4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1419

INFLUENCE OF STRESS LEVEL IN BENDER ELEMENT PERFORMANCE FOR TRIAXIAL TESTS

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ABSTRACT

Bender elements are piezoceramic transducers used to measure and monitor the initial shear modulus of soils during conventional laboratory tests. Until recently a simple interpretative model that implies propagation of a plane shear wave has been commonly used, in which the time of "first arrival" of the shear wave at the receiving element is used in the calculation of the shear modulus. However, this model does not incorporate many of the propagation characteristics observed in reality, such as attenuation and frequency dependence of the propagation velocity, which are the cause of a degree of subjectivity in the interpretation of the first arrival and have led to the introduction of frequency domain techniques. This paper examines the performance of bender elements in a sand sample subjected to high confining stresses, highlighting differences in the group velocity detected by a frequency domain method and the shear wave velocity as detected in the time domain.

Keywords: bender elements, shear stiffness, high pressure testing, wave propagation

INTRODUCTION

Bender elements are piezoceramic transducers used to measure and monitor the initial shear modulus of a material during the different stages of conventional laboratory tests (e.g. triaxial or oedometer tests). A pair of elements is required in each case. One element, embedded in one side of the sample, is electrically excited creating a wave that propagates along the material. This signal is then collected by another element located in the opposite side. The input and output signals are captured on the oscilloscope and then processed in order to determine the shear wave arrival time, from which the initial shear modulus is calculated. This technique has become increasingly popular since its introduction in the late 1970's. In particular during the last decade, bender-element based testing has been applied to a range of geomaterials and at ever higher stress levels. Much research effort has been directed towards understanding observed phenomena like near field effects, wave interference and dispersion (e.g. Jovičič et al., 1996). Attempts have been also made in order to refine or replace the existing interpretative model based on an interpretation of the first arrival of the shear wave at the receiving element (e.g. Blewett et al., 2000 and Arroyo et al., 2006), since it has been appreciated that the assumption of the propagation of a plane shear wave does not account for many characteristics observed in reality, such as attenuation and frequency dependency. Although the propagation mechanisms and the bender element system itself are now better understood, a fully consistent and objective interpretative model has yet to be produced.

The existing triaxial apparatuses in the Imperial College Soil Mechanics laboratory allow bender-element testing up to confining pressures of 25MPa. Systematic observations over a wide range of confining pressures, have enabled an assessment to be made of the effects of confining pressure on system performance. This is illustrated in this paper by presenting the results of an isotropic

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compression test on Toyoura sand for which bender element readings were taken up to an effective stress of 22.4 MPa.

EXPERIMENTAL SETUP

70 MPa triaxial apparatus

The test was carried out in a triaxial apparatus for elevated pressures with a capacity of up to 70MPa confining pressure (Figure 1). The main features of this apparatus have been reported by Cuccovillo and Coop (1999). A schematic diagram of its control systems is given in Figure 2. The 70MPa apparatus has full stress path capabilities and it is instrumented to measure stiffness from very small strains (0.0001%) to large strains (beyond 25%). Local axial strains are measured using a set of linear variation displacement transducers LVDTs located at opposite sides of a 50x100mm cylindrical sample. The local axial strain measurements are complemented by an external axial displacement transducer. Volume changes are measured using a 50cc Imperial College volume gauge. Radial and axial pressures below 0.8MPa are controlled through air pressure controllers acting via air/oil interfaces which are bypassed when higher pressures are required. Pressures higher than 0.8MPa are generated by means of amplification systems which consist of pneumatic displacement pumps, two regulating valves, a nitrogen gas accumulator and an oil reservoir. The apparatus is also fitted with platen mounted bender elements which allow the measurement of the shear modulus G_{vh} (i.e. with vertical wave propagation and horizontal polarisation).

Figure 1. The 70MPa Triaxial apparatus

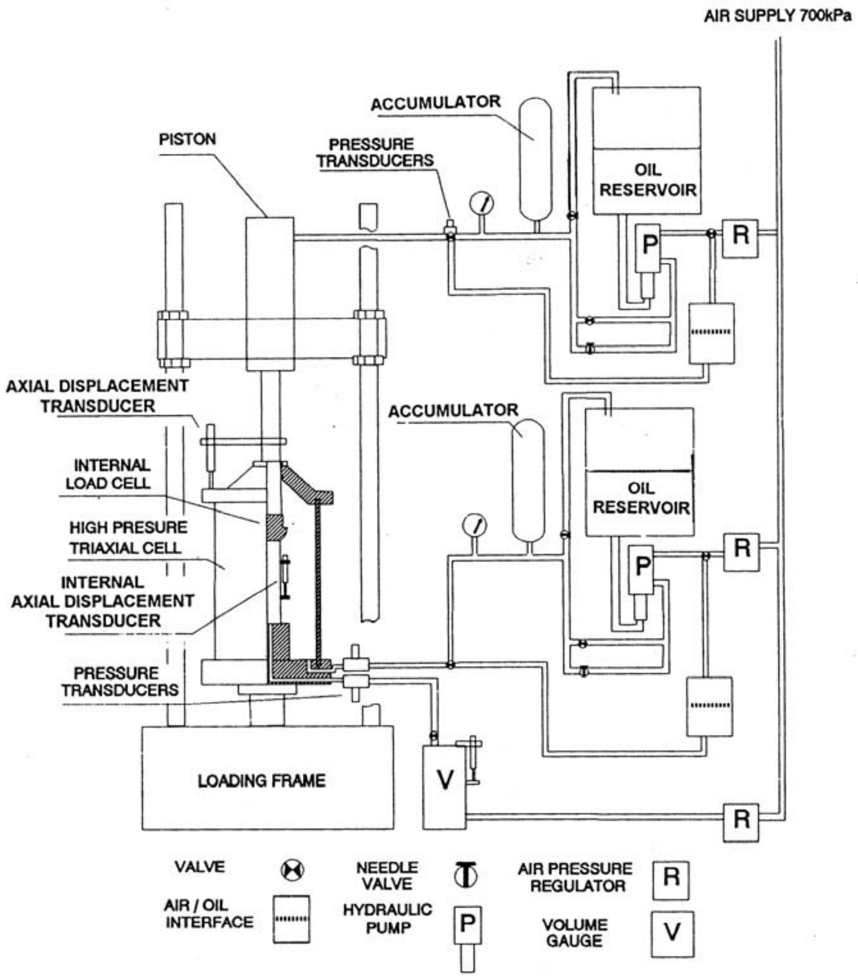


Figure 2. Schematic diagram of the control systems of the 70MPa Triaxial apparatus. After Cuccovillo and Coop (1999).

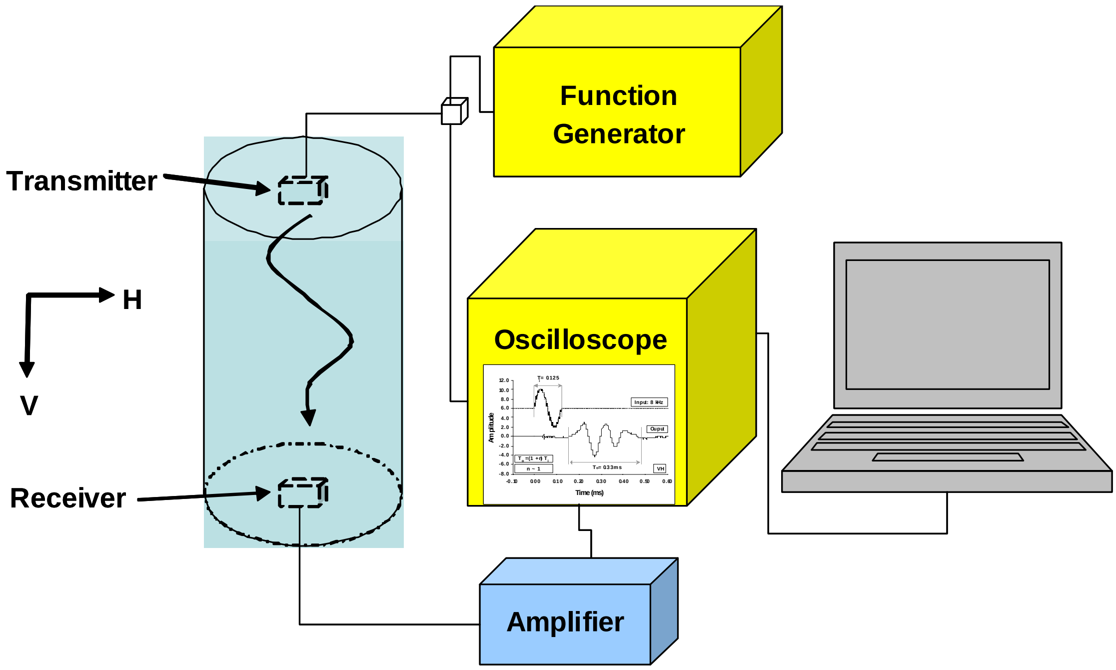


Figure 3. Bender element setup for the measurement of G_{vh} in a triaxial test

Bender elements

Figure 3 shows a schematic representation of the bender element setup. A pair of bender elements, transmitter and receiver, are embedded in opposite ends of the cylindrical soil sample. A function generator is used to produce a controlled input voltage which is sent both to the transmitter bender element and to an oscilloscope. The propagated wave that is created by the motion of the transmitter is then detected by the receiver element, which is connected to a signal amplifier. The amplified signal is then captured by the oscilloscope and displayed simultaneously with the transmitted wave, from which a simple interpretation of the first arrival time may be made. Both the input and output signals may also be transferred to a computer for more detailed interpretation.

Material

The test reported in this paper was performed on Toyoura sand, which is a predominantly quartzitic sand that is widely used in research, particularly in Japan. Its main properties are summarised in Table 1 and its particle size distribution shown in Figure 4. The parameters N and λ locate the isotropic Normal Compression Line in the plane of specific volume, v (= void ratio +1) against the logarithm of the mean (or in this case isotropic) effective stress, p'. The values are given for the straight section of the Normal Compression Line that may be detected at high pressures where particle breakage is dominant, and respectively define the projected intercept at p'=1kPa and the gradient.

Table 1. Properties of Toyoura Sand

Mean particle diameter D_{50}	0.17 mm
Specific gravity G_s	2.65
Minimum void ratio e_{min}	0.60
Maximum void ratio e_{max}	0.98
Critical state friction angle ϕ'_{cs}	31°
Location of normal compression line	N=3.57 , λ=0.198
Particle shape	Sub-rounded to sub-angular
Particle mineralogy	75% quartz, 22% feldspar, 3% magnetite

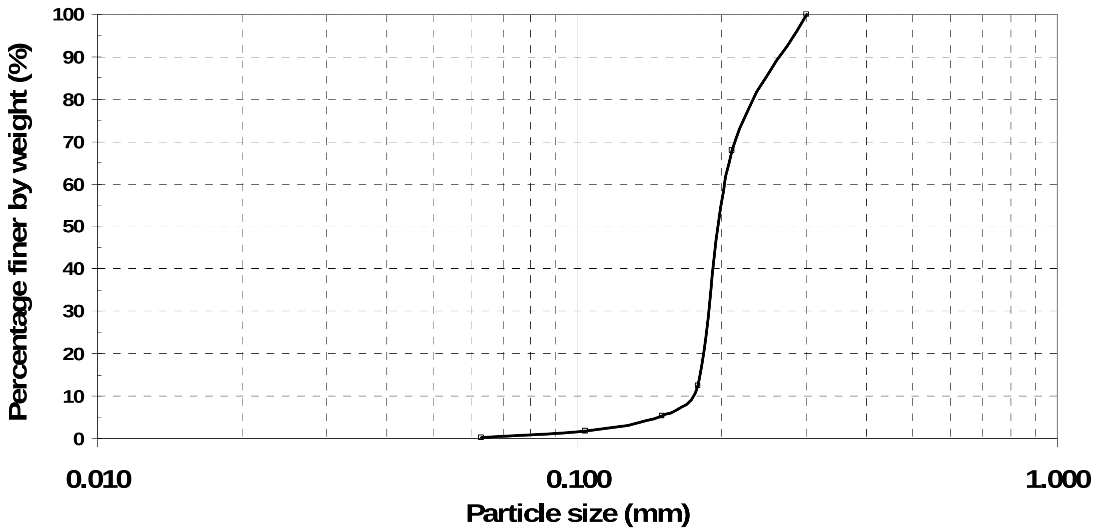


Figure 4. Particle size distribution of Toyoura Sand

Test description

The triaxial sample was prepared by pluviation through water and was then saturated under an isotropic effective stress of 50kPa and a back pressure of 600kPa. After saturation the back pressure was maintained constant at 600kPa and the cell pressure increased. On arrival to a target p', the stresses were kept constant until the volumetric changes in the sample were negligible. Then a bender element probe was carried out after which the cell pressure was again increased up to the next target p'. Each bender element probe consisted of a set of four pairs of input/output readings, each one having a different input frequency (e.g. 11, 13, 15 and 17kHz). The input signal used was a single shot sine pulse.

SYSTEM RESPONSE

Frequency domain

The transfer functions for the four different input frequencies were calculated using Fast Fourier transforms. Figure 5 shows the stacked phase angles (or phase factor) from the transfer functions for input frequencies of 13kHz, although it was found that the phase component was insensitive to the magnitude of the input frequency. Excitation with a continuous sine wave, with a manual calculation of the transfer function from a comparison of the received and transmitted wave forms, again gave almost identical phase and gain components. This confirmed the validity of using a single shot sine wave as the driving signal, since a continuous wave forces the system to vibrate at one frequency and is therefore not subject to the potential errors that might be introduced when more than one mode of vibration is excited, as may occur with pulse signals. In deriving the unwrapped phase angles, offsets are often introduced at points where the phase angle shows a local reversal; none have been used here, and within the range of frequencies on Figure 5, there are no reversals.

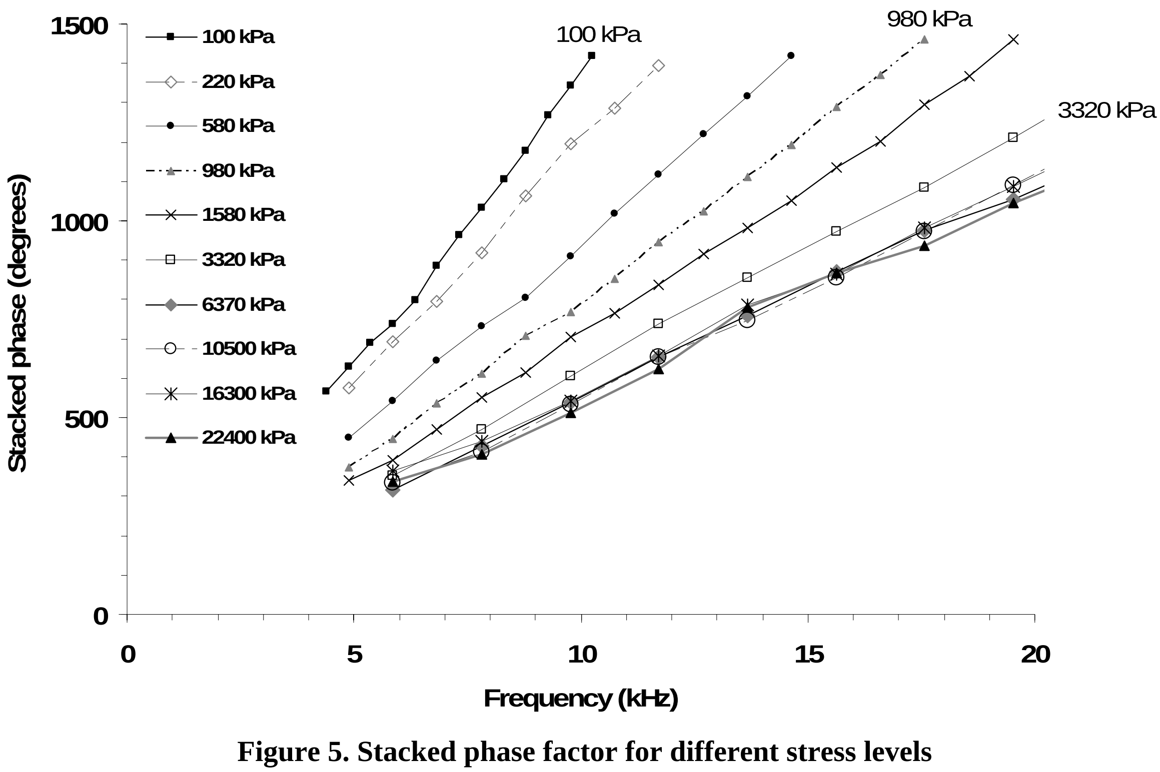


Figure 5. Stacked phase factor for different stress levels

For an ideal system there would be propagation of a plane shear wave with no dispersion or distortion, and the arriving wave would have the same frequency as that transmitted. In this case the phase factor would be a straight line passing through the origin with a gradient that would be the inverse of the arrival time. This arrival time from the phase factor is the group or phase velocity, which will be equal to the shear wave velocity for the ideal system. This has formed the basis of many frequency domain techniques (e.g. Arroyo et al., 2006). However, the actual system used is imperfect and is comprised not only of the soil sample but also the bender elements themselves as well as the boundaries of the sample and apparatus. Under free vibration it will be the characteristics of the complete system that will control the output spectrum. The arriving wave will therefore include modes of vibration in addition to that corresponding to the transmission of a planar shear wave, for example through reflection from the sample boundaries, and the group velocity, which now represents the velocity of a wave packet, may not correspond exactly with the shear wave velocity. At low frequencies (<5kHz) the gain determined by the Fast Fourier transform analysis was found to be small at all stress levels, giving poor definition, so that this section of the stacked phase angle is less reliable and has therefore been omitted. Poor definition of the stacked phase at low frequencies introduces, in several cases, an offset which results in linear trends not pointing towards the origin. This does not affect the calculated group velocities, as they are a function of the gradient only. For comparison purposes, the curves in Figure 5 have been offset and therefore they all point towards the origin.

In Figure 5 it can be seen that as the stress level increases the phase factor flattens, indicating a faster arrival time, but at stress levels from 6370kPa onwards, the phase factor no longer changes, and the arrival time is therefore constant. However, during isotropic compression the sample length changes and so the data should be analyzed in terms of velocity. In Figure 6 the group velocities have been calculated using the gradient of the phase factor on Figure 5 together with the bender element tip to tip travel distance, as recommended by Viggiani and Atkinson (1995). The tip to tip distance was calculated from the initial sample length and bender element dimensions, along with the changes of sample length measured by the LVDTs mounted on the sample. Even accounting for the sample length it can still be seen that there is a threshold stress level at around 6MPa, beyond which the group velocity no longer changes. This is an unexpected result because the sample continues to reduce its volume as it is compressed to higher stresses as can be seen in Figure 7. Monotonic loading probes measuring the elastic Young's modulus of the Toyoura sand continued to show an increasing stiffness up to the maximum stress reached and a threshold stress level has also been identified for London Clay above which group velocities are again constant (Alvarado, 2007).

Time domain

Time traces for the received signals at a selection of stress levels are given in Figure 8; zero time on these traces is taken at the first upward movement of the transmitted sine pulse. The frequencies used of 9-13 kHz were sufficiently high to avoid near field effects (Sanchez Salinero et al., 1986) and so in most cases a first arrival may be easily identified from the first upward deflection of the received wave. The only cases where the first arrival is more difficult to identify are Probes 7 and 8. This is partly because as the stress level increases the gain generally decreases while the noise in the signal remains of similar magnitude, so tending to obscure the received wave. This "noise" is not electrical in nature since it does not appear when the transmitted signal is not present. It can also be seen that there are some consistent features within it that must be the result of the system response. For example, there is a small peak that occurs at 0.08-0.09ms no matter what the confining pressure. This feature is unlikely to be a function of the soil response since the soil stiffness increases with the confining pressure, as can be seen for the reduction in the arrival time of the main part of the wave.

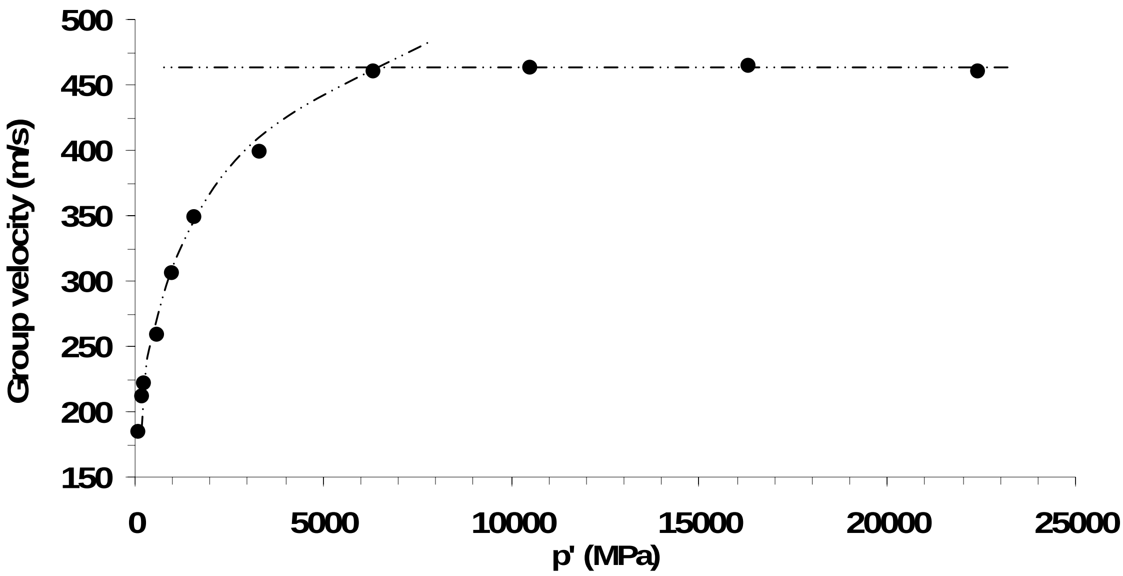


Figure 6. Variation of group velocity with p’ during isotropic compression

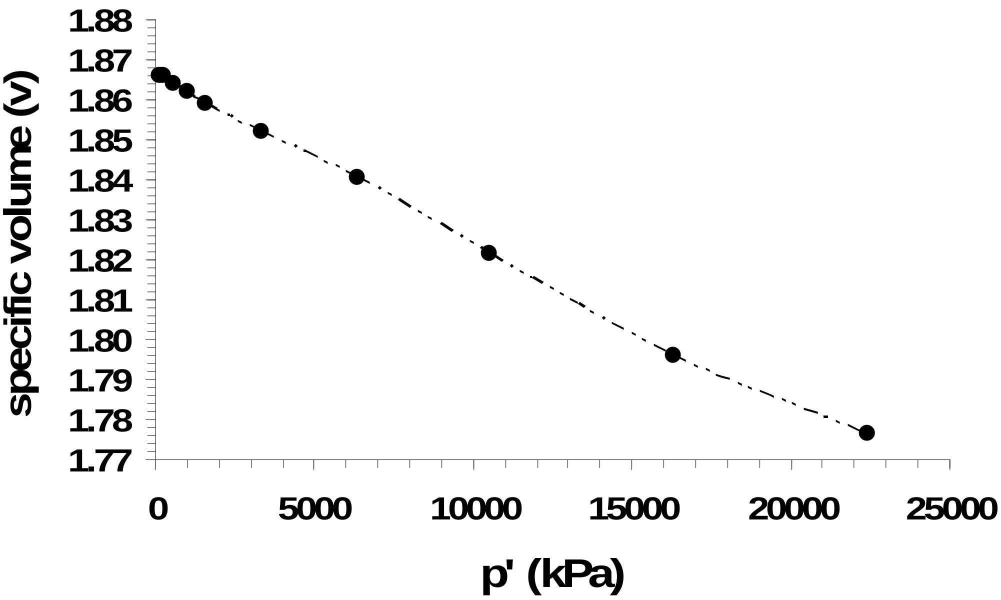


Figure 7. Variation of specific volume with p’ during isotropic compression

Because of the difficulty in identifying the arrival time for Probes 7 and 8, a procedure was adopted for measurements in the time domain, which was applied to all the measurements for consistency. This method is illustrated for Probe 7 in Figure 9. It consisted of first identifying the peak in the cross-correlation function, thereby identifying where, within the output signal, there is a component with the same frequency as the input, as this would be the most likely point of arrival of the shear wave (Figure 9b). The input frequency of 17kHz had been chosen because a peak in the gain of the transfer function at around this value suggested that this should be the resonant frequency for the shear wave. Having identified the approximate arrival time with the cross-correlation, the time domain traces for a variety of frequencies were re-examined in detail to identify manually the most likely first arrival of the shear wave (Figure 9b), discarding features within the received wave that were not consistent for all the frequencies used. The resulting first arrival points in Figure 8 show a consistent decrease of arrival time with increasing p', in contrast to the group velocities.

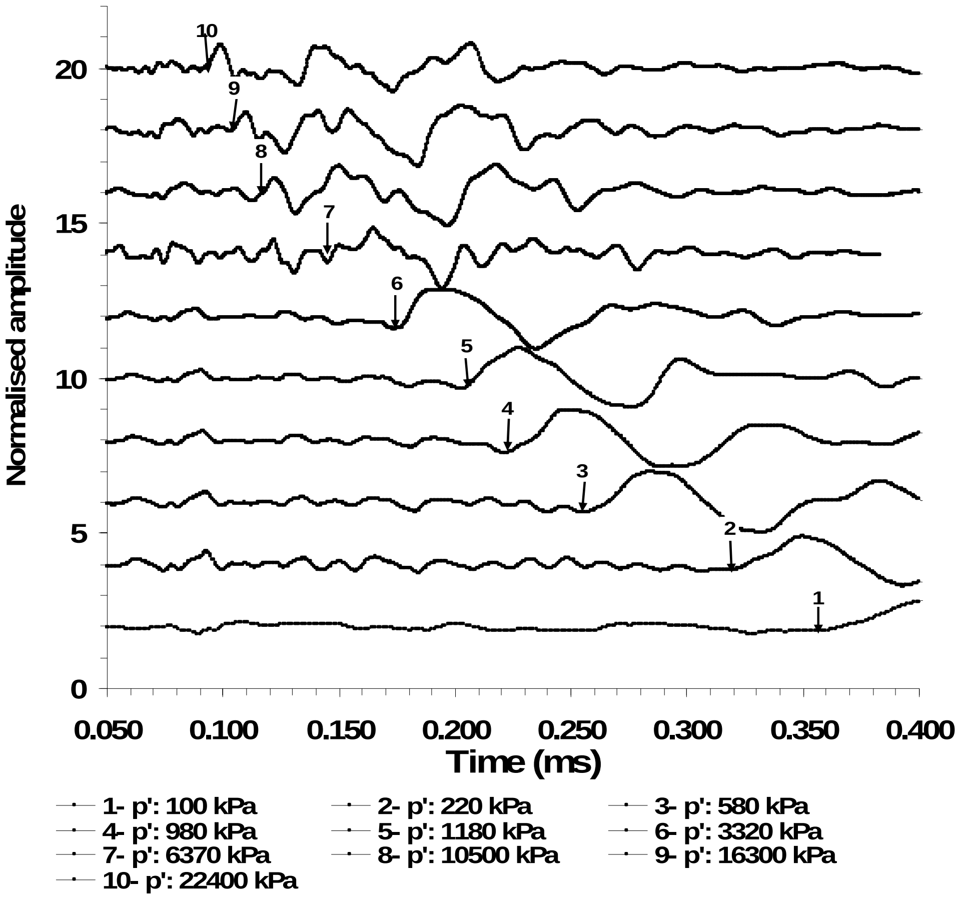
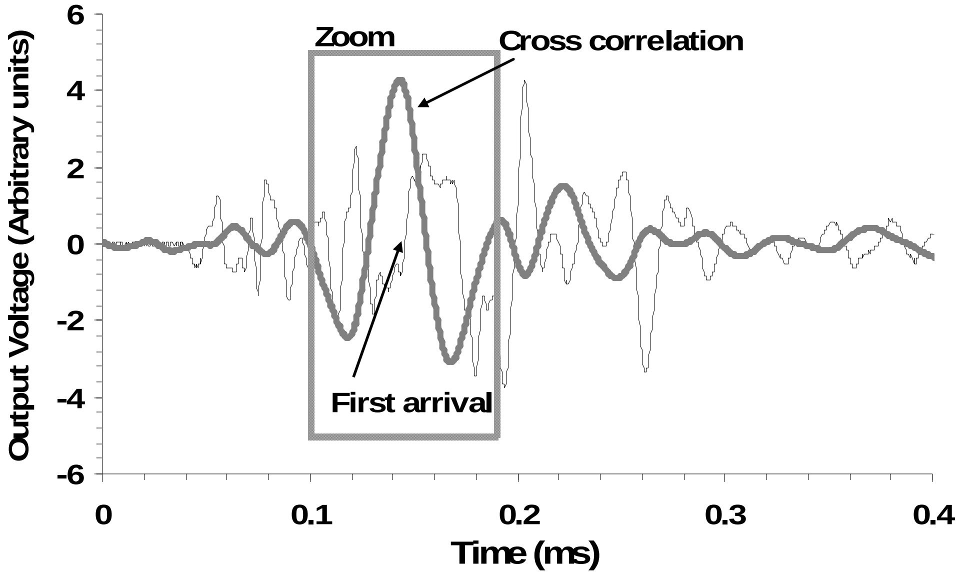
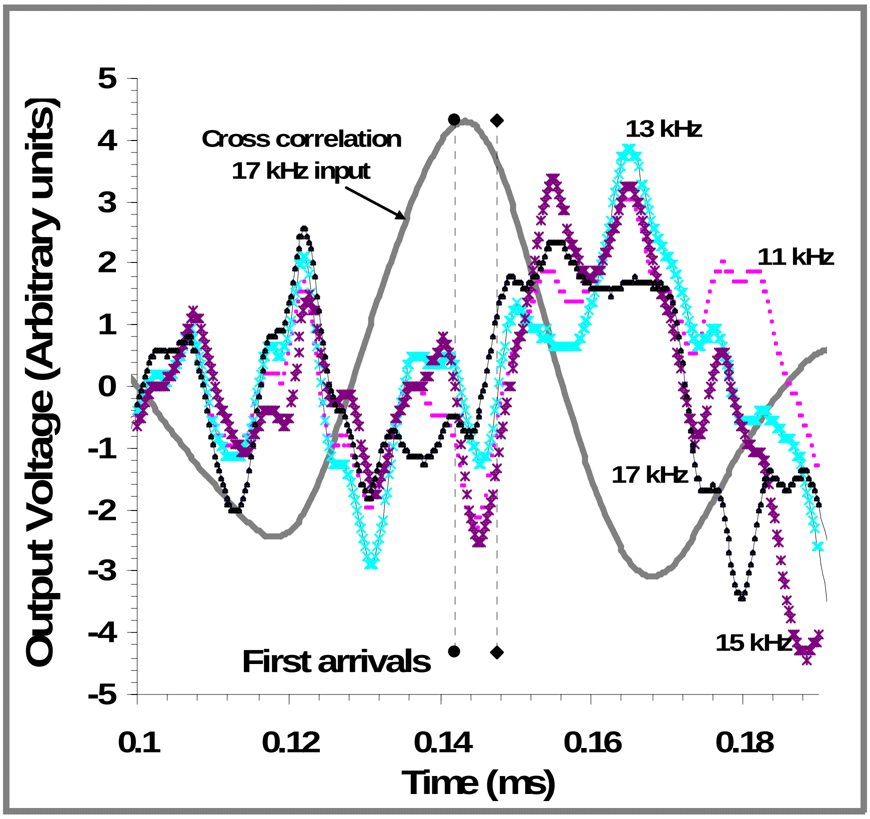


Figure 8. Selected first arrivals in the time domain



a) Output signal and cross correlation for 17kHz input



b) Detail of figure a) including output signals for 11, 13, 15 and 17 kHz output

Figure 9. Selection of first arrival time in the time domain for probe at p’=6370 kPa

Shear modulus

Initial shear moduli, G_{vh}, have been calculated from both the time and frequency domain analyses using:

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

where ρ is the mass bulk density of the soil and V_s is the shear wave velocity. The resulting values are plotted in Figure 10. At values of p' up to 6MPa the G_{vh} calculated from the group velocities are consistently around 16% lower than those from the shear wave velocity derived in the time domain. The time domain readings are in better agreement with the relationship reported by Tatsuoka (2005) for Toyoura sand and obtained from a number of dynamic and static methods (e.g. resonant column, monotonic load probes, cyclic load probes). At about 6MPa there appears to be a threshold beyond which the frequency domain measurements remain constant, while the time domain measurements continue to follow the same trend, although the data Tatsuoka used to define his relationship were usually below a p' of 1000kPa. This continued increase of stiffness agrees with measurements made of the Young's modulus with static probes, which were also found to continue increasing with p' (Alvarado, 2007). A constant stiffness would be a very unlikely result as the volume of the sample continues to decrease until the end of the test (Figure 7).

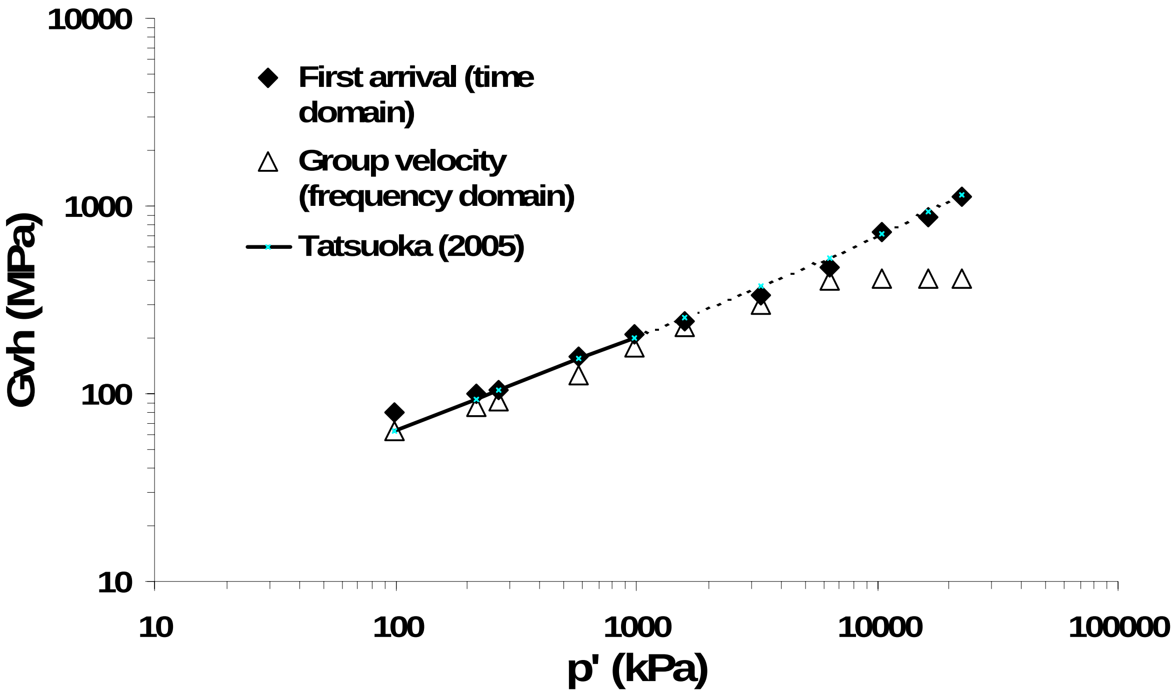


Figure 10. Initial shear moduli from time and frequency domain analyses

CONCLUSIONS

Analysis of the received waves from bender element tests conducted on a sand sample up to high pressures has revealed that there is an effect of confining pressure on the performance of the bender element system. This effect is clearly observed when looking at the group velocity of the propagated wave-packet, which indicates a threshold pressure beyond which group velocity becomes independent of the stress level. For the Toyoura sand, both the time and frequency domain methods give consistent stiffnesses below the threshold pressure, although those calculated in the frequency domain were about 16% lower than those obtained in the time domain. Beyond the threshold stress, which was about 6MPa for the Toyoura sand, it was found that the frequency domain method gives the very unlikely result of a constant stiffness with continued increase of confining stress. This suggests that in contrast with the assumption in current practice, group velocity and shear wave velocity are not necessarily equivalent at all stress levels.

AKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council and BP.

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