IN SITU SHEAR WAVE VELOCITY FROM MASW SURFACE WAVES AT NORWEGIAN SOFT CLAY SITES

Michael Long, Shane Donohue

School of Architecture, Landscape and Civil Engineering, University College Dublin (UCD), Earlsfort Terrace, Dublin 2, Ireland (Mike.Long@ucd.ie and Shane.Donohue@ucd.ie). Phone: +353-1-7167333. Fax: 353-1-7167399.

Abstract: The Multichannel Analysis of Surface Waves (MASW) technique, used to determine shear wave velocity (V_s) and hence small strain stiffness (G_{max}), has recently generated considerable interest in the geophysics community. This is because of the ease of carrying out the test and analysis of the data. The objective of this work was to assess the repeatability, accuracy and reliability of MASW surface wave measurements for use in engineering studies. Tests were carried out at 5 well-characterised Norwegian soft clay research sites where V_s had already been assessed using independent means. As well as being easy and quick to use MASW gave consistent and repeatable results. The MASW V_s profiles were similar to those obtained from other techniques. This work also confirms that MASW V_s clay profiles are comparable to those obtained by correlation with CPT. For these sites there also seems to be a good correlation between normalised small strain shear modulus and in situ void ratio or water content and the data fit well with published correlations for clays.

LIST OF SYMBOLS

a – attraction = $c'/\tan\phi'$),
c' – effective cohesion,
e_0 – in situ void ratio,
p_a – atmospheric pressure,
q_c – the measured cone tip resistance,
s_u – undrained shear strength,
w – natural water content,
z – depth of penetration of wave,
G_{max} – small strain shear modulus,
I_p – plasticity index,
$K_0 = \sigma'_{h0}/\sigma'_{v0}$,
M – oedometer constrained modulus = change in stress/change in strain ($\Delta\sigma'_v/\Delta\varepsilon$),
OCR – overconsolidation ratio,
S_t – sensitivity,
V_s – shear wave velocity,
ϕ' – in situ peak friction angle,
λ – wavelength,
ρ – density,
σ'_m – mean effective stress,
σ'_v – vertical effective stress.

1. INTRODUCTION

The measurement of the small strain shear modulus G_{max} of a soil is important for a range of geotechnical design applications. This usually involves strains of 10^{-3}% and less. According to elastic theory G_{max} may be calculated from the shear wave velocity using the following equation:

$$G_{max} = \rho \cdot V_s^2,$$ (1)

where:

G_{max} – shear modulus (Pa),
V_s – shear wave velocity (m/s),
ρ – density (kg/m^3).

Recently several researchers, e.g., Kaufmann et al. [13] (for shallow marine sediments), Harry et al. [8] (for a fluvial aquifer), Donohue et al. [4], [5] (for very stiff Irish glacial till and very soft clays and silts from Central Ireland, respectively) and Park et al. [24], have shown that V_s (and hence G_{max}) can be obtained cheaply and reliably using the Multichannel Analysis of Surface Waves (MASW) method.

The MASW technique has generated considerable interest in the geophysics community. In his editorial in a recent special edition of *Journal of Environmental and Engineering Geophysics*, Crice [3] suggests that "MASW is the wave of the future because of the usefulness and interpretability of the data and the potential for dramatically higher productivity".

The objective of this paper is to present the results of some MASW surveys carried out during the autumn of 2005 at five well-characterised Norwegian soft clay research sites. As other independent data for V_s and G_{max} exists for all of these sites the main objective of the study was to assess the reliability and accuracy of the MASW technique.

Note that much of the data presented in this paper has previously been published in a paper to *Canadian Geotechnical Journal* by Long and Donohue [16]. In this paper, focus has been placed on the clay sites and in particular additional data has been presented for the Onsøy research site.

2. MASW TECHNIQUE

2.1. SURFACE WAVE ANALYSIS METHODS

The steady state Rayleigh wave/Continuous Surface Wave (CSW) technique was introduced by Jones [12] into the field of geotechnical engineering. It was subse-

quently developed by others, such as TOKIMATSU et al. [31] and MATHEWS et al. [20]. The CSW method uses an energy source such as vibrator to produce surface waves.

In the early 1980's, the widely used Spectral Analysis of Surface Waves (SASW) method was developed by HEISEY et al. [9] and by NAZARIAN and STOKOE [23]. The SASW method uses a single pair of receivers that are placed collinearly with an impulsive source (e.g., a sledgehammer). The test is repeated a number of times for different geometrical configurations. CRICE [3] acknowledges the usefulness of SASW but suggests that solutions are neither unique nor trivial and that an expert user is required for interpretation. LO PRESTI et al. [17] and SOCCODATO [29] compared V_s derived from SASW with that obtained from other techniques for Pisa clay and Fucino clayey soil, respectively. Reasonable agreement was found in both cases.

The MASW technique was introduced in the late 1990's by the Kansas Geological Survey (PARK et al. [24]) in order to address the problems associated with SASW. The MASW method exploits multichannel recording and processing techniques that are similar to those used in conventional seismic reflection surveys. The MASW method has improved production in field due to multiple transducers, and improved characterisation of dispersion relationship by sampling spatial wave-field with multiple receivers. Advantages of this method include the need for only one-shot gather and its capability of identifying and isolating noise.

CRICE [3] illustrates how MASW survey data can be reliably interpreted by computer software without human intervention. The authors have found that this is only accurate for simple soil profiles. Significant user experience and intervention are required for more complex profiles as the inversion formulation in MASW can suffer the same uniqueness problems as in SASW. In the view of the authors an informed user is certainly important for MASW data analysis. The MASW method was used for the recording and processing of surface wave data for all eight sites discussed in this paper.

2.2. SHEAR WAVE VELOCITIES FROM SURFACE WAVES

The type of surface wave that is used in geotechnical surface wave surveys is the vertically polarised Rayleigh wave. In a non-uniform, heterogeneous medium, the propagation velocity of a Rayleigh wave is dependent on the wavelength (or frequency) of that wave. The Rayleigh waves with short wavelengths (or high frequencies) will be influenced by material closer to the surface than the Rayleigh waves with longer wavelengths (or low frequencies), which reflect properties of deeper material. This dependence of phase velocity on frequency is called *dispersion*. Therefore by generating a wide range of frequencies, surface wave surveys use dispersion to produce velocity and frequency (or wavelength) correlations called *dispersion curves*.

After production of a dispersion curve the next step involves the inversion of this curve using the software Surfseis, which was developed by the Kansas Geological

Survey (XIA et al. [33]). Surfseis performs the inversion procedure using a least-squares technique. Through analysis of the Jacobian matrix Xia et al. investigated the sensitivity of Rayleigh wave dispersion data to various earth properties. S wave velocities are the dominant influence on a dispersion curve in a high frequency range (>5 Hz). The inversion method produced by Xia et al. is an iterative method. An initial ten-layer earth model (S wave velocity, P wave velocity, density and layer thickness) is assigned automatically by the software at the start of the iterative inversion process. These layer properties are chosen by the software using the measured wavelength or frequency. The user has the option to intervene and set values if desired. A synthetic dispersion curve is then generated. Due to its influence on the dispersion curve, only the shear wave velocity is updated after each iteration until the synthetic dispersion curve closely matches the field curve.

2.3. TEST TECHNIQUE

An impulsive source (sledgehammer) was used to generate the surface waves. Seismic data was recorded using a RAS-24 seismograph and the corresponding Seistronix software. The field configuration (i.e., the number and spacing of geophones, geophone frequency, source offset) for each of the sites is detailed in the following sections. Typically the test configuration comprised either twenty-four 10 Hz geophones or twelve 4.5 Hz geophones spaced at 1 m centres over the survey length, see table 3. Although the 4.5 Hz geophones were used on the sites with the softest soils it was found that they provided little advantage over the higher frequency instruments. For the 10 Hz geophones the lower frequency level was not limited by their natural frequency and they could detect signals as low as 5 Hz. With the 4.5 Hz geophones the lowest recordable frequency was 2 Hz to 3 Hz. A similar finding is reported by PARK et al. [25], who discuss optimum acquisition parameters for MASW surveying.

3. THE SITES

A summary of the five sites surveyed is given in table 1 and their locations are shown in figures 1 and 2. These sites are all underlain by soft to firm homogeneous clay. Soil parameters for the eight sites are summarised in table 2.

Different MASW test parameters were used at each site depending on the site conditions and the physical constraints. These parameters are summarised in table 3.

Of all the sites surveyed that at Onsøy is perhaps the most uniform and well-characterised so most effort was placed on the work at this site. The Onsøy test site is the main soft clay research site currently used by the Norwegian Geotechnical Institute (NGI). Extensive research work has been carried out on the site since the late

1960's. It is located about 100 km southeast of Oslo, just north of the city of Fredrik-stad, see figure 2a. The site is underlain by very uniform marine clays of the order of 40 m in thickness and it is described in detail by LUNNE et al. [19].

Table 1

Summary of sites surveyed

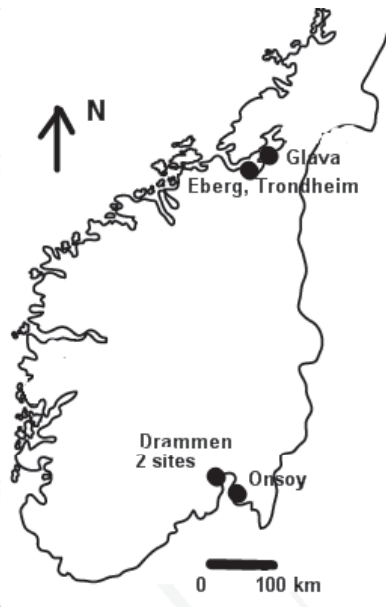| Location	Site	Soil type	Background references
Fredrikstad	Onsøy	soft clay	LUNNE et al. [19]
Drammen	Museum Park	soft clay	LUNNE and LACASSE [18]
	Danvikgata	as above	as above
Trondheim	Eberg	firm clay	ROMOEN [27], WESTERLUND [32]
Stjørdal	Glava	firm clay	SANDVEN [27], SANDVEN and SJURSEN [28]

Fig. 1. Location of sites in Norway

Similar to Onsøy extensive research has been carried out on the properties of Drammen clay by NGI since the early 1950's. The city of Drammen is some 50 km southwest of Oslo as shown in figure 2b. Over the top 10 m (zone of most interest here) the area is underlain by plastic Drammen clay ($I_p \approx 30\%$). A good summary of the properties of Drammen clay is given by LUNNE and LACASSE [18]. Two Drammen clay sites were surveyed, i.e., those located close to the city centre at Danvikgata and Museum Park.
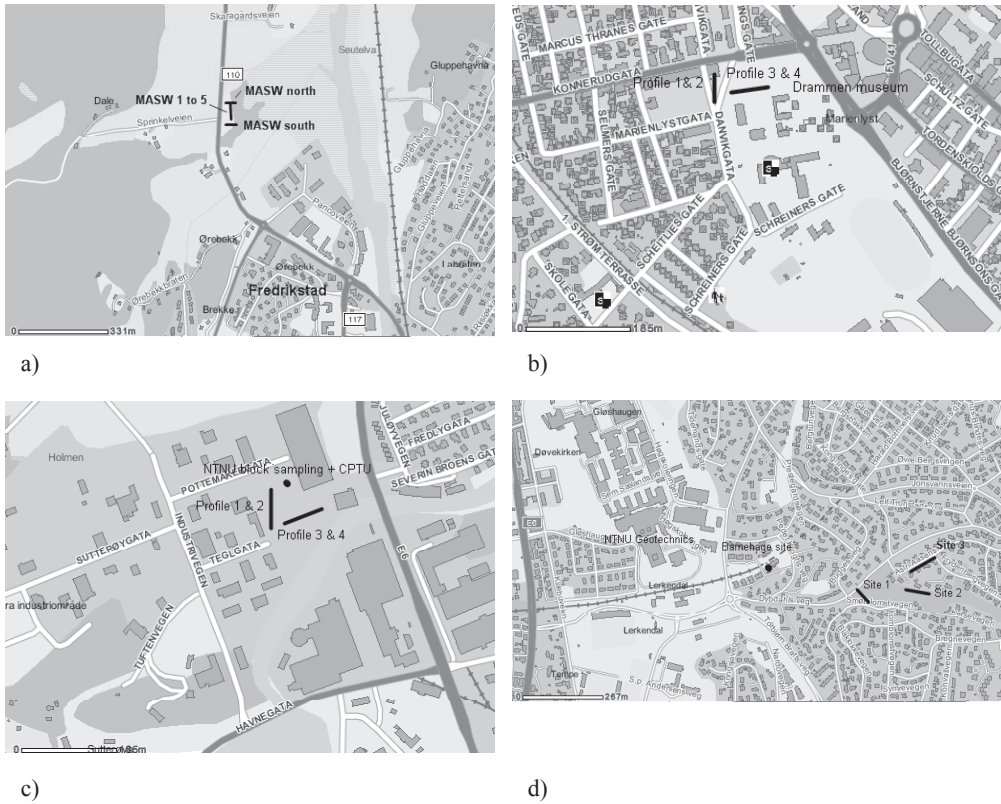
a)

b)

c)

d)

Fig. 2. Detailed plans of test locations: Onsøy (a), Drammen (b), Glava (c) and Eberg (d).
Maps courtesy Geodata AS, Norway (www.finn.no)

Table 2

Summary of soil parameters

Site	w (%)	ρ (Mg/m³)	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
Drammen sites[2]	50–55	1.72–1.78	48	30	18–30	7–8	1.5	100–170
Glava	30–35	1.8–2.0	30–60	15–30	30–50	7–10	4–5	100–350
Eberg	25–30	2.0	30	7–10	35–60	4–10	5–3	100–300

[1] From fall cone test.

[2] Two sites surveyed. Only upper Drammen plastic clay encountered.

Glava clay has been investigated by researchers at the Geotechnics Division of the Norwegian University of Science and Technology (NTNU, formerly NTH) since the

mid 1980's (e.g., SANDVEN [27], SANDVEN and SJURSEN [28]). This research site is located on the west side of the town of Stjørdal, which is about 35 km northeast of Trondheim, see figure 2c.

T a b l e 3

MASW test parameters at each site

Site	Number of geophones	Geophone spacing (m)	Geophone frequency (Hz)	Source receiver offset (m)	Depth of penetration (m)
Onsøy N-S	24	1	10	0, 2, 4	16.2
Onsøy E-W	12	1	4.5	0, 2, 4	12.3
Drammen sites	24	1	10	0, 2	10.6 / 10.4
Glava	24	1	10	0, 2	14.3
Eberg – Site 1	12	1	4.5	0, 2, 4, 8	10.3
Eberg – Site 2	12	1	4.5	0, 2, 3, 5	12.5
Eberg – Site 3	12	1.5	4.5	0, 2	11.1

Eberg clay has also been the subject of research at NTNU for some 30 years and results of tests in the Eberg area have been reported in many studies (e.g., JANBU [11]). The sites are located close to the NTNU campus and in a heavily developed part of Trondheim, see figure 2d. Therefore it has been necessary to test clay at several different locations in the general area. A new test site has recently been established (ROMOEN [26]).

4. RESULTS

4.1. ONSØY

A total of 7 MASW survey profiles were carried out at Onsøy. Test locations are shown diagrammatically in figure 2a and in detail (using the NGI grid references) in figure 3. Five of the tests were in a north-south direction and two in an east-west direction at the north and south ends of the test area. The locations were chosen to be as close as possible to relevant previous work on the site (seismic cone tests, cone penetration tests and block sampling). Test results are shown in figure 4. It can be seen that the test results are consistent and repeatable and clearly reflect the uniformity of the site. Below about 12 m the scatter between the different MASW profiles increases but then remains relatively constant with depth. Also below this level the thickness of individual layers that were determined from inversion increases with depth. A similar result has been reported by others for both SASW and MASW (e.g., STOKOE et al. [30], PARK et al. [24] and KAUFMANN et al. [13]). Independently carried out seismic

CPT (SCPT) data, by the University of British Columbia, was also available (EIDSMOEN et al. [6] and LUNNE et al. [19]) and these data are also shown in figure 4a. As for the MASW results the SCPT data are consistent. There is some small scatter in these data but overall it can be seen that for all practical purposes the V_s profiles from MASW and SCPT are alike.
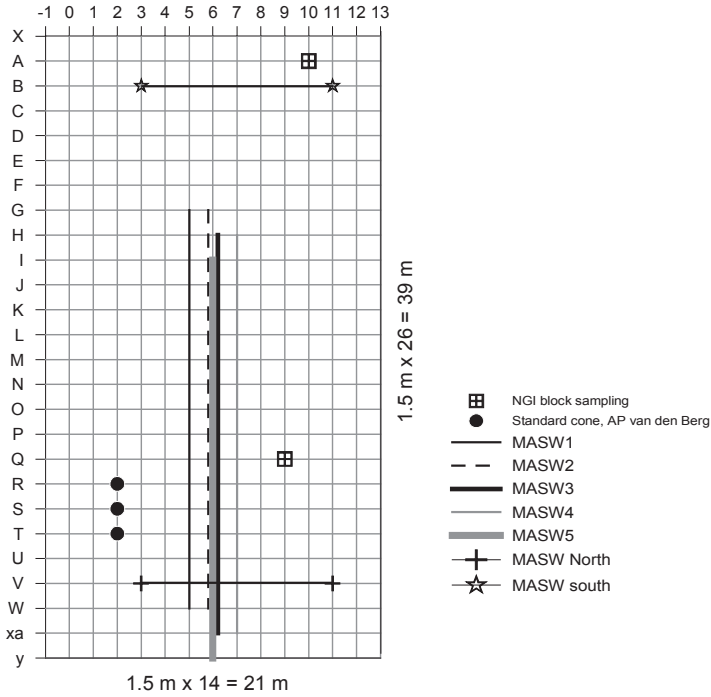

Fig. 3. Detailed test location for Onsøy site shown on NGI grid

MAYNE and RIX [21] suggested G_{max} can be derived empirically from CPT (cone penetration test) data using the measured cone tip resistance (q_c) and the empirically derived formula:

$$G_{max} = \frac{99.5 p_a^{0.305} q_c^{0.695}}{e_0^{1.13}}, \qquad (2)$$

where:
  q_c – the measured cone tip resistance (kPa),
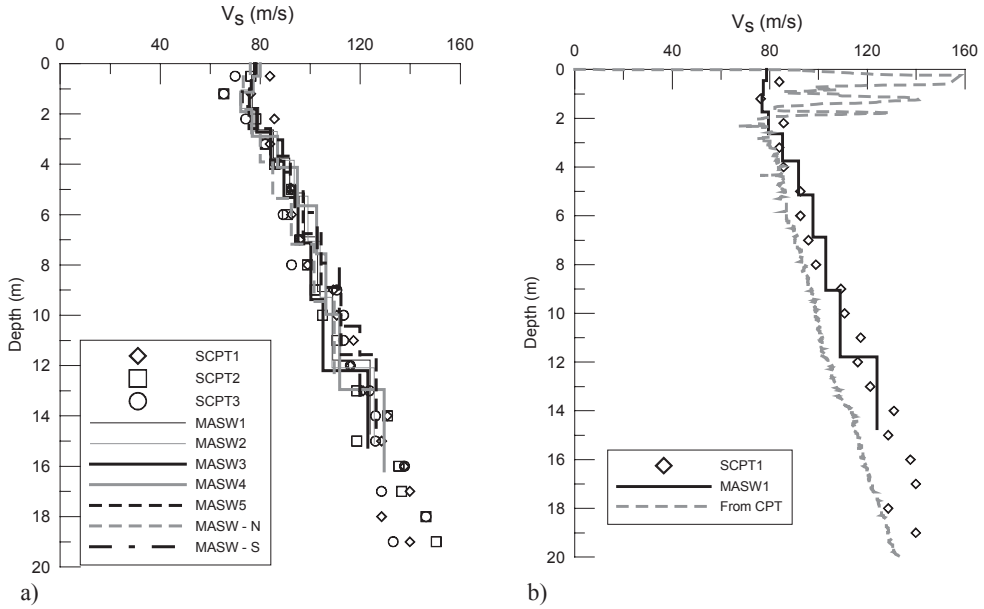 p_a – atmospheric pressure,
  e_0 – in situ void ratio.

Fig. 4. Test results for Onsøy clay: all data (a), comparison with CPT (b)

This correlation was based 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. In a later paper, MAYNE and RIX [22] 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 formula (1). MAYNE and RIX [22] derived the empirical formula:

$$V_s = 9.44 q_c^{0.435} e_0^{-0.532} , \tag{3}$$

where the units of V_s = m/s and q_c = kPa.

A comparison between SCPT, MASW and empirically derived V_s values from a typical CPT (test used here was Onsøy Test a.p. van den Berg, Icone1) is shown in figure 4b. The agreement is good, perhaps not surprisingly in this case as Onsøy was one of the sites used in the MAYNE and RIX [22] study.

4.2. DRAMMEN

Two Drammen clay sites were surveyed, i.e., those located close to the city centre, within about 40 m of one another, at Danvikgata (Profiles 1 and 2) and Museum Park (Profiles 3 and 4). Individual profiles were within 1 m of one another. These sites

were chosen to be as close as possible to other relevant work. MASW tests results together with the other available data are summarised in figures 5a and 5b, respectively. It can be seen that there is good consistency between the two adjacent MASW profiles at each location. V_s values for Danvikgata are slightly lower than those at Museum Park over the top 4 m to 5 m but below this the results are more or less identical. Below 8 m to 10 m the resolution of the recorded data, as evident in the greater scatter between the individual MASW profiles and the increase in layer thickness produced by inversion, is somewhat lower than for the shallower zone.
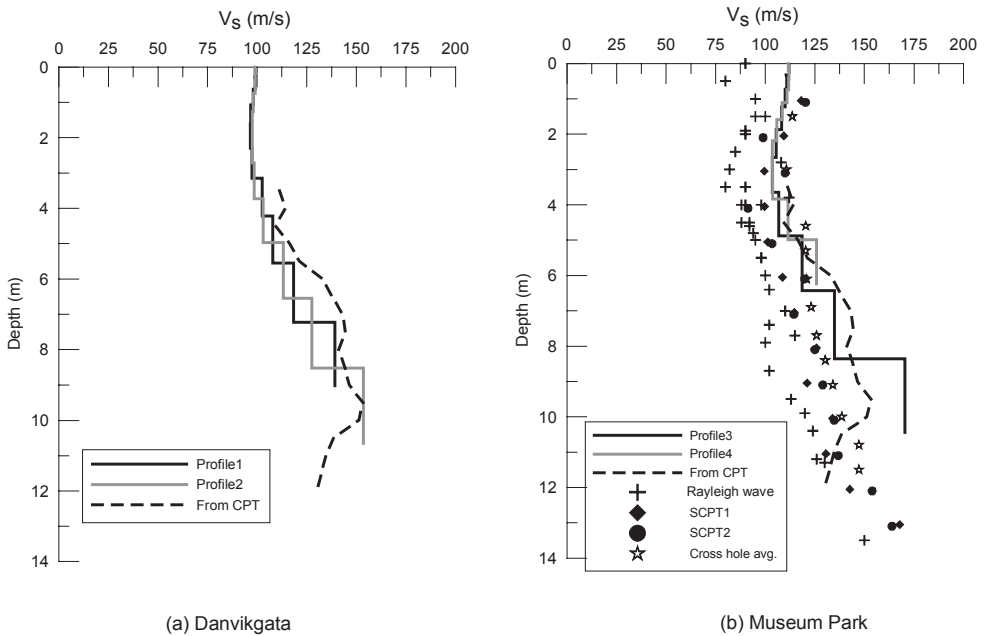

Fig. 5. Test results for Drammen clay sites: Danvikgata (a) and Museum Park (b)

V_s values derived from the Rayleigh wave tests (BRE [1], BUTCHER and POWELL [2]), from seismic CPT tests and from cross-hole seismic tests (EIDSMOEN et al. [6] and LUNNE and LACASSE [18]) are also available for the Museum Park site, as can be seen in figure 5b. The lowest V_s values (by some 15% to 20%) are given by the Rayleigh wave measurements.

There is generally good agreement between the MASW values and the cross-hole seismic values over the top 8 m. Below 8 m the MASW values are some 30% larger than those from cross-hole or SCPT. The SCPT data are more scattered and show good agreement with the Rayleigh wave measurements over the top 6 m but come closer to the cross-hole data below this depth.

A comparison between MASW and empirically derived V_s values from CPT (data from EIDSMOEN et al. [6]) is also shown in figure 5. The agreement is good, perhaps not surprisingly, as was the case for Onsøy, the Drammen site was used in the MAYNE and RIX [22] study.

4.3. GLAVA, STJØRDAL

Four profiles were taken at this site adjacent to previous CPT and block sample locations, and the results are presented in figure 6. There is a high degree of consistency between the results from the 4 profiles with V_s value being more or less identical. Again below 10 m to 12 m the data shows lower resolution.
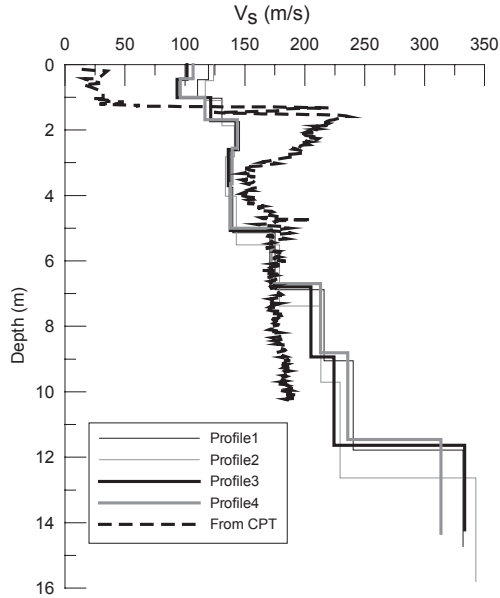

Fig. 6. Test results for Glava clay, Stjørdal

No independent V_s measurements are available for Glava and for this site it is only possible to compare the measured V_s profiles to those derived empirically from CPT, as shown in figure 6. This is considered to be a reliable approach based on the good results for Onsøy and Drammen. There is reasonable agreement between the two data sets between 5 m and 7 m. Below 7 m the CPT values (from SANDVEN [27]) tend to underestimate V_s and do not show the same trend of increasing V_s with depth.

4.4. EBERG

Three MASW profiles were carried out in the new test site area and the results are shown in figure 7. V_s values at Site 1 can be seen to be lower than those from the other 2 locations. At this site several meters of fill material is present due to works on the adjacent road. At the other two locations little or no fill is found.
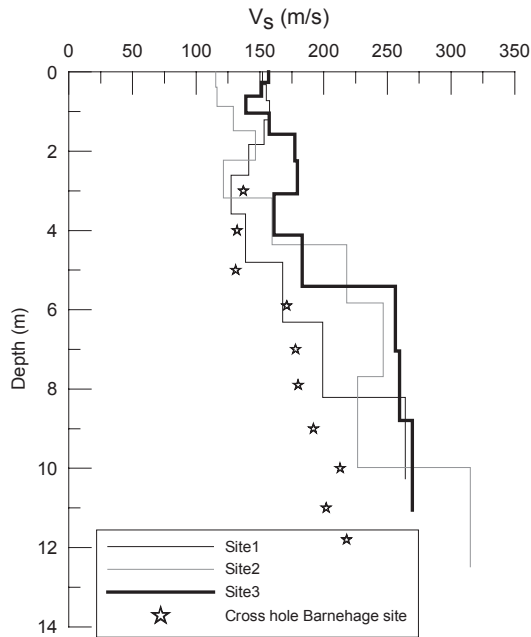

Fig. 7. Test results for Eberg

Cross-hole test data from WESTERLUND [32] are also shown in figure 7. These data were from the Barnehage site, which is located closest to and within about 250 m of Site 1. No fill was present at the Barnehage site and the agreement between MASW for Site 1 and the cross-hole is good, particularly above 8 m depth.

4.5. QUANTITATIVE ANALYSIS OF DATA

A quantitative analysis of the data is given in table 4. MASW results are compared with the other techniques over specific depth intervals. Not surprisingly MASW and SCPT or cross-hole data are in the closest agreement as all three techniques involve direct measurements of V_s. Typically MASW V_s is 7% higher than that obtained from SCPT or cross hole. More variable results are obtained for comparisons with CPT. On

average MASW V_s is between 5% greater and 17% less than corresponding V_s values derived from CPT.

Quantitative analysis of data

Site	Depth range (m)	MASW compared with	Percentage by which MASW V_s is higher
Clay sites			
Onsøy	> 3	SCPT	0
	> 3	CPT	10
Drammen Danvikgata	3.5–10	CPT	−8
Drammen Museum Park	1–6	SCPT	0
	6–10	SCPT	10
	1–6	cross hole	0
	6–10	cross hole	15
	all	CPT	0
Glava	2–5	CPT	−25
	5–7	CPT	0
	7–10	CPT	11
Eberg	3–6	cross hole	0
	6–12	cross hole	25

5. CORRELATIONS FOR CLAYS

It may be worth attempting some correlations between G_{max} (derived from V_s MASW) for the clay sites so that in future projects rapid estimates can be made for preliminary design and so that in situ or laboratory measurements can be verified. HARDIN [7] suggested that for clays, G_{max} depends on the in situ (or applied) stress (σ'), void ratio (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 void ratio and could be neglected (LEROUEIL and HIGHT [15]). The empirical equation describing the influence of the controlling factors on G_{max} can then be written as follows:

$$G_{max} = SF(e)(\sigma'_v \sigma'_h)^n P_a^{(1-2n)}, \qquad (4)$$

where:

$F(e)$ – a void ratio function,
n – a parameter indicating the influence of stress,
P_a – atmospheric pressure,
S – a dimensionless parameter characterising the soil under consideration.

For this work use was made only of the highest quality samples, i.e., Sherbrooke block samples for Onsøy, Drammen and Glava and thin-walled 54 mm steel tube sam-

ples for Eberg. Initially V_s values corresponding to sample depths were chosen and G_{max} calculated using the sample density and equation (1). Void ratio was calculated for the measured bulk density, water content and specific gravity. G_{max} values were then normalised by the corresponding in situ vertical effective stress (σ'_{v0}) (σ'_{v0}). G_{max}/σ'_{v0} typically varies between 250 and 1000. The relationship between G_{max}/σ'_{v0} against e is shown in figure 8a. As expected G_{max}/σ'_{v0} decreases with increasing e in a similar manner to that described by others, e.g., JAMIOLKOWSKI et al. [10], for a variety of soils.
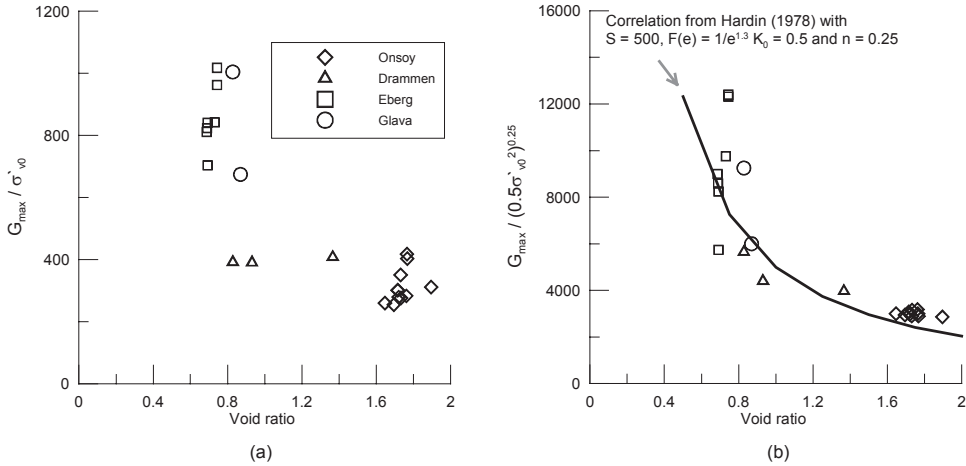

Fig. 8. Relationship between: G_{max} normalised by σ'_{v0} and void ratio e (a)
and G_{max} normalised according to HARDIN [7] and LEROUEIL and HIGHT [15] and e (b)

In figure 8b, the data has been normalised as suggested by HARDIN [7] and LEROUEIL and HIGHT [15], as described in equation (4). A line has been added corresponding to $S = 500$, $F(e) = 1/e^{1.3}$, $K_0 = 0.5$ and $n = 0.25$. It can be seen that the fit is good confirming that G_{max} values for Norwegian clays are consistent with a large volume of other published experimental data.

Norwegian practice (see, for example, JANBU [11]) is to normalise G_{max} 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 [14] suggested that G_{max} should be normalised by:

$$g_{max} = \frac{G_{max}}{\sigma'_m + a}, \qquad (5)$$

where σ'_m and a are the 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 in situ water content, in

a similar way to that proposed by JANBU [11] for oedometer moduli. Langø's data are shown in figure 9a and it can be seen that g_{max} is almost uniquely dependent on w. Note the data includes some from three of the sites under consideration in this paper.
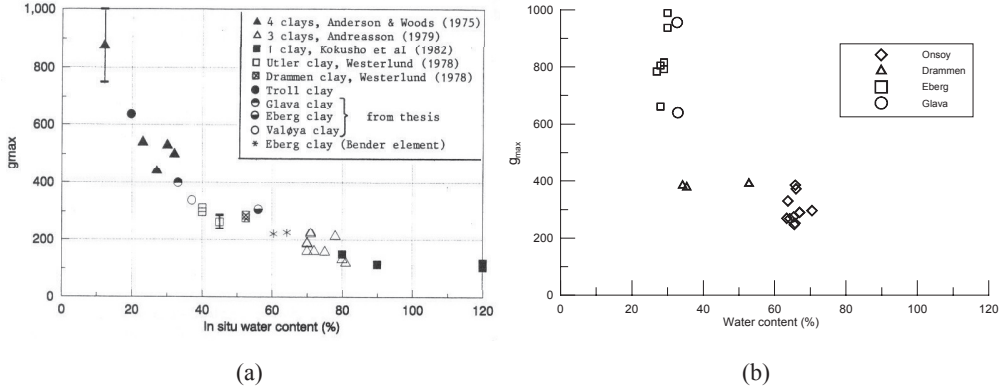

Fig. 9. Normalised shear modulus g_{max} versus water content from LANGØ [14] (a) and this study (b)

Data obtained during this study are shown in figure 9b. Here the data were normalised by the vertical effective stress (σ'_v) and attraction was assumed to equal 3 kPa (typical value for the clays under study from JANBU [11]). A reasonable correlation between g_{max} and w can be seen.

6. CONCLUSIONS

The objective of this work was to assess the repeatability, accuracy and reliability of MASW surface wave measurements made at five well-characterised Norwegian soft clay research sites. The following conclusions can be made:

1. The MASW technique was easy and quick to use and gave consistent and repeatable results.

2. MASW V_s profiles were, for all practical purposes, similar to those obtained from other techniques.

3. V_s values, derived from MASW, are typically 7% greater than those obtained from SCPT or cross-hole tests.

4. MASW V_s profiles are similar to those obtained by correlation with CPT using the procedure developed by MAYNE and RIX [22].

5. There seems to be a good correlation between normalised small strain shear modulus (either G_{max}/σ'_{v0} or g_{max}) and in situ void ratio or water content. Data for the Norwegian clays are consistent with the well-known relationship of HARDIN [7].

ACKNOWLEDGEMENTS

REFERENCES

[1] BRE, *Rayleigh wave measurements at Lierstranda, Holmen and Museumpark in Drammen, Norway*, Factual Report, Report G/GP/9015, 1990.

[2] BUTCHER A.P., POWELL J.J.M., *Practical considerations for field geophysical techniques used to assess ground stiffness*, [in:] *Advances in Site Investigation Practice*, Thomas Telford London, 1996, pp. 701–715.

[3] CRICE D., MASW, *The wave of the future*, Journal of Environmental and Engineering Geophysics, 2005, **10** (2), pp. 77–79.

[4] DONOHUE S., GAVIN K., LONG M., O'CONNOR P., G_{max} *from multichannel analysis of surface waves for Dublin boulder clay*, [in:] Proceedings of 13th. ECSMGE, Prague, 2003, Vanicek et al., eds., **2**, published by CGtS, Prague, pp. 515–520.

[5] DONOHUE S., LONG M., O'CONNOR P., GAVIN K., *Use of multichannel analysis of surface waves in determining G_{max} for soft clay*, [in:] Proceedings 2nd. Int. Conf. on Geotechnical Site Characterisation, ISC'2, Porto, published by MillPress, September 2004, **1**, pp. 459–466.

[6] EIDSMOEN T., GILLESPIE D., LUNNE T., CAMPANELLA R.G., *Tests with UBC seismic cone at three Norwegian research sites*, NGI Report No. 59040-1, 1985, 30/11/85.

[7] HARDIN B.O., *The nature of stress–strain behaviour for soils*, [in:] Proceedings ASCE Speciality Conference on Earthquake Engineering and Soil Dynamics, Pasadena, 1978, **1**, pp. 3–90.

[8] HARRY D.L., KOSTER J.W., BOWLING J.C., RODRIGUEZ A.B., *MASW generated during high-resolution seismic reflection profiling of a fluvial aquifer*, Journal of Environmental and Engineering Geophysics, 2005, **10** (2), pp. 123–134.

[9] HEISEY J.S., STOKOE K.H., MEYER A.H., *Moduli of pavement systems from Spectral Analysis of Surface Waves*, Transportation Research Record, 1982, No. 852, Washington D.C., pp. 22–31.

[10] JAMIOLKOWSKI M., LEROUEIL S., LO PRESTI D.C.F., *Theme Lecture: Design parameters from theory to practice*, [in:] Proceedings Geo-Coast, 1991, Yokohama, **2**, pp. 877–917.

[11] JANBU N., *Soil models in offshore engineering*, 25th Rankine Lecture, Geotechnique, 1985, **35** (3), pp. 241–281.

[12] JONES R., *In-situ measurements of the dynamic properties of soil by vibration methods*, Geotechnique, 1958, **8**(1), pp. 1–21.

[13] KAUFMANN R.D., XIA J., BENSON R.C., YUHR L.B., CASTRO D.W., PARK C.B., *Evaluation of MASW data acquired with a hydrophone streamer in a shallow marine environment*, Journal of Environmental and Engineering Geophysics, 2005, **10** (2), pp. 87–98.

[14] LANGØ H., *Cyclic shear modulus of natural intact clays*, PhD thesis, NTH, Trondheim, August 1991.

[15] LEROUEIL S., HIGHT D.W., *Behaviour and properties of natural soils and rocks*, [in:] Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils (*Natural Soils 2002*), NUS Singapore, December 2003, eds. Tan T.S. et al., published by Balkema, **1**, pp. 29–254.

[16] LONG M., DONOHUE S., *In situ shear wave velocity from MASW surface waves at eight Norwegian research sites*, paper submitted for publication in Canadian Geotechnical Journal, September 2006.

[17] LO PRESTI D.C.F., JAMIOLKOWSKI M., PEPE M., *Geotechnical characterization of the subsoil of Pisa Tower*, [in:] Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils (*Natural Soils 2002*), NUS Singapore, December 2003, eds. Tan T.S. et al., published by Balkema, **2**, pp. 909–946.

[18] LUNNE T., LACASSE S., *Geotechnical characteristics of low plasticity Drammen clay*, [in:] Proceedings of the International Symposium on Characterisation of Soft Marine Clays, Yokosuka, Japan, February 1997. *Characterisation of Soft Marine Clays*, Tsuchida and Nakase (eds.), published by Balkema, Rotterdam, 1999, pp. 33–56.

[19] LUNNE T., LONG M., FORSBERG C.F., *Characterisation and engineering properties of Onsøy clay*, [in:] Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils (*Natural Soils 2002*), NUS Singapore, December 2003, eds. Tan T.S. et al., published by Balkema, **1**, pp. 395–428.

[20] MATHEWS M.C., HOPE V.S., CLAYTON C.R.I., *The use of surface waves in the determination of ground stiffness profiles*, Proc. Institution of Civil Engineers Geotechnical. Engineering, 1996, **119** (Apr.), pp. 84–95.

[21] MAYNE P.W., RIX G.J., G_{max}–q_c *relationships for clays*, Geotechnical Testing Journal, ASTM, 1993, **16** (1), pp. 54–60.

[22] MAYNE P.W., RIX G.J., *Correlations between cone tip resistance and shear wave velocity in natural clay*, Soils and Foundations, 1995, **35** (2), pp. 107–110.

[23] NAZARIAN S., STOKOE K.H., *In situ shear wave velocities from spectral analysis of surface waves*, [in:] Proceedings 8th World Conf. on Earthquake Engineering, 1984, **3**, pp. 31–38.

[24] PARK C.B., MILLER D.M., XIA J., *Multichannel analysis of surface waves*, Geophysics, 1999, **64** (3), pp. 800–808.

[25] PARK C.B., MILLER D.M., MIURA H., *Optimum field parameters of an MASW survey* [Exp. Abs.], [in:] SEG-J, Tokyo, May 22–23, 2002.

[26] ROMOEN M., *Study of geological background and slope stability in Eberg, Trondheim*, Diploma thesis, NTNU, Trondheim, December 2005.

[27] SANDVEN R., *Strength and deformation properties of fine grained soils obtained from piezocone tests*, PhD thesis, NTH, Trondheim, 1990.

[28] SANDVEN R.B., SJURSEN M., *Sample disturbance in soils – results from an oversonsolidated marine clay*, [in:] Proceedings 1st Int. Conf. Geo. Site Characterisation, Atlanta, 1998, eds. Robertson and Mayne, published by Balkema, **1**, pp. 409–417.

[29] SOCCODATO F.M., *Geotechnical properties of Fucino clayey soil*, [in:] Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils (*Natural Soils 2002*), NUS Singapore, December 2003, eds. Tan T.S. et al., published by Balkema, **1**, pp. 791–807.

[30] STOKOE K.H., WRIGHT G.W. III, BAY J.A., ROESSET J.M., *Characterisation of geotechnical sites by SASW method*, [in:] Geophysical Characterisation of Sites, ed. Woods R.D., Oxford Publishers, 1994.

[31] TOKIMATSU K., KUWAYAMA S., TAMURA S., MIYADERA Y., V_s *determination from steady state Rayleigh wave method*, Soils and Foundations, 1991. **31**(2), pp. 153–163.

[32] WESTERLUND G.J., *Undersøkelser av dynamisk skjærmoduli i leire*, PhD thesis, Institute for Soil Mechanics and Foundation Engineering, NTNU, Trondheim, Norway, August 1978 (in Norwegian).

[33] XIA J., MILLER R.D., PARK C.B., *Estimation of near surface shear wave velocity by inversion of Rayleigh waves*, Geophysics, 1999, **64** (3), pp. 691–700.