GUIDANCE NOTE

Accuracy & reliability of ACSW data

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1. Introduction

GSS Advanced Continuous Surface Wave (ACSW) testing is a rapid, non-intrusive ground stiffness measurement technique which relies on determination of the ground's response to a vibratory source or 'shaker' (Heymann, 2007). The velocity of surface Rayleigh waves (V_r) generated are measured as they travel away from a seismic source across an array of geophones (*see Figure 1*). The velocity of the surface waves generated is related to ground stiffness, with the depth of wave penetration increasing with reducing frequency and increasing wavelength (λ).

Field testing provides an accurate measurement of surface wave velocity across a range of frequencies (f) resulting in a *dispersion curve* of V_r against f for the ground at the test location (*see Figure 2*). From this information *inversion* of the data can be undertaken to provide a shear wave velocity (V_s) against depth profile, which in turn can be used to generate values of small-strain shear modulus (G_0) and Young's Modulus (E) with depth. The results provided represent bulk stiffness over the length of the geophone array (typically 2-4m). There is good evidence to demonstrate that ACSW stiffness data is of equivalent quality to other techniques for accurate stiffness measurement, though it is typically more cost effective.

Figure 1: Typical ACSW test setup

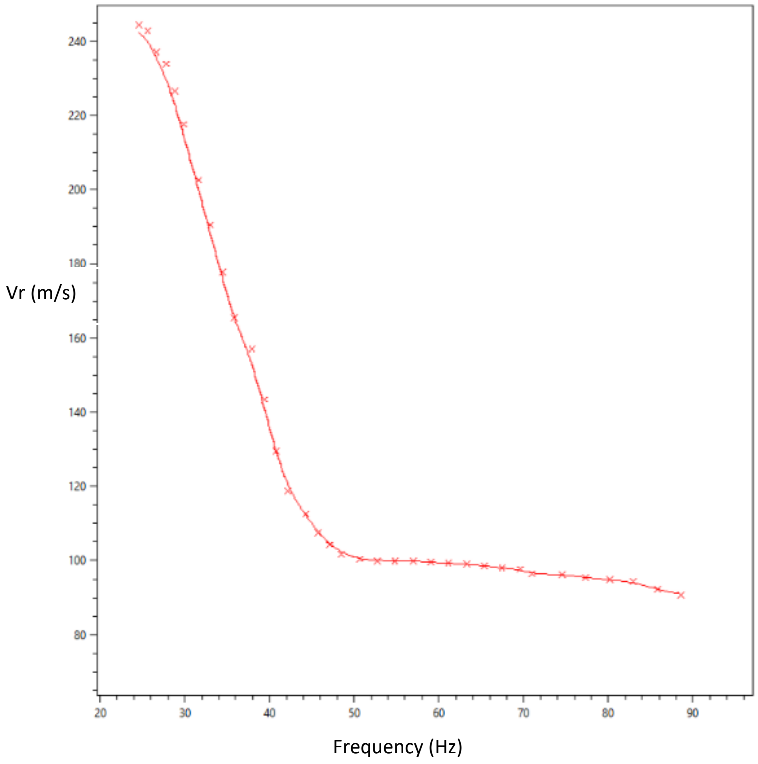


Figure 2: ACSW data dispersion curve, as generated by GSS C-DAS software

Following ACSW data collection the following is then undertaken to derive stiffness data for design:

i. Data quality checks followed by removal of outliers and stacking of data to provide a test location dispersion curve
ii. *Inversion* analysis of the dispersion curve to derive a Shear (S) wave velocity (V_s) profile
iii. Conversion of V_s values to small-strain shear modulus (G_0)
iv. Conversion of G_0 to Young's Modulus (E_0)
v. Strain softening of values of E_0 in accordance with the design strain

In order to undertake these processes some assumptions or input data is required. There is good evidence to confirm that, where properly undertaken, ACSW data compares favourably with other high quality stiffness data (*see Clayton, 2011*), even where ACSW testing is being undertaken 'blind' of information on ground conditions. This guidance note considers the sensitivity of ACSW test results to this additional information and the accuracy and reliability of the resulting stiffness profiles.

It is stressed that in all cases appropriate review by a competent and suitably experienced engineer is required for utilisation of ACSW testing data, taking into account available information on ground conditions. It must be remembered in comparing different data sources that significant lateral variation in ground conditions may occur, sometimes rapidly. Consequently, as for any geotechnical test data, ACSW data must always be used holistically as part of a wider ground investigation and geotechnical engineering assessment. The purpose of this guidance note is to enable a suitably qualified geotechnical engineer to understand the limits of accuracy of ACSW data and make appropriate allowance for this in selecting design values.

As necessary additional investigation may be required to provide correlations with, or confirm the results of, ACSW testing. Other investigations may also be required to provide other information (such as shear strength) which is not provided by ACSW data. Additional guidance notes are available which compare the results of ACSW testing to other methods of determining ground stiffness (ref GSS GN013, GN014, GN015 & GN016).

2. Reliability and repeatability

Each ACSW test comprises data acquisition during a sweep across the full range of shaker frequencies (Sweep test) and a series of discrete constant frequencies (Monotonic test). This provides two complete sets of dispersion curve data. During data capture GSS C-DAS software automatically checks the quality of data being recorded and the calibration of the geophones and shaker by:

- Comparing the frequency being measured by the geophones against that being generated by the source
- Comparing the phase difference across each pair of geophones to ensure the assumption of cross-isotropy (constant lateral stiffness) is within acceptable limits

Data out of specified tolerances is highlighted to the operator and automatically discounted. C-DAS allows on-site display of the dispersion curve, including comparison between monotonic and sweep data. Where significant poor quality or scattered data is observed the test methodology can be adjusted and tests can be repeated.

Poor quality data and scatter in the dispersion curve can occur due to:

- Poor ground response – typically recently placed/disturbed or highly variable material
- Significant lateral variation in stiffness over the geophone array - for example buried foundations
- Strongly multi-modal responses - typically where stiff surface layers present
- The effects of on-site noise - for example vibration from plant or machinery, high winds, heavy rain or EM sources

C-DAS allows the on-site review and comparison of test data (*see Figure 3*). Following data capture a review of data is undertaken to produce a test location dispersion curve by:

- Comparing monotonic values with sweep data to identify the extent of scatter and to discount data where a clear ground response cannot be identified (i.e. at the limits of the frequency response for the source being used)
- Removing outlier data representing scatter
- As necessary stacking repeat tests where excessive scatter was identified in the field
- Using C-DAS to plot a smoothed dispersion curve through the valid data representing the surface wave response of the ground for subsequent inversion
- Comparing adjacent test data to provide a sense check on data

Where scatter in data is such that a suitable dispersion curve cannot be reliably plotted through it, the test is not reported.

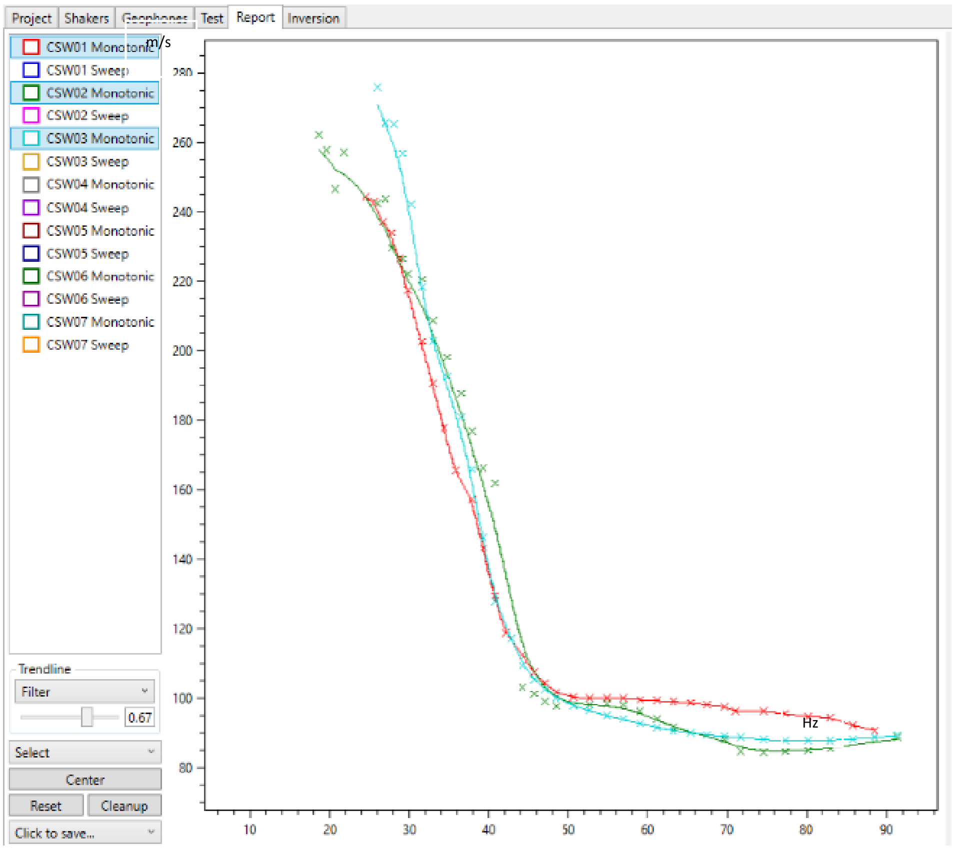


Figure 3: Example of on-site ACSW data dispersion curve comparison, as generated by GSS C-DAS software showing similar data with low scatter for adjacent tests

3. Depth and resolution

The depth to which ACSW data can reliably be obtained is a function of:

- The stiffness of the ground being investigated (longer wavelengths will be generated in stiffer ground for any given frequency)
- The power of the source – at some point the energy being imparted will be insufficient to fully excite the ground or be detectable over background noise resulting in unreliable data
- The limits of the arrangement of the geophone array – the geophone array must be sufficiently long or contain sufficient geophones to accurately define longer wavelengths whilst also limiting geophone spacing to approximately the shortest wavelength to be measured in order to limit the effects of aliasing

Resolution of layers is a function of the stiffness contrast between layers and their depth and the quality/scatter of data obtained. Typically distinct layers with a significant stiffness contrast and thickness in excess of around 5-10% of the wavelength can be resolved. This translates to a layer thickness of around 0.5m being resolved at a depth to 2-3m reducing in resolution to a layer thickness of around 1m between 4-6m and decreasing further with depth. Within these resolutions the effect of thinner layers will tend to be averaged. The specific depth resolution of stiffness profiles must therefore be considered with caution and comparison with intrusive investigation information is required, especially if the presence of thin layers of varying stiffness is to be established.

4. Inversion

Surface waves are formed by the interaction of P (pressure) and S (shear) waves in proximity to the ground surface. The influence of P waves in determining V_r is small compared to the influence of S waves and is generally ignored in calculating V_s (*see Equation 1 below*). Seismic tests are always undrained which for most saturated soils implies a Poisson's Ratio (ν) of 0.5. When soils are partially saturated or the soil matrix is stiffer than the porewater then Poisson's Ratios may be less than 0.5 resulting in the calculation of higher stiffness values. However the impact of Poisson’s Ratio (ν) in calculating V_s from Equation 1 is small resulting in less than a 10% variation for a range of 0.2 to 0.5. As most UK sites involve saturated 'soft' soils a conservative ν=0.5 is used by default in GSS inversions.

Equation 1 (Heymann, 2007)

$$\frac{V_r}{V_s} \cong \frac{0.874 + 1.117\nu}{1 + \nu}$$

The S wave velocity (V_s) is the key parameter required to permit determination of ground stiffness as obtained through inversion of the field dispersion curve. V_s is also widely used directly for characterisation of near surface ground properties.

A *simple inversion* may be undertaken by assigning the measured value of V_s to a fraction of the wavelength typically in the range λ/2 to λ/3. V_s can then be converted to a value of small strain stiffness, G_o (*see Figure 4 and Section 5 below*). A value of λ/2.5 has been found at GSS to generally provide a good fit to ground truthing data and is used as a default value where no other information is provided. It is noted however that the simple inversion process provides only an averaged stiffness depth profile and cannot resolve individual layers. These limitations may be of particular concern where data is *inversely dispersive* (i.e. where there is a local reduction in stiffness with depth).

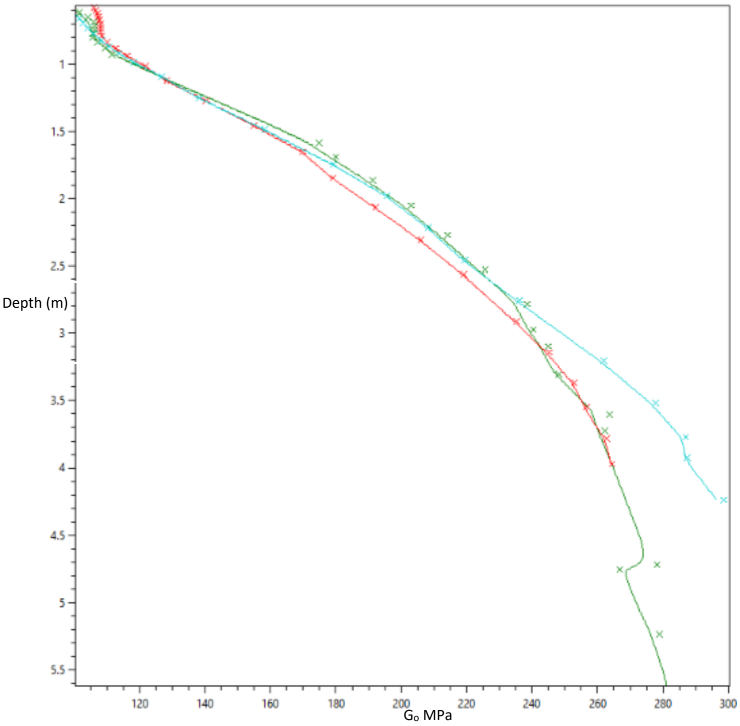
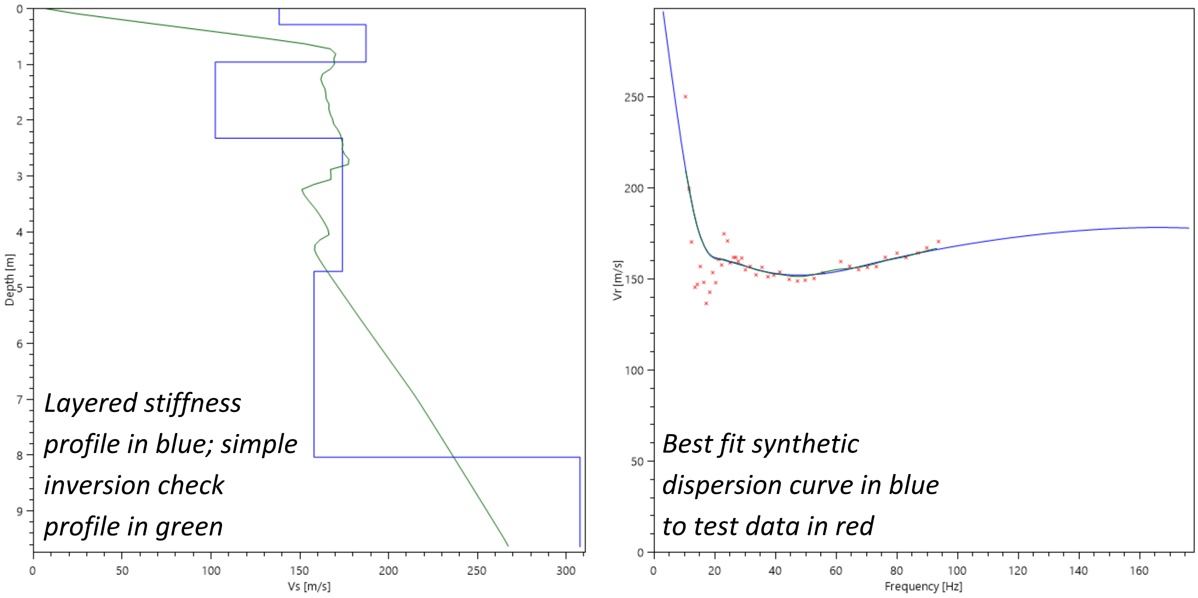


Figure 4: example of simple inversion data for three adjacent tests generated by GSS C-DAS software

In order to provide a layered soil stiffness profile, GSS undertakes an *advanced inversion* of the test dispersion curve. Due to the mathematical difficulties presented by forward modelling a layered V_s profile from dispersion curve data an inverse method is used whereby a synthetic dispersion curve is generated from an assumed layered V_s profile. The fit of the synthetic dispersion curve to the test dispersion curve is used to guide an iterative adjustment of the layered V_s profile until a good fit is obtained.

Advanced inversion is undertaken within GSS C-DAS software using a published algorithm (Leong & Aung, 2013) to generate the synthetic dispersion curve. A bespoke Monte Carlo method is then used by the software to adjust the assumed V_s profile to achieve the best fit between the synthetic and test dispersion curves. A sense check of the resultant layered profile is achieved by comparison with the simple inversion automatically generated by the software (*see Figure 5*).

The advanced inversion technique used implicitly assumes that the soil profile consists of horizontal layers (cross-isotropic) and as such lateral changes in ground stiffness are not modelled. Advanced inversion requires input or assumptions of soil density (γ) and Poisson's Ratio (ν) for each layer; unless otherwise stated and in the absence of other information, a typical soil density of 1.80Mg/m^3 and a Poisson's Ratio of 0.5 are assumed.


Layered stiffness profile in blue; simple inversion check profile in green

Best fit synthetic dispersion curve in blue to test data in red

Figure 5: Example of advanced inversion outputs generated by GSS C-DAS software.

Due to the non-linear, inverse nature of the advanced inversion process more than one solution may exist and historical ground investigation information can be useful in constraining the solution. Layer boundaries and stiffness data is not required for advanced inversion but information on anticipated stratigraphy, soil density and Poisson's Ratio may improve the accuracy of the inversion. However as noted above, for deriving V_s the effect of Poisson's Ratio within likely ranges is small and the impact of likely variation of unit weight within typical ranges is similarly limited. Within the typical ranges of assumed soil parameters the typical maximum variation in V_s derived from the advanced inversion is only about 10%. Hence in most cases a good representation of stiffness profile is possible without information on ground conditions.

5. Conversion of V_s to G_0

The shear wave velocity (V_s) profile derived by the inversion may be converted to a small-strain shear modulus (G_0) profile using the relationship $G = \rho.V_s^2$ (where ρ is soil density). It is seen that due to the form of this relationship G is far more sensitive to variation in V_s (square function) than ρ (direct function). Given that soil density generally varies within a relatively small range of 1.6 Mg/m^3 and 2.1 Mg/m^3 for most ground conditions, derivation of G_0 is therefore relatively insensitive to assumed soil density (if not known), and conservative (i.e. lower bound) if a low soil density is assumed.

If in the absence of other data a typical soil density of 1.80Mg/m^3 is utilised. The potential deviation in calculated shear modulus from this default value for the normal range of soil densities is 11% (ρ =1.6 Mg/m^3) and 17% (ρ =2.1 Mg/m^3 respectively). In order to improve accuracy further the output spreadsheet permits user defined values of soil density to be input where these are more accurately known.

6. Conversion of G_0 to E_0

G_0 may be converted to Young's Modulus (E) using the relationship $E=G.(2.(1+\nu))$. Unlike shear stiffness, E is affected by the soil pore water conditions as reflected in the associated value of Poisson's Ratio, which typically varies between 0.2 (fully drained) and 0.5 (for undrained saturated soils). Selection of an appropriate Poisson's Ratio value is therefore important in determining a representative E value for the prevailing drainage conditions. For drained conditions Poisson's Ratio is generally in the range 0.2-0.35 and therefore derived values of E are relatively insensitive to assumed values of Poisson's Ratio. If Poisson's Ratio is not known, then conservative (low) values may be selected, generating lower values of E (note that the value of Poisson's Ratio selected to derive values of E may be different to that adopted to derive V_s – *see Section 4 above for explanation*).

Selection of an appropriate value of Poisson's ration is an important design decision as it will reflect the anticipated soil drainage conditions, soil saturation level and loading period to be considered. As such selection of an appropriate value of ν is left to end users of the shear stiffness data provided via the facility to adjust ν in the data output spreadsheet provided. As a default a typical drained Poisson's Ratio of 0.26 is utilised in the output stiffness data. The deviation from the calculated value of E from this default value is between 15-25% (typical drained values of ν=0.2-0.35) and around 50% greater for ν = 0.5 (typical undrained value for saturated soils).

7. Strain softening

It is vital that the non-linear relationship between stiffness and strain (*see Figure 7*) is appropriately accounted for in the use of CSW derived small strain stiffness data as it can be seen from Figure 7 that the small strain stiffness values measured may be up to 5 times greater than the true stiffness associated with operational strains. Conveniently for most soils this strain-softening behaviour is remarkably consistent (*see shaded-in area in Figure 8*) allowing the use of a suitable strain-softening function (*see blue line on Figure 8*) within the design analysis to account for this behaviour.

Whilst, as described above, for most soils, the small-strain stiffnesses derived by CSW testing (G_0 and E_0) are upper-bound values this may not be the case for hard soils and rocks where initial strain stiffening may be associated with the closure of discontinuities. Likewise the strain stiffness response of certain less common geomaterials such as peat and landfill waste may not conform to the typical strain softening curve and require special consideration.

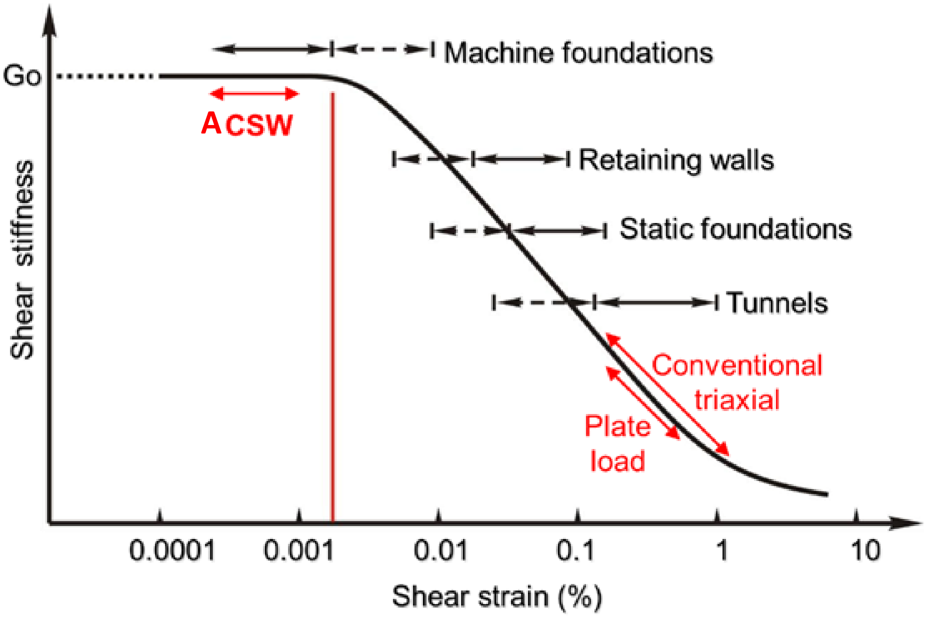


Figure 7. Typical strain stiffness response of soils showing strain levels associated with common geotechnical problems

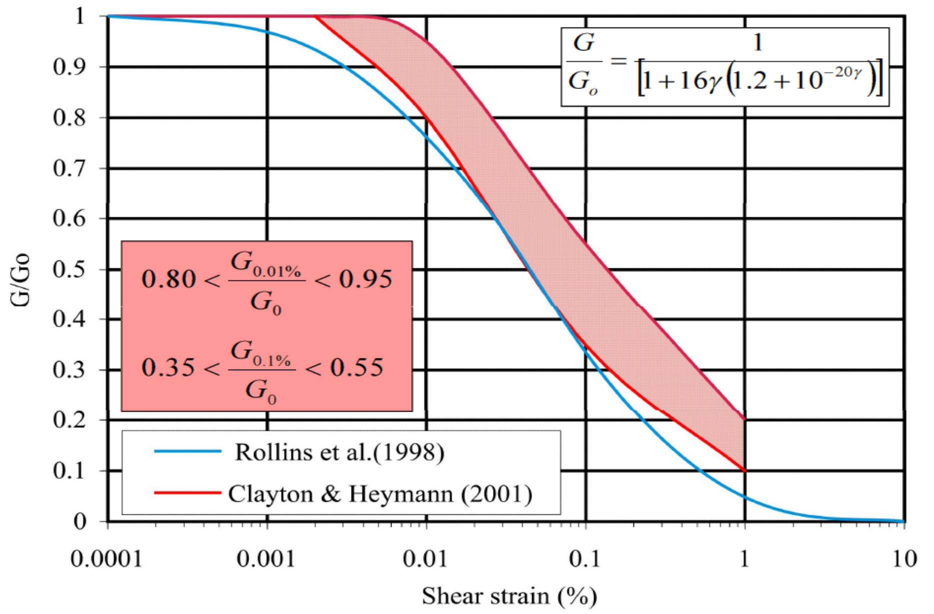


Figure 8. Strain softening response of common soils (pink shaded area) and lower bound Rollins *et al.* equation (blue line)

8. Discussion

An appropriate methodology is required during ACSW testing to check and calibrate the measurements in order to identify invalid data and to remove or smooth scattered data that may be generated from some site conditions. A means of reviewing and sense-checking data on site, including comparing adjacent tests and if necessary stacking data, is highly desirable and is provided by integral bespoke software such as GSS's C-DAS. However, inevitably, some small variations will remain between test results even where test locations are very close to one another due to the inherent variability of the ground's response. Ultimately such variations must be accounted for by normal good practice in assessing test data by comparing it with other ground investigation data and in selecting stiffness values appropriate for design. However, there is good evidence that much greater uncertainties exist with other test methods (such as empirical relationships) for which, unlike ACSW testing, primary test data are not based on undisturbed bulk ground stiffness (refer to GSS guidance notes GN013, GN014, GN015 & GN016).

It must be remembered that ACSW testing directly measures V_r profiles which can be converted to V_S profiles with high reliability and then subsequently converted to stiffness values subject to certain limitations. The technique is not intended as a means of ground profiling although where strong stiffness contrasts are associated with stratigraphy boundaries then these are reflected in V_S and stiffness profiles. Intrusive investigations will therefore always be required as part of normal ground investigation practice.

As demonstrated above, layer boundaries and stiffness data are not required for ACSW data inversion but information on anticipated stratigraphy, soil density, Poisson's Ratio and/or anticipated depth to groundwater may improve the accuracy of the inversion by better constraining the inversion model. In theory due to the non-linear, inverse nature of the inversion process, more than one solution to the dispersion curve may exist, hence an appropriate geotechnical sense check is always required for stiffness profiles obtained (as would be the case for any ground investigation data).

As explained above, in converting V_S to soil stiffness, assumed values of soil density and Poisson's Ratio (if not known) have a relatively small impact on stiffness values (*see Table 1 for summary*). Therefore, whilst an understanding of likely values of soil density and Poisson's Ratio will improve the accuracy of stiffness values calculated, assumed low values will result in normally conservatively low stiffness values.

In selecting values of soil density and Poisson's Ratio it must be remembered however that lower bound stiffnesses may not necessarily be conservative in all soil structure interaction or dynamic problems. Consequently, care needs to be taken in the selection of representative and appropriate values for deriving soil stiffnesses from V_S profiles as part of any geotechnical design.

Similarly, whilst there is good published information on strain softening functions for soils, these are not applicable for rock, rock masses or for some soils such as peat or collapsible ground.

Process	**Soil parameter required**	**Default GSS value**	**Comment**
Simple inversion V_r to V_s	Poisson's Ratio	0.5	Range of variation in V_s of less than 10% over natural range of Poisson's Ratio, however in most saturated 'soft' UK soils value of 0.5 is a good approximation and is otherwise conservative
Advanced inversion V_r to V_s	Poisson's Ratio	0.5	Range of variation of V_s for natural range of both Poisson's Ratio and soil density is typically less than 10%.
	Soil density	1.8 Mg/m^3	
Conversion of V_s to G_0	Soil density	1.8 Mg/m^3	Default value used is conservative (i.e. low) but is intended to be indicative only since output allows for user definition based on information on ground conditions.
Conversion of G_0 to E_0	Poisson's Ratio	0.26	Default value used is conservative (i.e. low) for drained conditions but is intended to be indicative only since output allows for user definition based on information on ground conditions and knowledge of design model.

Table 1. Summary of impact of assumed soil parameters in determining stiffness profiles using CSW data

Overall there is good data to suggest that, properly undertaken, ACSW testing can provide data of comparable quality to more expensive techniques such as downhole seismics or large-scale load tests (*see GSS Guidance Notes GN015 and GN016*). In comparison to the generally accepted limitations of empirical relationships for deriving stiffness, CSW testing data can in many cases provide order of magnitude improvement (*see Deighton & Rigby-Jones, 2016, and GSS Guidance Note GN013*). Furthermore, the speed and cost of CSW testing enables data on the variation in stiffness to be established that would be difficult for other high accuracy techniques, enabling appropriate assessment of the variation in site design stiffness to be undertaken.

As with all geotechnical engineering data, review is required in the context of the design being undertaken and against other available information to ensure suitability and comparability of ACSW data for use. In all cases it is assumed that design work is undertaken by suitably experienced and competent engineers, capable of assessing the appropriateness of the analysis models and input parameters.

9. GSS Guidance Notes

GSSGN001	Specifying ACSW testing
GSSGN002	Application of ACSW testing
GSSGN003	Analysis with ACSW test data
GSSGN013	Comparison of ACSW testing with stiffness measurement by empirical relationships with other soil properties
GSSGN014	Comparison of ACSW testing with stiffness measurement by laboratory testing
GSSGN015	Comparison of ACSW testing with stiffness measurement by in situ testing techniques
GSSGN016	Comparison of ACSW testing with stiffness measurement by other seismic techniques
GSSREF01	Useful ACSW references

10. References

Clayton, C. R. I. (2011) Stiffness at small strain: research and practice, *Geotechnique* 61, No. 1, 5–37 (2011 Rankine Lecture)

Deighton, M. and Rigby-Jones, J. (2016) Improved estimation of ground stiffness for railway projects using Continuous Surface Wave testing, *Ground Engineering*

Gordon, M. A. (1997) Applications of field seismic geophysics to the measurement of geotechnical stiffness parameters. PhD thesis, University of Surrey

Heymann, G. (2007) Ground stiffness measurement by the continuous surface wave test. *Journal of the South African Institution of Civil Engineering*. Vol.49, No.1, p25-31.

Leong, E. and Aung, A. (2013). Global Inversion of Surface Waves Dispersion Curves Based on Improved Weighted Average Velocity (WAVe) Method. *Journal of Geotechnical and Geoenvironmental Engineerin*g, 10.1061/(AS CE)GT.1943-5606.0000939 (Apr. 8, 2013).

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