USING ACSW FOR GEOTECHNICAL ASSESSMENT

Guidance Note SSGN020

Background

SoilSafe Advanced Continuous Surface Wave (ACSW) testing allows ground stiffness profiles to be determined rapidly and non-intrusively by measurement of the velocity of surface Rayleigh waves (V_r) over a range of frequencies (f) - see SSGN010 for a full description of the theory. Inversion of the V_r versus f data (the 'dispersion curve') allows determination of both a shear-wave velocity (V_s)profile and a Small Strain Shear Modulus (G_0) profile against depth. In this inversion process conservative assumptions of Poisson's Ratio and unit weight can be made to derive V_s and G_0 since within their normal ranges these influence the values relatively little (less than 10% in the case of V_s). Hence no prior information on ground conditions is normally required to derive a representative stiffness profile from ACSW data.

ACSW testing is principally used to provide representative bulk stiffness profiles for geotechnical design. However, ground stiffness can be used to provide an indication of other ground properties and ACSW testing's non-intrusive nature makes it an attractive means of supplementing or substituting other intrusive techniques.

This Guidance Note outlines a number of approaches for using ACSW testing data for the geotechnical assessment of sites. As for all test data, however, appropriate professional engineering judgement in the context of a suitable range of ground investigation information on must be applied in using ACSW data.

Profiling

Where the stratigraphy is known and is associated with a significant change in stiffness ACSW profiles can provide an indication of the stratigraphy change with depth, though care is required since depths profiles will not be as accurate as those obtained by intrusive means.

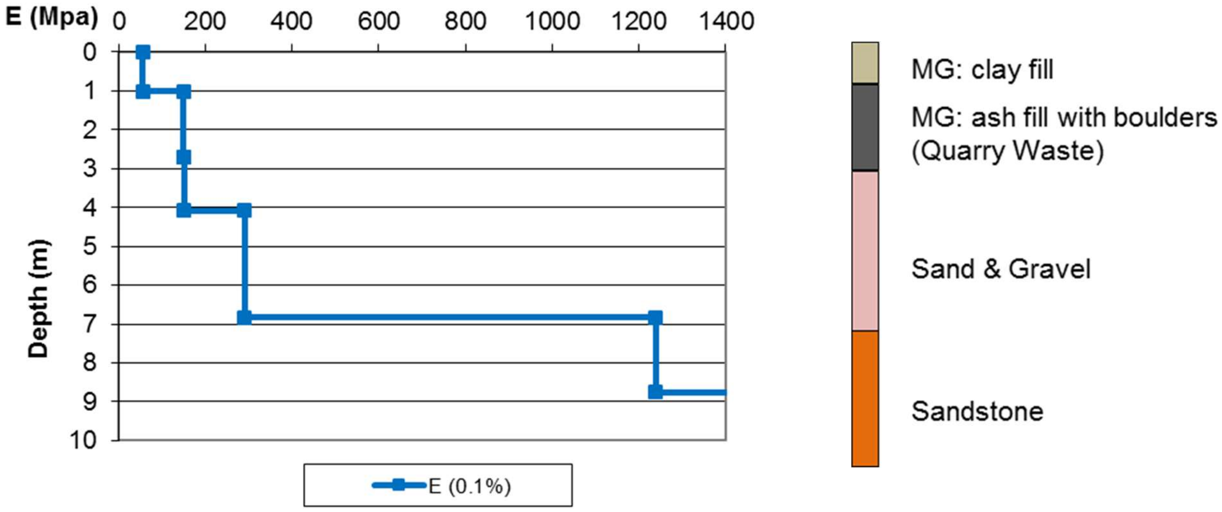

Figure 1: Correlations between borehole stratigraphy and ACSW stiffness profile.

With a suitably tight grid of tests, it may be possible to profile these changes in stiffness 3D and give an indication of lateral variation in stratigraphy.

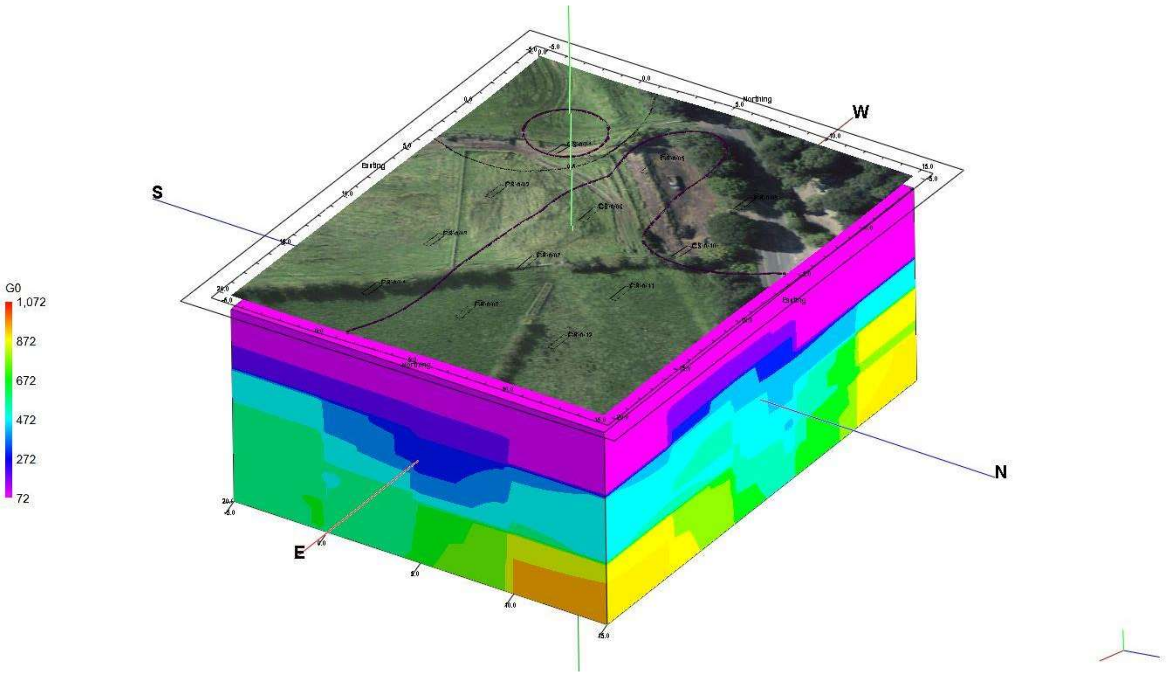

Figure 2: 3D stiffness modelling.

- **In using ACSW testing data for profiling, however, some caution is required since ACSW testing profiles measure stiffness variation with depth which may not necessarily reflect variations in stratigraphy. Weathered rock for example may be of similar stiffness to overlying soils. Other ground investigation information (such as historic boreholes) is recommended to provide control over correlation of stiffness profiles with stratigraphy**

- **ACSW testing profiles will not provide the same degree of accuracy as intrusive investigation if precise depths are required. ACSW profile resolution reduces with depth with a typical resolution of approximately 20% the depth of investigation**
- **Lateral resolution is limited by the extent of the test array (normally around 3m) and the lateral spacing of tests. Lateral variations in ground conditions within distances close to the array length at shallow depth are unlikely to be identified even with a very tight grid spacing**
- **Lateral variations in stiffness across distances less than the test array length will affect the quality of data since analysis assumes a constant lateral velocity and will result in data unsuitable for inversion**

Relationship for Seismic Assessment

Most seismic codes use Vs profiles for site classification (e.g. the US ASCE 7-10, see Table 1).

Table 1: ASCE 7-10 Table 20.2-1 seismic site classification using V_s30 *Shear Wave Velocity.*

V_s (m/s) for upper 30m of geologic profile	ASCE 7-10 seismic site class	ASCE 7-10 description
>1524	A	Hard Rock
762 - 1524	B	Rock
366 - 760	C	Very Dense Soil and Soft Rock
365 – 183	D	Stiff Soil
<183	E	Soft Clay Soil

Due to the perceived difficulty in obtaining Vs profiles considerable research has been undertaken into correlating more commonly available data such as SPT N values, CPT cone resistance (q_s) and undrained shear strength (C_u) with shear wave velocity (V_s). A review of many of these relationships is included in PEER2012/08 Guidelines for Estimation of Shear Wave Velocity Profiles. It should be noted of course that ACSW testing allows direct in-situ shear wave velocity profiles to be measured reliably, rapidly and cost effectively, however this research allows the relationship between ACSW derived data and common design parameters to be established for site characterisation.

Relationships with SPT N Values

Relationships between Vs and SPT N values are reviewed in detail by PEER2012/08, and recommendations made (see Table 2) for SPT N60-Stress equations which are assessed provide better correlation with Vs. The Vs-stress equations generally follow the form of the equation:

$V_s = a \bullet N_{60}{}^{b} \bullet \sigma'_v{}^{c}$ **where a, b & c are coefficients.**

Site specific correlation between ACSW test data and SPT N values should however be undertaken wherever possible. Derived SPT N values can be used to indicate relative density of granular deposits and for other design purposes. However, in the case of settlement analysis, the stiffness parameters derived directly from the ACSW Vs profile will provide a significantly more accurate means of determining ground movements than those based on SPT N values since they can be accurately adjusted for design strains using strain softening functions (see Guidance Note SSGN010).

Table 2: SPT-stress Vs correlation recommendations from PEER2012/08 Table 4.11.

Soil Type	Shear Wave Velocity for Quaternary Soils (m/s)	(Eq #)	Age Scaling Factors	
			Holocene	Pleistocene
All Soils	$30\ N_{60}{}^{0.215}\ \sigma'_v{}^{0.275}$	(4.17)	0.87	1.13
Clays & Silts	$26\ N_{60}{}^{0.17}\ \sigma'_v{}^{0.32}$	(4.40)	0.88	1.12
Sands	$30\ N_{60}{}^{0.23}\ \sigma'_v{}^{0.23}$	(4.77)	0.90	1.17
Gravels – Holocene	$53\ N_{60}{}^{0.19}\ \sigma'_v{}^{0.18}$	(4.98)	---	---
Gravels - Pleistocene	$115\ N_{60}{}^{0.17}\ \sigma'_v{}^{0.12}$	(4.102)	---	---

Relationships with CPT Data

Relationship between Vs and CPT end resistance are reviewed summarised in PEER2012/08, see Table 3. A further review is provided by NHCHRP Synthesis 368:2007 Cone Penetration Testing. Site specific correlations should however be used wherever possible to confirm the approaches set out in Table 3.

Table 3: Summary of published CTP-Vs correlations from PEER2012/08 Table 5.3.

Soil Type	Study	Geologic Age	Number of Data Pairs	r^2	V_S (m/s)	(Eq #)
All Soils	Hegazy & Mayne (1995)	Quaternary	323	0.70	$(10.1 \log(q_c) - 11.4)^{1.67}\ (100\ f_s/q_c)^{0.3}$	(5.6)
	Mayne (2006)	Quaternary	161	0.82	$118.8 \log(f_s) + 18.5$	(5.7)
	Piratheepan (2002)	Holocene	60	0.73	$32.3\ q_c{}^{0.089}\ f_s{}^{0.121}\ D^{0.215}$	(5.8)
	Andrus et al. (2007)	Holocene & Pleistocene	185	(H) 0.71 (P) 0.43	$2.62\ q_t{}^{0.395}\ I_C{}^{0.912}\ D^{0.124}\ SF^{a}$	(5.9)
	Robertson (2009)	Quaternary	1035	---	$[(10^{(0.55Ic+1.68)})\ (q_t - \sigma_v)/p_a]^{0.5}$	(5.10)
Sand	Sykora & Stokoe (1983)	---	256	0.61	$134.1 + 0.0052\ q_c$	(5.11)

	Baldi et al. (1989)	Holocene	---	---	$17.48\ q_c^{0.13}\ \sigma'_v{}^{0.27}$	(5.12)
	Hegazy & Mayne (1995)	Quaternary	133	0.68	$13.18\ q_c^{0.192}\ \sigma'_v{}^{0.179}$	(5.13)
	Hegazy & Mayne (1995)	Quaternary	92	0.57	$12.02\ q_c^{0.319}\ f_s^{-0.0466}$	(5.14)
	Piratheepan (2002)	Holocene	25	0.74	$25.3\ q_c^{0.163}\ f_s^{0.029}\ D^{0.155}$	(5.15)
Clay	Hegazy & Mayne (1995)	Quaternary	406	0.89	$14.13\ q_c^{0.359}\ e_0^{-0.473}$	(5.16)
	Hegazy & Mayne (1995)	Quaternary	229	0.78	$3.18\ q_c^{0.549}\ f_s^{0.025}$	(5.17)
	Mayne & Rix (1995)	Quaternary	339	0.83	$9.44\ q_c^{0.435} e_0^{-0.532}$	(5.18)
	Mayne & Rix (1995)	Quaternary	481	0.74	$1.75\ q_c^{0.627}$	(5.19)
	Piratheepan (2002)	Holocene	20	0.91	$11.9\ q_c^{0.269}\ f_s^{0.108}\ D^{0.127}$	(5.20)

Units q_c, q_t, f_s, σ_v and σ'_v are measured in kilopascals (kPa), and depth (D) is measured in meters (m). p_a = 100 kPa. [a]SF = 0.92 for Holocene and 1.12 for Pleistocene

Note: PEER2012/08 advises that where pore pressure measurements are available corrected cone resistance q_t should be used.

Relationships with Undrained Shear Strength

Undrained shear strength (C_u) can be estimated from values of cone resistance using a range of published correlations. However, PEER2012/08 also provides a simple direct relationship between shear wave velocity and C_u as determined by Dickenson, 1994:

$V_s = 23.C_u^{0.475}$ where V_s is measured in m/s and C_u in kPa

A range of other published relationships exists (see Table 4 for examples). Again, site correlations should be used where possible to refine any relationship used.

Table 4: Published relationships between V_s and C_u (S_u) from Moon & Ku, 2016.

Published Relationships	
$\text{Log}\ (s_u(\text{kPa})) = (\log(V_s\ (\text{m/s}) / 23) / 0.475$	Ashford et al. (1996)
$s_u\ (\text{kPa})\ (V_s\ (\text{m / s}) / 2.93^{1.59}$	Levesques et al. (2007b)
$s_u\ (\text{kPa}) = 0.001\ V_s{}^2\ (\text{m/s}) + 0.016\ V_s\ (\text{m/s}) + 60.8$	Long et al (2013)

Traditionally C_u has been used to estimate the undrained stiffness modulus of clays (E_u) in the absence of direct measurements (see Figure 3). This relationship can also be used in reverse to provide estimates of C_u from CSW stiffness data, however given the range of assumptions required and the relatively wide range of factors resulting the relationships set out in Table 2, combined with on-site calibration is likely to provide more accurate estimates.

Relationships with CBR Values

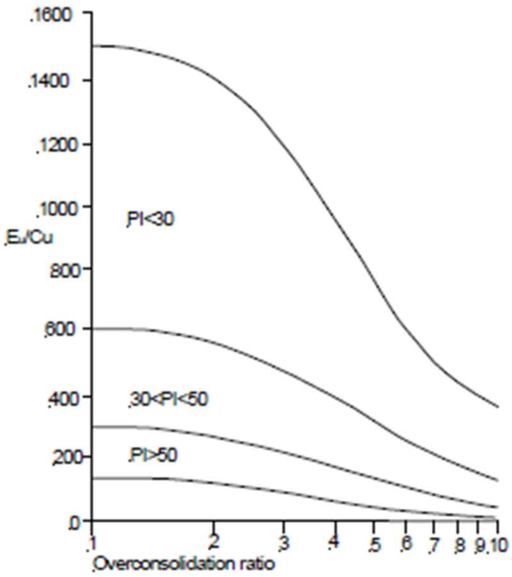

Figure 3: Correlation of E_u against C_u (after Jamiolkowski *et al, 1979)*

The relationship between CBR and Young's Modulus E is provided in TRRL Laboratory Report 1132 (Powell et al, 1984) as follows;

$E = 17.6\ (CBR)^{0.64}$ MPa where CBR is in per cent

This relationship is based on upon comprehensive testing undertaken by Jones (1958) who compared seismically measures soil stiffness values with CBR tests on both remoulded and undisturbed soil samples which makes the relationship particularly appropriate to the application of ACSW measured stiffness values.

Summary

Extensive research has indicated Vs profile data obtained by ACSW testing can provide a good indicator of ground properties other than stiffness. In all cases information on stratigraphy, and wherever possible additional testing, is required to confirm site-specific relationships. However, the benefits of a rapid non-intrusive investigation technique means that ACSW provides opportunities for initial surveys to assess ground conditions or to improve the coverage of information on larger sites.

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