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

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INTRODUCTION

The measurement of the small strain shear modulus, G_{max} of a soil is important for a range of geotechnical design applications. This usually involves strains of 10^{-3} % and less. According to elastic theory G_{max} can be calculated from the 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 e.g. 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 8 Norwegian research sites) and Park et al. (1999) 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 assesses 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. Raleigh waves are dispersive, i.e. in a non-uniform media, the propagation velocity of a Raleigh wave is dependent on the wavelength (or frequency) of that wave by:

$$\lambda = \frac{V_r}{f} \qquad (2)$$

where λ is the wavelength and f is the frequency of the Raleigh wave.

Raleigh waves with short wavelengths (or high frequencies) will be influenced by material closer to the surface than Raleigh waves with longer wavelengths (or low frequencies), which reflect properties of deeper material (Figure 1). Therefore by generating a wide range of frequencies, surface wave surveys use dispersion to produce velocity and frequency (or wavelength) correlations called dispersion curves. It is then necessary to invert the measured dispersion curves (Xia et al., 1999) to produce shear wave velocity – depth profiles.

The most significant difference between the popular Spectral Analysis of Surface Waves (SASW, Nazarian & Stokoe, 1984) and the MASW techniques, involves the use of multiple receivers with the MASW method (usually 12 to 60) compared to the SASW technique, which is based on a two geophone approach. An advantage of the MASW approach is the ability of the technique to identify and separate fundamental and higher mode surface waves. The MASW field procedure is also not as time and labour intensive as the SASW method, which involves several measurements at different source-receiver configurations.

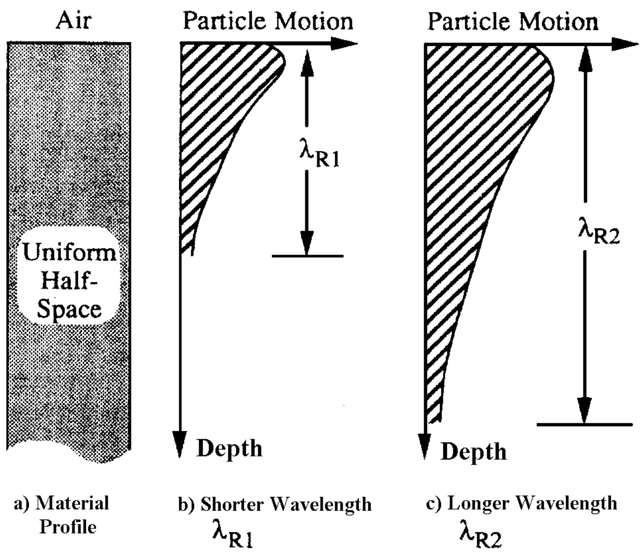

Figure 1. Approx. distribution of vertical particle motion with depth for two Raleigh Waves with different wavelengths (Stokoe et al., 1994)

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 2. A picture of the MASW works being performed at this location is shown in Figure 3.

Table 1. Summary of MASW test parameters

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

RESULTS FROM BOTHKENNAR

At least 5 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 include two surface wave techniques and the investigations were carried out by:

1. University of North Wales (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

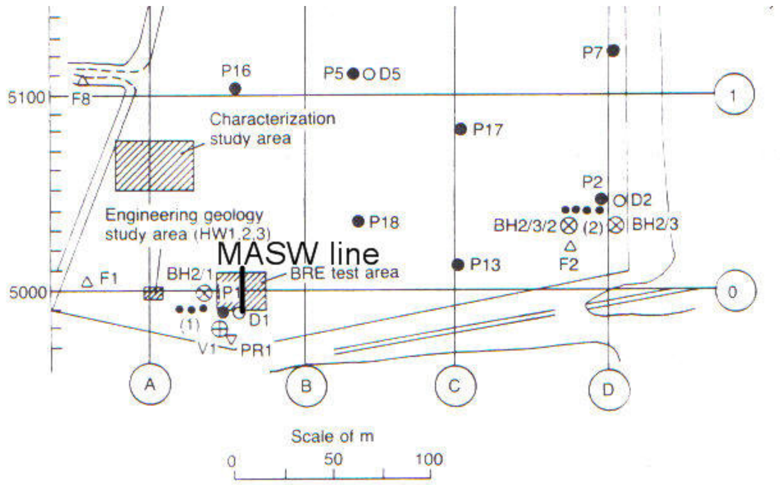

Figure 2. Test location at Bothkennar (amended map from Hight et al., 1992)

Figure 3. MASW testing at Bothkennar

All of the available data are shown on Figure 4. In Figure 4a a comparison is made between the two sets of SCPT data and the UNW SDMT results. The agreement is very good. Figure 4b 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_{hh} where the source was at the surface.

A clear implication of the data on Figure 4b 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 4b 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.

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. A limitation of both surface wave techniques, especially the CSW, is that the range of penetration is limited.

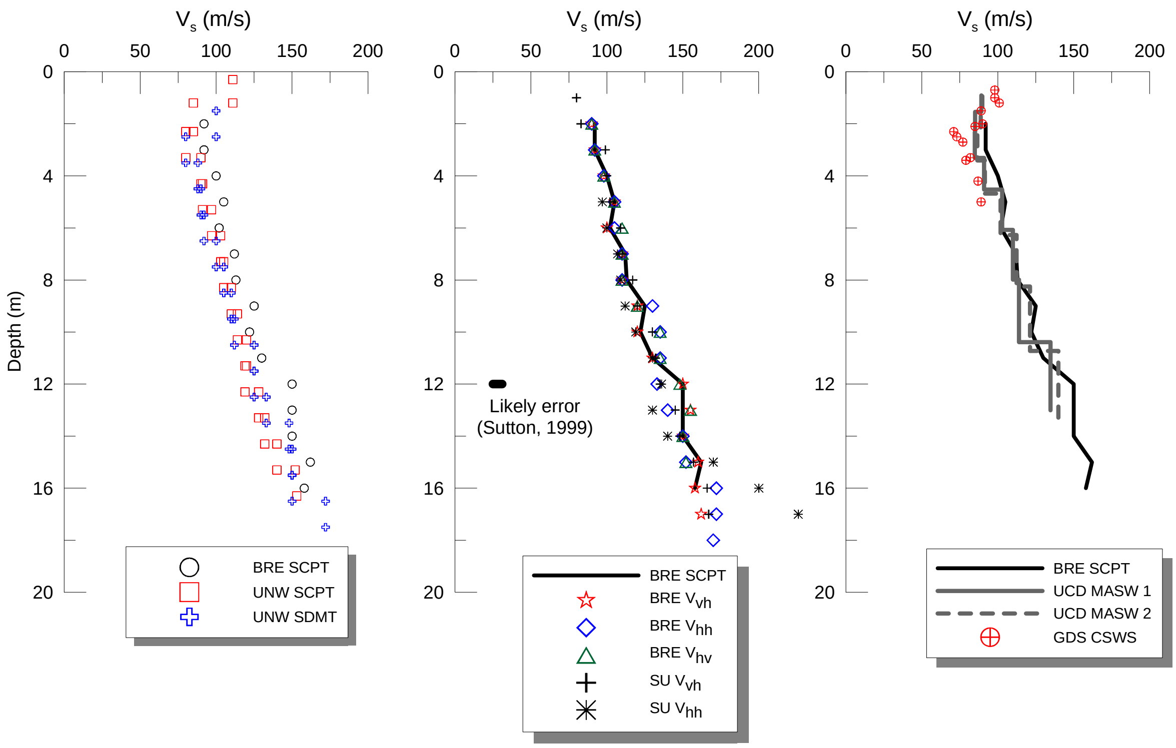

Figure 4. V_s data from Bothkennar: (a) BRE and UNW SCPT and SDMT, (b) BRE and SU cross-hole and (c) surface wave techniques

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.

ACKNOWLEDGEMENTS

The authors would like to thank the Bothkennar site owners for permission to access the site and for their co-operation during the testing.

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