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Title of paper: In situ shear wave velocity from MASW surface waves
at eight Norwegian research sites

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Title: In situ shear wave velocity from MASW surface waves at eight Norwegian research sites

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 8 well-characterised Norwegian clay, silt and sand 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 and for the clay sites the MASW V_s profiles were similar to those obtained from other techniques. Reasonable results were also obtained for the silt and sand sites, with the best result being obtained for the finer silt. 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.

Key words: soft clays; silts; sands; small strain stiffness; shear wave velocity

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:

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

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

Recently several researchers e.g. Kaufmann et al. (2005) (for shallow marine sediments), Harry et al. (2005) (for a fluvial aquifer), Donohue et al. (2003, 2004) (for very stiff Irish glacial till and very soft clays and silts from Central Ireland respectively) and Park et al. (1999) 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 (2005) 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 eight well-characterised Norwegian research sites. These are underlain by clays, sands and silts. 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.

MASW Technique

Surface wave analysis methods

The steady state Rayleigh wave / Continuous Surface Wave (CSW) technique was introduced by Jones (1958) into the field of geotechnical engineering. It was subsequently developed by others, such as Tokimatsu et al. (1991) and Mathews et al. (1996). 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 (1982) and by Nazarian and Stokoe (1984). The SASW method uses a single pair of receivers that are placed collinear with an impulsive source (e.g. a sledgehammer). The test is repeated a number of times for different geometrical configurations. Crice (2005) 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. (2003) and Soccodato (2003) 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., 1999) 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 (2005) 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 is 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 recording and processing of surface wave data for all eight sites discussed in this paper.

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., 1999). *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

(>5Hz). 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.

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. 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. (2002), who discuss optimum acquisition parameters for MASW surveying.

The Sites

General

A summary of the eight sites surveyed is given on Table 1 and their locations are shown on Figures 1 and 2. Five of the sites are underlain by soft to firm homogenous clay, two by silty material and one by loose to medium dense sand. Soil parameters for the eight sites are summarised on Table 2.

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

Clay sites

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 Fredrikstad, see Figure 2(a). 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. (2003a).

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 2(b). 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 (1999). Two Drammen clay sites were surveyed, i.e. those located close to the city centre at Danvikgata and Museum Park.

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, 1990, Sandven and Sjursen, 1998). This research site is located on the west side of the town of Stjørdal, which is about 35 km northeast of Trondheim, see Figure 2(c).

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, 1985). The sites are located close to the NTNU campus and in a heavily developed part of Trondheim, see Figure 2(d). Therefore it has been necessary to test at several different locations in the general area. A new test site has recently been established (Romoen, 2005).

Silt sites

The Os silt research site was developed relatively recently by the Norwegian Public Roads Administration (Statens Vegvesen) in order to investigate the properties of the silty soils found in the west of Norway (Long and Gudjonsson, 2005). It is located at Skeisleira in Os County, some 15 km south of the City of Bergen, see Figure 2(e).

Test programmes have been carried out at the Halsen research site by the Geotechnics Division at NTNU for over 30 years (Sandven, 2003). It is located towards the east side of the town of Stjørdal, some 5 km from the Glava clay research site, see above. The site was developed in conjunction with the construction of Halsen Public School (see Fig. 2f). Settlements of the school were measured both during and after construction and compared with laboratory derived parameters (Sandven, 2003).

Sand site

The site at Holmen Island, Drammen has been the main NGI loose sand research site since the early 1970's (Lunne et al., 2003b). The deposit comprises a lightly overconsolidated uniform loose to medium dense sand with only a little silt and gravel.

Similar to the work at Halsen this site was developed in conjunction with the construction of the Felleskjøpet grain silos as shown on Figure 2(g).

Results for clay sites

Onsoy

A total of 6 MASW survey profiles were carried out at Onsoy. Test results are shown in Figure 3(a). Five of the tests were in a north – south direction and one in an east-west. 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). 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 increase with depth. A similar result has been reported by others for both SASW and MASW (e.g. Stokoe et al., 1994, Park et al, 1999 and Kaufmann et al., 2005). Independently carried out seismic CPT (SCPT) data, by the University of British Columbia, was also available (Eidsmoen et al., 1985 and Lunne et al., 2003a) and these data are also shown in Figure 3(a). 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.

Mayne and Rix, (1993) 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:

$$[2] \quad G_{\max} = \frac{99.5 p_a^{0.305} q_c^{0.695}}{e_0^{1.13}}$$

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

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 (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 Formula 1. Mayne and Rix (1995) derived the empirical formula:

$$[3] \quad V_s = 9.44 q_c^{0.435} e_0^{-0.532}$$

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 3(b). The agreement is good, perhaps not surprisingly in this case as Onsøy was one of the sites used in the Mayne and Rix (1995) study.

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 (Profile 1 and 2) and Museum Park (Profile 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 4a and 4b respectively. It can be seen that there is good consistency between the two adjacent MASW profiles at each location. V_s value 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.

V_s values derived from Rayleigh wave tests (BRE, 1990, Butcher and Powell, 1996), from seismic CPT tests and from cross-hole seismic tests (Eidsmoen et al., 1985 and Lunne and Lacasse, 1999) are also available for the Museum Park site, as can be seen in Figure 4b. 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. 1985) is also shown in Figure 4. The agreement is good, perhaps not surprisingly, as was the case for Onsøy, the Drammen site was used in the Mayne and Rix (1995) study.

Glava, Stjørdal

Four profiles were taken at this site adjacent to previous CPT and block sample locations, and the results are presented in Figure 5. 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.

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 5. 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, 1990) tend to underestimate V_s and do not show the same trend of increasing V_s with depth.

Eberg

Three MASW profiles were carried out in the new test site area and the results are shown in Figure 6. 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.

Cross-hole test data from Westerlund (1978) are also shown in Figure 6. 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.

Results for silt sites

Os

At Os 3 MASW profiles were carried out, two of which were parallel and 1 m apart, the other perpendicular to the first two. As can be seen from Figure 7, the results are highly repeatable indicating the uniformity of the site. Data resolution seems to be lower below about 8 m.

As for Glava clay, no independent V_s measurements are available for this site and it is only possible to compare the measured V_s profiles to those derived empirically from CPT, as shown in Figure 7. Again very similar to Glava, below a depth of about 5m the CPT values tend to underestimate V_s and do not show the same trend of increasing V_s with depth. Overall the agreement is good, especially considering the Mayne and Rix (1995) correlations were intended for use with intact clays not silts.

Halsen

MASW profiles were taken at the two test locations, which had been used previously by NTNU. Test results are shown in Figure 8. Both profiles show similar results, with maximum differences of 25 m/s, perhaps not surprising given the general heterogeneity of the silty deposits in the area. Unlike all of the previously reported data, there is little tendency for an increase in V_s with depth. Only CPT data is available with which to compare the MASW results. The CPT data also shows no particular trend of increasing V_s with depth but in this case tends to overestimate V_s by some 40%. Again it should be noted these correlations were originally intended for clay.

Results for Holmen, Drammen sand site

The site area has been extensively developed (principally with concrete and asphalt paving) since the original research work and therefore it was only possible to obtain 1 MASW profile as shown in Figure 9. Test results are compared with Rayleigh wave measurements (BRE, 1990 and Butcher and Powell, 1996) as well as seismic CPT and cross-hole seismic test results (Eidsmoen et al., 1985 and Lunne et al., 2003b).

As pointed out by Butcher and Powell (1996) it is apparent that the Rayleigh wave, seismic CPT and cross-hole techniques appear to agree on the V_s profile even though both propagation and polarisation of each of the waves is different. The MASW data are higher than from the other techniques, but the differences in the resulting G_{\max} values are relatively small. Unfortunately the MASW profile was located some 30 m north east of the other tests and much closer to the influence of the Felleskjøpet grain silos (see Figure 2g) and this may have contributed to the difference in the results.

Quantitative analysis of data

A quantitative analysis of the data is given on 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 closest agreement as all three techniques involve direct measurements of V_s . Typically MASW V_s is 10% 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 25% less than corresponding V_s values derived from CPT.

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 (1978) 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, 2003). The empirical equation describing the influence of the controlling factors on G_{\max} can then be written as follows:

$$[4] \quad G_{\max} = SF(e) \left(\sigma'_v \sigma'_h \right)^n P_a^{(1-2n)}$$

where $F(e)$ is a void ratio function, n is a parameter indicating the influence of stress, P_a is atmospheric pressure and S is a dimensionless parameter characterising the considered soil.

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 samples for Eberg. Initially V_s values corresponding to sample depths were chosen and G_{\max} calculated using the sample density and Formula 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}). G_{\max}/σ'_{v0} typically varies between 250 and 1000. The relationship between G_{\max}/σ'_{v0} against e is shown in Figure 10(a). 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 10(b) the data has been normalised as suggested by Hardin (1978) and Hight and Leroueil (2003), 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} 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:

$$[5] \quad g_{\max} = \frac{G_{\max}}{\sigma'_m + a}$$

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 (1985) for oedometer moduli. Langø's data are shown in Figure 11(a) 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.

Data obtained during this study are shown in Figure 11(b). 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, 1985). A reasonable correlation between g_{\max} and w can be seen.

Conclusions

The objective of this work was to assess the repeatability, accuracy and reliability of MASW surface wave measurements made at 8 well-characterised Norwegian 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. For the clay sites the MASW V_s profiles were, for all practical purposes, similar to those obtained from other techniques.
3. MASW V_s values are typically 10% greater than those obtained from SCPT or cross-hole tests.
4. MASW V_s clay profiles are similar to those obtained by correlation with CPT using the procedure developed by Mayne and Rix (1995).
5. For the clay sites 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 (1978).
6. For the silt sites MASW V_s profiles agreed reasonable well with those obtained from CPT correlations, with the best result being obtained for the finer silt.
7. MASW tends to overestimate V_s at the single loose sand site but this may have been due to local site conditions.

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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

Table 1. Summary of sites surveyed

Location	Site	Soil type	Background references
Fredrikstad	Onsøy	soft clay	Lunne et al. (2003a)
Drammen	Museum Park	soft clay	Lunne and Lacasse (1999)
	Danvikgata	as above	As above
	Holmen Island	sand	Lunne et al. (2003b)
Trondheim	Eberg	firm clay	Romoen (2005)
			Westerlund (1978)
Stjørdal	Glava	firm clay	Sandven (1990), Sandven and Sjørusen (1998)
	Halsen	silt	Sandven (1990, 2003)
Bergen	Os - Skeisleira	silt (silty clay)	Long and Gudjonsson (2005)

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
Drammen	50 - 55	1.72 - 1.78	48	30	18 - 30	7 - 8	1.5	100 - 170
sites ²								
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
Os	28 - 35	1.9 - 2.1	5 - 25	7 - 16	20 - 60	20 - 400	1 - 3.5	50 - 300
Halsen	20 - 25	1.9 - 2.0	0 - 25	low	20 - 60	10 - 30	?	100 - 175
Holmen ³	18 - 25	2.0	0	n/a	$\phi' = 32^\circ$ - 34.5°.	RD = 25 - 40	n/a	140 - 180

1. From fall cone test

2. Two surveyed. Only upper Drammen plastic clay encountered.

3. ϕ' = in situ peak friction angle and RD = relative density

Table 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	24	1	10	0, 2	10.6 / 10.4
sites					
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
Os	24	1	10	0, 2	14.3
Halsen	24	1	10	0, 2	10.4
Holmen	24	1	10	0, 2	12.5

Table 4. Quantative analysis of data

Site	Depth range (m)	MASW compared with	Percentage by which MASW V_s is higher
<u>Clay sites</u>			
Onsøy	> 3	SCPT	0
	> 3	CPT	10
Drammen	3.5 - 10	CPT	-8
Danvikgata			
Drammen	1 – 6	SCPT	0
Museum Park	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
<u>Silt sites</u>			
Os	3.5 - 8	CPT	0
	8 - 10	CPT	25
Halsen	4 - 10	CPT	-40
<u>Sand site</u>			
Holmen	2 - 12	SCPT	33

Summary of figures

Fig. no	Title	Ref.
1	Location of sites in Norway	Dell+D(AK)/Papers/MASWNorway/Norge.tif
2	Detailed plans of test locations (a) to (d) clays sites: Onsøy, Drammen, Glava and Eberg; (e) and (f) silt sites; Os and Halsen and (g) sand site at Holmen.	Dell/Papers/MASWNorway/LocationofMASWtestsites.doc
3	Test results for Onsøy clay (a) all data, (b) comparison with CPT	Dell+D(AK)/Reports/MASWNorway/OnsoyVs.grf+OnsoyVsCPT.grf
4	Test results for Drammen clay sites	Dell+D(AK)/Reports/MASWNorway/DrammenVs.grf
5	Test results for Glava, Stjørdal clay	Dell+D(AK)/Reports/MASWNorway/GlavaVs.grf
6	Test results, Eberg	Dell+D(AK)/Reports/MASWNorway/EbergVs.grf
7	Test results for Os, Bergen silt	Dell+D(AK)/Reports/MASWNorway/OsVs.grf
8	Test results for Halsen Stjørdal silt	Dell+D(AK)/Reports/MASWNorway/HalsenVs.grf
9	Test results for Holmen, Drammen sand	Dell+D(AK)/Reports/MASWNorway/HolmenVs.grf
10	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+D(AK)/Papers/MASWNorway/NormGmaxandvoidratio.grf
11	Normalised shear modulus g_{max} versus water content (a) from Langø (1991) and (b) this study	Dell+D(AK)/Papers/MASWNorway/gmax.grf+Langogmax.jpg

Figures for paper by Long and Donohue on: In situ shear wave velocity from MASW surface waves at eight Norwegian research sites

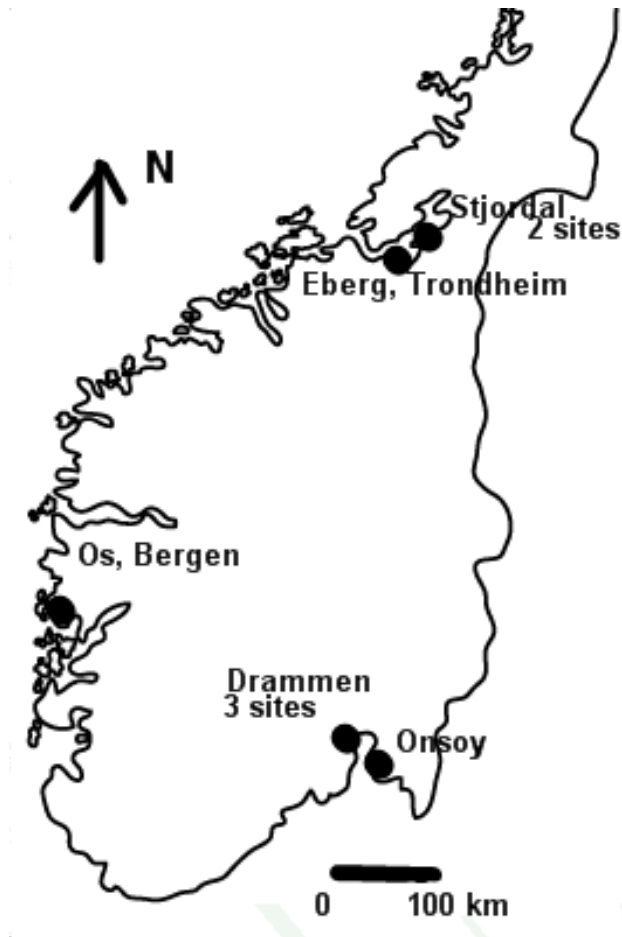


Fig. 1. Location of sites in Norway.

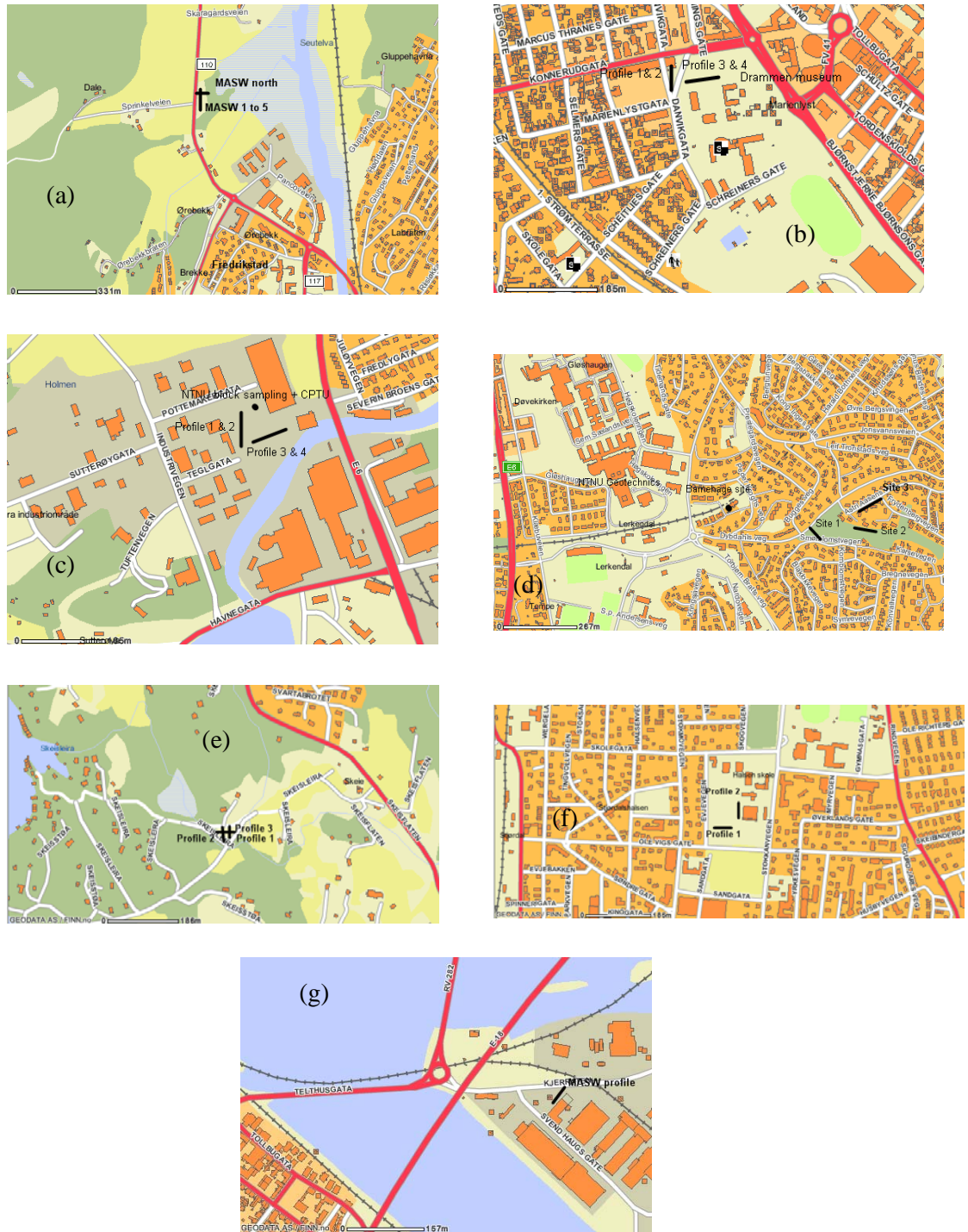


Fig 2. Detailed plans of test locations (a) to (d) clays sites: Onsøy, Drammen, Glava and Eberg; (e) and (f) silt sites: Os and Halsen and (g) sand site at Holmen. Maps courtesy Geodata AS, Norway (www.finn.no)

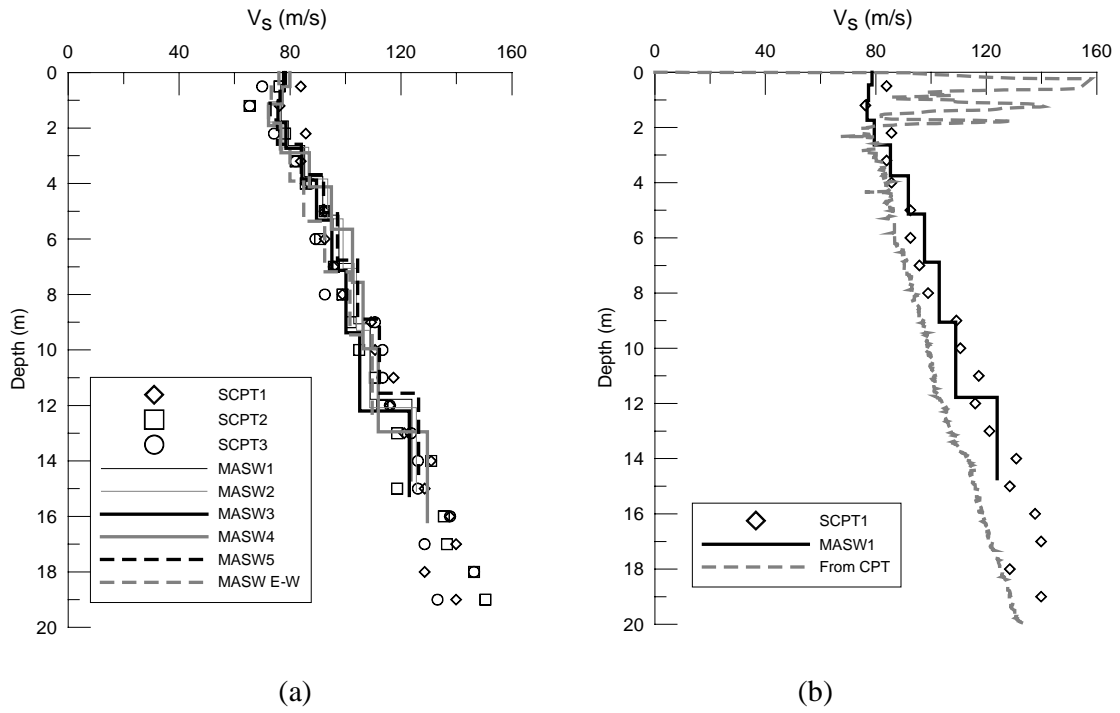


Fig. 3. Test results for Onsøy clay (a) all data, (b) comparison with CPT

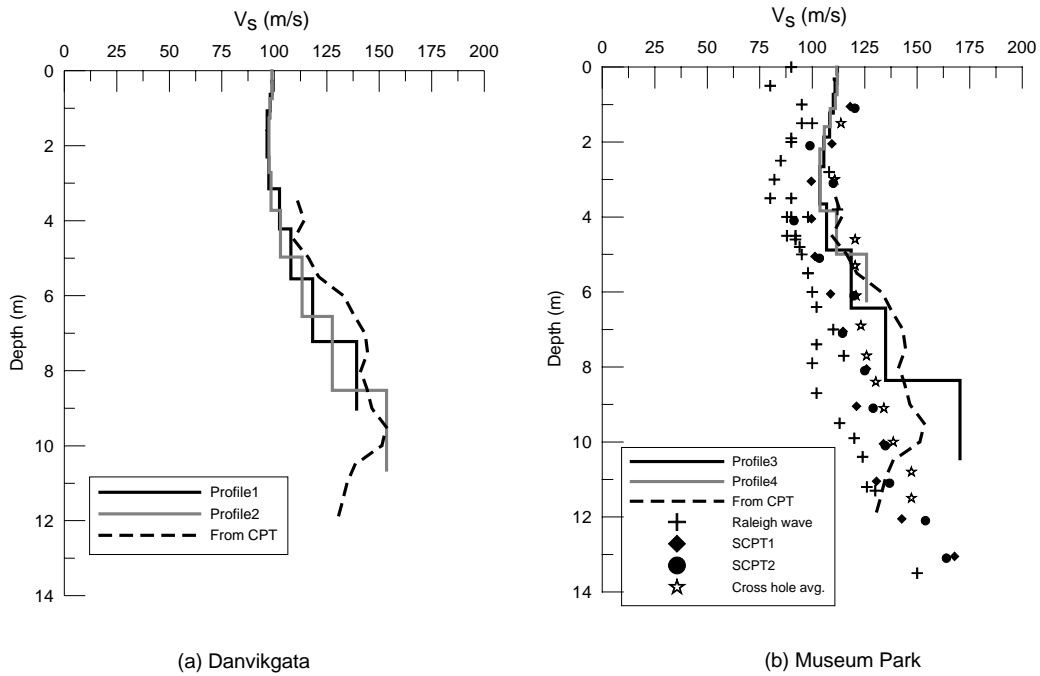


Fig. 4. Test results for Drammen clay sites: (a) Danvikgata and (b) Museum Park

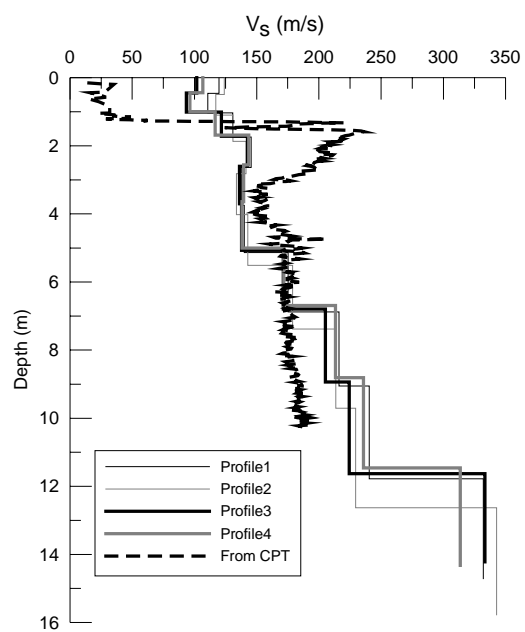


Fig. 5. Test results for Glava clay Stjørdal

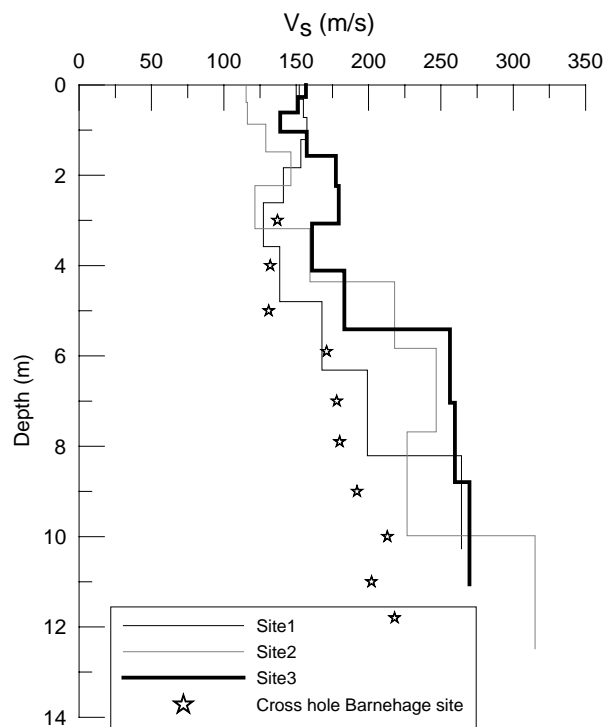


Fig. 6. Test results for Eberg

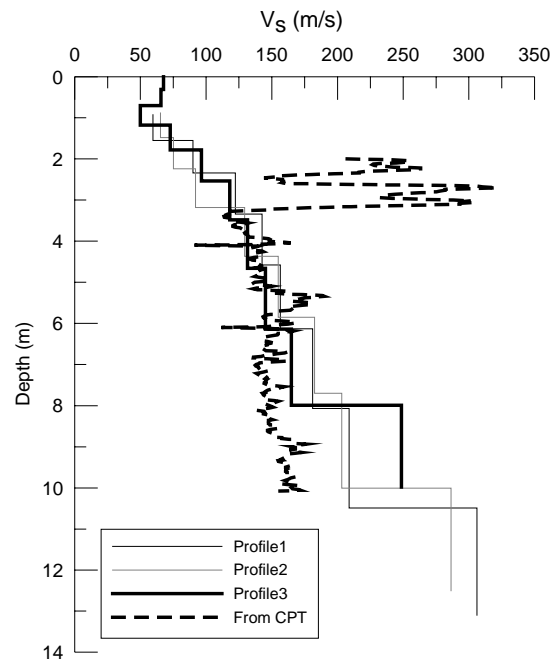


Fig. 7. Test results for Os, Bergen silt

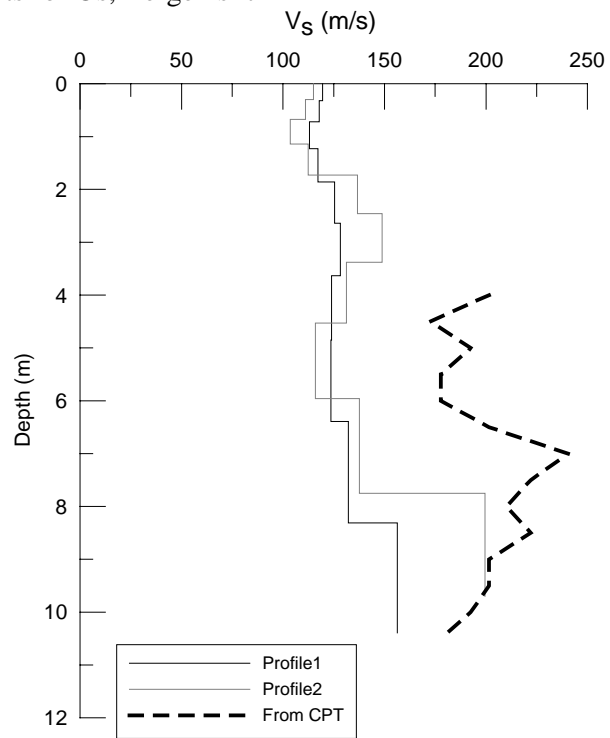


Fig. 8. Test results for Halsen, Stjørdal silt

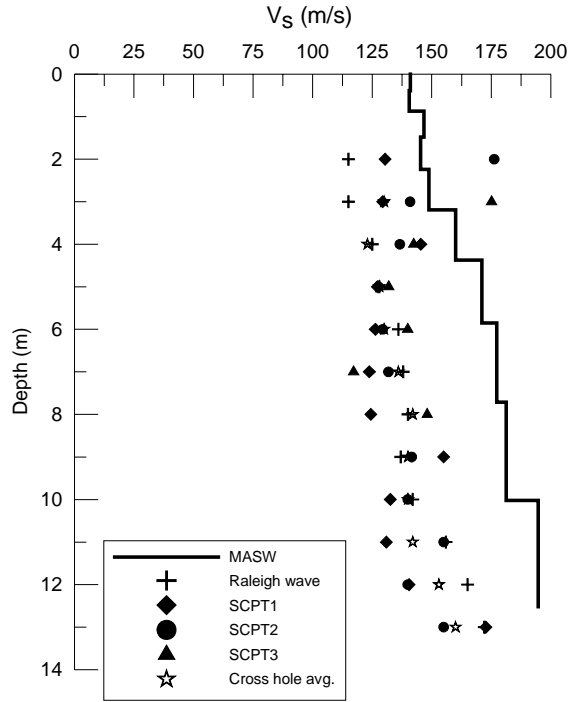


Fig. 9. Test results for Holmen, Drammen sand

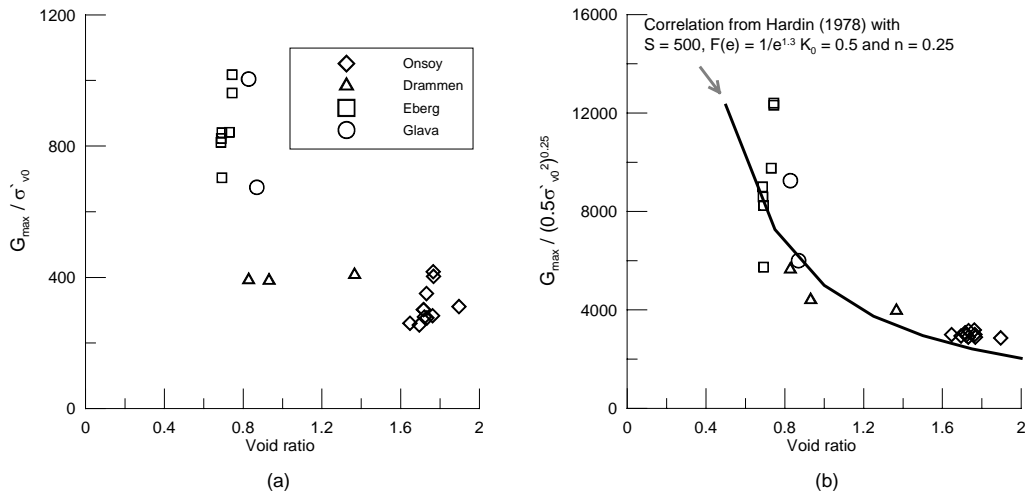
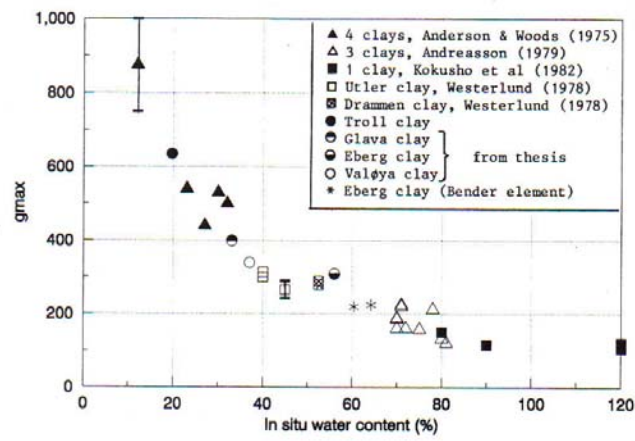
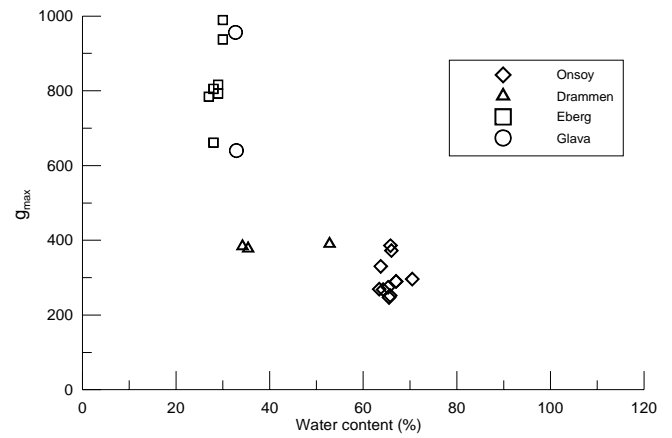


Fig. 10. Relationship between: (a) G_{max} normalised by σ'_{v0} and void ratio e and (b) G_{max} normalised according to Hardin (1978) and Hight and Leroueil (2003) and e



(a)



(b)

Fig. 11. Normalised shear modulus g_{max} versus water content (a) from Langø (1991) and (b) this study