Rapid, cost-effective and accurate determination of in-situ stiffness using MASW at Bothkennar

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Geophysical techniques and, in particular, seismic methods have received considerable attention in civil engineering over recent years, their role steadily increasing to the point where they play an important part in material characterisation and engineering design. This popularity arises from recent advances in both computational power and the geophysical techniques themselves. Furthermore, many geophysical methods are non-invasive which make them well suited and cost-effective in profiling spatially and temporally.

From a geotechnical engineering perspective the most popular geophysical techniques are seismic methods, possibly because they may directly measure a mechanical property, soil or rock stiffness. This usually involves strains of 10^{-3} % and less. The measurement of stiffness at this magnitude of strain is important for deformation prediction, as strains associated with most soil-structure interaction problems are generally less than 0.1% (Jardine et al., 1986). It has been shown by Stokoe et al., (2004) that stiffness-strain curves for a range of materials may contain considerable error if small strain stiffness values have not been incorporated. A significant overestimation of deformation may result, which could substantially increase the cost of a project. According to elastic theory the small strain shear modulus, Gmax, may be calculated from the seismic parameter, shear wave velocity, using the following equation:

$$G_{max} = \rho . V_s^2 \qquad (1)$$

where G_{max} = shear modulus (Pa), V_s = shear wave velocity (m/s) and ρ = density (kg/m^3).

Recently several researchers, for example: Park et al (1999), Donohue et al., (2003, 2004) for very stiff Irish glacial till and very soft clays and silts from central Ireland respectively; Long and Donohue (2007), for eight Norwegian research sites; and Donohue and Long (2008) have shown that V_s (and hence G_{max}) can be obtained cheaply and reliably using the Multichannel Analysis of Surface Waves (MASW) method. An opportunity arose to test and further assess the technique at the UK national soft clay research site at Bothkennar. The purpose of this note is to summarise the data recorded and to compare the resulting V_s measurements to other parallel data.

MASW technique

In geotechnical engineering, the most widely used surface waves are Raleigh waves that travel along the earth-air interface with a retrograde elliptical particle motion. Surface waves are very easy to detect as approximately two-thirds of the total energy from a vertical point source on the surface propagates in the form of Raleigh waves (Miller and Pursey, 1955).

Surface waves are dispersive, that is, in a non-uniform media, the propagation velocity of a surface wave is dependent on the wavelength (or frequency) of that wave. Surface waves with short wavelengths (or high frequencies) will be influenced by material closer to the surface than those with longer wavelengths (or low frequencies), which reflect properties of deeper material **(Figure 1)**. Therefore by generating a wide range of frequencies, this principle is used at each site under investigation, to produce plots of velocity against frequency (or wavelength) called dispersion curves.

A number of different surface wave techniques are available and currently in practical use worldwide. These are the Continuous Surface Wave (CSW, Mathews et al., 1996), the Spectral Analysis of Surface Waves (SASW, Nazarian and Stokoe, 1984) as well as the more recent Multichannel Analysis of Surface Waves (MASW) approach. Each of these approaches utilise the dispersive nature of surface waves to evaluate the elastic stiffness properties of the subsurface. The basic procedure for each of these techniques is divided into three stages (a) data acquisition, (b) dispersion curve evaluation and (c) inversion of the dispersion curve. This is illustrated in **Figure 2**.

The technique used in this study, the MASW approach, was introduced in the late 1990s by the Kansas Geological Survey (Park et al., 1999). As the name suggests this approach uses a multiple of equally spaced receivers (usually 12 to 60) that are deployed on the surface along a survey line. Each receiver is connected to a common multichannel recording instrument (usually a seismograph). This is the most significant difference between the CSW, SASW and the MASW techniques, both of which are usually based on a two-receiver approach. Also the MASW and SASW approaches generally use an impulsive source, such as a sledgehammer, to produce surface waves, whereas the CSW approach makes use of a frequency controlled vibrator.

The most significant advantage of the MASW approach is the ability of the technique to identify and separate fundamental and higher mode surface waves. This is particularly important on inversely dispersive sites (that is where a stiff layer overlies a softer layer, for example, ground improvement, pavement) and sites with large stiffness contrasts (for example, shallow bedrock). The MASW field procedure is also not as time and labour intensive as the SASW method, only requiring a single shot gather. The SASW approach involves several measurements at different source-receiver configurations.

The MASW technique may cost as little as £125-£175 per profile, which includes site work and all associated reporting.

Testing at Bothkennar

A summary of the test parameters used at Bothkennar is shown on **Table 1**. The location of the tests was within the BRE test area as shown on **Figure 3**. Data from two perpendicular MASW profiles was acquired. A picture of the MASW works being performed at this location is shown in **Figure 4**.

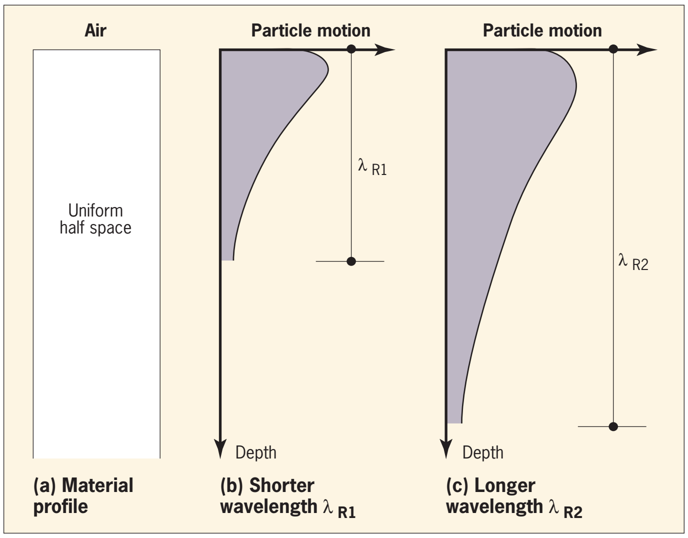

Figure 1. Approximate distribution of vertical particle motion with depth for two Raleigh Waves with different wavelengths (adapted from Stokoe et al., 1994)

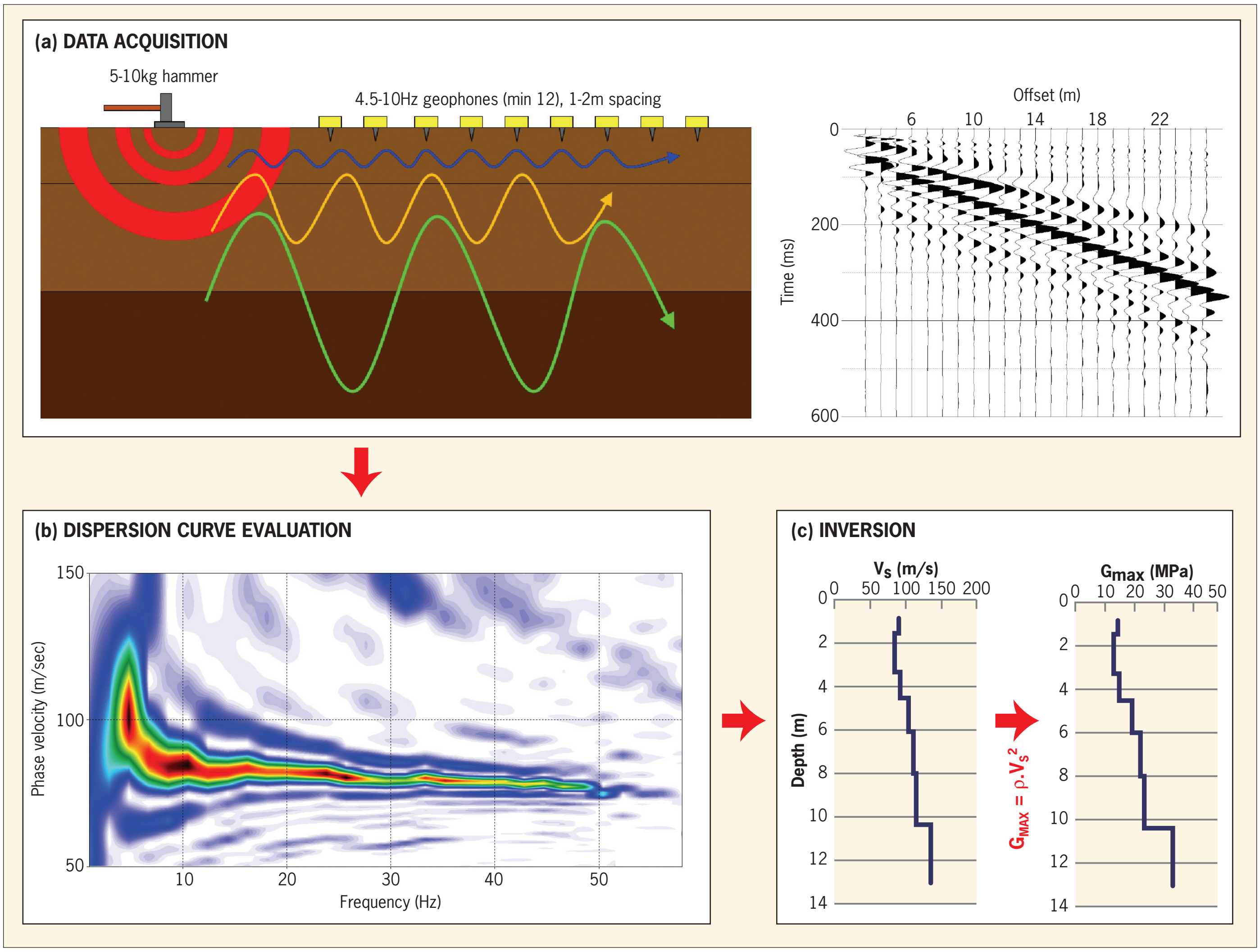

Figure 2. Outline procedure of the MASW technique:
(a) Acquisition of multichannel surface wave data, which includes the generation of surface waves using an impulsive source, their measurement using low frequency geophones and recording of the data using a multichannel seismograph. An example of some surface wave seismic data acquired at Bothkennar is provided here.
(b) Evaluation of a site dispersion curve from a dispersion image (Park et al., 1999). This particular image for Bothkennar clay is dominated by the fundamental mode of propagation.
(c) Inversion of the dispersion curve (Xia et al., 1999) to produce a sub-surface profile of shear wave velocity.

Results from Bothkennar

At least five investigations have been carried out at the Bothkennar research site for the purposes of determining shear wave velocity (V_S) and this comprehensive database allows an assessment of the reliability of the various techniques used. These two surface wave techniques and the investigations were carried out by:

1. University of North Wales (UNW) (Hepton, 1988): seismic cone (SCPT) and seismic dilatometer (SDMT)
2. UK Building Research Establishment (BRE) (Powell and Butcher, 1991, Powell, 2001, Hight et al. 2003): cross-hole and SCPT
3. Surrey University (SU) (Hope et al., 1999, Sutton, 1999): cross-hole
4. GDS Instruments Ltd. (Sutton, 1999): Continuous Surface Wave (CSW)
5. UCD (This note): MASW.

Test	No of geophones	Geophone frequency (Hz)	Geophone spacing (m)	Comments
MASW 1	24	10	1	Both lines in
MASW 2	12	4.5	2	BRE test area

Table 1. Summary of MASW test parameters

All of the available data are shown on **Figure 5**. In **Figure 5a** a comparison is made between the two sets of SCPT data and the UNW SDMT results. The agreement is very good. **Figure 5b** shows the cross-hole data from BRE and SU. The subscripts refer to the directions of propagation and wave polarisation respectively. The BRE work was carried out using conventional down-hole equipment, whereas the SU investigation included a novel technique for the determination of V_{hn} where the source was at the surface.

A clear implication of the data on **Figure 5b** is that the natural anisotropy of small strain stiffness of Bothkennar clay is very low. This has recently been confirmed by multi-directional bender element tests by Bristol University on high-quality block samples of the clay (Nash et al., 2006 and Sukolrat, 2007). Also shown in **Figure 5b** is the error of ±8% associated with the cross-hole work suggested by Sutton (1999). It can be seen that the agreement between the various sets of data is good and the scatter is generally of the same order of magnitude as the expected error.

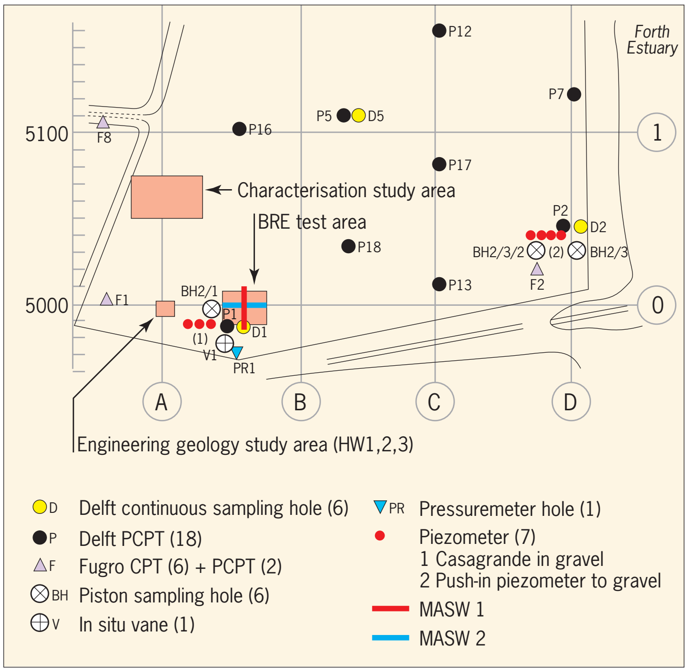

Figure 3. MASW profile locations at Bothkennar in addition to locations of previous investigations (amended map from Hight et al., 1992).

Figure 4. MASW testing at Bothkennar

Finally on **Figure 4c** the UCD MASW data and the GDS Instruments CSW data are compared with the BRE SCPT results. Again the agreement is excellent. In the MASW tests the use of low frequency (4.5Hz) geophones in MASW 2 only resulted in a marginal increase in the depth of penetration over MASW 1.

Donohue and Long (2008) observed fundamental mode Raleigh waves at frequencies as low as 4Hz, even when using geophones with a natural frequency of 10Hz. The use of low frequency 4.5Hz geophones may not, therefore, always result in an increase in depth.

The depth of penetration of the CSW approach was clearly limited in this case. It should also be noted that little or no difference was observed between the two perpendicular MASW profiles.

Conclusions

The important implication of the results presented above for practicing engineers is that in-situ shear wave velocity (and hence G_{max}) can be measured easily and reliably by a variety of methods. The results seem to be relatively independent of the technique used (having accounted for natural material anisotropy) and of the operator. The MASW surface wave technique provides a rapid, cost effective and reliable approach to obtaining such data.

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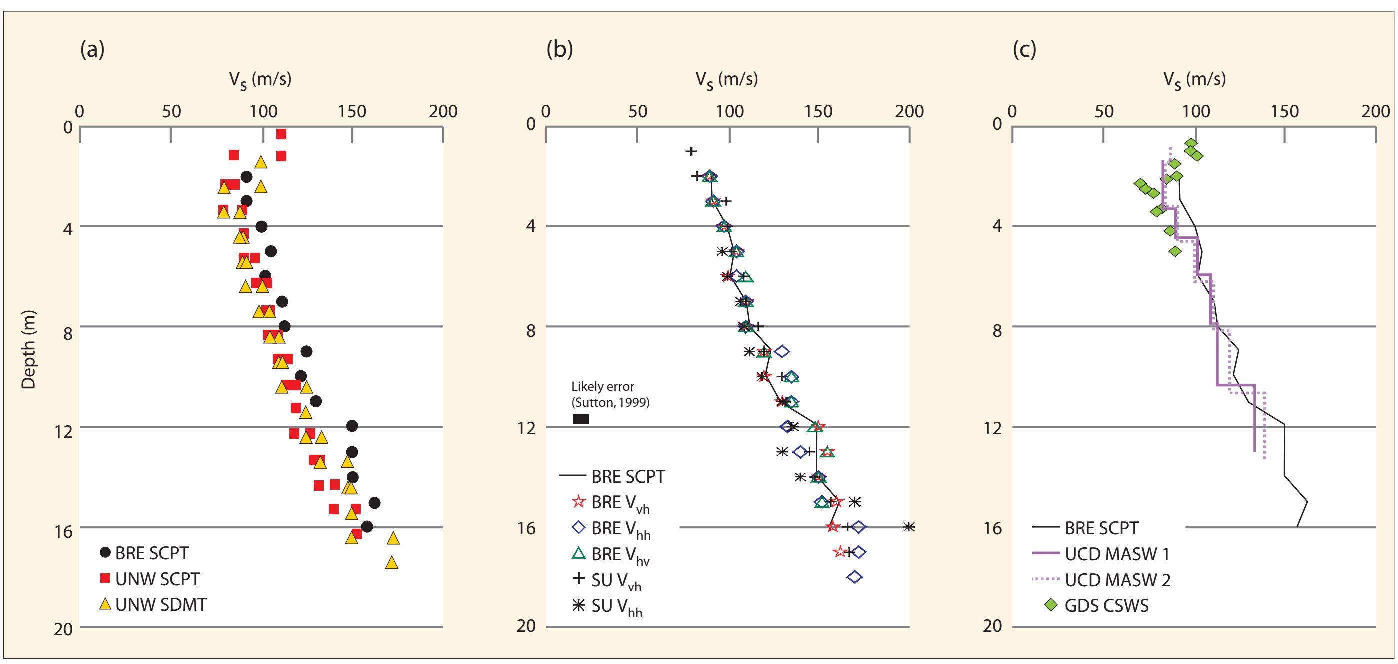

Figure 5. Vs data from Bothkennar: (a) BRE and UNW SCPT and SDMT, (b) BRE and SU cross-hole and (c) surface wave techniques

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