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Elastic Shear Modulus Of A Crushable Engineered Sand: A Laboratory Study Using Advanced Techniques

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ABSTRACT: The small-strain shear modulus (G_{max}) of soils is an essential property for the prediction of deformations and the seismic design of geo-structures. In the paper, a laboratory study of the dynamic behavior of a crushable engineered geo-material with promising applications as backfill, construction or foundation soil, is presented with a focus on G_{max}. A set of resonant column tests is carried out on reconstituted and dry samples and the small-strain shear modulus is derived based on torsional vibration of the specimens at first mode of resonance as well as based on bender element tests. The signal interpretation from the bender element tests is conducted by means of the first time arrival and the peak-to-peak methods. The results indicate a satisfactory comparison between different laboratory methods in measuring G_{max}. Small-strain shear modulus is expressed through a power-law type formula as a function of the confining pressure. The constants of this formula match better to the behavior of sands with irregular-shaped grains reported in the literature. The laboratory test results of the study comprise a preliminary investigation of the dynamic behavior of recycled aggregates, as part of an extensive experimental research work at UNSW Australia.

1 INTRODUCTION

The resonant column is the standard method in measuring the dynamic properties of geo-materials from very small to medium strain amplitudes (Richart et al., 1970, ASTM, 1992) including small-strain shear modulus, G_{max}, and the strain-dependent shear modulus, G, and material damping, D. G_{max} is an essential property in the prediction of deformations and the seismic design of geo-structures as well as the study of soil-foundation-structure interaction phenomena or foundation dynamics due to machine vibrations (Richart et al., 1970, Ishihara, 1996). The use of bender elements, proposed by Shirley and Anderson (1975), is becoming in recent years a popular experimental method in capturing the small-strain shear modulus of geo-materials (Lee and Sanatamarina, 2005, Leong et al., 2005). The resonant column is a medium-frequency laboratory method, with frequencies under consideration normally within a range of 20 to 200 Hz. On the other hand, the bender element method is a high-frequency technique with frequencies under consideration, as a common practice in laboratory testing, between 5 and 20 kHz.

In the study, a preliminary investigation of the small-strain shear modulus of a crushable engineered geo-material is presented. Both the resonant column and the bender element methods are implemented and the validation of the bender element interpretation for the time arrival is based on the resonant column test results. The crushable geo-material of the study is composed of recycled concrete aggregate which is a promising material in geotechnical and civil engineering applications (Poon and Chan, 2006, Tatsuoka et al., 2013).

2 MATERIALS AND EXPERIMENTAL PROCEDURES

The recycled concrete aggregate used in the study was provided by a supplier in New South Wales, Australia. The material was prepared through a series of sieves and a coarse fraction (fraction 1.18-2.36 mm) was used in the study. Specific gravity test (ASTM, 2002) indicated a value of G_s equal to 2.47. An image of the recycled concrete aggregate is given in Figure 1. Note that the shape of the grains, which plays a fundamental role in the dynamic behavior of geo-materials (e.g. Senetakis et al., 2012, 2013a, 2013b), is irregular, i.e. the particles are angular. A Stokoe-type resonant column (Cascante et al., 1998) with fixed-free ends was used in the study. The resonant column has embedded bender elements and thus the shear modulus of the sample can be studied by means of both medium-frequency (resonant column) and high-frequency (bender elements) tests. An image of the apparatus used in the study is given in Figure 2. The bender element inserts are composed of piezoelectric ceramic bi-morphs (Kumar and Madhusudhan, 2010). The drive system of the resonant column is composed of four coils and four magnets and the response of the specimen is recorded from accelerometer attached on its top.

Fig.1 Image of recycled concrete aggregate fraction 1.18-2.36 mm used in the study

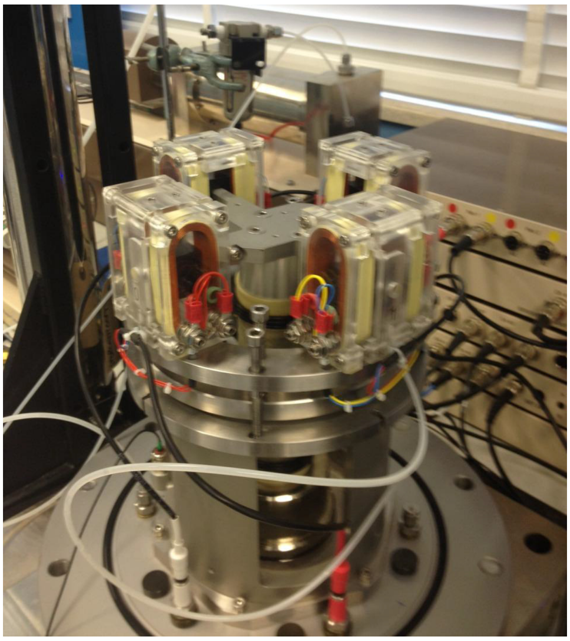

Fig.2 The Stokoe-type resonant column of UNSW Australia

A set of four specimens of 50 mm in diameter and 100 mm in length, approximately, was prepared in the resonant column apparatus. Variable initial densities were achieved by applying different compaction energies during sample preparation. The four specimens were prepared at void ratios of 1.183, 1.173, 1.248 and 1.233. Initially, the specimens were supported by a vacuum of about 5 kPa, before the set of the drive mechanism and the triaxial cell. The experiments were carried out in a range of isotropic confining pressures (p') from 25 to 800 kPa, typically at steps of 25, 50, 100, 200, 400, 600 and 800 kPa.

3 RESULTS AND BRIEF DISCUSSION

During resonant column test, at each step of p', the sample is excited in torsional mode of vibration in a range of frequencies and a spectrum by means of excitation of the sample on its top against frequency is derived. The resonant frequency (f_n) corresponds to the point of maximum excitation. For a fixed-free resonant column, the first mode of resonance is considered and the formulae from the theory of elastic waves propagation in prismatic rods is applied for further interpretations (Richart et al., 1970, ASTM, 1992). For the four specimens of the study, the resonant frequency ranged from about 32 to 82 Hz. Note that the resonant frequency for a given type of soil and a given density is affected dominantly by the sample geometry (Senetakis and Anastasiadis, 2015).

Based on the general formula of elastic wave propagation in prismatic rods and considering the boundary conditions of the sample, Equation (1) is derived, which is the fundamental equation in resonant column test analysis.

$$G \text{ or } G_{max} = \rho \times (2 \times \pi \times L)^2 \times \left(\frac{f_n}{F}\right)^2 \qquad (1)$$

where G is the shear modulus from small to medium strains, G_{max} is the small-strain (elastic) shear modulus, ρ is the mass density of the sample, L is the length of the sample, f_n is the resonant frequency and F is a non-dimensional frequency factor (ASTM, 1992).

Based on the mass density of the sample and the estimated resonant frequency, G_{max} for each sample and confining pressure was computed. G_{max} against p' plots for all samples are given in Figure 3. Fitting curves of the experimental data, of a power-law type, which are commonly adopted in soil dynamics research and practice, are also given in Figure 3. The general formula of the fitting curves is given in Equation (2).

$$G_{max} = a \times (p')^b \qquad (2)$$

In Equation (2), (a) is a constant which depends on soil type, grading and density and (b) is a power which depends on soil type. The power (b) reflects the particle contact response of a granular assembly which response is plastic to brittle in nature (Cascante and Santamarina, 1996). For granular soils, the exponent (b) depends, primarily, on the coefficient of uniformity, the shape and mineralogy of the grains (Cascante and Santamarina, 1996, Senetakis et al., 2012, 2013b, 2015). Based on the analysis of the results, the constant (a) and the power (b) for all samples were estimated and the values of these two elastic constants are summarized in Table 1. Note that the values of the power (b) ranged from 0.55 to 0.58, which represent effectively elastic constants of sands with irregular-shaped grains (Cho et al., 2006, Senetakis et a., 2012, 2015).

Table 1.Elastic constants (a) and (b) of recycled concrete aggregate samples based on the torsional resonant column tests

Sample No	Initial Void ratio	Initial density (kN/m^3)	a (MPa)	b
1	1.183	11.1	4.47	0.57
2	1.173	11.2	3.96	0.57
3	1.248	10.8	4.49	0.55
4	1.233	10.9	4.13	0.58

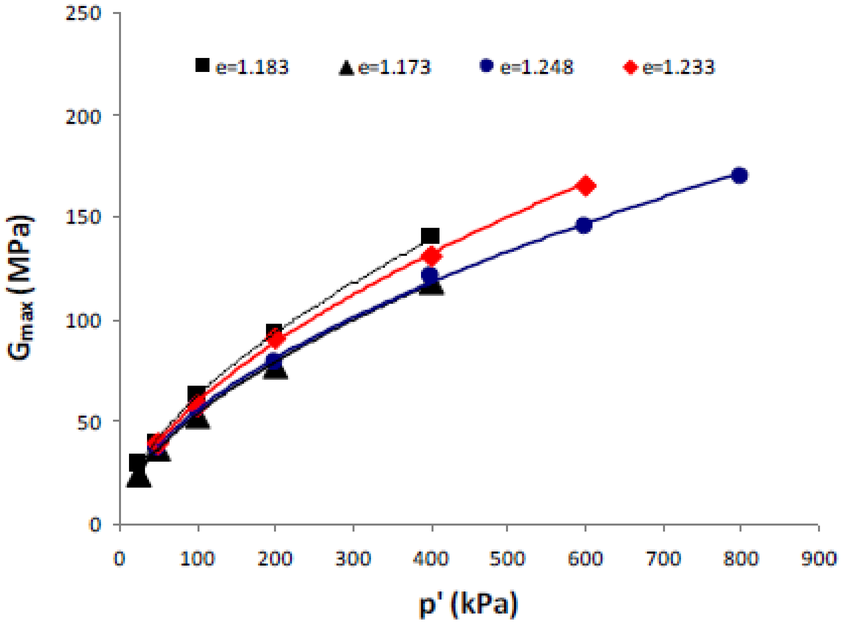

Fig.3 Small-strain shear modulus against confining pressure for all samples subjected to torsional resonant column testing

Apart from the excitation of the samples in torsional mode of resonant column testing, the samples were subjected to high-frequency (bender element) tests. A sinusoidal input signal with an amplitude of 14 V and a frequency of 10 kHz was applied. For the received signal analysis, the time arrival was estimated based on averaging the peak-to-peak and first time arrivals. Typical signal analysis and processing during the bender element tests of the recycled concrete aggregate samples is given in Figure 4. The interpretation for the time arrival is also depicted highlighting the two different methods used (i.e. peak-to-peak and first time arrivals).

By averaging the time arrivals from the peak-to-peak and first time arrival methods, the shear wave velocity (V_s) of the samples was estimated. Based on the well-known formula of Equation (3), G_{max} of the samples, from the bender element tests, was computed.

$$G_{max} = \rho \times V_s^2 \tag{3}$$

A comparison of the measured small-strain shear modulus between the resonant column and the bender element test methods for all samples is given in Figure 5. The results indicated excellent agreement between the different methods in measuring G_{max}. Note that the resonant column is the standardized and well-established method in measuring small-strain shear modulus, whereas the bender element signal analysis incorporates uncertainties which may arise because of some degree of subjectivity during the interpretation of the time arrival including near field effects. Thus, the results in Figure 5 validated the excellent performance of the bender element interpretation adopted in the study.

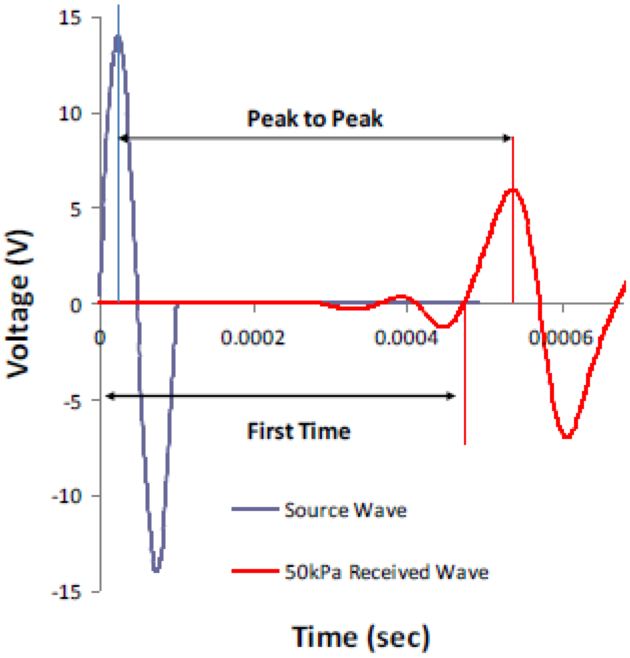

Fig.4 Example of interpretation of bender element tests: Sinusoidal input signal and estimation of time arrival based on different methods (sample with e = 1.183)

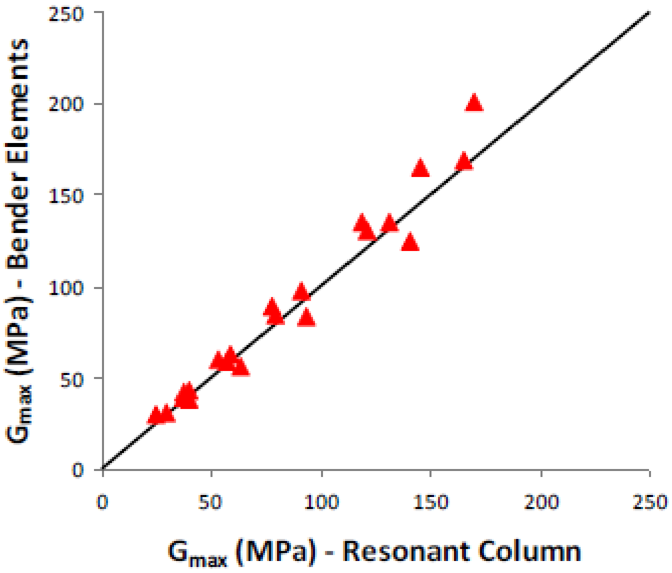

Fig.5 Comparison of small-strain shear modulus of recycled concrete aggregate between resonant column and bender element tests

4 CONCLUSIONS:

The study reported, briefly, dynamic test results on dry samples of recycled concrete aggregate which is a crushable engineered geo-material with promising applications in geotechnical engineering projects. Torsional resonant column tests were conducted on samples under isotropic conditions of confinement, prepared at variable initial densities. The G_{max}-p' relationship of the recycled concrete aggregate, through the exponent (b), was found similar to that of sands with irregular-shaped grains. Bender element tests were conducted to the same samples and for the signal analysis and processing the peak-to-peak and first time arrival methods were used. The comparison between the resonant column and the bender element tests was excellent which validated the interpretation method used for the bender element tests.

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