The magnitude and variation of pore pressures in glacial till slopes and their effect on slope stability

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ABSTRACT
The progressive failure of cuttings in overconsolidated heavy clays has been observed and documented, particularly for London clays (Vaughan and Walbancke 1973, Vaughan 1994). The process of ageing and softening of other clays, particularly glacial tills, is not well established. It is likely that either strain softening or some viscous deformation occurs near the toe of a cutting and this leads to progressive deformation in the soil and ultimately yielding or slope failure. The process of softening or yielding is most likely influenced by the level of effective stress and the cyclic changes in effective stress / pore water pressure in the soil (Potts et al. 1997). A number of deep cuttings in glacial till have been instrumented in the North of Ireland to monitor and record fluctuations in positive pore water pressure in glacial till slopes in response to changes in the underlying hydrogeologic system or due to surface environmental factors. This data will be used along with a laboratory test programme to evaluate the effect of cyclic pore water pressures on the deformation / stability of large cuttings in glacial tills in Northern Ireland.

RÉSUMÉ
La rupture progressive des taillements des argiles Lourdes sur-compactées a été observée et documentée, particulièrement pour les argiles de Londres (Vaughan and Walbancke 1973, Vaughan 1994). Le processus de vieillissement et d'adoucissement d'autre argiles, particulièrement les glacials, n'est bien établi. Il est probablement possible que soit l'adoucissement de déformation ou une sorte de déformation visqueuse se produit tout près de la base du taillement et ceci provoque une déformation progressive dans le sol et ultimement une rupture de pente. Le processus d'adoucissement ou déformation est probablement influencé par le niveau de la contrainte effective et le changement de cycles de la contrainte effective / pression des pores d'eau dans le sol (Potts et al. 1997). Un nombre de taillements profond dans les pentes d'argile glacial ont été instrumenté dans le nord de l'Irlande pour poursuivre et enregistré les fluctuations dans les pressions positives des pores d'eau dans les pentes d'argile glacial qui sont due de changement d'hydrologie du système ou de facteurs environnant de la surface. Les données vont être utilisées avec les résultats de laboratoire pour évaluer l'effet cyclique des pressions des pores d'eau sur la déformation / la stabilité de large taillements dans les argiles glacials de l'Irlande du Nord.

1 INTRODUCTION

The long-term stability of slopes in overconsolidated clays has been of particular interest to geotechnical engineers extending from the work of Skempton (1964) in the early 60's to more recent work by Potts et al. (1997) and Smethurst et al. (2006).

Slopes excavated in overconsolidated clay are subject to stress release and environmental changes which lead to variations in pore water pressure over time. This can result in gradual changes in volume and/or deformation which results in the delayed collapse of the cuttings through progressive failure. Studies of delayed collapse of slopes have been widely researched (Vaughan and Walbancke 1973, Skempton 1964, Potts et al. 1997, Smethurst et al. 2006, Clarke et al. 2007). These authors have focused on a mechanism of progressive failure through a reduction in long-term shear strength due to ageing of the clay over time; however, the mechanisms responsible for this loss of strength are not fully understood.

Investigation of a large cutting in glacial till in the North of Ireland has demonstrated that significant temporal and seasonal changes in pore water pressure do occur over time (Clarke 2007). This raises the question as to whether these materials also experience an associated deformation and possibly loss of strength which may lead to instability. In addition, it is expected that future climate change will further exacerbate the magnitude of cycles in pore pressure in these slopes created by seasonal changes in the water table elevation.

In 1999 a slope failure occurred in Dromore, Northern Ireland (Figure 1) where a cutting excavated in the 1970's failed after a prolonged period of exceptionally wet weather. The cutting, excavated in heavily overconsolidated lodgement till was some 19m high at a slope angle of 1V:2H. The slope failure was found to have been caused by a combination of factors including the presence of relict failure planes, long-term strength reduction due to progressive failure, strain softening and dissipation of excess negative pore water pressures generated during the excavation (Hughes et al. 2007).

In 2004 the Department for Regional Development, Roads Service (RS) in Northern Ireland, began a project to improve a strategically important road link between Belfast and Dublin. A section of this route at Loughbrickland was upgraded to a dual two-lane carriageway with improved horizontal alignment and a substantial excavation undertaken to accommodate the new road. This site is 10 miles south of the Dromore cutting and due to its similarity in geology and geometry it was considered an important research opportunity by both Queen's University Belfast (QUB) and RS (Figure 1).

A site investigation (SI) was performed at Loughbrickland in 1999/2000 by RS prior to the construction of the new road and a further investigation by QUB in early 2004. Both investigations involved the use of trial pits and boreholes to characterise the site geology. The QUB investigation then became an ongoing monitoring project to observe the hydrogeology of the site.

The monitoring involved the continued use of the SI boreholes. Vibrating wire (VW) piezometers were installed to monitor deep pore water pressures within the cutting post-excavation.

Data from the VW piezometers, meteorological data, laboratory strength testing and insitu permeability tests were combined to characterise the stability of the cutting both during and post-excavation and to assess the possible effect of future climate change projections. The geotechnical data collected and meteorological data for the area were numerically modelled using GeoStudio Seep/W and Slope/W packages to assess any possible effect of climate change on a cutting of this nature. Based on the full study Clarke (2007) concluded "*that projected climate change scenarios will have minimal effect on the stability of slopes in the climate region studied*".

This project will extend this previous work by investigating the mechanisms controlling variations in pore water pressure at three research sites in the North of Ireland along with an evaluation of the potential impact that these pore pressure variations may have on deformation/stability. The three sites include Loughbrickland, Craigmore and Tullyhappy (Figure 1). The sites have been identified by QUB, RS, and Northern Ireland Rail (NIR) as sites of potential risk and sites which have visual evidence of some distress.

These sites are all cut slopes through heavily overconsolidated glacial lodgement till and are being instrumented to monitor pore water pressure, surface water balance, water table elevation and meteorological conditions. This data will be used along with a laboratory testing programme and numerical modelling tools to evaluate the effect of cyclic pore water pressures on the

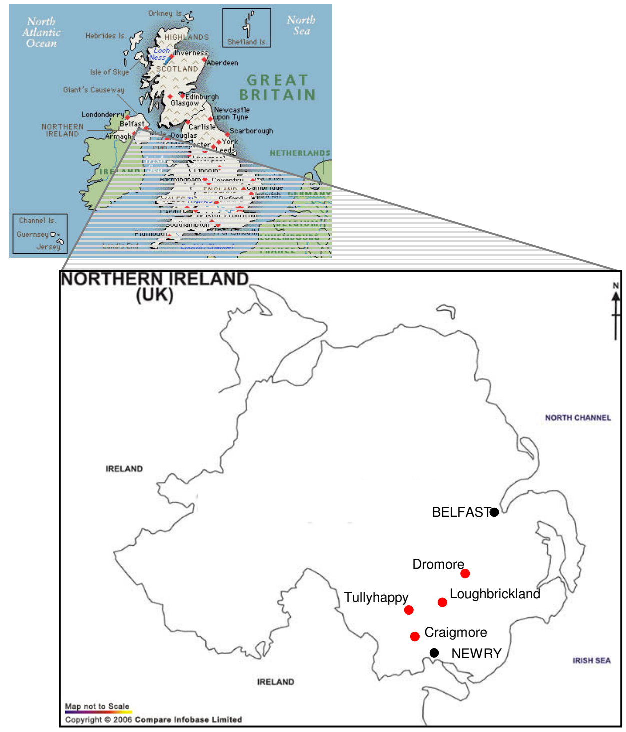


Figure 1. Location map of research sites. (From wwp.greenwichmeantime.com and www.mapoftheworld.com)

deformation / stability of large cuttings in glacial tills in Northern Ireland.

This paper aims to introduce the research sites and to discuss the proposed programme of laboratory testing aimed at quantifying the magnitude of possible shear strength loss or reduction in stiffness due to variations in pore water pressure within a slope.

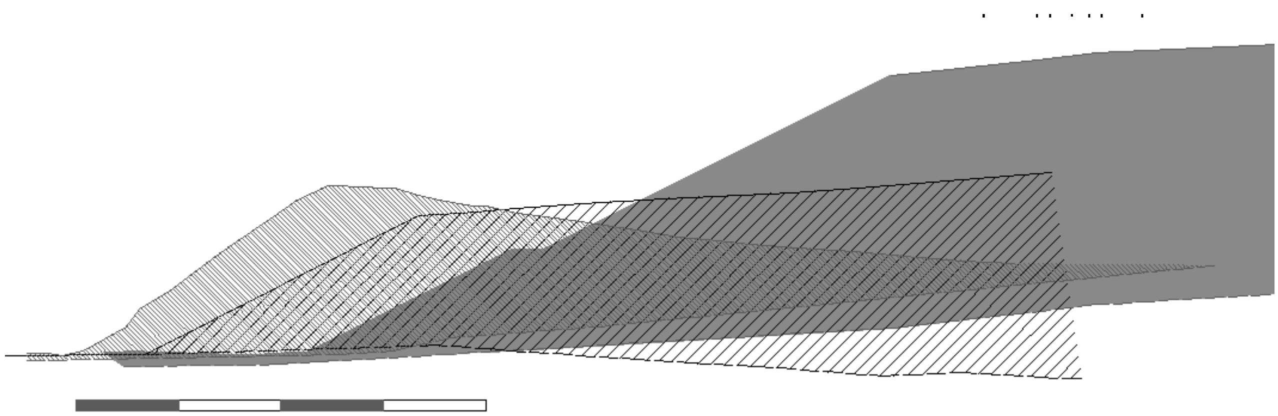
This paper is written and presented in partnership with a second paper submitted to the conference (McLernon et al. 2009) which further outlines the history of the sites and other aspects of the research programme currently being undertaken at QUB.

2 INTRODUCING THE RESEARCH SITES

The geology of the three sites is described in more detail in a companion paper by McLernon et al. (2009). The sites are very closely located in an area shaped during the late Midlandian glaciation, which retreated approximately 20,000BP.

The cutting at Loughbrickland was excavated in 2004 as part of a new road layout along the A1, a strategically important Belfast to Dublin route. The cutting stands 25m high at a slope angle of approximately 26° and is excavated through Drumlin topography typical of the North of Ireland. The soil profile is composed of stiff glacial lodgement till overlying completely weathered to moderately weathered Greywacke (Shale) (Clarke 2007).

Flowing artesian conditions developed across the base of the cutting during excavation due to the upper



bedrock surface acting as a confined aquifer. The excavation underwent some slope instability and was eventually stabilized by the excavation of a deep toe drain to the bedrock surface. Due to the large size of the cutting and steep angle of the slope, a programme monitoring pore water pressure with depth began in 2004 and will be continued during this study.

Tullyhappy, excavated in the 1970's, was recently reviewed as part of a possible road widening project on the A28 Armagh Road northwest of Newry (Figure 1). The slope is 12m in height and stands at an angle of 27°. It is excavated through lodgement till overlying Silurian shale. There are signs of shallow failures and bent tree trunks along the slope at the toe suggesting the slope angle is over-steep.

The third site is a railway cutting at Craigmore (Figure 1) excavated in the 1850's through heavily overconsolidated glacial till. It is approximately 17m high, at a slope angle of 36°. The bedrock at this site is Granodiorite of the Gala group from the Newry Igneous Complex, a heavily impermeable rock which daylights to the rear of the slope. Shallow failures have been observed at the toe of the slope in recent years, after a long period of stability. The geometry of the three sites is compared graphically in Figure 2 above, and highlights the differences in height, depth to bedrock and slope angle for the three sites.

2.1 Geotechnical Properties

A preliminary comparison of the geotechnical properties of the glacial till at the three sites (Tullyhappy, Craigmore and Loughbrickland) can be developed from some of soil properties obtained to date. Soil samples were extracted from boreholes during initial site investigations at each site and laboratory testing carried out. Both disturbed and undisturbed samples were collected. Particle size distribution, Atterberg limits and triaxial testing were preformed to compare the geotechnical properties at each site. The data collected is shown in Figures 3 to 5 below. The three tills are well graded with some granular matrix and are of low to intermediate plasticity. Atterberg limits for each of the sites are typical of overconsolidated tills with moisture contents lying below the plastic limit. A limited number of triaxial tests show strength values which are typical for Irish glacial tills (Table 1), with the exception of an outlier for the cohesion for a sample from Tullyhappy. Data shown for Loughbrickland is summarised from previous work by Clarke (2007). Further testing at these sites is pending.

Table 1. Shear Strength data for glacial till at the three study sites.

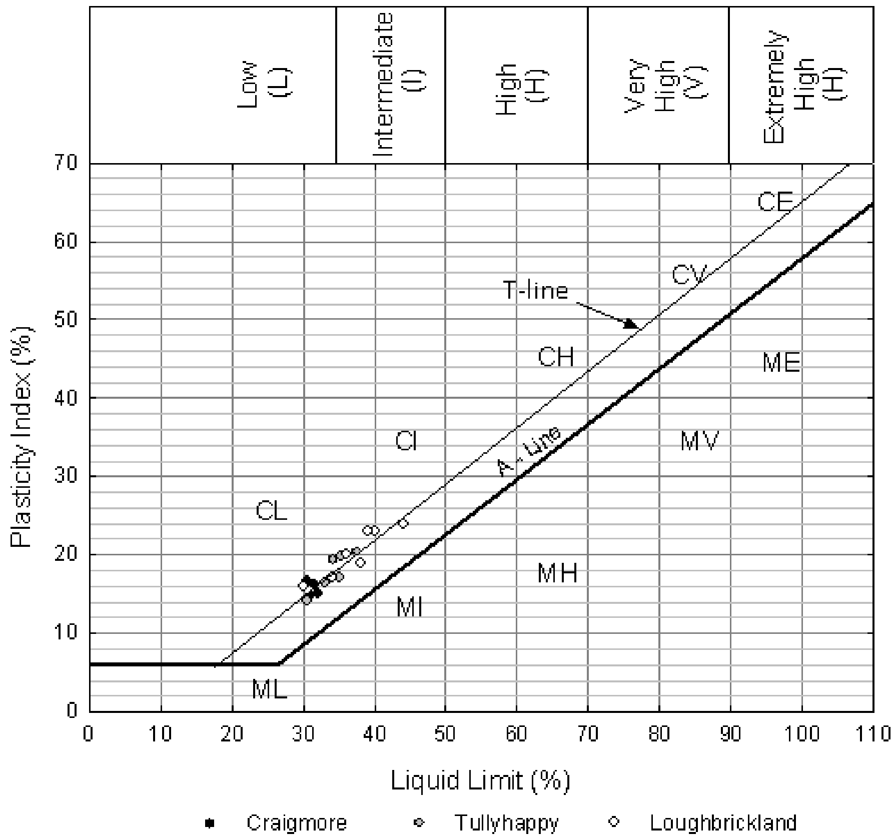
Location	Tullyhappy	Craigmore	Loughbrickland
Depth (mBGL[1])	9.7	10.6	-
c' (kPa)	21*	8	8 - 11
φ'(°)	26	31	30 - 32
φ' critical (°)	28	32	

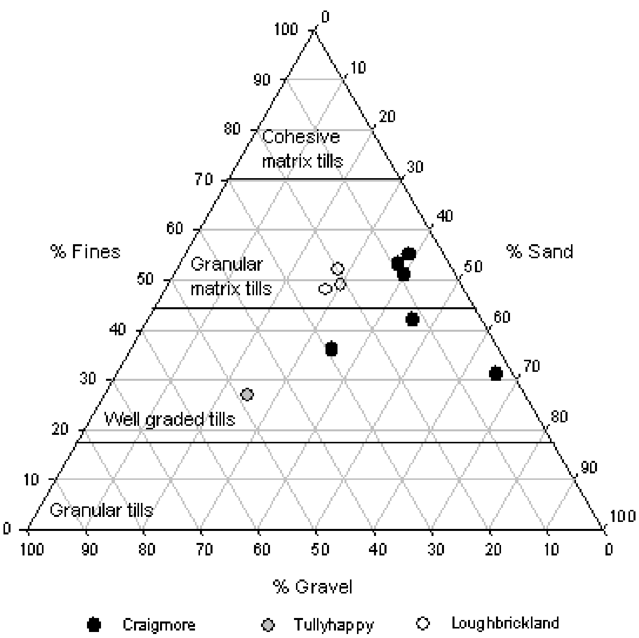
[1] Meters below ground level * suspect value/ outlier

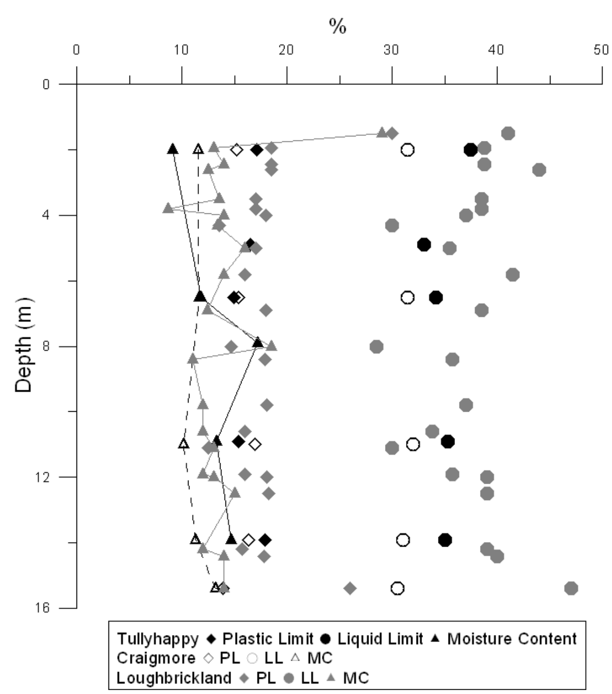
3 FIELD MONITORING

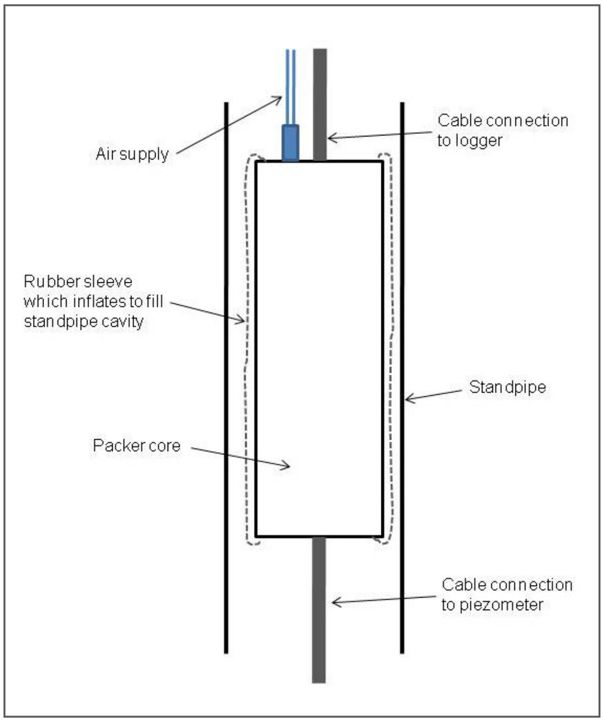
Boreholes were drilled to bedrock on each of the three sites to collect both undisturbed and disturbed soil samples for soil testing. A programme of pore water pressure and climate monitoring has begun involving nested vibrating wire (VW) piezometers and a weather station. The VW piezometers are housed in 50mm diameter standpipes, with three standpipes in each borehole, at varying depths within the boreholes. The tip of the VW piezometer sits at approximately 500mm above the base of each standpipe. The bottom one metre of the standpipe is slotted and surrounded in gravel to allow groundwater flow into and out off the standpipe.

A packer is used above the VW piezometer to improve the response of piezometer to fluctuations in pore water pressure. The packer is a simple pneumatic system which plugs the standpipe above the VW piezometer (Figure 6).


Low (L)
Intermediate (I)
High (H)
Very High (V)
Extremely High (H)
CE
CV
T-line
CH
ME
CI
A - Line
MV
CL
MH
MI
ML
Plasticity Index (%)
Liquid Limit (%)
Craigmore
Tullyhappy
Loughbrickland


Cohesive matrix tills
Granular matrix tills
Well graded tills
Granular tills
% Fines
% Sand
% Gravel
Craigmore
Tullyhappy
Loughbrickland


%
Depth (m)
Tullyhappy ◆ Plastic Limit ● Liquid Limit ▲ Moisture Content
Craigmore ◇ PL ○ LL △ MC
Loughbrickland ◆ PL ● LL ▲ MC



A piece of bicycle tyre tubing is attached to a plastic sealed tube and inflated within the standpipe, below standing water depth, to effectively plug the standpipe from the atmosphere above.

Monitoring at Loughbrickland will be continued and enhanced. There are currently two boreholes, three standpipes in each, containing six nested piezometers in total. The piezometers are measuring pore water pressure at varying depths within each borehole; deep, mid-depth and shallow (Figure 7). Additional boreholes are to be installed within the next month including a new borehole to bedrock at the top of the slope; this will investigate the extent of under-draining in the bedrock created by the toe drain. A borehole at the berm has also been included since this is the likely area of greatest deformation, should a slide occur. An additional borehole will be installed at the toe of the slope to investigate the effects of toe drainage.

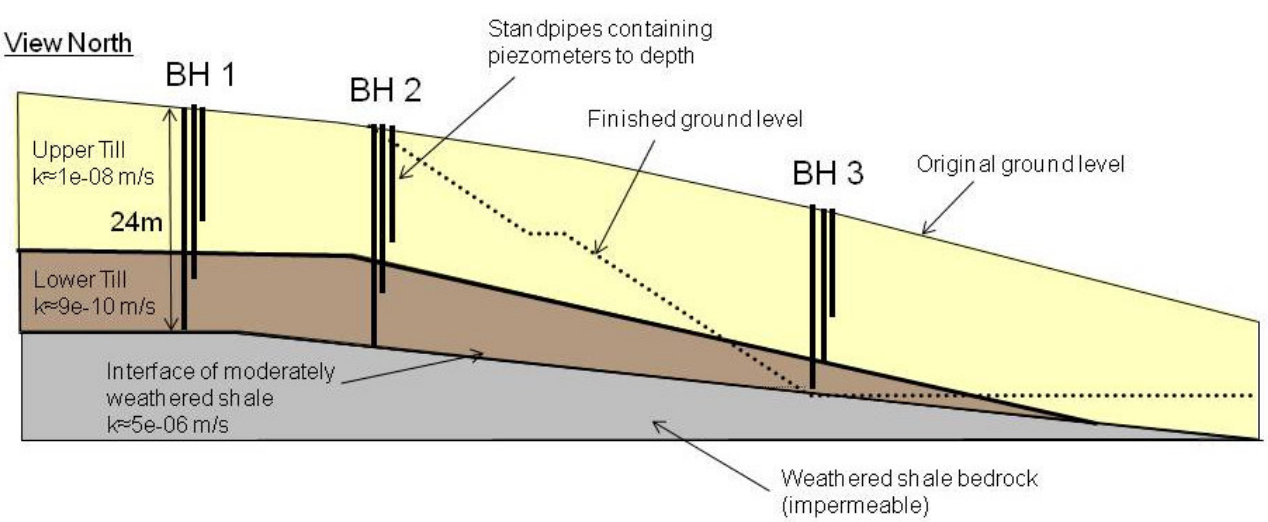
At Tullyhappy there are two boreholes, positioned similarly to those at Loughbrickland, measuring pore water pressure at varying depths. There are three boreholes at Craigmore, each containing nested piezometers and logging continuously.

Meteorological data will be collected at the Craigmore site via a weather station connected to a datalogger, all the sites are located within a ten mile radius. The weather station will collect data on precipitation, wind speed and direction and humidity. A run-off channel will be constructed to measure surface run-off and assess infiltration into the soil. The meteorological data from the British Atmospheric Data Centre (BADC) has been used in all preliminary interpretations of the data collected to date. The BADC have numerous meteorological stations across the UK, two of which are located within ten miles of the study sites at Glenanne and Magherally.

3.1 Data and initial analysis

A full geotechnical and hydrogeological assessment is currently underway for each site. This will include not only additional laboratory testing but also insitu testing of hydraulic conductivity using the installed wells. Additional instrumentation is planned to map near surface soil moisture and water table fluctuations in response to climatic conditions. Calibrated numerical models are also being developed to simulate the hydrogeological response of the pore-pressures within the till to both surface environmental conditions and the deeper hydrogeologic system. Additional modelling of coupled groundwater flow and stress conditions will be developed in order to link mechanisms of pore pressure fluctuations to geotechnical behaviour.

An example of the type of data currently being collected is illustrated in Figure 8. Pore water pressure



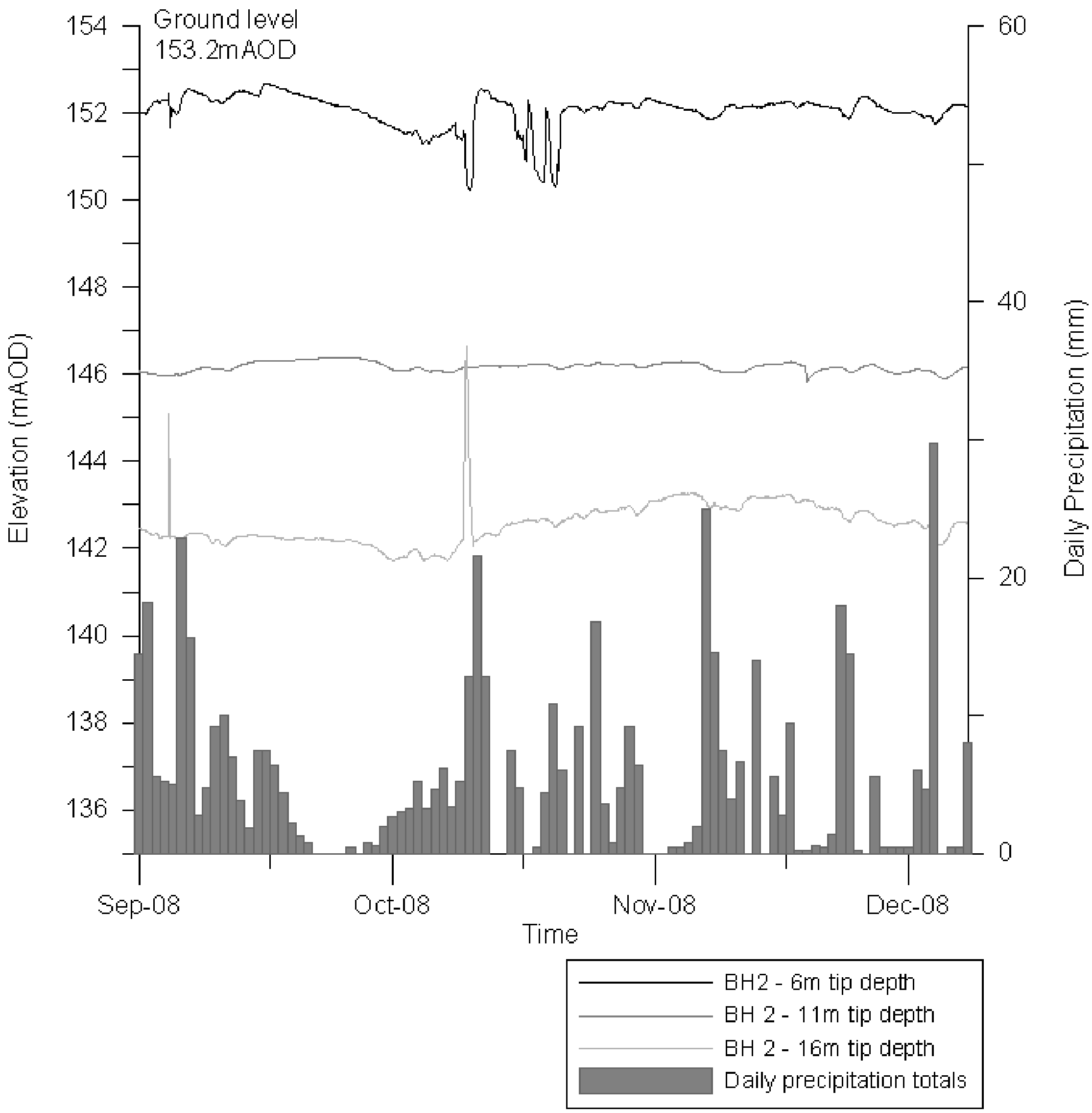
data logged on site by the nested piezometers has been plotted alongside rainfall data to investigate possible trends in the fluctuation of pore water pressure in the till. At this early stage of the project, manual dips of groundwater levels are also recorded and these show agreement with those values recorded by the VW piezometers. The graph shows pore water pressure head levels from three piezometers in BH2 and daily precipitation totals at the Tullyhappy site. The readings are a true reflection of the pore water pressures within the till but in some cases there have been problems with the reliability of the packer system and their ability to stay inflated, these initial difficulties are being resolved and the VW piezometer are continuing to log at each of the sites.

4 LABORATORY TESTING

A companion laboratory programme will evaluate whether tracking the evolution of stress within these clays from deposition through unloading during excavation and then through repeated pore pressure cycling can lead to changes in deformation (bulk) moduli or strength over time.

An attempt will be made to follow a typical stress path for an element near the toe of the slope using a reconstituted sample of the fine fraction of glacial till from one of the sites. It would be preferable to utilize undisturbed samples for this testing but given the stony nature of these tills it may not be possible to collect sufficient or adequate samples for small scale laboratory testing.

However an attempt will be made to also obtain representative samples from site and subject them to current insitu stress conditions and then take them through cyclic variation of pore water pressure. The



testing is performed using the (Bishop and Wesley 1975) stress path apparatus. Samples will be subject to extension loading whilst cycling pore water pressure. It is anticipated that changes in strength due to pore pressure cycle may be difficult to define accurately but that changes in modulus may provide some indication of the role these fluctuations may have on behaviour. Numerical modelling along a similar line as that undertaken by Potts et al. (1997) could then be used to evaluate this potential behaviour.

5 CONCLUSION

This paper introduces the research being undertaken at QUB investigating pore water pressure variations in glacial lodgement till cuttings in the North of Ireland. Three cuttings have been instrumented; Loughbrickland, Tullyhappy and Craigmore, characterisation of the geotechnical properties and hydrogeological regime has begun, monitoring of seasonal changes in pore water pressure will continue. A programme of laboratory testing and numerical modelling will investigate the possible effects of pore water pressure variations on deformation, shear strength and instability. Initial evaluation of the data shows, consistently across the three sites, attenuated and delayed pore water response with depth.

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