

Determination of very small strain shear modulus of Auckland residual soils using bender elements

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ABSTRACT: Bender elements test is a convenient technique and frequently employed for shear wave velocity measurement at small strain due to its simplicity and reliability. This paper presents the details of the apparatus setup, preparation and installation of bender elements and soil specimen preparation procedures adopted throughout the experimental processes. Preliminary experimental results on fully saturated undisturbed Auckland residual soil demonstrated consistent shear wave velocities at different frequencies and good quality of triggered and received signals. Furthermore, small strain shear modulus (G_{max}) of undisturbed Auckland residual clays measured using bender elements satisfactorily agreed with the G_{max} obtained from monotonic small strain triaxial tests.

1 INTRODUCTION

Seismic technique is a powerful method that provides a non-destructive approach to investigate and profile sub-surface properties of earth materials in order to predict accurately the ground deformation and acceleration expected during a seismic event. In-situ measurement or laboratory tests are normally used to investigate the low strain amplitude shear modulus that is required as a fundamental input parameter in the dynamic analysis of wide ranges of geotechnical engineering applications including foundation design, settlement prediction, soil improvement control and liquefaction assessment. Since the development of bender element (BE) test in late 1970s, the method has gained popularity and been incorporated in many geotechnical testing apparatus, such as oedometer, triaxial, simple shear box and resonant column.

This paper discusses the development processes of bender element system which was integrated into an existing small strain triaxial testing apparatus (Ibrahim, et al., 2009). The objective was to develop a testing apparatus that could provide more information from multiple tests on a single specimen at the small strain level. Thus the integrated system was able to eliminate potential errors due to the highly variable nature of Auckland residual soil and provided a meaningful comparison of maximum shear modulus between monotonic and dynamic loading tests.

2 BENDER ELEMENT SYSTEM

Bender element test is a non-destructive dynamic method that has been used to measure the soil stiffness at very small strain level. Shirley and Hampton (1978) were the first to measure shear wave velocity through laboratory-prepared kaolinite samples using bender elements. It was considered as a significant development in geotechnical testing technique as BE test provided a simple, yet proven to be reliable and cost effective method. Figure 1 shows a typical schematic diagram of bender element system integrated in the triaxial apparatus. Basically the system comprises of two bonded thin piezo-electric plates, which are usually coated with epoxy resin. Two such elements (transmitter and receiver) are normally placed opposite one another and the BE cantilever inserted at a small distance into the soil sample. The transmitter element distorts or bends when subjected to the voltage signal from function generator and creates the shear waves. The shear wave travels through the specimen and causes the receiver element to vibrate and the arrival time of signal is recorded by an oscilloscope. The interval between the times of transmitted and received signal is calculated as the travel time (t_s) of the shear wave. Shear wave velocity (V_s) is then calculated by dividing the distance travelled by the shear

wave over the travel time (t_s) taken. The shear wave travel distance is normally considered as the length between tip to tip (L_{tt}) of bender elements.

$$V_s = \frac{L_{tt}}{t_s} \quad (1)$$

The maximum shear strain induced by bender elements was measured to be less than 10^{-5} (0.001%) and therefore the shear modulus determined using BE test is relevant at the very small strain range (Dywick and Madshus, 1985). By assuming the soil as a perfectly elastic material, the relationship between shear wave velocity (V_s) and the elastic or maximum shear modulus (G_{max}) is as follows:

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

where, ρ is the bulk density of the soil specimen.

Interpretation of bender element test parameters is relatively straightforward as most parameters are pre-determined before the test is conducted. The only difficulty that could compromise the integrity of the G_{max} calculated is the determination of shear wave arrival time (t_s). The arrival time is estimated as the time between the start of voltage pulse input to the transmitting bender element and the first deflection in the output signal from the receiving bender element. Many of the later researches carried on bender element test were done to either improve or produce most reliable methods to determine the arrival time (Arroyo et al., 2006; Lee and Santamarina, 2005; Greening and Nash, 2004; Arulnathan, et al., 1998). Normally, the interpretation of t_s needs more caution as it might be misinterpreted with the compression wave (P-wave) and ambient noise that masked the arrival of shear wave at the receiver. Table 1 briefly discusses the problems and some recommendations normally associated with the bender element test particularly with the arrival time determination (Wang et. al., 2007; Arroyo et al., 2006; and Leong et. al. 2005). These recommendations provide useful information in the development processes of bender element system. Thus the BE system used in the study was developed in accordance with these recommendations whenever possible.

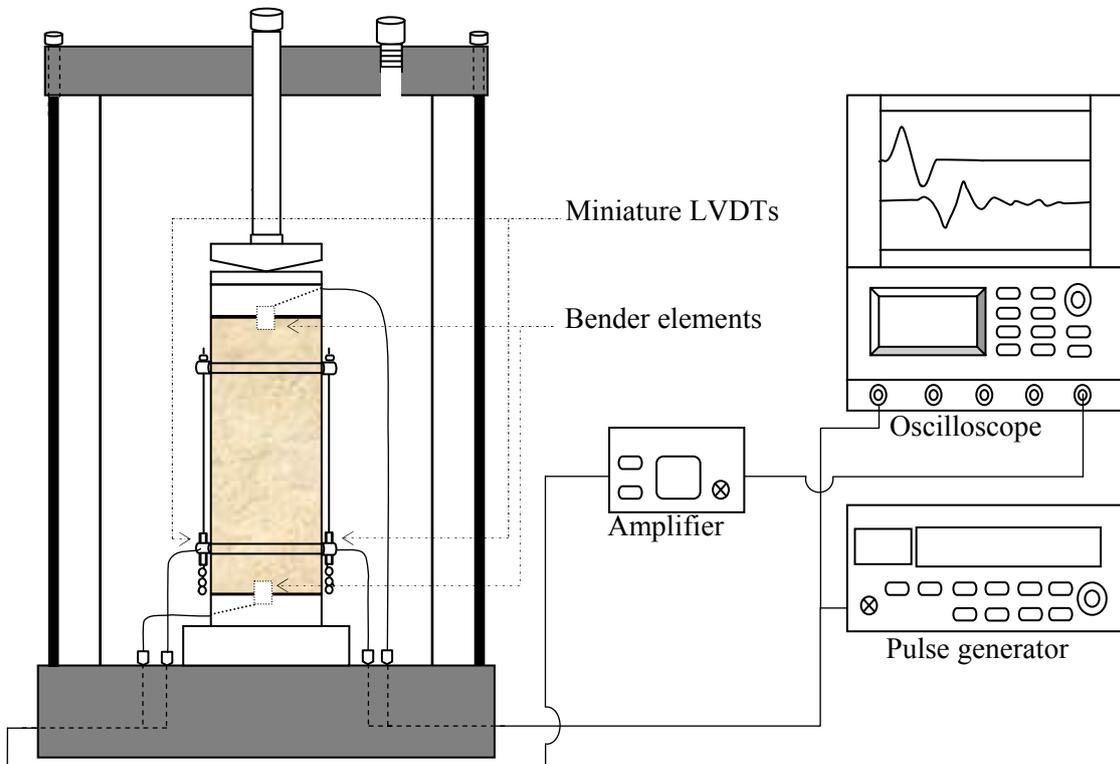


Figure 1. Modified small strain triaxial apparatus

Table 1: Problems and recommendations in bender element test

Sources of error	Recommendations
Near field effect/Multiple reflections from the boundary	Short bender element cantilever produces higher energy. The wave path length to wavelength ratio (L_n/λ) ≥ 1 Higher frequency produces shorter wavelength as ($\lambda = V_s/f$) and slenderness effect (Height to diameter of specimen ratio), $H/D \geq 2$ reduces near field effect from boundary reflection.
Time delay in transfer function	Power amplifier and signal amplifier to improve the transmitted and received signals Correction due to the time delay caused by the transfer function of receiver system.
Solid fluid interaction effect	Proper insulation is critical when testing on wet/saturated specimens especially for long hours test.
Waveform shape of input signal	Sinusoidal wave usually preferred due to several issues with square wave, such as it did not resemble the original transmitted signal and more distortion at the beginning of receiving signal.

2.1 Development process of BE apparatus

The procedure adopted in this research was based on the recommendations of previous researchers in order to eliminate or at least minimise the potential errors and also to improve the transmitted and received signals. Therefore, several technical requirements have to be followed in order to achieve a noise-free environment, leak-free connection system, good insulation and perfect-vertical alignment of bender elements, good contact between BE and soil, and good shielding of cables and electronic equipment. The development procedures undertaken are briefly discussed in this paper.

Preparation of bender element sheet and wiring processes

The element used in the study is 0.51 mm thick brass reinforced piezoelectric sheet produced by Piezo System Inc. Table 2 presents the technical specifications of the piezoelectric as general guidelines due to the fact that some properties are physically- and dimensionally-dependent parameters. The piezoelectric sheet was carefully cut to the desired dimensions and surface cleansed to prepare the surface for soldering. The presence of paint, residue or dirt on the surface of the piezo sheet could prevent a strong bond between epoxy and element. The ineffective bonding would create a weak region and possibly crack under continuous vibration and high pressure. Therefore, the element was dipped in cleansing agent (acetone) to remove the insulation paint, wiped clean and dried before the wiring process and the application of epoxy resin.

There are two connection methods available, namely series and parallel (Figure 2). Based on previous study (Brignoli et al., 1996), parallel connection was proven to vibrate more strongly than series connection with the same applied voltage, thus producing higher energy. However, in the present BE apparatus development, the series connection was used for both transmitter and receiver elements due to the simplicity of the wiring process and the availability of coaxial cable with the designated apparatus wiring system. The limitation is also due to the fact that the piezoelectric sheet available was suitable for the series connection system. To overcome this limitation, a transmitted signal of 10 volts and a power amplifier at the receiver were used. The coaxial cable with minimum shield coverage of 90% provided satisfactory protection against environmental noise due to electromagnetic signal interference. Tables 2 and 3 provide general information regarding the properties of piezoelectric sheet and coaxial cable used in the study.

Table 2. Piezoelectric bending actuators (brass reinforced) (after Piezo Systems Co.)

Stiffness (N/m)	Capacitance (nF) series operation	Rated voltage (V_p) series operation	Resonance frequency (Hz)	Free deflection (μm)
1100	14.5	± 180	350	± 250

Table 3. Coaxial cable technical specifications (after Raychem Limited)

Characteristic Impedance	Capacitance pF/m	Voltage withstand Volts	Dielectric concentricity	Shield coverage	Operating frequency
50 ± 2 ohms	98 maximum	1000 minimum	80% minimum	90% minimum	2.7 GHz maximum

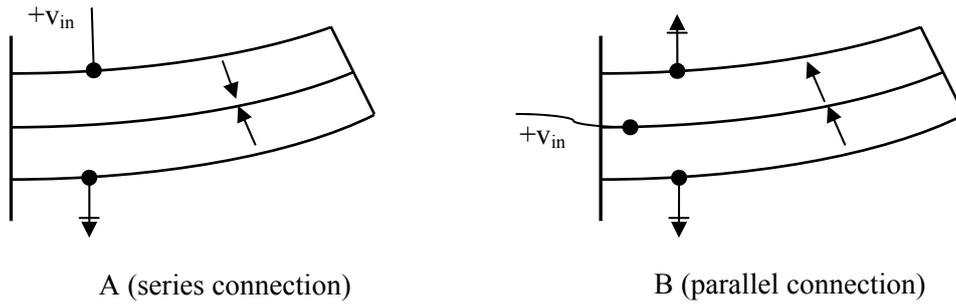


Figure 2: Series and parallel connection systems in bender element

Table 4. Bender element specification

Component	Properties
Bender element	<ul style="list-style-type: none"> - Nickel electrodes both sides and average elastic modulus is $6 \times 10^{10} \text{ N/m}^2$ - Length (L) = 18 mm , Height (H) = 18 mm , Thickness (T) = 0.5mm (before coating) - $L_c = 20 \text{ mm}$, $H_c = 20 \text{ mm}$, $T_c = 1.5 \text{ mm}$ (after coating with epoxy)

Epoxy resin coating and the installation of BE

Epoxy coating is one of the crucial processes in BE development. Proper coating would prevent damage to the BE, such as potential short circuit during the experiment and also would allow BE to vibrate at maximum capacity. Care was taken during epoxy resin mixing process to avoid bubbles entrapped within the epoxy, which could possibly reduce the strength of epoxy coating. A brass split mould was designed to ensure a thin layer of coating with satisfactory strength could be achieved. Mould release agent was used to assist the removal process after curing time. The utilization of the mould provided consistency and control in the production of bender elements especially in terms of thickness and shape. Table 4 shows BE sheets specification before and after coating.

Installation of BE on the top cap and base pedestal was performed to achieve perfect vertical alignment. It was reported by Arroyo et al., (2006) that the maximum energy radiation is achieved within 30° of vertical alignment and a perfectly vertical installation would assist in producing maximum energy of triggered and received signals. Perfectly vertical bender elements also minimize the near field effects caused by the boundary reflection. To achieve this, the installation of BE was carried out in two stages, where the first stage was to ensure perfectly upright bender element and the second step was to ensure that the system was leakage-free especially in the connection system so that it can survive high pressure and long hours of test.

In the first stage, the groove on the base pedestal and top cap for BE was filled with the liquid epoxy resin and left for a week to achieve maximum strength while the BE was held firmly vertical. After that, another epoxy resin filling was applied to plug the hole. The filling must be carried out without getting air bubbles trapped in the epoxy and therefore syringe was used to assist filling work as it was effective to minimize the problem. Figure 3 shows the installation and integration of BE system into the existing small strain triaxial apparatus.

Soil specimen preparation

Special attention needs to be taken when preparing the soil specimen in BE test. The technique adopted in preparing the slot/cut of the specimen ends should induce minimum disturbance and the most important is that the cut provides a good contact between the BE and the soil specimen. The initial good contact is vital especially when the test is carried out at low consolidation pressure. Normally the contact between BE and soil gets better and significantly improves at higher isotropic consolidation pressures.

The slot on both ends must also lie along the centre line and have the same orientation. Therefore, a special cap (Figure 4A) was designed with specified size slot in the middle to assist the process. The special cap was proven to be useful in the specimen preparation and provided a good orientation

between bender elements of top cap and base pedestal. A slightly smaller slot compared to the actual BE size and positioned vertically at both top and bottom will ensure the maximum energy can be produced and received during the test, thus improving the clarity of received signal. Details of the sampling and specimen preparation are shown in Figure 4. Figure 4A shows the application of grooving cap after the final trimming of soil specimen using three-part split mould. The orientation of groove cap was set by referring to the guideline made on the three-part split mould and this technique was proven to be capable of producing consistent standard slot for all specimens. Figure 4B shows the square end specimen with bender element slot on top. Figure 4C and 4D show the initial and final set up of bender element and small strain test.

3. SOIL PROPERTIES AND EXPERIMENTAL TEST CONDITION

3.1 Properties of soil specimen

Auckland residual soil is a product of in-situ chemical weathering of Waitemata sediments group and a highly variable material in its natural condition (Kikkawa et al., 2008). The soil sample used in this study was obtained from a construction site in Orewa, located approximately 45 minutes driving north from Auckland central business district. Samples were obtained by pushing 200mm diameter and 200mm long sampling tubes which were fitted with a low angle cutting shoe into the ground at the desired depth using a hydraulic jack. The soil specimen with 75 mm diameter and 150 mm height was then prepared according to the methods mentioned above. It was saturated at 700 kPa back pressure until B value > 0.95 was reached, followed by application of isotropic consolidation pressure (σ_c'), after which bender element test was commenced. The physical properties of the soil samples are listed in Table 5.

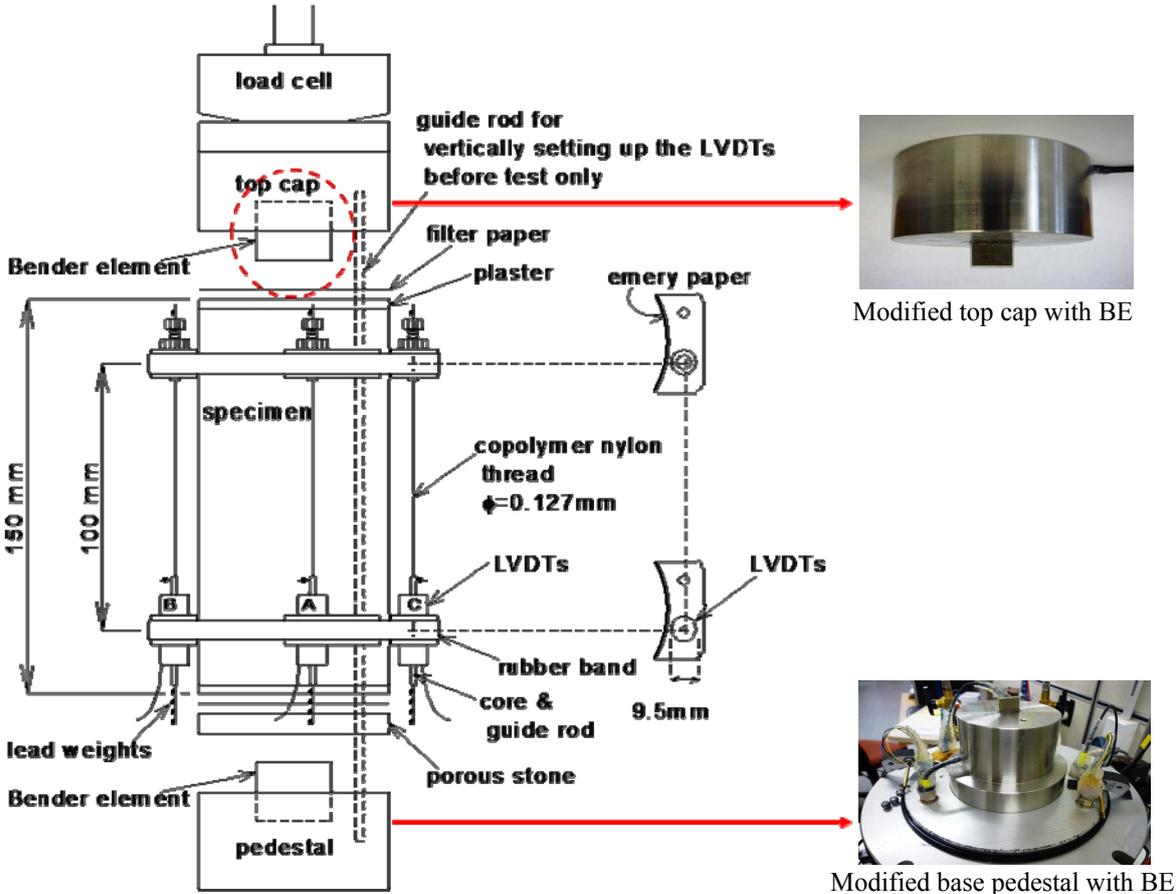


Figure 3. The integration of BE on the small strain triaxial apparatus.

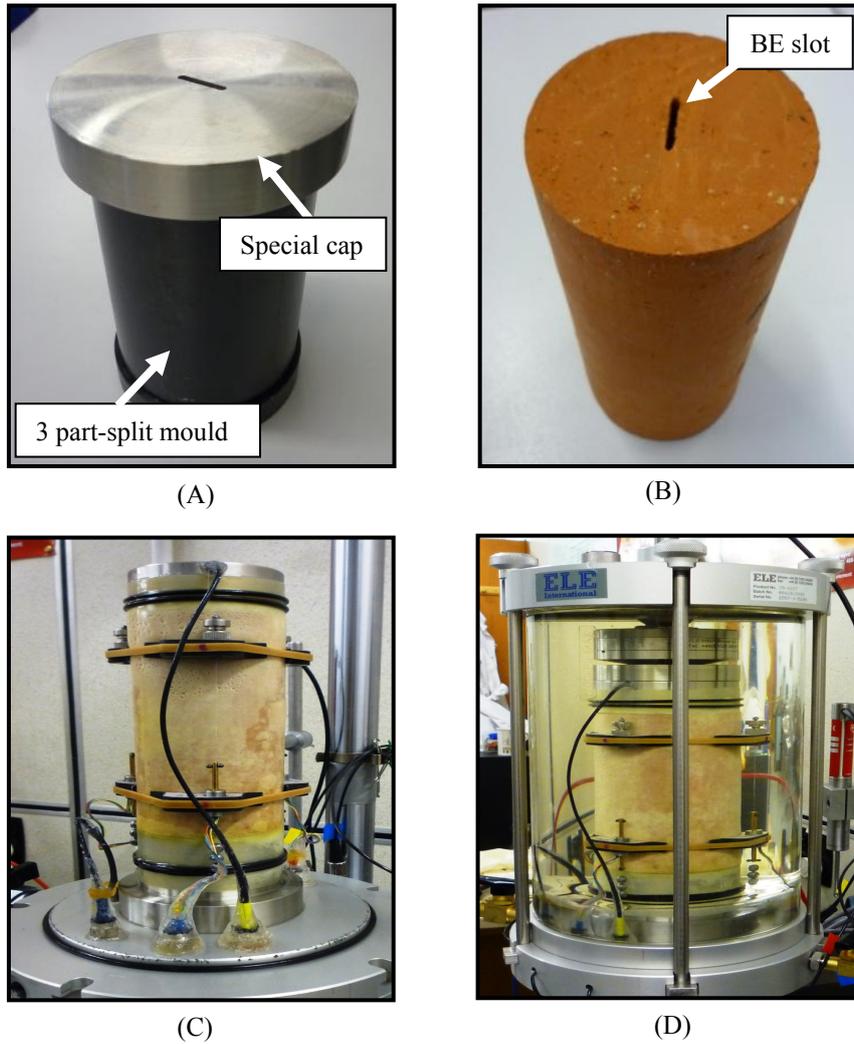


Figure 4. Soil specimen preparation procedure for BE test

Table 5. Index properties of Auckland residual soil

Specific gravity, G_s	2.63 – 2.65
Liquid limit, w_{LL} (%)	68 – 72
Plastic limit, w_{PL} (%)	38 – 40
Plasticity Index, I_p	30 – 32
Natural water content (%)	35 – 41
Bulk density of specimen, ρ (kg/m^3)	1.827 – 1.864

3.2 Bender element test

The BE system used in this study was supported by 2 MHz Yokogawa FG110 synthesized function generator and a Yokogawa DL1200A 4 channels 100 MHz oscilloscope. The oscilloscope permitted on-screen manual calculation of arrival time (t_s) using measurement cursors and moreover, the transmitted and received signals could be downloaded directly to a computer using 16 bit AD data acquisition system for post analysis. Manual determination of arrival time could be performed satisfactorily at $10\mu\text{s}$ resolution of $500\mu\text{s}$ points per division. The test was carried out using sinusoidal wave at the frequency range between 1500 Hz up to 3000 Hz.

4. TEST RESULTS AND DISCUSSION

In the bender element test, the peak to peak arrival time was chosen in determining t_s due to the consistency and the clarity of triggered and received waves obtained in the oscilloscope and downloaded data using 16 bit A/D converter. Figure 5 shows an example of transmitted and received

signals for peak to peak determination (left figure) and first deflection (right figure). The first arrival or deflection signal was masked either by the deflection of the compression wave or the electrical noise that distorted the received signal. This created difficulty in obtaining t_s . Figure 6 presents the t_s obtained at different frequencies applied. It clearly indicates that only small variations occurred and the good consistency of t_s was obtained within the ranges of 2000 to 3000 Hz.

The G_{max} of undisturbed Auckland residual soil ranging from 60 kPa to 225 kPa from BE tests and monotonic small strain triaxial tests reported by MSa'don et al. (2010) are shown in Figure 7. The results from bender element tests indicate that shear modulus is dependent on the effective stress with the relationship given by

$$G_{max} = 3092(\sigma_{c'})^{0.55} \quad (3)$$

where, G_{max} and $\sigma_{c'}$ are in kPa.

The maximum difference between the G_{max} obtained by bender element (BE) and monotonic small-strain triaxial tests (SSTT) was less than 7% throughout the range of the effective confining pressure applied in the tests. This good agreement showed the capability of both methods (BE and SSTT) in measuring G_{max} at very small strain range accurately. It should be mentioned that in the SSTT performed using miniature LVDTs attached to the specimen, the maximum strain level used to calculate the G_{max} was $1.5 \times 10^{-3}\%$, which was considered as the elastic range. The results indicated that at very small strain level, the G_{max} of undisturbed Auckland residual soil was hardly influenced by the type and rate of loadings (dynamic and monotonic loadings). Thus the G_{max} obtained could be directly used for the analysis of either monotonic- or dynamic-related problems.

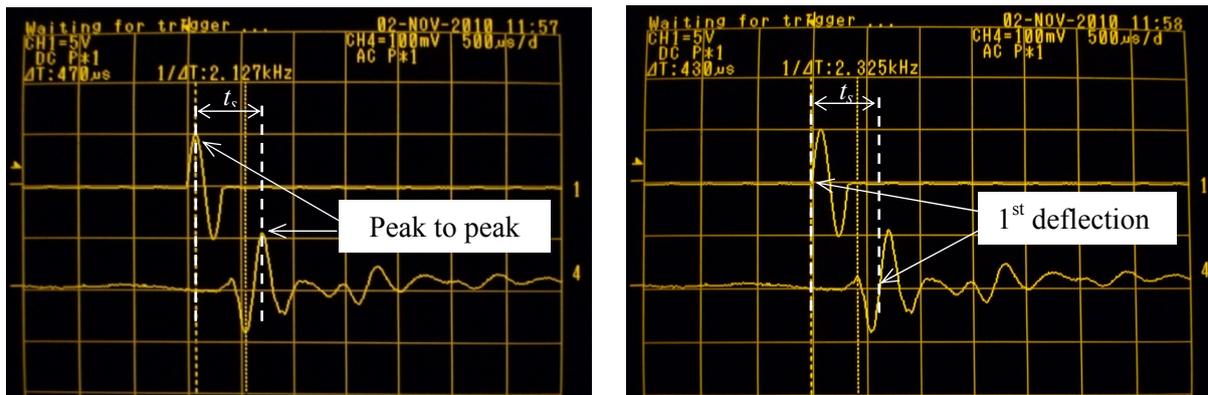


Figure 5. Time arrival determination using peak to peak and first deflection method

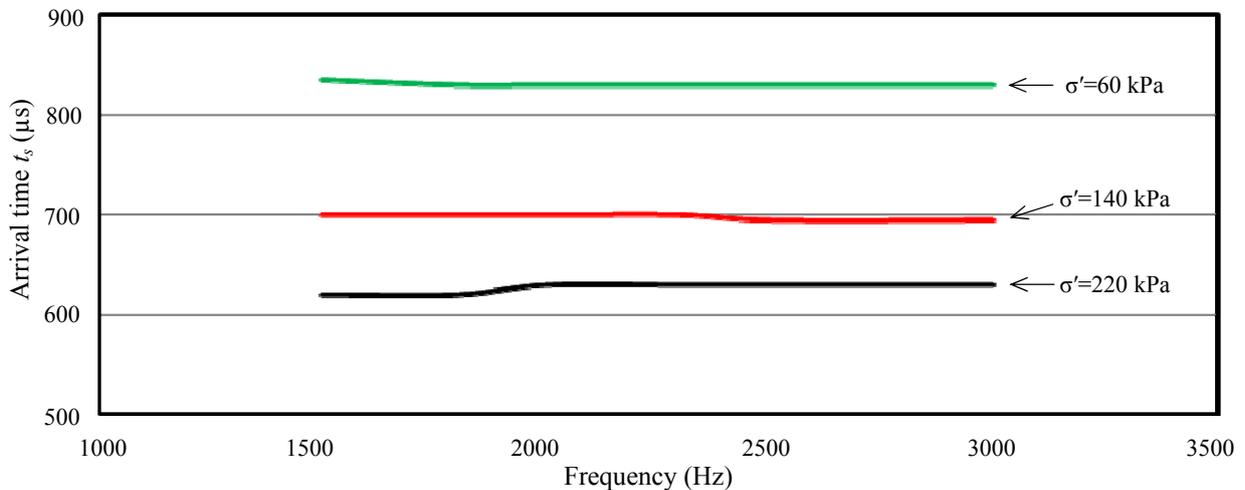


Figure 6. Variation of arrival time with regards to the different frequencies applied.

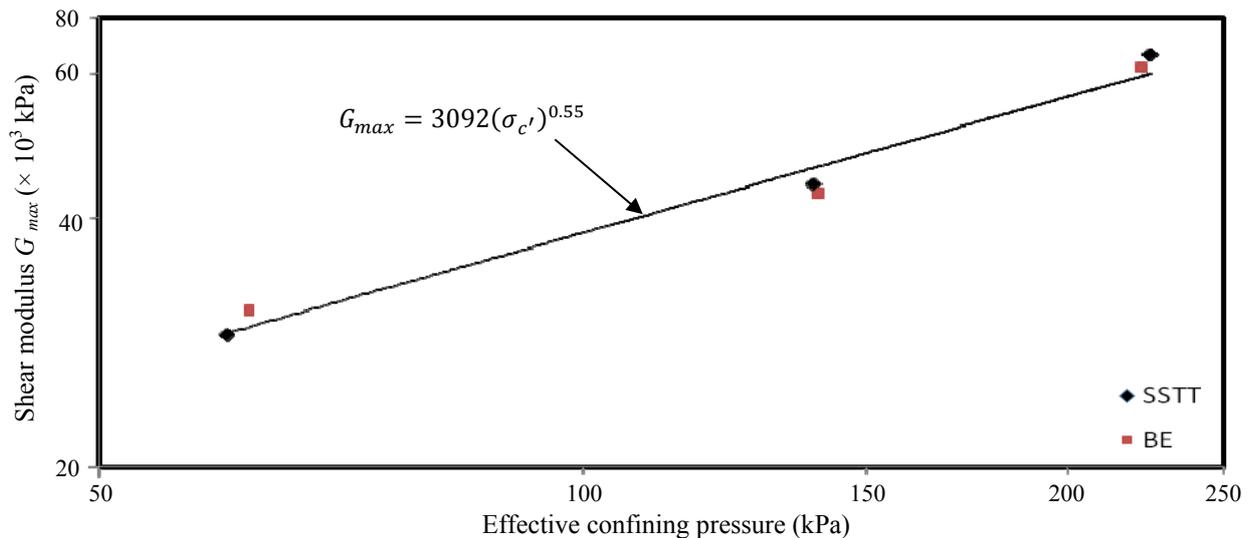


Figure 7. G_{max} of Auckland residual soil under various effective confining pressures

5. CONCLUSIONS

This paper presented the development processes undertaken in incorporating bender element system into the existing small strain triaxial apparatus. The procedures adopted successfully eliminated or minimised the problems associated with bender element testing. The good quality of received signal with minimum distortion and environment noise allowed the direct reading of the shear wave arrival time using peak to peak method. Thus, the objective of the study to integrate BE system into an existing small strain triaxial apparatus was successfully implemented.

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