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Title of paper: Characterisation of Norwegian marine clays with combined shear wave velocity and CPTU data

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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_{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 $\Delta u/\sigma_{v0}'$ 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] $$G_{\max} = \rho V_s^2$$

where ρ = 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_{max} for preliminary design or for verification of in situ or laboratory measurements.

Hardin (1978) suggested that for clays, G_{max} depends on the in situ (or applied) stress (σ'), 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_{max} can then be written as follows:

[2] $$G_{\max} = S \cdot F(e)\left(\sigma_v^{'}\sigma_h^{'}\right)^n p_a^{(1-2n)}$$

where F(e) is a void ratio function, σ_v' and σ_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_{max}/σ_{v0}' typically varies between 200 and 1000 and as expected G_{max}/σ_{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_{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_{max} should be normalised by:

$$[3] \qquad g_{max} = \frac{G_{max}}{\sigma_m` + a}$$

where σ_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_{max} against w, in a similar way to that proposed by Janbu (1985) for oedometer moduli.

Figure 2a shows g_{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_{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_{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_{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_{max} depends on e_0, σ_{v0}' and OCR. Since measured cone resistance (q_c) also depends on σ_{v0}' and OCR, previous researchers have sought a relationship between G_{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_{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:

[4] $V_s(m/s) \approx 0.1 q_c(kPa)$

[5] $G_{\max} = 2.8 q_c^{1.4}$

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:

[6] $G_{\max} = 2.78 q_c^{1.335}$

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_{max} upon e_0, however requires that q_c is only successful as a profiler of G_{max} if e_0 is included in the correlation and they derived empirically the formula:

[7] $G_{\max} = \dfrac{99.5 p_a^{0.305} q_c^{0.695}}{e_0^{1.13}}$

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_{max} had to be calculated from V_s using Equation 1. Mayne and Rix (1995) derived the empirical formulae:

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

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

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:

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

where u_0 = ambient pore pressure and σ_{v0} = total overburden stress

However Simonini and Cola (2000) simply assumed B_q to be the ratio between Δu 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_{max} was obtained when incorporating B_q* as follows:

[11] $$G_{max} = 21.5 q_t^{0.79} \left(1 + B_q^*\right)^{4.59}$$

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:

[12] $V_s = 2.944 q_t^{0.613}$

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 e_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:

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

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:

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

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.

[15] $$V_s = 1.961 q_t^{0.579} \left(1 + B_q\right)^{1.202}$$

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_{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 ($=q_{net}/\sigma'_{v0}$) 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:

[16] $$V_{s1} = \frac{V_s}{\left(\frac{\sigma_{v0}`}{p_a}\right)^{0.5}}$$ (Mayne et al., 1998)

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 /σ_{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 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_{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_{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.

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List of symbols

a = attraction = $c'/\tan\phi'$)

c' = effective cohesion

e_0 = in situ void ratio

f_s = sleeve friction measured during CPTU tests

p_a = atmospheric pressure = 100 kPa

q_c = the measured cone tip resistance

q_{net} = net cone resistance = q_t - σ_{v0}

q_t = corrected cone tip resistance

u_0 = ambient pore water pressure

u_2 = pore pressure measured during CPTU tests

w = natural water content

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

G_{max} = small strain shear modulus

I_p = plasticity index

K_0 = $\sigma'_{h0}/\sigma'_{v0}$

OCR = overconsolidation ratio

Q_t = normalised cone resistance = q_{net}/σ'_{v0}

S_t = sensitivity

V_s = shear wave velocity

V_{s1} = mormalised shear wave velocity

ρ = density

σ'_m = mean effective stress = ⅓ $(\sigma'_{v0} + 2\sigma'_{h0})$

σ_{v0} = in situ vertical total stress

σ'_{h0} = in situ horizontal effective stress

σ'_{v0} = in situ vertical effective stress

Table 1. Summary of sites surveyed

Location	Site	Soil type	V_s measured by*	Background references
Fredrikstad	Onsøy	soft clay	SCPT / MASW	Lunne et al. (2003), Long and Donohue (2007)
Drammen	Danviksgata	soft clay	SCPT / MASW / Raleigh / Cross hole	Lunne and Lacasse (1999), Long and Donohue (2007)
	Lierstranda	soft clay	MASW / Raleigh	Lunne and Lacasse (1999), Lunne et al. (1997b)
Trondheim	Eberg	soft clay	SASW / Seismic ref.	Røsand (1986), Sandven (1990), Langø (1991)
	Berg	firm clay	MASW / Cross hole	Rømoen (2005), Westerlund (1978), Long and Donohue (2007)
	Tiller	soft to firm (quick) clay	SASW	Sandven (1990), Sandven et al. (2004)
Stjørdal	Glava	firm clay	MASW / SASW	Sandven (1990), Sandven and Sjursen (1998), Long and Donohue (2007)
Akershus	Eidsvoll	firm to stiff clay	MASW	NGI files
	RVII	soft clay	MASW	Long et al. (2009)
Offshore west Norway	Troll	soft clay	SCPT	Lunne et al. (2007)
Scotland	Bothkennar	soft clay / silt	SCPT / SDMT / MASW / CSW Cross hole	Hight et al. (1992), Long et al. (2008)

* Terms defined in Introduction

Table 2. Summary of soil parameters

Site	w (%)	ρ (Mg/m^3)	clay (%)	I_p (%)	s_u[1] (kPa)	S_t[1]	OCR	V_s (m/s)
Onsøy	60 - 65	1.635	40 - 60	33 - 40	15 - 35	4.5 - 6	1.5 - 1.3	80 - 140
Danviks-gata[2]	50 - 55	1.72 – 1.78	48	30	18 – 30	7 – 8	1.5	100 - 170
Lier-stranda	32 - 42	1.83 – 1.95	31 - 36	13 - 19	10 - 45	7 - 15	1.4 – 2.0	125 - 175
Eberg	50 - 70	1.6 – 1.8	42 - 62	7 - 11	10 - 15	5 - 10	1 – 2	65 - 175
Berg	25 - 30	2.0	30	7 - 10	35 - 60	4 - 10	5 - 3	100 - 300
Tiller	30 - 45	1.8 – 2.0	35 - 40	2 - 8	20 - 65	5 - 1000	2 – 4	75 - 225
Glava	30 - 35	1.8 – 2.0	30 - 60	15 - 30	30 - 50	7 - 10	4 - 5	100 - 350
Eidsvoll	25 - 35	1.9 – 2.0	37 - 48	13 - 19	60 – 100	2 - 5	2 - 6	175 - 250
RVII	30 - 40	1.82 – 1.89	28 - 45	8 - 18	15 - 35	7 - 135	1.2 – 2.6	170 - 270
Troll	19 - 70	1.68 – 2.13	24 - 49	20 - 37	5 - 50	2 – 5.5	1.5	40 - 340
Both-kennar	66 - 72	1.58 – 1.61	17 - 35	42 - 53	25 - 35	8 - 13	2	102 - 144

1. From fall cone test
2. Only upper Drammen plastic clay encountered.

Figure captions and Summary of figures

Fig. no	Title	Ref.
1	Relationship between: (a) G_{max} normalised by σ'_{v0} and void ratio e and (b) G_{max} normalised according to Hardin (1978) and Hight and Leroueil (2003) and e	DELL/Reports/MASWNorwayHost06/NormGmaxandvoidratio.grf
2	Normalised shear modulus g_{max} versus (a) water content, (b) void ratio and (c) plasticity index	DELL/Reports/MASWNorwayHost06/gmax.grf
3	q_t versus V_s for Norwegian soft clay database	DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVs.grf
4	V_s measured and predicted from (a) original Mayne and Rix (1995) expression and (b) modified version of this expression	DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsMayneandRix.grf
5	V_s measured and predicted from (a) original Simonini and Cola (2000) expression and (b) modified version of this expression	DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsSimandCola.grf
6	V_s measured and predicted from new expression involving q_t and B_q	DELL/Papers/CanGeoJnl/NorskClaysVsqt/qtVsBq.grf
7	Robertson et al. (1995) soil classification chart with data for Norwegian soft clays	DELL/Reports/CPTUStudy/Phase2/NorskClaysQtG0qtOCR.grf
8	Possible new classification chart based on Q_t and V_{s1}	DELL/Reports/CPTUStudy/Phase2/NorskClaysQtVs1OCR.grf
9	Possible new classification chart based on V_{s1} and $\Delta u/\sigma'_{v0}$	DELL/Reports/CPTUStudy/Phase2/NorskClaysVs1DeluOCR.grf
10	Comparison between soft clays, stiff clays and sands on $Q_t - V_{s1}$ chart	DELL/Reports/CPTUStudy/Phase2/GlobalQtVs1.grf

Figures for paper by Long and Donohue on: Characterisation of Norwegian marine clays with combined shear wave velocity and CPTU data

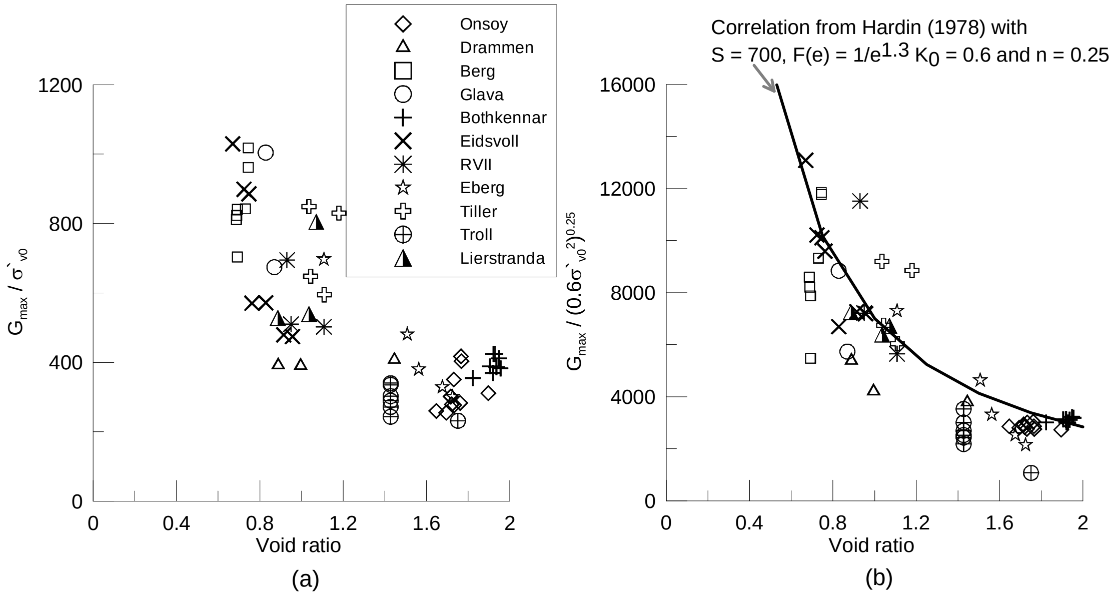

Fig. 1. Relationship between: (a) G_{max} normalised by σ'_{v0} and void ratio e and (b) G_{max} normalised according to Hardin (1978) and Hight and Leroueil (2003) and e

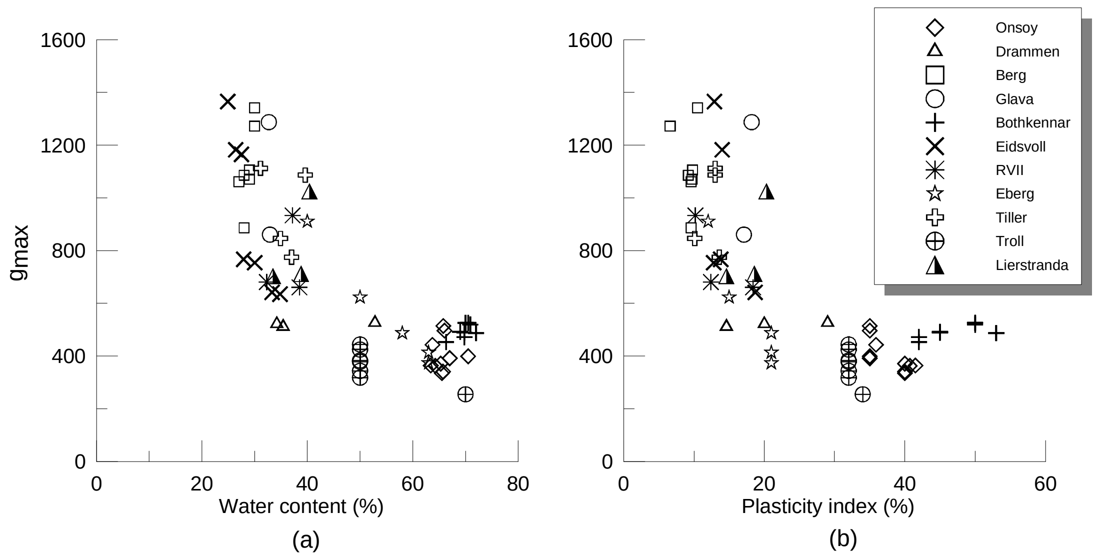

Fig. 2. Normalised shear modulus g_{max} versus (a) water content, (b) void ratio and (c) plasticity index

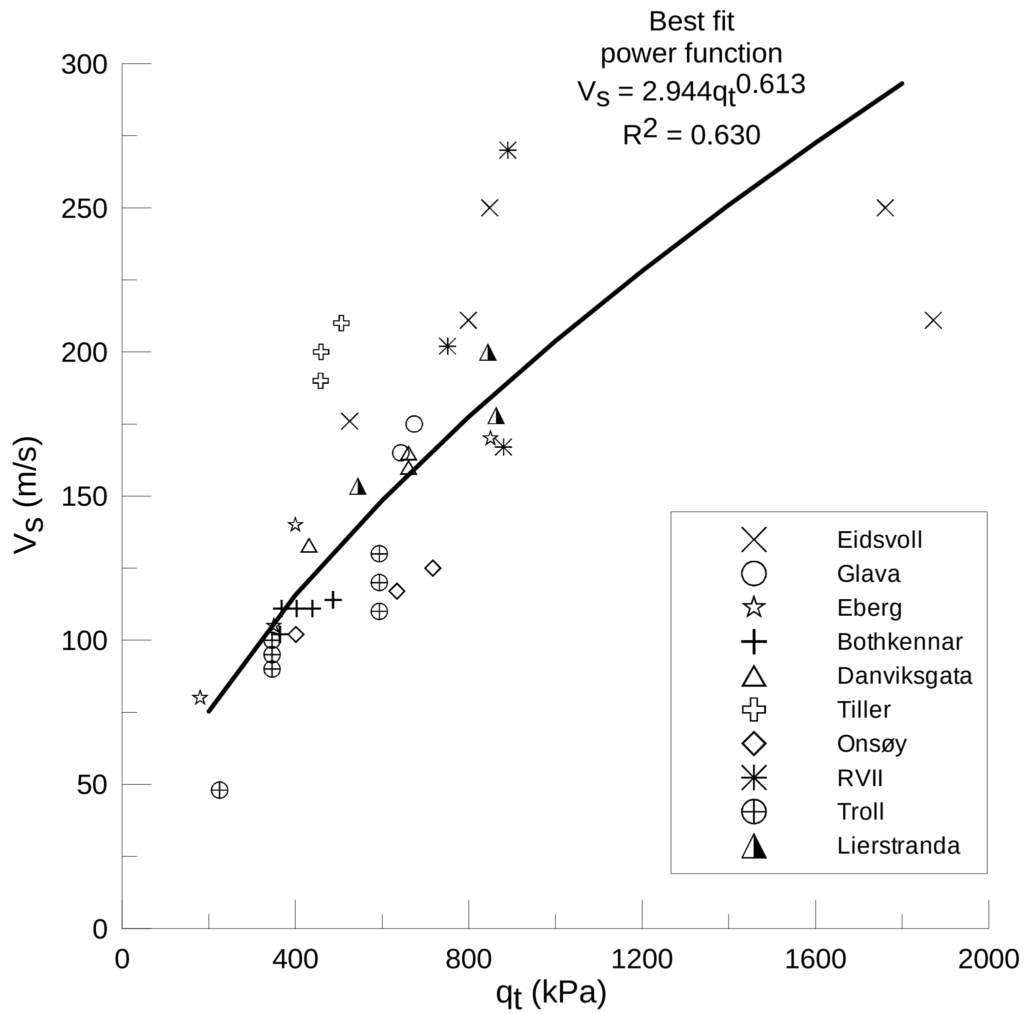

Fig. 3. q_t versus V_s for Norwegian soft clay database

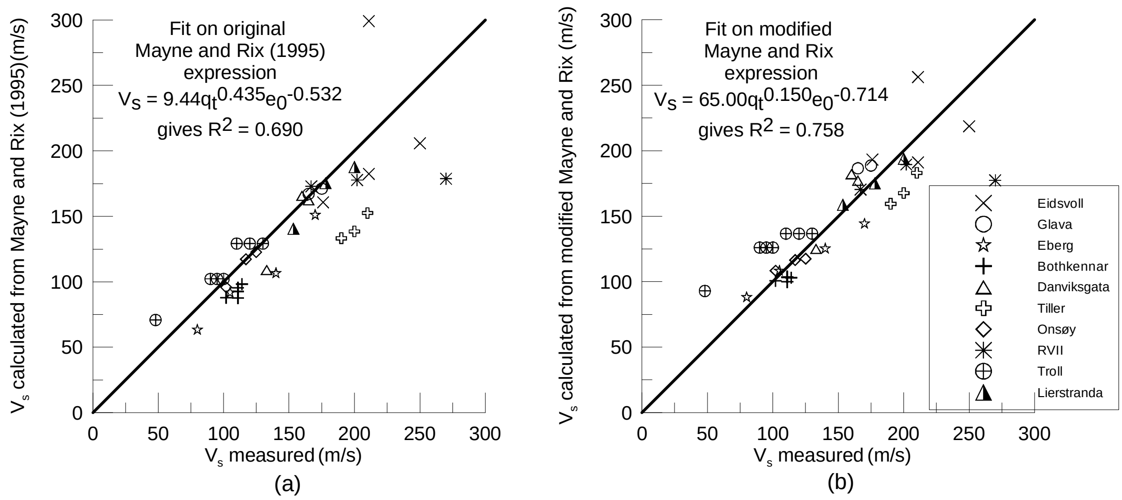

Fig 4. V_s measured and predicted from (a) original Mayne and Rix (1995) expression and (b) modified version of this expression

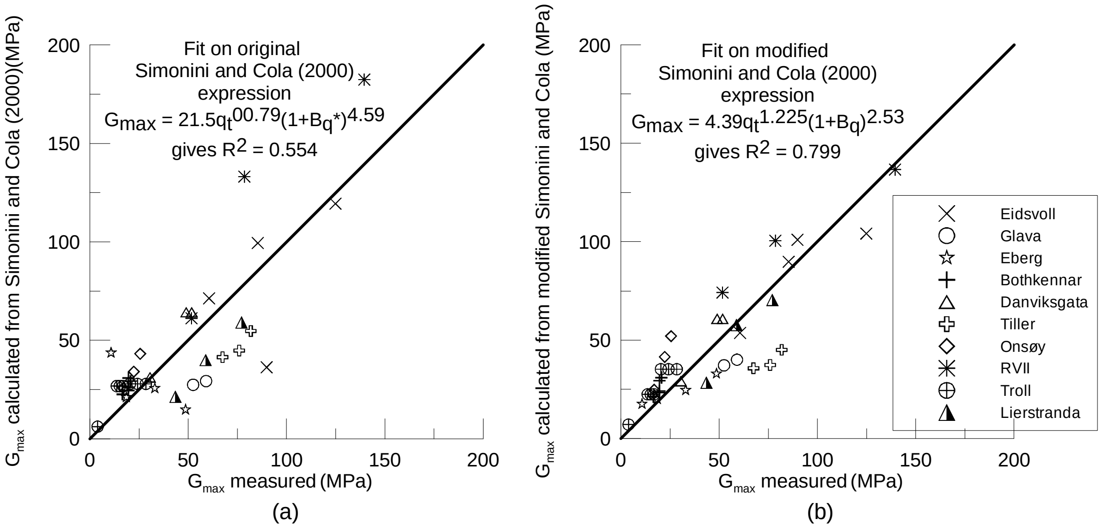

Fig 5. G_{max} measured and predicted from (a) original Simonini and Cola (2000) expression and (b) modified version of this expression

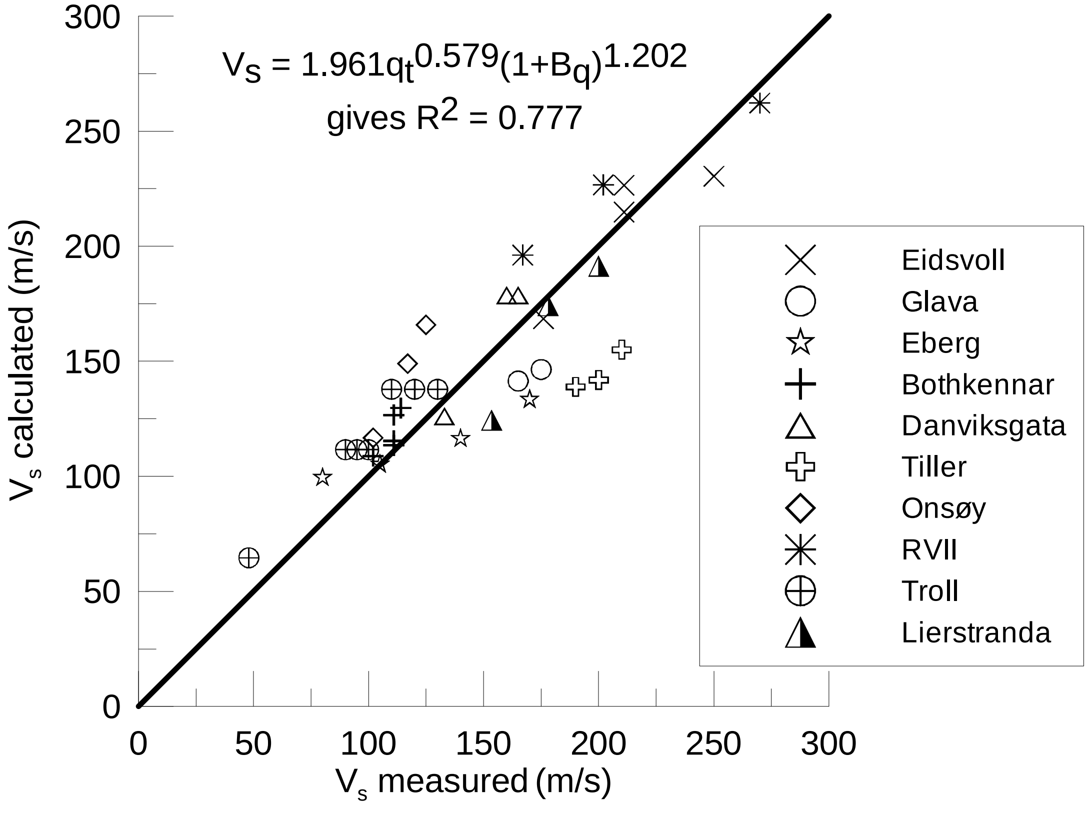

Fig. 6. V_s measured and predicted from new expression involving q_t and B_q

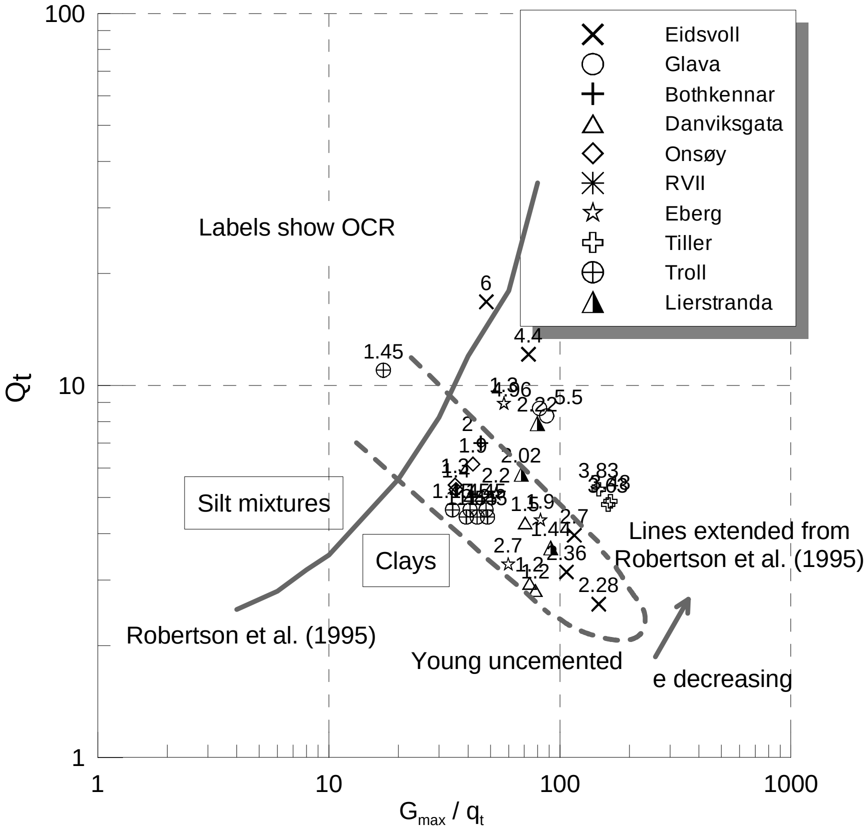

Fig. 7. Robertson et al. (1995) soil classification chart with data for Norwegian soft clays (material zones extended by authors)

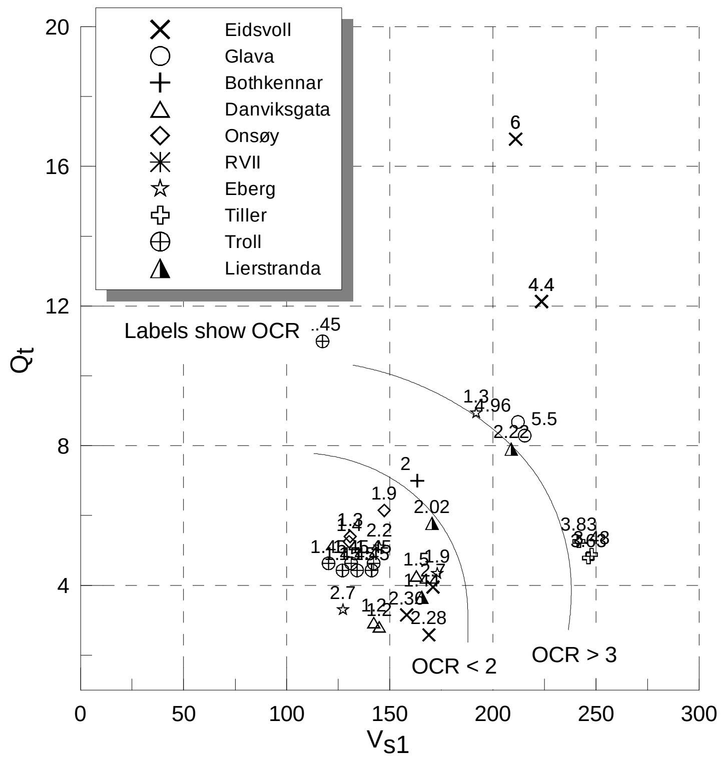

Fig. 8. Possible new classification chart based on Q_t and V_{s1}

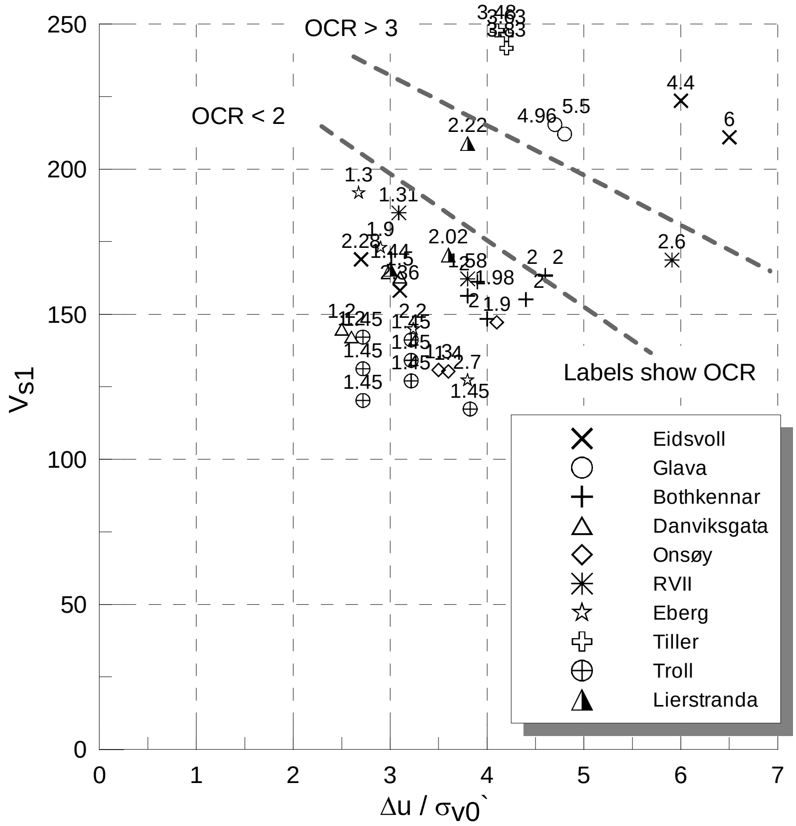

Fig. 9. Possible new classification chart based on V_{s1} and $\Delta u/\sigma'_{v0}$

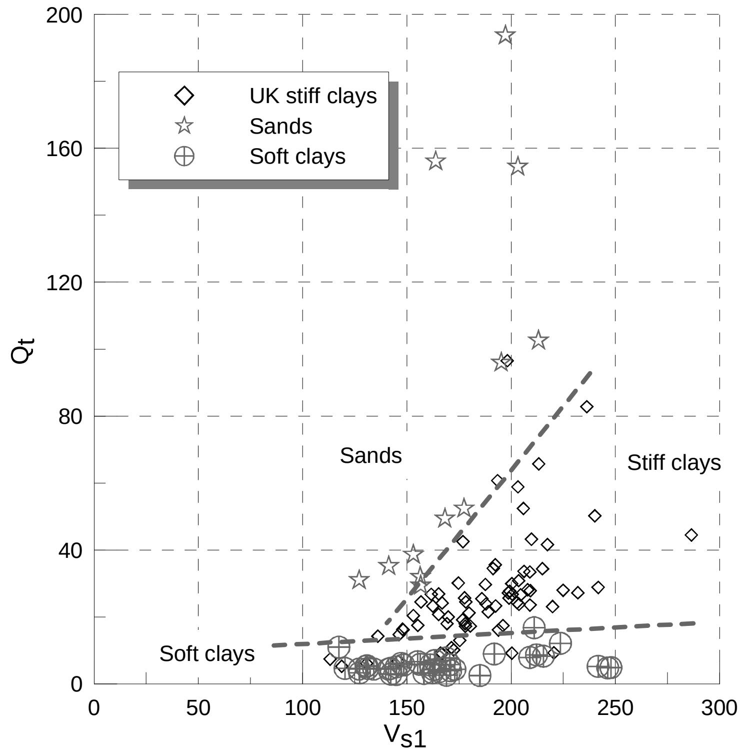

Fig. 10. Comparison between soft clays, stiff clays and sands on $Q_t - V_{s1}$ chart