Estimation of in situ soil stiffness of glacial tills in Northern Ireland from barometric response

Carse, L., Hughes, D.A.B. & McLernon, M.
Queen's University Belfast, Belfast, United Kingdom
Barbour, S.L. & Relland, K.
University of Saskatchewan, Saskatoon, SK, Canada

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ABSTRACT
Small strain stiffness is required in numerical modelling of the stress-deformation behaviour of geotechnical structures. However the measurement of small strain stiffness, particularly for stiff stony glacial tills, is very difficult. Undisturbed sampling is practically impossible and even with good quality samples; laboratory measurements of stiffness are unreliable. In situ stiffness measurement using intrusive testing techniques or down hole geophysics methods can also be unreliable due to the heterogeneity of the soils and borehole disturbance.

Surface mechanical loading will generate a pore pressure change at depth in a saturated clay formation. When the surface loading is barometric pressure, this change in pore pressure is referred to as barometric efficiency. Techniques are currently being developed to estimate the in situ small strain stiffness of these tills using the response of sealed piezometers to changes in barometric pressure. Hydrogeologists have utilised deep pore water pressure transducers in clay formations to monitor changes in surface water balance on a scale of hectares. This paper discusses the use of deep pore water pressure transducers to measure the variation of bulk stiffness with depth in this low permeability stony clay formation.

RÉSUMÉ
La rigidité à faible déformation est nécessaire dans la modélisation numérique du comportement contrainte-déformation des structures géotechniques. Toutefois, la mesure de la rigidité à faible déformation, en particulier pour les argiles glaciales rocheuse et raides, est très difficile. L'échantillonnage non remanié est pratiquement impossible et même avec des échantillons de bonne qualité; des mesures en laboratoire de la rigidité ne sont pas fiables. La mesure de l'élasticité in-situ utilisant des techniques de tests intrusifs ou des méthodes de géophysique de puis peut aussi être peu fiables en raison de l'hétérogénéité des sols et la perturbation de forage.

La surface de chargement mécanique va générer un changement de pression interstitielle en profondeur dans une formation argileuse saturée. Lorsque la surface de chargement est une pression barométrique, ce changement de pression interstitielle est visée à l'efficacité barométrique. Les techniques sont actuellement mis au point pour estimer la rigidité de contrainte in situ de ces petites caisses en utilisant la réponse de piézomètres scellés aux changements de pression atmosphérique. Les hydrogéologues ont utilisé des capteurs de pression des pores en profondeur de l'eau dans les formations argileuses pour surveiller les changements dans l'équilibre des eaux de surface à l'échelle d'hectares. Cet article traite de l'utilisation de l'eau des pores en profondeur transducteurs de pression pour mesurer la variation de la rigidité en vrac avec la profondeur dans cette formation d'argile de faible perméabilité pierreux.

1 INTRODUCTION

Geotechnical engineers routinely measure in situ pore-pressures as part of geotechnical investigations or long-term monitoring. In many cases the instruments utilised in these studies are highly responsive and accurate instruments such as vibrating wire piezometers (VWP). In general, the 'noise' in these measurements, which lies within the range of a few kilo Pascals (kPa), is often ignored since the pore-pressure variation which is of interest is in the range of 10's of kPa. However a portion of this noise can be related directly to variations in formation pressures, which arise in response to mechanical loading as a result of fluctuations in barometric pressure.

This phenomenon was first documented by Jacob (1940); he observed that the stress in a saturated soil formation, at a known depth, is a combination of barometric pressure and the weight of the formation above that point. '*This load may be considered as being borne in part by the solid "skeleton" of the aquifer and in part by the water confined therein*' (Jacob, 1940).

Barometric pressure change is applied at ground surface as a mechanical loading and is transmitted to depth as a stress change which can be recorded as a pore-pressure change. The degree to which this mechanical loading can be identified at depth is termed the loading efficiency of the formation and is used to determine the compressibility or stiffness of a saturated soil.

Skempton (1954) and Bishop (1954) demonstrated that loading efficiency arises from the same mechanism which geotechnical engineers describe as 'B-bar' ($\bar{B}$).

$$\frac{\Delta u}{\Delta \sigma_p} = \bar{B} \qquad [1]$$

where Δu is the change in pore pressure and $\Delta \sigma_p$ is the change in barometric pressure.

$\bar{B}$ is the constrained, one-dimensional variation of Skempton's pore-pressure coefficient, B and has been used by hydrogeologists (Rojstaczer, 1988 and van der Kamp, 1997) to determine formation compressibility in the form:

$$\bar{B} = \frac{1}{1 + (\alpha / n\beta)} \qquad [2]$$

where α is the compressibility (or stiffness) of the soil structure; β is the compressibility of water and n is the porosity of the clay.

The use of a large till deposit as a full-scale geological 'weighing lysimeter' is demonstrated in detail in the work of van de Kamp and Gale (1983) and others including in the research of Rojstaczer (1988), Domenico and Schwartz (1998) and Barr et al. (2000). Anochikwa (2009) and Anochikwa et al. (2011) built upon the work of van der Kamp (1997) to show that this nterpretation can be used to measure changes in total soil moisture at surface, in a way that enables a continuous water balance to be estimated simply using monitored pore-pressure fluctuations. In order to isolate the component of pore water pressure fluctuation due to soil moisture loading, Anochikwa (2009) had to subtract the influence of longer term pore water pressure changes as a result of water table fluctuations. This was done using coupled seepage and stress modelling.

2 RESEARCH STUDY AREA

Three study sites have been chosen to investigate the stiffness of glacial till deposits, in the north of Ireland. The sites; Loughbrickland, Craigmore and Tullyhappy, are located in County Down, Northern Ireland, site locations are shown in Figure 1.

The following sub-sections will describe the geology of the study area, brief details of the individual research sites and outline the instrumentation used in the investigation. Further information can be found in Carse (PhD, 2011) and McLernon (PhD, 2011).

2.1 Geology

Northern Ireland as a country is small in area but rich in geology, for an area of less than 14,000km^2 it contains rocks from a wide variety of geological time periods. Evidence can be found for geology of all time periods from the Moinian to the recent Quaternary, only excluding Cambrian (Mitchell, 2004).

In County Down, where the research sites are located, the bedrock is part of the Southern Uplands-Down-Longford Terrane (Ordovician – Silurian). This is the predominant bedrock across County Down and consists of Lower Palaeozoic marine sedimentary rock as shown in Figure 2. The bedrock geology consists of greywacke, sandstones, siltstones, mudstones, shales and grits, manly of Ordovician age (McCabe et al., 1999). There are areas of younger intrusions in the south such as that of the Newry Igneous Intrusion. The bedrock geology in this area is of Tertiary granite and granodiorite rock.

The overlying drift geology in this area is of Late to Main Midlandian Till, a glacial deposit of lodgement till set down during the retreat of the last ice sheets. These glacial sediments can vary greatly in thickness from a few meters to upwards of 25m (Doran, 1992).

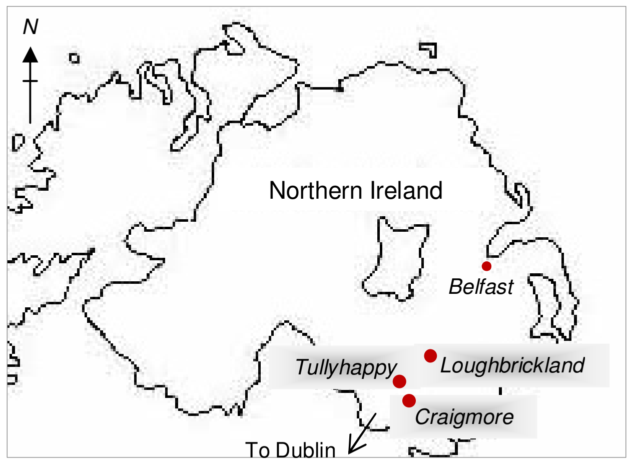

Figure 1: Location map of the research sites.

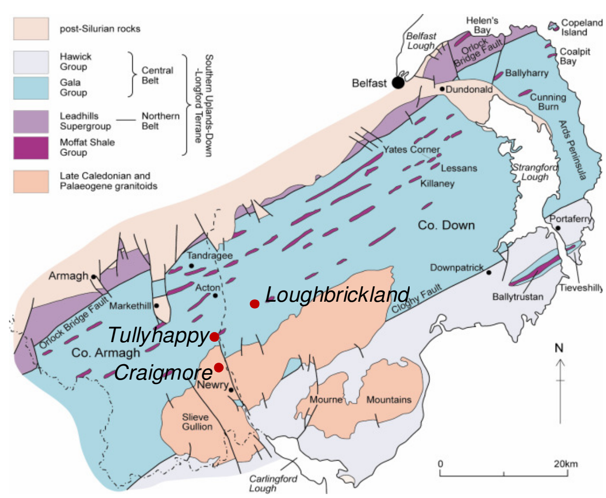

Figure 2: Geology of research sites (© Crown copyright. Reproduced with the permission of the Director, Geological Survey of Northern Ireland)

2.2 Research sites

Three research sites have been selected due to their geology, geometry and proximity to important infrastructure. Each site consists of a slope, cut through Drumlin topography and is adjacent to either a major road or railway. Loughbrickland and Tullyhappy are each road cuttings and Craigmore is situated on the railway network.

At Loughbrickland the slope was constructed in 1997 as part of a road widening scheme on a strategically important Dublin to Belfast road route. The slope is 24m in height and sits at a slope angle of 25°. The slope is cut through glacial till, drift geology typical for the area and locally known as Boulder Clay. The underlying bedrock geology is Silurian shale.

At Craigmore the slope was cut in the 1850's to facilitate the laying of a section the Belfast to Dublin railway track. The slope is 16m high and sits at an angle of 36°, there are clear signs of recent and long term failures along the full length of the cutting. The cutting is through glacial till and the bedrock in this location is granite, of the Newry Igneous Intrusion.

The Tullyhappy site is located along the A28 Armagh Road north of Newry, a 12m high slope, excavated at an angle of 27° in the early 1970's. The slope was excavated through Boulder Clay overlying Silurian shale.

2.3 Instrumentation

A range of instrumentation has been installed at the sites to monitor soil moisture balance. Deep pore pressure transducers, near surface soil moisture probes and a weather station, have been located at one or more of the sites, to give a full account of temporal soil moisture and environmental changes.

A series of monitoring wells have been completed at each location. Monitoring wells consist of boreholes driven to the bedrock containing stacked standpipes installed at varying depths. Standpipes of 50mm diameter, with a one metre slotted tip, were bedded in gravel to allow groundwater flow into and out of the standpipe. The borehole was then backfilled with bentonite to the base of the next standpipe to ensure hydraulic independence between monitoring points. Vibrating Wire Piezometers (VWP) were then installed 500mm above the base of each standpipe, one instrument in each standpipe and generally two to three standpipes per borehole see Figure 4(a), (b) and (c). VWPs were sealed into the standpipes with inflatable packers to ensure rapid head response was recorded and that the readings were representative of the head at that depth.

A weather station was installed at Craigmore to record precipitation, wind speed and direction, levels of sunlight and barometric pressure. As the sites are in close proximity (<5mile radius) it was considered adequate to use one weather station as representative of all the sites. Barometric pressure was measured at both Craigmore and Loughbrickland.

Near surface soil moisture probes in the form of tensiometers and frequency domain reflectometry probes were installed in the top 2m of the ground to assess the near surface water balance. The data obtained from these instruments is not discussed in this paper.

2.4 Material properties

Full site investigations took place at each of the sites during installation of the boreholes. Field and laboratory tests were carried out to determine material properties; field tests included rising and falling head tests. Disturbed and undisturbed samples were collected for testing in the laboratory. Laboratory testing for particle size distribution, moisture contents, Atterberg limits and strength testing were completed. A summary of material properties at each of the sites can be found in Table 1.

Table 1: Summary and comparison of material properties from the three research sites

Property	**Craigmore**	**Loughbrickland**	**Tullyhappy**
L.L. (%)	29 – 32	32 – 41	30 – 38
P.L. (%)	14 – 17	14 – 17	15 – 27
P.I.	12 – 17	16 – 25	10 – 20
M.C. (%)	8 – 19	~	9 – 17
Unit weight (kN/m^2)	22	21.5 – 22.7	21
Upper till K_{sat} (m/s)	~	7e-09	~
Lower till K_{sat} (m/s)	2e-09	5e-10	2e-09
Bedrock K_{sat} (m/s)	1.7e-05	1.2e-06	1.2e-06
c' (kPa)	8	0 – 11	21*
φ' (°)	31	30 – 32	(26 – 28)*
Porosity, n	0.25 - 0.35	0.18 - 0.35	0.25 - 0.35

*triaxial cell results unreliable (based on one test only)

3 GLACIAL TILL STIFFNESS

The compressibility of the till at each of the three research sites was estimated from the barometric response. The following section provides an example of how the theory of loading efficiency has been applied to the research sites.

As shown in Equation 2, if the porosity of the clay is known, the field pore water pressure and barometric pressure data can be used to derive values for $\bar{B}$. van der Kamp (1991) and Anochikwa et al. (2009) show that this can be done by selecting a continuous pore-pressure record for which there are known barometric pressure change events. In some cases there may be a need to filter the data for pore water pressure response to earth tides or tidal fluctuations. A trial and improvement method is then used to determine the correct $\bar{B}$ value for each depth.

The method used in this paper is as follows; data from one VWP is examined graphically in Figure 5, (i) initially a factor, $\bar{B}$ (<1) is applied to the barometric pressure to align it with the chosen pore water pressure data, (ii) the factored barometric data are then subtracted from the original pore water pressure readings and the result is a pore pressure graph with barometric mechanical loading removed. This method allows the researcher to determine what fraction of pore water pressure change can be attributed to change in barometric pressure and therefore determine compressibility according to depth. The method is specifically used on portions of the data where barometric pressure fluctuations are pronounced and infiltration levels are low. Figure 5 shows two examples of the method used with data from the Craigmore site, borehole BH1. Table 2 contains stiffness values derived from the data and relative strain ranges. Strain values are a best estimate of direct strain based on those stiffness values and applied stress.

4 CONCLUSION

This preliminary study outlines a method of estimating in situ small-strain stiffness for these tills.

Although stiffness may have been expected to increase with depth according to increases in confining pressure, the values shown in Table 2 suggest there is not a consistent increase in stiffness with depth. There is also a marked variability in stiffness between the three sites. This variation in stiffness and textural differences across the sites may both be attributed to the depositional effects during the lying down of the lodgement till or some differences in weathering processes over time. A full account of the material properties for the three sites can be found in Carse et al. (2009).

The levels of stiffness seen here are comparable to stiffness values obtained by Clayton and Heymann (2001) for London Clay, a similarly overconsolidated material, with an undrained secant Young's Modulus of 240MPa. The direct strain calculated here is then used to compare to the current available literature for stiffness at small strain. These strain levels are in the same range (10^{-6}% - 10^{-4}%) as those shown by Auld (1977) which are believed to be representative of the operational strain levels experienced by foundations and retaining structures.

The data lies within the expected range and some variability can be seen across the three sites. Further work has recently been completed to estimate in situ stiffness using seismic refraction and laboratory stiffness using stress path testing for these sites. This data will be presented in the near future.

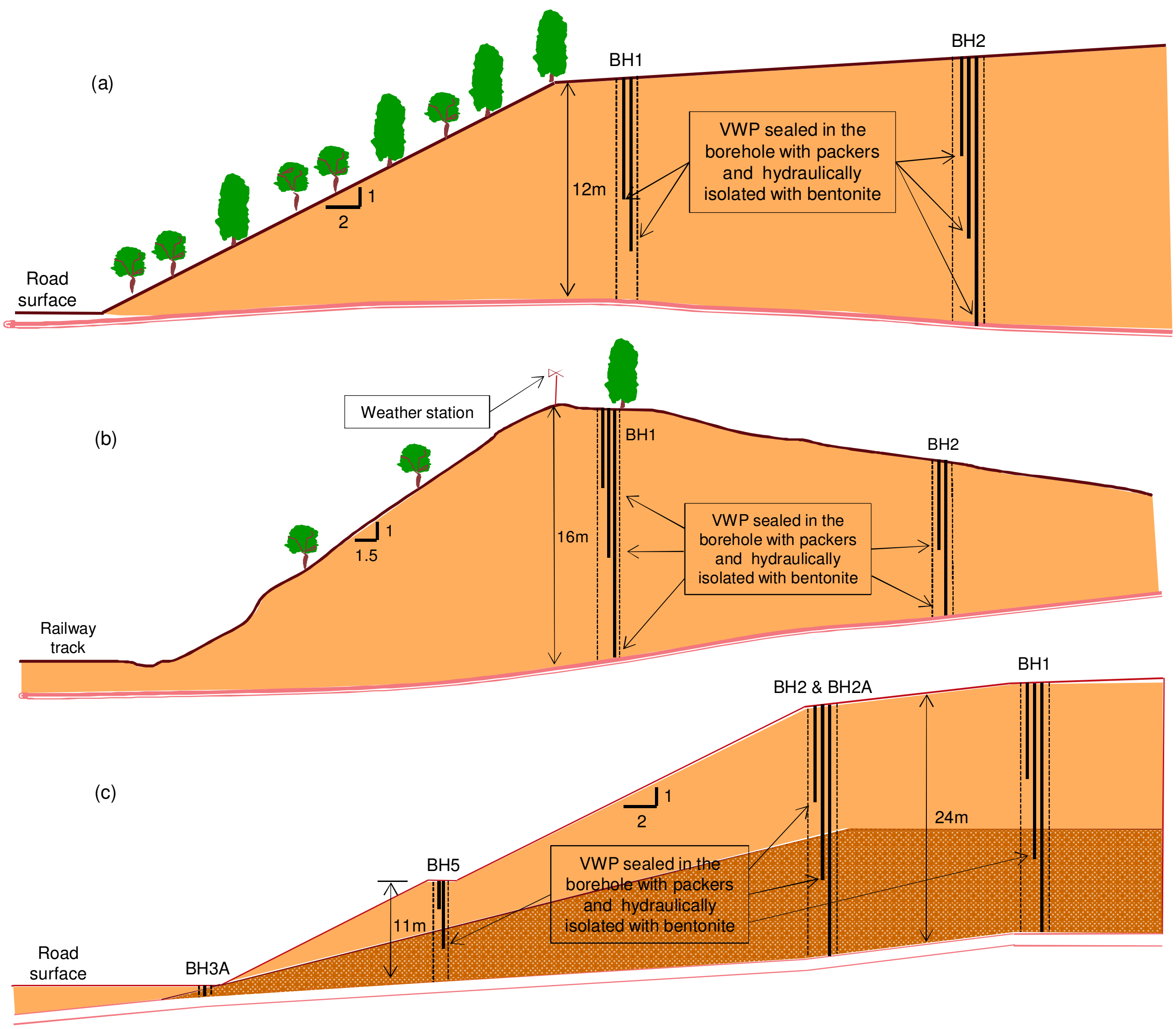

Figure 4: Schematic cross sectional diagrams of sites; (a) Tullyhappy, (b) Craigmore and (c) Loughbrickland and their instrumentation.

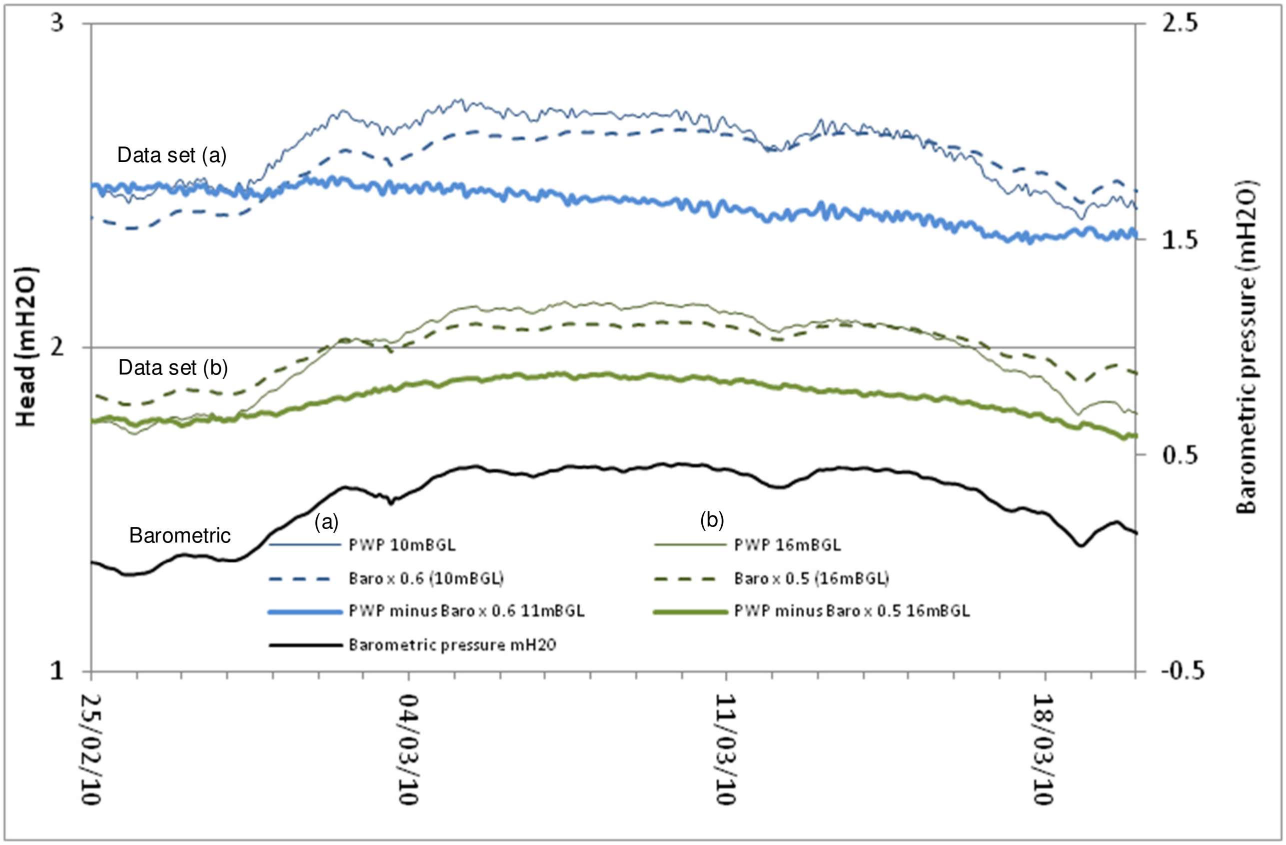

Figure 5: Example data used with barometric response method for calculating in situ stiffness

Table 2: In situ stiffness values derived from barometric response data.

Site	Depth (mBGL)	Stiffness			
		K (MPa)	G (MPa)	E (MPa)	Strain level (%)
Craigmore	5	~	~	~	~
	10	3500 – 19000	750 – 4000	2000 – 11500	5.0e-05 – 8.7e-06
	15	2000 – 8100	400 – 1800	1200 – 5000	8.3e-05 – 2.0e-05
Loughbrickland	6	~	~	~	~
	10	2500 – 15000	550 – 3200	1500 – 9000	6.7e-05 – 1.1e-05
	18	8400 – 25000	1800 – 5300	5000 – 15000	2.0e-05 – 6.7e-06
Tullyhappy	4	~	~	~	~
	9	900 – 2000	150 – 450	500 – 1200	2.0e-04 – 8.3e-05
	15	1400 – 4500	300 – 950	800 – 2600	1.3e-04 – 3.8e-05

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