Some recent developments on geophysical testing of peat

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ABSTRACT
This paper highlights recent developments in the application of geophysics to geotechnical engineering in peat. For example GPR can accurately profile peat thickness and inform on internal peat structure. Together with GPS and LiDAR imaging, GPR can be used to develop high quality 3D site images thus providing valuable information for scheme planning and for landslide studies. Despite the very low velocity values encountered work presented here shows that the shear wave velocity of peat can be reliably measured by a variety of methods. This paper describes the development of a lightweight portable sonde which has proven useful for this purpose. Work is ongoing on developing a relationship between shear wave velocity and peat undrained shear strength for the purposes of landslide stability assessments.

Keywords: Peat, geophysics, ground penetrating radar, shear wave velocity, landslides, undrained shear strength.

1 INTRODUCTION

There are many different facets of studying the engineering parameters of peat soil including the determination of the mechanical, electrical, chemical and decompositional properties. The study of many of these elements is difficult and their interrelationships are complex. As a material to be studied, peat has its own difficulties, many of them associated with the conditions required for the formation of this uniquely complex material. Access, stability, sampling and surveying each form their own challenges to site investigations.

It is out of the need to exploit, preserve or develop upon this fragile environment that much of the research and development of various testing methodologies has emerged. For example:

- the development of GPR as a technique for measuring peat thickness came about from the need to estimate the peat as a resource for exploitation in power generation,
- the need for robust peat stability assessment for upland windfarm projects has led to the development of the combined approach using GPR, Lidar and GPS,
- the latest development of geophysical research has come about due to the need to accurately determine the undrained shear strength of peat in situ.

In this paper some of these recent developments are described and examples are given of their application to the study of Irish peat. It is hoped that the techniques and approaches identifed will be of use to engineers working in similar environments elsewhere. Finally topics which require further research work are identied.

2 GROUND PENETRATING RADAR (GPR)

2.1 Introduction

Ground Penetrating Radar (GPR) techniques involve the transmission and reflection measurement of electromagnetic waves. The penetration depth achievable depends on the nature of the peat (especially its electrical conductivity), the location of the water table and on the frequency of the transmitted wave. Work at Lund University in Sweden by Ulriksen (1979), Ulriksen (1980), Ulriksen (1983), Bjelm & Ulriksen (1980) and Bjelm (1980) investigated various factors related to the technique and showed that not only could the peat thickness be estimated accurately, information can be obtained on the material beneath the peat.

These techniques have been also used successfully for many years in Sweden, e.g. Carlsten (1988) and Finland, see Saarenketo et al. (1992) for the determination of the thickness of both the road pavements and that of the underlying peat. Edil (2001), Warner et al. (1990), Francese et al. (2002) and Plado et al. (2011) have reported similar findings for work in the US, Canada, Italy and in Estonia respectively.

2.2 Peat thickness from GPR

To date most equipment has involved moving a single frequency antenna over the surface of the peat. For example Trafford (2009) reported on the use of 100 MHz and 250 MHz transmitters for the assessment of large areas of peatlands in Central Ireland, either by man-hauling the antenna or by use of all-terrain vehicle (Figures 1a and 1b).

A variety of challenging conditions can therefore be dealt with. Trafford (2009) found that the maximum depth of penetration for the 100 MHz transmitter in Irish raised bogs was typically 6 m. Transmitters with varying input frequency have also been used to achieve greater penetration depth. For example, for the equipment shown on Figure 1c, the input frequency can be altered by varying the length of the boom.

Figure 1. Investigation of peat with GPR (top) man-hauling 250 MHz equipment (middle) all-terrain vehicle with 100 MHz unit (bottom) variable frequency antennae.

In Ireland it has been found that a good compromise between depth of penetration and resolution is possible by combining results from two different frequency inputs, e.g. 80 MHz and 40 MHz.

Further details on the techniques used and on the calibration of the equipment can be found in Trafford (2009) or in Long (2015).

Figure 2. Clara raised bog in Central Ireland

2.3 Thickness & internal structure of peat

In order to investigate the effectiveness of the GPR equipment, specifically in its ability to locate the thickness of the peat and to resolve the internal structures in the peat some work was carried out at Clara raised bog in Central Ireland. The test site is shown on Figure 2.

Clara bog is one of the few large raised bogs remaining in Ireland in a relatively intact state. The bog was subject to a Irish / Dutch research study, into the hydrology and biology of the peat as well as distribution of spatial patterns within the peat and the mechanics of peat formation, in the late 1980's and early 1990's, see for example Smit (1989) or Van der Molen and Wijmstra (1994). As a result the bog was acquired by the Irish National Parks and Wildlife Service (NPWS) and together with the nearby Raheenmore bog has been the subject of the Irish Raised Bog Restoration Project funded by the EU LIFE Nature programme.

Feehan and O'Donovan (1996) report that similar to many Irish bogs, in the 18th and 19th, centuries a road was made across Clara bog. Road construction involved drainage and it is thought that as a result up to 5 m of settlement has occurred and the effects of the settlement extend up to 500 m into the bog.

The peat at Clara was sampled using a "Russian" peat corer which produces a 0.5 m long hemispherical sample of peat, similar to that shown on Figure 3. Some logs of the peat at Clara are shown on Figure 4.

Figure 3."Russian" coring of peat

The peat material has been classified according to the scheme described originally by von Post and Granlund (1926) as extended by Hobbs (1986). Both probes were taken on a GPR profile which was perpendicular and westwards from the Clara - Rahan road which bisects the bog. The probes were about 10 m north of an elevated wooden walkway (see Figure 2). P1 was located some 20 m from the road (at the 13 m mark on the GPR line) and P2 was some 80 m from the road (at 60 m on the GPR line).

P1 proved the base of the peat at about 5.65 m. The water content log shows a relatively uniform peat with average water content of some 1350%. This is on the higher end of that normally recorded in Irish peat. The peat overlies a thin layer of very soft clay / silt which overlies calcareous marl. Both have much lower water content than the peat.

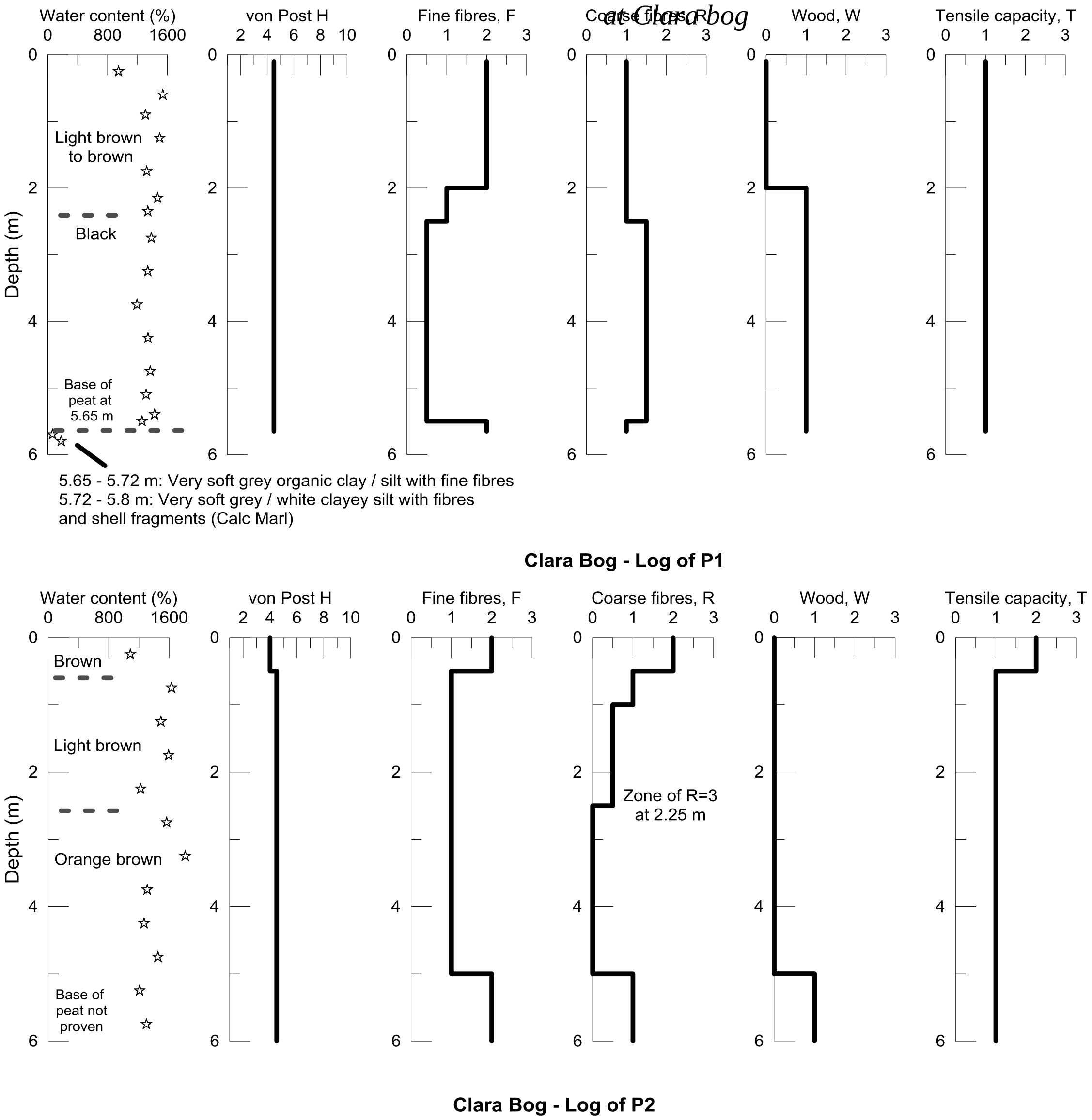


Figure 4. Peat logs from Clara bog

(H = degree of humification: 1-10, F = fine fibres: 0-3, R = coarse fibres: 0-3, W = wood: 0-3, T = tensile strength: 0-3, P = plastic: 0 or 1)

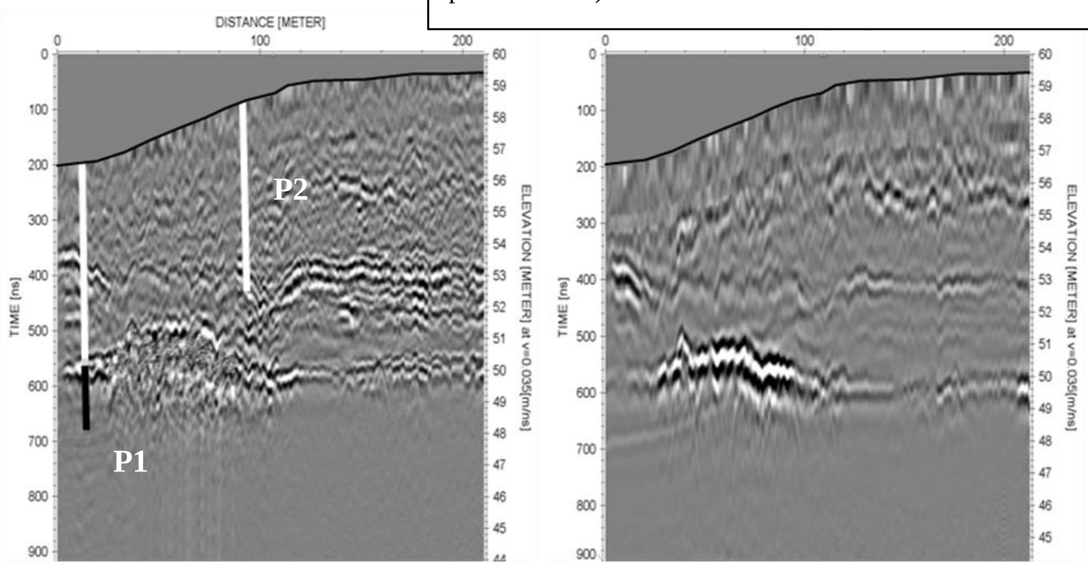


Figure 5. Output for 80 and 40 MHz transmitters at Clara bog

There is a clear difference in the peat above and below about 2.5 m (circa 54 mOD). Above 54 mOD the peat is light brown to brown in colour, has a relatively high fine fibre content but low coarse fibre and wood content. Below this level the colour of the material is black and there are less fine fibres but more coarse fibres and wood.

GPR traces across the probes are shown on Figure 5. Output from two different signal input frequencies is used. The base of the peat at approximately 5.6 m in P1 is clearly identified in the GPR data. In addition GPR is able to resolve some internal boundaries in the peat, for example one at about 2.5 m, which is in agreement with the physical log of the peat as described above.

The base of the peat was not proven in P2. The depth limit of the Russian corer with the available rods is 6 m. The GPR trace suggests that the peat base is actually at about 7 m depth. The water content log at P2 shows more variability than P1. The average water content of the peat is some 1420%. It is perhaps not surprising that this value is greater than P1 due the consolidation effects of the Clara – Rahan road.

In P2 the peat can be sub-divided into two zones with a border at about 2.25 m to 2.5 m (consistent in both the P2 log and in the GPR trace). There is a particularly wet zone of peat below about 2.5 m. This corresponds to a definite later of very high coarse content fibres below which the coarse fibre content drops to a low value in uniform orange brown peat.

2.4 Present day commercial application

GPR work is now usually linked to an accurate GPS system which allows spatial relocation to GPS co-ordinates as well as providing topographic information. These systems are now being used regularly in design and risk assessment for infrastructural works on peatlands. The example on Figure 6 is for a windfarm site in western Ireland where the combined GPR, LiDAR and GPS data are integrated to produce contour maps for planning and design purposes.

3 LANDSLIDE RISK ASSESSMENT

Landslides in peatland areas are relatively common in Ireland, see for example Boylan et al. (2008). Assessment of the risk of landslides is a major issue in planning and design of infrastructural projects in upland areas.

As peat slope failures for the most part resemble planar translational slides Dykes and Kirk (2001; Hendrick (1990; Long and Jennings (2006; Warburton et al. (2003), these stability assessments are generally undertaken using relatively simple infinite slope analysis approaches. According to Haefli (1948) and subsequently Skempton and DeLory (1957), the factor of safety, FOS, for a planar translation slide, if the peat is assumed to behave in an undrained manner is given by Equation 1.

$$FOS = \frac{s_u}{\gamma_b z Sin\beta Cos\beta} \qquad (1)$$

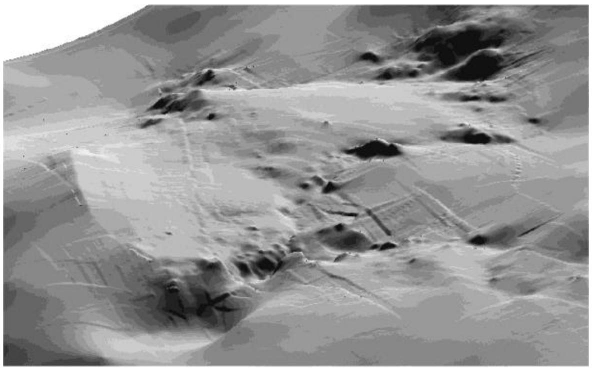
where: s_u = undrained shear strength of peat, γ_b = bulk unit weight, β = slope angle on base of sliding and z = depth of failure surface.

As the bulk unit weight of peat in Ireland is generally about 10 kN/m^3, the main unknowns are the values of β and s_u.

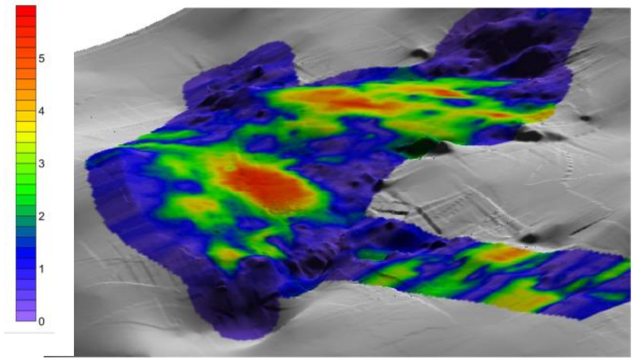
The assessment of peat slope stability often involves the use of relatively coarsely spaced physical soundings and surface slope assessments. With the provision of topographical Lidar data and the ability to collect continuous profiles of peat thickness using GPR, more detailed assessments of basal peat slopes and slope stability can be obtained.

Using the assessment of infinite slope analysis it is possible to provide potential risk maps of a site in order to predict where interaction with the ground may pose a potential hazard.

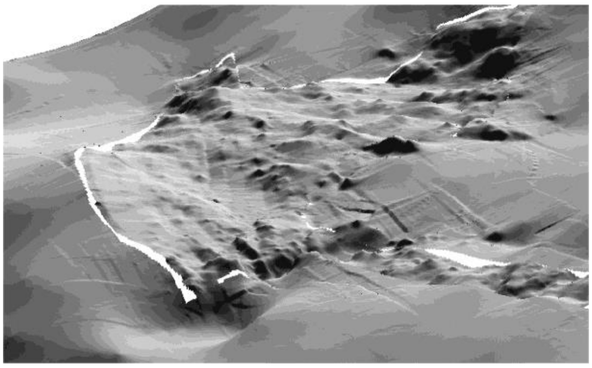
Figure 6 shows the stages employed in the production of potential risk maps for a site.



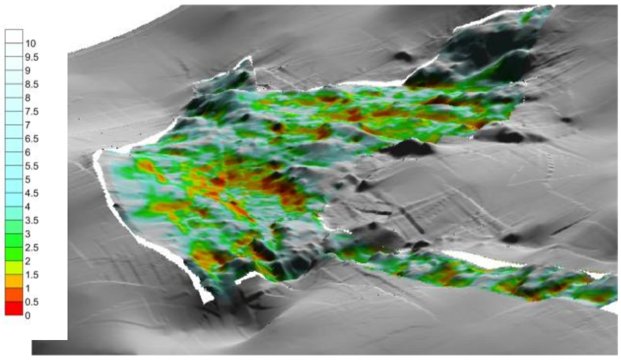
a) Surface topography from Lidar data



b) Peat Thickness (m)



c) Sub Peat topography



d) Potential Risk map showing sub peat topography with FOS

Figure 6. Results from GPR investigation of peat site in Connemara, Ireland.

By virtually stripping away the peat it is possible to accurately determine the sub peat slope and therefore produce a map of the FOS of the site. The potential risk map approach to assessing a site identifies areas where additional testing and peat sampling should be carried out,

One key element to the assessment of potential risk is s_u across a site. This is often determined from laboratory DSS testing of block samples taken from site. The need for a robust, practical methodology for the determination of s_u becomes increasingly obvious when sites are being assessed using much more detailed thickness and basal slope information. Many ‘hidden slopes’ would potentially fail and may have failed in the past but have now reached a relatively stable state due to being constrained by the subsequent build-up of the peat soil. In these situations it is essential to assess whether a slide is kinematically possible and how future interaction will affect slope stability.

4 IN SITU MEASURMENT OF SHEAR WAVE VELOCITY IN PEAT

4.1 Introduction

Characterisation of the stress-strain behaviour of soils is an integral part of many geotechnical design applications, including site characterization, settlement analyses, seismic hazard analyses, site response analysis and soil-structure interaction. The shear modulus (G) of geomaterials is highly dependent upon strain level. The small-strain shear modulus (G_{max} or G_0) is typically associated with strains on the order of 10^{-3}% or less. With information of G_{max}, the shear response at various level of stain can be estimated using published modulus reduction curves (i.e. G/G_{max}). According to elastic theory, G_{max} may be calculated from the shear wave velocity using the Equation 2:

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

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

G_{max} can be measured in the laboratory using a resonant column device or bender elements. Laboratory testing requires very high-quality, undisturbed samples which is a challenging task in peat. Additionally, laboratory tests only measure G_{max} at discrete sample locations, which may not be representative of the entire soil profile.

Unlike laboratory testing, in situ geophysical tests do not require undisturbed sampling, maintain in situ stresses during testing, and measure the response of a large volume of soil. In situ measurement of V_s has become the preferred method for estimating the small strain shear properties and has been incorporated into site classifications systems and ground motion prediction equations worldwide.

In addition Eurocode 8, for seismic design, requires an earthquake risk assessment to be carried out for all important structures. Sites are classified based on the V_s of the top 30 m of the soil profile (V_{s30}).
Some important practical applications of the knowledge of V_s in peat include that for the development of high speed railways across peaty ground in Belgium and in Norway as described by Gupta et al. (2010) and Berggren et al. (2010) respectively.

4.2 Previously published V_s values in peat

V_s values in peat are very low. For example Tanaka (2014) measured V_s in the range 22 m/s to 44 m/s, with a seismic CPT, for depths of between 0.5 m and 2.5 m at a site in Hokkaido, Japan. Amaryan (1993) reported a wide scatter of values for Russian peat varying between 11 m/s and 44 m/s and he suggested: “studies are incomplete because of the scarce technology and poor techniques.....a satisfactory solution has not yet been achieved”.

In view of the uncertainties involved, a study involving two different methods, namely direct shear wave transmission and down-hole shear wave transmission was undertaken at the Clara site and the results obtained are as follows.

4.3 V_s by down-hole method

A portable downhole sonde has been developed in order to take V_s readings through the vertical peat column with a view to correlating V_s to undrained shear strength.
The sonde was connected to a seismograph and recorded as single channel data at different depths within the peat. A shear wave was produced at the surface by striking a hammer against a block within the peat. An integral trigger within the source was used to start the recording of the traces. A reference geophone was also used to check the consistency of the time break. The integral trigger switch was found to be both reliable and repeatable. The down-hole field set-up is shown on Figure 7.

The down-hole sonde and shear wave source are shown in diagrammatic form on Figure 8 and in the photograph in Figure 9.

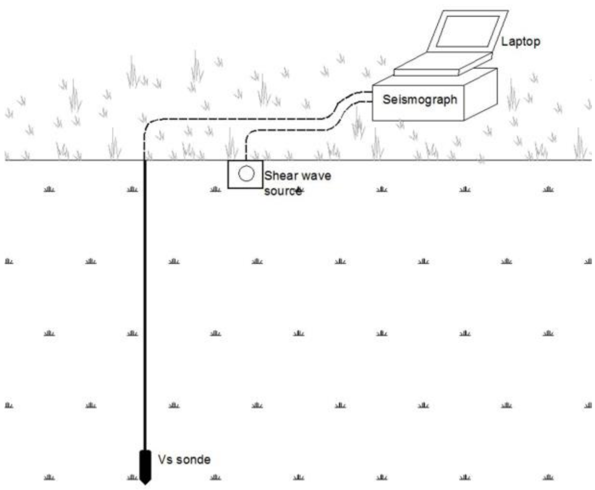


Figure 7. Downhole Field Setup

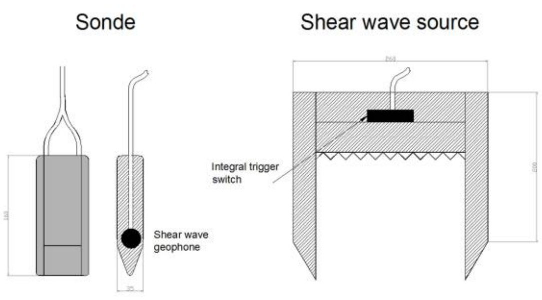


Figure 8. Downhole sonde and shear wave source

Figure 9. Downhole sonde and shear wave source

Figure 10 shows the results from the downhole Vs testing showing relatively constant Vs of c. 16 m/s. The Von Post log at this location showed a relatively consistent level of humification of the peat with H = 4.

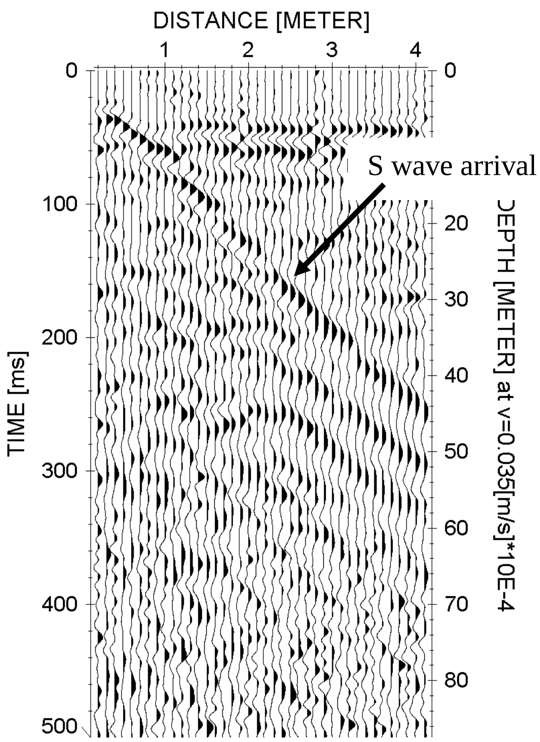


Figure 10. Downhole record showing V_s of about 16 m/s

4.4 V_s by direct shear transmission

This method involves the use of shear wave geophones on the surface at 0.5 m spacing and the generation off a shear wave at the surface in the same way as for the downhole V_s measurements. That data were collected to act as a control for the V_s downhole measurements. The method samples the upper layers of the peat and provides a bulk reading of V_s of the peat.

The results of the survey are shown on Figure 11. The shot record shows both P wave and S wave arrivals with the shear wave being dominant due to the orientation of the geophones. The V_s of about 15.7 m/s shows a good level of consistency with the readings from the downhole sonde.

4.5 Relationship between V_s and s_u

The other significant unknown in the stability assessment (Equation 1) is the value if s_u. Many techniques are available for the determination of s_u but these rely on either high quality samples or the need to bring heavy equipment onto a site in order to carry out in situ testing.

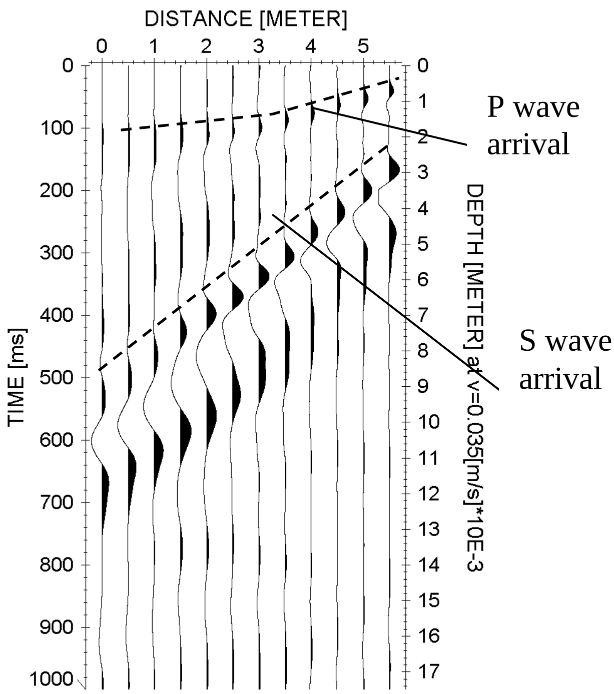


Figure 11. Direct shear wave transmission record

A review of available methods is given by Long and Boylan (2012).

If it were possible to obtain a relationship between V_s and s_u, then given the ability to measure V_s on peat bogs with light and portable equipment as described above, it might be possible to use the geophysical technique to give reliable estimates of s_u.

It is well know that laboratory derived s_u in peat is related strongly to the consolidation stress used in the test, especially if this stress exceeds the presonsolidation stress (p_c'), see for example Boylan and Long (2014).

Some work has therefore been carried out to determine the relationship between V_s and consolidation stress. This work was carried out in the laboratory using bender elements as shown on Figure 12.

The samples used were 70 mm in diameter and had an initial height of about 67 mm. Testing has shown that this approximately 1:1 ratio is the most efficient from the point of view of signal interpretation. The bender elements used were specifically designed for work in peat and had a protrusion of about 3 mm into the specimen. A sine wave pulse of frequency 2 kHz was applied and the time of first arrival determined.

A typical relationship between V_s and consolidation stress is shown on Figure 13. It is clear that there is a linear relationship between the applied consolidation stress and the resulting V_s in the peat.

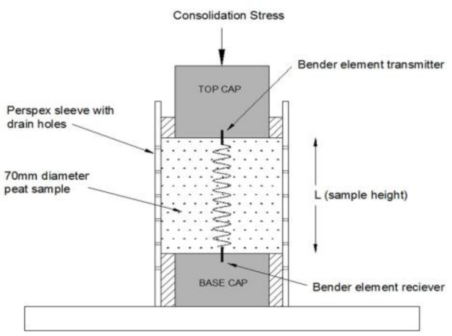


Figure 12. Laboratory bender element set-up

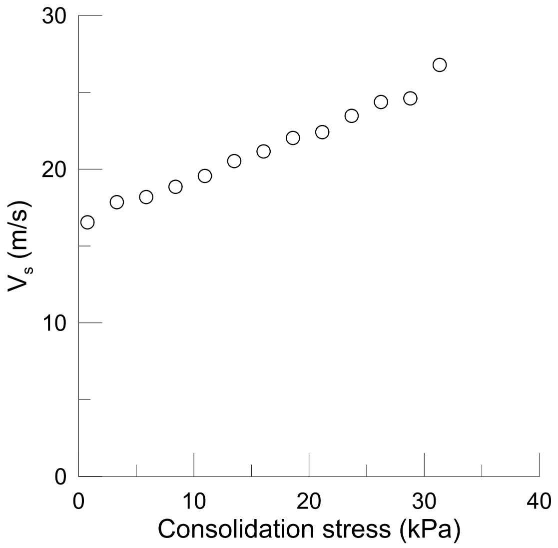


Figure 13. V_s versus consolidation stress

Although further work is required on this topic it is clear that the approach holds some promise.

5 CONCLUSIONS

This paper has provided a review and an update on some recent developments on geophysical testing of peat for civil engineering purposes. It was found that:

- GPR is a powerful tool for determination of peat thickness. Once peat thickness is obtained, the GPR data can be combined with GPS and LiDAR imaging to yield data such as the sub-bottom peat profile. The slope of the peat base can be obtained for use in landslide assessment studies.
- GPR can also give details of the internal structure of the peat and of the soils beneath the peat.
- Although the literature suggests that shear wave velocity measurements in peat are difficult due to the low values obtained, it has been shown here that it is possible to obtain consistent values with a variety of techniques.
- A lightweight down-hole sonde has been described for the purposes of measuring V_s of peat in remote environments.
- Work is ongoing on the development of a relationship between in situ V_s and the undrained shear strgth of peat for the purposes of landslide stability assessment.

REFERENCES

Amaryan, L.S. (1993) *Soft soil properties and testing methods*, Rotterdam: Balkema.

Berggren, E.G., et al. (2010) "Identification of substructure properties of railway tracks by dynamic stiffness," *Sound and Vibration*, Vol. 329, No. 19, pp 3999 - 4016.

Bjelm, L. (1980) "Geological interpretation with subsurface interface radar in peat lands," Lunds Tekniska Högskola. Teknisk Geologi, p 6p.

Bjelm, L., and P. Ulriksen (1980) "System för torvmark sundersökning med radar. Slutrapportetapp," Lunds Tekniska Högskola. Teknisk Geologi, p 104p.

Boylan, N., et al. (2008) "Peat slope failure in Ireland " *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 41, No. 1, pp 93-108.

Boylan, N., and M. Long (2014) "Evaluation of peat strength for stability assessments," *Institution of Civil Engineers Journal of Geotechnical Engineering*, Vol. 167, No. GE5, pp 421 - 430.

Carlsten, P (1988) "Geotechnical properties of peat and up-to-date methods for design and construction," Swedish Geotechnical Institute (SGI), Varia 215.

Dykes, A. P. , and K. J. Kirk (2001) "Initiation of a multiple peat slide on Cuilcagh Mountain, Northern Ireland," *Earth Surface Processes and Landforms*, Vol. 26, pp 395-408.

Edil, T.B. (2001) "Site characterisation in peat and organic soils," *Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories*. Bali, Indonesia, pp 49-59.

Feehan, J. , and G O'Donovan (1996) *The bogs of Ireland – An Introduction to the Natural, Cultural and Industrial Heritage of Irish Peatands*: UCD Environmental Institute.

Francese, R., et al. (2002) "Geophysical investigation within the Zennare Basin (Venice) " In: C. Campostrini, Ed., *Scientific Research and Safeguarding of Venice (CORILA Research Program 2001-2003 - Vol. I, 2001 Results)*: Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, Italy, pp 229 - 239.

Gupta, S., et al. (2010) "Numerical modelling of vibrations from a Thalys high speed train in the Groen Hart tunnel," *Soil Dynamics and Earthquake Engineering - Elsevier Press*, Vol. 30, No. 3, pp 82 - 97.

Haefli, R. (1948) "The stability of slopes acted on by parallel seepages," *Proc. 2nd ICFSMFE*, pp 134-148.

Hendrick, E. (1990) "A Bog Flow at Bellacorrick Forest, Co. Mayo," *Irish Forestry*, Vol. 47, No. 1, pp 32-44.

Hobbs, N. B. (1986) "Mire morphology and the properties and behaviour of some British and foreign peats," *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 19, pp 7-80.

Long, M. (2015) "Developments in the use of geophysics in geotechnical engineering in soft ground," *XVIth European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE)* Edinburgh, Scotland Thomas Telford Ltd., pp 129 - 150

Long, M., and N. Boylan (2012) "In situ testing of peat – a review and update on recent developments," *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, Vol. 43, No. No. 4, December, pp 41 - 55.

Long, M., and P. Jennings (2006) "Analysis of the peat slide at Pollatomish, Co. Mayo, Ireland," *Landslides*, Vol. 3, No. 1, pp 51-61.

Park, C.B., et al. (1999) "Multichannel analysis of surface waves," *Geophysics*, Vol. 64, No. 3, pp 800 - 808.

Plado, J., et al. (2011) "Ground-penetrating radar study of the Rahivere peat bog, eastern Estonia," *Estonian Journal of Earth Sciences*, Vol. 60, No. 1, pp 31 - 42.

Saarenketo, T., et al. (1992) "GPR applications in geotechnical investigations of peat for road survey purposes," *Geological Survey of Finland, Special Paper 16*: Geological Survey of Finland, Special Paper 16, pp 293 - 305.

Skempton, A.W., and F.A. De Lory (1957) "Stability of natural slopes in London Clay," *Proc. 4th ICSMFE*. Rotterdam, pp 72-78.

Smit, R. (1989) "The hydrology of a hummock-hollow complex on Clara Bog in Ireland in relation to chemistry and vegetation." Internal Report 265, Hugo de Vries Laboratory, University of Amsterdam.

Tanaka, H. (2014) "Geotechnical properties of peaty ground in Hokkaido, Japan " In: Z. Mlynarek, and J. Wierzbicki, Eds., *Proceedings 5th International Workshop CPTU and DMT in soft clays and organic soils*. Poznań, Poland,: Exemplum, Poland.

Trafford, A. (2009) "Mapping thickness of raised peat bog deposits using GRP," *Proceedings EAGE Near Surface 2009, 15th Annual Meeting of Environmental and Engineering Geophysics*. Dublin: EAGE.

Ulriksen, P. (1979) "Geo-radar för torv djups bestämning," Lunds Tekniska Högskola. Teknisk Geologi, p 6p.

Ulriksen, P. (1980) "Investigation of peat thickness with radar," Lunds Tekniska Högskola. Teknisk Geologi, p 14p.

Ulriksen, P. (1983) "Computer processing of subsurface impulse radar data," *International symposium on soil and rock investigations by in-situ testing*. Paris, pp 335 - 340.

Van der Molen, P. E., and T. A. Wijmstra (1994) "The thermal regime of hummock-hollow complexes on Clara Bog, Co. Offaly " *Biology and Environment: Proceedings of the Royal Irish Academy (RIA)*, Vol. 94B (3) pp 209 - 221.

von Post, L. , and E. Granlund (1926) "Peat resources in southern Sweden," *Sveriges geologiska undersökning, Yearbook*, Vol. 335, No. 19.2 Series C, pp 1 – 127.

Warburton, J., et al. (2003) "Anatomy of a Pennine Peat Slide, Northern England," *Earth Surface Processes and Landforms*, Vol. 28, No. 5, pp 457-473.

Warner, B.G., et al. (1990) "The application of ground penetrating radar to peat stratigraphy of Ellice swamp, southwestern Ontario," *Canadian Journal of Earth Sciences*, Vol. 27, pp 932 - 938.