General

Advanced Continuous Surface Wave (ACSW) testing system as developed by Ground Stiffness Surveys Limited (GSS) is a ground stiffness measurement technique which relies on measurement 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. 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). ACSW 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.

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. 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* (see section below).

The shear wave velocity profile derived by the *inversion* may be converted to a small strain shear modulus (G_o) using a simple relationship with soil density (see section below). Given the nature of the relationship with, and limited variance of, soil density the derivation of G_o is relatively insensitive to assumed soil density if not known.

G_o may be converted to Young's Modulus (E) through a simple relationship with Poisson's Ratio (see section below). Selection of an appropriate Poisson's Ratio value is important in determining a representative Young's Modulus value for the prevailing drainage conditions.

Stiffness values obtained by CSW testing (G_0) are small-strain stiffness values relevant to strain levels below approximately 0.002%. Strain levels for geotechnical structures on soils typically vary between 0.01% and 0.1% (Mair, 1993) and modification of the small strain shear stiffness (G_0) is typically required for geotechnical design and may be undertaken through the use of strain-softening functions (see section below).

Appropriate review by a competent and suitably experienced engineer is required for utilisation of CSW testing data.

Ground conditions

Rapid variations in ground conditions can occur. The ground stiffness profiles provided relate to the ground stiffness conditions observed at each test location, and hence the possibility of encountering ground conditions at other locations significantly different from those recorded cannot be discounted. ACSW testing provides bulk stiffness values for the volume of soil lying beneath the test geophone array (typically 3m length). Testing assumes a cross-isotropic soil (constant lateral stiffness) and therefore any rapid lateral variation in stiffness along the line of the test may affect the validity of results.

As with the interpretation of all geotechnical testing, assessment of design stiffness profiles requires consideration of the inherent variability of the ground. Whilst ACSW testing provides a high-quality means of measurement of the representative bulk soil stiffness profile at each test location, it cannot account for variations in stiffness profile between test locations. It also cannot be assumed that ground stiffness continues to increase below the base of the measured stiffness profile. As a result, when using ACSW data to determine design ground stiffness profiles the context of the site-specific geological setting and other ground investigation data must always be considered.

Field data acquisition

Field data is acquired using GSS designed and constructed seismic sources in conjunction with an array of five 4.5Hz vertical geophones logged using in-house data acquisition hardware and software controlled by a portable field computer. Details of the seismic source utilised for testing and geophone spacing and arrangement is detailed in project-specific reporting.

Field data quality control is undertaken through checking of noise levels and phase angle shift between adjacent geophones. To provide further control on data quality and provide redundancy, both monotonic testing (data acquisition at a range of discrete frequencies) and frequency sweep testing (data acquired during a period of steady increase in frequency) are undertaken at each test location.

The maximum frequency of each seismic source provides a limit to the surface layer resolution possible. For example, at the 90Hz maximum frequency of the GSS mechanical Standard Shaker (SS) on a soft to firm clay (V_s=180m/s) produces a wavelength of 2m (i.e.180/90) corresponding to an approximate minimum layer resolution of 0.7m. Consequently, were shallow layers of lower or higher stiffness present to this depth, they would not be resolved.

The minimum frequency for which an acceptable signal can be produced determines the depth of profile possible. For the GSS standard shaker a minimum frequency of 10Hz is typically possible corresponding in a stiff clay (V_s=180m/s) to a wavelength of 18m (i.e.180/10) corresponding to typical profile depth of 6-9m.

Where clients require increased surface resolution or profile depth, then this should be discussed at the project planning stage so that allowance can be made for use of the appropriate seismic source(s)

Inversion

Following field acquisition of the *dispersion curve* data processing is required to produce a shear wave velocity (V_s) versus depth profile which may then be converted to a G_0 profile.

The relationship between V_s, V_r and Poisson's Ratio (ν) ratio is shown in Equation 1 below, from which it can be seen that the impact of Poisson's Ratio is relatively small (less than 10% for a range of 0.2 to 0.5).

Equation 1 (Heymann, 2007)

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

Historically a *simple inversion* process of assigning the measured value of V_s to a fraction of the wavelength has been used (typically λ/2 to λ/3) but this process provides only an averaged stiffness depth profile and cannot resolve layers. These limitations may be of particular concern where the stiffness profile is complex (i.e. stiff surface layer present or locally reduction in stiffness with depth). A value of λ/2.5 has been found by GSS to generally provide a good fit to ground truthing data and is used as a default value for simple inversion where no other information is provided. Poisson's Ratio of 0.5 (conservative for stiffness generated and reflecting the undrained response of saturated soils to seismic loading during testing) are assumed in the calculation of V_s for simple inversion unless stated otherwise.

In order to provide a layered soil stiffness profile, GSS undertakes an *advanced inversion* whereby a synthetic shear wave velocity profile is iteratively adjusted to solve the best fit profile of layer boundaries and V_s corresponding to the measured field dispersion curve, typically using a suitable forward model.

The *advanced inversion* techniques used implicitly assume 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 (ϒ) and Poisson's Ratio (ν) for each layer; unless otherwise stated. The impact of the variation of these parameters over normal ranges low, typically less than 10%. A typical soil density of 1.80Mg/m^3 and Poisson's Ratio of 0.5 (conservative and reflecting the undrained response of saturated soils to seismic loading during testing) are assumed in the calculation.

Due to the non-linear, inverse nature of the *advanced inversion* process more than one solution may exist and historical ground investigation information may be required to constrain the solution. Layer boundaries and stiffness data is not required for inversion but information on anticipated stratigraphy, soil density, Poisson's Ratio and/or anticipated depth to groundwater will improve the accuracy of the advanced inversion by better constraining the inversion model.

Due to mathematical limitations of available *advanced inversion* techniques, in certain scenarios the field dispersion curves may be not be suitable for *advanced inversion*. In these circumstances a *simple inversion* may be most appropriate. The stiffness profile arising from *simple inversion* represents an *approximate average stiffness to the depth given*. This limitation prevents the modelling of discrete layers and attenuates the magnitude of any rapid changes in stiffness present. These effects must be considered when using stiffness profiles derived by *simple inversion* for design.

Small strain stiffness

The shear wave velocity (V_s) profile derived by the *inversion* may be converted to a small-strain shear modulus (G_o) profile using the relationship $G = \rho.V_s^2$ (where ρ is soil density). Given that soil density typically varies between 1.6 Mg/m^3 and 2.1 Mg/m^3 for most ground conditions (24% variation), derivation of G_o is therefore relatively insensitive to assumed soil density (if not known), and conservative (i.e. lower bound) if a low soil density is assumed. Unless otherwise stated typical soil density of 1.80Mg/m^3 is used to derive G_o values for the simple inversion unless otherwise stated.

G_o may be converted to Young's Modulus (E) using the relationship $E=G.(2.(1+ v))$. Unlike shear stiffness, E is affected by the stiffness of the soil pore water with Poisson's Ratio, varying 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 which results in a 32% range of calculated E values. If Poisson's Ratio is not known, then conservative (low) values may be selected, generating lower values of stiffness.

A default typical lower-bound soil density of 1.80Mg/m^3 and typical drained Poisson's Ratio of 0.26 are utilised by GSS in the advanced inversion output data where no site-specific information has been provided. These values may be adjusted in the output spreadsheet where site specific values have been determined or to reflect undrained drainage conditions in saturated soils.

In selecting values of soil density and Poisson's Ratio it is noted, however, that lower bound stiffnesses may not necessarily be conservative in all soil structure interaction or dynamic problems and therefore 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 by the user.

Strain softening

For most soils, with appropriate selection of soil density and Poisson's Ratio (see above), the small-strain stiffnesses derived by CSW testing (G_0 and E_0) are upper-bound values and at intermediate strain levels stiffness decreases. For most soils strain-softening behaviour is remarkably consistent, allowing the use of a suitable strain-softening function within the design analysis to account for this behaviour. Softened stiffness modulus values applicable for most soils are presented for a default typical strain of 0.1% using the function developed by Rollins *et al.* (1998) which generally provides lower bound values, though other strain-softening functions are available (e.g. Clayton & Heymann 2001). The default value of strain may be adjusted in the GSS output spreadsheet to determine stiffness values for typical soils at other strain levels. *Consideration of the applicability of any strain-softening function and determination of design strains must be undertaken by the user as part of geotechnical design. The strain softening function presented is not applicable for rock, rock masses or for some soils such as peat or collapsible ground.*

Use of ACSW data

Reporting provides a V_s profile based on the available information on ground conditions provided by the client to constrain the inversion undertaken. In some circumstances more than one solution to the advanced inversion is possible and therefore, where limited information exists, this may limit the accuracy of the inversion. *It is the user's responsibility to satisfy themselves that the ground profile determined from testing is reasonable based on the anticipated ground conditions and that the technique is appropriate for obtaining the necessary ground stiffness data*. As a result, it is essential for design that ACSW data is used by a suitably qualified and experienced geotechnical engineer in conjunction with other geotechnical information (such as exploratory holes).

Care must be taken where ACSW testing is being used to confirm the approximate depth of strata. ACSW testing is not designed as a profiling tool and more accurate means of determining stratigraphic boundaries exist. Stratigraphic boundaries may not be identified where they are not associated with a clear stiffness contrast. In some cases, limitations of the inversion process may not identify all boundaries, particularly for thin layers and at depth. *Any use of ACSW for profiling must be undertaken as part of the evaluation of other available data.*

GSS Guidance Notes

GSSGN001 Specifying ACSW testing

GSSGN002 Application of ACSW testing

GSSGN003 Analysis with ACSW test data

GSSGN009 Accuracy & reliability of ACSW data

References

1. Clayton, C R I and Heymann, G (2001) The stiffness of geomaterials at very small strains. Géotechnique, 51(3):245–256.

2. 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.

3. Rollins, K M, Evans, M D, Diehl, N B and Daily, W D III (1998) Shear modulus and damping relationships for gravels. ASCE, Journal of Geotechnical and Geoenvironmental Engineering, 124(5):396–405.

Additional information on ACSW testing and application as well as further references are available from the GSS website.