Effect of vegetation on the long-term stability of road and rail cuttings in glacial tills

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ABSTRACT
There has been a rapid expansion of transportation infrastructure within Northern Ireland, much of it involving the excavation of large cut slopes in glacial till associated with motorway expansion, widening or alignment improvements. The long-term performance of these cuttings in glacial till is not well understood as highlighted by several slope failures within these cuttings over the past few years. Given the known issues of time dependent instability of overconsolidated clay slopes and more recent concerns over the influence of climate change on infrastructure performance it is important to develop an understanding of the mechanisms controlling the short term and long term stability of these slopes with a view to improving methods of design, construction as well as performance monitoring.

RESUME
Il y avait un développement rapide des infrastructures de transport dans l'Irlande du Nord, dont plusieurs comprenait de large excavation des taillements des pentes dans des argiles glacials associé avec l'expansion des autoroutes, élargissement ou amélioration des alignements. La performance à longue terme de ces coupures dans les argiles glacials n'est pas bien comprise comme a été démontré par plusieurs rupture des pentes entre ces taillements durant les années passées. Etant donné l'incertitude de l'instabilité dans le temps des pentes d'argile sur-compactée et l'importance de l'influence du changement de climat sur la performance des infrastructures, il est important de développer une connaissance des mécanismes qui contrôlent la stabilité à court terme et à longue terme de ces pentes dans le but d'améliorer les méthodes de design, de construction et de suivi de performance.

1 INTRODUCTION

A series of slope failures in cuttings in glacial till in the North of Ireland over the past 15 years has generated increased interest in identifying the mechanisms responsible for these instabilities. The 1999 failure of a cut slope along the A1 motorway at Dromore, in County Down some 30 years after its construction was of particular concern (Hughes, Sivakumar et al. 2007). This failure appeared to be due to a combination of strain softening, weathering, the existence of a relict slip plane and dissipation of pore water pressure.

More recently, a large new cut slope on a similar Drumlin formation constructed near Loughbrickland, County Down has allowed the role of hydrogeologic controls on stability to be explored in more detail. Monitoring and numerical modelling of pore-pressure dynamics suggested that the slope was of marginal stability and susceptible to seasonal or inter-annual variations in pore-pressure (Clarke 2007).

This paper describes ongoing research associated with the stability of cuttings in glacial till in Northern Ireland as part of a collaborative study with a large, multi-university group under the title of CLIFFS (Climate impact forecasting for slopes). CLIFF*S* is an EPSRC-funded network based at Loughborough University which brings together academics, government agencies, stakeholders, consultants and climate specialists to improve our ability to assess the role of climate change on the frequency of slope instability (Dixon, Dijkstra et al. 2006).

Previous CLIFFS research involved the monitoring of a clay cutting in a London Clay (Smethurst, Clarke et al. 2006). In order to evaluate the role of surface water balance fluctuations on seasonal fluctuations in pore water pressures in the till, near surface moisture content changes were used along with meteorological data to construct a water balance for the site. Suction measurements were used to evaluate the extent of near surface pressure fluctuations induced by summer transpiration of vegetation. It was anticipated that seasonal fluctuations in pore-pressure induced by climate variability might lead to repeated volume change within the clay that would contribute to strain softening and progressive failure.

Further work has also been carried out by Mott MacDonald on the relationship between climate and vegetation on railway embankments (Scott, Loveridge et al. 2007). These embankments were constructed by end tipping high plasticity clay fill and have experienced considerable seasonal deformation which has been detrimental to the performance of railway lines. A parallel study carried out between a heavily vegetated and a grass embankment noted that large suctions were generated within the vegetated slope during the summer time. These suctions were sufficient to maintain low pore pressures even over the winter period. Subsequent modelling demonstrated that this provided enhanced stability, although the vegetated slope is likely to pose serviceability problems associated with volume change arising from shrink swell cycles.

There has been little investigation into the effects of seasonal fluctuations in near surface suctions on pore pressure response in glacial tills in N. Ireland. The opportunity to investigate this further has arisen due to the ongoing monitoring of the Loughbrickland cutting and the addition of two additional instrumented sites for long-term monitoring by the rail and road authorities.

The research described in this paper is being undertaken in parallel with that described by Carse et al. (2009) at this conference. In order to minimize repetition readers are encouraged to review both papers simultaneously in order to obtain a full picture of the full research program. The work by Carse et al. (2009) will focus on the role of cyclical pore water pressures on the potential for slope deformation and/or strain softening within these same glacial till slopes.

1.1 UKCP09 Future Climate predictions

The fifth generation of UK climate change scenarios will be introduced in 2009 as part of UKCP09. These scenarios describe how the climate of the UK might change during the 21st century and is an update on the previous UKCIP02, which contained different climate change scenarios, based on low, medium and high emissions (Hulme, Jenkins et al. 2002). Current predictions from UKCIP02 show that N. Ireland will experience a change in precipitation by 2080 which includes a reduction in summer precipitation of between 15 to 30% for the low emission scenarios and 30 to 45% for high emission scenarios. Less dramatic but still significant are the winter changes; a 0 to 15% increase in precipitation for the low emission scenario to 15 to 30% for the high emission case Furthermore temperature is expected to rise by as much as 2.8% for the region.

The general change to warmer drier summers and wetter winters, coupled with the increase in extreme rainfall events will likely lead to changes in near surface pore pressures which are seasonally greater than they are now. If the current environmentally driven changes in pore pressure are influencing long-term slope stability then it is inevitable that climate change will only accentuate this problem. Quantifying the risks related to these changes in climate is the key overarching goal of the current research.

2 SITE CHARACTERISATION / STUDY AREAS

The three sites studied in this research are all located in Drumlin swarms in Counties Down and Armagh, N. Ireland (Figure 1). Two of these are road cuttings (Loughbrickland and Tullyhappy) along major arterial roads and one (Craigmore) is along the main railway line from Belfast to Dublin. The Loughbrickland site is a large cutting constructed along the A1 in 2004 and studied by Clarke (2007). It is considered to be of marginal stability, with recommendations for further monitoring. The second road cutting is at Tullyhappy along the A28 Armagh road. This cutting was constructed in the 1970's, and is approximately 12m in height from base to crest cut at a slope of 27°. The third cutting is a railway cutting along the Belfast to Dublin route constructed in the 1850's, and is approximately 17m high with a slope of 35°. Both the cuttings at Craigmore and Tullyhappy are showing signs of instability with bent trees and some surficial failures.

Figure 1. Site locations in the North of Ireland (Google Maps 2009)

It is in the interest of Road and Railway authorities that these sites be monitored over a number of annual climatic cycles in order to observe the response of both deep pore water and near surface moisture to climate and meteorological conditions. Calibrated models of these annual cycles are being developed so that the potential impact of changes in the hydrogeologic regime or climatic conditions can be evaluated to assess long-term performance and the need for remedial measures to ensure long-term stability.

2.1 Geology of the region

The geology and hydrogeology of N. Ireland varies widely over a relatively small area. The most important geologic units associated with this study are the Moinian to the Quaternary periods.

2.1.1 Pre-Quaternary (bedrock) Geology

The geology in the area of the research sites contains Ordovician to Silurian rocks. The area is of the Southern Uplands-Down-Longford Terrane and many younger intrusive complexes can be seen within it. This region is constructed of Lower Paleozoic marine sedimentary rocks with widespread folding and faulting observed within them. One such intrusion in this region is that of the Newry Igneous Complex, a Grandiorite rock emplaced in Silurian greywacke and mudstone.

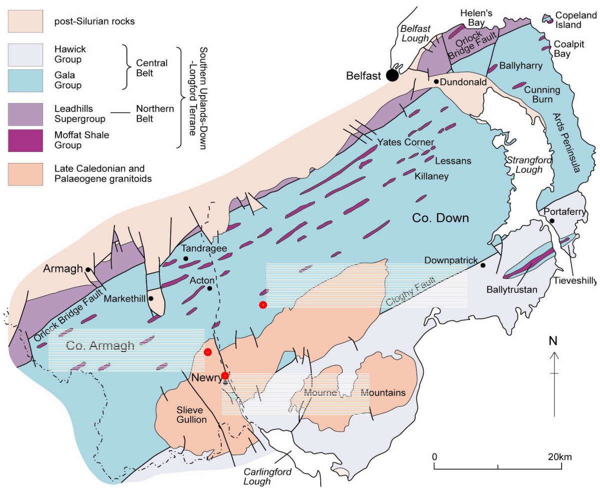


Figure 2. The Southern Uplands-Down-Longford Terrane In N. Ireland (The Geological Survey of Northern Ireland 2004)

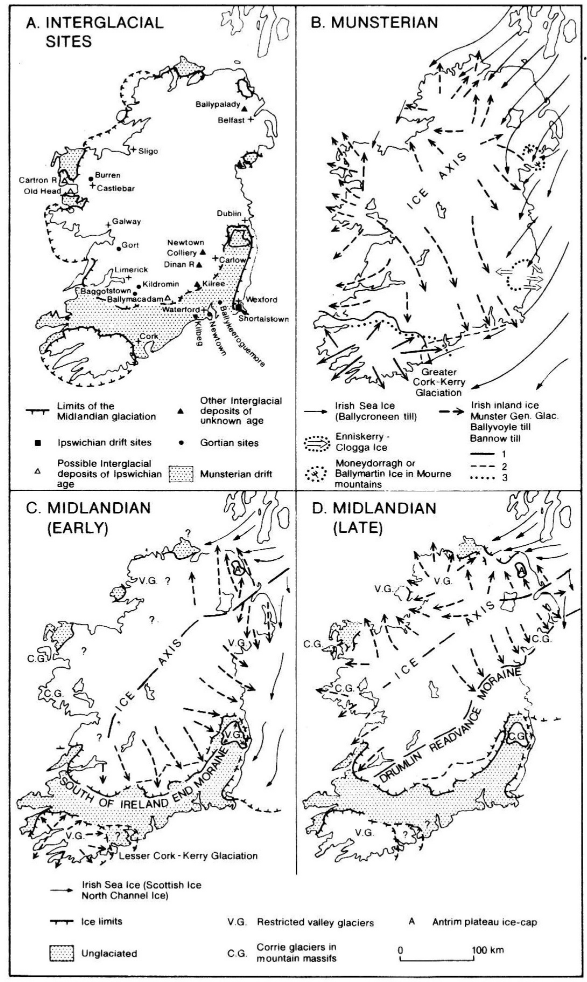
The bedrock at Loughbrickland and Tullyhappy is Silurian shale of the gala group, a largely fissured rock (Figure 2). The Craigmore site lies within the Newry Igneous Complex and therefore is a Granodiorite igneous rock of late Palaeozoic era, an impermeable hard granite rock weathered at the surface where the till has been deposited. (GSNI 2004)

2.1.2 Pre-Quaternary (drift) Geology

As can be seen from Figure 3 there have been various stages of glaciation in Ireland, and hence variation in the genesis of the tills. The glacial deposits associated with the research sites are all comprised of Late Midlandian till deposited by ice that moved south-west from a Scottish source and southwards across the area from the Lough Neagh basin. This ice flow is reflected in the numerous Drumlins that dominate the topography of the area.

The lodgement till in these landscapes was likely formed by frictional resistance between the existing bedrock and the glacial bed. These glacial sediments can vary greatly in thickness from a few meters to upwards of 25m (Doran 1992). The tills covering each of the research sites is that of lodgement or glacial till commonly known as boulder clay. This soil is an over-consolidated material consisting of frequent boulders originating from the underlying bedrock.

2.2 Site Investigation



The site investigation and the results of laboratory tests undertaken at Queen’s University Belfast (QUB) on recovered samples confirmed both the expected bedrock and drift geology at each of the sites.

A review of the geotechnical properties of these units is provided in the companion paper by (Carse, McLernon et al. 2009).

3 HYDROGEOLOGY AND MODELLING

3.1 Site Instrumentation

As outlined in the companion paper by Carse et al. (2009), each of the three research sites are being monitored currently using nested vibrating wire piezometers, installed with packers to improve response time of the instrumentation. In order to further explore the role of environmental factors (e.g. climate and vegetation) on pore pressure fluctuations within these cuttings, the sites will be further instrumented to gather profiles of water content at various slope positions along with shallow water table monitoring and meteorological monitoring. A Frequency Domain Reflectometry (FDR) system (EnviroSCAN/Diviner 2000) will be used to monitor near surface water contents and will be used along with monitored meteorological conditions to establish a surface water balance for each site.

It is planned to use meteorological data along with moisture content and water table monitoring to develop a water balance model for each site. This model can then integrated with the hydrogeologic models to evaluate the controls on pore pressure fluctuations with time throughout the cuttings under various climatic and hydrogeologic conditions.

It is anticipated that once a calibrated model is developed it will be integrated with models of stability and stress/strain analyses in order to evaluate both the stability of the slope and the possibility of strain-softening over the longer term.

3.2 Seepage and Stability monitoring

Each of the three sites in this study have a similar geologic framework; however each site has its own unique hydrogeological regime. Conceptual and numerical models of the hydrogeologic regime at each site were previously modelled as part of an MEng thesis conducted by (Hughes, McLernon et al. 2008a, Hughes, McLernon et al. 2008b).

The primary objective of this study is to establish the primary controls on pore-pressure fluctuations within the till cuttings over time. The two sources of these fluctuations are the deep underlying hydrogeologic regime formed along the till/bedrock interface and the water table fluctuations created by environmental factors (e.g. precipitation/evapotranspiration). Once the general causes of these processes are more fully understood the potential implication of climatic change, and/or changes in site specific hydrogeologic or environmental conditions on the long-term deformation and stability of these slopes can be evaluated.

Figure 4 outlines the pore water pressure distributions observed at each of the sites compared to modelled values. The key to effective modelling of the sites in future will be matching the modelled to the observed head profiles. To date only the Loughbrickland site has had comprehensive investigation thus the trend between observed pressures and those modelled are similar.

Seep/W will be used to model a steady state condition (Geoslope International 2003a). The main boundary conditions for each of the sites are a representative head at the toe of each of the cuttings or where ponding is observed on site and along the upper surface a flux boundary condition based on net infiltration rates typical of the region, including the effects of evapotranspiration from vegetation and surface run-off(30 – 70mm/year). Any other boundaries are no flow. Each of models are similar with some form of bedrock (more permeable) at the base, with Glacial till (less permeable) overlain. Once a seepage regime is established that simulates the measured field pore pressure response, the model is coupled with a Slope/W stability analysis to derive a factor of safety for each of the sites.

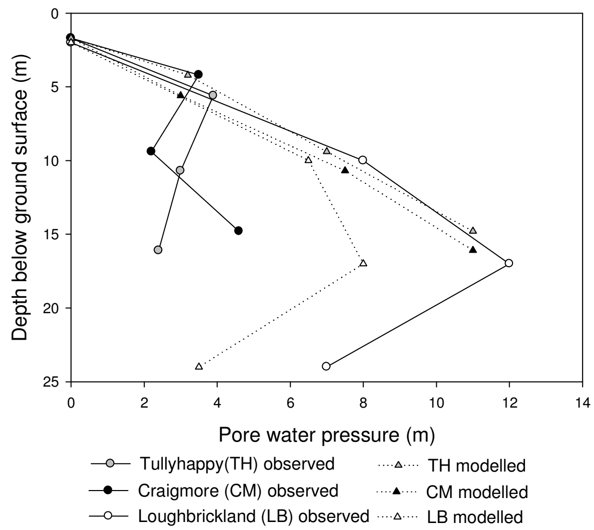


Table 1 Soil strength and hydraulic conductivity used in seepage and stability models for the three study sites

Property	Tullyhappy/ Craigmore	Loughbrickland
c' (kPa)	8	8 - 11
φ'(°)	32	30 - 32
Unit weight (kN/m^2)	20	20
Ksat (m/s) (Till)	7x10^{-9}	7x10^{-9} – 5x10^{-10}
Ksat (m/s) (Bedrock)	1x10^{-7}- 2x10^{-8}	1.2x10^{-6}

Preliminary modelling of the hydrogeologic regimes and the associated stability of the three cuttings is presented in this paper based on the initial site characterization, and existing field and laboratory measurements. Some of the soil parameters have been chosen based on previous work at Loughbrickland (Clarke 2007) along with initial laboratory strength tests for Tullyhappy and Craigmore sites. Only limited initial insitu tests of hydraulic conductivity have been carried out at the Craigmore site, consequently, assumed values of hydraulic conductivity will be selected based on the soil description and texture in comparison to the existing data for the tills at Loughbrickland. The properties of the weathered bedrock surface at Tullyhappy are similar to those at Loughbrickland so the value of Ksat utilized in the Loughbrickland modelling will also be used for the Tullyhappy site. The bedrock at the Craigmore site is from a different outcrop of relatively impermeable granite and will be assumed to be a lower flow boundary in the modelling. Table 1 summarises both the strength and hydraulic conductivity values used in the preliminary models. The strength parameters have been established from initial Undrained Isotropic Consolidation tests and permeability derived from previous work by Clarke (2007).

3.2.1 Craigmore rail cutting

The Craigmore railway cutting is somewhat unusual in its cross-section as it has a water table, often at surface at the back ofthe slope. This condition is most likely due to shallow bedrock which daylights in the field to the rear of the slope. The general flow regime for this site is illustrated in the results from the steady state seepage model shown in Figure5 (a)i. and was developed using a head boundary condition as observed by ponding along the right side of the model, a zero flux boundary at the base of the model and a net infiltration rate of approximately 40mm/year applied across the top of the till surface.

The general trend is that the top of the cutting acts as a groundwater divide leading to discharge both at the toe of the cutting and to the lowland to the west of the cutting. This is consistent with the presence of an observed seepage face on the face of the cutting and ponding in the field to the rear of the slope. The orientation of the bedrock is such that it would promote a predominant flow toward the face of the cutting.

Initial slope/W analysis produced a factor of safety ranging from 0.8 to 0.9 based on high and low water table scenarios as observed in the field and assuming the shear strength values outlined in Table 1. These low factors of safety are not surprising given the steepness and height of the cutting. Observed failures at the site are similar in geometry to the critical slip surface shown in Figure 5(a)ii.

3.2.2 Tullyhappy road cutting

The topography of the Tullyhappy site continues to rise beyond the crest of the cutting (Figure 5 (b). The bedrock surface at this site is also dipped at a skewed angle from the slope suggesting that a two dimensional representation of the groundwater flow system might be quite approximate. Further geophysical site investigations are planned to try to establish a more detailed description of this interface.

In spite of this limitation, the modelling highlights the strong control provided by the cutting geometry and the presence of the underlying bedrock interface on groundwater flow.

Initial slope/W analysis produced a factor of safety ranging from 1.1 to 1.3 based on high and low water table scenarios as observed in the field. The results are in broad agreement in that only some signs of distress, such as bent trees and shallow failures, have been observed to date.

3.3 Loughbrickland road cutting

The Loughbrickland site, as characterized in previous research by Clarke (2007), is composed of two layers of till with significantly different values of hydraulic conductivity. The layering of an upper and lower till is often typical in Irish drumlin formation. The water shed divide at the top of the hill is also used as a watershed divide boundary with an annual average recharge of 45mm/year applied to the upper surface with the allowance for a free surface to develop anywhere along the slope.

Monitoring of this site was undertaken prior, during and after cut excavation and led to a number of interesting observations. Flowing artesian conditions developed at the toe of the slope during the last stages of construction as the excavation approached its final depth and this led to a shallow slip and softening of the excavation base. This situation was remediated through the construction of a deep toe granular trench drain right to the bedrock surface, allowing the bedrock aquifer to dewater. With this in mind the site has been modelled with and without the presence of the deep toe drain installed to establish a factor of safety for the slope and consider the implications of the drainage failing.

As with the Tullyhappy site, Figure 5(c) shows that all recharge moves laterally within the upper till, vertically downward across the lower till which has a lower hydraulic conductivity, and then laterally within the permeable bedrock surface.

When the toe drainage is operative, the critical slip surface tends to move into the upper till where lateral flow within this layer leads to discharge to the slope face. When the toe drain is inoperative the pore-pressures within the bedrock aquifer rise and the critical failure surface moves towards the base of the cutting within the lower till.

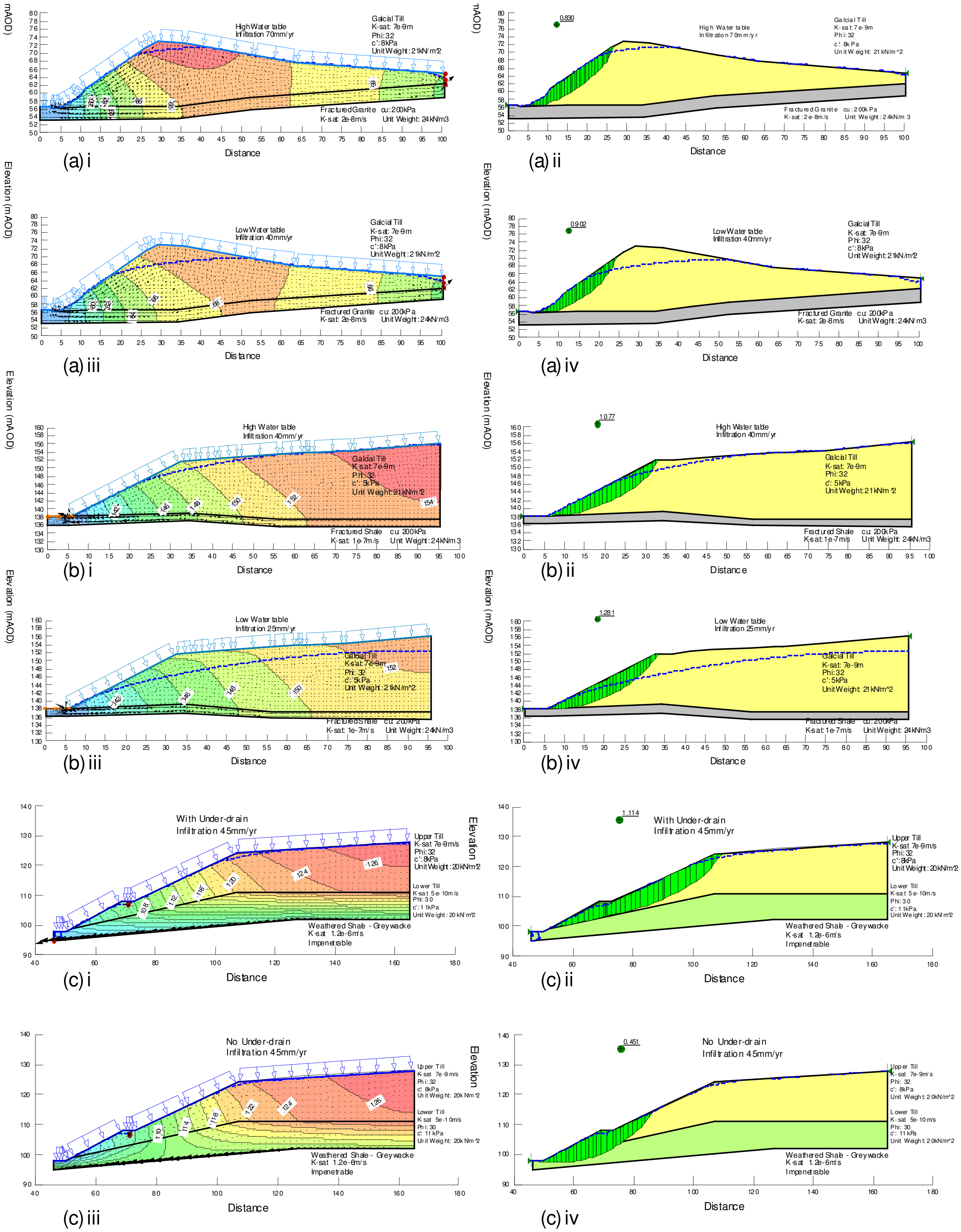
The process of modelling the sites has been useful to highlight the complexities in each of the 3 research sites with each being unique. In order to more fully understand the behaviour of the sites additional testing both laboratory based and insitu will be required. These will hopefully enhance the modelling process making thereby allowing better assessments of cuttings to be made.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The subject of this paper was to outline the research that is being undertaken in the North of Ireland into cuttings in glacial tills. It is widely agreed that there is much scope for further research into the behaviour of this complex variable material.

The modelling process coupled with observed readings from previous and current monitoring show that there is much to understand about the interaction of topography, geology on the hydrogeologic system and subsequent distribution of pore water pressure and slope stability.

In order to more fully understand the links between near surface moisture the role of vegetation and deeper pore water pressure, shallow standpipes coupled with automated FDR readings in the near surface will be used. Further in situ testing will include the use of pump/ falling head tests, infiltrometer testing and validation of groundwater vulnerability mapping. This data along with meteorological data that will be collected on-site will help to build a water balance model and in turn a better picture of the hydrogeologic processes in glacial till and the implications of climate change.



High Water table
Infiltration 70mm/yr
Galcial Till
K-sat: 7e-9m
Phi:32
c':8kPa
Unit Weight:21kN/m^2
Fractured Granite cu:200kPa
K-sat: 2e-8m/s Unit Weight: 24kN/m3
Low Water table
Infiltration 40mm/yr
High Water table
Infiltration 40mm/yr
Fractured Shale cu: 200kPa
K-sat: 1e-7m/s Unit Weight: 24kN/m3
Low Water table
Infiltration 25mm/yr
With Under-drain
Infiltration 45mm/yr
No Under-drain
Infiltration 45mm/yr
Upper Till
K-sat 7e-9m/s
Phi:32
c':8kPa
Unit Weight:20kN/m^2
Lower Till
K-sat 5e-10m/s
Phi:30
c':11kPa
Weathered Shale - Greywacke
K-sat 1.2e-6m/s
Impenetrable
0.830
0.902
1.077
1.281
1.114
0.451
Elevation (mAOD)
Distance
(a) i
(a) ii
(a) iii
(a) iv
(b) i
(b) ii
(b) iii
(b) iv
(c) i
(c) ii
(c) iii
(c) iv

ACKNOWLEDGEMENTS

The authors would like to thank the Department of Regional Development, Roads Service (John Irvine) and Northern Ireland Railways (Mark Atkinson) for their funding and support of the research projects. Further thanks are extended to the Geotechnical Society of Ireland Trust Fund for their additional sponsorship of the research.

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