Laboratory determined shear modulus values for Beaufort Sea clay

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ABSTRACT
Two laboratory methods are used in this study to determine the shear modulus (G_{max}) of Canadian Beaufort Sea clay. The methods were consolidated undrained (CU) triaxial testing and bender element testing. Based on limited testing, the CU determined G_{max} is 85% greater than the G_{max} values measured with the bender elements. Neither the triaxial nor the bender method was proven accurate or inaccurate, as both sets of calculated shear values seem independently reliable and correlate well with the effective consolidation pressures. Usage of both test methods may give a more reliable range for the actual G_{max} rather than either test independently.

RÉSUMÉ
Deux méthodes laboratoire était utilisé pendent cet étude pour déterminer la module de cisaillement du glaise de la Mer Beaufort Canadien. Les méthodes utilisées sont la méthode consolidée pas égoutté (CU) triaxial et la méthode des bender elements. Basé sur les essais limités, le CU a déterminé que la G_{max} est 85% plus petite que les valeurs qu'était données avec la méthode des bender elements. Aucun des deux methods était révélé d'être ni précis ni imprécis en tonte que les deux ensembles du modules cisaillement ont l'air d'être indépendantes fiable et se corrélation bien avec les pressions consolidation effectifs. L'usage des deux méthodes pourrait donnée in série plus fiable des valeurs réel de G_{max} qu'un ou l'autre test indépendantes.

1 INTRODUCTION

The shear modulus (G_{max}) or soil stiffness of a soil is required to predict soil strains due to shear stresses, such as those caused by ice scouring. Recent physical model test research (Been et al 2008) suggests that soil stiffness plays an important role in the degree of subgouge deformation beneath the base of an ice scour. This has direct application to the definition of an appropriate burial depth for resource pipelines in the Canadian Beaufort Sea. The G_{max} obtained from laboratory testing of Beaufort Sea clay will aid in the refinement of ice scour modeling, replacing approximated values with laboratory test results. The sediment samples used in this study were collected as part of a regional Geological Survey of Canada seedbed sampling program in the Canadian Beaufort Sea (Figure 1).

The shear modulus of a soil is traditionally determined indirectly in the laboratory using CU and CD triaxial testing (Menzies et. al. 2001). A more recent development in the technology of geotechnical laboratory testing is the use of piezoelectric (bender) elements to measure shear velocity which is used to calculate G_{max} The usage of piezoelectric elements has great potential for measuring soil parameters due to their simple operation and short test duration. The purpose of this study is to compare G_{max} determined from triaxial testing and bender elements for Beaufort Sea clay samples.

2 BACKGROUND INFORMATION

Piezoelectric materials have asymmetrical crystal structures or electrically polar crystals such that when an electric pulse is sent through the material, the material will deform (Lee & Santamarina 2005). Conversely, if a mechanical force is applied to deform the material, the material releases electrical energy called piezoelectricity. Bender elements are based on the usage of the embedded piezoelectric plates to create and receive the compression (P-wave) and shear wave (S-wave) pulses, using the receiver element to provide data on the wave propagation through the sample. Through simple data analysis, the G_{max}, Young's modulus (E) and Poisson's Ratio (ν) of the sample medium can be established.

GDS Instruments Ltd. and GeoDelft (GDS Instruments Ltd. 2004) have developed a bender element system that incorporates a personal computer interface, instead of the traditional oscilloscope, to allow for increased options and enhanced data analysis. The GDS bender element system is compatible with existing GDS computerized triaxial systems (Menzies, 1988). The GDS bender system in use for this study is the combined S-wave and P-wave vertical transmission system.

3 LABORATORY EQUIPMENT

The laboratory testing was conduced at the Geological Survey of Canada (Atlantic) geotechnical laboratory. The two triaxial testing systems used for this study were controlled with GDS software. Each system consists of a Bishop and Wesley stress path triaxial cell connected to a computer through three digital pressure/volume controllers (Figure 2). The pressure/volume controllers control cell pressure, back pressure and lower chamber pressure (axial pressure).

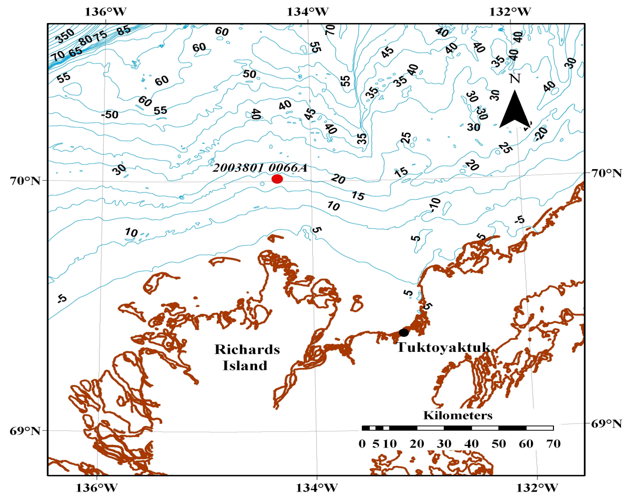

Figure 1. Sample site location

A solid state pressure transducer was used to measure the pore pressure at the bottom of the sample. The applied axial load on the sample was measured by a 5KN submersible load cell, eliminating the friction effects on the load measurements. Axial displacement was measured with a linear displacement transducer installed on the frame of the triaxial cell. The applied pressures are reported continuously and recorded at user specified intervals.

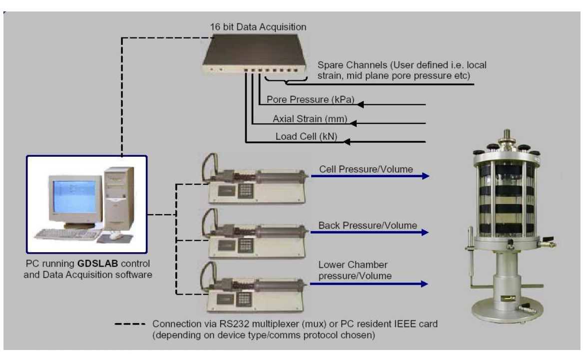

Figure 2. Computerized monitoring and control triaxial system (GDS Instruments Ltd., 2004)

The bender elements are installed in the top cap and base pedestal of the triaxial cell (Figure 3). The top cap contains a divot for the addition of a loose ball bearing which enables proper mating of the top cap with the submersible load cell during axial loading. GDS software allows the user to choose the source wave properties including amplitude, voltage, wave shape and frequency. The data are collected using a 16 bit acquisition card with a sampling frequency of 200kHz/channel. The control box provides power to the transducers, conditions the input and output signals, amplifies the source signal and switches between P-wave and S-wave circuits. The data collected from the test indicates the waveform of the source signal and the resulting waveform appearing at the receiver (Figure 4).

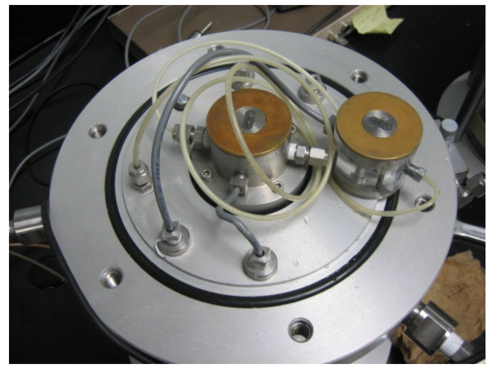

Figure 3. Bender elements installed in the top cap and base pedestal of the triaxial cell

The time of travel can be found directly by identifying or 'picking' the point of first arrival using the recorded data to plot the amplitude of the waveform (voltage) versus the elapsed time. Variations on the method of identifying the first point of arrival have been addressed in detail by a number of authors including Viggiani and Atkinson (1995), Blewett et al. (2000) and Lee and Santamarina (2005). In general, a simplification of these results can be made to specify the point of first arrival of a P-wave as the initial point of inflection and the point of first arrival of a S-wave as the point of first inversion (Brignoli et al. 2005).

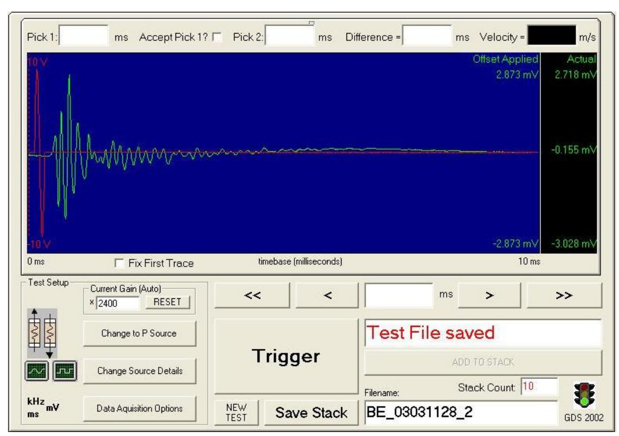

Figure 4. Typical source and receiver data for a bender element test

4 TEST METHODS

The Beaufort Sea clay samples used in this study were taken from a 0.5m square box core. The box corer used consisted of a box core and frame equipped with an impact released spade. The clay samples were retrieved from the same box core using a 10.0cm diameter ABS plastic core liner. The liner was inserted into the box core using a vacuum backpressure technique to prevent sample compression.

4.1 Soil Classification

The Beaufort Sea soil samples used in the triaxial and bender element testing were classified using the Unified Soil Classification System. Atterberg limit tests for Liquid Limit and Plastic limit were completed as defined by the American Society for Testing and Materials, ASTM - D4318. A grain size analysis was completed as a hydrometer analysis as specified by ASTM - D422.

4.2 Triaxial Tests

Independent triaxial tests were conducted on two different samples from the same box core. The CD and CU tests were performed concurrently using different Bishop and Wesley triaxial cells and controller systems. The multistage CU test was conducted with a 50mm diameter sample in a large Bishop and Wesley triaxial cell using standard pressure/volume controllers. The large cell is used to accommodate the bender element electrical cable flow-throughs. The CD test used a smaller Bishop and Wesley triaxial cell, a 38mm diameter sample and advanced pressure/volume controllers. The advanced controllers enabled better resolution and test control. The two triaxial tests were monitored and controlled by a single PC connected to both systems.

4.2.1 Consolidated Drained (CD) Triaxial Test

The consolidated drained test was performed according to ASTM D3080-04 using the wet preparation method, to estimate Young's modulus (E), Poisson's ratio (ν) and shear modulus (G_{max}). A thin-walled sampling tube (100mm long, 38mm ID) with a sharp cutting edge was pushed into the sediment core and then extruded with the sediment from the core liner. The sample was trimmed with a wire saw to a height of 78mm. Initial measurements of dimensions, weights and water contents were taken after the sample was trimmed. A 240kPa back pressure and 250kPa cell pressure were applied to the sample to ensure 100% saturation. A B check was conducted to verify > 0.95% saturation. The sample was then consolidated to 25kPa. After the consolidation, the sample was sheared to failure using a strain rate of 0.0001 mm/min.

The shear modulus of the soil was determined from the calculated Poisson's ratio and Young's modulus using (Bardet 1996):

$$\nu = \frac{\lfloor 1 - \Delta\varepsilon_{xyz(initial)} / \Delta\varepsilon_{z(initial)} \rfloor}{2}$$

[1]

$$E = \frac{\Delta q}{\Delta\varepsilon_{z(initial)}}$$

[2]

where ε_{xyz} = volumetric change, ε_z = axial strain (within linear range) and q = deviator stress.

4.2.2 Consolidated Undrained (CU) Triaxial Test

The purpose of the CU multistage test was to establish Young's modulus and calculated shear modulus at various confining pressures and void ratios. The results of this test also provided the stress paths and the failure envelope of the soil.

The CU multistage test procedure generally follows ASTM standard D4767-04. A thin-walled sampling tube (120mm long, 50mm ID) with a sharp cutting edge was pushed into the core and then extruded with the sediment from the core liner. The sample was trimmed with a wire saw to a height of 110mm. Initial measurements of dimensions, weights and water contents were taken after the sample was trimmed. A 240kPa back pressure and 250kPa cell pressure were applied to the sample to ensure 100% saturation. A B check was conducted to verify > 0.95% saturation. After the sample was consolidated to 25kPa an axial load was applied to the sample by increasing the lower chamber pressure. The applied strain rate was 0.04mm/min. This axial loading continued until the sample started to fail, at which point the axial load pressure was removed. The sample was then reloaded at 0.04mm/min. The second loading provides a well defined stress-strain curve, removing the effect of the initial docking of the sample. This procedure was repeated for consolidation pressures of 50kPa and 100kPa.

The shear modulus, G_{max}, was calculated using (Das, 2002):

$$G_{max} = \frac{E}{2(1+\nu)}$$

[3]

where E = Young's modulus and ν = Poission's ratio.

4.2.3 Bender Elements

The bender element tests were performed during the CU triaxial test. S-wave and P-wave tests were performed on the sample after each consolidation and shear stage of the CU triaxial test. Consolidation pressures were 25kPa, 50kPa and 100kPa. Analysis of the S-wave results provided the shear wave velocity at each test stage. The shear wave velocity, V_s, of the sample was determined as:

$$V_s = \frac{d}{t}$$ [4]

where d = distance from tip to tip of the piezoelectric elements and t = travel time of first arrival. The shear modulus was calculated using:

$$G_{\max} = \rho V_s^{\,2}$$ [5]

where ρ = bulk density of the soil sample. Young's modulus, E, and Poisson's ratio,ν were found using:

$$E = \rho V_s^{\,2}\left(\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2}\right)$$ [6]

$$\nu = \frac{1}{2}\left(\frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2}\right)$$ [7]

where V_p is the compressional wave velocity.

5 TEST RESULTS

5.1 Soil Classification

The sediment was classified as a fat clay (CH) with a liquid limit of 51%, and a plastic limit of 26.0%. The sample consisted of 4% sand, 23% silt and 73% clay.

5.2 Consolidated Drained Triaxial Test

The results of the CD triaxial test are presented in Figures 5 and 6. Figure 5 displays the results as an axial strain versus axial stress plot. Figure 6 presents the s' versus t stress-path relationship. The determined values for

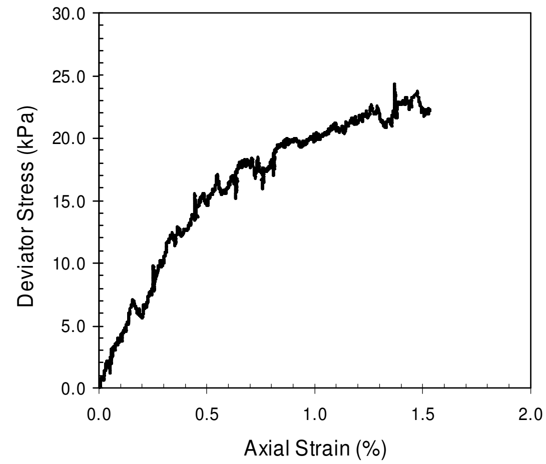

Figure 5. Stress-strain relationship for the CD test at 25kPa consolidation pressure

Poisson's Ratio, Young's modulus and shear modulus were 0.42, 4.91MPa and 1.73MPA respectfully. The shear stage of the CD test was conducted over 8 days. The pore pressure measurements at the base of the sample varied by ± 2kPa during the axial loading.

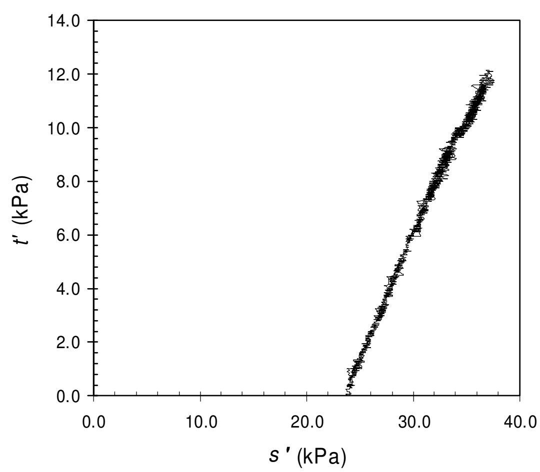

Figure 6. Stress path of effective stress for the CD test at 25kPa consolidation pressure

5.3 Consolidated Undrained Triaxial Test

Young's modulus (E) was determined as the average of the initial loading and reloading portions of the stress-strain curves (Figure 7). The stiffness of the soil, Young's modulus, and shear modulus all increased with increasing consolidation pressure. The CU test results are summarized in Table 1 and figure 8.

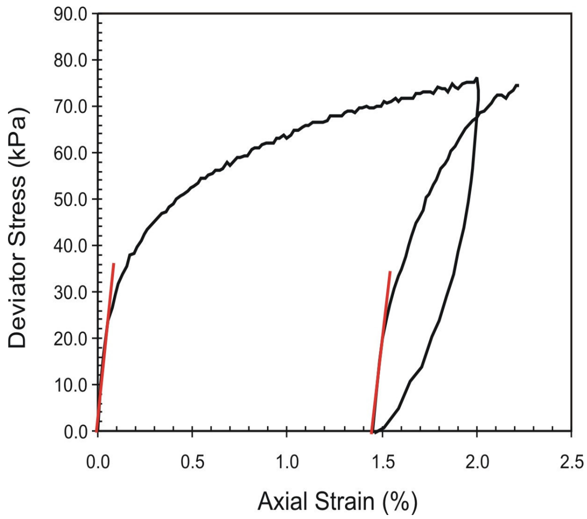

Figure 7. Stress-strain relationship for the loading and reloading portion of the CU test at 100kPa consolidation pressure

5.4 Bender Elements

Shear and compression wave data were collected after

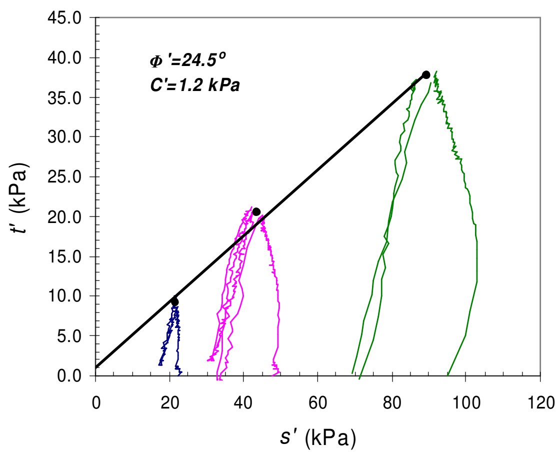

Figure 8. Stress path of effective stress and strength envelope for the CU test

Table 1. Summary of CU test results for the Beaufort Sea clay sample. Shear stress and effective mean stress values are at failure.

Confining Pressure (kPa)	Shear Stress (kPa)	Effective Mean Stress (kPa)	Void Ratio	Young's modulus (MPa)	Shear modulus (MPa)
0			1.39		
25	9.3	22.9	1.25	8.1	2.8
50	20.6	45.8	1.16	11.2	3.9
100	40.9	94.8	1.07	37.3	13.1

the saturation, consolidation stages and throughout the shear stages. The S-wave data provided clear waveforms for graphical analysis (Figure 9).

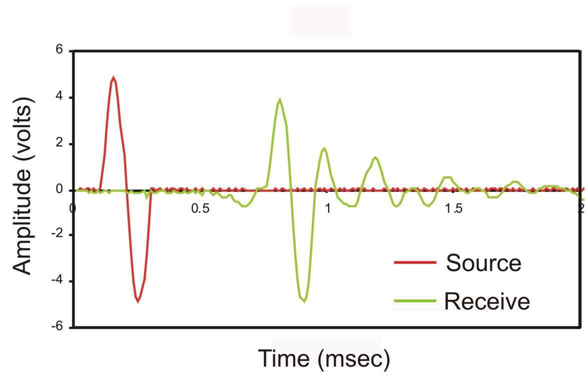

Figure 9. S-wave propagation through the Beaufort Sea clay sample at 100kPa consolidation

The P-wave data did not produce smooth waveforms as the data contained an exceptional amount of noise (Figures 10) which made it impossible to consisting determine the point of first arrival. Therefore an assumed P-wave velocity of 1500 m/s was used in the calculation of E and ν (Eq. 6 and 7). It should be noted that the P-wave velocity has very little effect on the calculated E and ν values.

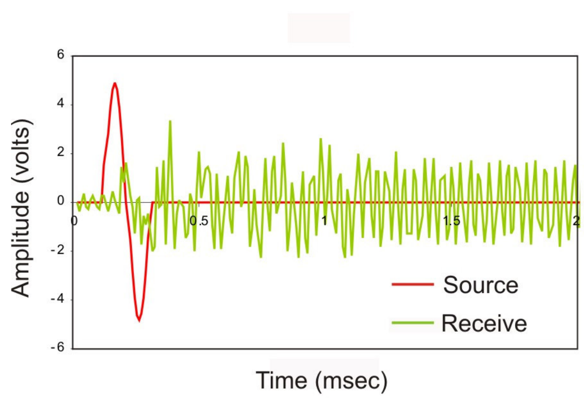

Figure 10. P-wave propagation through Beaufort clay sample at 100kPa consolidation

The bender element results are summarized in Table 2. The shear wave velocities are very similar to those measured by Brignoli et al (1996) on undisturbed offshore clay samples. Brignoli et al (1996) measured shear water velocities ranging from 100m/s to 180m/s for confining pressures of 25kPa to 100kPa.

Table 2. Summary of bender test results for the Beaufort Sea clay sample

Confining Pressure (kPa)	Bulk Density (Mg/m^3)	Shear-Wave Velocity (m/s)	Young's Modulus (Mpa)	Shear Modulus (MPa)	Poisson's Ratio
0	1.39	48.2	12.3	4.1	0.499
25	1.25	90.7	44.6	14.9	0.498
50	1.16	121.8	82.2	27.4	0.497
100	1.06	178.4	179.6	60.1	0.493

6.0 ANALYSIS

The results from the bender tests are inconsistent with the triaxial CD/CU test results. The values for E and G_{max} for 25kPa consolidation obtained from the CD and CU tests are similar. Young's modulus values determined from the CU test at 50kPa and 100kPa are lower than the suggested ranges for moderate and hard clay (Bowles 1988). E values calculated from both the CU and bender tests increase with the consolidation pressure as expected. The E values determined from the bender element results vary within a maximum of 85% from the E values determined from the linear elastic stress-strain relationship of the CU test. The bender element tests produced G_{max} values that have as much as 85% difference to those values calculated from the CU test results using the Young's modulus–Poisson's ratio relationship presented in equation [3].

Although the shear modulus values are inconsistent between the two types of tests, there is excellent correlation between the E (Figure 11) and the G_{max} (Figure 12) and confining pressure obtained using both test methods. The linear variation of E and G_{max} with the confining pressure, calculated with both the CU test results and the Bender test results, implies that the data obtained from both test methods may be viable.

In comparison to the expected range (Bowles 1988) the results from the CU test consistently produce lower E and G_{max} values. The E value calculated from the CU test results at 25kPa is only 8MPa, a value that would be expected for soft clay. The CU test continues to underestimate values of E and G_{max} at higher confining pressures.

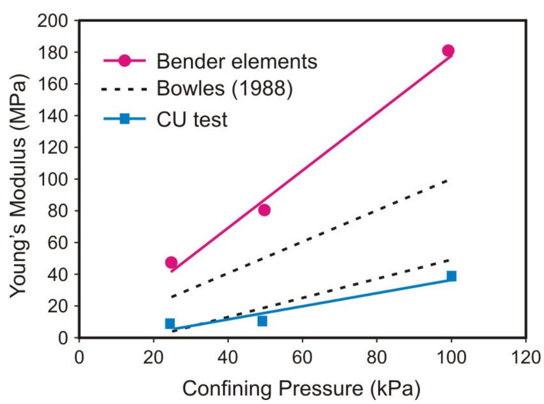

Figure 11. Variation of Young's modulus with consolidation pressure calculated from the CU and bender tests

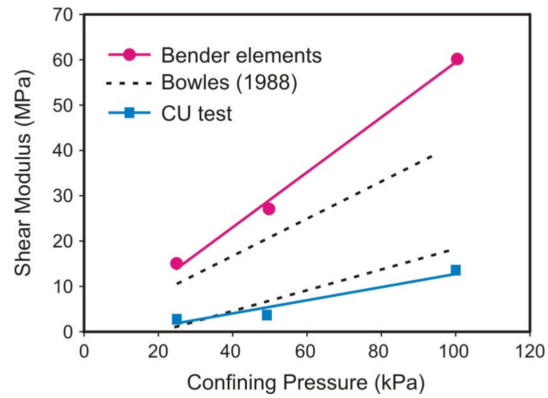

Figure 12. Variation of G_{max} of Beaufort Sea clay with consolidation pressure calculated from the CU and bender tests

The results from the bender tests indicate higher than expected E and G_{max} values at all consolidation pressures (Figures 11 and 12). This may indicate that the application of bender test results overestimates E and G_{max}. As the two methods of testing seem to provide the upper and lower limits of expected E and G_{max} values, using the results from both methods could aid in providing a better estimate of E or G_{max} values as opposed to relying on only one method.

The calculated value of Poisson's ratio from the CD test is lower then that calculated from the bender element tests. The accuracy is questionable due to the inherent difficulties of verifying the viability of a single data point. The theory governing a CD test is difficult to reproduce in a laboratory situation due to the extremely small strain rate that must be applied to the sample to prevent any increase in pore pressure (Menzies et al., 2002). The Poisson's ratio however has relatively little impact (Table 3) in shear modulus values calculated from the CU test results and could not account for the differences in the G_{max} values obtained using the two methods.

Table 3. Shear Modulus (MPa) values for Poisson's ratio of 0.25, 0.42 and 0.50.

Confining Pressure (kPa)	Young's Modulus (MPa)	Poisson's ratio 0.25	Poisson's ratio 0.42	Poisson's ratio 0.50
25	8.14	3.25	2.87	2.71
50	11.29	4.52	3.99	3.76
100	37.36	14.95	13.19	12.45

The G_{max} calculated from the CU test results is also dependent on the value of Young's modulus at a given consolidation pressure. Young's modulus is another calculated parameter that may include error due to instrumentation or interpretation of the recorded data. In the system setup, the axial strain was calculated by a linear displacement transducer on the exterior of the triaxial cell. Although the linear displacement transducer provides values for the overall strain on the sample, the resolution of the instrument may not be fine enough to report what the actual, instantaneous strain is for locations within the soil sample especially at small strains. If the strain felt within the centre of the sample is less than the overall strain, the usage of the linear displacement transducer data will result in a calculated E that is lower than the actual value (Menzies et al., 2002). An underestimation of Young's modulus would result in low calculated G_{max} values.

The G_{max} calculated from the bender element test is dependent on the calculated shear wave velocity. The interpretation of the point of first arrival is the most critical factor in the calculation of shear wave velocity. The point of first arrival for this study was visually selected as the point of first inversion on the graphical representation of the voltage attenuation of the receiver element. However if the selection of the point of first inversion was incorrect, the calculated shear wave velocity would also be incorrect.

The designation of the point of first inversion as the point of first arrival of the shear wave is a simplification of shear wave propagation through soil. There are many papers published on the subject of determining the actual point of first arrival of a shear wave (Blewitt et al., 2000), (Lee & Santamarina, 2005), (Leong, et al., 2005), (Viggiani & Atkinson, 1995). A number of these journals advise against "picking" a point (such as the point of first inversion) due to the complexities and individuality of wave behavior through a soil sample (Leong, et al., 2005). If the point of first inversion is the correct point of arrival of the shear wave, the interpretation of the inversion point may also cause error in the reported shear wave velocity. A number of wave phenomena, such as the nearfield effect (P-waves propagated through the sample along with the S-waves) may interfere with the actual arrival of the S-wave. The noise created by the P-wave propagation could be wrongly interpreted as shear wave reception and the point of first inversion chosen too early (Lee & Santamarina, 2005).

The choice of the point of first arrival is critical to the calculated value of G_{max}, since G_{max} varies directly with the square of the shear wave velocity. Applying possible alternate choices for the point of first inversion to the calculation of shear modulus indicates the effect (Figure 13) of the interpretation of the received S-wave signal. The variation of the chosen point of first arrival within a single wavelength varies the calculated G_{max} from 40MPA (t = 0.82ms) to 88MPa (t = 0.59ms). In comparison to the triaxial tests, the value of 40MPa for G_{max} resulting from the time of arrival of 0.82ms is 67% higher than the value of 13.19MPa calculated from the CU test.

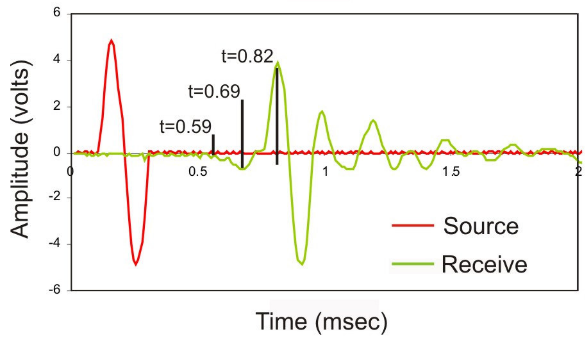

Figure 13. Alternative values for arrival times of S-wave at 100kPa consolidation

The interpretations and calculations suggest that the use of triaxial results may indicate conservative, low values for the shear modulus of a soil. In contrast, the use of bender element results may over-estimate values for the shear modulus. The G_{max} calculated from triaxial tests are sensitive to the calculated E values, which are respectively sensitive to local strain measurements. Error in the estimated shear modulus obtained through CU/CD test may be due to the inability to accurately measure the local strain within the sample, affecting both the calculation of Young's and the shear moduli. The difficulty in accurately identifying the point of arrival of a shear wave transmitted through a sample, causes ambiguity as to whether the calculated shear wave velocity and shear modulus is truly representative of the material. Based on the calculated estimates from both methods, the triaxial CD/CU and bender element test results appear to provide possible lower and upper bounds to the actual value of the shear modulus of a material.

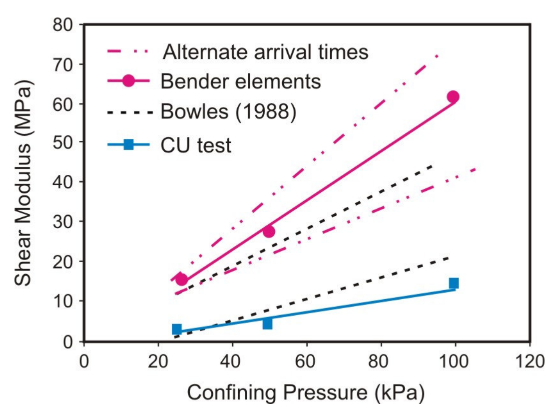

Figure 14. Effect of using various points of first arrival time of the shear wave on calculated shear modulus values

7.0 CONCLUSIONS

The calculated values for the shear modulus of similar Beaufort Sea clay specimens obtained from the triaxial method and from the bender element method are dissimilar. There is an 85% difference between the value of G_{max} calculated from the results of the bender method and the value of G_{max} calculated from the results of the triaxial tests. Although the results are not numerically similar, there is a definite similarity between the relationship of the calculated values of G_{max} from each method and the consolidation pressure at which G_{max} is calculated. Both sets of data produce similar trend lines in the variation of G_{max} with confining pressure.

The triaxial method consistently produces lower values for the shear modulus. It is inferred that this method may tend to underestimate the actual value of the shear modulus at small strains. The accurate determination of G_{max} may be impeded in triaxial testing due to the difficulty in determining Poisson's ratio in the laboratory and the difficulty in accurately measuring the actual strains in the soil sample using measurement devices external to the triaxial cell.

The bender element method consistently produces higher values for the shear modulus, possibly overestimating the actual shear modulus value. The most likely cause for error in the G_{max} calculation is the determination of the shear wave velocity through the sample. If the shear wave recorded at the receiver element is not properly interpreted, the chosen point of first arrival of the shear wave may not correspond to the actual point of arrival of the shear wave at the receiver. The misinterpretation of the receiver waveform is a critical source of error in the calculation of the shear modulus, as the error is propagated due to the variance of G_{max} with the square of velocity.

The consistent relationship between the calculated shear modulus from each test method and the effective confining pressure indicates that each set of data could be considered independently reliable. This may suggest that the concurrent usage of both triaxial and bender element methods for a soil sample would provide a more complete spectrum within which the actual shear modulus value can be found, rather than relying on a single method to obtain an accurate value for G_{max}.

8 RECOMMENDATIONS

The large difference between the results obtained from the triaxial tests and the bender element tests suggest that additional testing and/or alterations to the current testing procedures and data analysis may be required to improve the results. The subject of largest concern in the triaxial testing are the measurements of axial and volumetric strain in the CD test, and the measurement of axial strain in the CU test. The subject of greatest concern in the bender element test is the determination of the point of first arrival at the receiver element. To clarify the point of first arrival of the shear wave, a comparison of results obtained from cross correlation models (Viggiani et al., 1995), frequency domain analysis (Blewett et al., 2000) or waveform matching (Lee & Santamarina, 2005) should be conducted.

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