G_{max} from Multichannel Analysis of Surface Waves for Dublin Boulder Clay

G_{max} pour une Argile Glaciaire de Dublin mesuré à partir de la méthode "Multichannel Analysis of Surface Waves"

S. Donohue, K. Gavin, M. Long,
University College Dublin, Ireland; shane.donohue@ucd.ie

P.O. Connor,
Apex Geoservices Ltd., Dublin, Ireland

KEYWORDS: Multichannel, Surface Waves, glacial till, shear modulus, Discrete Particle Scheme.

ABSTRACT: The applicability of the Multichannel Analysis of Surface Waves (MASW) method for the measurement of the small strain shear modulus, G_{max} is examined here for an Irish glacial till deposit. G_{max} profiles from MASW are compared with conventional seismic test results. A synthetic earth model is generated using a Discrete Particle Scheme (DPS) was also used to evaluate the software, Surfseis. The MASW method compares well with both the conventional seismic methods and the synthetic model.

RÉSUMÉ: L'applicabilité de la méthode "Multichannel Analysis of Surface Waves (MASW)" pour la mesure du coefficient de cisaillement à faible déplacements G_{max} est examinée pour un sol glaciaire Irlandais. Les profils établis à partir de la method MASW sont comparés avec les résultats des éssais sismiques conventionels. Un model syntéthique de sol généré à partir de l'utilisation d'un schéma de particule discret a été aussi utilisé pour évaluer le logiciel, Surfeis. La méthode MASW se compare bien avec la méthode sismique conventionel et aussi avec le model syntéthique.

1 INTRODUCTION

Due to difficulties in measuring small strains, the small strain shear modulus (G_{max}) is usually measured indirectly in the field or in the laboratory. Field methods may be either intrusive or non intrusive.

Intrusive field methods include cross-hole, uphole, downhole and seismic cone surveys where seismic sources and receivers are located either between boreholes or between the surface and a point in a borehole or cone. Non-intrusive field surveys include seismic reflection and refraction where the shear wave velocity is measured directly and surface wave surveys where it is calculated from the surface wave velocity.

Laboratory methods used to compute G_{max} include the resonant column method and the bender element method where it is evaluated from the shear wave velocity measured in the experiment.
G_{max} is related to the shear wave velocity by:

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

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

In this paper G_{max} is evaluated using the Multichannel Analysis of Surface Waves (MASW) method for two sites in the Dublin area. The results are compared with the cross hole seismic and seimic refraction methods.

2 DUBLIN BOULDER CLAY

The glacal till that underlies most of Dublin is referred to as Dublin Boulder Clay or DBC and was deposited during the Pleistocene period when much of Ireland was covered by an ice sheet. DBC is locally separated into an upper brown boulder clay and lower black boulder clay. The properties of these two tills differ, the brown being firm to stiff and the black boulder clay being very stiff or hard. Occasional sand and gravel layers/ lenses are also seen in the material. Dublin boulder clay has a water content of approx. 11% (±3), plasticity index of approx. 11% (±2), a clay fraction of 15% (±5) and a permeability of 1×10^{-11} to 1×10^{-8}, Lehane and Simpson (2000).

There is a difficulty in acquiring undisturbed samples due to the presence of boulders and cobbles. Due to this, non-intrusive geophysics such as surface wave surveys have an advantage over intrusive geotechnical and geophysical methods.

3 SURFACE WAVE ANALYSIS METHODS

The Steady state Raleigh wave / Continuous Surface wave (CSW) technique was introduced by Jones (1958) into the field of geotechnical engineering. It has been developed further by Abiss (1981), Tokimatsu et al. (1991) and Mathews et al. (1996). The CSW method uses an energy source such as vibrator to produce surface waves.

In the early 1980's the widely used Spectral Analysis of Surface Waves (SASW) method was developed by Heisey et al (1982) and by Nazarian and Stokoe (1984). The SASW method uses a single pair of receivers that are placed collinear with an impulsive source (e.g. a sledgehammer). The test is repeated a number of times for different geometrical configurations.

The Multichannel Analysis of Surface Waves (MASW) technique was introduced in the late 1990's by the Kansas Geological Survey, (Park et al., 1999). The MASW method exploits proven multichannel recording and processing techniques that are similar to those used in conventional seismic reflection surveys. Advantages of this method include the need for only one shot gather and its capability of identifying and isolating noise. The MASW method was used for recording and processing of surface wave data for the two sites listed in this paper.

4 SHEAR WAVE VELOCITIES FROM SURFACE WAVES

In a non-uniform, heterogeneous medium, Raleigh waves exist with phase velocities that are dependant on their wavelengths. The Raleigh waves with short wavelengths (or high frequencies) will be influenced by material closer to the surface than the Raleigh waves with longer wavelengths (or low frequencies), which reflect properties of deeper material. This dependence of phase velocity on frequency is called dispersion and the correlation between phase velocity and frequency (or wavelength) is called a dispersion curve. After production of a dispersion curve the next step involves the inversion of the measured dispersion curve to produce a shear wave velocity – depth profile.

As an initial estimate, dispersion curves may be interpreted by assuming that the depth of penetration, z of a particular wave is a fraction of its wavelength, λ:

$$z = (\lambda/n) \tag{2}$$

where n is a constant. The value of n is commonly chosen as either 2 or 3. Surface wave phase velocity, V_r, is then converted into shear wave velocity, V_s using equation (3).

$$V_s = (V_r/p) \tag{3}$$

where p is a function of Poisson's ratio, ν. For $\nu = 0.2$, p =0.911 and for $\nu = 0.5$, p=0.955, therefore incorrectly approximating ν has minimal effect on V_s.

The software Surfseis performs the inversion procedure using a least-squares technique developed by Xia et al.(1999). Through analysis of the Jacobian matrix Xia et al. investigated the sensitivity of Raleigh wave dispersion data to various earth properties. S wave velocities are the dominant influence on a dispersion curve in a high frequency range (>5Hz). The inversion method produced by Xia et al. is an iterative method. An initial earth model (s wave velocity, p wave velocity, density and layer thickness) is specified at the start of the iterative inversion process. A synthetic dispersion curve is then generated. Due to its influence on the dispersion curve only the shear wave velocity is updated after each iteration until the synthetic dispersion curve closely matches the field curve. The Kansas Geological Survey produced the software Surfseis for use with the MASW method. Surfseis is evaluated in section 6 of this paper.

5 RESULTS

The results for two sites in the Dublin area are discussed here. The sites are (1) Dublin Port Tunnel and (2) St. James Hospital. The results for the Dublin Port tunnel site are compared with corresponding cross hole (Cabarkapa et al., 2003) and seismic refraction (BMA, 1999) results and the St. James Hospital results are compared with a corresponding cross-hole survey.

5.1 Dublin Port Tunel – WA2 site

The soil profile for the WA2 site from borehole logs consists of approx. 2.5m of brown sandy gravelly clay (brown boulder clay), approx. 14m of black sandy gravelly clay (black boulder clay), brown sandy gravelly clay for another 3m, approx. 4m of sand and gravel, and a further 9m (approx.) of black sandy gravelly clay (black boulder clay), which is underlain by limestone.. The field setup for the Dublin Port Tunnel site consisted of 12 receivers (4.5Hz geophones) at 2m intervals collinear with a chosen source location. Two source locations were chosen for the profile, the first at a source receiver offset of 2m and the second at 24m. The two profiles were then combined to create a pseudo 24 channel seismic section. G_{max} values computed for the MASW survey at Dublin Port Tunnel are presented in Fig. 1.

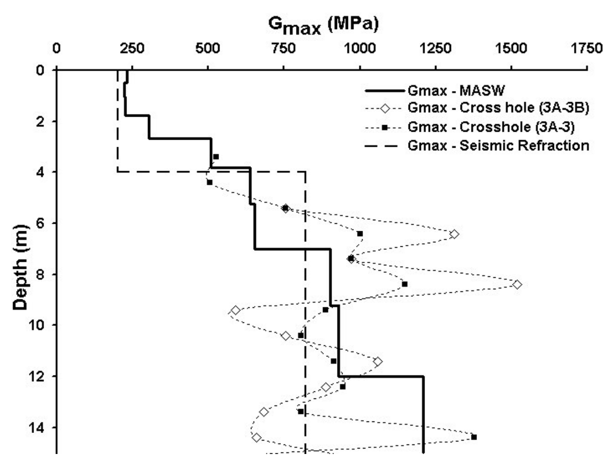

Figure 1. Gmax from MASW compared with corresponding cross-hole and seismic refraction surveys for Dublin Port Tunnel

The inversion process in the MASW method produces a profile of a series of steps or layers (Fig. 1). The depth of penetration for the surface wave, MASW method for this particular survey was 15m. For comparison G_{max} profiles from the conventional cross hole and seismic refraction methods are also shown in this figure. All surveys were located close to one another. Although the seismic refraction survey provides limited information regarding inter-layer G_{max} variations, the result is very similar to the MASW produced profile. Also the MASW profile compares reasonably well with both cross hole profiles even though there is considerable variation in the results of the two cross hole profiles themselves. The MASW profile defines the upper brown boulder clay layer to a depth of 2.6m and black boulder clay from 2.6m to the end of the profile with G_{max} increasing gradually with depth. As shown in Fig. 1 the MASW method shows G_{max} increasing from 300 MPa at 2m depth to 1210 MPa at a depth of 15m.

5.2 St. James Hospital – Luas site

The soil profile for the St. James Hospital site consists of an upper layer of about 1.7m of fill overlying boulder clay, which continues to the end of the profile.
The field setup at this site was exactly the same as at the Dublin Port Tunnel site with 4.5Hz geophones located at 2m intervals collinear with two source locations, at 2m and at 24m. Again a pseudo 24 channel (46m) seismic section was produced by combining the two records.

The results of the surface wave survey are compared with results from a corresponding cross hole survey in Fig. 2. The MASW profiles ran directly between the two boreholes that were used in the cross hole survey thereby permitting a direct comparison between the two methods. The profile in Fig. 2 compares very well with its corresponding cross hole survey. The fill can be clearly defined in the MASW survey to a depth of 2.2m. The boulder clay is then defined by an increase in G_{max} from this depth to 13.75m, the maximum depth of penetration for the profile. G_{max} is seen to increase from 235MPa at 2.4m depth to 1180 MPa at 13.75m depth.

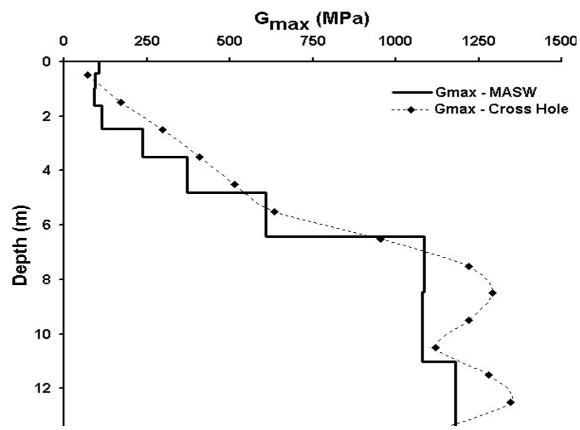

Figure 2. Gmax from MASW compared with corresponding cross-hole survey for St. James Hospital

6 DISCRETE PARTICLE SCHEME

6.1 Overview

To evaluate the performance of the software, Surfseis, a Discrete Particle Scheme (DPS) was used. Developed in the Department of Geology, University College Dublin, Toomey and Bean (2000), the DPS allows the user to generate a synthetic earth model consisting of interacting particles. The particles are arranged in a closely packed isotropic hexagonal configuration where each particle is assigned a density, diameter and P wave velocity. V_s may be determined as the V_p to V_s ratio is fixed at 1.73. Also V_r is calculated, equation (3), using a value for Poisson's ratio of 0.25, which is fixed for the DPS. G_{max} was determined for the model using equation (1).

A geophysical experiment is set-up in the model with a source created and receivers (geophones) planted in the uppermost layer of particles. The output from this synthetic geophysical experiment is a seismogram. This synthetic seismogram is then converted to a format that is compatible with Surfseis and input into the software.
As the elastic moduli and wave velocities of the model are known the software was examined to see if it determines their correct values. A number of different models were tested, varying the number of layers, the layer thickness and stiffness. The results for a five layer model are presented in section 6.2.

6.2 DPS Model

This Model is a 5 layer model where the first four layers are 1.5m thick and the fifth layer extends to the base of the model. The particle diameter for this model is 0.1667m. The model is 600 particles wide (100.02m) and 501 particles deep (83.5m). There is an increase in G_{max} with each deeper layer. The elastic properties and wave velocities of this model are listed in Table 1 below.

Table 1. Elastic Properties and Wave Velocities for the DPS Model where Vp = P wave velocity, Vs = S wave velocity, Vr = Raleigh wave velocity, ρ = density, ν = Poisson's ratio, G_{max} = small strain Shear Modulus

	Depth (m)	V_s (m/s)	V_r (m/s)	V_p (m/s)	ρ (kg/m^3)	ν	G_{max} (MPa)
Layer 1	1.5	115.6	106.4	200	1850	0.25	24.72
Layer 2	3.0	144.5	132.9	250	1900	0.25	39.67
Layer 3	4.5	173.4	159.5	300	1950	0.25	58.63
Layer 4	6.0	202.3	186.1	350	2000	0.25	81.85
Layer 5	83.5	231.2	212.7	400	2000	0.25	106.9

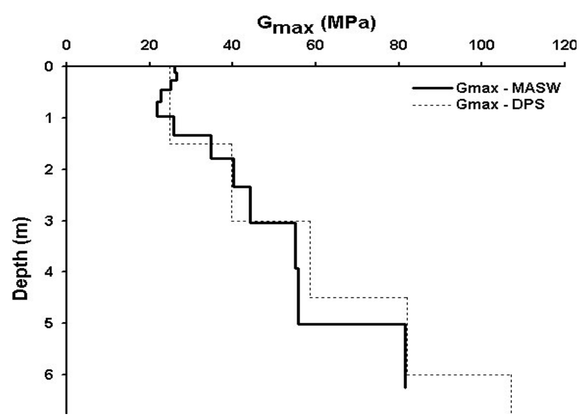

Figure 3: G_{max} profile for the DPS model comparing the Surfseis (MASW) produced profile with the actual G_{max} profile created in the DPS

The G_{max} profile for the DPS Model is shown in Fig. 3 along with the output MASW profile produced using the software, Surfseis. As shown the Surfseis produced G_{max} profile compares very well with the actual DPS G_{max} profile. The deepest layer was not detected, however, as the maximum depth using the MASW method was only 6.25m, which was due to numerical constraints when selecting the input source frequency. It is worth noting that G_{max} obtained by the MASW method differs by less than 5% for the first 4 layers from the actual DPS profile.

7 CONCLUSIONS

Shear wave velocity profiles were obtained in the field using the Multi Channel Analysis of Surface Waves (MASW) method at two sites in the Dublin area to determine the small strain shear modulus, G_{max} of Dublin boulder clay and to compare the MASW derived stiffness profiles with corresponding cross hole and seismic refraction profiles.

In the Dublin Port Tunnel site, where the cross hole surveys are quite variable the MASW, G_{max} profile compares well with both the cross hole and seismic refraction surveys.

In the Luas site at St. James Hospital the G_{max} profile produced from the MASW survey again compared well with a corresponding cross hole profile.

A Discrete Particle Scheme (DPS) was then used to generate a layered earth model. A synthetic seismogram was produced from the model and was input in the software, Surfseis. As G_{max} for each of the models layers is known, Surfseis was examined to see if it determined their correct values. As shown the profiles compare very well.

The MASW method is also a quick, non-invasive tool that effectively determines near surface stiffness-depth profiles.

8 ACKNOWLEDGEMENT

The authors wish to thank Dr. C.J. Bean, Mr. M. Moellhoff, Apex geoservices, John Barnett & Associates and Irish Geotechnical Services Limited (I.G.S.L.) for their assistance.

9 REFERENCES

Abiss, C.P. (1981). Shear wave measurements of the elasticity of the ground. Geotechnique, Vol. 31(1), 91-104.

BMA, (1999). Factual report on the geophysical survey for the proposed Dublin port tunnel from Whitehall to Dublin Port on behalf of Dublin Corporation. Vol. 9(7).

Cabarkapa, Z., Milligan, G.W.E., Menkiti, C.O., Murphy, J., Potts, D.M. (2003). Design and performance of a large diameter shaft in Dublin Boulder Clay. BGA Int. Conf. On Foundations, Dundee.

Heisey, J.S., Stokoe, K.H and Meyer, A.H. (1982). Moduli of pavement systems from Spectral Analysis of Surface Waves. Transportation Research Record, No. 852, Washington D.C., 22-31.

Jones, R. (1958). In-situ measurements of the dynamic properties of soil by vibration methods. Geotechnique, Vol. 8(1), 1-21.

Lehane, B.M. and Simpson,B. (2000). Modelling glacial till under triaxial conditions using a BRICK soil model. Can. Geotech. J. 37, 1078-1088.

Mathews, M.C., Hope, V.S., and Clayton, C.R.I. (1996). The use of surface waves in the determination of ground stiffness profiles. Proc. Instn Civ. Engrs Geotech. Engng, 119, Apr., 84-95.

Nazarian, S., and Stokoe, K.H. (1984). In situ shear wave velocities from spectral analysis of surface waves. Proc. 8th world conf. On earthquake engineering. Vol.3, 31-38.

Park, C.B., Miller, D.M., and Xia, J. (1999). Multichannel Analysis of surface waves. Geophysics, Vol. 64, No.3, 800-808.

Tokimatsu, K., Kuwayama, S., Tamura, S., and Miyadera, Y. (1991). V_s determination from steady state Rayleigh wave method. Soils and Foundations, Vol. 31(2), 153-163.

Toomey, A., and Bean, C.J. (2000). Numerical simulation of seismic waves using a discrete particle scheme. Geophys. J. Int., 141, 595-604.

Xia, J., Miller, R.D., and Park, C.B. (1999). Estimation of near surface shear wave velocity by inversion of Raleigh waves. Geophysics, Vol.64, No. 3, 691-700.