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Bender element measurement of small strain shear modulus of cement-treated marine clay – Effect of test setup and methodology

Huawen Xiao [b], Kai Yao [b], Yong Liu [a,b,*], Siang-Huat Goh [b], Fook-Hou Lee [b]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, PR China
[b] Department of Civil & Environmental Engineering, National University of Singapore, Singapore

HIGHLIGHTS

- Measurement of small strain shear modulus of cement-treated marine clay using bender element is examined.
- Infilling with appropriate material will help to ensure consistency in received signal.
- A modified cross-correlation method with window control is proposed.

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ABSTRACT

This paper examines the effect of experimental methodology on the measurement of small strain shear modulus of cement-treated marine clay using bender element. The specimens tested have cement content ranging from 20% to 50%, this being the typical range of cement content used for ground improvement in relation to underground construction. The experimental aspects studied include specimen set-up, travel time identification, excitation frequency and specimen size effects. The results indicate that, where a pre-made slot is used for the bender element, infilling the slot with an appropriate material will help to enhance probe-soil contact, reduce the sensitivity of the measurements to slot size accuracy and ensure consistency in received signal. Both the first arrival and first peak approaches for travel time determination are found to be sensitive to the system. The conventional cross-correlation method was also found to give erroneous measurements when the second peak is higher than the first. A modified cross-correlation method with window control is proposed which works well with both bender element systems studied. The source frequency used should also be higher than 3 kHz and the wave path length to wave length ratio should be larger than about 0.73. Finally aspect ratio of much higher 2 may also lead to erroneous measurements and should be avoided.

1. Introduction

Cement jet grouting and deep mixing for stabilization of deep excavation and underground construction works typically involve a cement content of 20% or greater (e.g. [19,36,25,30]). In such cases, the main objective is often to control ground movement. For instance, construction activities in the vicinity of Mass Rapid Transit infrastructure in Singapore are not permitted to cause movement to any part of the structure larger than 15 mm. As such, stiffness, especially at low strain, is often a more pertinent requirement than strength. In such instances, the small strain behavior of cement-treated soil, including its small-strain modulus, is an important parameter.

The bender element test has been widely used for small strain modulus measurement (e.g. [14,8,9,27,46]). However, there remains considerable variance in the testing methodology, such as the characteristics of the bender elements, installation procedure, specimen size, waveform and frequency of the transmitted signal and travel time determination method (e.g. [39,23,29,24,15,46,11,4,16]). For instance, both time and frequency domain methods have been used for travel time identification (e.g. [12,32,46,37,38,13,10,7,20,16,35]). Up to now, there is still not a universally accepted method for all scenarios. Similarly, the near-field effect has also been studied (e.g. [26,46,21]), and various values for the limiting wave path length to wave length ratio have been proposed (e.g. [33,5,2,27]). Some studies have reported the specimen size effect (e.g., [3]) whereas others have reported none

* Corresponding author at: State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, PR China.
E-mail address: liuy203@whu.edu.cn (Y. Liu).

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(e.g., [11]). The results to-date indicate that the applicability of different methods are dependent upon the scenario to which they are applied, especially the type of soil to be tested.

Although there has been a significant development on bender element test methods for natural soils, much less work has been done on bender element testing of cemented-soils and rocks. Ferreira et al. (2014) [16] reported that there are still limitations on the applicability of the bender element test for stiff geomaterials, owing to greater impedance of the tested material. Although some bender element tests have been conducted on cement-treated soils [10,7,17,13], most of them were for specimens with less than 10% of cement content. There remains a scarcity of work on cement-treated soil specimens with higher cement content. More importantly, test conditions and procedures for ensuring stable and reliable results for such materials are still not well-established.

This paper examines the experimental techniques for measuring small strain shear modulus of cement-treated marine clay with cement contents up to 50% using bender element tests. Specimens with different mix ratios were prepared and tested using two different bender element systems. Resonant column test results were used as a benchmark for assessing the bender element results. Specimen set-up, excitation frequency, travel time measurement and specimen size effects are examined. Different time-domain methods for estimating travel time are also evaluated. A modified cross-correlation method with window control that possesses greater robustness with respect to test system and cement content is proposed.

2. Materials and test program

2.1. Materials

The cement-treated clay was made by admixing Singapore Upper Marine clay and Ordinary Portland Cement (OPC) slurry. The constituents of the marine clay are 10.8% colloid, 22.5% clay, 55.5% silt and 11.2% very fine to medium sand. Its liquid and plastic limits are 74% and 31%, respectively. Prior to cement mixing, the clay was wet-sieved to remove seashells and coarse debris.

Table 1 shows the mix ratios of the cement-treated clay tested, expressed in terms of the mass ratio of dry soil solid (S): cement solid (C): water (W) at the point of mixing. The cement content A_w is defined as the mass ratio of cement to dry soil solid, that is C:S. The water content C_w is defined as the mass ratio of water to dry soil and cement solids, that is W: (S + C). The procedure used for the preparation of the specimens is similar to that reported by Xiao et al. [42], Xiao and Lee [41], and Xiao et al. [43,44]. The marine clay was mixed with cement slurry with the water-cement ratio needed to achieve the desired mix ratio in a mechanical mixer for around 10 min. For every kilogram of soil and cement solids, 15 ml of a naphthalene-based superplasticizer, was added to improve mixability.

The soil-cement admixture was casted into cylindrical polyvinyl chloride split-molds and then vibrated to expel the air voids. Specimens were cured under de-ionized water without loading. The specimens' diameter ranges from 35 mm to 70 mm and their height ranges from 50 mm to 140 mm. The reference specimen size for bender element tests was 50 mm diameter by 100 mm height. Specimens with 35 mm diameter and 70 mm height were used for specimen size effect study and resonant column test. In addition, bender element tests were also conducted on specimens with 50 mm diameter by 50 mm height and 70 mm diameter by 140 mm height to study the specimen size effect.

2.2. Test program

The two bender element test systems used herein were acquired from GDS and Wykeham Farrance, hereafter termed GDSBE and WFBE, respectively. Both systems use bender elements which are 10 mm wide and 0.5 mm thick. In both systems, the source signal is a single sine-wave input pulse. The GDSBE system has a data acquisition speed of 500,000 samples per second and 16-bit resolution. Its bender elements have a protrusion length of 1.5 mm into the soil. The WFBE system has a data acquisition speed of one million samples per second and 16-bit resolution. The initial protrusion length of the WFBE bender element was 10 mm, but preliminary trials showed that, with this protrusion depth, the elements were easily damaged during shear wave triggering, probably owing to the high stiffness of the cement-treated soil specimens. The protrusion length was thus reduced to 2.5 mm to prevent further damage. Another possible configuration to avoid damage

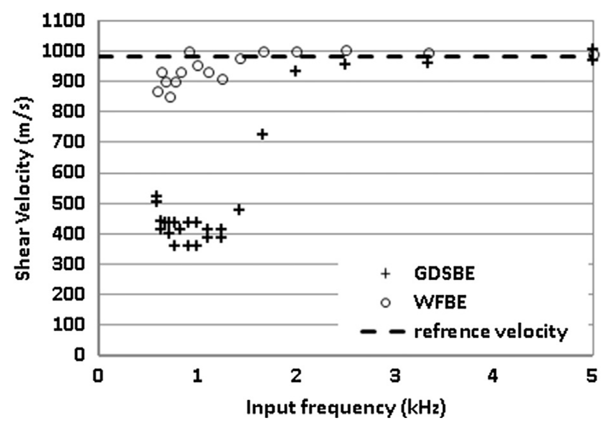

Fig. 1. Shear wave velocity versus input frequency obtained from GDS and WF bender element test system for Acrylic cylinder specimen.

Fig. 2. Specimen with cut slot after curing.

Table 1
Mix ratio used in this study.

Mix proportion S:C:W	Cement content Aw (%)	Water content C_w (%)	Curing period (days)	Specimen dimension		Unconfined compressive strength (kPa)
				D (mm)	H (mm)	
5:1:6	20	100	7	35–70	70–140	495
10:3:13	30	100	7	50	100	800
2:1:3	50	100	7	35–70	50–140	1200
2:1:4	50	133	7	50	100	445