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Title of paper:	**Assessment of sample quality in soft clay using shear wave velocity and suction measurements**

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INTRODUCTION

Sampling disturbance in soft clays may result in poor estimates of geotechnical parameters, leading to potentially significant and costly design errors. Evaluation of sample quality is, therefore, essential if design parameters derived from laboratory tests are to be deemed reliable. A number of different approaches have been traditionally used to evaluate sample disturbance. Techniques that are considered reliable include measurements of volumetric strain (Kleven et al., 1986), and the normalised change in void ratio, $\Delta e/e_0$ (Lunne et al., 1997). Most of these approaches, however, require reconsolidation back to in-situ stresses, a process that may require a number of days of testing. This is a particular problem for offshore sampling, where rapid assessment of sample quality could significantly improve efficiency.

A number of studies in recent years have observed that laboratory determined shear wave velocities (V_s), and corresponding small strain shear modulus, G_{max}:

$$G_{max} = \rho . V_s^2 \tag{1}$$

are generally lower than the in-situ equivalent, and have attributed this difference to sampling disturbance (Shiwakoti et al. 2000; Porcino & Ghionna 2004). These studies involved reconsolidation of laboratory specimens back to their in-situ stress, before measurement of V_s. For a quick assessment of sample quality, Hight & Leroueil (2003), Nash (2003) and Landon & DeGroot (2007) used portable bender element kits to measure V_s, immediately after removal from the subsurface on unconfined samples. Hight & Leroueil (2003) also suggested simultaneous soil suction (u_r) measurements, enabling differences between unconfined and in-situ stress state to be taken into account.

The use of suction measurements for sample quality evaluation was introduced by Ladd & Lambe (1963), who proposed using the ratio u_r/σ'_{ps} to evaluate disturbance, where σ'_{ps} is the effective stress for a "perfect" sample. Calculation of σ'_{ps} is, however, not straightforward and requires knowledge of Skempton's pore pressure parameter, A_u

(consequent to the release of deviatoric stress), and K_0 (coefficient of earth pressure at rest). Authors such as Tanaka et al. (1996) and Carrubba (2000) have recently used u_r normalised by the in-situ vertical effective stress (σ'_{v0}) to evaluate disturbance. Tanaka et al. (1996) suggested that for high quality samples of normally to lightly overconsolidated clay, u_r is approximately 1/5 σ'_{v0} to 1/6 σ'_{v0}. Recently, Tanaka & Tanaka (2006) and Tanaka (2008) suggested that suction does not have a consistent relationship with in-situ vertical effective stress and that this hypothesis needs to be treated cautiously. Ladd & Lambe (1963) and Hight & Leroueil (2003) recognised that when taken alone, "u_r cannot indicate the amount of destructuring that has occurred".

This paper describes the use of unconfined V_s and u_r measurements to assess the quality of soft clay samples. Samples of varying quality are assessed using conventional techniques, whose results are compared to assessments derived according to V_s and u_r measurements. A tentative criterion for quantifying sample disturbance is proposed, which is based on V_s and u_r measurements.

DESCRIPTION OF SITES AND TECHNIQUES

The soft soils investigated during this study were located at Onsøy in Norway and at Ballinasloe and Bogganfin in Ireland (Table 1). A number of samplers of varying quality were used, the dimensions and features of which are given in Table 2.

Onsøy, Norway

The Onsøy test site is the main soft clay research site used by the Norwegian Geotechnical Institute (NGI). Onsøy is underlain by an extensive deposit of uniform marine clay, as described by Lunne et al. (2003).

In this paper comparisons are made between Sherbrooke block, 76mm steel and 54mm composite piston samples at two depths (approximately 10m and 13m). The Scandinavian displacement approach was adopted for the piston sampling, wherein the sampler (with the piston in front of the sampling tube) was pushed down to the desired depth without preboring.

Ballinasloe and Bogganfin, Ireland

The Ballinasloe and Bogganfin test sites (Donohue, 2005), located in the midlands of Ireland, are both underlain by post glacial lacustrine clay. Although generally uniform, the soils contain some thin silt laminations (1mm to 2mm).

For this work, comparisons are made between 100mm ELE fixed piston and open drive U4 samples. Samples were obtained with the ELE sampler using standard (30^o) and modified cutting edges (5^o). In addition to the Scandinavian displacement approach, the conventional technique of sampling from the bottom of a shell and auger (open percussive) borehole was used. Interestingly, the moisture content and bulk density of the Ballinasloe U4 samples (Table 3) are quite different from the piston tubes indicating that the material, which is known to have a high coefficient of consolidation, c_h (Long and O'Riordan 2001), has possibly been densified by drainage of excess pore pressure from the silt lenses during sampler driving. The moisture content and bulk density of the U4 samples from Bogganfin, however, do not appear to be significantly different from the piston tubes.

Testing Techniques

In-situ V_s measurements were obtained from the seismic cone (SCPT - Eidsmoen et al., 1985) and Multichannel Analysis of Surface Waves (MASW - Long & Donohue

2007; Donohue & Long 2008) techniques. Measurements of shear wave velocity, using these techniques, may be performed relatively quickly (30 minutes for MASW, 120 minutes for SCPT) at an onshore sampling location, although offshore seismic cone measurements will take longer. V_s was measured on unconfined samples, using bender elements (vertically propagating, horizontally polarised) and interpreted using both first arrival and cross correlation techniques. Shear wave velocities should ideally be measured in the same direction in both the laboratory and the field in order to to mitigate the effect of anisotropy; however, in the present case, stiffness anisotropy was not significant, as discussed by Donohue (2005).

Measurement of u_r was made using a number of techniques (Donohue & Long 2009), such as the filter paper method, the cell pressure loading technique, a small scale tensiometer and a Japanese approach. Of these, Donohue & Long (2009) found the Japanese approach (Tanaka & Tanaka 2006) to be the best combination of speed and accuracy. In this technique a saturated high-air-entry disk (air entry value of 200 to 300 kPa) is used, which has small pores of uniform size. The disk acts as a membrane between air and water and once it is saturated with water, air cannot pass through the disk due to the ability of the contractile skin to resist the flow of air. A specimen is placed on the high-air-entry ceramic disk, without a membrane, and the suction is simply monitored until it becomes constant. Using this simple approach, suctions may be measured relatively quickly, in less than 30 minutes (Tanaka 2008). Suction measurements detailed in this paper are computed from the mean of these techniques. At Onsøy, a suction probe developed by the University of Massachusetts, Amhurst (Poirier et al., 2005), was also used. Using this approach, suctions may be measured in less than 15 minutes. Measurements of V_s and u_r were performed on all samples either immediately after extrusion, or after removal from the ground (block samples).

ASSESSMENT OF SAMPLE QUALITY USING CAUC TRIAXIAL TESTING

A summary of the most important parameters, obtained from anisotropically consolidated undrained (CAUC) triaxial tests carried out on the soils under study, are given in Table 3.

Onsøy

An assessment of both the consolidation and shearing parameters (Table 3), indicates that the block samples are generally of superior quality, although the deeper 76mm sample appears to be of good quality. CAUC stress-strain curves and stress path plots are shown in Figure 1(a and b). Results are shown for Block, 76mm and 54mm diameter samples from a depth of approximately 10.3m. The block samples are clearly superior to both the 76mm and 54mm diameter samples, exhibiting a much clearer peak at a lower strain and a greater degree of strain softening post peak. The 54 mm diameter specimens exhibit the lowest undrained shear strength (s_u) and highest strain at peak stress (ε_f). The stress paths (plotted in s', t' space) followed by the block specimens reach a slope close to the “perfect” slope of 1 horizontal to 3 vertical, pre-peak, corresponding to minimum plastic volumetric strain (Lunne et al., 1997), indicating that much of the natural structure has been retained.

Ballinasloe and Bogganfin

According to the consolidation and shearing stage parameters, the 5^o modified piston tube produced superior samples (Table 3) particularly when used with the displacement approach at Ballinasloe. Typical CAUC stress-strain and stress path plots for Ballinasloe and Bogganfin are shown in Figure 1(c,d,e and f), and a number of different responses are discerned. Interestingly, the U4 and 30^o conventional specimens show dilative behaviour, in comparison to contraction exhibited by the modified piston tubes, consistent with the densification observed previously. The stress-strain plots indicate that the modified piston tube samples are superior, with more clearly defined peaks occurring at lower strains and there is greater strain softening post peak.

SHEAR WAVE VELOCITY RESULTS

Unconfined shear wave velocities (V_{s0}) and corresponding in-situ V_s are presented in Figure 2. As shown in the figure, at Onsøy the MASW and SCPT V_s profiles are almost identical (Long & Donohue 2007). V_s was also measured on unconfined specimens of completely remoulded material. Sample cuttings were remoulded at their in-situ density and water content. The highest velocities recorded for Onsøy samples were those of the block samples immediately after removal from the ground. These values were greater than those measured on the same blocks in the laboratory, in Ireland. This large reduction in V_s could be due to transportation damage, or to some other time effect. The lowest V_s was measured on the 54mm diameter piston samples.

Shear wave velocities measured on samples of Ballinasloe and Bogganfin clay are significantly lower than their in-situ equivalent (Figures 2b and 2c). The 5^o modified piston tube samples exhibit consistently higher velocities than either the 30^o conventional or U4 samples. V_s of the U4 samples from Ballinasloe is similar to the remoulded V_s, indicating poor quality, in accordance with what was found with the CAUC test data.

The shear wave velocities measured in the laboratory are normalized using the in-situ V_s data and compared with $\Delta e/e_0$ in Figure 3 for all sites. The relationship between these parameters has been characterised with Pearson's correlation as follows: $r=-0.78$, $p<0.001$, $n=22$. The block samples from Onsøy exhibit the highest normalised V_s, and the U4 samples from Bogganfin and Ballinasloe are characterised by the lowest normalised

V_s. For Ballinasloe and Bogganfin, the modified 5^o piston tube samples are clearly superior, particularly when used in conjunction with the displacement technique at Ballinasloe.

SUCTION RESULTS

Suction values measured at each of the sites are presented in Figure 4 and compared to $0.2\sigma'_{v0}$, as suggested by Tanaka et al. (1996), for high quality samples. The block samples from Onsøy exhibit the highest suctions and lie closest to $0.2\sigma'_{v0}$. It is again uncertain whether, for the block samples, the difference between in-situ and laboratory suctions are due to measurement technique, transportation damage or to some other time effect.

The 5^o displacement samples possess consistently higher suctions for Ballinasloe, and lie closest to $0.2\sigma'_{v0}$. Suctions measured on the piston samples from Bogganfin are slightly higher than for the U4 samples, although the differences between the different piston samples are negligible.

Suctions measured on the samples from all sites are normalised using the in-situ vertical effective stress (σ'_{v0}) and compared with $\Delta e/e_0$ in Figure 5. There is a significant correlation between these parameters ($r=-0.67$, $p<0.001$, $n=22$) which tends to a suction value of about $0.2\sigma'_{v0}$ for $\Delta e/e_0 = 0$. This trend is also observed for the individual sites under investigation.

COMBINATION OF V_s AND u_r

Having observed the relationships between shear wave velocity and suction with $\Delta e/e_0$, the following normalized parameters have been derived empirically to evaluate disturbance:

$$L_{vs} = \frac{V_s insitu - V_{s0}}{V_s insitu - V_s remoulded} \tag{2}$$

$$L_u = \frac{0.2\sigma'_{v0} - u_r}{0.2\sigma'_{v0}} \tag{3}$$

The use of remoulded shear wave velocities in L_{vs} takes into account the lowest possible V_s, when the sample is completely destructured. A L_{vs} of zero would be considered completely undisturbed, as V_{s0} would equal the in-situ V_s. The use of the L_u parameter is supported by the trend recognised in Figure 5, which, as mentioned previously, gives a suction value close to $0.2\sigma'_{v0}$ at $\Delta e/e_0 = 0$. This also takes into account the conclusions of Tanaka et al. (1996). Where a material has a u_r greater than $0.2\sigma'_{v0}$, as is the case with Singapore clay (Tanaka 2008) and Bothkennar clay (Hight, 2000), a similar extrapolation will be required, although it is believed that $0.2\sigma'_{v0}$ is relevant to the sites under investigation here. The use of σ'_{ps} (Ladd and Lambe, 1963), or σ'_{v0} instead of $0.2\sigma'_{v0}$ in L_u, may be more relevant to sites where higher suctions are measured, although this would make determination of sample quality difficult for the sites investigated here, as the differences in L_u would be very small.

A tentative criterion combining V_s and u_r is proposed in Figure 6 for the quantification of sample disturbance. This involves plotting L_{vs} against L_u. The relationship between these parameters is again significant ($r=0.83$, $p<0.001$, $n=26$). The $\Delta e/e_0$ criterion, which classifies sample quality into either “very good to excellent”, “good to fair”, “poor” or “very poor”, was used to develop the V_s and u_r classification proposed here. Both the L_{vs} and L_u values of each of the samples tested were associated to a sample quality level according to the corresponding level they would match within the $\Delta e/e_0$ classification system, as shown in Figure 6. As shown, the degradation of block sample quality between sampling in Norway and testing in Ireland has not decreased the quality of the samples out of the very good to excellent zone. This criterion also confirms the superiority of the 5^o displacement samples at the Irish sites.

The L_{vs} - L_u technique has an advantage over the $\Delta e/e_0$ criterion, in terms of speed of measurement, particularly if a portable suction probe is used. It is recognised, however, that in addition to unconfined measurements of V_s and u_r, this approach requires an in-situ measurement of shear wave velocity which may be time consuming, depending on the particular technique selected and the site conditions.

CONCLUSIONS

Estimation of sample quality is usually performed after reconsolidation of samples back to in-situ stresses, an inefficient process, which may take a number of days to be carried out. The use of unconfined shear wave velocity and suction measurements, as discussed in this work, makes it possible to assess rapidly sample quality.

Samples of varying quality were tested using conventional assessment techniques, performed in conjunction with V_s and u_r measurements, at three soft clay sites. Reasonably clear relationships were observed between the various parameters at each of the sites. Unconfined V_s measurements were found to be best correlated with the parameters used traditionally for assessing disturbance.

A tentative empirically derived criterion, based on samples tested in this project, was proposed to quantify sample disturbance combining both V_s and u_r measurements. The proposed L_{vs} - L_u sample disturbance criterion classifies samples similarly to conventional methods, such as $\Delta e/e_0$. The L_{vs} - L_u technique has a significant advantage over the $\Delta e/e_0$ criteria in terms of speed of measurement, particularly if a portable suction probe is used. Further work using this criterion on different materials is important so as to test its usefulness.

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NOTATION

AR	area ratio = $(D_e^2 – D_c^2) / D_c^2$
A_u	pore pressure parameter corresponding to release of deviatoric stress
D_c	internal diameter at cutting edge
D_e	external diameter of cutting shoe
D_i	internal diameter
e_0	initial void ratio
G_{max}	small strain shear modulus
ICR	inside clearance ratio = $(D_i - D_c) / D_c$
K_0	ratio of horizontal to vertical in-situ effective stress

L_{vs}	normalised shear wave velocity parameter for sample quality assessment
L_u	normalised suction parameter for sample quality assessment
OCR	overconsolidation ratio
q_t	corrected piezocone end resistance
s'	mean effective stress = $(\sigma'_1 + \sigma'_3)/2$
s_u	undrained shear strength
t'	shear stress = $(\sigma'_1 - \sigma'_3)/2$
u_r	soil suction
V_s	shear wave velocity
V_{s0}	unconfined shear wave velocity
V_{vh}	vertically propagating horizontally polarised shear wave
w	moisture content
α	sampler cutting edge angle
$\Delta e/e_0$	normalised change in void ratio
ε_f	strain at peak in triaxial test
ε_{vol}	volumetric strain
σ'_1	major principal effective stress
σ'_3	minor principal effective stress
σ'_{v0}	in-situ vertical effective stress
σ'_{ps}	perfect sampling stress (Ladd and Lambe, 1963)
ρ	bulk density

REFERENCES

Brooker, E.W., and Ireland, H.O. (1965). Earth pressures at rest related to stress history, *Canadian Geotechnical Journal* **2**, No.1, 1–15.

Carrubba, P. (2000). Stress relief disturbance and residual pore pressure in cohesive soils. *Soils and Foundations* **40**, No.1, 57-72.

Donohue, S. (2005). Assessment of sample disturbance in soft clay using shear wave velocity and suction measurements, *PhD Thesis*, University College Dublin.

Donohue, S. and Long, M. (2008). Assessment of an MASW approach incorporating discrete particle modeling, *Journal of Environmental and Engineering Geophysics* **13**, No. 2, 57-68.

Donohue, S. and Long, M. (2009). Suction measurements as indicators of sample quality in soft clay, *ASTM Geotechnical Testing Journal* **32,** No. 3, 286-297. DOI: 10.1520/GTJ101416.

Eidsmoen, T., Gillespie, J., Lunne, T. and Campanella, R.G. (1985) Tests with the UBC seismic cone at three Norwegian sites, *NGI report,* No. 59040–1, 30/11/1985, Oslo.

Hight, D.W. (2000). Sampling effects in soft clay: an update. *Proc. 4th International Geotechnical Conference*, Cairo, 1-41.

Hight, D.W. and Leroueil, S. (2003). Characterisation of soils for engineering purposes. *Characterisation and Engineering Properties of Natural Soils*, Tan et al. (eds) **1**, 255–362, Balkema.

Kleven, A., Lacasse, S. and Andersen, K.H. (1986). Foundation engineering criteria for gravity platforms, *Soil Parameters for Offshore Foundation Design*. Part II, NGI Report 40013-34, April.

Ladd, C.C. & Lambe, T.W. (1963). The strength of “undisturbed” clay determined from undrained tests. *ASTM Special Tech. Pub. No. 361, Symposium on Laboratory Shear Testing of Soils*, 342 –371.

Landon, M.M., DeGroot, D.J. and Sheehan, T.C. (2007). Non-destructive sample quality assessment using shear wave velocity. *ASCE, J. Geotech. and Geoenvir. Engrg*. **133**, No. 4, 424-432.

Long, M. and O'Riordan, N.J. (2001). Field behaviour of very soft clays at the Athlone embankments. *Géotechnique* **51**, No. 4, 293-309.

Long, M. and Donohue, S. (2007). In situ shear wave velocity from multichannel analysis of surface waves (MASW) tests at eight Norwegian research sites. *Canadian Geotechnical Journal* **44,** No.5, 533-544.

Lunne, T., Berre, T. and Strandvik, S. (1997). Sample disturbance in soft low plasticity Norwegian clay. *Proc. Sym. On Recent Developments in Soil and Pavement Mechanics, Rio de Janeiro*, June 1997, 81–92, Balkema.

Lunne, T., Long, M. and Forsberg, C.F. (2003). Characterisation and engineering properties of Onsøy clay. *Characterisation and Engineering Properties of Natural* Soils, Tan et al. (eds), 1, 395-428, Balkema.

Nash, D.F.T. (2003). The use of bender elements in the assessment of sample disturbance, *Presentation to Seminar on Sampling Disturbance*, Dublin, 17th December 2003.

Poirier, S.E., De Groot, D.J., and Sheahan, T.C. (2005). Measurement of suction in marine clay as an indicator of sample disturbance. *Proc. GeoFrontiers 2005 Congress, Site Characterisation and Modelling,* Geotechnical Special Publication 138, ASCE Geo-Institute, Austin, Texas.

Porcino, D. and Ghionna, V.N. (2004). Comparison between in-situ and laboratory tests results on undisturbed frozen samples for a natural coarse sand. *Proc. Int. Conf. on Site Characterization, 2, ISC 2,* Porto **2**, 1843–1850.

Shiwakoti, D.R., Tanaka, H., Tanaka, M. and Mishima, O. (2001). A study on small strain shear modulus of undisturbed soft marine clays. *Proc. 10th Int. Offshore and Polar Eng. Conf*, Seattle, 455-460.

Tanaka, H., Sharma, P., Tsuchida, T., and Tanaka, M. (1996). Comparative study on sample quality using several types of samplers. *Soils and Foundations* **36**, No.2, 57-68.

Tanaka, H. and Tanaka, M. (2006). Main factors governing residual effective stress for cohesive soils sampled by tube sampling. *Soils and Foundations* **46**, No.2, 209-219.

Tanaka, H. (2008). Sampling and sample quality of soft clays. *Proc. of the 3rd International Conference on Site Characterization, (ISC3)*, Taipei, 139-157.

Property	**Onsøy**	**Ballinasloe**	**Bogganfin**
Moisture content (%)	55 – 67	29 - 42	24 - 45
Bulk density (Mg/m^3)	1.6 – 1.7	1.8 – 2.0	1.8 – 2.2
Initial void ratio (e_0)	1.5 – 1.8	0.7 – 1.3	0.6 – 1.3
Clay content (%)	51 – 69	40 - 49	25 - 40
Liquid limit (%)	55 – 70	32 - 39	29 - 43
Plasticity index	25 – 50	15 - 21	12 - 25
Sensitivity (field vane)	6 - 8	3 - 5	1.5 – 3
OCR	1.3 – 1.7	1.1	1.1
K_0	0.5 – 0.7	0.5*	0.5*
q_t (kPa)	500 at 10m – 675 at 14m	200 - 500	200 - 300
Depth of water table (m)	0.2	1	1

Table 1. Basic site properties (definitions supplied in notation index). * estimated from relationship with plasticity index (Brooker and Ireland, 1965)

Sampler	**Length (mm)**	**α (deg)**	**D_c (mm)**	**D_e (mm)**	**D_i (mm)**	**AR (%)**	**ICR (%)**	**Drilling technique**
NGI / Geonor 54mm Piston	800	15	54	64	54.3	44	0.6	Displacement
NGI / Geonor 76mm Piston	866	9	76	80	76	11	0	Displacement
Sherbrooke	350	-	250	-	-	-	-	Pre auger
ELE 100	100	30	101.4	104.8	101.4	6.8	0	Pre auger (conventional)
ELE 100 (modified)	100	5	101.4	104.8	101.4	6.8	0	Pre auger (conventional)
ELE 100 (modified)	100	5	101.4	104.8	101.4	6.8	0	Displacement
U4	45.7	20	104.1	117.4	105.6	27	1.4	Pre augur

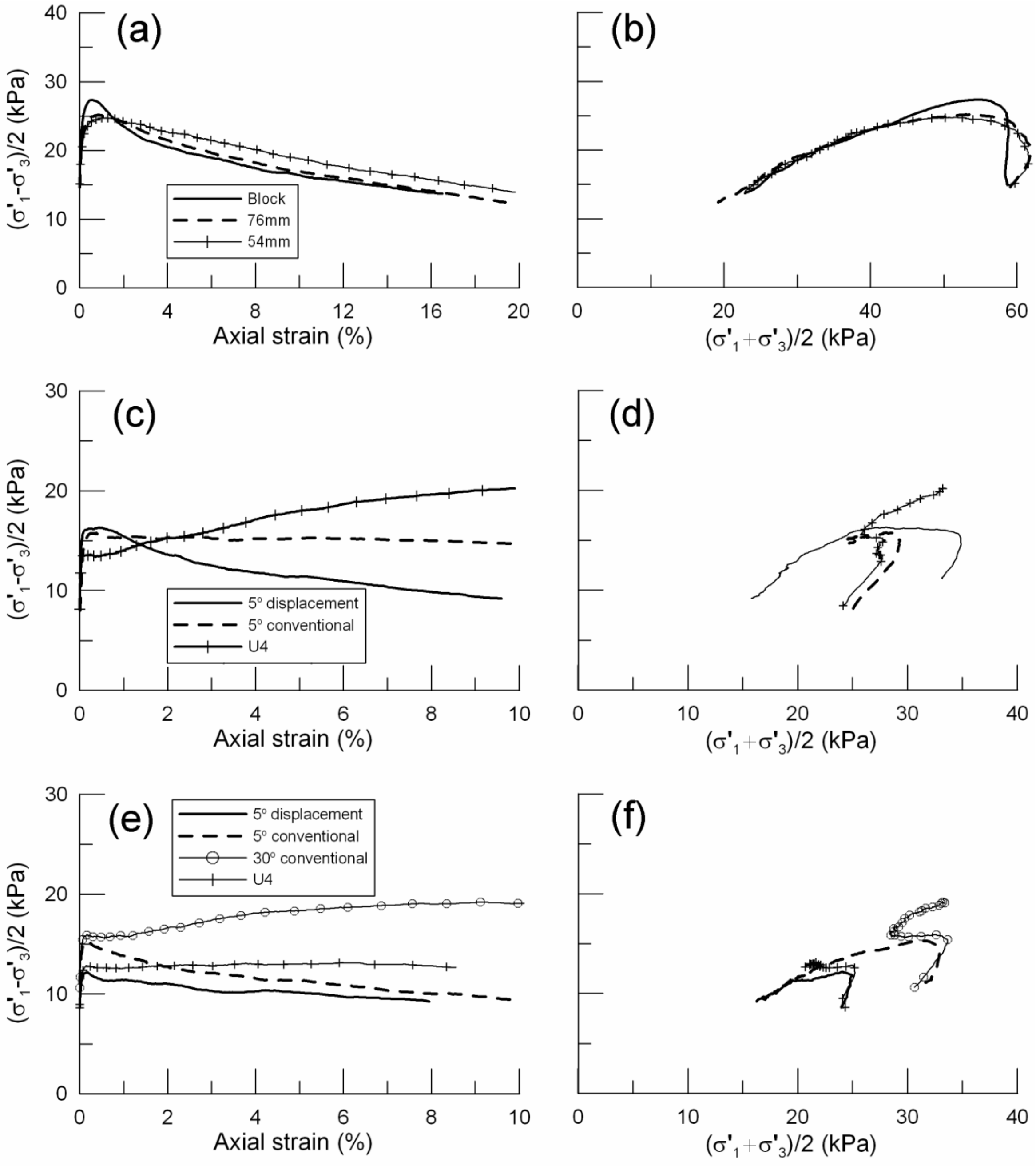
Table 2. Summary of the dimensions and features of the samplers used (definitions supplied in notation index)

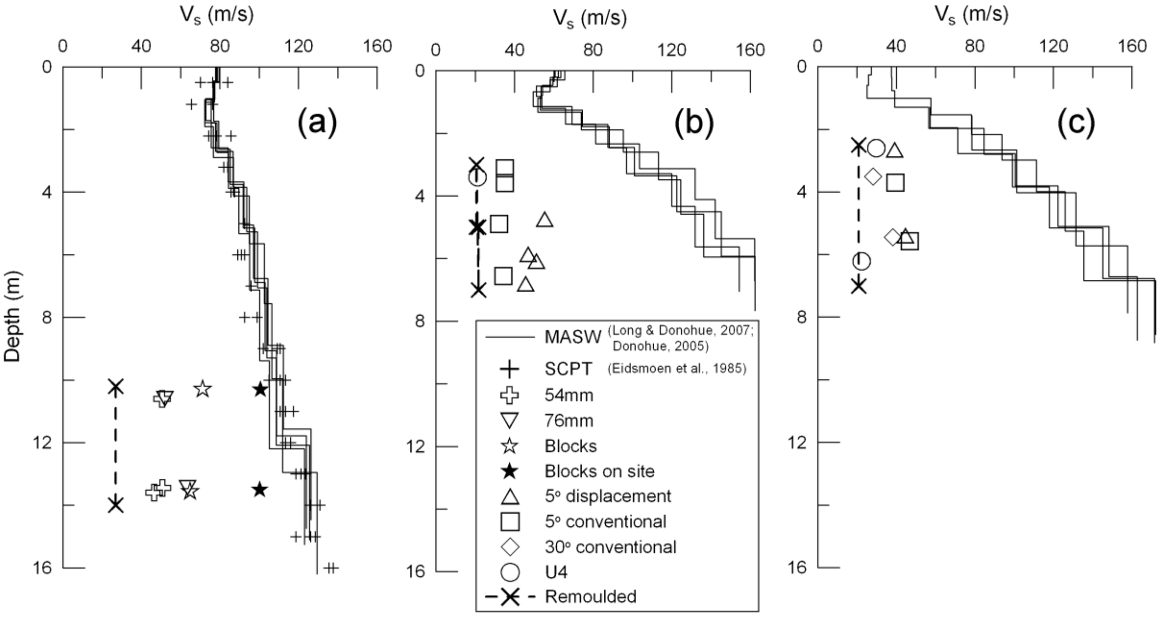
Site	Depth (m)	Sample method	w (%)	ρ (Mg/m^3)	σ'_{v0} (kPa)	ε_{vol} (%)	$\Delta e/e_0$	Sample Quality *	s_u (kPa)	ε_f (%)
Ons	10.3	Block	69	1.67	73	2.5	0.037	1	26.7	0.6
Ons	10.3	Block	66	1.63	73	2.0	0.032	1	27.5	0.5
Ons	13.6	Block	66	1.66	94	2.5	0.039	1	32.7	0.5
Ons	13.6	Block	66	1.66	94	2.0	0.032	1	31.7	0.4
Ons	10.6	54mm	63	1.62	75	3.8	0.060	2	24.9	1.1
Ons	13.5	54mm	59	1.60	93	6.0	0.095	3	30.2	0.9
Ons	10.6	76mm	64	1.61	75	2.5	0.039	1	25.4	0.8
Ons	13.5	76mm	62	1.64	93	1.8	0.029	1	33.4	0.7
Bal	4.7	5^o disp	33	1.92	44	3.2	0.068	2	16.5	0.4
Bal	5.9	5^o disp	37	1.87	53	3.9	0.079	3	18.2	0.2
Bal	6.8	5^o disp	29	1.95	61	2.8	0.063	2	22.3	0.1
Bal	3.5	5^o conv	31	1.87	34	3.4	0.072	3	16.0	0.5
Bal	4.9	5^o conv	34	1.96	45	6.4	0.139	3	16.5	0.2
Bal	6.5	5^o conv	35	1.95	59	6.2	0.132	3	21.0	0.2
Bal	3.4	U4	18	2.01	32	4.4	0.118	3	20.4	>10
Bog	2.65	5^o disp	31	1.90	33	4.5	0.097	3	12.3	0.1
Bog	5.39	5^o disp	28	1.89	58	3.6	0.078	3	20.7	0.2
Bog	5.68	5^o disp	27	1.98	60	3.0	0.071	2	22.6	1.0
Bog	3.7	5^o conv	34	1.83	42	4.0	0.080	3	15.4	0.1
Bog	5.57	5^o conv	29	1.94	59	3.7	0.084	3	21.7	0.1
Bog	3.51	30^o conv	29	1.98	41	6.1	0.141	4	19.2	8.0
Bog	2.6	U4	30	2.00	32	7.3	0.170	4	13.3	5.8
Bog	6.21	U4	31	1.97	65	11.3	0.254	4	25.6	6.1

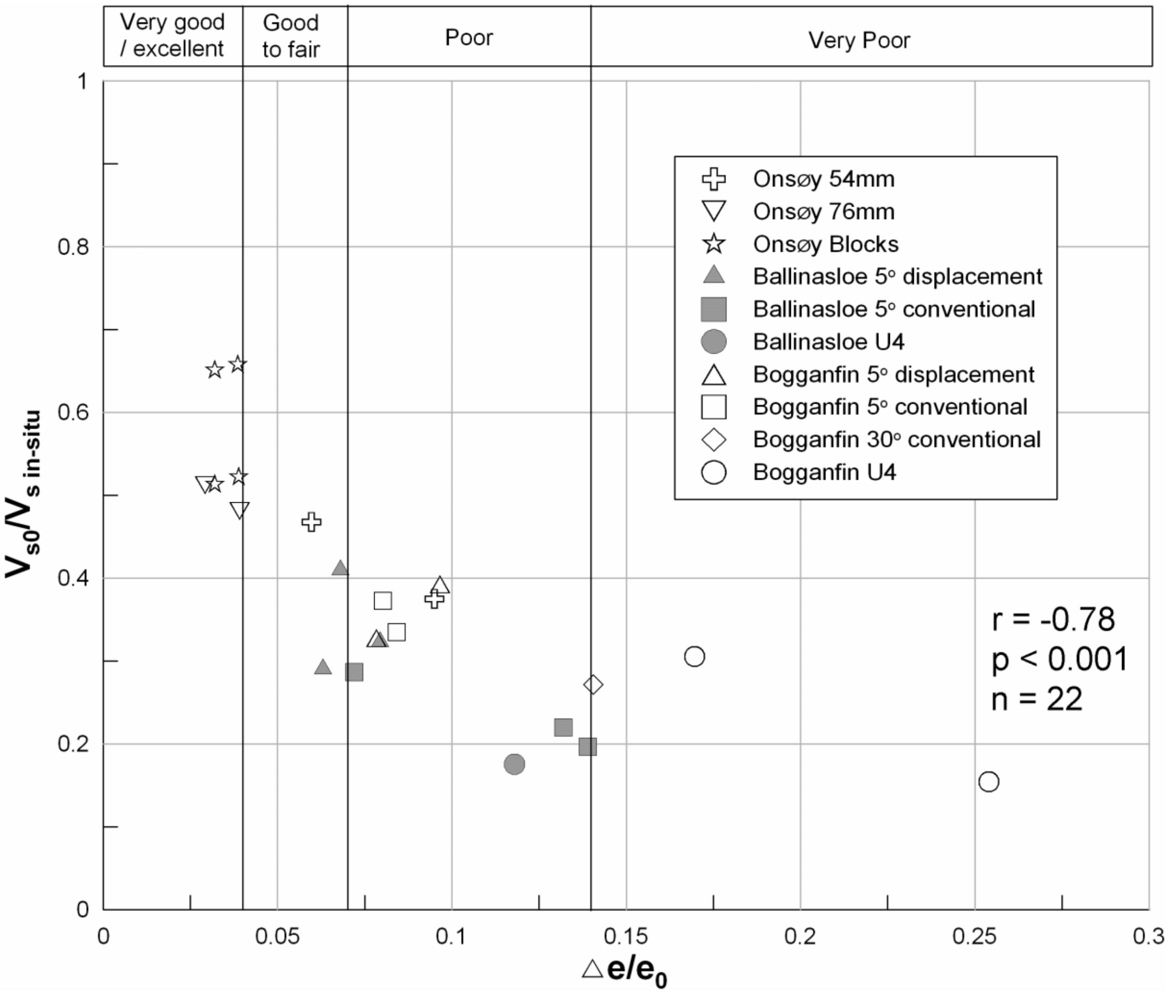
Table 3. Summary of CAUC tests (definitions supplied in notation index). * Sample quality from Lunne et al. (1997) where 1 = Very good to excellent, 2 = Good to fair, 3 = Poor, 4 = Very Poor

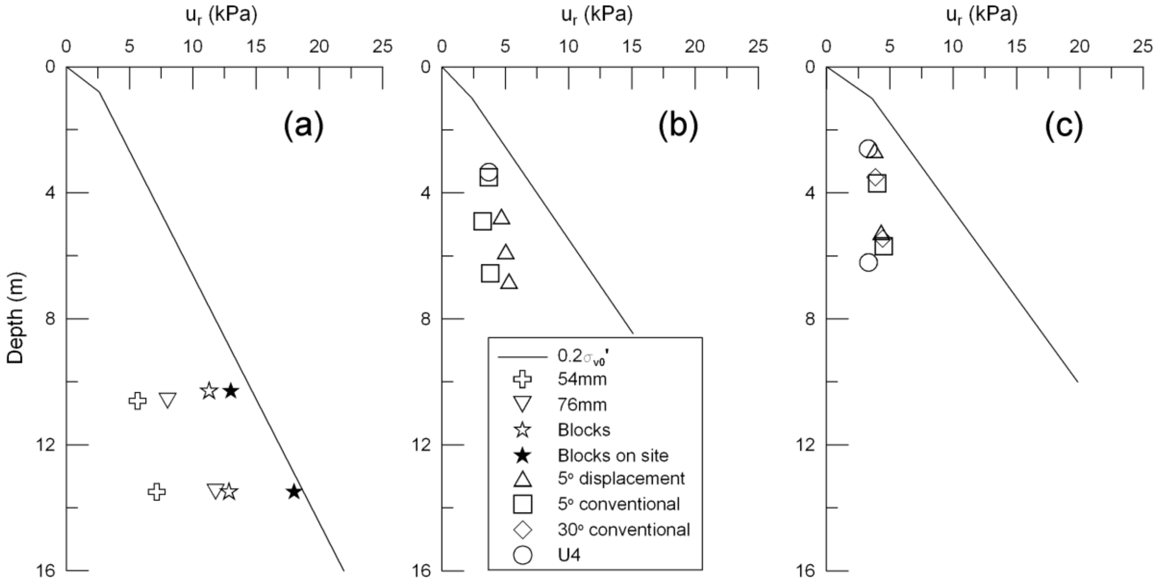
FIGURE CAPTIONS

Figure 1	CAUC stress-strain and stress path plots for (a,b) Onsøy, (c,d) Ballinasloe and (e,f) Bogganfin
Figure 2	Unconfined V_s measurements compared with in-situ V_s for (a) Onsøy (b) Ballinasloe and (c) Bogganfin
Figure 3	Sample quality comparison: V_{s0} normalised by in-situ V_s compared with $\Delta e/e_0$ on all sites
Figure 4	Suction measurements performed on samples from (a) Onsøy (b) Ballinasloe and (c) Bogganfin
Figure 5	Sample quality comparison: variation of u_r/σ'_{v0} with $\Delta e/e_0$
Figure 6	The proposed L_{vs}-L_u sample quality criterion applied to samples from Onsøy, Ballinasloe and Bogganfin

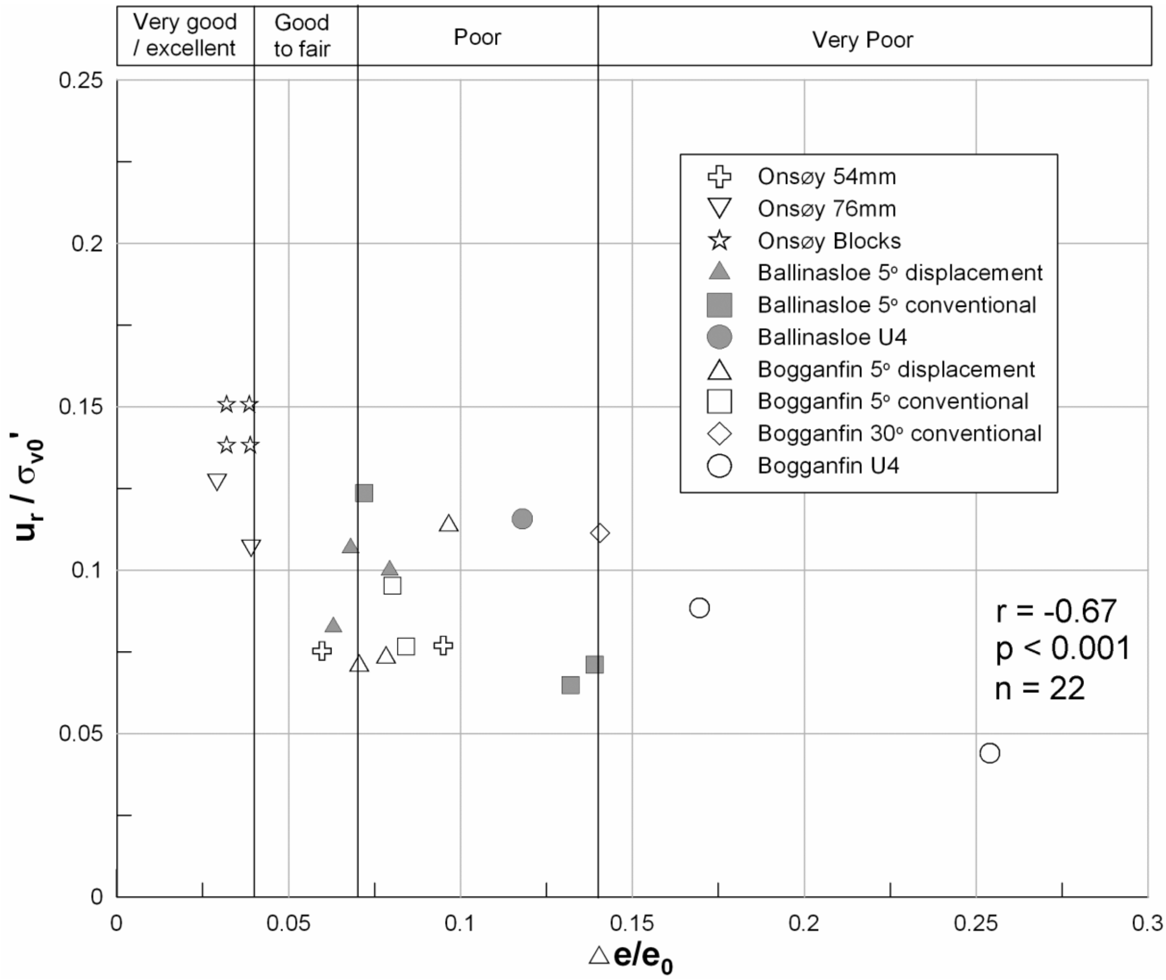

(a)
(b)
(c)
(d)
(e)
(f)
$(\sigma'_1-\sigma'_3)/2$ (kPa)
$(\sigma_1-\sigma_3)/2$ (kPa)
Axial strain (%)
$(\sigma'_1+\sigma'_3)/2$ (kPa)
Block
76mm
54mm
5° displacement
5° conventional
U4
30° conventional
0
4
8
12
16
20
10
30
40
2
6
60

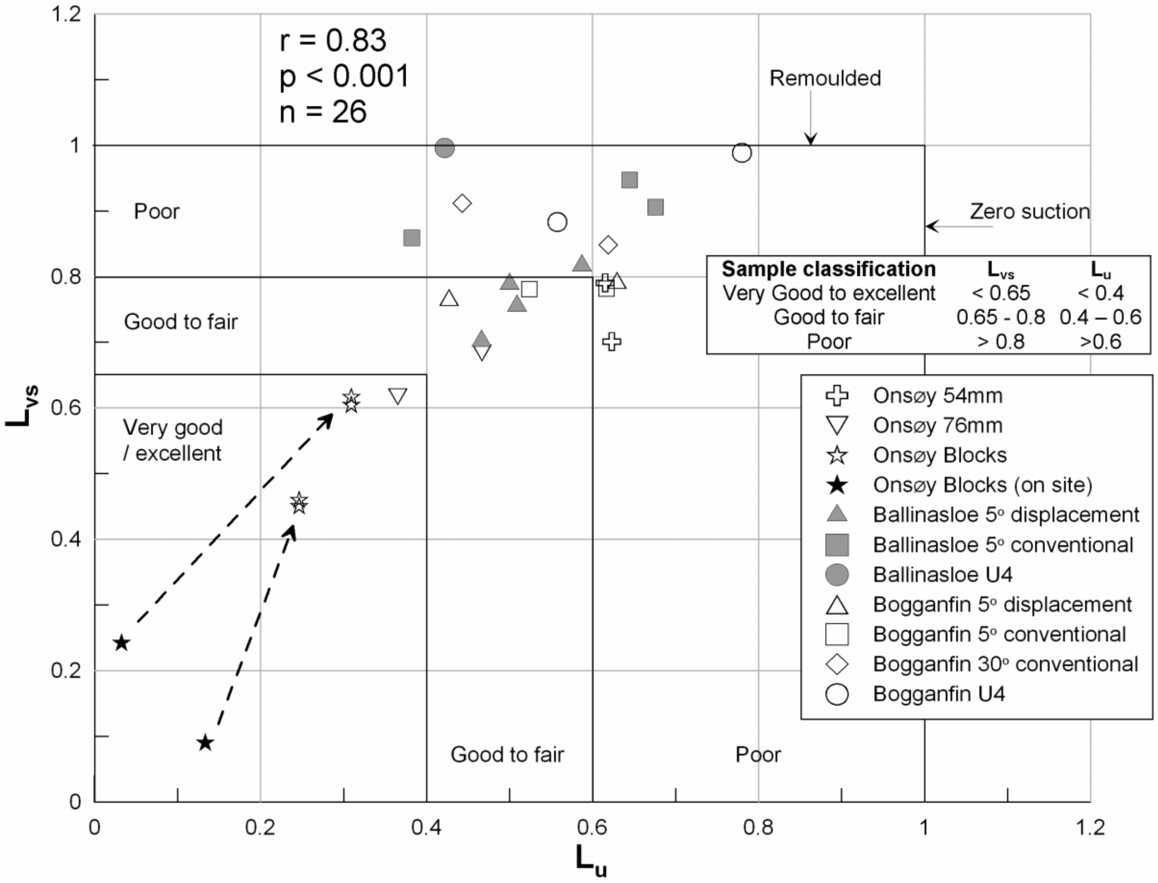

V$_s$ (m/s)
0
40
80
120
160
Depth (m)
0
4
8
12
16
(a)
(b)
(c)
MASW (Long & Donohue, 2007; Donohue, 2005)
SCPT (Eidsmoen et al., 1985)
54mm
76mm
Blocks
Blocks on site
5° displacement
5° conventional
30° conventional
U4
Remoulded


Very good / excellent
Good to fair
Poor
Very Poor
Onsøy 54mm
Onsøy 76mm
Onsøy Blocks
Ballinasloe 5° displacement
Ballinasloe 5° conventional
Ballinasloe U4
Bogganfin 5° displacement
Bogganfin 5° conventional
Bogganfin 30° conventional
Bogganfin U4
r = -0.78
p < 0.001
n = 22
$V_{s0}/V_{s\ in\text{-}situ}$
$\triangle e/e_0$
0
0.2
0.4
0.6
0.8
1
0
0.05
0.1
0.15
0.2
0.25
0.3



u_r (kPa)
0
5
10
15
20
25
Depth (m)
0
4
8
12
16
(a)
(b)
(c)
0.2σ_v0'
54mm
76mm
Blocks
Blocks on site
5° displacement
5° conventional
30° conventional
U4


Very good / excellent
Good to fair
Poor
Very Poor
Onsøy 54mm
Onsøy 76mm
Onsøy Blocks
Ballinasloe 5° displacement
Ballinasloe 5° conventional
Ballinasloe U4
Bogganfin 5° displacement
Bogganfin 5° conventional
Bogganfin 30° conventional
Bogganfin U4
r = -0.67
p < 0.001
n = 22
0.25
0.2
0.15
0.1
0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
u_r / σ_{v0}'
$\Delta e/e_0$


r = 0.83
p < 0.001
n = 26
Remoulded
Zero suction
Poor
Good to fair
Very good / excellent
Good to fair
Poor
Sample classification | L_{vs} | L_u
Very Good to excellent | < 0.65 | < 0.4
Good to fair | 0.65 - 0.8 | 0.4 – 0.6
Poor | > 0.8 | >0.6
Onsøy 54mm
Onsøy 76mm
Onsøy Blocks
Onsøy Blocks (on site)
Ballinasloe 5° displacement
Ballinasloe 5° conventional
Ballinasloe U4
Bogganfin 5° displacement
Bogganfin 5° conventional
Bogganfin 30° conventional
Bogganfin U4
L_{vs}
L_u
0
0.2
0.4
0.6
0.8
1
1.2