Stiffness Degradation and Sample Damage of Clay Shales in a River Valley Landslide

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ABSTRACT
The research demonstrates the use of laboratory and in-situ testing to determine a level of stiffness degradation with sampling methods in Cretaceous clay shale. Several sampling methods are used to gather relatively undisturbed samples of the shale at depth. The stiffness of the recovered samples was evaluated using both small strain and engineering strain increments. Several in-situ testing methods including surficial and downhole geophysics as well as barometric compensation are used to gather in-situ, small strain modulus at depth. The data presented in this paper will show the level of damage in the shale bedrock with sampling as well as the stiffness degradation with strain. These values were then compared with empirical methods to determine the most accurate method of predicting stiffness degradation for modelling of strain dependent problems.

RÉSUMÉ
La recherche démontre l'utilisation d'essais en laboratoire et in situ pour déterminer un niveau de dégradation de la rigidité avec des méthodes d'échantillonnage dans le schiste argileux du Crétacé. Plusieurs méthodes d'échantillonnage sont utilisées pour recueillir des échantillons relativement intacts du schiste en profondeur. La rigidité des échantillons récupérés a été évaluée en utilisant à la fois de petites déformations et des incréments de déformation technique. Plusieurs méthodes de test in situ, y compris la géophysique de surface et de fond de trou ainsi que la compensation barométrique, sont utilisées pour recueillir in situ un petit module de déformation en profondeur. Les données présentées dans cet article montreront le niveau d'endommagement du socle schisteux avec échantillonnage ainsi que la dégradation de la rigidité avec la déformation. Ces valeurs ont ensuite été comparées à des méthodes empiriques pour déterminer la méthode la plus précise de prédiction de la dégradation de la rigidité pour la modélisation des problèmes dépendants de la déformation.

1 INTRODUCTION

Approximately 12 km south-east of Borden, Saskatchewan in the North Saskatchewan River valley there are three bridges that make up the Highway 16 river crossing. Of these three bridges, one is decommissioned to traffic, while the other two remain active as a main portal between Alberta and Saskatchewan. A very slow landslide below the current Highway 16 bridges on the southeast valley wall is taking place at approximately 414 meters above sea level (masl) which is approximately 35-40 meters below the current ground surface, dependent upon location. The landslide's rate of movement is believed to be affected by pore-pressure dynamics and in the recent past (2009-2011) has spiked to a rate of movement of approximately 27 mm/year from an average 2-3 mm/year in years with extreme rainfall and snowmelt events. The lateral extent of the landslide is not fully characterized and is believed to go beyond the highway's limits as shown in Figure 1.

Figure 1. Borden Bridge landslide site (Google Earth)

1.1 Stiffness at the Borden Bridge Site

The high smectite content found within the bedrock (Lea Park Shale) has created a weak zone that has resulted in the slip surface. The constant shearing on site has created residual strength for the shale and has resulted in a fully mobilized stiffness in the shale. It is important to have an understanding of how the target material will deform with strain for representative modeling of lateral deformation and displacement predication. As any geomaterial deforms, the stiffness degrades and approaches a residual value (Clayton, 2011; Vardanega & Bolton, 2013).

The stiffness of a material is defined by the secant shear stiffness, *G* and reduces progressively by the slippage of intergranular contact with ongoing shear strain. Using high-quality sampling, a level of damage to the samples, the material stiffness, and preferred drilling, storage, and testing methods for clay shales is further explored within this paper.

1.2 Objective

Using a combination of in-situ and laboratory testing, the non-linear shear modulus behaviour will be quantified for the Lea Park Formation Shale at the Borden Bridge site. The testing conducted will also show a level of damage to the differing samples and attempt to quantify if there is a sizable difference in loss of stiffness resulting from sample recovery, storage, and testing.

This project is limited to a bedrock stiffness analysis using a combination of historical site knowledge/testing combined with new field and laboratory analysis of the Lea Park Formation shale on the south-eastern side of the Borden Bridge site.

The stress-strain behaviour of soil is highly non-linear but a soil's stiffness is understood to decay with strain by orders of magnitude (Atkinson, 2000; Vardanega & Bolton, 2013) depending on the imposed strain increment. Typically, seismic shear waves are considered to be the smallest measurable shear stiffnesses and are typically represented by the 10^{-6} strain range. Seismic testing can be used to calculate the shear wave velocity of the secondary wave (S-wave) which can be converted to a shear modulus. Because the imposed strains are so small (10^{-6} – 10^{-4} % (Clayton & Heymann, 2001; ASTM, 2008)), seismic testing cannot result in either plastic or creep deformations. Therefore, the strains that are measured are purely elastic in nature. Lastly, it is also common to normalize a given shear modulus, (G_i) relative to the very small strain, seismic value (G_0).
The characterization of variable soil stiffness with respect to shear strain can be particularly applicable to lateral deformation problems which are not as well represented in linear-elastic perfectly plastic models.

The stiffness of rock is affected at differing levels of strain. At very small elastic strains the stiffness is at its maximum and as the material strains, the modulus decreases and approaches a plastic state. As shown below in Figure 2, the typical elastic shear modulus, *G* of a clay material is expected to strain between 0.01 % - 1 % for most engineering projects; this will be referred to as design strain (Mair, 1993). Conventional laboratory testing typically represents strains larger than 1 %. This means specialized testing is typically needed to further understand material deformation when subjected to strain less than typical design strain levels. Figure 2 has also been adapted to show the expected strain range of the testing completed both *in-situ* and in laboratory for this research.

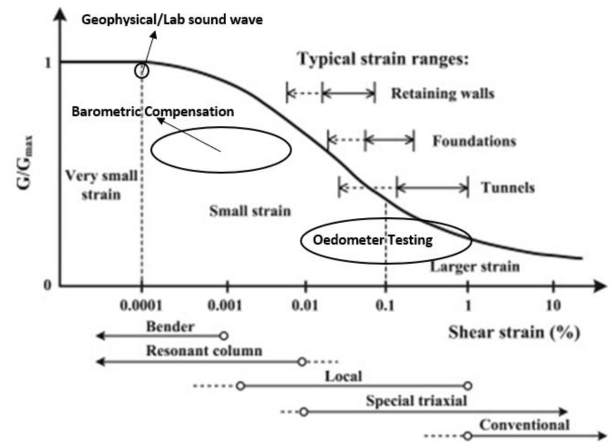

Figure 2. Normalised Stiffness Degradation Curve and Expected Strain Ranges for this Project (Adapted from (Mair, 1993, Likitlersuang et al., 2013))

Laboratory testing has typically been relied upon to represent strength and elastic modulus for geotechnical predictive models. However, laboratory testing is not fully representative of site conditions as it is well known that heavily overconsolidated soil samples (particularly clay shale) are influenced by the levels of damage from sampling and testing. From the time a shale is sampled to the time it is tested it will incur varying levels of damage dependent on how much care is taken to maintain its internal fabric, *in-situ* stresses, natural water content, and pore-water chemistry. Sample damage has been illustrated through stiffness determination at varied levels of strain (Clayton, 2011; Lim et al., 2018; Smith et al., 2018).

Similar methods were employed in this research whereby surface and downhole geophysics were compared to results of laboratory sonic pulse velocities measured in recovered shale samples. At larger strains, laterally confined tests including barometric compensation was compared to oedometer tests on recovered samples of shale. By determining the sample's modulus *in-situ* at small strain using multiple tests ($\gamma < 0.01\%$), the stiffness is believed to be able to be projected forward to predict stiffness at design levels of strain ($\gamma > 0.01\%$) (Smith et al., 2018). The full stiffness degradation curve for a material could result in a better prediction of lateral deformations on the particular site.

2.1 In-situ Testing and Very Small Strain Stiffness

In-situ testing for this research makes up the basis of the Lea Park Formation shale stiffness and will be used to normalize and project all stiffness data gathered throughout the following work. The in-situ testing will yield values of stiffness at very small strain increments.

2.2 Barometric Compensation

Barometric compensation was used to determine the loading efficiency (LE) to define the one-dimensional compressibility, m_v of the soil formations at the Borden Bridge site. The m_v of the soil is used to determine the stiffness and shear modulus *G* of the intact and shear zone for the Lea Park Formation shale using a Poisson's ratio calculated from evaluation of P and S waves.

2.3 Geophysics

A geophysical survey is an effective non-destructive method of determining the shear modulus of a soil or weak rock in-situ. A field program conducted at the Borden Bridge site allowed data to be gathered both on surface and down a drilled borehole. The surficial geophysical survey included multichannel analysis of surface waves (MASW), whereas the downhole testing included full waveform sonic (FWS), and vertical seismic profiling (VSP). The seismic testing conducted in the laboratory was the lab sound wave velocity analysis. All shear strains for the very small strain modulus determination methods are all assumed to plot at 10^{-6} strain level (Clayton & Heymann, 2001; ASTM, 2008).

2.4 Shale Damage

Shales are known to be troublesome materials to sample as they are prone to excessive damage in the sampling, storage, and testing processes (Ewy, 2015). Maintaining the *in-situ* water content and pore-water chemistry during these processes is very important (Ewy, 2015). If the pore-water chemistry changes within a shale, the capillary forces decrease and ultimately vanish, causing a loosening effect known as capillary swelling (Chenevert & Amanullah, 2001). This loosening effect will cause irreversible changes in the shale fabric and therefore change its behaviour (Chenevert & Amanullah, 2001). The shale will now no longer yield representative testing results compared to *in-situ* conditions (Ewy, 2015). Because most shales in Canada were deposited in saline environments, these bedrocks are hydrophilic and typically absorb water from drilling. Additional sample degradation can occur during exposure to atmospheric conditions, which results from poor sample preservation, storage, and testing methods.

2.5 Sampling

When sampling any material in geotechnical engineering practice, the quality of the sample is typically dictated by its purpose (Clayton & Siddique, 1999). Damage to a material can take place at all major stages of sampling, including drilling, sampling, de-stressing upon sampling and recovery, storage, extrusion, and testing (Hight et al.,1992; Clayton & Siddique, 1999).

An engineer should always attempt to limit the damage associated with a shale sample to keep it as close to a representation of *in-situ* stresses, strains, and properties as possible.

Shale sampling was completed using three methods. The purpose was to ascertain how significant sampling and storage of clay shales is on the measured properties at intermediate and larger strains. This study represents one data point, but the results are consistent with other deep well drilling industries. Traditional sampling such as double-tube coring and storing in a core box was used as a comparison for newer methods in this study to aid in quantifying sample damage and stiffness reduction.

2.6 Sampling at Borden

The samples recovered using a double-tube core barrel with a drilling mud are denoted as "mud core" samples. Additional samples were recovered using a Pitcher sampler are denoted "Pitcher" samples. The final sampling method was completed using a double-tube core barrel but with waste canola oil as the drilling fluid. These samples are denoted as "oil core" samples.

The mud core samples were taken from the core barrell and cellophane wrapped and stored in a moisture controlled room. Care was taken to limit damage during transportation and extraction for testing.

Tube samples were taken using a Pitcher sampler through the shear zone (Pitcher samples). The Pitcher samples were logged based on the visual appearance at the base of the sample and sealed with paraffin wax at both ends. After the wax cooled, the samples were submerged into a non-polar fluid (canola oil) within a 114.3 mm PVC tube, sealed, and the headspace was pressurized with nitrogen to ~ 345 kPa within an hour of sampling. Repressurization was carried out as an attempt to minimize the sample damage resulting from destressing following recovery.

Double-tube coring was then used with a non-polar drill fluid (canola oil) to limit pore-water fluid exchange within the shale during the drilling process (oil core samples). These samples were taken up from the core barrel where they were immediately logged and coated in canola oil at the ground surface. Once logged, the samples were wrapped in cheesecloth, completely waxed, loaded into PVC tubes, and pressurized in the same manner as the Pitcher samples. Both the Pitcher and oil core samples were stored vertically in a moisture-controlled room and under pressure until testing.

2.7 Shear Wave Velocity Testing

A perfectly sampled and preserved sample would exhibit a similar small strain shear modulus as those recorded *in-situ* using seismic tests. Deviation from the *in-situ* G_0 can be attributed be an indication of sample damage (Clayton, 2011).

A sonic pulse wave is initiated from one end of a sample and the time of travel through the sample is measured. By knowing the dimensions of the sample tested, a corresponding sonic velocity is calculated. Sonic wave pulse tests can be used to compare a reduction in stiffness in a recovered sample relative to *in-situ* conditions. It is important to understand that a shear wave is not produced when using a sonic wave pulse test. As a result, the corresponding shear modulus obtained should be used with caution. There are reported issues associated with anisotropy, travel distance, sample damage, and sample diameter. Sonic pulse wave testing was completed on all three samples.

2.8 Oedometric Modulus

Both oedometric testing and barometric compensation are comparable testing methods as they are both laterally confined and loaded vertically. For the oedometer as long as the lateral deformations of the oedometer ring are limited to below 0.04% strain as per ASTM standard the sample is considered to be confined and the test is valid (ASTM, 2012). The oedometric modulus, E_{oed}, which is calculated from the slope of a recompression or unload curve from an oedometer test converting incremental axial strain assuming radial displacements are negligible. This oedometric modulus can be converted with the use of the Poisson's ratio to calculate a deformation modulus, *E* and a shear modulus, *G*. The *G* value here represents the engineering level strain increment for the Lea Park Shale and will be used to aid in quantifying sample damage among the different sampling methods.

The apparent pre-consolidation pressure can be found through multiple methods while conducting oedometer tests. The pre-consolidation pressure can be used as method of determining damage to a sample in laboratory testing for conventional soils (Leroueil & Vaughan, 1990). A degradation of structure within a sample is believed to result in a reduced pre-consolidation pressure as opposed to a less disturbed sample (Leroueil & Vaughan, 1990).

3 RESULTS

3.1 Barometric Compensation

The barometric compensation was completed using both visual interpretation methods and barometric response functions (BRF).

The visual loading efficiency values were calculated over 10 day intervals with the exception of the one week interval tests calculated from the original data gathered on site. The original data was logged at 4 hour intervals as opposed to the 10 minute intervals used for this work. The loading efficiency values were then averaged over the duration of the sample range of several months and shown in Table 4.3 below. The chosen porosity for barometric compensation was 0.39 based on the average initial void ratio found in the lab to be 0.63.

Table 1. Ten-day Interval of Visual Barometric Compensation

Data Range and Sample Depth (masl)	Average Loading Efficiency γ	G (MPa)	Shear Strain
11/17 - 02/18 BH501[1] 414	0.56	193	8.8x10^{-6}
10/18 - 03/19 BH501 414	0.63	132	5.8x10^{-6}
10/18 - 03/19 BH502 412	0.86	36	2.4x10^{-5}
10/18 - 03/19 BH502 407	0.88	31	2.9x10^{-5}
10/18 - 02/19 BH503 410.5	0.89	27	2.9x10^{-5}
10/18 - 02/19 BH503 406.5	0.89	28	3.0x10^{-5}
10/18 - 03/19 BH504 407.8	0.89	27	3.2x10^{-5}
10/18 - 03/19 BH504 400.6	0.86	36	2.1x10^{-5}
10/18 - 03/19 BH505 408.5	0.90	25	3.1x10^{-5}

[1]indicates one-week intervals were done prior to resetting the logging interval to 10-minutes

The highest modulus values were found in the seven-day interval determination of LE. However, due to the logging interval, there is a lower confidence in the data of LE, and these results are considered less representative of the Lea Park Formation shale stiffness.

Table 2 shows the calculated values of loading efficiency using a BRF at various depths and across the date ranges specified for each vibrating wire piezometer.

Table 2. Elastic Properties of Lea Park Shale based on Barometric Compensation (BRF)

Data Range and Sample Depth (masl)	Loading Efficiency γ	G (MPa)	Shear Strain
10/18-03/19 BH501 414	0.51	202	6.5 x10^{-6}
10/18- 03/19 BH502 412	0.71	85	1.5 x10^{-5}
10/18-03/19 BH502 407	0.73	77	1.7 x10^{-5}
10/18-02/19 BH503 410.5	0.83	42	2.8 x10^{-5}
10/18-02/19 BH503 406.5	0.84	39	3.0 x10^{-5}
10/18-02/19 BH505 408.5	0.78	55	2.4 x10^{-5}

The visual method for determining *G* in the Lea Park Formation shale yielded values ranging from 25 MPa at a shear strain increment of 3.1x10^{-5} to 193 MPa at a shear strain increment of 8.8x10^{-6}. The BRF method yielded *G* values ranged from 39 MPa at a shear strain increment of 3.0x10^{-5} to 202 MPa at a shear strain increment of 6.5x10^{-6}.

3.2 Shear Wave Velocity in the Laboratory

The variation in shear modulus for each Lea Park Formation shale sample showed the most degraded stiffness in the Pitcher samples, followed by the oil core, and finally the mud core. The mud core samples were expected to have the most degraded stiffness as they in theory would be the most damaged from the time of sample, transport, and storage. There was no obvious explanation for this finding, other than the likelihood that sample selection bias played a role.

Table 3. Sonic Wave Velocity Determination of Shear Modulus for Lea Park Shale.

Sample Type	S-wave time (μs)	Shear Wave Velocity (m/s)	G (MPa)
Oil Core	28.78	723.37	1047
	28.58	674.85	911
	25.85	854.87	1462
Pitcher	36.18	609.62	743
	36.52	638.22	815
Mud Core	27.91	1020.06	2081
	27.31	966.07	1867
	24.66	918.76	1688

3.3 Pre-consolidation Pressure Analysis

The Pitcher samples had a large range of pre-consolidation pressure which varied from 1.94 – 5.27 MPa with an average of 3.07 MPa. The mud core samples pre-consolidation pressure varied from 4.73 – 5.63 MPa with an average of 5.13 MPa. The oil core samples pre-consolidation pressure varied from 5.70 – 7.70 MPa with an average of 6.62 MPa. Based on this analysis it would suggest that the Pitcher samples would be the most damaged, which agrees well with the sonic testing. The oil cored samples however, now demonstrated the highest pre-consolidation stress and a likely lower degree of damage, which was consistent with the original hypothesis that non-polar preservation of samples would result in better test data.

Furthermore, Lim et al. (2018) discussed the sample damage associated with a reduced compression index C_c post yield or post pre-consolidation pressure as it correlated with a reduced modulus in clay soil samples.

The research completed as part of this study evaluated the compression and swelling indices. The values for compression index were taken after the apparent pre-consolidation pressure for each test was reached. The pre-consolidation pressure was determined using the Dissipated Strain Energy Method (DSEM) method (Wang and Frost, 2004). The swelling index, C_s was taken from the first unload cycle.

The mud core samples resulted in the lowest values for C_c and C_s. The values ranged from 0.11 – 0.19 for C_c with an average of 0.15 and C_s values ranging from 0.02 – 0.05 with an average of 0.04. The Pitcher samples ranged in C_c from 0.24 – 0.67 with an average of 0.36 and C_s values of 0.04 – 0.10 with an average of 0.07. The oil core samples were the highest and ranged in C_c from 0.60 – 0.93 with an average of 0.77 and C_s values of 0.7 – 0.9 with an average of 0.8. The substantially higher compression indices found after reaching the pre-consolidation pressure in the oil core samples would suggest a higher sample quality than both the Pitcher and mud core samples (Lim et al., 2018).

3.4 Stiffness Degradation and Modulus Determination

The determination of very small strain modulus (10^{-6}) is established primarily using in-situ methods and one laboratory method for the Borden Bridge landslide research which included VSP, MASW, FWS, and lab sound wave velocity testing. The small strain (10^{-5} to 10^{-4}) in-situ method chosen was the measurement of the response of the Lea Park Shale aquifer to barometric loading. Smith et al., (2018) has previously illustrated stiffness degradation with applied strain increment on Pierre Shale using barometric compensation compared to oedometer testing. The findings of Smith et al's. (2018) study projected a line of expected stiffness with increasing strain increment and resulted in most oedometer testing plotting below the projected line. Smith et al., (2018) believed this to show a level of damage to the samples used in the oedometer tests. The tests from Smith et al's. (2018) study were all completed on poorly handled samples and therefore are believed to have previously destroyed diagenetic bonds prior to testing. However, if a relatively undisturbed sample is tested the diagenetic bonds are expected to be destroyed during testing resulting in a reduction stiffness with strain (Smith et al., 2018).

The laboratory comparison of modulus determination and sample damage for the Lea Park Formation shale at the Borden Bridge site was based on the works of Lim et al's (2018) comparison of multiple drilling sample methods completed in soil which was used determine a level of damage in sampling.

The key differentiator in the stiffness determination of this research was meant to primarily be the difference in drilling and sampling methods used to retrieve the shale samples. Where possible the samples were held equal in terms of storage, sample preparation, and testing as to illustrate a difference in stiffness at the design strain increment as a representation of drilling methods as opposed to testing methods.

The values for shear modulus measured at the Borden Bridge (in-situ and laboratory) were plotted with respect to strain considering the different sampling and storage methods. The log-log graph of shear modulus vs shear strain for all tests completed on the Lea Park Formation shale are plotted below in Figure 3.

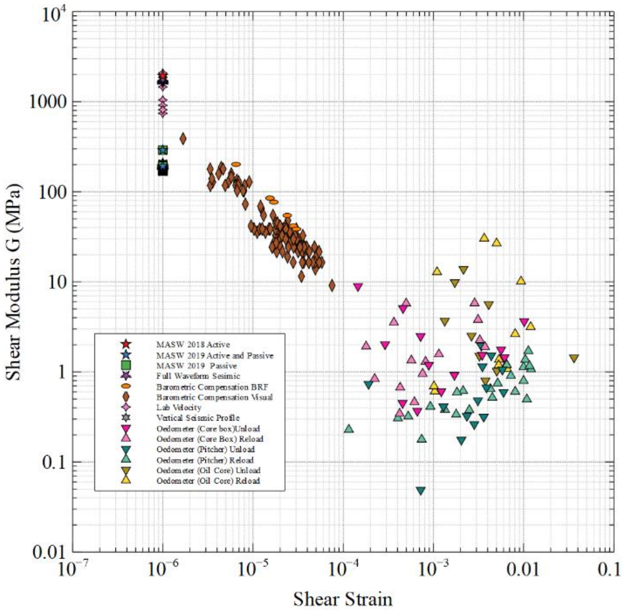

Figure 3. Shear modulus versus shear strain for Lea Park Shale using in-situ and laboratory methods

The in-situ very small strain modulus of the Lea Park Formation shale near the shear zone is believed to be close to 200 MPa as the VSP data has the highest accuracy with depth.

The chosen in-situ very small strain shear modulus for this analysis was based on the VSP and MASW survey data. The confidence level was high for this data as the depth specific determination of S-wave from the VSP in combination with multiple stacked data points of the MASW for verification. The maximum shear modulus G_0 was chosen to be 206.3 MPa, which was the average of the VSP modulus found within the Lea Park Formation near the shear zone 410.2 – 420.0 masl. The barometric compensation was completed within vibrating wire piezometers in the shear zone using both the BRF and visual methods and clearly shows a reduction in stiffness with strain. The reduction in stiffness has a very sharp drop off beyond a shear strain of 10^{-5} when shown normalized to the in-situ VSP data as shown in Figure 4.

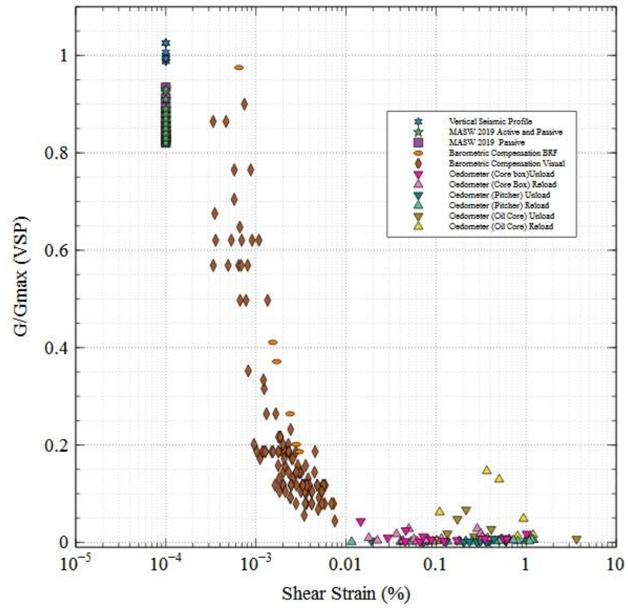

Figure 4. Stiffness degradation curve modulus normalized to vertical seismic profile modulus values

3.5 Oedometric Stiffness

The oedometric data was the most surprising of all the results obtained in this study. Based on the theories of swelling, ion exchange and degradation of the shales, it was anticipated that the conventionally cored shale would exhibit the lowest stiffness of the three sampling methods. The Pitcher sampler was expected to yield a comparable result for stiffness to the sample drilled in canola oil since both would have had limited exposure to fresh water. However, the Pitcher samples demonstrated the largest reduction in stiffness when tested in the laboratory. The large shear forces induced when cutting a sample into a tube during drilling is what is believed to have caused the large reduction in stiffness. This could also be in part due to the extrusion process from the Pitcher tube and placement into the oedometer ring. The sample was pushed out directly into the oedometer ring which may have resulted in damage to the sample.

Figure 4 illustrates the complete non-linear shear modulus behaviour based on the data set accumulated during this study, while Figure 5 illustrates the calculated elastic moduli based on the oedometer tests alone. The difference in modulus with the varied sample methods is also highlighted in Table 4 below.

Table 4. Oedometer determination of shear modulus and shear strain for Mud Core, Pitcher, and Oil Core samples

Sample Type	Average Shear Modulus G (MPa)	Average Shear Strain (%)
Mud Core	2.25	0.18
Pitcher	0.70	0.45
Oil Core	6.31	0.60

The average modulus of the Pitcher sampler tests was only around 10% of those measured in samples recovered using canola oil. These data clearly demonstrate that the type of sampling and the use of a non-polar drill fluid has a sizeable impact on the engineering strain of a given sample. The conventionally drilled mud core tests resulted in an average modulus slightly less than 30% that the oil cored sample. Based on these findings for stiffness using oedometric testing on shales, this would suggest that for the purpose of mechanical properties of an extremely weak rock such as the Lea Park Shale, traditional mud coring may result in an slightly conservative estimation of the shale stiffness.

The Pitcher sampler was discussed by Morgenstern and Thomson (1971) to be a preferable method of sample recovery as the mechanical values gathered were comparable to that of Shelby tube samples while allowing for greater ease of sampling and higher recovery. While the ease of recovery is absolute when using the Pitcher sampler, it appears based on this research that the induced shear forces on the sample during the sampling process may result in a reduced stiffnesses and significant impact on the overall fabric of the shale at design strain increments.

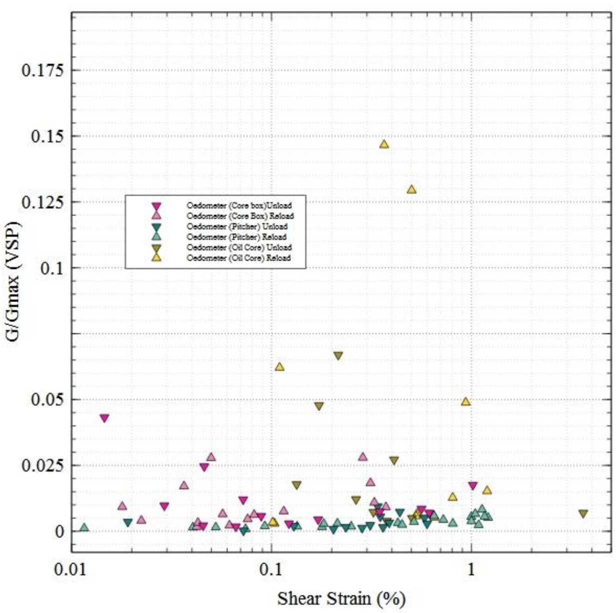

Figure 5. Stiffness degradation curve modulus normalized to vertical seismic profile modulus values

Once the data was normalized to 206.3 MPa, the in-situ very small strain modulus values were combined with the barometric compensation moduli. The combination of the small strain modulus values and laboratory values then yielded a full curve using the linear regression.

An issue encountered at this point was when the different oedometric stiffness sampling methods were separately fitted with the in-situ moduli, there was very minimal difference in the stiffness degradation curves. The minimal difference was from the equation used which may have hidden the results based on the smoothness of the curve. An attempt was made to create three distinct curves of stiffness degradation that would highlight the variation at a larger strain. Because of the lack of sensitivity to the fitted data, a piecewise analysis (Figure 6) for the curve fitting was then used to separate the small strain and larger strain modulus determined in the field and laboratory.

The chosen Poisson's ratio for the oedometric determination of stiffness was close to 0.5 which would suggest that the value is an undrained Poisson's ratio. However, it is worth noting that when using a Poisson's ratio of 0.38 as opposed to the chosen 0.48 the values of shear modulus would be larger by close to a multiple of 3. The increase in G would change proportionately for each modulus value found and the sample damage determination would not change quantitatively, it would only shift the values upward on the curve.

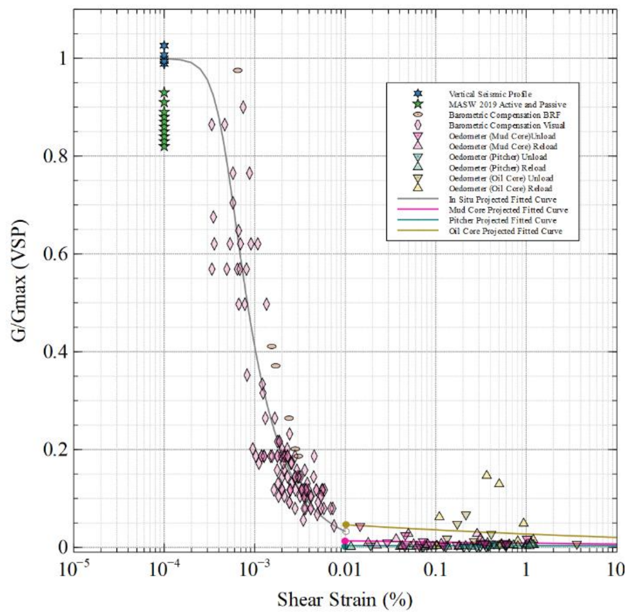

Figure 6. Curve fitted to combined in-situ shear modulus versus differing sample methods for oedometer test samples with data overlaid for the Lea Park Formation shale.

The piece-wise curves shown in Figure 6 are the combined in-situ data normalized to the averaged VSP data within the Lea Park Shale surrounding the shear zone at an elevation of 420.4 to 410.2 masl. The larger strain modulus values were curve fitted to show their degradation with strain. The oil cored samples plot well above the in-situ projection and has the stiffest response beyond 0.01 % strain of all sampling types. Surprisingly, the Pitcher sampler data results in a nearly horizontal line showing a fully degraded stiffness within the shale even at moderate strains. The conventionally cored samples indicate a degraded stiffness below the projected line but above the Pitcher sampler.

Strain dependent problems such as the slow-moving landslide at the Borden Bridge site, tunneling problems, retaining walls, and other geotechnical problems can largely rely on understanding how the stiffness of the material is expected to degrade with strain (Mair, 1993). Therefore, the accuracy of the stiffness found in laboratory testing can dictate remediation or design efforts and design strain increments. Understanding that from this research, the expected stiffness when projected forward to design strain levels using in-situ methods such as geophysics and barometric compensation, the actual stiffness as determined by the oil core samples may be higher than originally expected. When attempting to understand the stiffness using laboratory methods at design strain, if traditional mud rotary coring or Pitcher samples are used, the values gathered may be as low as 10% of the best measured stiffness available to the material.

4 CONCLUSIONS

The stiffness degradation of the Lea Park shale has been shown in this research using very small strains (10-6), intermediate strains (10^{-6} – 10^{-4}) and larger (design) strain increments ($>10^{-4}$) using multiple sampling, storage, and testing techniques. The primary conclusions of the study found that for the Lea Park Formation shale:

- The sample type that showed the most damage through stiffness reduction in lab sonic wave velocity, and oedometric stiffness was the Pitcher sampler. The oil coring that took the most care to control pore-fluid interactions and thereby limit sample disturbance was able to yield the highest stiffness values and are believed to be the closest representation of the actual stiffness based on other, non-destructive test methods. The standard mud coring sample yielded a higher stiffness than the Pitcher, but lower than the oil core samples. The reduction in stiffness on average from the Pitcher sampler to the oil core was nearly a factor of 10.
- A stiffness degradation curve was developed to further estimate the expected stiffness of the Lea Park Formation as it is strained through the extremely slow-moving landslide. The data acquired in this research could lead to further in-depth strain dependent modeling of the Lea Park Formation shale.
- The sample damage for the differing sample methods was evaluated without stiffness determination through the apparent pre-consolidation pressure, and the compression index found in the oedometer tests. The higher apparent pre-consolidation pressures found for the oil-core samples suggested the least damage to the samples followed by the mud core samples, and finally the Pitcher samples. This agreed with the stiffness determination for the Pitcher sample being the most damaged sample. The compression index found for the samples after the apparent pre-consolidation pressure was reached in the oedometer tests yielded the highest value for the oil core samples followed by the Pitcher samples, then the mud core samples. The higher post pre-consolidation compression index suggests a less damaged sample within the oil core samples.

The combination of testing results found on site and in the laboratory yield the belief that when special care to limit sample damage and maintain the pore-water chemistry, and water content is taken a more representative stiffness of the shale can be maintained. The use of a full stiffness degradation curve from higher quality sampling practices could be further utilized to avoid overly conservative designs done in displacement dependent engineering projects.

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