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<td><strong>Names of authors:</strong></td>
<td>Michael Long¹ and Shane Donohue¹</td>
</tr>
<tr>
<td><strong>Affiliation of authors:</strong></td>
<td>1: School of Architecture, Landscape and Civil Engineering, University College Dublin (UCD), Ireland</td>
</tr>
<tr>
<td></td>
<td>(<a href="mailto:Mike.Long@ucd.ie">Mike.Long@ucd.ie</a> and <a href="mailto:Shane.Donohue@ucd.ie">Shane.Donohue@ucd.ie</a>)</td>
</tr>
<tr>
<td><strong>Contact address:</strong></td>
<td>Michael Long, School of Architecture, Landscape and Civil Engineering, University College Dublin (UCD), Newstead Building, Belfield, Dublin 4, Ireland.</td>
</tr>
<tr>
<td></td>
<td>Phone: +353-1-7163221</td>
</tr>
<tr>
<td></td>
<td>Fax: +353-1-7167399</td>
</tr>
<tr>
<td></td>
<td>e-mail: <a href="mailto:Mike.Long@ucd.ie">Mike.Long@ucd.ie</a></td>
</tr>
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Title: Characterisation of Norwegian marine clays with combined shear wave velocity and CPTU data

Abstract: A database of research quality CPTU and shear wave velocity information for Norwegian marine clays has been assembled so as to study the small strain stiffness relationships for these materials and to examine the potential use of CPTU and $V_s$ data in combination for the purposes of characterising these soils. Data for sites where high quality block sampling was carried out have mostly been used. Improvements have been suggested to existing correlations between $G_{\text{max}}$ or $V_s$ and index properties for these soils. Recent research has shown that CPTU $q_t$ and especially $u_2$ and $V_s$ can be measured reliably and repeatably and are not operator or equipment dependant. Therefore a new soil classification chart involving $Q_t$ and normalised shear wave velocity ($V_{s1}$) or $V_{s1}$ and $\Delta u/\sigma_{v_0}'$ is presented. Using this chart it is possible to clearly distinguish between clays of different OCR.

Key words: soft clays; shear wave velocity; cone penetration tests; overconsolidation ratio
**Introduction**

As the piezocone cone penetration test (CPTU) grows more popular throughout the world, it is also becoming more commonplace to combine the standard test with measurements of shear wave velocity ($V_s$) using the seismic CPT (SCPTU). Recent work by Long (2008) and others has shown that $V_s$ can be measured in situ easily and reliably by a variety of methods. For soft reasonably isotropic clays, the results seem to be relatively independent of the technique used and of the operator. Therefore if SCPTU results are not available, they could be substituted with results from other techniques such as seismic dilatometer (SDMT), continuous surface wave (CSW), spectral analysis of surface waves (SASW) or multi channel analysis of surface waves (MASW).

In parallel, work by various researchers such as Powell and Lunne (2005a), Long (2008), Boylan et al. (2008), Tiggelman and Beukema (2008) and Lunne and Powell (2008) have shown that for CPTU tests in soft clays, if the pore pressure measurement system is sufficiently well saturated, the measured pore pressure ($u_2$) is the parameter that shows least variation from one type of CPTU equipment to another. This research also demonstrates that corrected end resistance ($q_t$) values show somewhat more variation from one type of equipment to another as compared with $u_2$. Measured sleeve friction ($f_s$) shows most variation from one type of equipment to another and these values should be treated with caution.

As CPTU $u_2$ (and possibly $q_t$) and $V_s$ are two of the more reliable and accurate parameters that can be obtained from in situ testing, it seems logical then to attempt to use them in combination for the purposes of characterising and classifying soft clays.

In this paper data from eleven soft to firm clay sites are used in order to investigate these ideas. For all of these sites research level CPTU and $V_s$ data were
available. In addition results of high quality laboratory tests on Sherbrooke block samples were available for most of the sites.

In this paper relationships between small strain shear modulus ($G_{max}$) (or $V_s$) and index properties are first examined in order to check that the soil properties are consistent with other published data. Existing relationships between $V_s$ and $q_t$ are then examined and some new correlations are proposed. Finally some suggestions are made for a new soil classification chart involving CPTU and $V_s$ data.

The Sites

A summary of the ten sites surveyed is given on Table 1. Most of the sites were developed for research purposes either by the Norwegian Geotechnical Institute (NGI) or by the Geotechnics Division of the Norwegian University of Science and Technology (NTNU formerly NTH). Nine of the sites are onshore Norway, one is located offshore Norway and the last is located at Bothkennar in Scotland. This latter site was included, as its characteristics are well known internationally. UCD have carried out MASW work on the site and NGI have carried out block sampling and testing at the Bothkennar site.

Soil parameters for the eleven study sites, over the depth range for which shear wave velocity and high quality sample data are available, are summarised on Table 2.

Correlations between $G_{max}$ and $e$ or $w$

Long and Donohue (2007) attempted to relate $G_{max}$ to natural water content ($w$) or in situ void ratio ($e_0$) for four of the Norwegian clay sites. Note that $G_{max}$ is directly related to $V_s$ by:

$$[1] \quad G_{max} = \rho V_s^2$$

where $\rho =$ density.
Here data for seven additional sites is included in an attempt to improve these correlations and to investigate which of the index parameters is the most useful. The overall objective of this work is to check that these soils fall into the framework well established for other materials and also to allow engineers working on future projects to make rapid estimates of $G_{\text{max}}$ for preliminary design or for verification of in situ or laboratory measurements.

Hardin (1978) suggested that for clays, $G_{\text{max}}$ depends on the in situ (or applied) stress ($\sigma'$), $e$ and overconsolidation ratio (OCR). It has however been shown that the effects of OCR are, to a large extent, taken into account by the effect of $e$ and could be neglected (Leroueil and Hight, 2003). The empirical equation describing the influence of the controlling factors on $G_{\text{max}}$ can then be written as follows:

$$G_{\text{max}} = S \cdot F(e)(\sigma_{v'}, \sigma_{h'})^{n} p_a^{(1-2n)}$$

where $F(e)$ is a void ratio function, $\sigma_{v'}$ and $\sigma_{h'}$ are the vertical and horizontal effective stresses respectively, $n$ is a parameter indicating the influence of stress, $p_a$ is atmospheric pressure (100 kPa) and $S$ is a dimensionless “structure” parameter characterising the considered soil.

As can be seen on Figure 1a $G_{\text{max}}/\sigma_{v0'}$ typically varies between 200 and 1000 and as expected $G_{\text{max}}/\sigma_{v0'}$ decreases with increasing $e$ in a similar manner to that described by others, e.g. Jamiolkowski et al., (1991) for a variety of soils. On Figure 1b the data have been normalised as suggested by Hardin (1978) and Hight and Leroueil (2003), (Equation 2). A line has been added corresponding to $S = 700$, $F(e) = 1/e^{1.3}$, $K_0 = 0.6$ and $n = 0.25$. It can be seen that the fit is good confirming that $G_{\text{max}}$ for Norwegian clays are consistent with a large volume of other published experimental data.

Norwegian practice (see for example Janbu, 1985) is to normalise with respect to the sum of consolidation stress and attraction, so as to obtain a dimensionless
parameter which depends on friction only. For the case of small strain shear modulus, Langø (1991) suggested that $G_{\text{max}}$ should be normalised by:

$$
[3] \quad g_{\text{max}} = \frac{G_{\text{max}}}{\sigma_m' + a}
$$

where $\sigma_m'$ and $a$ are the mean effective consolidation stress and the attraction ($a = c'/\tan\phi'$) measured in a triaxial test respectively. He suggested a systematic variation of the normalised shear modulus may be obtained by plotting $g_{\text{max}}$ against $w$, in a similar way to that proposed by Janbu (1985) for oedometer moduli.

Figure 2a shows $g_{\text{max}}$ data from this study. Attraction ($a$) was assumed to equal 3 kPa, which is a typical value for the clays under study from Janbu (1985). There is a reasonable correlation between $g_{\text{max}}$ and $w$. The data form roughly two groups. There is more scatter in the data where water content is about 30% ($e \approx 0.8$). According to Janbu (1970) $w$ of about 30% corresponds to the division between normally to lightly overconsolidated clay and moderately overconsolidated clay. Therefore it would seem that the effects of overconsolidation on $G_{\text{max}}$ are not completely taken into account by $w$ (or $e$) and there may be some merit in normalising these data by preconsolidation stress rather than in situ vertical effective stress.

The data are plotted against plasticity index ($I_p$) on Figure 2b. Again there is reasonable agreement, with $g_{\text{max}}$ being relatively independent of $I_p$ for values greater than about 25%. A similar analysis was performed using liquidity index but no clear pattern emerged.

**Correlations between $q_t$ and $V_s$**

**Previously published correlations**

As discussed by Mayne and Rix (1993) and others $G_{\text{max}}$ depends on $e_0$, $\sigma_v0'$ and OCR. Since measured cone resistance ($q_c$) also depends on $\sigma_v0'$ and OCR, previous
researchers have sought a relationship between $G_{\text{max}}$ and $q_c$ despite the fact that they are operable at different ends of the strain spectrum.

Mayne and Rix, (1993) summarise site-specific correlations between $G_{\text{max}}$ or $V_s$ and $q_c$. For example Jaime and Romo (1988) and Bouckovalas et al. (1989) found that for Mexico city clays and Greek clays respectively that:

\[ V_s (m/s) \approx 0.1 q_c (kPa) \]  \hspace{1cm} \text{(4)}

\[ G_{\text{max}} = 2.8 q_c^{1.4} \]  \hspace{1cm} \text{(5)}

Mayne and Rix (1993) established a database from on 31 different sites in Europe and North America, where CPT and SASW or SCPT data was available. All were clay sites with varying OCR, strength and stiffness. Two of the sites were the same as used in this study namely Drammen and Onsøy. The equation of the best – fit regression line from an assumed log – log relationship was found to be:

\[ G_{\text{max}} = 2.78 q_c^{1.335} \]  \hspace{1cm} \text{(6)}

which is very similar to the expression derived by Bouckovalas et al. (1989), see Equation 5.

Mayne and Rix (1993) also found that the strong dependence of $G_{\text{max}}$ upon $e_0$, however requires that $q_c$ is only successful as a profiler of $G_{\text{max}}$ if $e_0$ is included in the correlation and they derived empirically the formula:

\[ G_{\text{max}} = \frac{99.5 p_a^{0.305} q_c^{0.695}}{e_0^{1.13}} \]  \hspace{1cm} \text{(7)}

where $q_c$ is in units of kPa and $p_a$ = atmospheric pressure in kPa, $e_0$ = in situ void ratio.

In a later paper Mayne and Rix (1995) argued that in order to reduce scatter the correlation should be between $q_c$ and $V_s$ as these are both directly measured
parameters. In the earlier study $G_{\text{max}}$ had to be calculated from $V_s$ using Equation 1. Mayne and Rix (1995) derived the empirical formulae:

$$V_s = 1.75q_c^{0.627} \quad [8]$$

$$V_s = 9.44q_c^{0.435}e_0^{-0.532} \quad [9]$$

As there was only a small change in the resulting correlation coefficient, Powell and Lunne (2005b) suggest that Equations 7 or 9 are only slightly better than the simpler ones based only on $q_c$. Another important issue with both Mayne and Rix equations is that they make use of the uncorrected cone resistance, $q_c$, rather than the corrected value, $q_t$. This is because much of their data was obtained before the introduction of the piezocone.

As the reconstruction of the in situ void ratio profile can be a difficult task, particularly given the cost of high quality undisturbed sampling, Simonini and Cola (2000) suggest that the CPTU pore pressure parameter $B_q$ could be used to replace $e_0$ in the correlation. The standard derivation of $B_q$ (Lunne et al., 1997a) is:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} = \frac{\Delta u}{q_{net}} \quad [10]$$

where $u_0$ = ambient pore pressure and $\sigma_{v0}$ = total overburden stress

However Simonini and Cola (2000) simply assumed $B_q$ to be the ratio between $\Delta u$ and $q_c$ (termed $B_{q^*}$ here to avoid confusion). They show that, when considering relatively lightly overconsolidated mixed deposits in Venice, a better correlation between $q_t$ and $G_{\text{max}}$ was obtained when incorporating $B_{q^*}$ as follows:

$$G_{\text{max}} = 21.5q_t^{0.70}(1 + B_{q^*})^{4.59} \quad [11]$$

**New correlations for Norwegian clay database**

Data for the ten Norwegian soft clay sites, plotted simply in terms of $q_t$ and $V_s$, are shown on Figure 3. In order to permit later normalisation or correlation against index
properties each data point represents a single high quality sample (all block samples except for Troll and Eberg where thin walled tube sampling was used). The best fit power function, namely:

\[ V_s = 2.944q_t^{0.613} \]

is also shown. Regression analysis gives a moderate \( R^2 \) of 0.630. Those data which show the greatest scatter are from Eidsvoll, where OCR values are relatively high, and Tiller and RVII, where sensitivity, \( S_t \), is high.

Measured \( V_s \) values and those predicted by the original Mayne and Rix (1995) expression (Equation 9) are shown on Figure 4a. It can be seen that in general the Mayne and Rix (1995) expression underpredicts the \( V_s \) for Norwegian soft clays by some 20%. Note that here \( c_0 \) has been reliably determined from high quality block samples. The correlation coefficient, \( R^2 \), is 0.690 which, consistent with the comments made by Powell and Lunne (2005b), is not a significant improvement on that from the simple \( V_s - q_t \) relationship. The data points which show most scatter are again from the high OCR Eidsvoll site and the high \( S_t \) RVII site.

The relationship can be improved using multiple regression analysis, as shown on Figure 4b to give an improved formula, namely:

\[ V_s = 65.00q_t^{0.150} e_0^{-0.714} \]

with \( R^2 = 0.758 \).

A similar exercise has been carried out using the Simonini and Cola (2000) formula (Equation 11) on Figure 5a and 5b. Here \( G_{max} \) has been calculated from the measured \( V_s \) value using the density measurements from block samples. It can be seen that a much better correlation coefficient \( R^2 \) of 0.799 (compared to 0.554) can be achieved by modifying the constants in the expression and using \( B_q \) rather than \( B_{q*} \). The resulting expression is:
Logically then a new expression can be developed which relates $V_s$ directly with $q_t$ and $B_q$ as follows and as shown on Figure 6. This relationship yields an $R^2$ value of 0.777 for the Norwegian soft clay database.

$$G_{\text{max}} = 4.39q_t^{1.225} \left(1 + B_q\right)^{2.53}$$

**Discussion**

A major issue with the most commonly used correlation by Mayne and Rix (1995) is that it relies on the measured cone resistance ($q_c$) rather than the corrected one ($q_t$). It is well known that in soft clays the correction can be very significant perhaps of the order of 15% in many cases. Secondly it also relies on the in situ void ratio ($e_0$) as input. This parameter can be very susceptible to sampling disturbance. Hence in this paper a database comprising high quality samples and research level CPTU tests have been assembled in order to minimise these uncertainties and improve the Mayne and Rix (1995) correlation for use in Norwegian soft clays or similar materials.

Unfortunately this new correlation (Equation 13) also relies on $e_0$ as input. This parameter is not always readily available, especially at an early stage in the investigation, as sampling and laboratory testing are required. Therefore two additional correlations have been proposed for these materials, which do not need laboratory data as input. The first which involves the pore water pressure parameter ($B_q$) is a revision of the Simonini and Cola (2000) expression (Equation 14) and the second (Equation 15) is a new expression which relates $q_t$ and $B_q$ directly to $V_s$ rather than to $G_{\text{max}}$.

All three formulae have similar correlation coefficients and are considered equally reliable.
Enhanced soil characterisation using CPTU and $V_s$ data

Existing classification chart

Robertson et al. (1995) proposed a CPTU soil classification chart (or perhaps more correctly termed a soil behaviour chart) based on normalised cone resistance $Q_t$ ($=q_{net}/G'_{v0}$) and normalised small strain shear modulus ($G_{max}/q_t$). This chart was intended mostly for identifying “unusual” soils such as highly compressible sands, cemented and aged soils and clays with either high or low void ratio. A portion of the chart (focus on clays and silts) is shown on Figure 7. The x-axis has been extended from a maximum value of 100 to 1000. The data for the sites under study here mostly fall as expected in the zone of “young uncemented” soils. Note the boundaries of this region have also been extended in parallel with the extension of the x-axis. Data for the moderately overconsolidated sites, e.g. Eidsvoll, Glava, and Tiller, fall above the zone of young un-cemented soils consistent with the pattern suggested by Robertson et al. (1995).

Proposed new chart

Charts of the type presented by Robertson et al. (1995) have been criticised in the literature because:

1. They involve a plot of one parameter against another, which is a function of the first parameter.

2. They use log scales on the axes; thus masking any trends.

Therefore attempts are made here to study the application of alternative charts, using $V_s$, but avoiding these two issues. On Figure 8 $Q_t$ values are plotted against normalised shear wave velocity $V_{s1}$, where:
Similarly on Figure 9 $V_{s1}$ is plotted against $\Delta u/\sigma_{v0}'$. This latter parameter was originally proposed by Azzouz et al. (1983) so as to avoid the use of cone resistance but at the same time to take into account the effect of overburden stress. Schneider et al. (2008) also use this parameter in a new CPTU based soil classification chart.

On both charts a clear division can be made between the lightly overconsolidated material (OCR < 2) and the moderately overconsolidated soils (OCR > 3). Arguably the $V_{s1} / \Delta u/\sigma_{v0}'$ formulation separates the data more clearly and has less scatter.

The $Q_t$ against $V_{s1}$ data for the Norwegian soft clays is compared to that for high quality sand samples (data from Mayne, 2006) and for UK stiff clays (Lunne et al., 1997a, Powell et al., 1988, Hight et al., 2003 and Powell and Butcher, 2003) on Figure 10. It can be seen that in a global sense the soft clay data is consistent with that of other materials. A similar proposal was made by Gillespie (1990) who suggested a plot of $G_{max} / q_t$ versus $q_t / \sigma_{v0}'$ should be used. However it was found here that the $Q_t$ against $V_{s1}$ formulation separates the data sets more clearly.

**Discussion**

Classification charts such as those of Robertson et al. (1986 and 1995) have been successfully used in geotechnical engineering practice for some time. However the charts have been criticised as they involve plotting one parameter against a derivative of the same parameter and also they make use of log scales, thus potentially masking trends. In addition recent research (e.g. Long, 2008) has shown that CPTU sleeve friction ($f_s$) can be unreliable in soft clays and that pore water pressure ($u_2$) and shear wave velocity can be determined much more reliably. Hence in this paper two new charts are suggested which avoid these problems and make use of $V_s$ and $u_2$ more

\[ V_{s1} = \frac{V_s}{\left(\frac{\sigma_{v0}'}{\sigma_{v0}}\right)^{0.5}} \]  

(Mayne et al., 1998)
directly. In addition it has been shown that if the data are plotted in this way extra information on the OCR of the soils can be determined. Also it has been shown that the Norwegian soft clay data fits the trend for other materials in a global sense.

Conclusions

1. A database of research quality CPTU and shear wave velocity data for Norwegian marine clays has been assembled so as to study the small strain stiffness relationships for these materials and to examine the potential use of CPTU and $V_s$ data in combination for the purposes of characterising these soils.

2. In general the small strain stiffness behaviour of Norwegian soft clays follow the framework published for other soils. It is possible to get satisfactory estimates of $G_{\text{max}}$ using correlations with water content ($w$), void ratio ($e$) or plasticity index ($I_p$). It would seem that the influence of overconsolidation on $G_{\text{max}}$ is not completely taken into account by normalisation by $w$ (or $e$).

3. Reasonable estimates of $V_s$ can be obtained from correlation with CPTU $q_t$ using modified versions of the Mayne and Rix (1995) or Simonini and Cola (2000) formulae or from a new expression involving $q_t$ and $B_q$. It would seem that use of $B_q$ as a substitute for $e_0$ leads to an improvement in the predictions for Norwegian soft clays.

4. A new soil classification chart involving $Q_t$ and normalised shear wave velocity ($V_{s1}$) or $V_{s1}$ and $\Delta u/\sigma_{v0}'$ is presented. Using this chart it can be seen that the soft clay data is consistent with that of other materials and also is possible to give reliable estimates of the stress history and OCR of the soft clay materials.
Acknowledgements

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List of symbols

\( a = \text{attraction} = c'/\tan \phi' \)

\( c' = \text{effective cohesion} \)

\( e_0 = \text{in situ void ratio} \)

\( f_s = \text{sleeve friction measured during CPTU tests} \)

\( p_a = \text{atmospheric pressure} = 100 \text{ kPa} \)

\( q_c = \text{the measured cone tip resistance} \)

\( q_{net} = \text{net cone resistance} = q_t - \sigma_{v0} \)

\( q_t = \text{corrected cone tip resistance} \)

\( u_0 = \text{ambient pore water pressure} \)

\( u_2 = \text{pore pressure measured during CPTU tests} \)

\( w = \text{natural water content} \)

\( B_q = \text{CPTU pore water pressure parameter} = (u_2-u_0)/q_{net} \)

\( G_{max} = \text{small strain shear modulus} \)

\( I_p = \text{plasticity index} \)

\( K_0 = \sigma_{h0}'/\sigma_{v0}' \)

\( OCR = \text{overconsolidation ratio} \)

\( Q_t = \text{normalised cone resistance} = q_{net}/\sigma_{v0}' \)

\( S_t = \text{sensitivity} \)

\( V_s = \text{shear wave velocity} \)

\( V_{s1} = \text{normalised shear wave velocity} \)

\( \rho = \text{density} \)

\( \sigma_{m}' = \text{mean effective stress} = 1/3 (\sigma_{v0}' + 2\sigma_{h0}') \)

\( \sigma_{v0}' = \text{in situ vertical total stress} \)

\( \sigma_{h0}' = \text{in situ horizontal effective stress} \)
\( \sigma'_{v0} = \text{in situ vertical effective stress} \)

**Table 1. Summary of sites surveyed**

<table>
<thead>
<tr>
<th>Location</th>
<th>Site</th>
<th>Soil type</th>
<th>( V_i ) measured by*</th>
<th>Background references</th>
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<td>Fredrikstad</td>
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<td>soft clay</td>
<td>SCPT / MASW</td>
<td>Lunne et al. (2003), Long and Donohue (2007)</td>
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<td>soft clay</td>
<td>MASW / Raleigh</td>
<td>Lunne and Lacasse (1999), Lunne et al. (1997b)</td>
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<td>SASW</td>
<td>Sandven (1990), Sandven et al. (2004)</td>
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<td>firm to stiff clay</td>
<td>MASW</td>
<td>NGI files</td>
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<td>soft clay</td>
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<td>Bothkennar</td>
<td>soft clay / silt</td>
<td>SCPT / SDMT / MASW / CSW Cross hole</td>
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Table 2. Summary of soil parameters

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<th>Site</th>
<th>w (%)</th>
<th>ρ (Mg/m³)</th>
<th>clay (%)</th>
<th>Ip (%)</th>
<th>s_u (kPa)</th>
<th>S_u (kPa)</th>
<th>OCR</th>
<th>V_s (m/s)</th>
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<td>7 – 8</td>
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<td>31 - 36</td>
<td>13 - 19</td>
<td>10 - 45</td>
<td>7 - 15</td>
<td>1.4 – 2.0</td>
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<td>Eberg</td>
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<td>1.6 – 1.8</td>
<td>42 - 62</td>
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<td>10 - 15</td>
<td>5 - 10</td>
<td>1 – 2</td>
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<td>Berg</td>
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<td>35 - 60</td>
<td>4 - 10</td>
<td>5 - 3</td>
<td>100 - 300</td>
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<td>Tiller</td>
<td>30 - 45</td>
<td>1.8 – 2.0</td>
<td>35 - 40</td>
<td>2 - 8</td>
<td>20 - 65</td>
<td>5 - 1000</td>
<td>2 – 4</td>
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<td>Glava</td>
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<td>30 - 50</td>
<td>7 - 10</td>
<td>4 - 5</td>
<td>100 - 350</td>
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<td>1.9 – 2.0</td>
<td>37 - 48</td>
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<td>60 – 100</td>
<td>2 - 5</td>
<td>2 - 6</td>
<td>175 - 250</td>
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<td>RVII</td>
<td>30 - 40</td>
<td>1.82 – 1.89</td>
<td>28 - 45</td>
<td>8 - 18</td>
<td>15 - 35</td>
<td>7 - 135</td>
<td>1.2 – 2.6</td>
<td>170 - 270</td>
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<td>Troll</td>
<td>19 - 70</td>
<td>1.68 – 2.13</td>
<td>24 - 49</td>
<td>20 - 37</td>
<td>5 - 50</td>
<td>2 – 5.5</td>
<td>1.5</td>
<td>40 - 340</td>
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<td>Bothkennar</td>
<td>66 - 72</td>
<td>1.58 – 1.61</td>
<td>17 - 35</td>
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<td>25 - 35</td>
<td>8 - 13</td>
<td>2</td>
<td>102 - 144</td>
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</table>

1. From fall cone test

2. Only upper Drammen plastic clay encountered.
## Figure captions and Summary of figures

<table>
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<th>Fig. no</th>
<th>Title</th>
<th>Ref.</th>
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<td>Relationship between: (a) $G_{\text{max}}$ normalised by $\sigma'<em>{v0}$ and void ratio $e$ and (b) $G</em>{\text{max}}$ normalised according to Hardin (1978) and Hight and Leroueil (2003) and $e$</td>
<td>DELL/Reports/MASWNorwayHost 06/NormGmaxandvoidratio.grf</td>
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<td>2</td>
<td>Normalised shear modulus $g_{\text{max}}$ versus (a) water content, (b) void ratio and (c) plasticity index</td>
<td>DELL/Reports/MASWNorwayHost 06/gmax.grf</td>
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<td>3</td>
<td>$q_t$ versus $V_s$ for Norwegian soft clay database</td>
<td>DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVs.grf</td>
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<td>4</td>
<td>$V_s$ measured and predicted from (a) original Mayne and Rix (1995) expression and (b) modified version of this expression</td>
<td>DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsMayneandRix.grf</td>
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<tr>
<td>5</td>
<td>$V_s$ measured and predicted from (a) original Simonini and Cola (2000) expression and (b) modified version of this expression</td>
<td>DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsSimandCola.grf</td>
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<tr>
<td>6</td>
<td>$V_s$ measured and predicted from new expression involving $q_t$ and $B_q$</td>
<td>DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsBq.grf</td>
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<td>7</td>
<td>Robertson et al. (1995) soil classification chart with data for Norwegian soft clays</td>
<td>DELL/Reports/CPTUStudy/Phase2/NorskClaysQtG0qtOCR.grf</td>
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<td>8</td>
<td>Possible new classification chart based on $Q_t$ and $V_{s1}$</td>
<td>DELL/Reports/CPTUStudy/Phase2/NorskClaysQtVs1OCR.grf</td>
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<td>9</td>
<td>Possible new classification chart based on $V_{s1}$ and $\Delta u/\sigma'_{v0}$</td>
<td>DELL/Reports/CPTUStudy/Phase2/NorskClaysVs1DeluOCR.grf</td>
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<td>10</td>
<td>Comparison between soft clays, stiff clays and sands on $Q_t \div V_{s1}$ chart</td>
<td>DELL/Reports/CPTUStudy/Phase2/GlobalQtVs1.grf</td>
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**Figures for paper by Long and Donohue on:** Characterisation of Norwegian marine clays with combined shear wave velocity and CPTU data

**Fig. 1.** Relationship between: (a) $G_{\text{max}}$ normalised by $\sigma'_0 v_0$ and void ratio $e$ and (b) $G_{\text{max}}$ normalised according to Hardin (1978) and Hight and Leroueil (2003) and $e$

**Fig. 2.** Normalised shear modulus $g_{\text{max}}$ versus (a) water content, (b) void ratio and (c) plasticity index
Best fit power function
\[ V_s = 2.944q^{0.613} \]
\[ R^2 = 0.630 \]

**Fig. 3.** \( q_t \) versus \( V_s \) for Norwegian soft clay database

\[ \text{Fit on original Mayne and Rix (1995) expression} \]
\[ V_s = 9.44q^{0.435}e^{-0.532} \]
\[ \text{gives } R^2 = 0.690 \]

\[ \text{Fit on modified Mayne and Rix expression} \]
\[ V_s = 65.00q^{0.150}e^{-0.714} \]
\[ \text{gives } R^2 = 0.758 \]

**Fig 4.** \( V_s \) measured and predicted from (a) original Mayne and Rix (1995) expression and (b) modified version of this expression
Fig 5. $G_{\text{max}}$ measured and predicted from (a) original Simonini and Cola (2000) expression and (b) modified version of this expression.

$$G_{\text{max}} = 21.5q_{t}^{0.79}(1+Bq)4.59$$
$$gives \ R^2 = 0.554$$

Fit on modified Simonini and Cola (2000) expression
$$G_{\text{max}} = 4.39q_{t}^{1.225}(1+Bq)^2.53$$
$$gives \ R^2 = 0.799$$

Fig. 6. $V_s$ measured and predicted from new expression involving $q_t$ and $B_q$

$$V_s = 1.961q_t^{0.579}(1+Bq)^{1.202}$$
$$gives \ R^2 = 0.777$$
Fig. 7. Robertson et al. (1995) soil classification chart with data for Norwegian soft clays (material zones extended by authors)

Fig. 8. Possible new classification chart based on $Q_t$ and $V_{s1}$
Fig. 9. Possible new classification chart based on $V_{s1}$ and $\Delta u/\sigma' v_0$

Fig. 10. Comparison between soft clays, stiff clays and sands on $Q_t - V_{s1}$ chart