Ground Stiffness Surveys

GUIDANCE NOTE

Using ACSW to determine rock properties

June 2018

GN019

Background

GSS Advanced Continuous Surface Wave (ACSW) testing allows ground stiffness profiles to be determined non-intrusively by measurement of the velocity of surface Rayleigh waves (V_r) over a range of frequencies (*f*) - *see GN010 for a full description of ACSW 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_o, since within their normal ranges these have a relatively small influence the values derived (in the case of V_s less than 10%). Hence no prior information on ground conditions is normally required to derive a representative stiffness profile from ACSW data.

This Guidance Note outlines a number of approaches for using ACSW testing data to assess rock quality and to derive rock properties. 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.

Qualitative assessment

Where there is a significant stiffness contrast associated with a change in stratigraphy ACSW profiles can provide an indication of the stratigraphy change with depth. Since unweathered rock is normally much stiffer than any overlying soils, ACSW testing is usually good at distinguishing rockhead.

ACSW can therefore provide a means of qualitatively assessing variation in rockhead depth, particularly where other means of investigation are limited and provided the general stratigraphy at the site is understood.

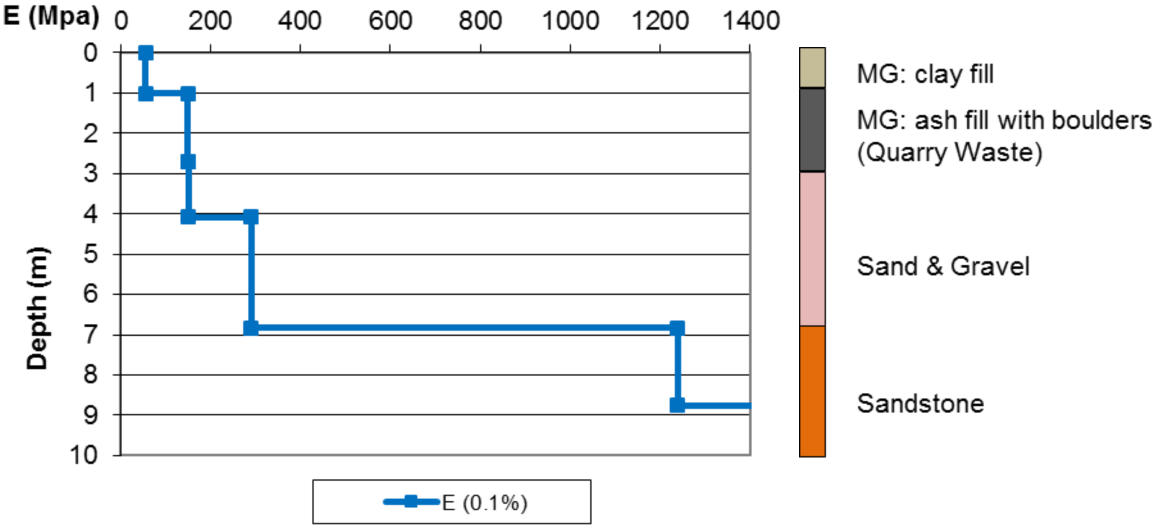

Figure 1: Correlations between borehole stratigraphy and ACSW stiffness profile

In addition, ACSW may be able to identify changes in rock quality or zones of poor rock – such as where collapsed mine workings, deep weathering or solution features are present, though normally a tight test grid is required.

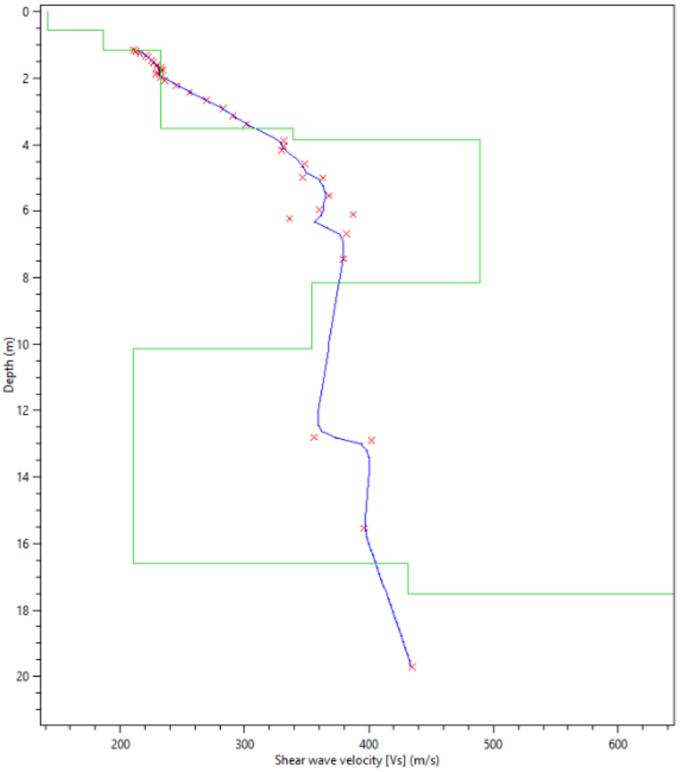

Figure 2: Low stiffness zone in chalk in an area of collapsed mineworkings

In using ACSW 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

Seismic assessment

ASCE standards for seismic design provide a site classification based on the shear wave velocity of the upper 30m of the ground profile (V_{s30}) – *see Table 1 below*. Using this table ACSW data can provide a classification of ground conditions and a basis for seismic design of structures.

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

Table 1: ASCE 7-10 Table 20.2-1 seismic site classification using V_{s30} Shear Wave Velocity

Excavatability

Seismic velocity is commonly used as a preliminary means of assessing the quality of rock excavation. Typically compression wave velocity (V_p) has been used (*see Table 2 for example*), but shear wave velocity (V_s) also provides a similar measure (*See Choudhury & Sitharam, 2009*). V_s & V_p are related by Poisson's Ratio (ν) ratio according to the relationship shown in Equation 1 below.

$$\frac{V_p}{V_s} = \left[\frac{2(1-\nu)}{(1-2\nu)}\right]^{\frac{1}{2}}$$

Equation 1

From Equation 1 it can be seen that the impact of Poisson's Ratio is small, and furthermore in consolidated rocks it can be estimated as typically at around 0.26 - giving a value of V_p of about $1.7.V_s$, allowing equivalent V_s values to be determined for published V_p criteria.

Rippability Class (Caterpillar D9G with single-tooth)	V_p (m/s) range	Approximate equivalent V_s (m/s) range
Easily Ripped	<1050	<620
Moderately Difficult Ripping	1050 -1500	620 - 880
Difficult Ripping	1500 - 2000	880 - 1170
Not Rippable	>2000	> 1170

Table 2: Rippability assessment using seismic velocities
(based on Caterpillar Handbook of Ripping 12th Edition and Stephens, 1978)

Comparisons between field seismic velocities and those measured from intact rock can also be used to evaluate the extent of discontinuities. Table 3 shows the classification proposed by Hobbs, 1974, intended for use in settlement analysis but which could be used for qualitative preliminary discontinuity assessment. Seismic velocities assumed here are V_p and therefore this approach would necessarily be subject to on-site calibration.

Rock quality classification	RQD (%)	Fracture frequency per metre	Velocity Index [a] $(V_f/V_L)^2$	Mass factor (j)
Very poor	0 - 25	15	0 - 0.2	0.2
Poor	25 - 50	15 - 8	0.2 - 0.4	0.2
Fair	50 - 75	8 - 5	0.4 - 0.6	0.2 - 0.8
Good	75 - 90	5 - 1	0.6 - 0.8	0.5 - 0.8
Excellent	90 - 100	1	0.8 - 1.0	0.8 - 1.0

[a] Where V_f= wave velocity in field & V_L = wave velocity in laboratory

Table 3: Rock mass factor values from Tomlinson, 1995 (after Hobbs, 1974)

Design stiffness parameters

For transient loading a small strain stiffness (G_o) as derived from ACSW test data is appropriate for both soils and rocks. However, in soils small strain stiffness is assumed to be a maximum value, which may not be the case in rocks where stiffness may be controlled by the effect of discontinuities.

In soils, a strain-softening curve function can be readily used to convert values of G_0 to design values of Young’s Modulus (E) - *see Guidance Note GN002*. For weathered rocks where stiffness is controlled by the matrix, this approach may also be applied to obtain design stiffnesses.

In intact massive rock, the small-strain stiffness may represent a suitable stiffness under design load. However, in more fractured rock stiffness may vary according to loading. In strong, closely fissured and jointed rocks stiffness may initially increase (‘work hardening’) as tightening of joints controls mass stiffness. Rock stiffness under load in is therefore dependent on rock type and quality, hence site or rock type specific correlations may be required.

Matthews (1993) found that V_s measurements in highly fractured chalks used to calculate stiffnesses values provide good predictions of settlement up to yield stresses. BGS report RR/01/02 (2002) reports the use of V_s and V_p values to provide Young's moduli and lithology for the Mercia Mudstone and Maddison et al. (1996) describe the use of V_s measurements in this material to determine stiffness values for the design of the Second Severn Crossing. Similar site-specific relationships could be developed for other rock types where suitable data exists or is obtained.

Limitations

This document is intended to indicate potential approaches for the use of ACSW data by suitably qualified geotechnical engineers as part of a general design review. It may be subject to periodic review and change. No guarantees as to accuracy are made and where necessary original references and relevant design guidance should be reviewed. ACSW test data should be reviewed against all available information on ground conditions as part of an appropriately scoped ground investigation.

References

ASCE 7-10 Minimum Design Loads for Buildings and Other Structures

BGS Report RR/01/02 (2002) Engineering geology of British rocks and soils; Mudstones of the Mercia Mudstone Group

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GSS Guidance Note GN002 – Application of ACSW data

GSS Guidance Note GN010 - Description and limitations of ACSW technique

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