The use of multichannel analysis of surface waves in determining G_{max} for soft clay

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ABSTRACT: The measurement of the small strain shear modulus, G_{max} is determined using the Multichannel Analysis of Surface Waves (MASW) method for two soft clay sites in Ireland. G_{max} profiles generated using the MASW method compare very well with values derived empirically from CPTU data and also with results of laboratory triaxial testing. A synthetic earth model 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.

1 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} may be calculated from the shear wave velocity using the following equation:

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

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

Several techniques are commonly used to measure V_s in both the field or in the laboratory. Intrusive field methods include cross-hole, down-hole and seismic cone methods. In these surveys seismic sources and receivers are located either between boreholes or between the surface and a point in a borehole or cone. Non intrusive field methods used to determine V_s include seismic reflection and refraction and surface wave surveys.

Laboratory methods used to compute V_s include the resonant column method and the bender element method where a shear wave is transmitted using a piezoceramic element from the top of the soil specimen and recorded with another piezoceramic element at the bottom. In this paper G_{max} is evaluated using the Multichannel Analysis of Surface Waves (MASW) method for two soft clay sites in the Irish midlands.

2 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 others, such as 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. Donohue et. al. (2003) used the MASW method for determining G_{max} for very stiff glacial till. The MASW method was used for recording and processing of surface wave data for the two sites discussed in this paper.

3 SHEAR WAVE VELOCITIES FROM SURFACE WAVES

The type of surface wave that is used in geotechnical surface wave surveys is the vertically polarised Raleigh wave. In a non-uniform, heterogeneous medium, the propagation velocity of a Raleigh wave is dependent on the wavelength (or frequency) of that wave. 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 is illustrated in Figure1.

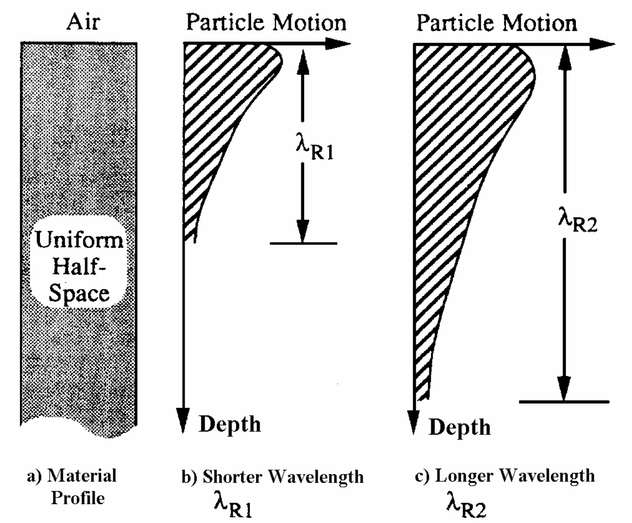

Figure 1. Approx. distribution of vertical particle motion with depth for two Raleigh Waves with different wavelengths (Stokoe et al., 1994)

This dependence of phase velocity on frequency is called dispersion. Therefore by generating a wide range of frequencies surface wave surveys use dispersion to produce velocity and frequency (or wavelength) correlations called dispersion curves.

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 = 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 ν = 0.2, p =0.911 and for ν = 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.

4. THE SITES

4.1 General

The two sites involved in this study have been used by researchers at UCD for several years and are generally well characterized. They are located at Athlone and Portumna towards the centre of Ireland. Full details of the Athlone site are given by Long and O'Riordan (2001). Conaty (2002) describes the sites at Portumna. The deeper soft soils at these sites are glacial lake deposits, which were laid down in a large pro-glacial lake, which was centred on the middle of Ireland, during the retreat of the glaciers at the end of the last ice age some 10,000 to 20,000 years B.P.

As the climate became warmer and vegetation growth was supported on the lake-bed, the depositional environment changed and the upper soils have increasing organic content. At the three sites the ground surface is underlain by two thin organic layers, calcareous marl and peat. The calcareous marl was formed when water super-saturated in calcium carbonate comes out of solution due to upward artesian flow.

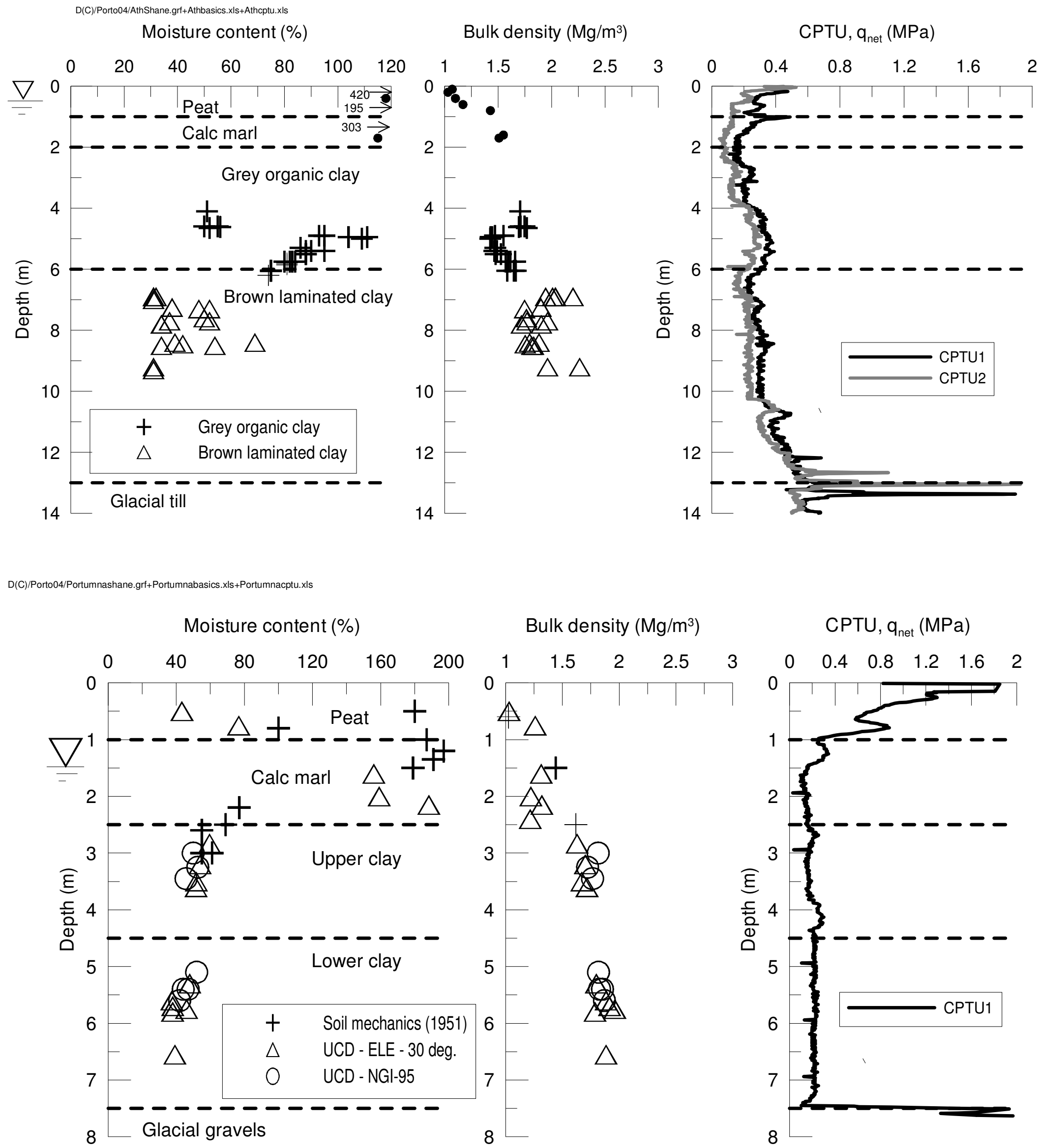

Figure 2a and b. Basic soil parameters Athlone and Portumna sites.

4.2 Athlone

At Athlone, two distinct strata were formed, as can be seen on Figure 2a. The lower soils are very soft brown horizontally laminated (varved) clays and silts with clearly visible partings typically 1 mm to 2 mm thick. These deposits are referred to as the brown laminated clay. They have average moisture content and bulk density of about 40% and 1.9 Mg/m^3 respectively. Though there is some scatter in the data, there is no apparent trend in the parameters with depth. The brown laminated clay has a clay content of about 35% and has an average plasticity index (I_p) of about 18%.

For the brown laminated clay, laboratory strength data from high quality Sherbrooke block samples fall on or close to the $0.3\sigma^1_{v0}$ line. However as detailed by Long and O'Riordan (2001) various vane tests and the cone pressuremeter tend to underestimate the strength, probably because of device insertion effects. Field vane sensitivity is about 2.5.

As the climate became warmer, the depositional environment changed and the upper soils show only some signs of varving and have an increasing organic content. The material deposited under these conditions is homogenous grey organic clay and silt.

As can be seen on Figure 2a, at about 4 m depth, its moisture content is about 55% and then increases to 110% before decreasing with depth to about 70%. Average bulk density is about 1.6 Mg/m^3 . In addition clay content and average I_p are of the order of and 25% and 40% respectively. These latter are higher than for the brown clay as a result of the increased organic content.

For the grey organic clay, strength data from both vane tests and laboratory testing shows considerable scatter. However values are generally greater than $0.3\sigma^1_{v0}$ suggesting that some overconsolidation of the material has taken place. Average field vane sensitivity is about 8.5.

In the peat and calcareous marl material, the moisture content values are very high being consistently over 200%, with corresponding low bulk density values of the order of 1.2 Mg/m^3 and 1.4 Mg/m^3.

Piezocone (CPTU) q_{net} values are very low for all layers. They are slightly higher, however, in the peat and marl possibly due to the effects of fibrous inclusions. Values increase from about 0.15 MPa to 0.35 MPa in the grey organic clay, then fall back to about 0.2 MPa in the brown laminated clay followed by a gradual increase with depth, particularly below 10.5 m to about 0.6 MPa.

4.3 Portumna

As can be seen from Figure 2b, the Portumna clays are relatively uniform. In these deeper clay layers moisture content falls from about 50% in the upper clay layer to 40% in the lower layer. The corresponding bulk density values are 1.7 Mg/m^3 and 1.85 Mg/m^3. Additional data shows that the clay content is about 40% and I_p is 22%.

The peat layer has a very variable natural moisture content, which ranges between 45% and 180% and a corresponding bulk density of less than 1.2 Mg/m^3. Equally the marl material has very high moisture content and a relatively low bulk density of about 1.25 Mg/m^3.

Laboratory strength data from reasonable quality piston samples, suggests that the clay material is slightly overconsolidated with values falling in the range $0.4\sigma^1_{v0}$ to $0.5\sigma^1_{v0.}$ Again vane strength values are lower, perhaps due to disturbance effects. Limited data on field vane sensitivity suggest that it is less than 5.

High CPTU q_{net} values were recorded in the peat, due probably to the effects of fibres. In the marl and in the layers below, values show almost no increase with depth, except perhaps in the upper clay layer and remain constant at about 0.25 MPa.

5 RESULTS OF MASW SURVEYS

5.1 General

The results of the MASW surveys for the two soft clay sites are discussed here. An impulsive source (sledgehammer) was used to generate the surface waves. The MASW results are compared to results from CPTU tests in terms of the cone tip resistance q_c. An empirical relation proposed by Mayne and Rix, (1993) was used to estimate G_{max} from the q_c data:

$$G_{max} = 99.5(p_a)^{0.305} * (q_c)^{0.695} / (e_0)^{1.13} \qquad (4)$$

where q_c = the measured cone tip resistance (kPa) p_a = atmospheric pressure, e_0 = in situ void ratio.

In Section 6, the software, Surfseis, used to generate the shear wave velocity profiles before conversion to G_{max} profiles is also evaluated here using a discrete particle scheme.

5.2 *Athlone*

Three separate MASW survey lines were performed for the Athlone site to test the repeatability of the survey. The MASW lines were all parallel and located at two metre intervals. All tests were carried out at the same location (Profile D from Long and O'Riordan, 2001) as the CPTU and the Sherbrooke block sampling discussed above. The field set up for each of the Athlone survey lines consisted of 12 receivers (4.5 Hz geophones) at 1m intervals collinear with a chosen source location. Two source locations were chosen for each profile, the first at a source receiver offset of 1 m and the second at 13 m. The results from the two offsets were then combined to create a pseudo 24 channel seismic section.

The depth of penetration of the MASW method for each of the profiles was 8.75 m, which was adequate for the site. The limitation to this depth resulted from a combination of not being able to produce lower frequencies using the impulsive source and the limitation of 4.5 Hz geophones. G_{max} values computed for the MASW survey at Athlone are presented in Fig. 3 along with the empirically derived profiles from the CPTU tests.

There is good agreement between the three MASW profiles for this site. There is a slight increase in the variation of the three profiles with depth. The difference in the top few metres is negligible and the maximum difference at 8.75 m depth is 2.4 MPa. There is also variation in G_{max} estimated from the two CPT cone tip resistance (q_c) profiles, indicative of ground variability.

The MASW results give similar and very low G_{max} values for the peat and marl, with the boundary between the marl and grey organic clay being clearly defined. It is also possible to define a boundary between the grey organic clay and the lower brown laminated clay.

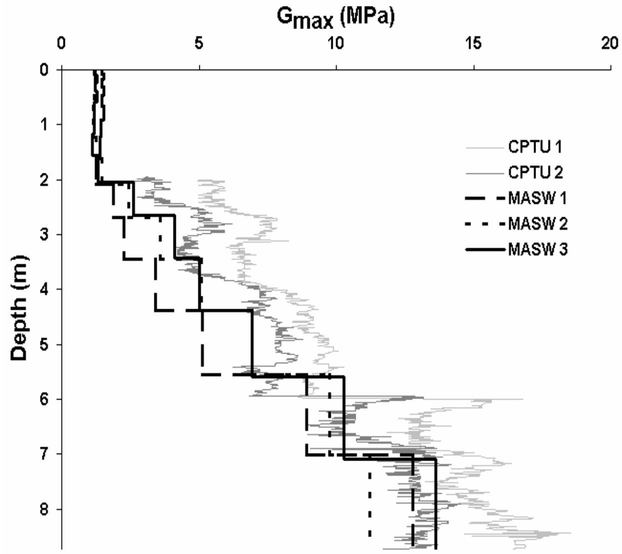

Figure 3. G_{max} from three MASW profiles compared with corresponding two CPT profiles for Athlone

CPTU data for the peat and calcareous marl has been ignored as the Mayne and Rix (1993) approach was never intended to be used for such materials. All the G_{max} values are very low for these very soft clays. While the first CPTU profile (CPTU1) gives a consistently higher result than the MASW profiles the second, CPTU2, gives a very similar result. In general the CPTU estimated profiles give higher G_{max} than the MASW results. Typically the CPTU approach gives values 30% higher than for the MASW survey for the grey organic clay and 20% higher for the brown laminated clay. However the values involved are so small that these differences are considered negligible.

5.3 *Portumna*

Two separate MASW survey lines were performed for the Portumna site to again test the repeatability of the survey. The MASW lines were parallel and located two metres apart and in the same location as the CPTU work and boreholes which yielded the piston samples described above.. The field set up for the Portumna site also consisted of 12 receivers (4.5 Hz geophones) at 1 m intervals collinear with a chosen source location.

Four source locations were chosen for the first profile, two on one side collinear with the receivers and another two on the opposite side. The source – receiver offsets for each side of the profile were at 1 m and 13 m. The results from the two offsets were then combined to create pseudo 24 channel seismic sections.

Two source locations were chosen for the second profile again at offsets of 1 m and 13 m to create another pseudo 24 channel seismic section. G_{max} values computed for the MASW surveys at Portumna are presented in Figure 4 along with a corresponding CPT profile. As explained above two profiles for the same set-up were acquired by switching the position of the source to the opposite side (labelled MASW 1a and MASW 1b (Opposite) in Fig. 4).

The depth of penetration of the MASW method for the survey lines, MASW 1a and MASW 1b (Opposite) was 8.75 m and for the MASW 2 profile the maximum depth was 10 m which were more than adequate for this site. Figure 4 only shows data to depth of 7.5 m because it is the range of interest for the soft clay material.

There is very good agreement between the three MASW profiles for this site. As in the Athlone site there is a slight increase in the variation of the three profiles with depth. Also as before the MASW survey clearly delineates the interface between the marl and the underlying clays. G_{max} calculated from the CPTU cone tip resistance (q_c) shows excellent agreement with the MASW profiles. A slight difference between the profiles occurs at the top of the clay layer at a depth of 2.5 m to 3.5 m where the CPTU derived G_{max} is slightly higher than any of the corresponding MASW profiles. As shown in Figure 4 the MASW method shows G_{max} increasing for the soft clay from 3 MPa at 2.5m depth to 16 - 19 MPa at a depth of 7.5m. The CPT estimated G_{max} for the clay increases from 7 MPa at the top of the stratum to 18.5 MPa at its base.

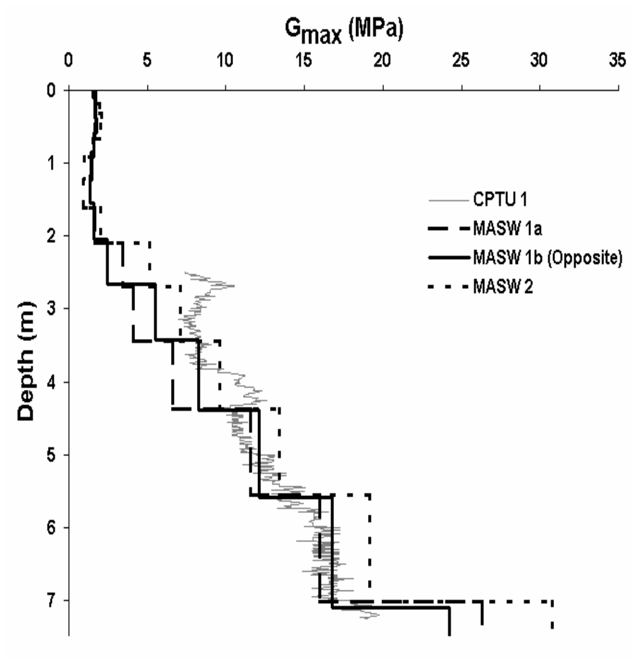

Figure 4. G_{max} from three MASW profiles compared with corresponding two CPTU profiles for Portumna

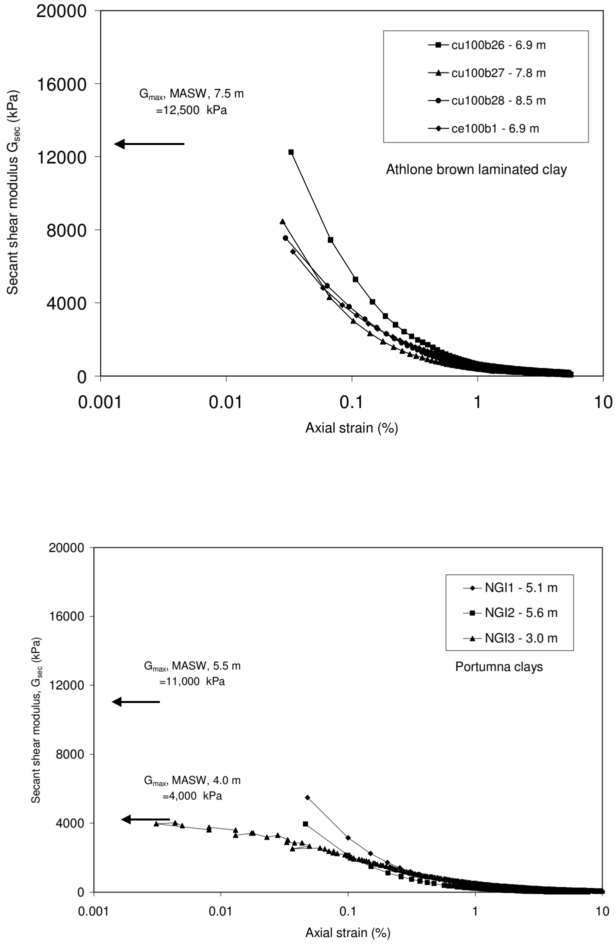

Figure 5. Comparison between laboratory test data and MASW output for (a) Athlone brown laminated clay and (b) Portumna clay.

5.4 *Comparison with laboratory test data*

A comparison between laboratory CAUC (anisotropically consolidated undrained compression) triaxial test data and MASW survey output is shown for Athlone brown laminated clay and Portumna clay on Figure 5a and 5b respectively. For Athlone the tests were carried out on high quality Sherbrooke block samples and for Portumna samples obtained using the NGI 95 mm diameter piston sampler was used. Strain resolution for Athlone is generally better as the axial displacement was measured using specimen mounted local gauges (Hall effect transducers).

It can be seen that the MASW G_{max} values relate well with the laboratory for these two lower plasticity clays. For the high plasticity Athlone grey organic clay (not presented here) the laboratory data yields higher stiffness values. The reason for this is not clear and warrants further study.

6 DISCRETE PARTICLE SCHEME

6.1 *Overview*

In order to evaluate the performance of the software, Surfseis, which is the main analysis tool in the MASW method, 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 (Figure 6) 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 input 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 two models are presented in Sections 6.2 and 6.3. The Shear wave velocity profiles for both models are very similar to the range of velocities that were observed in the field surveys of Athlone and Portumna. The reason for this was to test Surfseis for low velocity profiles. Donohue et al. (2003) tested the same software for higher velocities.

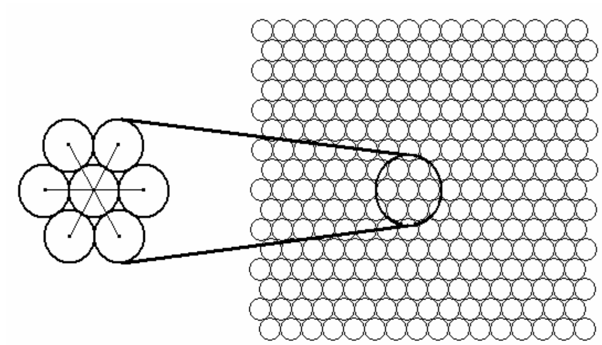

Figure. 6. The discrete particle scheme consists of particles arranged in a hexagonal geometry. Each particle is bonded to its six surrounding neighbours

Towards the end of the synthetic seismogram for the first DPS model a very small amount of noise was apparent. This was caused by reflections off the sides and bottom of the model. Although it is shown to have little or no impact on the MASW profile a second model was created (section 6.2) that was both wider and deeper so that any reflections would arrive later in the seismogram and so would not have an impact on the surface waves.

6.2 *DPS Model 1*

This Model is a 4-layer model where the first two layers are 1m thick, the third layer is four metres thick and the fourth extends to the base of the model. The particle diameter for this model is 0.1667m. The model is 510 particles wide (85m) and 501 particles deep (83.5m). There were 24 receivers selected at 1m intervals and the source to receiver offset was 1m. 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. Input parameters for the DPS Model where V_p, V_s and V_r are the P wave, S wave and Raleigh wave velocities, ρ = density and G_{max} = small strain shear modulus

	Depth (m)	V_s (m/s)	V_r (m/s)	V_p (m/s)	ρ (kg/m^3)	G_{max} (MPa)
Layer1	1	30	27.7	52	1200	1.08
Layer2	2	35.3	32.5	61	1300	1.59
Layer3	6	50.3	46.3	87	1600	4
Layer4	83.5	85	78.1	147	1800	13

The G_{max} profile for this DPS Model is shown in Fig. 7 along with the output MASW profile produced using the software, Surfseis. The depth of penetration for the MASW survey was 15m. This limitation was due to numerical constraints because the source to receiver offset could not be increased without the addition of noise to the end of the synthetic seismogram.

The Surfseis produced G_{max} profile compares well with the actual DPS G_{max} profile. The only difference of note between the two profiles is that the MASW method slightly underestimates G_{max} of the deepest layer by a maximum of 1.5 MPa. Also the MASW method shows the deepest layer beginning at 7m, an error of 1m. This was because the start of deepest layer in the DPS passes through the center of one of the inverted MASW layers. The MASW inversion then selected a G_{max} value in between the deepest layer and the layer directly above it.

The small amount of noise that was apparent on the synthetic seismic section appears to have no impact on the resultant G_{max} profile as shown below in Fig. 7.

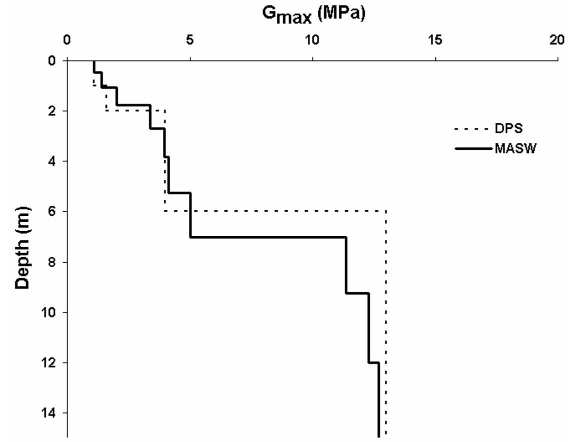

Figure 7. G_{max} profile for the first DPS model compared with the corresponding Surfseis (MASW) produced profile.

5.3 *DPS Model 2*

A second larger DPS model was created to eliminate the small amount of noise that was observed in the previous model. An extra layer was also added to increase the complexity of the model. This Model is a 5-layer model where the first layer is 1m thick, the second 1.5m, the third and fourth are both 2m thick and the fifth extends to the base of the model. The particle diameter for this model is also 0.1667m. This model is 600 particles wide (100.02m) and 601 particles deep (100.19m). There were 24 receivers selected at 1m intervals and the source to receiver offset was 1m. There is an increase in G_{max} with each deeper layer. The elastic properties and wave velocities of this model are listed in Table 2 below.

Table 2. Elastic Properties and Wave Velocities for the DPS Model where V_p, V_s and V_r are the P wave, S wave and Raleigh wave velocities, ρ = density and G_{max} = small strain Shear Modulus

	Depth (m)	V_s (m/s)	V_r (m/s)	V_p (m/s)	ρ (kg/m^3)	G_{max} (MPa)
Layer1	1	34.7	31.9	60	1300	1.59
Layer2	2.5	39.8	36.7	69	1400	2.24
Layer3	4.5	50.3	46.3	87	1600	4
Layer4	6.5	60.1	55.3	104	1700	6.12
Layer5	100.19	75.1	69.1	130	1800	10.125

The G_{max} profile for this DPS Model is shown in Figure 8 along with two output MASW profiles produced using the software, Surfseis. The only difference between the two MASW profiles was the center frequency of the source that was input into the DPS model. Center Frequencies of 7Hz and 12 Hz were selected for this.

Both Surfseis produced G_{max} profiles compare well with the actual DPS G_{max} profile. The 7Hz source detected all of the layers in the model and as with DPS model 1 the only difference of note between the DPS and the MASW profile is that the MASW method again slightly underestimates G_{max} of the deepest layer by a maximum of 1.2 MPa. The maximum depth using this frequency was 15m. This was again due to numerical constraints because the source to receiver offset could not be increased without the addition of noise to the end of the synthetic seismogram.

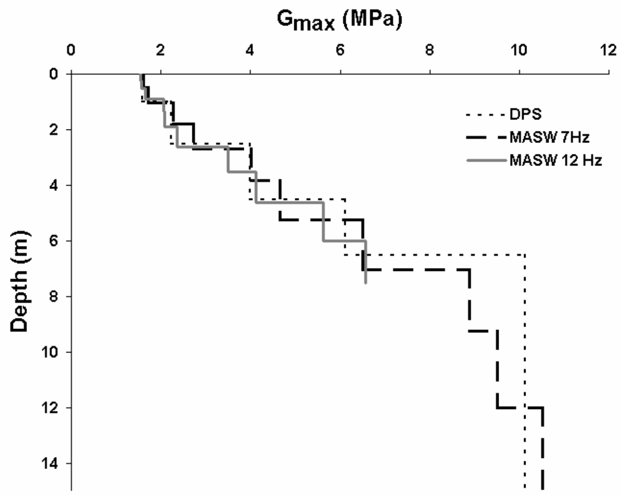

Figure 8. G_{max} profile for the second DPS model compared with the corresponding Surfseis (MASW) produced profile

Due to its higher input center frequency (shorter wavelength) the12Hz source did not detect the deepest DPS layer (Section 3). The maximum depth using this frequency was 7.5m.

7 CONCLUSIONS

Shear wave velocity profiles were obtained in the field using the Multi Channel Analysis of Surface Waves (MASW) method at two soft clay sites in the Irish Midlands to determine the small strain shear modulus, G_{max} of this material and to compare the MASW derived stiffness profiles with corresponding CPT derived profiles.

At both sites the MASW produced profiles compared very well with values derived empirically from CPTU results.

The "depth of penetration" of the MASW signals was limited to about 9 m, which was adequate for these sites. However if deeper profiles are required it is recommended that lower frequency geophones are used along with a source that my produce lower frequencies such as a continuous source (vibrator).

A Discrete Particle Scheme (DPS) was then used to generate two separate layered earth models. A synthetic seismogram was produced from both models 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.

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