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An evaluation of strain softening of glacial tills as a result of pore pressure dynamics

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ABSTRACT

Deep-seated progressive failures of cuttings in heavily overconsolidated clays have been observed in the field and are well documented, especially for London Clays (Potts, Kovacevic, & Vaughan, 1997; Smethurst, Powrie, & Clarke, 2006; Take, 2003), however, the process of softening and the development of a rupture surface in other clays, including the clay fraction of glacial tills, is still to be established. Recent decades have witnessed extreme weather conditions in Northern Ireland with dry summers and wet winters. The dynamics of this pore pressure variation can trigger strength reduction and progressive plastic straining, both of which will lead to slope failure. The aim of this research is to evaluate the effect of pore pressure variations on the deformation and long-term stability of large cuttings in glacial tills in Northern Ireland. This paper outlines the overall research program and presents initial laboratory findings (Carse, 2013).

RÉSUMÉ

Des ruptures progressives et profondes dans des argiles lourdes surconsolidés ont été observées dans le site et ont bien documentées, en particulier pour les argiles de Londres (Potts, Kovacevic, et Vaughan, 1997; Smethurst, Powrie, & Clarke, 2006; Take, 2003), cependant, le processus de ramollissement et le développement d'une surface de rupture dans d'autres argiles, y compris la fraction argileuse des tills glaciaires, doivent être établis. Les dernières décennies ont été marquées par des conditions climatiques extremes en Irelande du Nord, avec des étés secs et des hivers humides. La dynamique de cette variation de la pression interstitielle peuvent déclencher la réduction des forces et des paliers plastiques progressives, conduira à une rupture de la pente. Le but de cette recherche est d'évaluer l'effet des variations de pression interstitielle sur la déformation et la stabilité à long terme de grandes coupes dans les tills glaciaires en Irlande du Nord. Ce document présente l'ensemble du programme de recherche et présente les résultats de laboratoire initiales (Carse, 2013).

1 INTRODUCTION

Northern Ireland has approximately 25,000km of road network which encompass a substantial number of large cuttings in glacial till. Slope failures lead to disruption to transport routes and incur significant financial resources.

A potential failure mechanism for these large cuttings is the progressive failure generally attributed to pore pressure dynamics. (Sivakumar, Hughes, Clarke, & Glynn, 2007). This can be a deep-seated progressive failure, which is common in stiff overconsolidated clays, or near surface progressive failures, with a maximum failure plane depth of 4m below ground level (Hutchinson, Prior, & Stephens, 1974), which are typical of the debris flows along the North Antrim Coast Road, Northern Ireland. These pore-pressure dynamics have been shown to be driven by seasonal dynamics in recharge associated with the near surface water balance.

A second paper has been submitted to the conference (Lynch, Bell et al. 2013) which outlines the site characterisation and geotechnical/climate monitoring methods implemented by Queen’s University Belfast, and Roads Service NI. The research sites have been identified by Queen’s University Belfast, Roads Service NI and Northern Ireland Rail as potential risks and important research opportunities.

This paper aims to outline how this data will be used alongside a companion laboratory programme and numerical modelling tools to evaluate the effect of cyclic pore water pressures on shear strength and stiffness reduction, using a modified elasto-viscoplastic constitutive soil model to capture time effects in GeoStudio, as outlined by Burland (Figure 1).

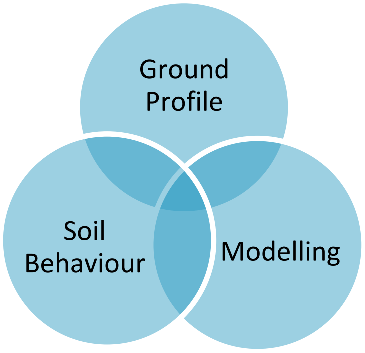

Figure 1: Burland Triangle

Seasonal changes result in various weather patterns causing cycles in pore water pressure in slopes. These pore pressure variations cause the soil to undergo volumetric cycles of swelling and shrinkage. This cyclic action results in a build-up of progressive plastic strains, which will eventually lead to softening of the soil.

This softening action will result in the mechanism of progressive failure through a reduction in the long-term shear strength. The stability of a slope depends on the shear strength, and so it can be postulated that a change in strength over time is a function of pore pressure dynamics, i.e. a function of climate. This is the sequence of events the study is based upon.

2 RESEARCH SITES

A deep cutting in glacial till on the A1 Belfast-Newry dual carriageway, Loughbrickland in Northern Ireland, was chosen as the primary site for this research. This is due to a sequence of slope failures at Dromore starting in 1998 along the same major route. One of the factors postulated for the slope failure at Dromore was a long-term shear strength reduction due to progressive failure, strain softening and dissipation of excess pore water pressures generated during the excavation (Sivakumar et al., 2007). The research program has also been extended to a railway cutting at Craigmore with similar geology (Figure 2). All of the sites are within a 10 mile radius.

Figure 2: Location of Research Sites; Map data ©2013 Google

The two sites are cut through heavily overconsolidated glacial lodgement till and are fully instrumented to monitor pore water pressure, surface water balance, water table elevation and meteorological conditions (Figures 3 & 4).

Loughbrickland is a 25m high slope at a slope angle of approximately 26˚ which was excavated in 2004 through Drumlin topography typical to that of Northern Ireland to improve the horizontal alignment of the A1 road (Figure 3). The soil profile is composed of a weathered Greywacke overlain by a stiff glacial lodgement till (Clarke, 2007). The upper layer of till is heavily weathered so it has been illustrated by two layers in Figure 3.

During excavation flowing artesian conditions occurred at the toe of the slope, due to the upper bedrock surface acting as a confined aquifer (Carse, McLernon, Hughes, Sivakumar, & Barbour, 2009). This instability was stabilised by installing a deep toe drain to the bedrock surface. Site investigations were carried out in 1999 prior to excavation, a further investigation in 2004, and a newly instrumented cross-section in 2012-2013. The pore pressure variations on the site have been monitored since 2004 and will continue throughout this study.

The instrumentation currently installed on the site consists of Vibrating Wire Piezometers (VWP) at a variety of depths; some of the VWP are installed in the traditional standpipe, sealed with a packer in the borehole and hydraulically isolated with bentonite pellets. Others are installing directly into a cement-bentonite grout. A piezometer is on site monitoring changes in barometric pressures.

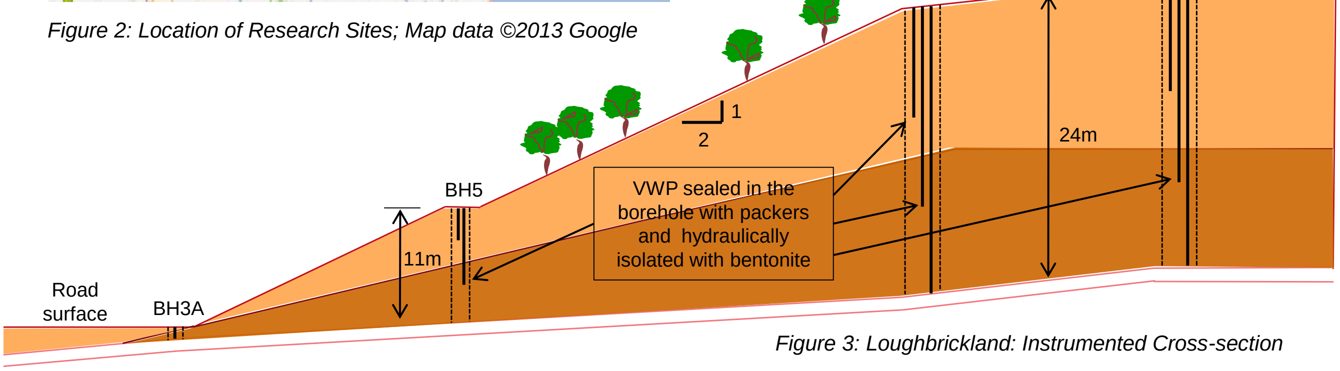

Figure 3: Loughbrickland: Instrumented Cross-section

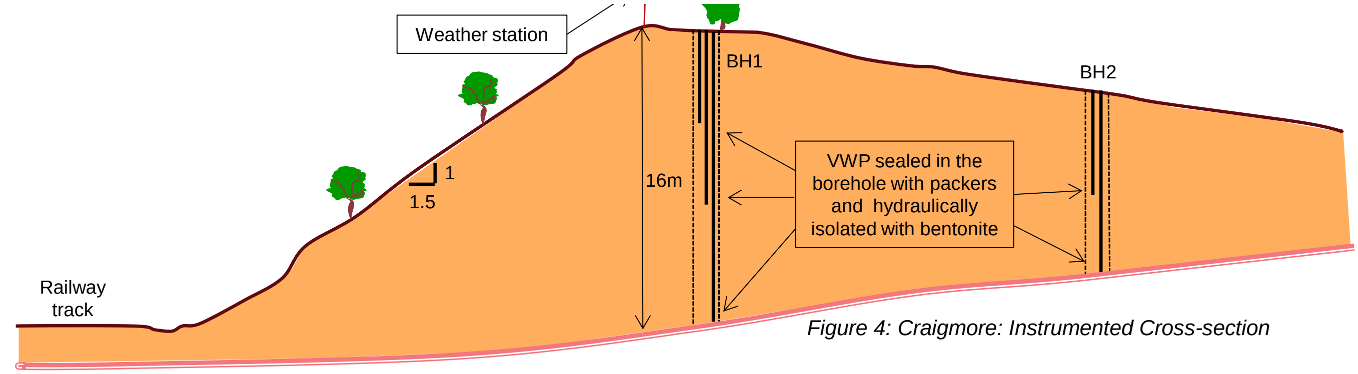

Figure 4: Craigmore: Instrumented Cross-section

Craigmore is a railway cutting which was excavated in the 1850's through heavily overconsolidated glacial till (Figure 4). It has a slope height of 17m, and a slope angle of approximately 36˚. In this case, the glacial till overlays Granodiorite, a heavily impermeable rock, which surfaces to the rear of the slope (Carse, 2013).

The instrumentation currently installed on site consists of VWP with packers in standpipes (Figure 4), an onsite weather station, and near surface Enviroscans and tensiometers.

2.1 Geotechnical Properties

The geotechnical properties of the research sites were covered in detail by previous studies (Carse et al., 2009; Clarke, 2007; McLernon, Carse, Hughes, Barbour, & Dixon, 2009) and a summary is shown below in Table 1. Particle size distribution, Atterberg limits and triaxial testing will all be repeated throughout the testing programme for Loughbrickland.

Table 1. Shear Strength data for glacial till.

Location	Loughbrickland	Craigmore
Depth (mBGL[1])	-	10.6
c' (kPa)	8-11	8
Φ' (º)	30-32	31
Φ' critical (º)		32

[1]Meters below ground level

3 FIELD MONITORING

A newly instrumented cross-section at Loughbrickland was installed in December 2012-January 2013 with three boreholes drilled to bedrock. All samples collected were disturbed, and will be reconstituted for laboratory testing. Two 10m boreholes were installed on the berm of the slope, with nested vibrating wire piezometers; one with a traditional 50mm standpipe and packer technique as implemented across the rest of the site (Carse et al., 2009), and one with an optimized cement-bentonite grout (Gustin, Karim, & Brouwers, 2007; Mikkelsen & Green, 2003) to improve the accuracy of the data acquisition.

The optimized mix for this geotechnical application has a water/binder ratio of 0.60 and 5% bentonite. The insitu performance of the response time of piezometers to changes in pore water pressure of the parent soil, in this case glacial till, is under investigation. The optimized mix underwent rigorous rheological and strength testing (Sonebi, Hughes, Harley, & Lynch, 2012).

The new cross-section has three boreholes: two for comparing the installation techniques, and one measuring pore water pressure at varying depths from the top of the slope. An additional borehole will be installed to bedrock at the top of the slope to investigate the under-draining of the bedrock created by the toe drain.

Operational strain levels in geotechnical structures are very small, so knowledge of the stiffness at this strain level is important in geotechnical modelling and design. Matthews, Clayton et al. (2000) has shown that laboratory stiffness levels are similar to field seismic measurements; this will be investigated through seismic resistivity surveys and barometric efficient theory (Carse, 2013).

4 LABORATORY INVESTIGATION

The laboratory investigation will primarily focus on progressive straining and strength reduction caused by pore water pressure dynamics. The testing will be carried out on reconstituted overconsolidated samples as extracting undisturbed samples from glacial till is not practical; the samples will be made up of the fine fraction of glacial till (<5mm).

The stress regime within a slope is complex with different principle stress directions at the top and bottom of slope as shown in Figure 5.

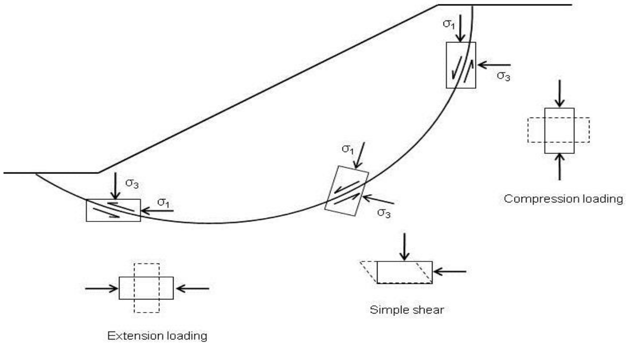

Figure 5: Principle Stresses in a Slope

The laboratory investigation will attempt to replicate these stress conditions and the samples will be subjected to cyclic pore water pressure variation (up to 10^3). The testing will be carried out in a stress path cell with internal radial and vertical strain gauges. The course of investigation is planned in order to answer two key aspects: (a) reduction on strength and (b) progressive deformation with time.

4.1 Initial Findings

A preliminary study has been carried out replicating the development of plastic strains using a strain-controlled triaxial apparatus with cyclic effective stress loading. These initial findings have been modelled in GeoStudio SIGMA/W using an elasto-plastic constitutive soil model.

Some initial observation (Carse, 2013) is illustrated in Figure 6. The plot is of a sample of glacial till under a confined load with no change in deviator stress resulting in an increase in shear strain. This clearly shows that progressive deformation is of a concern given the development of shear strain under a constant deviator stress. The progressive plastic strain build-up is shown in both (a) compression, and (b) extension tests, representing the stress state at the top and bottom of the cutting.

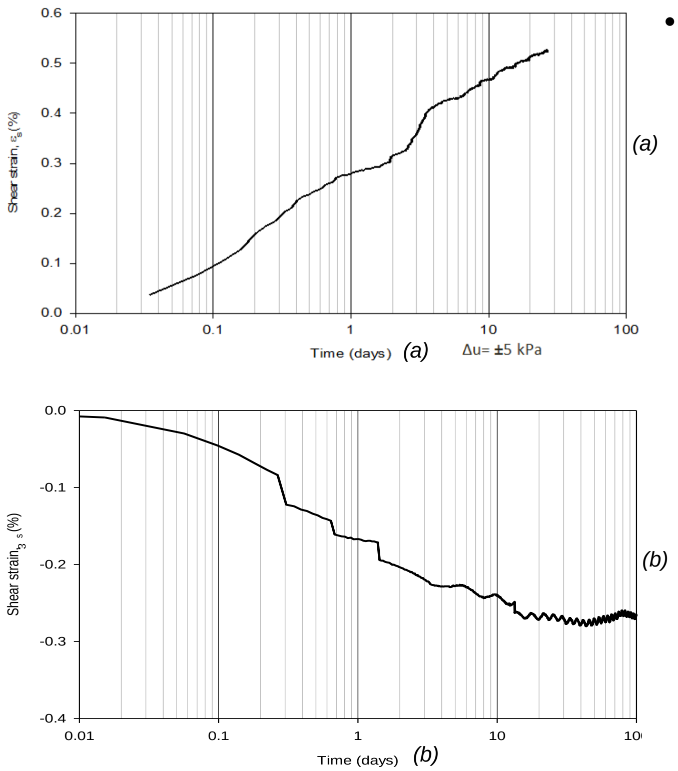

Figure 6: Build up of progressive strains with Δq=0 (a) compressive loading, (b) extension loading

4.2 Laboratory Programme

The following approach will be adopted in order to answer the two key aspects (reduction in strength and progressive deformation with time):

- Establish pore pressure cycle rate, and rate of loading under isotropic confining pressures.
- Trial filter strips in order to accelerate the consolidation process (Mackinnon, Sivakumar, Cairns, & Zaini, 2010).
    - Carry out a fully drained control test, where Δu=0, to assess as to whether or not there is a build-up of progressive strains.
- Establish failure envelope and critical state line (CSL) for the reconstituted samples under compression and extension loading. Use a stress-controlled system to define the peak strength, and a strain-controlled system to define the residual strength (Figure 7).
- Each sample will undergo a typical stress path for an element near the toe of the slope (extension) or an element at the top of the slope (compression) as outlined in Figure 7. The sample will be taken to 90% of the peak shear strength, and the pore pressure will be subjected to a pore pressure variation. The stress path cell will be stress-controlled until the sample reaches peak, and will switch to strain-controlled for the duration of the test until it reaches a residual value (Figure 8). These two systems will be used to observe the progressive strain build up.
- Another system will be used to monitor strength reduction, and stiffness reduction by installing bender elements in the sample (Dyvik & Madshus, 1985).
- As shown in Figure 8, the cycling will initially be taken from 90% of the peak strength. With the given time restraints, if possible, an investigation will also be carried out to determine the effects of subjecting the sample to pore pressure variations post peak.

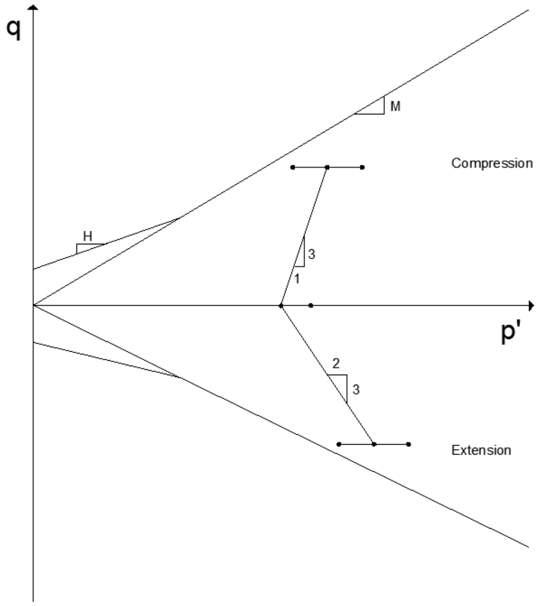

Figure 7: Critical state envelopes, and stress paths to be followed during testing

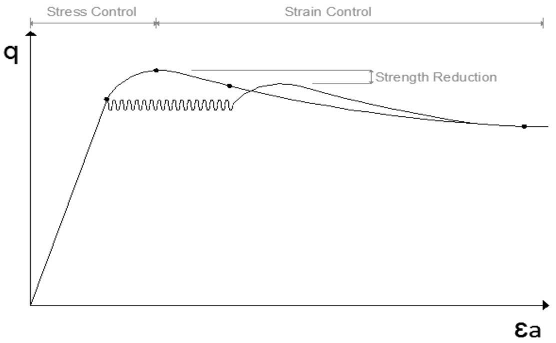

Figure 8: Stress path to be followed showing possible strength reduction

The testing will be carried out on the fine fraction of glacial till. This is based upon the assumption that a rupture surface will develop through the clay content, as it is more susceptible to failure. The grain size distribution from Loughbrickland is well graded with some granular matrix (Carse et al., 2009). The removal of particles > 5mm will also have an effect on the overall water content of the soil sample.

5 NUMERICAL MODELLING

A site model will be established in GeoStudio's SIGMA/W which has been modified in the form of an elasto-viscoplastic constitutive model for foundations (Kelln, Sharma, Hughes, & Graham, 2009). This research will attempt to extend this model to slope stability analysis, incorporating time effects on strength caused by the pore pressure dynamics.

5.1 Elasto-plastic model

Previous work by Carse, 2013 has been modelled in GeoStudio SIGMA/W, as a coupled transient seepage model using an elasto-plastic constitutive soil model. Elasto-plastic constitutive soil models, such as the modified Cam Clay model commonly used in critical state soil mechanics, does not change with time. This model is based upon the assumption that soil deforms as a continuum, with an instantaneous development of irrecoverable plastic strains.

This time-independent development of plastic strains is inconsistent with the observed time-dependent stress-strain behaviours of clays (e.g. Cassagrade and Wilson, 1951; Tavenas et al. 1978). In order to understand the development of progressive plastic strains, the use of a time-independent elasto-plastic model, such as the modified Cam clay model, is inadequate in describing the stress-strain behaviour of such soils. This time-dependent (viscous) behaviour is evident in the loading-rate dependency of undrained shear strengths and preconsolidation pressures, i.e. the size of the yield surface (Kelln, Sharma, Hughes, & Graham, 2008).

5.2 Elasto-viscoplastic model

An improved elasto-viscoplastic (EVP) framework for modelling time-dependent behaviour of soils (Kelln et al., 2009) will be used. The viscoplastic straining mechanism is simply the continuous readjustment of particle contacts with time. A soil under constant effective stress, with pore pressure equilibrium will still undergo progressive plastic strains, as shown in Figure 6.

Using this improved EVP model will allow the model to capture the concept of soil particles restructuring with time. This time induced change in strength will be accelerated by pore-pressure fluctuations associated with variable climatic conditions, including the anticipated increasing frequency of extreme events.

The modified model will be initially calibrated against the laboratory scenario where the boundary conditions are clearly defined. This will then be extended to the full scale field application (Figure 9).

6 CONCLUSION

This paper introduces the research being undertaken at Queen's University Belfast into the effect of pore pressure dynamics on glacial tills in Northern Ireland.

The three strands of study as outlined will lead to a more accurate method of predicting progressive failure in glacial tills. The laboratory programme and numerical model will investigate the effect of pore pressure variations across the two research sites on deformation, reduction in shear strength and stiffness, thus soil instabilities.

This will aid Roads Service NI and Northern Ireland Railway in managing their geotechnical risks, allowing them to take remedial action when necessary.

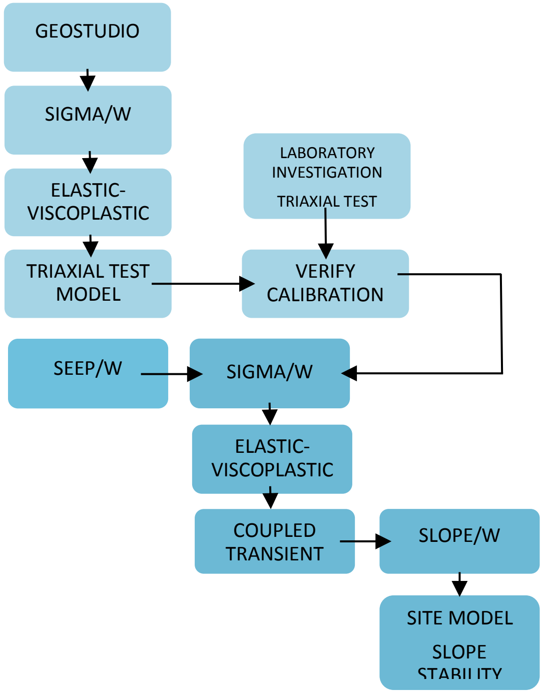

Figure 9: Finite Element Modelling Regime

7 ACKNOWLEDGEMENTS

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9 NOMENCLATURE

c'	Effective Cohesion
Φ'	Effective Angle of Internal Friction
Φ'crit	Effective Angle of Internal Friction (critical)
σ'_1	Vertical Principle Effective Stress
σ'_3	Lateral Principle Effective Stress
ε_s or ε_a	Shear Strain
q	Deviator Load
u	Pore water Pressure
M	Gradient of Critical State Line in q:p'