Links between small and large strain behavior of Presumpscot clay

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**ABSTRACT:** The objective of this paper is to demonstrate possible links between shear wave velocity and strength of Presumpscot clay. A laboratory study of direct simple shear and consolidated drained triaxial tests was performed on high quality samples of Presumpscot clay carved from a block sample and Shelby tubes. Shear wave velocity was measured in all the tests using bender elements. The ratio of $G_o/S_u$ was compared to published data of 13 different soils and the agreement was good. The ratio $G_o/\sigma_{1f}'$ from the drained tests ranged from 130 to 170, and previous research by the authors has shown that this ratio may be constant for a given dilative soil. In addition, it was found that the shear wave velocity measured during shear reached a peak value and then decreased prior to full mobilization of the soils’ strength. This suggests that, for sensitive soils such as the Presumpscot clays, in situ measurements of shear wave velocity may have the potential to be used as an early warning system for failure.

1 INTRODUCTION

The increasing use of bender elements to measure shear wave velocity in geotechnical laboratory testing equipment has made possible a variety of studies linking small and large strain behavior of soils. Laboratory measurements of shear wave velocity have been used to evaluate sample disturbance in clays (Landon et al. 2007), the effects of aging (Baxter and Mitchell 2004), and cyclic resistance (Baxter et al. 2008; Ahmadi and Paydar 2014).

Shear wave velocity ($v_s$) is an attractive soil property because it is directly related to the soils’ small strain stiffness ($G_o$) by $G_o = \rho v_s^2$, where $\rho$ is the bulk density. Values of $G_o$ obtained from measurements of $v_s$ are used extensively to evaluate the response of a soil profile to earthquake loading (i.e. site response analyses). Linking small strain measurements to large strain behavior such as strength and compressibility, however, is more controversial. The common argument against such a link is that there is so much changing as a soil approaches failure (e.g. shear band formation, contractive or dilative volume change, pore pressure generation) that cannot be captured by an elastic measurement.

However, shear wave velocity in soils is primarily a function of void ratio and effective stress, and is also significantly influenced by stress history, fabric, age, degree of cementation, and other factors. Large strain properties such as strength and volume change characteristics are also influenced by these same factors, so it is not unreasonable to think that a link can exist between shear wave velocity and strength. Because of the sensitivity of shear wave velocity to the effects of soil fabric, it may be a useful tool for characterizing the behavior of sensitive soils like the Presumpscot clays.

The objective of this paper is to present the results of direct simple shear and drained triaxial compression tests on samples of Presumpscot clay in which the vertically propagating shear wave velocity was measured. Most of the samples were carved from a high quality block, with some tube samples also tested. Values of $G_o$ obtained from $v_s$ were compared to measured values of undrained shear strength and effective stresses at
failure, and the results are compared to published values from the literature.

2 LABORATORY TESTING PROGRAM

2.1 Properties of Soils Tested

Samples of Presumpscot Clay were obtained from a high quality Sherbrooke block sample and two undisturbed Shelby tubes collected in Falmouth, Maine by Dr. Melissa Landon from the University of Maine (Langlais 2011). The samples were obtained at depths of 4.3 m, 6.7 m, and 11 m for the block sample and Shelby tubes, respectively. A summary of relevant soil properties is listed in Table 1.

Table 1. Properties of Presumpscot Clay tested in this study.

<table>
<thead>
<tr>
<th>USCS Classification</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit (%)</td>
<td>56</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>32</td>
</tr>
<tr>
<td>Natural Water Content (%)</td>
<td>45-50</td>
</tr>
<tr>
<td>Coefficient of Consolidation (cm²/sec)</td>
<td>0.004</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.72</td>
</tr>
</tbody>
</table>

The grain size distribution is shown in Figure 1. The preconsolidation stress ($\sigma'_p$) was determined from three incremental load consolidation tests (Figure 2), and the values ranged from 140-156 kPa.

2.2 Shear Wave Velocity System

Shear waves were generated and received by piezoceramic bender elements mounted in the end caps of the direct simple shear (DSS) and isotropically consolidated drained triaxial compression equipment (CID). A 20 Volt peak-to-peak single sine wave was sent to the transmitting bender element using a function generator. The received signal was amplified and filtered using a low-noise preamplifier (Sharma 2010).

For the DSS tests, the shear wave travel time was measured at the end of consolidation to the estimated in situ vertical effective stress using an oscilloscope. The arrival time was estimated visually using the first zero crossing of the received signal as recommended by Lee and Santamarina (2005). The frequency of the transmitted wave was varied from 3 to 30 kHz to evaluate the effect of frequency on shear wave velocity. For the range of stresses tested in this study (20 to 150 kPa), varying the frequency from 3 to 30 kHz resulted in a 10-20% change in shear wave velocity.

For the consolidated drained triaxial tests, values of shear wave velocity were measured at the end of consolidation to the estimated vertical effective stress and throughout the shearing phase. Matlab was used to trigger the transmitted signal and store both the transmitted and received signals. The frequency of the transmitted signals...
was 3 kHz, which was chosen based on the length of the samples and the clarity of the received signals (Guadalupe-Torres 2013; Sharma 2010). The received signals were both amplified and filtered, and the shear wave travel time (i.e. first arrival) was estimated from the time difference between the first peaks of the transmitted and received signals. (e.g. peak-to-peak method as described by Lee and Santamarina 2005). This was shown to introduce <5% error compared to the first zero crossing, however it greatly simplified the automation of the measurements. Details of the measurement system can be found in Sharma (2010). For both the DSS and the CID triaxial tests, the shear wave velocity \( v_s \) was calculated by \( v_s = L/\Delta t \), where \( L \) is the tip-to-tip distance between the bender elements at the time of the measurement and \( \Delta t \) is the shear wave arrival time.

2.3 Sample Preparation and Testing Matrix

Samples were either carved from a block or extruded from a Shelby tube before being trimmed to their final dimensions. Photographs of the sample preparation process for the DSS and CID triaxial tests are shown in Figures 3 and 4. Prior to extrusion, the Shelby tube samples were debonded by cutting the soil away from the inside of the tube using a thin wire (Ladd and Degroot 2003). The testing matrix for the DSS and CID tests is shown in Table 2.

3 RESULTS

3.1 Direct Simple Shear Tests

The DSS tests were performed using an automated system developed by the Geocomp Corp. Samples were confined using stacked rings, which have been shown to yield comparable results to tests performed with wire-reinforced membranes (Baxter et al. 2010). The samples were not back pressure saturated, and undrained shearing was accomplished by maintaining constant volume during shear. Excess pore pressures during shear were inferred from the changes in vertical stress required to maintain constant volume (Dyvik et al. 1987). For the consolidation stages, a Load Increment Ratio (LIR) of 0.5 was used to better define the preconsolidation stress. The samples were sheared at a shear strain rate of 5%/hour (ASTM D6528).

Two direct simple shear tests were performed on samples carved from the block sample. The block was obtained from a depth of 4.3 m, and based on the unit weight of the soil and the stratigraphy the vertical effective stress was estimated to be 30 kPa.

Figure 3. Carving and trimming DSS samples from a block sample.

The preconsolidation stress was estimated to be 156 kPa from an incremental load consolidation test (Figure 5), indicating that the soil is overconsolidated. The samples were collected along the Presumpscot River bank at the site of previously constructed bridge piers, so it is possible that some combination of loading and unloading in addition to sensitivity is responsible for the measured overconsolidation. Although
there is a clear break in the consolidation curve in Figure 5 and the preconsolidation stress is easily identified, the sample quality is classified as “good to fair” according to the approach proposed by Lunne et al. (1997).

Figure 4. Trimming of triaxial test samples from a block sample.

Table 2. Test matrix for the DSS and CID tests.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Consolidation Stresses (kPa)</th>
<th>Overconsolidation Ratios (OCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSS</td>
<td>30, 156</td>
<td>5, 1</td>
</tr>
<tr>
<td>CID</td>
<td>30 (2 tests), 42, 70</td>
<td>5, 3, 2</td>
</tr>
</tbody>
</table>

Also shown in Figure 5 is the consolidation behavior of the two DSS tests; one was consolidated to 30 kPa (OCR~5) and the other was consolidated to a vertical effective stress of 156 kPa (OCR=1). It is clear from this figure that the lateral confining system in the DSS system is not as rigid as the consolidometer, resulting in significantly more vertical strain during consolidation and some sample disturbance.

Shear wave velocity was measured at the end of each consolidation stage and the results are shown in Figure 6. Also plotted in Figure 6 for comparison are measured values of shear wave velocity of a high plasticity clay from the Gulf of Mexico and an organic silt from Providence, Rhode Island that have been tested extensively at the University of Rhode Island. Figure 7 shows the stress-strain and pore pressure behavior of the two DSS tests.

Figure 5. Consolidation behavior of two DSS tests and an incremental load consolidation test from the same depth.

Figure 6. Shear wave velocity measurements at the end of consolidation for Presumpscot clay as well as a high plasticity clay (GoM – Gulf of Mexico) and an organic silt from Providence, RI.

Figure 7. Shear stress-shear strain and stress path behavior of DSS tests.
In order to link small strain (\(v_s\) or \(G_o\)) and large strain behavior (undrained shear strength, \(S_u\)), the ratio of \(G_o/S_u\) was calculated and compared to published data. Andersen et al. (2008) has shown that there is a relationship between \(G_o/S_u\) and Plasticity Index (PI) for a variety of clays over a range of overconsolidation ratios (OCR). Table 3 shows the relevant data used to calculate \(G_o/S_u\) for the Presumpscot clay and Figure 8 shows the \(G_o/S_u\) values compared to the published work of Andersen et al. (2008). Also shown in the figure are \(G_o/S_u\) ratios for the high plasticity clay and organic silt shown in Figure 6. The agreement with the published data is good, which suggests that both \(G_o\) and \(S_u\) are affected in a comparable way by the sensitivity of the Presumpscot clay, and that shear wave velocity measurements may be useful in estimating the undrained shear strength.

Table 3. Small and large strain results from DSS tests on Presumpscot clay.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>(\rho) (Mg/m³)</th>
<th>(G_o) (MPa)</th>
<th>(S_u) (MPa)</th>
<th>(G_o/S_u) (min)</th>
<th>(G_o/S_u) (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.68</td>
<td>19.29</td>
<td>28.73</td>
<td>34.9</td>
<td>552</td>
</tr>
<tr>
<td>8</td>
<td>1.73</td>
<td>12.35</td>
<td>17.52</td>
<td>16.0</td>
<td>771</td>
</tr>
</tbody>
</table>

1 Calculated from the minimum shear wave velocity.
2 Calculated from the maximum shear wave velocity.

Table 3. Small and large strain results from DSS tests on Presumpscot clay.

3.2 Consolidated Drained Triaxial Tests

Four CID triaxial tests were performed on samples carved from the block sample and extruded from two Shelby tubes. These tests were performed as part of a larger study investigation possible links between small strain shear modulus and effective stress strength parameters for dilative soils (Sharma et al. 2010; Guadalupe et al. 2013). An automated system manufactured by the Geocomp Corp. was used, and consists of a computer controlled load frame and two flow pumps to control cell and sample pressures. The flow pumps allow for automatic back pressure saturation of the samples and measurement of volume change during consolidation and shear.

![Figure 8. G_o/S_u ratios for Presumpscot clay compared to results from the literature and tests on other soils performed by the authors (adapted from Andersen et al. 2008).](image)

![Figure 9. Stress-strain and volume change behavior of Presumpscot clay from CID triaxial tests. Tests 05-30 (A and B) involved block samples and tests 02-70 and 03-42 involved Shelby tube samples (A and B).](image)
in situ stresses (30 kPa, 42 kPa, and 70 kPa) which corresponded to OCRs of 5, 3, and 2. As described previously, shear wave velocity measurements were taken both during the consolidation and shear phases.

The results of the CID triaxial tests are shown in Figures 9 and 10. Figure 9 shows the stress-strain and volumetric strain behavior during shear for the four tests. The two tests from the block sample exhibited clear strain softening behavior, while the two Shelby tube samples did not exhibit any strain softening behavior. All four samples exhibited contractive volume change behavior.

Figure 9 shows the stress-strain behavior during shear for the four CID tests. Figure 10 shows values of small strain shear modulus and shear wave velocity for the four CID tests measured during shear. Similar to the stress-strain behavior, the block samples show a clear peak in small strain shear modulus during shear. It is interesting to note, however, that in all four tests the values of $G_o$ (and $v_s$) reached a maximum and then decreased before full mobilization of the shear strength (e.g. maximum deviator stress). This behavior has been observed in a variety of dilative and weakly cemented soils, and suggests that shear wave velocity can capture the destructuring of a sensitive soil prior to failure (Sharma et al. 2011; Guadalupe et al. 2013).

In order to link small and large strain behavior under drained conditions, the ratio of $G_o$ and $\sigma_{1f}$ for the four tests on Presumpscot clay. The ratio of small strain shear modulus at the end of consolidation and the major principal effective stress at failure ($G_o/\sigma_{1f}$) ranged from 130 to 170, with an average of 146. Despite the scatter in these preliminary results, this ratio may help estimate stresses at failure from in situ shear wave velocity measurements.

Table 4. Summary of CID triaxial test results for Presumpscot clay.

<table>
<thead>
<tr>
<th>OCR</th>
<th>$\sigma_{1f}$ (kPa)</th>
<th>$c_o$</th>
<th>$v_s$ (m/s)</th>
<th>$G_o$ (MPa)</th>
<th>$\sigma_{1f}$ (MPa)</th>
<th>$G_o/\sigma_{1f}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>30</td>
<td>1.34</td>
<td>104</td>
<td>19</td>
<td>0.110</td>
<td>172</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>1.33</td>
<td>97</td>
<td>16</td>
<td>0.121</td>
<td>136</td>
</tr>
<tr>
<td>3</td>
<td>42</td>
<td>1.30</td>
<td>95</td>
<td>16</td>
<td>0.124</td>
<td>129</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>1.27</td>
<td>127</td>
<td>28</td>
<td>0.192</td>
<td>147</td>
</tr>
</tbody>
</table>

4 SUMMARY AND CONCLUSIONS

The increasing use of bender elements to measure shear wave velocity in geotechnical laboratory testing equipment has made possible a variety of studies linking small and large strain behavior of soils. Shear wave velocity in soils is primarily a function of void ratio and effective stress, but it is also significantly influenced by stress history, fabric, age, degree of cementation, and other factors. Because of this sensitivity to the effects of soil fabric, shear wave velocity may be a useful tool for characterizing the behavior of the sensitive soils like the Presumpscot clays. This paper presented the results of direct simple shear and drained triaxial compression tests on samples of Presumpscot clay in which the vertically propagating shear wave velocity was measured. Most of the samples were carved from a high quality block, with some tube samples also tested.

For the direct simple shear tests, values of shear wave velocity were measured at the end of consolidation prior to undrained shearing of the samples. The ratio of small strain shear modulus (calculated from the shear wave velocity) to undrained shear strength (i.e. $G_o/S_u$) was compared to published data of 13 different soils of varying stress histories and plasticities. The agreement with the published data was good, which suggests that both $G_o$ and $S_u$ are affected in a comparable way by the sensitivity of the...
Presumpscot clay, and that shear wave velocity measurements may be useful in estimating the undrained shear strength.

![Figure 11. $G_0/\sigma'_{1f}$ ratios for the four CID tests on Presumpscot clay.](image)

For the drained triaxial compression tests, shear wave velocity was measured throughout the consolidation and shear stages using an automated system. Four tests were performed at different values of effective consolidation stress and overconsolidation ratios. The ratio of the small strain shear modulus at the end of consolidation and the major principal effective stress at failure ($G_0/\sigma'_{1f}$) ranged from 130 to 170. Previous research by the authors has shown that this ratio is constant for a given dilative soil and is independent of stress history, density, and degree of cementation. Although more work needs to be done to validate this approach, this ratio may help estimate stresses at failure from in situ shear wave velocity measurements. In addition, it was found that the shear wave velocity measured during shear reached a peak value and then decreased prior to full mobilization of the soils’ strength. This suggests that, for sensitive soils such as the Presumpscot clays, in situ measurements of shear wave velocity may have the potential to be used as an early warning system for failure.

5 ACKNOWLEDGEMENTS

The samples of Presumpscot clay used in this study were generously given by Dr. Melissa Landon of the University of Maine. Funding for this study was provided by the U.S. National Science Foundation under grant no. CMMI-1031135. This support is greatly appreciated.

6 REFERENCES


