense specimen having e_o = 0.712 and D_r = 90%.



(a)

(b)

Fig. 1. (a) Schematic of metal housing with the disk transducer in top cap (b) Bottom pedestal with disk transducer at the center.

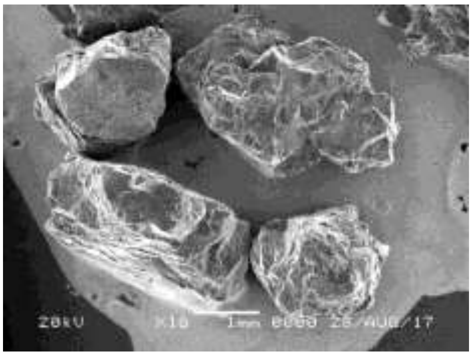
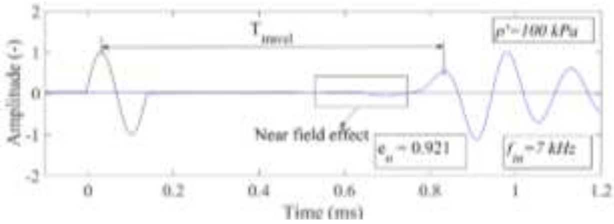


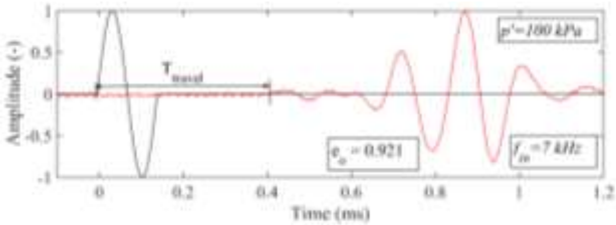
Fig. 2. SEM image of the tested silica sand.

4 TESTING AND DATA INTERPRETATION

Samples were first consolidated to p' = 100 kPa, and wave velocities were measured at different excitation frequencies (f_{in}). Later, samples were compressed monotonically at a strain rate of 0.0003% per sec, while keeping the cell pressure (σ_3') consant at 100 kPa. Wave measurements were conducted without stopping the triaxial loading. The excitation wave signals in the present study were generated using a digital function generator and amplified by a bipolar amplifier. Sinusoidal waveforms of frequencies ranging from 5 kHz to 20 kHz were applied to the specimens, and the input and output signals were recorded using an oscilloscope (Figs. 3 and 4). The peak-to-peak method was adopted to evaluate the arrival time for S-wave signals (Fig. 3(a)) as the rise points are affected by the presence of a near-field effect. The V_s evaluated from the peak-to-peak method and rise-to-rise method were in good agreement (within 2%), but elaborate discussions have not been reported here. The rise-to-rise method was adopted to determine the P-wave arrival time (Fig. 3(b)). Figs. 4(a) and 4(b) present the S-wave and P-wave arrival, respectively, during shearing at axial strain (ε_a) of 8.9%. The received P-wave signal has been greatly amplified due to the increase in the normal stress (σ_1') component.

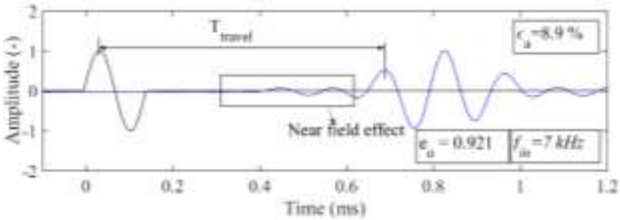


(a)

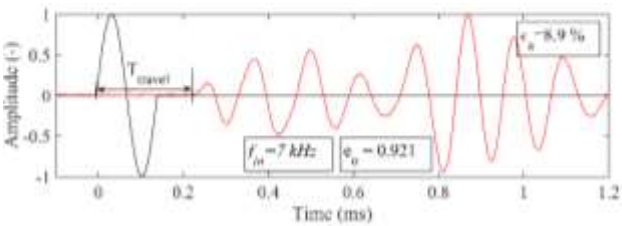


(b)

Fig. 3. Wave signals at ε_a = 0% for loose case and sample length of 149.77 mm (a) S-wave (b) P-wave. (Signal amplitude is normalized by the maximum value.)



(a)



(b)

Fig. 4. Wave signals at ε_a = 8.9% for loose case and sample length of 136.85 mm (a) S-wave (b) P-wave. (Signal amplitude is normalized by the maximm value.)

5 RESULTS AND DISCUSSIONS

Figsures 5(a) and 5(b) depict the variation in the shear wave velocities (V_s) and compression wave velocities (V_p) respectively for various input frequencies (f_{in}). For S-wave, f_{in} = 7 kHz was considered for wave measurements during shearing, so that input and output exhibit a similar dominant frequency.

Figure 6(a) shows the relationship between the deviatoric stress (q = σ_1'–σ_3') and the axial strain (ε_a), and between the volumetric strain (ε_v) and ε_a. Referring to Fig. 6(b), for the dense and medium dense samples, V_s increases sharply with the increase in axial strain (up to about 0.2%), but with further increase in the axial strain, V_s drops gently. For the loose specimen, V_s increases with strain level up to about 2.2%, but with further increase in strain level V_s drops gradually. The rate of drop in V_s for the loose specimen is lower than the dense and medium dense specimens, and at a large strain level, V_s of all three specimens tend to converge. The axial strain level at which the V_s value drops can be hypothesized to be similar to the axial strain level at which the change in the fabric of the specimen takes place, i.e. the strain level at which the specimen shows a dilative behavior (can be visualized from the relationship between ε_v – ε_a in Fig. 6(a)).

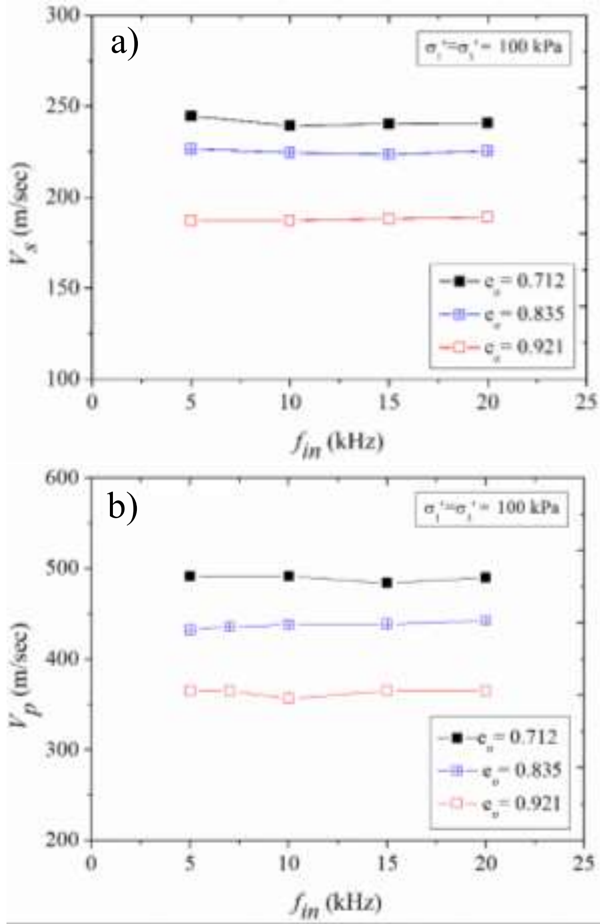


Fig. 5. Variation in (a) V_s (b) V_p with excitation frequency (f_{in}) (peak-to-peak method for V_s, rise-to-rise method for V_p).

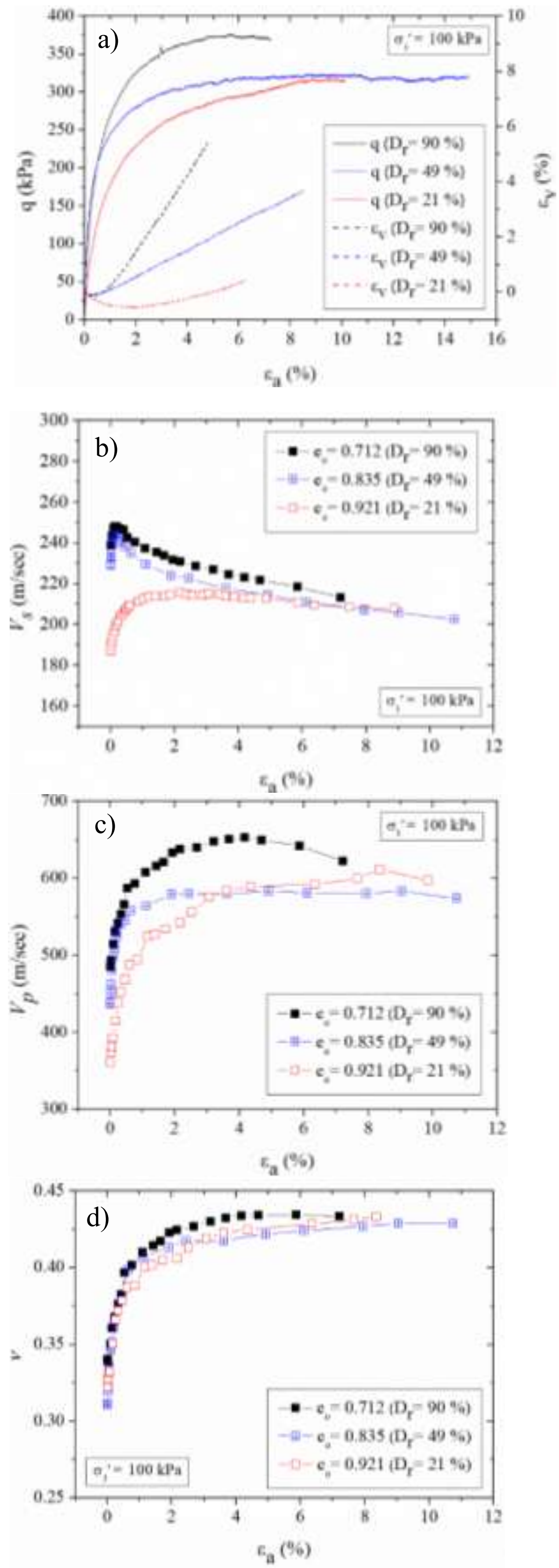


Fig. 6. Mechanical responses of dense and loose samples during triaxial compression. Relationship between (a) q – ε_a (b) V_s-ε_a (c)

V_p-ε_a (d) ν– ε_a.

The variation of compression wave velocity (V_p) with axial strain is illustrated in Fig. 6(c). The V_p values of specimens having different initial void ratios also tend to converge at large strain levels. It can be hypothesized that there exists a critical wave velocity which the specimens tend to reach during shearing.

Figure 6(d) illustrates the variation in Poisson's ratio (ν) with axial strain. The Poisson's ratio (ν) is calculated using both V_S and V_P as:

$$\nu = \frac{V_P{}^2 - 2V_s{}^2}{2V_P{}^2 - 2V_s{}^2} \qquad (1)$$

The Poisson's ratio of all the three specimens increases monotonically with the increase in axial strain. This shows that the increment of the normal component of stress (σ_1') has a significant effect on compression wave velocity as compared to shear wave velocity.

Figure 7(a) portrays the variation of V_s at different geometric mean stress ($\sqrt{\sigma_1'.\sigma_3'}$) during triaxial shearing. It is observed that V_s of all three specimens tends to converge at large anisotropic stress levels.

Figure 7(b) shows the variation in V_p with normal stress level (σ_1') during shearing. As the compression wave velocity depends greatly on the normal stress acting in the propagation direction, it is observed that V_p increases significantly with the increase in normal stress (σ_1'); this agrees with prior research (e.g. Bellotti et al. 1996). Furthermore, the rate of increase in V_p is faster for the loose specimen as compared to the denser specimens, and V_p of all three specimens tends to converge at large stress levels.

6 CONCLUSIONS

In the present study, piezo-ceramic disk-shaped transducers have been employed to measure the shear wave and compression wave velocities of silica sand in both isotropic and anisotropic stress states. Elastic wave velocities of specimens prepared at different void ratios tend to converge at a large axial strain similar to the stress-strain relationship. The increment of normal stress component (propagation direction) has a significant influence on compression wave velocity as compared to shear wave velocity. This leads to an increase of the Poisson's ratio with increased axial strain. Variations of V_p, V_s and ν with axial strain were measured successfully using the proposed disk-shaped transducers; this technique can be adopted for assessing and monitoring change in in-situ ground properties subjected to external loads for a long term.

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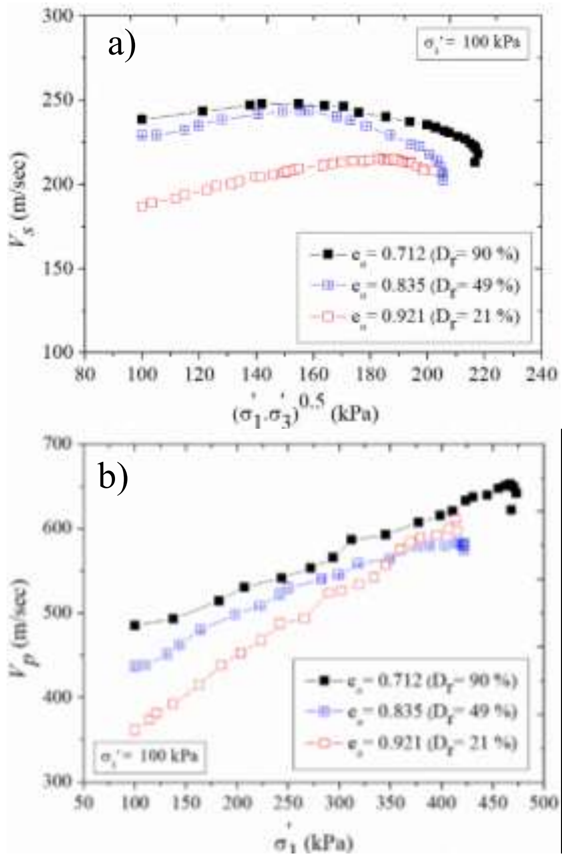

Fig. 7. Variation in (a) V_s (b) V_p with anisotropic stress states during triaxial compression.

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