Undrained shear strength and stiffness of Irish glacial till from shear wave velocity

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Introduction
Much of the ground engineering work carried out in Ireland involves glacial tills. These tills were deposited beneath the ice sheet that covered much of Ireland during the Pleistocene period, some 18,000 years ago. For example, much of the city of Dublin is underlain by a glacial deposit known colloquially as Dublin boulder clay (DBC).

It is known that the ice thickness in Dublin was approximately 1km and that several advances and retreats of the glaciers occurred in the area. The grinding action of this sheet as it eroded the underlying rocks coupled with its loading effect resulted in the formation of a hard lodgement till which in engineering terms is characterised by being very dense/hard, of very high stiffness and of low permeability.

A particular characteristic of the Irish tills, say when compared to similar material in the UK, is the presence of large cobbles and boulders. These make in situ investigation and sampling of the material extremely difficult. In particular the standard penetration test (SPT) can give erratic and unreliable results.

In addition, SPT tests are carried out in conjunction with cable percussive boring and there are significant limitations with this technique in relation to sample quality in tills and identification of thin horizons or layers.

In recent years there have been significant advances in techniques available to obtain high quality rotary core of glacial tills for example using the Geobor S or sonic drilling techniques (Long and Menkiti, 2007, Long et al, 2009, Quigley et al, 2011). However, these techniques are expensive and are only used on large or important projects. Geobor S coring is typically 25% more expensive than P size (85mm diameter) coring in glacial tills.

In parallel there has been rapid advances in some relatively cheap and practical geophysical methods, such as the multi-channel analysis of surface waves (MASW) technique (Donohue et al, 2003). MASW gives a profile of shear wave velocity ($V_s$) against depth from which the small strain stiffness ($G_{low}$) can be easily determined from the relationship with density ($\rho$):

$$G_{low} = \frac{4}{3}\rho V_s^2$$

Currently MASW has been used widely in wind farm projects in upland areas, particularly during the preliminary geotechnical investigation phase, where remote sites mean that access is constrained.

In this paper the link between strength and stiffness from high quality laboratory tests on cores and MASW $V_s$ measurements at a number of sites will be explored to investigate the potential of using MASW to generally profile the undrained shear strength and stiffness of Irish tills.

Initially the use of the SPT for this purpose will be examined using data from a recent case history.

Standard penetration testing in DBC

Recently a ground investigation was carried out in Dublin for the proposed Metro North project and the focus is on work done towards the northern end of the line from Drumcondra to Lissencall where the ground conditions comprise relatively homogenous DBC over limestone bedrock. A series of MASW profiles were carried out along the length of the proposed railway and SPT test data is also available for boreholes drilled immediately adjacent to the MASW surveys. These data have been chosen for this comparison as all the MASW testing was carried out by the same crew and the SPT tests were carried out with recently calibrated equipment (BSI, 2002).

A comparison between $V_s$ and SPT $N$ for this dataset is shown on Figure 2. Note the data have been

![Figure 1: A MASW survey was carried out for the Dublin Metro North project with a 2D $V_s$ profile generated by towing a "streamer" of geophones along the route to collect data every 6m](image1)

![Figure 2: SPT $N$ versus $V_s$ for Dublin Metro North project](image2)
sub-divided into tests on the upper brown boulder clay (U/Bc), which is typically 2m or so in thickness, and the underlying upper black boulder clay (UBbc), see Skipper et al. (2015) for details of the soils.

There is considerable scatter in the data. Although there is no doubt some variability in the V₃ measurements it is felt that much of this scatter is due to the nature of the SPT testing in these very stony soils. The relationship between V₃ and N for clays reported by Pitsilakis et al. (1999) is also shown on the plot. The other data sets combined data for various clays but it can be seen that the DPC is much stiffer than the other published data. Nonetheless, it is clear that use of SPT-based correlations for Irish glacial till would be highly unreliable and a better technique is required.

**Relationship between MASW and laboratory data**

It is proposed instead to compare V₃ from MASW and undrained shear strength (s₀) from triaxial tests on the high quality rotary cores of various Irish glacial tills. Data from 12 sites is presented. Eight of these are from the Dublin area, where V₃ values are relatively high. These data are complemented by four others from throughout Ireland, where, in general, lower V₃ values were recorded.

Figure 3 shows a plot of s₀ from the tests on the cores (mostly Geo3or S) and V₃ from MASW. As can be seen V₃ values in the range 200 m/s to 1100 m/s are encompassed. As shown, there is a reasonably strong relationship between s₀ and V₃, with s₀ increasing with increasing V₃. The coefficient of correlation for the trend line shown is 0.87. Beyond a V₃ of about 400 m/s the relationship appears to be more or less linear.

An important design parameter in geotechnical engineering is the ratio of Gₘₐₓ to s₀. For design the Gₘₐₓ value needs to be reduced to allow for strains around real structures. However, for structures in Irish glacial tills these strains are often very small. A value of 300 is typically used in design for stiff clays and tills; Stroud (1988). This value was, however, determined from testing and insitu observations of the behavior of British till and is felt by practising engineers to be conservative for Irish tills. A plot of Gₘₐₓ/s₀ against V₃ is shown on Figure 4. There is a clear pattern of increasing Gₘₐₓ/s₀ with increasing V₃, until a value of about 450 m/s where the Gₘₐₓ/s₀ values level off at about 2,500 on average, albeit there remains a reasonably large scatter in the data. However, all of the measured values are significantly higher than the traditionally adopted Gₘₐₓ/s₀ = 300 from Stroud (1988).

**Conclusions**

The main objective of this work was to explore the link between high quality laboratory strength tests on Geo3or S and similar cores and MASW derived shear wave velocity measurements of Irish glacial till: A clear relationship was observed between V₃ and s₀ for the sites studied across a wide range in V₃ values.

Therefore it seems that savings can be made in ground investigations by utilising geophysical techniques in combination with a reduced number of boreholes.

**References**


