The impact of hydrogeology on the instability of a road cutting through a drumlin in the North of Ireland

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Abstract

This paper describes the hydrogeological processes which caused unexpected instability and quick conditions during the excavation of a 25m deep cutting through a drumlin in County Down, Northern Ireland. A conceptual hydrogeological model of the cutting, based on pore pressures monitored during and after the excavation demonstrates how quick conditions at the toe of the cutting caused liquefaction of the till. Stability of the cutting was re-established by draining the highly permeable, weathered Greywacke which underlies the drumlin, through the use of a deep toe drain. In spite of this drainage, the cutting was only marginally stable due to the presence of a low permeability zone in the till above the bedrock which limits the reduction of elevated pore pressures within the upper to mid-depths of the drumlin. The factor of safety has been further improved by the addition of vertical relief drains at the crest and berm of the cutting to relieve the pore-pressures within the upper till by intercepting the weathered bedrock. The paper also highlights the importance of carrying out an adequate site investigation compliant with Eurocode 7 and additional monitoring in excavations in stiff, low permeability till.

Keywords

Geotechnical Engineering; Roads and Highways; Site Investigation.

1.0 Introduction

There are few documented case studies which have explored the nature of the hydrogeology of drumlin swarms in Northern Ireland, fewer still that have directly illustrated the importance of these hydrogeological systems to the geotechnical performance of the civil infrastructure, such as road and rail cuttings. This unique case history highlights the critical importance for geotechnical engineers to fully understand the hydrogeology within drumlins and the impact it may have on the geotechnical performance. This case study describes the conditions encountered in a large (25m high) excavation, through a drumlin formed in lodgement till near Loughbrickland, Northern Ireland in 2004. It tracks the hydrogeological behaviour from the start of excavation, through the onset of flowing artesian conditions (which led to quick conditions at the toe of the slope), to the subsequent stabilisation of the excavation using drainage.

There have been few opportunities to examine in detail the stability of large cuttings in till slopes in Ireland, as most alignment designs have avoided the creation of large cut or fill slopes. However, recent efforts to improve road alignments on existing carriageways have required larger earthworks. The stability of these large cuttings in Northern Ireland have generally been assessed by characterisation of the geotechnical and geological properties within a series of borings aligned with the proposed carriageway and applying generalised slope stability criteria without detailed consideration of the site specific hydrogeology. The Loughbrickland cutting was designed using this standard approach; however, in this case, what appeared to be a simple excavation, through an essentially stiff and ‘dry’ till was almost compromised, and certainly made more difficult, by a flow regime generated during construction which led to the development of ‘quick’ conditions and a toe failure.

The objectives of this paper are to characterise the hydrogeology of a large drumlin in Northern Ireland, and to illustrate how the hydrogeological conditions, combined with the construction sequence, led to elevated pore-pressures and upward gradients within the toe of the cutting, which eventually led to quick conditions at the base of the excavation and instability of the slope. The paper also states the required remedial measures which were implemented to provide sufficient stability.

1.1 Hydrogeology of drumlins

Little previous work has been carried out on characterising the groundwater flow through drumlins in Ireland using field data. Fitzsimons and Misstear (2006) highlight the importance of developing a conceptual understanding of the influence of geology on recharge mechanisms and recharge rates in tills. Using a soil moisture budget with a one-dimensional numerical model, Fitzsimons and Misstear (2006) verified that the most important factor controlling the recharge coefficient is the hydraulic conductivity of the till. These investigations are however literature studies with sensitivity analyses of soil moisture budget parameters and of hypothetical scenarios of till properties and hydraulic gradients with little field data available.

Fissuring in till has also been recognised as having a fundamental influence on soil properties such as the hydraulic conductivity which will then affect the hydrogeology of drumlins. McGown has published a number of papers (McGown & Radwan, 1974; McGown *et al.*, 1974; McGown & Radwan, 1975) which show that fissuring present in Scottish deformation tills led to preferential flow of water through the fissures. Hanranhan (1977) has also observed fissures in Irish till, and an investigation into the failure of a till cutting in Northern Ireland revealed a layer of heavily fissured, stone-free, brown clay coincident with the basal slip plane (Hughes *et al.*, 2007). Fissures were observed in the till at the Loughbrickland site at the toe of the excavation and could be attributed to some combination of shear deformation during formation of the till, stress relief during the excavation and high hydraulic gradients through the till at the base of excavation.

2.0 Background

In 2004, Roads Service, now TransportNI (TNI) (One of two core groups within the Department for Regional Development (DRD), Northern Ireland) commenced a construction project to upgrade a section of road to dual carriageway on the A1, the main Belfast to Dublin road (Euro Route 1) near Loughbrickland (Figure 1). The improvement in horizontal road alignment necessitated the excavation of this major cutting through a drumlin. The road cutting at Loughbrickland has many similarities to the cutting that failed at Dromore (Hughes *et al*., 2007). They are both located in the same geological setting and drumlin field. Loughbrickland is only 17km South-West of Dromore (Figure 1) and the road cutting is similar in geometry and excavated depth.

TNI recognised that the Loughbrickland cutting provided an excellent research opportunity to better understand the effect of climate on the mechanisms that govern the long-term strength and stability of tills as well as the importance of understanding the influence of drumlin composition, till structure and hydrogeology on slope stability. As a result, TNI initiated a research partnership with Queen's University Belfast (QUB) to study the hydrogeology and long-term stability of cuttings in till. TNI facilitated this project by providing funding for a ground investigation, geotechnical instrumentation and practical assistance. The research project commenced after the geotechnical design had been completed, and therefore the research findings were not available to inform the geotechnical design of the cutting or the construction sequence. The characterisation of the hydrogeological system subsequently developed by QUB was able to inform the remedial works undertaken during construction (as discussed later in the article). The site has since provided an 11 year continuous dataset of pore water pressures in the cutting, from the beginning of construction to present, which is giving a unique understanding of how the internal pore water pressures in the till are affected by seasonal weather cycles.

2.1 Site description, ground investigation and instrumentation

The cutting is situated on a drumlin known as The Three Sisters (Figure 1), approximately 125 metres above mean sea level (drumlin hollow approximately 80mAOD). The A1 in this region passes through agricultural land, which is typically described as glacial terrain comprised of drumlin swarms. The location of the Loughbrickland cutting, County Down, was subjected to at least two glacial advances during the Midlandian stage, from 75,000 to 10,000 years ago (Doran, 1992). It was the last major re-advance of ice, around 25,000 years ago (Late Midlandian), when ice moved generally northwards and southwards from a Lough Neagh ice axis depositing and moulding the till into the numerous drumlins that dominate the topography of the area (McCabe *et al*.,1999). It is generally accepted that the drumlins of Northern Ireland were formed by deposition beneath fast flowing ice (Dardis and McCabe, 1984), resulting in a thick layer of upper lodgement till overlying a core of lower (older) lodgement till (Hill, 1968). The location of the Loughbrickland site is shown on a geology bedrock map in Figure 2.

The preliminary site investigation (SI) was completed by TNI prior to the initial road design (Construction Service, DFP, 2000). Fieldwork for this investigation was carried out between August 1999 and February 2000. The preliminary TNI site investigation covered the entire 11km stretch of new dual carriageway, but the boreholes at the Loughbrickland cutting did not extend to the full depth of the cutting as the vertical alignment of the road was lowered prior to construction. A limited subsequent ground investigation to install monitoring equipment at the location of the cutting was undertaken in January - February 2004, just prior to commencement of construction and excavation on site in the spring of 2004 (Clarke 2006; Clarke, 2007). Figure 3 shows the borehole locations within the road cutting.

TNI’s initial site investigation included: five trial pits (opened using a light mechanical excavator) to a maximum depth of 3m and 9 boreholes drilled (percussively) to a maximum depth of 19m. This investigation confirmed the Geological Survey Northern Ireland descriptions (GSNI, 2004) that the drumlin was predominately cohesive lodgement till. The material was described as slightly sandy, clayey silt with cobbles and boulders. Two of the boreholes located within the main section of the road cutting showed an extensive depth of till (12-19m). Unfortunately, these boreholes were not continued to bedrock and no measurements of pore pressure were made. Granular soils were identified in a few boreholes (well graded sands and gravels), in trial pits (silty sand layers), and in the rock truthing boreholes along the toe of the cutting (Figure 3b). The underlying bedrock was encountered in further boreholes and trial pits, showing it to consist of completely to moderately weathered Greywacke with completely weathered slaty mudstone interbeds, typical of the Gala Group bedrock geology of the area (Anderson, 2004). The bedrock surface reflects to some extent the drumlin topography as evident in seismic refraction surveys (seismic velocity tomography) used to map the bedrock surface. The compression (P) wave velocities of the bedrock surface were approximately 4000m/s with the P-wave velocities within the overlying tills ranging from 300-3000m/s, generally increasing with depth (Kulpa, 2013). The surveys concluded that the surface of the bedrock is often highly fractured and therefore has a high hydraulic conductivity although it may not be continuously hydraulically connected.

The Loughbrickland cutting is 25m high, with a slope angle of approximately 26°. The site has a number of layers, including agricultural soil (0-1mBGL), underlain by an upper till layer (1-10mBGL) and a lower till layer (10-24mBGL). Beneath the till, a layer of dense sandy gravelly material (bedrock contact zone) overlies the weathered greywacke (0.5-1.3m thickness) as illustrated in Figure 3(c). The till layers have a maximum depth of 24m at the centroid of the drumlin, with decreasing depth with distance. It is a dense material consisting of particles ranging in size from fine clays to mass boulders.

The geotechnical properties of the tills were measured in a subsequent SI carried out by QUB in January - February 2004 and the natural water content, along with the Atterberg liquid and plastic limits are presented in Table 1. The water contents were calculated for the matrix after discarding the stony material retained on the 5mm sieve. The water content with the gravel or large particles sizes included are also presented for comparison to highlight that the matrix (stone-free) water contents are generally 30-50% higher than the intact sample water contents. This correction was carried out as the authors believed that the till behaviour was dominated by the clay matrix and, given the variability of the stone content in the tills, the matrix water content was more indicative of the soil behaviour. A summary of the Particle Size Distribution (PSD) ranges for the Loughbrickland site is also presented in Table 1, alongside typical PSD ranges for another cutting site along the A1 at Dromore (Figure 1) as well as typical ranges for Dublin Boulder Clays. It can be seen that the material is variable in nature, but with clay contents between 16 and 26%. During excavation of the cutting, large inclusions of soils with a higher clay content were also observed (Figure 4). These inclusions reinforce the appreciation of the highly heterogeneous nature of drumlin formations. Zones of highly plastic clays within the drumlins could potentially coincide with rupture surfaces, leading to the development of zones of softening within cut slopes, as was observed by Hughes *et al.* (2007) at the failure of the Dromore cutting.

A range of soil strength parameters as determined from laboratory and field testing (Clarke, 2007; McLernon, 2014; Carse, 2014), with the selected characteristic values used in the slope stability analysis are presented in Table 2. The natural matrix water content of the tills is marginally lower than the plastic limits highlighting the stiff nature of this material. The Atterberg limits are plotted on the ‘A’ line chart and the values lie along the ‘T’ line as predicted by Trenter (1999).

2.2 Estimation of *in situ* hydraulic conductivity

The hydraulic conductivity of the till was measured using *in situ* methods such as falling or rising head tests within screened standpipes, or through the use of infiltrometer tests, such as the Guelph permeameter in the near surface zone; the results from these tests are reported in Figure 5. The upper most metre of the drumlin comprises the A and B soil horizons, with its genesis in the upper till. The hydraulic conductivity of this near surface soil is in the range of $1\text{x}10^{-7}$ to $1\text{x}10^{-5}$m/s. Below this near surface layer lies an upper till, in which the hydraulic conductivity is still greater than one would expect based on texture alone, with hydraulic conductivity values ranging from $1\text{x}10^{-9}$ to $4\text{x}10^{-8}$m/s. The water table within the drumlin lies within this upper till layer at depths ranging from near surface to nearly 12m below ground, fluctuating seasonally. The hydraulic conductivity of the lower till ranges from $1\text{x}10^{-10}$ to $3\text{x}10^{-9}$m/s. The general decrease in hydraulic conductivity with depth is likely to be the result of decreasing fracturing with depth associated with weathering (e.g. historical wet/ dry cycles) or as a result of depositional processes (e.g. shearing). Similar observations have been reported by van der Kamp & Hayashi (2009). The division of the till profile into an upper and lower till is based on both the measured hydraulic conductivity values and the observed hydraulic gradients (see Section 4.1 for more detail on the division of the till profile).

The bedrock underlying the till is comprised of an upper, highly permeable zone of weathered and fractured bedrock, overlying more intact bedrock. The hydraulic conductivity of the weathered bedrock zone is estimated to be in the order $1.0\text{x}10^{-6}$ m/s as measured by Kulpa (2013).

2.3 Instrumentation

Figure 3(a) shows the layout of the initial piezometers at the site. A series of nested piezometers were installed at the crest of the cutting, 20m behind the crest and beneath the toe of the cutting prior to excavation. Three piezometers were installed in each borehole at one third and two thirds the overall depth of the till layer, and also in the fractured surface of the bedrock (Fig. 3c). The vibrating wire piezometers were all placed in 50mm standpipes with a 1m slotted screen tip backfilled with gravel. The boreholes were backfilled with bentonite between each standpipe tip to ensure there was no direct hydraulic connection between each piezometer. In order to improve the response time of the piezometers, pneumatic packers were used to limit the intake volume (Clarke, 2007).

3.0 Construction Chronology and Observations

The Loughbrickland excavation was undertaken as a series of stepped benches using a truck and shovel type of excavation. The location of the standpipes in boreholes 3 and 4 were exposed during the excavation, therefore the standpipes were periodically cut to the level of the excavation and protective manhole covers replaced over the standpipes as the excavation proceeded. It is important to note that there were no significant 'step' changes in the monitored heads within the standpipes located in the bedrock contact zone (BH1-1, BH2-1 and BH4-1). Subsequent flowing artesian conditions developed at the toe of the cutting as the elevation of the overlying clay till dropped below the head level within these standpipes (Figure 6). Ultimately, these conditions became critical with the uplift pressure exceeding the overburden pressure with subsequent quick conditions of the till and the initiation of a toe failure.

The excavation chronology and head conditions within the bedrock zone at the toe of the slope are summarised in Figure 6. This Figure shows the head levels within all the standpipes in the bedrock contact zone (BH1-1, BH2-1 and BH4-1) and the excavated level at BH 4. In general, there were four distinct stages to the excavation as summarised below.

3.1 Stage 1 Natural drumlin hydrogeological flow system **(9th March – 22nd April 2004)**

The initial head levels within the 3 standpipes in the bedrock contact zone correlated closely highlighting the relatively low gradients within the bedrock aquifer due to the presence of a till confining layer down-gradient of the toe. The similar head levels within the bedrock aquifer suggest that the weathered bedrock was highly permeable and hydraulically connected.

3.2 Stage 2 Excavation with minor drop in hydraulic head **(22nd April – 23rd July 2004)**

The major excavation period commenced on 22nd April 2004, and during the next three months the bedrock acted as a confined aquifer with head levels in the bedrock contact zone reducing gradually by approximately 1m.

3.3 Stage 3 Development of flowing artesian conditions and initial dissipation of heads due to flow to excavation **(23rd July – 1st September 2004)**

On 23rd July, the level of the excavation dropped below the elevation of the head in the standpipes (BH1-1, BH2-1 and BH4-1, Figure 6) resulting in the development of flowing artesian conditions within the bedrock aquifer over the toe of the cutting. Standpipe BH4-1 was not sealed and this resulted in a continual discharge of water from the standpipe of approximately 0.1 l/s. Although the flow out of BH4-1 was relatively small and not expected to cause significant drawdown in the aquifer, there was a clear rapid drop in head in BH1-1 and BH2-1 due to discharge into the excavation.

3.4 Stage 4 Initiation of critical conditions and increased rate of head drop with time (1st September – 11th November 2004)

Standpipe BH4-1 was cut off following excavation of this standpipe location on September 1st. (BH1-1 and BH2-1 still allowed monitoring of bedrock contact zone head levels). Seepage from the excavation face and base continued during this time. It was anticipated that further excavation would result in loss of toe stability; however, a decision was made to manage water and excavation conditions using conventional sumping and excavation methods. The excavation of an additional 4m of overburden resulted in the development of critical conditions in which the overburden stress was less than the uplift pore water pressure. This ultimately resulted in a failure of a section of the cutting toe with three shallow slip failures (Figure 7) due to the unexpected development of flowing artesian (quick) conditions, a condition which is more commonly associated with non-cohesive soils. Figure 3(b) and 6 illustrates the location of the potentiometric surface of the aquifer compared to the excavated ground surface. Figure 8 illustrates the repair of the surface failures at the toe of the cutting as a result of the developed artesian conditions.

In order to stabilise the toe a series of boreholes were drilled into the bedrock contact zone along the toe of the slope to allow a relief of the excess pore pressure within the bedrock aquifer (November, 2004 - Figure 3). Figure 3 shows the 20 rock boreholes (RT) that were drilled to the bedrock surface. These holes highlight the presence of layers of till, gravelly sand and weathered greywacke rock. The boreholes were completed from North-South (RT1-20) and were cored to the bedrock through the bedrock contact zone. It was interesting to note that there was no water strike in boreholes RT1-5, despite RT5 being located within the bounds of the toe failure. In addition the material underlying the till (RT1-5) consisted of 0.5-3.5m of dry gravelly sand. Based on the drilling program and a comparison of the heads within the bedrock aquifer relative to the ground surface it was determined that the primary source of the flowing artesian conditions was between RT6-13. Borehole 6 was the first borehole where a water strike occurred and flowing artesian conditions were observed (Figure 3b). Water flow was observed immediately when the bedrock contact zone was reached during drilling. Flowing artesian conditions continued to be observed in RT6-13, whilst RT14-16 remained flooded and RT17-21 and RT1-5 were dry. A standpipe placed in RT10 (close to original BH3) at the bedrock contact was used to observe head conditions. As shown in the photograph in Figure 7(b) the elevation of these heads were above the excavated ground elevation of 107.5m (Figure 6) clearly demonstrating the flowing artesian conditions.

The bedrock contact zone is integral to the hydrogeological regime in the drumlin. The bedrock contact zone has been identified throughout the site in various boreholes. The layer was identified as a highly permeable zone (>1×10^{-5}m/s) which can serve as an under drain to the till if it is free to drain. The pre-excavation head levels (approximately 107.1m) within this unit as measured in the lower standpipes in BH1, BH2 & BH3 were very similar and were observed to respond simultaneously. The presence of this confined aquifer was also identified in many of the subsequent rock truthing boreholes along the toe of the cutting, and was potentially part of the same continuous zone (Figure 3b). No further boreholes were cored to assess the spatial extent of the aquifer contained within the bedrock contact zone in the east-west direction. TNI cored a borehole (BH7 – see Figure 9) which was located approximately 20m east of BH3 (closer to Lough Brickland). The borehole ended within the till at a depth of 19.0m (92.3mAOD).

In order to provide post-construction control of heads within this unit, it was decided to construct a deep toe drain. Construction of the toe drain resulted in the complete dissipation of the heads within this aquifer in all four boreholes (Figure 6) and ultimately resulted in the lower weathered bedrock returning to a confined or possibly even an unconfined aquifer.

Monitored head levels stabilised following the installation of the toe drain. Figure 10 summarises the equilibrium pore water pressures and head levels within each standpipe (11th April 2005). It is important to note that the head levels within the upper zone are similar to those pre-excavation; however, draining of the bedrock contact zone reduced the pore water pressures at the bedrock surface and across the lower till.

4.0 Analysis

The relationship between the evolving hydrogeological system during excavation and the resulting impact this had on geotechnical stability is more clearly illustrated in this section through the development of a conceptual and numerical model of the hydrogeology and slope stability of the section. The existing site characterisation information along with monitoring data are used to first construct a conceptual and numerical model of the pre-construction conditions.

For the purposes of this paper, the flow system is conceptualised as a topographically driven groundwater flow system in which recharge occurs across the upland of the drumlin, with subsequent discharge to the lower slope and wetlands at the toe of the drumlin. The system is simulated as a steady-state flow system based on estimates of average annual recharge. Ongoing work, exploring the dynamic nature of the seasonal recharge highlights that there is little recharge to the till during the summer growing season when the soil zone develops a soil moisture deficit (SMD). Once this SMD is overcome by rainfall exceeding evapotranspiration, water is released into the till during the autumn and winter, resulting in a rapid rise of the water table within the upper till. When the SMD condition is re-established in the spring, the water table slowly falls as water is drained from the upper till by lateral flow due to the slope of the drumlin and vertically through the lower till and into the underlying weathered bedrock aquifer.

A surface flux (q) is applied across the drumlin to represent the average annual recharge to the drumlin. The value of this flux is estimated by simulating the flow through the drumlin using estimated hydraulic conductivity values and matching the observed values of the average annual heads. Following this initial characterisation of the system, the recharge rate and properties are held constant and the evolution of the system is illustrated as a series of ‘equilibrium’ flow systems developed as a result of the presence of the excavation.

4.1 Generalised flow system prior to excavation

The flow domain was conceptualised as two layers of till (upper and lower till) overlying the weathered bedrock zone. The presence of an upper and lower till zone is supported by more recent seismic refraction surveys which show a clear increase in shear wave velocities (Vs) from approximately 400 to 700m/s corresponding to an increase in stiffness. There is a slight change in colour from grey to dark grey. The watershed divide running along the centre of the drumlin was taken to also represent a groundwater divide, and is consequently a lateral zero flux boundary. Recent investigations including seismic surveys have provided further support for this assumption (Kulpa, 2013). The base of the weathered bedrock zone serves as a lower impermeable boundary condition. Lough Brickland provides a constant head boundary (83mAOD) for the flow domain and the lower slope position is identified in the model as a potential seepage zone which allows groundwater to discharge to the ground surface if the head exceeds those of the ground surface. The model was constructed within a commercial finite element seepage analyses package called SEEP/W (GeoStudio, 2010).

Figure 11 shows the simulated flow system based on the pre-construction geometry for an annual recharge rate of 35mm (Clarke, 2007). The modelled results were in strong agreement with the equilibrated field observations prior to construction (22nd April 2004) as shown in Figure 12. This agreement is not unique and would be attainable with any assigned recharge rate as long as the proportionality between the recharge rate and the hydraulic conductivity of the till units was maintained. However; given that the hydraulic conductivity used for the two till units is consistent with the hydraulic conductivity measured *in situ* the results seem reasonable. Recent work at the site (McLernon, 2014) has been undertaken to define the seasonal variations in recharge based on detailed field monitoring of the active surface zone and soil water balance modelling. McLernon’s (2014) work suggests that the annual average recharge rates may be higher (~ in the range of 40 to 70mm/year).

The drumlin hydrogeologic regime (Figure 11b) is a typical example of a topographically driven flow system (Freeze and Cherry, 1979). A hinge point has been drawn in Figure 11(b) representing the transition between recharge and discharge into the drumlin. The subtle variation in hydraulic conductivity between upper and lower till zones has a strong influence on the location of the seepage face in the drumlin and the distribution of head within the upper till. There is a distinct contrast in the seepage regimes for the upper and lower till zones. The seepage in the upper till zone is predominately lateral in contrast to the vertical downward seepage in the lower till zone. This is also typical of layered regional hydrogeologic systems as described in Freeze and Cherry (1979). In the lower slope, groundwater flow is vertically upwards resulting in surface seepage from the slope. Field observations and anecdotal evidence from the local farmer has confirmed that the lower slope is soft and wet throughout the year in contrast to the upper slope.

The stability of the drumlin slope prior to excavation was analysed using the pore-pressure regime represented by the simulated flow system and the laboratory measured strength parameters outlined in Table 2. Analyses were undertaken using the limit equilibrium, Morgenstern-Price method with the use of the commercial software package, SLOPE/W (GeoStudio, 2010).

4.2 Analyses of Excavation to Failure Sequence

The simulated steady-state flow system during excavation shown in Figure 13 highlights that there were relatively minor decreases in head within the underlying weathered bedrock and the till during the excavation prior to the onset of flowing artesian conditions and critical uplift. Critical uplift conditions developed during the final stages of excavation, with the total head in the confined aquifer exceeding the elevation at the base of the cut. Advancing the excavation to 98mAOD, the lowest point of the cutting caused three shallow slip failures and a failure in the cutting toe.

The minimum FoS calculated for the natural slope prior to excavation using the drumlin seepage analysis was 2.3. This high FoS highlights that the drumlin was in a stable condition in spite of the elevated water pressures and saturated conditions at the toe of the slope prior to excavation. An analysis of the stability of the slope for the conditions that existed immediately after excavation is shown in Figure 14. This analysis points to the potential formation of an approximately circular toe failure with an optimised factor of safety (FoS) marginally greater than unity (FoS=1.0). It should be noted however that this extended failure surface was never actually generated in situ as the quick (flowing artesian) conditions led to sloughing at the toe of the cutting (Section 3.4).

The value of constructing a toe drain into the bedrock surface to dissipate any excess pressures within the bedrock aquifer can be assessed by assigning a drainage boundary condition (i.e. h=z) to the location of the drain. The groundwater flow and stability analyses for this condition are illustrated in Figure 15. It is interesting to note that the presence of the toe drain does result in a marginal improvement in stability of the slope (FoS = 1.1), however, a FoS of 1.1 is not considered an adequate long-term factor of safety for design, and therefore additional drainage was required to further strengthen the slope. The reason for this initial marginal increase is apparent if the flow system before and after construction of the toe drain is compared. Although the heads within the lower aquifer are reduced, the drain has little impact on the heads within the upper till layer. This unconfined flow system is still causing elevated pore-pressures near the base of the slope at the interface between the two till units. A further increase in the FoS of this slope requires either flattening of the slope above this location or further drainage to relieve the pore-pressures within the upper till. This latter option was trialled by TNI in 2015 with the construction of vertical relief drains from ground surface at the crest and berm of the cutting through the till, vertically into the underlying fractured bedrock. This vertical drainage has resulted in a localised further increase of the FoS to 1.4.

5.0 Conclusion

During the excavation at the Loughbrickland site, the unique hydrogeological conditions combined with the construction sequence, led to elevated pore-pressures and upward gradients within the toe of the cutting. This eventually led to artesian (quick) conditions at the base of the excavation and instability of the slope. A toe drain was added to dissipate excess pressures; however this only marginally improved the FoS. Vertical relief drains were subsequently installed at the site to aid the drainage of the upper till layer, using the drainage of the fractured bedrock layer to drain below the site, which has further increased the FoS.

The consequences of a limited preliminary site investigation prior to site development led to a situation where the toe of the slope failed, which will have softened the till in a zone which is susceptible to progressive failure (Harley *et al*., 2014). Climate variability has brought more extreme weather conditions, which has proven to trigger slope failures across the UK, especially during the extreme events of 2012 where rainfall records showed it to be the second wettest year in the UK since national records began in 1910. The pore pressures at the Loughbrickland site have been continuously monitored since excavation in 2004, providing a unique long-term dataset to better understand the hydrogeological conditions of a till cutting and to further investigate the effect of pore pressure dynamics on tills in Northern Ireland.

This case study reinforces the necessity of carrying out a full ground investigation in compliance with Eurocode 7, with the associated development of a Conceptual Site Model characterising the soil properties and hydrogeology. This should be completed before any ground works commence in order to inform the geotechnical design and reduce geotechnical risk, even where works involve an apparently benign excavation through a stiff, low permeability till. The case study illustrates the usefulness of continuous monitoring of pore pressures during and post-construction; this data significantly informed the design of the remediation.

The road network in Northern Ireland encompasses a substantial number of large cuttings in tills. Further research sites in similar geological settings have since been identified as potential risks for failure by QUB, TNI and Northern Ireland Railways (NIR); they have continued managing infrastructure slopes by funding continued research (Carse, 2014; McLernon, 2014; Harley *et al*., 2014; Lynch *et al*., 2013). Assessing the condition of old cuttings is a vital exercise in maintaining the integrity of transport infrastructure in the UK. Research into predictive modelling of failure modes due to climate change and reduced long-term shear strength is ongoing, as well as modelling of drainage remediation methods so as to aid the road and rail authorities to better manage their geotechnical assets.

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Figure captions

Figure 1. Location map (grid in ETRS_1989_UTM_Zone_29N): (a) A1 Carriageway: Belfast to Dublin Euroroute 1 (b) Contour map of drumlin landscape surrounding ‘The Three Sisters’ drumlin and proposed horizontal alignment of new dual carriageway.

Figure 2. Location of the Loughbrickland research site and geology bedrock (The Geological Survey of Northern Ireland, 2004).

Figure 3. Locations of boreholes within road cutting (a) Plan of excavation showing borehole locations, bedrock contact zone rock truthing boreholes (RT1-20), and location of Section A-A (b) Vertically expanded cross-section along toe of the slope, including material logs, showing location of flowing artesian conditions (c) Section A-A showing geological profile and borehole locations.

Figure 4. Photograph taken during excavation of the Loughbrickland cutting, showing inclusion of high plasticity clay (Clarke, 2007).

Figure 5. Permeability of the Loughbrickland site: A and B horizon, upper and lower till and weathered rock zone.

Figure 6. Development of flowing artesian condition in the bedrock contact zone at the base of the excavation, showing bedrock water pressures exceeding the overburden total stress.

Figure 7. Photographs showing (a) the toe failure as a result of the developed flowing artesian conditions in the bedrock contact zone – September 2004, and (b) the water flow beside BH3 caused by artesian conditions in the bedrock contact zone (location at RT10; Figure 3a).

Figure 8. Photograph of the repair of cut surface failures as a result of the developed artesian conditions – September 2004.

Figure 9. Overview of the observation sites, including TNI BH7, and the location of Section B-B, the 2D groundwater model cross-section at the road cutting, Loughbrickland, Co. Down (Clarke, 2007).

Figure 10. Pore water pressure and head distribution: (a) pore water pressure and (b) relative head levels versus depth from ground surface (11th April 2005).

Figure 11. (a) SEEP/W model showing boundary conditions for initial steady state analysis (b) Total head (mAOD) diagram of initial steady state seepage analysis pre-excavation through section B-B (using SEEP/W).

Figure 12. Initial steady state model verification: comparison of field and simulated head data (Borehole 1, 2 & 3).

Figure 13. (a) Post-excavation stratigraphy (b) Seepage regime showing head contours (mAOD) (c) Artesian seepage conditions at toe showing total head contours (mAOD).

Figure 14. Post-excavation factor of safety of major slope failure (using SLOPE/W).

Figure 15. Post-remediation conditions, contrasting k with under drainage (a) Stratigraphy and boundary conditions (b) Seepage analysis showing head contours (mAOD) (c) Slope stability analysis.

Table captions

Table 1. Summary of soil classifications.

Table 2. Summary of soil strength parameters as measured in the laboratory (Clarke, 2007; McLernon, 2014; Carse, 2014).