

Comparison of Bender Element and Ultrasonic wave Methods for Determining the Small Strain Shear Modulus of Treated Silt

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ABSTRACT: The small-strain shear modulus is a mechanical property which can be used to evaluate the evolution of soil mechanical properties. Various methods exist for the measurement of this parameter, each with advantages and limitations depending on the material properties. The Bender Element method, commonly used for soil testing, is effective for small-strain shear modulus measurements but poses challenges when applied to rigid materials like treated silt. Specifically, low-frequency, low-amplitude waves often result in significant energy loss, making it difficult to detect wave arrival time accurately. In contrast, the ultrasonic wave method, traditionally used for rigid materials such as concrete, employs high-frequency, high-amplitude waves, which appears more suitable for treated soils. In this study, the shear modulus of lime- and binder-treated silt was measured using both Bender Element and ultrasonic wave methods. The former has been proved to be unreliable due to the material's high stiffness. The latter, however, provided more consistent results, demonstrating its suitability for assessing the variations of the mechanical properties of treated silt.

KEYWORDS: Bender Element, Ultrasonic wave, Shear Modulus, Treated Soil, .

1 INTRODUCTION

Chemical stabilization using lime, cement, and other hydraulic binders is widely employed to enhance the strength and stiffness of fine-grained soils. The small-strain shear modulus (G_{max}) is a key parameter for assessing these improvements. Bender element (BE) testing is a common laboratory method for measuring G_{max} , but its interpretation is notoriously difficult—especially for small samples—due to electrical noise, wave reflections, and uncertainty in identifying the first arrival time. These challenges make it difficult to track the evolution of mechanical properties, as many factors can influence the results. Furthermore, the low signal amplitude, combined with the high stiffness of treated materials, often leads to significant attenuation, making the received signal harder to be distinguished from background noise. To address these limitations, this study explores the use of the ultrasonic wave method, which produces higher amplitude waves and offers improved reproducibility, for determining the mechanical properties of treated soils.

2 MATERIALS AND METHODS

2.1 Materials

The silt studied was collected from a construction site located in the northeast of Paris (Roissy-en-France, France). Its main geotechnical properties are presented in Table 1. According to the new GTR (Guide des Terrassements Routiers) classification which is in accordance with standard EN 16907-2, this soil is classified as a low-plasticity silt (F2).

Table 1. Characterization of studied silt.

Parameter	Symbol	Value	Unit
Liquid limit	w_L	37.7	-
Plastic limit	w_p	20.7	-
Plasticity index	I_p	17	-
Specific gravity	G_s	2.64	Mg/m ³
Methylene blue	VBS	2.67	g/100g

Optimum moisture content	w_{OPN}	16	%
Optimum dry density	$\rho_{d,OPN}$	1.73	Mg/m ³

The treatment was made using quicklime and hydraulic binder (ROC-AS) composed of more than 70% of granulated blast furnace slag, classified as N4 in accordance with standard EN 13282-2 and provided by EQUIOM 2SG (France). Relevant characteristics are provided in Table 2.

Table 2. ROC-AS characteristics

Parameter	Value
Composition	≥ 70% ground granulated blast furnace slag
Bulk density	1 t/m ³
90 μm sieve residue	< 15%
Initial setting time	> 150 minutes
Compressive strength at 56 days	32.5 MPa ≤ UCS ≤ 52.5 MPa

2.2 Experimental set-up

2.2.1 Ultrasonic wave

Ultrasonic wave measurements were conducted using an EPOCH XT portable ultrasonic flaw detector (Olympus, Japan) shown in Figure 1. The console was connected to a pair of transducers functioning as both the emitter and receiver of the sound waves. Although this equipment is primarily designed for detecting flaws in industrial materials such as concrete, it was repurposed in this study for geotechnical testing.

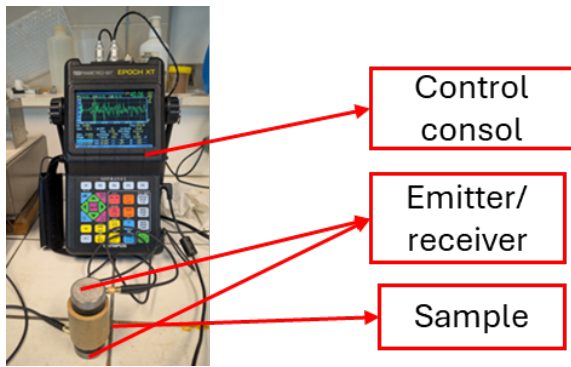


Figure 1. Ultrasonic wave set-up.

The EPOCH XT is capable of generating both shear and compressive waves with voltages of up to 500 V and frequencies ranging from 100 kHz to 1 MHz. The time delay between the emitted and received waves can be directly read from the console.

2.2.2 Bender Element

The bender element setup consists of four main components, as illustrated in Figure 2. The function generator produces an electrical signal with controlled frequency, amplitude, and waveform. This signal is subsequently amplified to a maximum amplitude of 25 V and transmitted to the bender element. Depending on the wiring configuration, the bender element can be used to generate either compressional or shear waves. In this study, only the transmission of shear waves through the sample was considered.

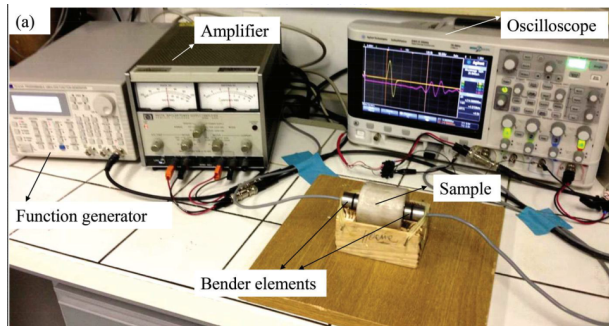


Figure 2. Bender element set-up.

2.3 Test procedures

2.3.1 Sample preparation

To prepare the sample, the natural soil was first oven-dried, ground, and sieved through a 2 mm mesh. Subsequently, the soil was humidified by spraying tap water and thoroughly mixed to achieve a target water content of 18.5%, which corresponds to the optimum water content plus 2.5%. The mixture was then sealed in a plastic bag and left for a minimum of 24 h to ensure moisture homogenization.

Once homogenization was complete, the soil was ready for treatment. Different binder contents were incorporated into the soil, but all samples were initially mixed with 1% quicklime to improve the workability and better simulate the field conditions. The soil-lime mixture was allowed to cure for one hour before the binder was added. After the treatment process, a predetermined mass of the mixture was placed into a cylindrical mold with a diameter of 38 mm and compacted using a press until a height of 38 mm was achieved. The mass introduced into the mold was calculated to ensure that the final sample was compacted at the optimal water content and attained a dry density close to 1.73 Mg/m³. After compaction, the

samples were wrapped in plastic film and left in a sealed container for a 7- and 30-day curing.

The characteristics of the sample tested for this paper are listed in Table 3.

Table 3. Specification of the tested samples

Sample	Lime content (%)	Binder Content (%)	Density (Mg/m ³)	Height (mm)	Curing time (Days)
Sample 1	0	0	2.078	38.03	0
Sample 2	1	3	2.028	38.02	7
Sample 3	1	3	2.069	37.14	7
Sample 4	1	4	2.022	38.12	7
Sample 5	1	4	2.018	38.14	7
Sample 6	1	5	2.022	38.12	7
Sample 7	1	5	2.025	38.08	7
Sample 8	1	3	2.015	38.30	30
Sample 9	1	3	2.033	37.99	30
Sample 10	1	4	2.020	38.13	30
Sample 11	1	4	2.031	37.96	30
Sample 12	1	5	2.035	37.91	30
Sample 13	1	5	2.034	37.93	30

2.3.2 Ultrasonic wave testing

Before each test, the height, diameter, and mass of each sample were measured. Ultrasonic wave testing was then conducted by first applying a contact gel to each surface of the sample before placing it between the emitter and receiver units. Care was taken to ensure that both transducers were positioned as parallel as possible. An ultrasonic wave was applied using a voltage of 475 V and a frequency of 100 kHz. The time delay between emission and reception was then recorded directly from the console, as illustrated in Figure 3.

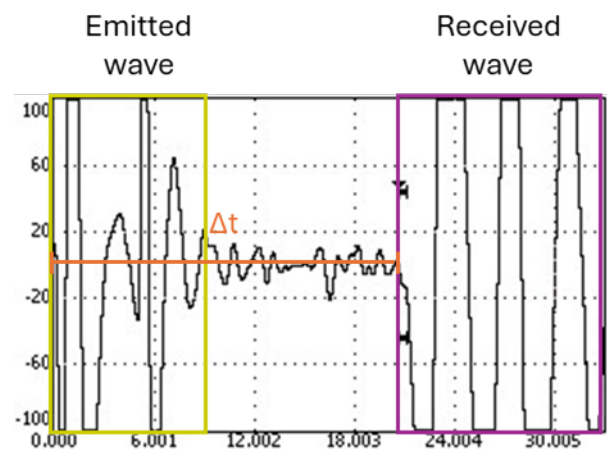


Figure 3. Typical EPOCH XT reading.

Once the time of arrival was determined, the wave velocity was calculated using Equation (1).

$$V_s = \frac{h}{\Delta t} \quad (1)$$

where V_s is the shear wave velocity (m/s), h the height of the sample (m) and Δt the time of first arrival of the wave (s).

The shear small strain shear modulus can then be calculated using equation (2).

$$G_{max} = \rho V_s^2 \quad (2)$$

G_{max} is the small strain modulus (MPa), ρ the bulk density (Mg/m^3) and V_s the shear wave velocity (m/s).

2.3.3 Bender element testing

The sample height, diameter, and mass were measured prior to testing. A small groove was then made on each of the two cylinder faces at the line of contact with the bender element as shown in Figure 4.



Figure 4. Surface groove.

The sample was then placed between the two bender elements, and a signal was transmitted through it. For this test, the wave frequency was set to 50 kHz and the voltage to 25 V. The time delay between the emitted and received signals was recorded from the oscilloscope. The shear wave velocity and the small-strain shear modulus were subsequently calculated using Equations (1) and (2).

3 EXPERIMENTAL RESULTS

3.1.1 Ultrasonic wave results

The time delay between the emitted and received signals was determined directly from the oscilloscope output, as illustrated in Figure 3. By performing this test on all samples listed in Table 3, the small-strain modulus curve shown in Figure 5 was obtained.

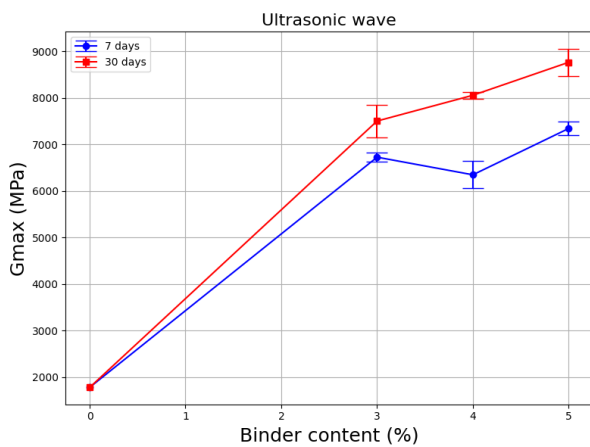


Figure 5. Ultrasonic wave results

An expected trend of increasing small-strain modulus with higher binder content and longer curing times was observed, with relatively low variance in the results.

3.1.2 Bender Element results

The bender element test results were recorded from the oscilloscope, as shown in Figure 6. The received wave amplitude appeared to be attenuated by a factor greater than 10^4 , making the time of arrival difficult to be determined. Even with the signal processing applied by the oscilloscope, electrical noise remained visible at this level of precision, and the received signal appeared to be superimposed on the noise, further complicating its identification.

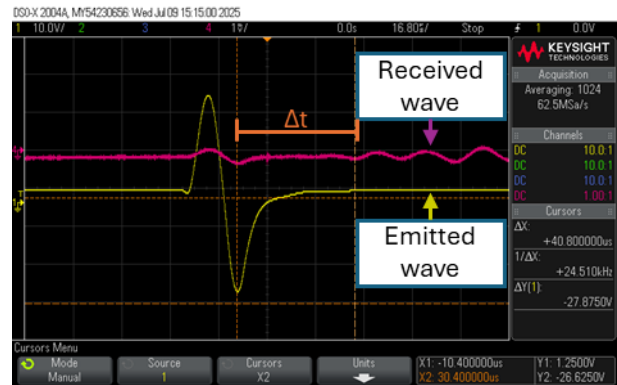


Figure 6. Typical Bender element Reading

Nevertheless, some results could still be extracted, allowing the calculation of the small-strain shear modulus and the plotting of the results, as shown in Figure 7.

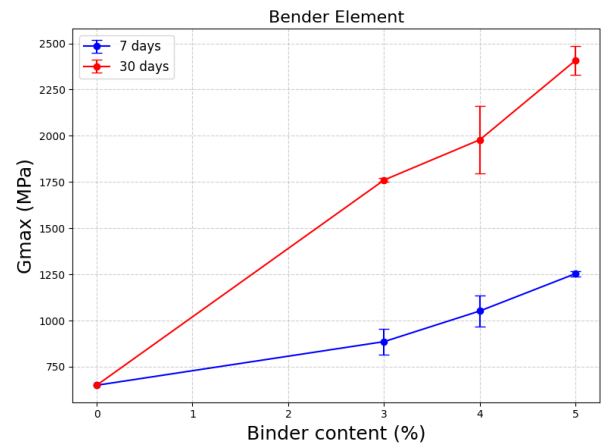


Figure 7. Bender element results

Although an increase in small-strain modulus was observed with higher binder content, the calculated values were approximately four to seven times lower than those obtained using the ultrasonic wave method. The velocities measured in the initial tests suggest that, given the sample size and a test frequency of 50 kHz, the first arrival signal was likely superimposed on the electrical noise. This implies that the time delay measured in the bender element tests corresponds to an n^{th} iteration of the transmitted signal rather than the true first arrival, which explains the discrepancy in small-strain modulus values.

4 DISCUSSION AND CONCLUSIONS

When comparing the results of both methods, the measured values differ substantially, particularly when contrasted with those of the untreated material. The slope of the increase in values obtained from ultrasonic wave testing appears more representative of the mechanical property gains typically expected from hydraulic binder treatment, showing a steeper rise relative to the untreated material. Moreover, the high amplitude of the emitted ultrasonic signal facilitates clear detection of the received wave, making the results easier to be interpreted and reproduced. In contrast, Figure 6 illustrates that bender element results are more operator-dependent; although the values for each sample may appear consistent, there is no guarantee that another operator would select the same reference points for time-of-arrival determination.

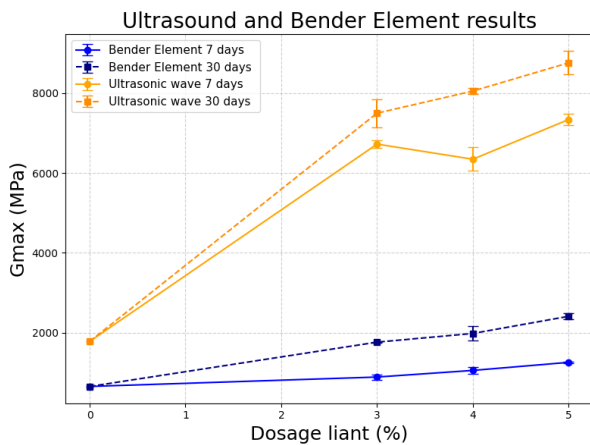


Figure 8. Bender element results

The difficulty in assessing the time delay for treated materials may be attributed to their increased stiffness, which makes the needed incitation energy and frequency higher. Given the limited frequency and amplitude range of the bender element system, it is challenging to conduct reliable comparative studies on the materials of interest in this study. In contrast, the ultrasonic wave method appears more suitable in this context, providing a quick means of evaluating the small-strain shear modulus, particularly for smaller samples. Nevertheless, the accuracy of the values obtained should be verified using a more precise technique, such as resonant column testing.

5 REFERENCES

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