

CORRELATING BENDER ELEMENT AND ELECTROMAGNETIC MEASUREMENTS TO EVALUATE CLAY'S STIFFNESS

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ABSTRACT: Soil's stiffness is usually measured in the laboratory in an indirect manner, such as by derivation from the gradient of a stress-strain plot. It requires numerous tests and may be compounded by errors from the original measurement itself. As such, the bender element test has become rather popular among researchers for determining the small strain moduli of soils with minimal / temporal disturbance to the specimens. This paper examines the possibility of relating the bender element data with the dielectric constant obtained from the same soil specimen using an electromagnetic test setup. As both tests are non-destructive, they can be easily repeated on the same specimen over a period of time without the necessity of duplicate specimens. A clay sample was used in the present study, with varying water content corresponding to different 1-dimensional compression stresses. It was generally found that the resulting stiffness change was detectable from both the shear wave velocity (v_s) obtained from the bender element tests, as well as the dielectric constant (ϵ) of the electromagnetic measurements, with fairly good correspondence between the two. These results shed light on the possibility of relating relevant geotechnical parameters with both the measurements for establishing a unique set of signatures for stiffness monitoring and determination in soils.

Keywords: Stiffness, Bender element, Electromagnetic waves, Dielectric constant

1. INTRODUCTION

Extensive field as well as laboratory tests and measurements are necessary to ascertain the suitability of in situ soils for supporting a particular structure, often incurring significant costs and time consumption. This is especially so for the laboratory tests, where undisturbed soil samples must be retrieved, preserved and transported to the relevant facilities for the various tests. As such, it is always favourable to minimize test samples retrieval by implementing non-destructive measurements with the ease of repetition and cross-check.

This paper attempts to describe one such endeavour by using the bender element and electromagnetic techniques to monitor stiffness change in clay soil. Test specimens were prepared from kaolin powder at various water contents, on which both the tests were performed. A series of oedometer tests were also carried out to simulate actual post-consolidation improved stiffness of the soil in correspondence with measurements using the bender element and electromagnetic methods. The data obtained were cross-correlated to determine the effectiveness of monitoring stiffness with both the methods. A correlation chart was established as a quick guide to the clay's stiffness as well as undrained shear strength.

2. MATERIALS AND METHODS

The soil sample was prepared by admixing kaolin powder with water. These samples with different water contents were used to establish the basic correlation between water content of the soil and the electromagnetic measurements. Oedometer test was also carried out with corresponding monitoring of the stiffness change with both the tests. As can be perceived, the soil's water content is the parameter linking measurements obtained from both the non-destructive tests, as elaborated in the ensuing section of the paper.

Bender elements are piezoelectric ceramic devices wired in such manner as to transmit and/or receive compression or shear waves. The direction of motion of the bender element inserted to normally no more than 5 mm of the ends of a soil specimen, whether perpendicular or parallel with the orientation of the specimen, produces the respective waves. It has become rather widely adopted in geotechnical testing in the past decade due to its simplicity, e.g. [1]-[4], though the definition of the wave arrival time remains very much an area of subjectivity. Nonetheless as long as caution is taken in conducting the test, and that the same arrival time identification method is used throughout the exercise, the errors or inconsistencies are expected to be systematic, e.g.

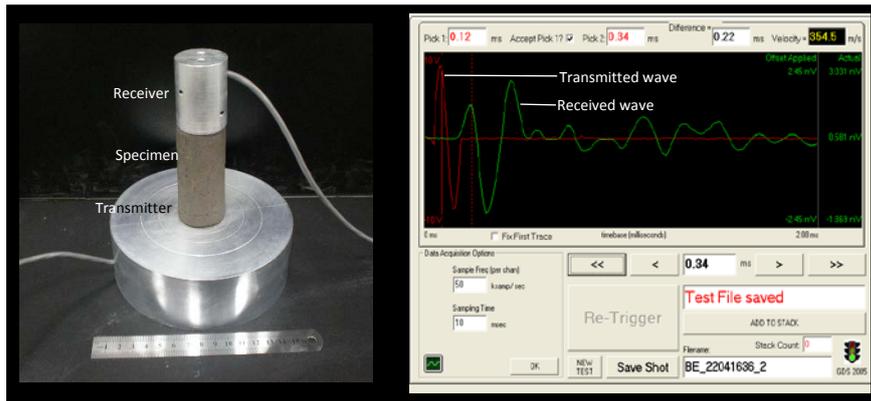


Fig.1 Bender element test setup.

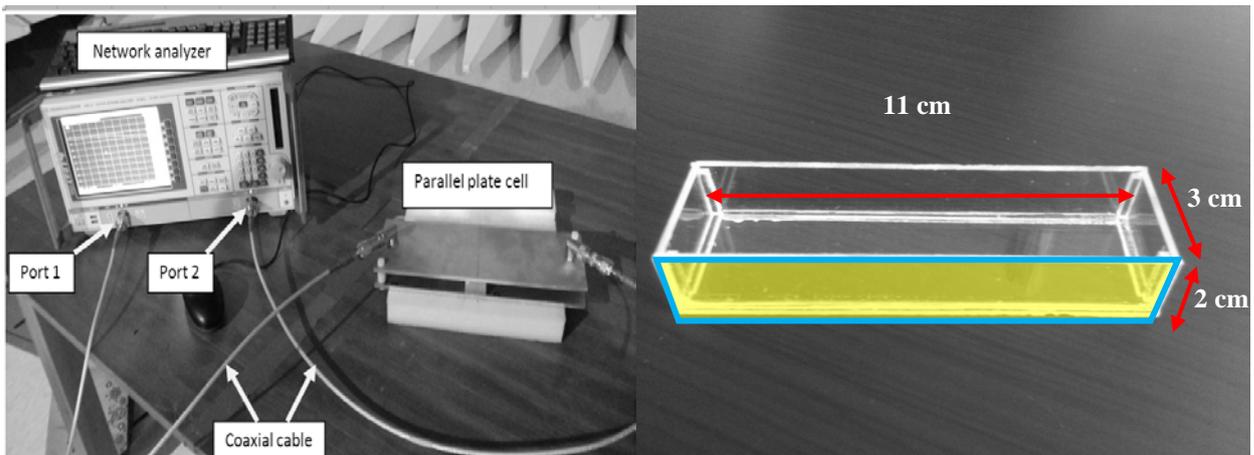


Fig.2 Electromagnetic test setup.

reported by [5] & [6], and can be minimized with some normalization manipulations, for instance.

The wave arrival time was determined by taking the time lapse between trigger of the wave (time zero) and first detection by the receiver, as depicted as the initial positive deflection in the received wave form captured on screen. The shear wave velocity (v_s) was then easily computed by dividing the tip-to-tip distance of the bender elements on both ends of the specimen with the arrival time determined. Note that only shear waves were adopted in the present work to avoid masking of the actual velocities by the compression wave propagating through the pore water instead of the soil skeleton, i.e. giving P-wave velocity of the water, ≈ 1480 m/s. The GDS BE system was used in the present study (Fig. 1). The specimens were cylindrical, 38 mm in diameter and 76 mm in height subjected to the bender element test (input frequency 650 Hz).

The electromagnetic method is a potential alternative method to determine key soil properties such as compressibility, strength and hydraulic conductivity. Referring to reports in [7], the high dielectric constant of water compared to soil solids makes the dielectric constant of moist soil highly dependent on the moisture content of soil, making it a viable tool for estimating the amount of

moisture present in a soil mass. The dielectric permittivity is found to be the most suitable electromagnetic parameter for soil testing, attributed to the high-frequency permittivity parameters of waveforms produced by measurement systems with low attenuation. The properties of the waveforms are used to derive simple relations for estimation of low and high frequency permittivity values from characteristic points of the waveforms [8]. The present study adopted a setup developed in-house (Fig. 2), which comprised of a network analyzer (Rohde & Schwarz), a pair of coaxial cable and a parallel plate cell. The soil sample was placed in a rectangular acrylic mould of 3 cm x 11 cm x 2 cm. The system was conditioned to measure S-parameters over the frequency range of 10 MHz to 14 GHz. The measured S-parameters were saved in a Matlab programme for subsequent computations of the relative permittivity or dielectric constant.

3. RESULTS AND DISCUSSIONS

3.1 Bender element measurements

Fig. 3 shows v_s plotted against w , with a fairly good correlations indicated in the correlation

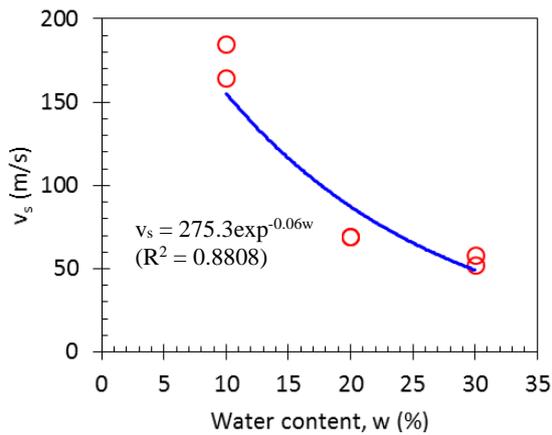


Fig.3 $v_s - w$.

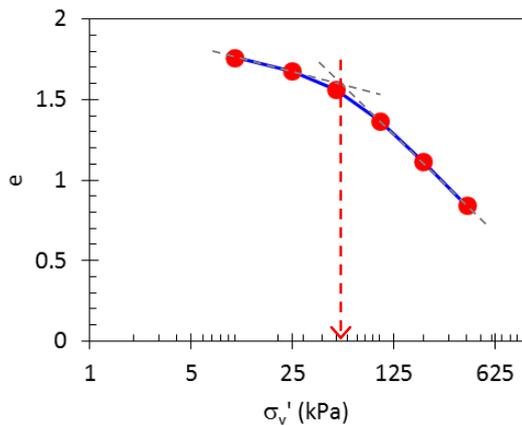


Fig.4 $e - \sigma'_v$.

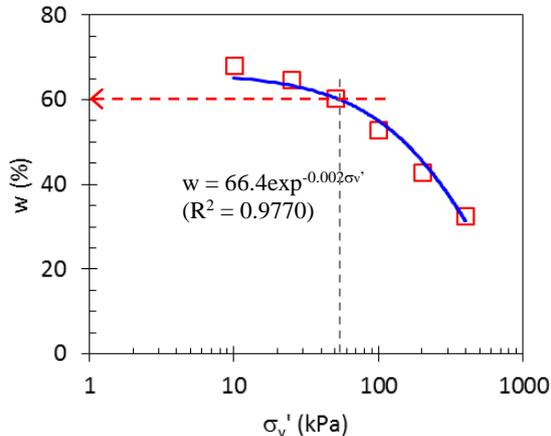


Fig.5 $w - \sigma'_v$.

coefficient, i.e. $R^2 = 0.8808$. With increased water content, the soil's structural skeleton essentially collapses into a liquefied mass. The solid particles are dispersed within the large amount of pore water present, resulting in excessive damping or impedance of the shear wave propagation. Note too that the perpendicularly traversing motion induced by the shear waves diminishes with reduced stiffness of the medium, such as a watery soil mass. As such, the shear waves take a longer time to travel between the transmitting and receiving ends of the specimens, resulting in declining v_s .

Note that shear waves would traverse through only the solid structure of a medium (i.e. soil's skeleton), unlike compression or P- waves which could be propagating via both the solid and liquid phases. It should be cautioned though that shear waves tend to be significantly impeded by damping effect in a high water content soil, making identification of the arrival time difficult. Signals captured are usually of poor quality with no discernible first major deflections, and the output waveforms are invariably distorted with little semblance to the originally transmitted waves. Such deformations of the captured waveform indicate incongruence between the input and output signals.

3.2 1-dimensional compressibility

The 1-dimensional compression curve was derived from a standard oedometer test on the soil specimen (Fig. 4), while Fig. 5 depicts the same data in terms of water content change. As consolidation causes gradual dissipation of excess pore water with an applied load, the settlement recorded (i.e. represented by the void ratio, e) is directly proportionate to the water content of the soil specimen at the end of a particular loading stage. The w values shown in Fig. 5 were actual measurements taken of samples from the post-consolidation specimens. With expulsion of the excess pore water and zeroing of the excess pore water pressure, the exerted load was progressively transferred to the soil's skeleton. This consequently enhanced the soil's stiffness as a whole, with greater load-bearing capacity compared to its original form, i.e. stiffness improvement.

The yield stress (σ'_y) of the soil can be approximately derived from the gradient change in the $e - \sigma'_v$ (Fig. 4). In this case σ'_y was found to be about 55 kPa and corresponding to almost 60 % of water content (the soil's liquid limit is ≈ 50 %). Beyond this point, the soils essentially lost its inherent structure and underwent substantial settlement with increased load, i.e. onset of virgin compression.

3.3 Relating v_s and compressibility

It follows that with v_s governed by w , and that w is of direct relation to the void ratio changes upon loading of the soil specimen, v_s can be correlated with e as shown in Fig. 6. With greater load applications in the oedometer test, more significant pore water dissipation took place, resulting in increased settlement or void ratio reduction. The outcome of the process was the stiffening of the soil matrix, as captured by the v_s increment in Fig. 6. Of course, with an oedometer

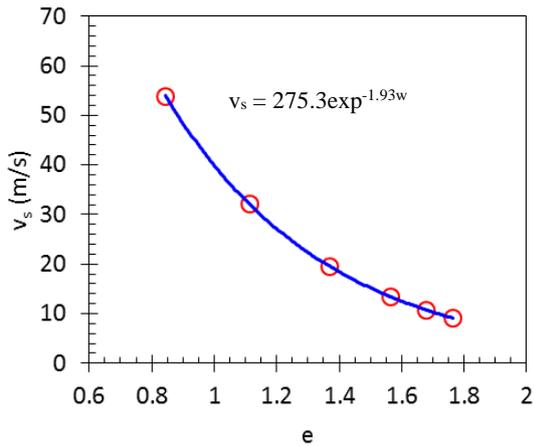


Fig.6 $v_s - e$.

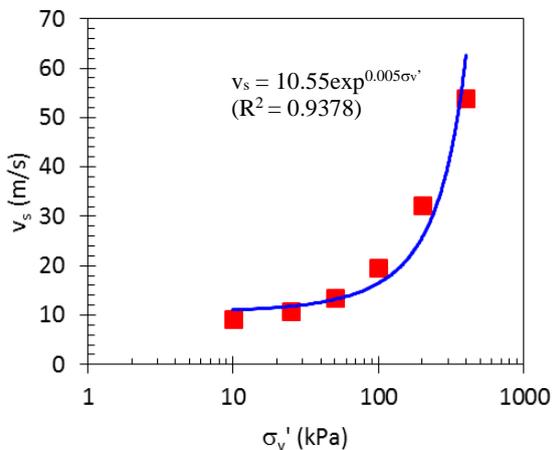


Fig.7 $v_s - \sigma_v'$.

cell incorporated with bender elements, actual real-time v_s changes could be monitored as the consolidation occurs, such as reported by [9]. The current indirect correlation method notwithstanding, it was considered suffice for the end-of-primary consolidation v_s values to be inferred from the corresponding water content.

3.4 Electromagnetic measurements

Fig. 8 summarizes the electromagnetic measurement of dielectric constant (ϵ) on the soil specimen prepared at different water contents. The specimens subjected to the electromagnetic test were carefully prepared so as to have the same density and water content as the oedometer counterparts. Clearly a linear regression line can be plotted through the data points, indicating the rising trend of ϵ with increased w . It ought to be mentioned that the measurement mechanism of the electromagnetic test setup is rather sensitive, leading to the scatter of data obtained.

The scatter in Fig. 8 may be due to several factors, including the inaccuracy of water addition in the soil, the non-uniform distribution of water in the soil, the possibly variable calibration conditions, the misalignment (albeit small) of the

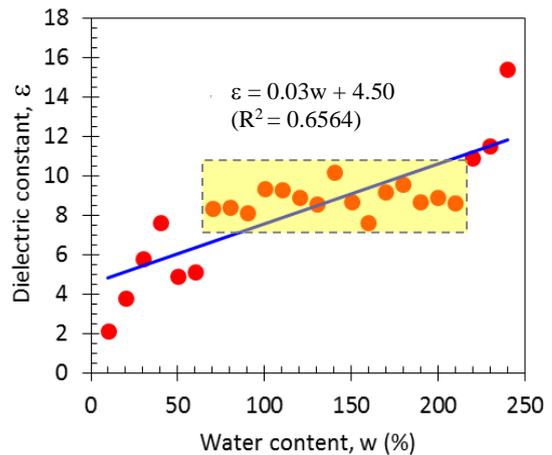


Fig.8 $\epsilon - w$.

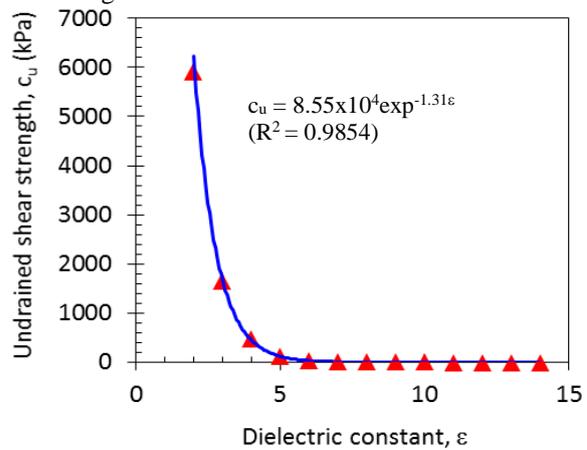


Fig.9 $c_u - \epsilon$.

mould placed in between the parallel plates, and possibly uneven contact surface of the soil with the top plate.

The electromagnetic field surrounding the soil was apparently subjected to significant influence of water present in the soil specimen. The correlation in Fig. 8 enables estimation of the soil's improved stiffness via the water content, which is directly related to the compressibility of a saturated specimen. For practical purposes, one would only need to identify the ϵ or v_s value of a soil specimen to ascertain the stiffness, without having to subject the soil sample to the time-consuming oedometer test.

It is also interesting to note in Fig. 8 that between the water content of 70-210 %, ϵ has remained relatively unchanged (see boxed-in area). This is suggestive of either a rather large range of moisture content within which the electromagnetic measurement system could not respond reflexively, or that there genuinely exists a small difference in ϵ for a given range of water content. This was not ascertained in the present study though. In addition, ϵ appears to increase linearly with the water content up to about 40 %. This corresponds with the decline in v_s as the soil approaches its liquid limit, i.e. ≈ 50 % (Fig. 3).

Taking the gradient of the regression line passing through the origin (Fig. 8), the ε/w ratio was found to be approximately 17.8.

3.5 Correlation with strength

It is intuitive to expect that the rise in stiffness of a soil would be accompanied a proportional increase in strength as well. Fig. 9 relating the undrained shear strength (c_u) and e was derived from the Author's past work with the same soil [10]. Note that the change in ε in the lower strength range (<200 kPa) is far less significant than in the higher strength range. As problematic in situ clay soils are usually found in the low strength range, the electromagnetic measurement technique appears to lack the sensitivity necessary to detect the changes.

Furthermore soils do not normally have compressive strengths greater than 1 MPa (e.g. soft rocks), hence it is more relevant to examine the c_u - ε correlation within the common lower strength range for foundation clay soils. Nonetheless, it does show that the increment in strength corresponds with a reduction in water content, which in a clay soil indicates an improvement of the stiffness with expulsion of excess pore water via consolidation. The much higher c_u within the low ε range can be explained by the lower water content of the soil with advanced consolidation, and hence greater stiffness.

4 CONCLUSION

The shear wave velocity (v_s) and dielectric constant (ε) were both non-destructive techniques for monitoring stiffness change in clay soils. The present work examined the measurements with an artificially prepared soil sample, i.e. kaolin at different water contents. It was found that the soil with higher water content gives lower v_s and higher ε , with corresponding decrease in void ratio (e) and increase in stiffness respectively. However there seems to be a certain range of water content which elicited very similar ε measurements, suggesting a 'blind' zone of electromagnetic detection of the changes in the soil. A more refined test programme will be required to ascertain the sensitivity of the test for soil characterisation purposes. Besides, further work is necessary to identify the influence of other relevant factors on the measurements performed, such as pore water chemistry, confining pressure and presence of different-size particles in the soil.

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