Small Strain Behaviour of Auckland Residual Soil

A. Ibrahim[1], R. P. Orense[2] and M. J. Pender[3]

[1]Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland, NEW ZEALAND, PH (64 9) 373-7599; FAX (64 9) 373-7462; email: nakio76@yahoo.com
[2]Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland, NEW ZEALAND, PH (64 9) 373-7599; FAX (64 9) 373-7462; email: r.orense@auckland.ac.nz
[3]Department of Civil and Environmental Engineering, University of Auckland, Private Bag 92019, Auckland, NEW ZEALAND, PH (64 9) 373-7599; FAX (64 9) 373-7462; email: m.pender@auckland.ac.nz

ABSTRACT

This paper discussed briefly the procedures adopted in bender element tests performed on undisturbed Auckland residual soil specimens under fully saturated condition. In addition, seismic dilatometer tests were conducted at the same location where the soil samples were obtained to investigate the maximum shear modulus of the soil. Experimental results from bender element tests showed that the maximum shear modulus satisfactorily agreed with the values obtained from seismic dilatometer tests. These confirmed that the procedures adopted throughout the experiments produced good quality and reliable results.

Keywords: Bender elements test, Auckland residual soil, maximum shear modulus, small strain

1 INTRODUCTION

Auckland's present-day landform is built mostly on the Waitemata sedimentary rocks. In-situ weathering of Waitemata group sandstones and siltstones produced cohesive residual soils, which are either dominated by silt or clay materials. The formation process of residual soils, which is completely different from sedimentary soils, and the existence of macro-voids, caused the nature of these subsurface materials to be highly variable. Moreover, unusual clay minerals i.e., allophane and halloysite that are commonly derived from volcanic ash, basic rocks or finely comminute parent materials are found in certain parts of the Auckland residual soil. These stiff, jelly-like minerals coat the sand and silt grains and maintain a porous, low density structure with weak strength. The depth of the in-situ weathering profile ranges from a few metres to a few tens of metres at the very maximum, with the water table often relatively deep and subject to fluctuations due to the weather conditions (Wesley 2010; Kenny 2008; Kikkawa et al., 2008; Pender et al., 2000).

The determination of small-strain stiffness of ground is crucial in the performance-based seismic design of foundations and soil structures. As the biggest city and the engine of economy in New Zealand, the understanding of the Auckland residual soil behaviour under seismic loading is vital to ensure Auckland as a sustainable and earthquake resistant city. A research has been conducted with the development of small strain triaxial apparatus to investigate the small strain stiffness of undisturbed Auckland residual soil. The system utilised three submersible miniature linear variable differential transducers (LVDTs), which are capable of measuring axial displacements smaller than 1 micron. In addition, bender elements (BE) system was installed to the modified triaxial apparatus to allow meaningful comparison of maximum shear moduli from both tests (Ibrahim et al., 2011a).

This paper discusses the BE and seismic dilatometer tests conducted on undisturbed Auckland residual soil samples taken from a site at Orewa, which is located approximately 45 minutes driving north from Auckland CBD. Brief discussion is presented on the bender elements system which was developed with special care to ensure the clarity of received signals that is normally perceived as the main source of errors in the bender element test. The details of the experimental procedures followed throughout the development process, sampling techniques and experimental set up to achieve high quality data were discussed by Ibrahim et al. (2011a; 2011b). The maximum shear moduli (G_{max}) obtained from laboratory tests are then compared with the results of seismic dilatometer tests (sDMT) performed at the same location.

2 BENDER ELEMENT TEST

Bender element (BE) test is a non-destructive test, which is simple and yet a reliable method of investigating soil stiffness at very small strain. Since its development in the 1970's, the BE test gained popularity and further improvements have taken place. The BE system has been successfully installed in conventional laboratory apparatus, such as shear box, oedometer and triaxial machine to develop an integrated testing system (Leong et al., 2005 and Kawaguchi et al., 2001). Figure 1 shows the diagram of the integrated small strain traxial system developed by the authors. The system integrates bender elements and miniature LVDTs attached directly to the soil specimen and allows the investigation of soil stiffness under both monotonic and dynamic loading.

Basically the BE system comprises of a pair of in-line bonded thin piezo-electric plates; namely, the transmitter and receiver. The transmitter element distorts or bends when subjected to a voltage signal from function generator and creates shear waves while the opposite element (the receiver) captures the arrival of shear wave signal. Shear wave velocity (V_s) is calculated by dividing the shear wave travel distance, which is the interval between tip to tip of bender elements (L_{tt}), by the travel time (t_s) taken. By assuming the soil is a perfectly elastic material, the relationship between the maximum shear modulus (G_{max}), bulk density (ρ) and the shear wave velocity (V_s) is given as follows.

$$G_{max} = \rho V_s^2 \quad (1)$$

Determination of G_{max} from bender element test is relatively straightforward as the bulk density of the specimen and the L_{tt} used in the calculation are pre-determined quite accurately before the test is performed. The main issue that could compromise the value of G_{max} is the error related to the determination of t_s.

In general, the method used to determine the t_s could be divided into two types; namely, time and frequency domain. The time domain method is more frequently used by researchers as compared to the latter due to its simplicity. Determination of t_s from first deflection of the received signal is the most commonly used method, and is the method adopted in this research. However, until today there is no single standard procedure adopted and no superiority of one method to the other in term of accuracy in arrival time determination (Chan, 2010; Lee & Santamarina, 2005).

The accuracy and reliability of the t_s determination is highly dependent on the capability of the system in minimising the near field effect that affects the quality of received signal during the BE test. Several factors, such as the boundary limitation, signal deflection and environmental noise interference contribute toward the severity of near field effect. In order to minimise the near field effect, several factors, such as the specimen height to the diameter ratio (or slenderness ratio, *H/D*), the wave path length to wavelength ratio (L_{tt} / λ) and the frequency of triggered signal should be taken into consideration (Wang et. al., 2007; Arroyo et al., 2006; Leong et. al. 2005; and Fratta & Santamarina, 1996).

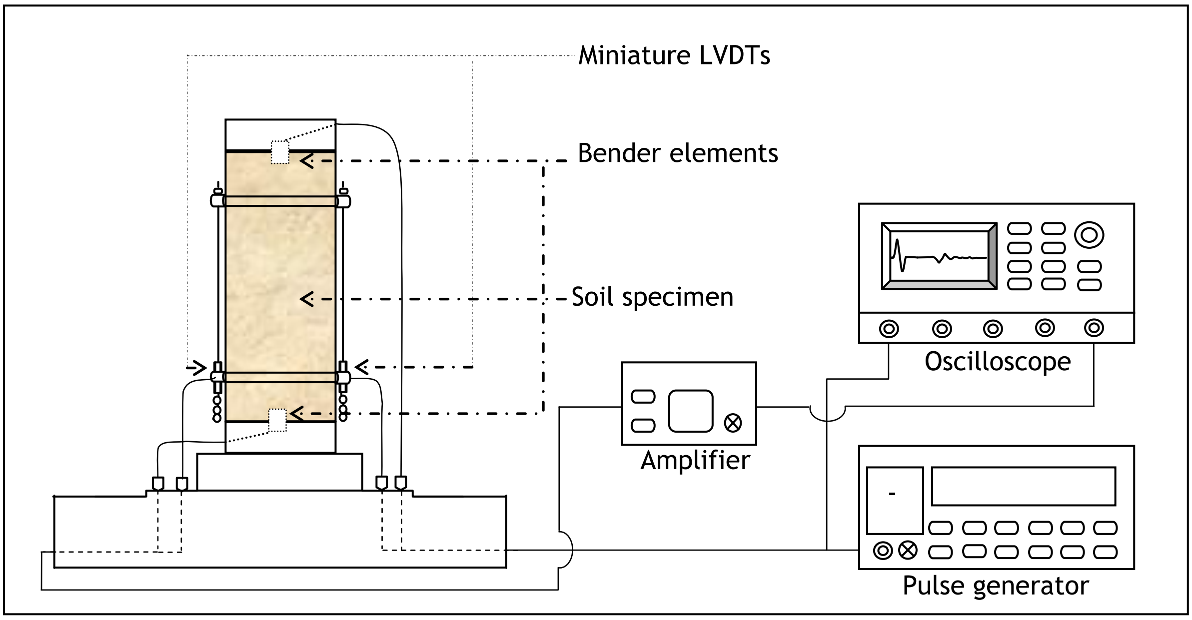


Figure 1. Bender elements installed in the small strain triaxial system

In the integrated system of small strain triaxial apparatus, the slenderness ratio is fixed as the standard triaxial test specimen was adopted in the sample preparation. Therefore, the frequency of triggered signal is the important parameter to improve the clarity of the received signal. Figure 2 presents the direct downloaded screenshots of triggered and received signal in both normal and inversed conditions. It shows that the distortion of the signal arrival (within the red dotted circle) diminished when the frequency is increased from 1 kHz up to 10 kHz. Figures 3 (a) and (b) present the variation of the calculated G_{max} with respect to the frequency of triggered signal and L_{tt} / λ ratio, respectively. The L_{tt} / λ ratio is actually an interrelated parameter with the frequency level of the triggered signal. The application of lower frequency of triggered signal produces higher wavelength and larger amplitude thus inducing signal distortion from the boundary reflection. This caused near field effects that distorted the first arrival of received signal as shown in Figure 2. Conversely, the application of higher level of signal frequency produces shorter wavelength and smaller amplitude thus minimising the near field effect from the boundary reflection. This explains the almost constant G_{max} observed in Figures 3a and 3b as the signal frequencies are increased. Similar observation was reported by Chan (2010) that constant G_{max} was observed at frequencies of triggered signal higher than 7 kHz.

Table 1 summarises BE test results from a single undisturbed Orewa soil specimen subjected to different stages of isotropic consolidation pressures. The tests were carried out using sinusoidal waves with frequency ranging between 3 kHz up to 13 kHz. The t_s was determined as the time between the start of input signal from the transmitting bender element and the first deflection in the output signal in the receiving bender element as shown in Figure 2.

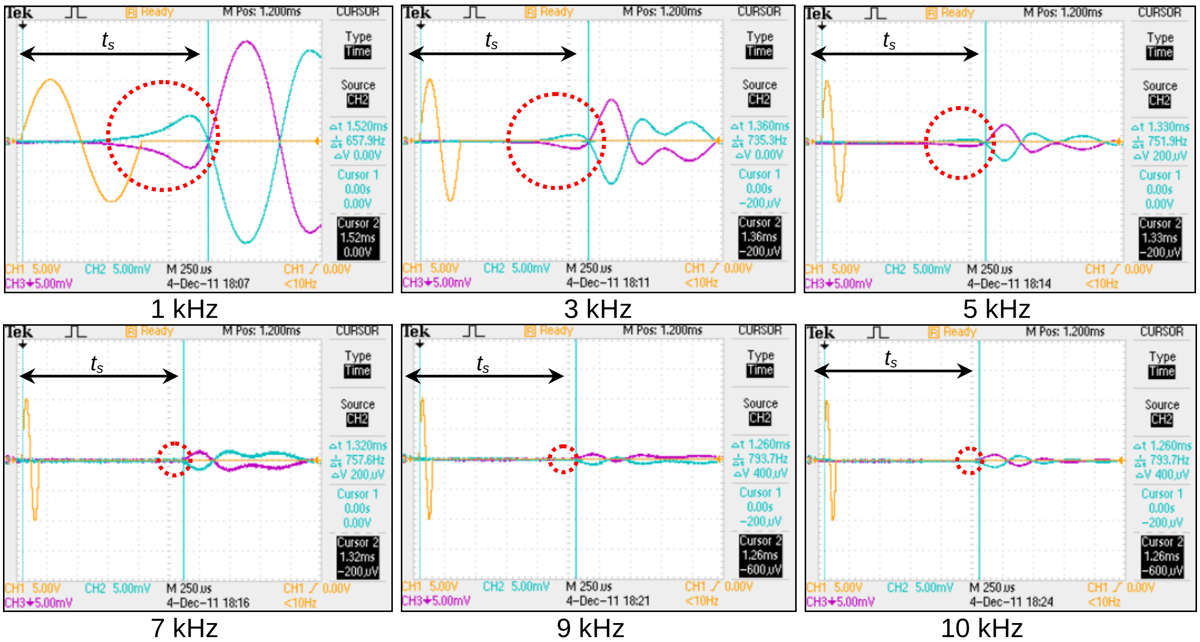
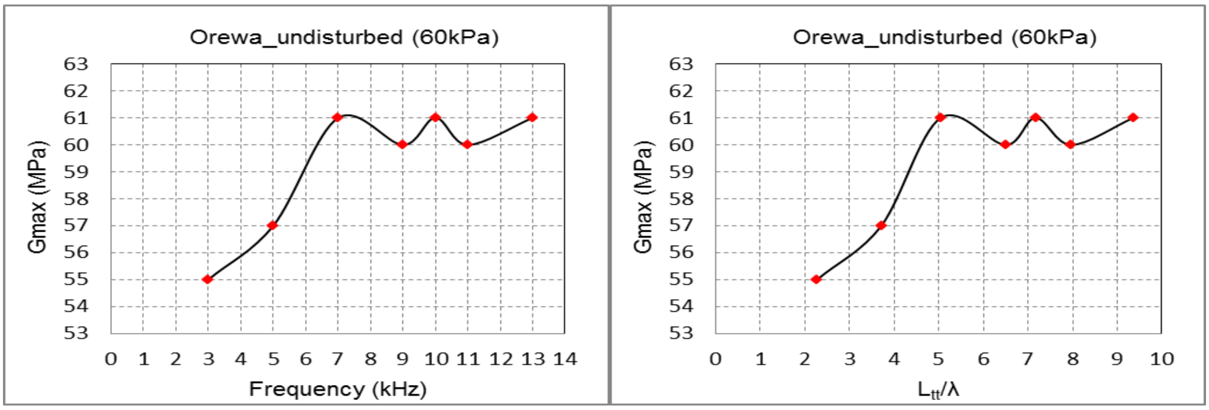


Figure 2. The reduction in near field effects of received signal as the triggered signal is increased from 1 kHz up to 10 kHz



(a) (b)

Figure 3. The calculated G_{max} with respect to the (a) frequency level; and (b) L_{tt} / λ ratio

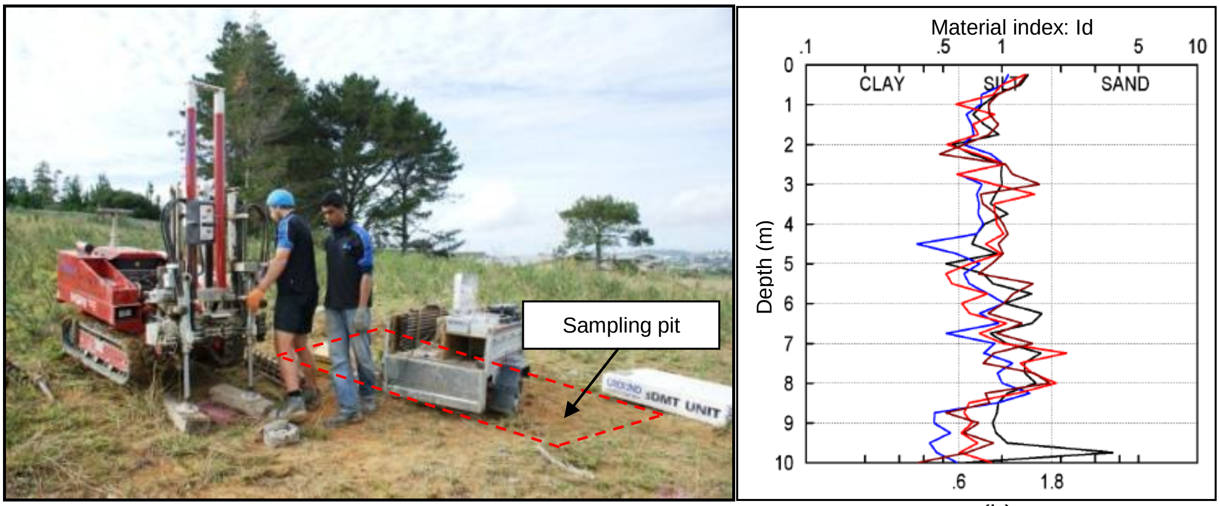
Table 1: Bender elements test results on undisturbed Auckland residual soil sample

ECP (kPa)	t_s (μs)	L_{tt} (mm)	ρ_{bulk} (Mg/m^3)	V_s (m/s)	G_{max} (MPa)
10	810	132	1.79	163	48
20	812	132	1.79	164	48
40	766	132	1.79	173	54
60	721	132	1.79	184	61
100	655	132	1.80	202	73
150	614	132	1.80	216	84

The specimen used in the BE test is 75 mm diameter and 150 mm height. The average penetration of both BE cantilevers into the soil sample is 18 mm, thus the L_{tt} is taken as 132 mm. The BE system is supported by 2 MHz Yokogawa FG110 synthesized function generator and a Tektronix TDS 2024C oscilloscope. The oscilloscope permitted on-screen manual calculation of arrival time using measurement cursors and furthermore, the transmitted and received signals could be downloaded directly to the computer. The V_s and G_{max} indicated in the table were obtained at frequencies > 10 kHz, as explained in Figure 3.

3 SEISMIC DILATOMETER TEST (sDMT)

The seismic dilatometer test (sDMT) is the extension of standard dilatometer test (DMT) that now includes the interval measurement of seismic wave velocity. The original DMT was developed in the 1970s by Prof. Marchetti and since then, the test has been used all around the world and has been gaining popularity. sDMT was performed at the site to determine shear wave velocity profile. To avoid possible discrepancies in soil stiffness related to site variability, the test was performed close to the sampling pit as shown in Figure 4a, which had been backfilled prior to the test. Figure 4b shows the material index from the sDMT conducted at four different points. The material indices were quite consistent up to 9 m depth. The water table was measured at nearly 3 m depth. The undisturbed soil samples for laboratory tests were obtained at approximately 1.5 m depth.
The seismic test was carried out at 500 mm depth intervals with the first reading taken at 1 m depth from the ground surface. An electrically operated Autoseis hammer was used to generate a shear wave that propagates through the ground. The Autoseis hammer provides consistent energy for each hammer blow and optimises the shear wave generation throughout the test. The shear wave signals were recorded by the geophones in the seismic module and the signals were sent back to a computer system as seismographs for analysis purposes. The seismographs from both geophones were shown as similar waves but with the time lag due to the fact that one of the geophones is 490 mm deeper than the other. A computer program allowed the two seismographs to be re-phased and so that the actual travel time difference of the shear wave could be calculated. The shear wave velocity of the soil layer between the two geophones was calculated from the interval between the two geophones divided by the difference in travel time.



(a) (b)

Figure 4. (a) sDMT conducted at Orewa site; and (b) Material index from sDMT test

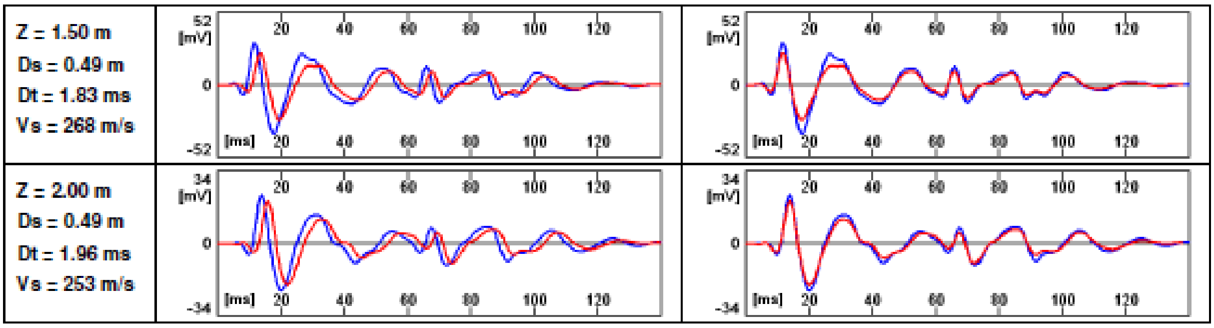


Figure 5. Examples of recorded (left) and re-phased (right) of seismographs from sDMT data

Figure 5 shows examples of the recorded and re-phase seismographs at 1.5 m and 2 m depth. The left side column of Figure 6 shows the depth level (Z) of test performed, the distance between two geophones (Ds), the difference in travel time recorded (Dt) and the shear wave velocity (Vs) of the soil layer.

4 RESULTS AND DISCUSSION

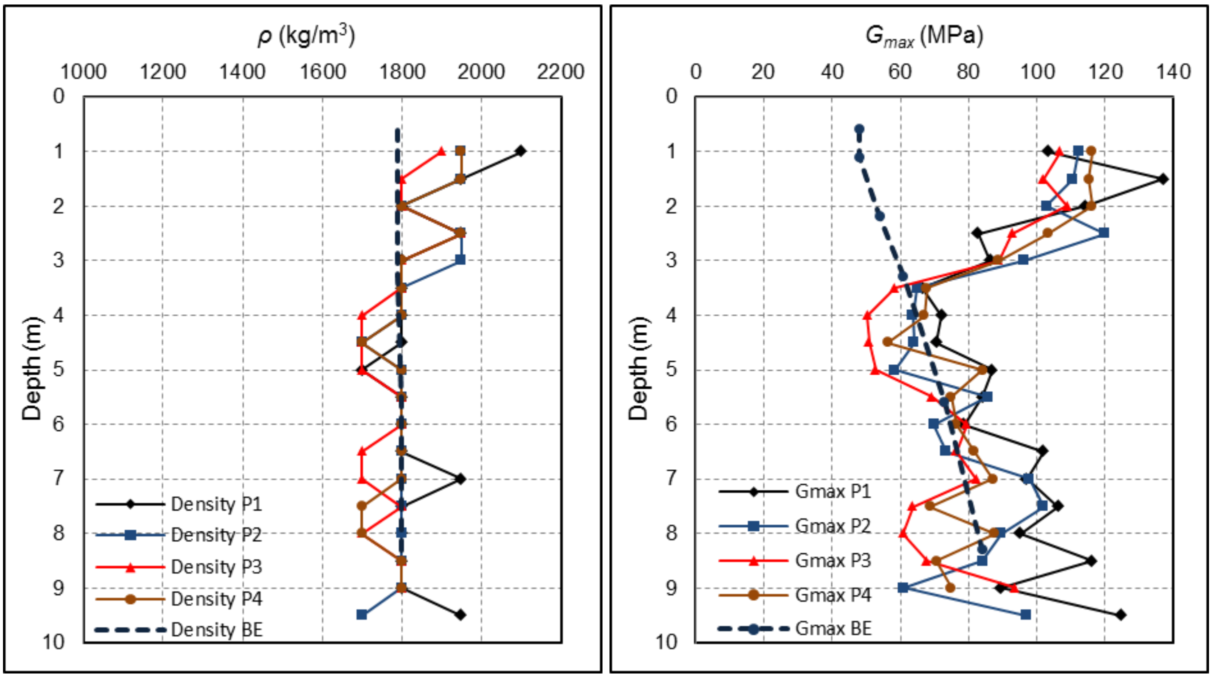
SDMT tests were conducted at four different points, all in the vicinity of the sampling pit. Figure 6a shows that the bulk density of BE specimen compared well with the values derived from sDMT measurement. The comparison between the G_{max} values, interpolated from the bender element test results, with those from sDMT in Figure 6b shows satisfactory agreement at depth between 3 - 9 m. Note that the BE results shown were interpolated from the V_s values from laboratory tests considering the appropriate ECP applied and bulk unit weights of the soil.
The discrepancies that occurred at the top 3 m of soil layer could be explained based on the difference between site and laboratory test conditions. Bender elements tests were performed under fully saturated condition, whereas the actual condition at the top 3 m is partially saturated. Under unsaturated condition, matric suction plays an important role by providing higher effective stress to the soil. Thus the G_{max} of soil under unsaturated soil is expected to be much higher than the soil under fully saturated condition with similar applied pressure due to the extra effective stress induced by matric suction. Sawangsuriya et al., (2009) conducted a study on modulus-suction-moisture relationship and found that shear wave velocity of the soil specimen increased as the matric suction increased and the volumetric water content decreased (i.e., as the specimen was drying along soil water characteristic curve).

5 CONCLUSIONS

The results presented in this paper indicated that the application of higher frequency of triggered signals successfully minimised the near field effects that normally distorted the arrival of received signal in bender element test. The clarity of signal with minimum distortion allowed direct reading of the shear wave arrival time using first deflection method. The G_{max} calculated from BE test satisfactorily agreed with field test data, confirming the reliability of the BE test.

6 ACKNOWLEDGEMENTS

The first author would like to express gratitude to the Ministry of Higher Education (MOHE) Malaysia and the University of Teknologi MARA (UiTM) for the scholarship support. The assistance of laboratory technicians throughout the development of the integrated small strain triaxial apparatus is also acknowledged.



(a) *(b)*

Figure 6. (a) Variation of bulk density of BE specimen and of field samples with depth; and (b) Comparison of G_{max} obtained from the BE and sDMT results

REFERENCES

Arroyo, M., Muir Wood, D., Greening, P. D., Medina, L., and Rio J. (2006). "Effects of sample size on bender-based axial G_o measurements." *Geotechnique*. Vol. 56 (1), pp. 39-52.

Chan, C. M. (2010). "Bender element test in soil specimens: Identifying the shear wave arrival time." *EJGE*, Vol. 15, 1263-1276.

Fratta, D., and Santamarina, J. C. (1996). "Wave propagation in soils: Multi-mode, wide-band testing in a waveguide device." *Geotechnical Testing Journal*, Vol. 19(2), 130-140.

Ibrahim, A., Orense, R. P., and Pender M. J. (2011a). "Determination of very small strain shear modulus of Auckland residual soils using bender elements." *Proc. Ninth Pacific Conference on Earthquake Engineering (PCEE 2011*), paper 147.

Ibrahim, A., Orense, R. P., Pender, M. J., Tai, A., and Kikkawa, N. (2011b). "Laboratory determination of small strain shear modulus of Auckland residual soil." *International Symposium on Deformation Characteristics of Geomaterials*, (IS Seoul 2011). 232-239.

Kawaguchi, T., Mitachi, T., and Shibuya, S. (2001). Evaluation of shear wave travel time in laboratory bender element test. *Proceeding 15th International Conference on Soil Mechanics and Geotechnical Engineering*, Instanbul, Balkema, pp. 155-158.

Kikkawa, N., Pender, M., Orense, R. and Liu, P. (2008). Void structure of Auckland residual soil using X-ray CT scanning, *Proceeding of 18th New Zealand Geotechnical Society Symposium,* Auckland*.*

Lee, J. S., and Santamarina, J. C. (2005). "Bender elements: Performance and signal interpretation." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 131 (9), 1063-1070.

Leong, E. C., Yeo, S. H. and Rahardjo, H. (2005). "Measuring shear wave velocity using bender elements." *Geo technical Testing Journal* Vol. 28 (5), pp. 488-498.

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. (2001). The flat dilatometer test (DMT) in soil investigations: A report by the ISSMGE Committee TC16. *IN SITU 2001, International conference on in situ measurement of soil properties*, Bali.

Pender, M., Wesley, L., Twose, G., Duske, G., and Pranjoto, S. (2000). Compressibility of Auckland residual soil. *Proceeding of GeoEng 2000*.

Sawangsuriya, A., Edil, T. B., and Bosscher, P. J. (2009). "Modulus-suction-moisture relationship for compacted soils in postcompaction state." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 135 (10) 1390-1403.

Wang, Y. H., Lo, K. F., Yan, W. M., and Dong, X. B. (2007). "Measurement biases in the bender element test." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 133(5), 564-574.

Wesley, L. D. (2010). "*Geotechnical Engineering in Residual Soils.*" New Jersey, John Wiley & Sons. 1-12.