Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-159

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Assessment of shear wave velocity variation in compacted soil using pulse transmission techniques

Évaluation de la variation de la vitesse des ondes de cisaillement dans un sol compacté à l'aide de techniques de transmission d'impulsions

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ABSTRACT: In this paper, two techniques for benchmarking shear wave velocity in compacted soil during drying are compared. The two techniques considered are both pulse transmission techniques, i.e. bender elements and ultrasonic pulse testing. In past studies, bender elements have been used to monitor the shear wave velocities in soil media whereas ultrasonic pulse tests have been mainly used for determining pulse velocities of rocks because the soil media have higher damping characteristics. While the ultrasonic pulse test system is less established in geotechnical engineering applications compared to bender elements, it is less intrusive as the specimens do not need to be protruded. The results suggest that both pulse transmission systems provide comparable wave responses and thus appropriate for more wide use in geotechnical applications.

RÉSUMÉ: Dans cet article, deux techniques d'évaluation de la vitesse des ondes de cisaillement dans un sol compacté pendant le séchage sont comparées. Les deux techniques considérées sont des éléments de flexion-extension et des tests d'impulsions ultrasonores. Dans des études antérieures, des éléments de flexion-extension ont été utilisés dans le sol, tandis que les tests d'impulsions ultrasoniques ont été utilisés dans le roches. Bien que le système de test par impulsions ultrasoniques soit moins établi que les éléments de flexion -extension, il est moins intrusif car les échantillons n'ont pas besoin de faire saillie. Les résultats suggèrent également que les deux systèmes de transmission d'impulsions fournissent des réponses comparables et donc appropriés pour une utilisation plus large dans les applications géotechniques en sols.

Keywords: Pulse transmission test; unsaturated soils; compacted soils; ultrasonic testing; bender elements.

1 INTRODUCTION

Two configurations of the piezoelectric elements are used for soils testing, namely bender elements and ultrasonic transducers (Figure 1). The former is characterised by two piezoelectric ceramic elements joined to each side of an intermediate conduction shim, mounted vertically and embedded in a specimen (Santamarina et al., 2001). When a DC voltage, usually in the form of a sine wave, is applied to the bender element it deforms converting the electrical input into mechanical energy in the form of a shear wave. Comparatively, ultrasonic transducers consist of a polarised piezoelectric element with two electrodes on either face, bonded to a low impedance platen (wear plate). Excitation to produce shear waves is achieved when a voltage is applied to the element, aligning the polarized molecules causing it to change shape (Suwal and Kuwano, 2013). The piezoelectric element in the transducer is generally one half the thickness of its selected frequency. Unlike bender elements the frequency of the ultrasonic tests can not be altered during testing. The platen is also one quarter the thickness of the selected frequency of the transducer to ensure it is in phase with the piezoelectic element. The backing material generally has low impedance to attenuate waves travelling into the transducer. A couplant is also required between the platen and the specimen to ensure good contact to efficiently transmit the shear wave. Due to this configuration ultrasonic transducers do not require penetration of the specimen to transmit a wave, thus negating disturbance due to the insertion of the bender element tip, waterprofing and element robustness problems. This is especially important when considering changes in water content, as penetration may be difficult in dry clays or initial penetration may become too large or small due to volume changes. Despite this ultrasonic transducers are less common. Table 1 summarises the testing conditions of ultrasonic and acoustic testing in a variety of soils. Its clear that ultrasonic tests have only been conducted on a limited range of soils and few comparisons have been made between ultrasonic and bender element testing techniques. This is important to consider due to the differences in wave propagation and configuration.

This paper therefore presents a comparison between the shear modulus results for bender elements and ultrasonic shear wave transducers upon drying for compacted kaolin clay at different water content levels.

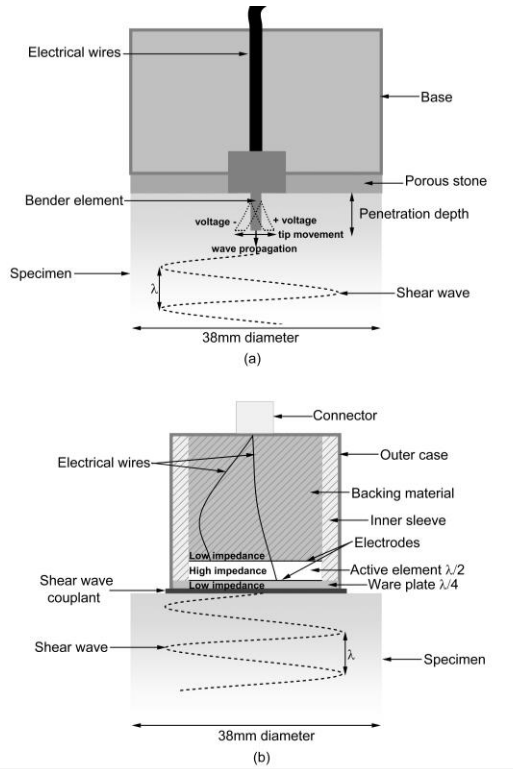

Figure 1. Pulse transmission tests: (a) bender elements and (b) typical ultrasonic transducer.

2 EXPERIMENTAL WORK

2.1 Compaction characteristics and drying

The kaolin clay specimens used in this study comprise of 62% medium and fine silt and 38% clay, with a liquid limit of 56% (fall cone), plasticity index of 23% and specific gravity of 2.61 (BS EN ISO 17892-12:2018+A2:2022). The specimens were statically compacted using a static stress of 1400 kPa (76mm x ⌀38mm). Compaction was completed in two layers to ensure consistent density througout the specimes (Walker et al., 2023). Figure 2 shows a comparison between standard Proctor (BS 1377-2:2022), and static compaction at 1400 kPa. Results show that at the optimum moisture content after static compaction specimens achieve >90% of the maximum Proctor dry unit weight. Statically compacted specimens were prepared at the OMC to mimick field conditions. Air drying was conducted at constant 40℃ from the compacted water content (28.0%) to target water contents levels including 21.5% and 15.0%. Water content was controlled during drying by monitoring the weight of specimens to target weights. To ensure an even distribution of water content prior to the measurement of small strain stiffness, specimens were allowed to equilibrate for a minimum of 24 hours. This was determined by prior testing presented in Walker et al. (2023).

Table 1. Summary of literature testing conditions used in ultrasonic and acoustic pulse transmission techniques.

	Materials	Dimensions (diameter × length; mm)	Confining stress (kPa)	Testing frequency
Leong et al., 2004	kaolin	70 × 60	800	P wave: 90 kHz S wave: 76 kHz
	Compacted residual mudstone (S_r 1.0 and S_r 0.6)	70 × 105-118	800	
Brignoli et al., 1996	Saturated Ticino sand	50 × 100	30-500	P wave: 100 kHz S wave: 3 – 10 kHz
	Reconstituted saturated Pontida silty clay	50 × 100	50-500	
	Undisturbed offshore clay	50 × 100	30-100	
Cheng and Leong, 2014	Saturated kaolin	60 × 100-140	-	P wave: 100 kHz S wave: 49 kHz
	Changi sand (S_r 0.5)	60 × 100-140	-	
Mulmi et al., 2008	Dry Toyoura sand	50 × 100	50, 100, 200, 400	P wave: 4 – 16 kHz S wave: 4 – 16 kHz
Miturski et al., 2021	Compacted stabilized clay	80 × 80	Unconfined	P wave: 54 kHz
Slavova et al., 2010	Low plasticity silt	70 × 50	Unconfined	P wave: 46 kHz S wave: 39 kHz
Nakagawa et al., 1996	Saturated kaolin Saturated fine sand	- × 101	98 -490	P wave:200 kHz S wave: 3-5 kHz
George, 2009	Bonny silt Heterogeneous mixture of sand, silt and clay	100 × 125	Unconfined	P wave: 20 kHz S wave: 20 kHz

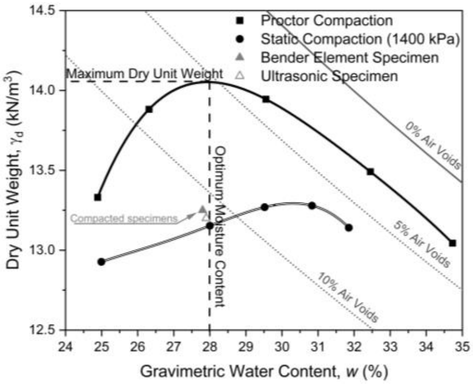

Figure 2. Compaction for kaolin clay (modified after Walker et al., 2023).

2.2 Pulse transmission tests

The bender elements (BE) system (VJ Tech) comprises of two elements (11.25mm long, 1.8mm wide, protruding thickness of 3.2mm) cantilevered in a pedestal and top cap. The signal was generated by a sine wave (VJ Tech Clisp software) and data was acquired using a sampling rate of 1000 kHz and 16-bit resolution for frequencies between 0.5 to 15 kHz. The shear wave for the ultrasonic system (USS) was generated by a 2 volt square wave (Pundit Lab system). A digital oscilloscope with a 12 bit resolution and 6250 kHz sampling rate was used to capture the data. Olympus normal incidence shear wave transducers (V150-RB), were used to transmit and capture the shear wave response and couplant was used to ensure good contact. Staking of approximelty 20 signals was used to mitigate background noise. The travel time (Δt_s) of the shear wave was detemined from the intial drop in the square wave (USS) and first rise in the sinusoidal wave (BE), to the first deflection of the received wave for both systems to allow suitable comparison. The shear modulus (G_0) was subsquently calculated as follows:

$$V_s = \frac{L_{pp/tt}}{\Delta t_s} \tag{1}$$

$$G_0 = \frac{\gamma_b}{g} V_s^2 \tag{2}$$

where the V_s is the shear wave velocity, L_{tt} and L_{pp} is the tip to tip or platen to platen distance, γ_b is bulk unit weight and g is the gravity acceleration. The 2.4 µs delay derived from the travel of the shear wave through the ultrasonic transducer's platen was also considered in the V_s calculation (Walker et al., 2023).

3 RESULTS

Identical compacted kaolin specimens (Table 2) were dried to selected gravimetric water contents and both bender elements and ultrasonic systems captured the variation in shear wave velocity. The shear wave response for both systems is presented in Figure 3, in addition to the wave travel path and wave length ratio ($L_{tt/pp}/\lambda$) of the chosen waveforms required to mitigate the influence of the near field effects (Arulnathan et al., 1998). Notably due to the increased frequency of ultrasoinc testing, the impact of the near field effect is mitigated. Tests were conducted at different water content levels show a reduction in travel time attributed to the increase in matric suction and thus stiffness of the soil. The arrival time of the BE is less than the USS as a result of the shorter distance between piezoelectric crystals due to the required BE specimen penetration. A comparison between the shear modulus for each technique is presented in Figure 4. The results show good agreement between both techniques at the selected water contents. The small discrepancy between techniques likely originates from interpretation of the waveforms in the time domain.

4 CONCLUSIONS

The benchmarking results established for both configurations of piezoelectric elements (BE and USS pulse transmission testing) show comparable shear waves response for both techniques. The results demonstrate the feasibility to conduct shear wave measurements without penetration using ultrasonic equipment. The implementation of ultrasonic testing in geotechnical applications not only can help reduce specimen disturbance but also problems due to penetration in dry soils. The results also demonstrate the feasibility of higher frequencies associated with ultrasonic testing for compacted soils. However, it must be noted that frequency during ultrasonic testing cannot be altered.

Table 2. Initial compacted conditions used in the bender element and ultrasonic testing.

Pulse Transmission	Material	Gravimetric Water Content, *w*: %	Dry Unit Weight, γ_d:KN/m^3	Void Ratio, *e*
Bender elements	kaolin clay	27.9	13.2	0.931
Ultrasonic	kaolin clay	27.5	13.3	0.927

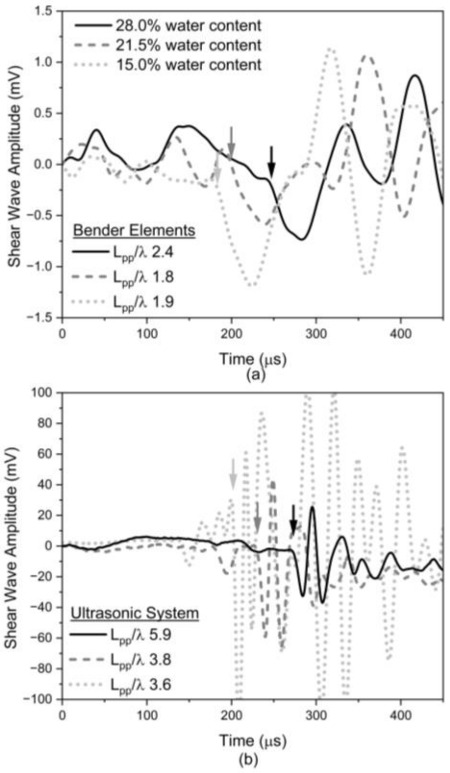

Figure 3. Received waveforms for compacted kaolin clay for (a) BE and (b) USS; arrows indicate Vs arrival.

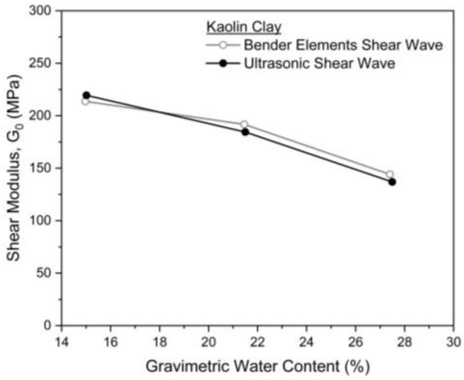

Figure 4. G_0 comparison between BE and the USS during drying at selected water contents.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the School of Civil Eng. and financial support provided by EPSRC (EP/T517860/1). The assistance provided by Andrew Birch and Prof. Barry Clarke is gratefully appreciated.

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