The Performance of Road Embankments on Glacial Deposits in Ireland

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Abstract

Glacial deposits are very common as foundation soils supporting road embankments in Ireland and are typically present in almost all road projects. Despite this there is limited research data linking the settlement performance of embankments to the compressibility and consolidation properties of such soils. This is largely due to the difficulties in obtaining representative, high quality undisturbed samples and laboratory testing of glacial deposits, which exhibit a large range of gradation particle sizes including gravels, cobbles and boulders.

The paper presents the results of several case histories of foundations and monitored road embankments supported on glacial deposits located throughout Ireland. In situ field compressibility and consolidation parameters are back calculated from field performance and correlated to standard index properties such as liquid limit, plasticity index, particle size gradations and SPT N values. Some general conclusions plus recommended ways to predict embankment performance from commonly obtained geotechnical test data are suggested. Identification of difficult glacial soil types requiring special investigation and treatment or improvement are suggested.

Keywords: embankments, performance monitoring, case history, glacial till, compressibility, consolidation.

1 Introduction

Glacial deposits are very common as foundation soils supporting road embankments in Ireland and are typically present in almost all road projects. Despite this there is limited research data linking the settlement performance of embankments to the compressibility and consolidation properties of such soils. This is largely due to the difficulties in obtaining representative, high quality undisturbed samples and laboratory testing of glacial deposits, which exhibit a large range of gradation particle sizes including gravels, cobbles and boulders.
Attempts have been made to assess compressibility (either constrained modulus M’ or coefficient of volume change m_v, where M’ = 1/m_v) through oedometer testing of undisturbed and reconstituted samples e.g. Lehane and Simpson (2000). Hanrahan (1977) quotes a range of M’ from 27 to 270 MPa for Irish glacial tills with moisture contents from 8% to 27% for low stress range from 27 to 54 kPa. As discussed by Trenter (1999) and Farrell (2010) laboratory testing tends to overestimate the true in situ soil compressibility in glacial soils due to exclusion of coarse fraction, changes in moisture content and destructuring of any cementation effects. Standard 75mm diameter by 20mm high laboratory oedometer tests on “undisturbed” samples are invariably performed on the more cohesive, fine grained portion of the till profile, tending to exclude those with significant stone content.

These measures all produce a significant bias in laboratory test data and in practice engineers have resorted to applying semi empirical correlations with in situ Standard Penetration Test data. The most widely used correlation in Ireland and UK (Eqn 1) is ascribed to Stroud and Butler (1975) who expanded earlier work by Stroud (1974) on similar correlations for insensitive clays and weak rocks:

\[ m_v = \frac{1}{f_2 N} \]

(Eqn 1)

Stroud and Butler initially derived the correlation factor f_2 to laboratory measured values of m_v for stress increments of 100 kPa in excess of the in situ effective overburden stress, which can be approximated to a 5m high embankment fill load. Detailed correlation data was only obtained for 6 sites, mostly located in northern England with Plasticity Index (PI) ranging from 18 to 23% in boulder clays and 35 to 38% in laminated clays. A range of values for correlation factor f_2 to laboratory measured values of m_v from 440 to 600 kN/m² was reported for UK tills and 750 kN/m² was reported for one Canadian till site. The trend of increasing f_2 with reducing PI is shown in Figure 1.

![Figure 1 Variation of Correlation Factor f_2 (KN/m²) with Plasticity Index PI (Stroud & Butler, 1975)](image_url)

Stroud & Butler (1975) further argued that the vertical drained elastic modulus E’_v is related to SPT N and E’_v / N should also be a constant for a material of given plasticity. They presented data for field measurements of foundation settlements on four Canadian sites underlain by glacial till with a ratio of E’_v / N typically from 1,500 to over 2,000 kN/m², for tills with PI from 12 to 17. This is at least double the correlation developed from laboratory measured values of m_v and is explored later in this paper. A range of secant shear modulus G (at shear strains up to 1%) from 10 to 20 MPa was reported by Trenter (1999) for UK tills derived from in situ 865mm diameter plate testing at three test sites.
Where the constrained modulus $M^* = 1 / m$, is derived from field settlement data from embankment filling over a wide area, $E'_v$ has been derived from equation 2 (generally assuming $v = 0.25$ for stiff glacial tills $E'_v = 0.83M'$):

$$M^* = E'_v (1-v) / (1+v) \cdot (1-2v)$$

(Eqn 2)

In contrast to compressibility modulus, there is even less documented guidance on relevant coefficient of consolidation $c_v$ values for glacial till soils. Trenter (1999) reports a range of values generally between 1 and 3 m$^2$/year for English tills and somewhat higher range of 2.5 to 8.5 m$^2$/year in Scottish tills. Hanrahan (1977) reports a range of $c_v$ from 7 to 270 m$^2$/year, but at low stress ranges. Lehane and Simpson (2000) suggest values within the range of 20 to 60 m$^2$/year for Dublin Boulder Clay.

### 2 Summary of Case Histories


This data is derived from instrumented load tests on a 1.5m square trial footing maintained in stages at relatively very high pressures of 825 kPa and then 1013 kPa over incremental time period of 3 weeks and 3 months respectively. Representative classification test and SPT N profiles are given in Figure 2.

![Figure 2 Index Data and SPT N for Tallaght Town Centre (Long & Menkiti 2007).](image)

**M7 / M8 Motorway, Co. Laois.**

A 41 km motorway was constructed in the Irish midlands Co. Laois from 2007 to 2010 which included field settlement plate monitoring of several embankments. Settlements of embankments founded on glacial tills were in all cases less than 75mm and generally less than 40mm for embankment heights from 3m to 9m. Drainage was typically observed to be rapid upon loading and frequently had ceased within 3 to 6 months of final load application.

Construction dewatering within a tunnel access shaft WA2 resulted in a significant drawdown of between 10m and 17m from an initial water table depth of 3m over a period of around two weeks. Average settlements of 6.3mm occurred quickly (mostly within a further month) within a 31m thick deposit of Dublin boulder clay.

M9 Motorway Service Area, Kilcullen, Co. Kildare

Earthworks including embankments up to 8.5m high for new slip roads, roundabouts and approach to an overbridge were constructed in 2014. The eastern side of the interchange contained a 2m to 3m thick layer of soft glacial melt water deposits with very low SPT N values from 3 to 7 blows / 300 mm beneath a firm - stiff cohesive till and underlain by gravels at depths of 5.5m to 7m. A ground improvement scheme consisting of prefabricated vertical drains installed at 1.3m c/c triangular spacing was constructed and performance monitored by settlement plates and piezometers.

Filling rates actually achieved were slower than originally planned and averaged only 0.5m / week for the first 4 weeks followed by a filling rate of 1 m/week giving a total filling duration of 8 to 10 weeks. Maximum settlements of 95mm and 49 mm were observed at SP6 and SP1 respectively. Both the settlement and piezometer records confirmed that drainage was rapid and consolidation was effectively complete within 4 to 5 weeks from the mid point of loading.

A2 Shore Road, Belfast

The A2 Shore Road involved a 4km length of a coastal route on the northern outskirts of Belfast. Earthworks on a side access road included the main embankment filling of up to 8.5m height on approach to an overbridge which was monitored by settlement plates and piezometers. The ground profile comprised on firm - stiff cohesive glacial till underlain by weathered Mercia Mudstone deposits at depths of between 4.0m to 7.2m. PI for this glacial deposit was high at 20 to 27%.

A ground improvement scheme local to the overbridge approaches was constructed with surcharge filling and a hold period of around 9 months. Embankment fill heights of between 5.2m and 8.7m. produced maximum settlements of between 30mm and 80 mm.

M6 Motorway Service Area, Athlone, Co. Westmeath

Earthworks including embankments up to 8.6m high for new slip roads, roundabouts and approach to an overbridge were constructed in 2014. The geomorphology of the site indicates varied glaciolacustrine and glacial meltwater deposits, with the MSA footprint to the northeast containing soft peat soils. The overbridge and approaches are sited over a local ridge of granular glacial soils.

Upon investigation the presence of pockets and linear channels of soft uniform intra-glacial deposits with high moisture contents and Plasticity Index (PI) > 20%. A ground improvement scheme consisting of excavation and replacement of near-surface soft deposits coupled with hold periods or surcharge loading (Service Area Link Road) over any underlying soft ground remaining in-situ was constructed. Note that in the absence of an SPT-N value at the specific level, a correlation to undrained shear strength \( c_u = 5.0 \text{ kN/m}^2 \) as per Stroud & Butler (1975) has been assumed at the Westbound Roundabout.

Embankment performance was monitored by a combination of settlement plates and survey monuments. Filling rates actually achieved were slower than originally planned and averaged only 0.4m / week overall. Maximum settlements of 55mm to 65mm were observed. The settlement records yielded estimates for field \( c_u \) of between 5 and 11 m²/year.

Limerick Tunnel Approach Roads, Limerick

A 10 km long bypass of Limerick City was constructed from 2006 – 2010 with about 3km of the route directly underlain by fill soils or glacial tills. Data for a location at the tie in of Clonmacken Link to the existing road network with 6m of glacial soils under a 5m high embankment is given in Table 1.
The field performance data base contains a total of seven sites and 14 monitored locations in Ireland as summarised in Table 1. The range of natural moisture content is from 4% to 38% with average values per location ranging from 10 to 25%. Average proportion of fine fraction (silt and clay) passing 63 micron sieve size per location is typically from 29% to 46%. The average range of plasticity index per location is from 6 to 24%. These values broadly compare well with ranges cited by

<table>
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<tr>
<th>Site Location</th>
<th>&lt;63 µm (%)</th>
<th>LL (%)</th>
<th>PI (%)</th>
<th>Nat. Moist (%)</th>
<th>Till T (m)</th>
<th>SPT N</th>
<th>Load/ Fill Ht (kPa*/m)</th>
<th>Settlement (mm)</th>
<th>E_v (MPa)</th>
<th>t_05 (wks)</th>
<th>c_v (m^2/yr)</th>
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<td>9</td>
<td>12</td>
<td>5.3</td>
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</table>

**Table 1:** Summary of Glacial Till Classification and Field Test / Monitoring Results

1. Effective depth of loading from 1.5m square test area.
2. A correlation to Cu using $f_1 = 5$ as per Stroud & Butler (1975) was assumed to derive SPT-N.

3 Discussion

The field performance data base contains a total of seven sites and 14 monitored locations in Ireland as summarised in Table 1. The range of natural moisture content is from 4% to 38% with average values per location ranging from 10 to 25%. Average proportion of fine fraction (silt and clay) passing 63 micron sieve size per location is typically from 29% to 46%. The average range of plasticity index per location is from 6 to 24%. These values broadly compare well with ranges cited by
Hanrahan (1977) for Irish lodgement, ablation, and englacial tills. Some sites at M7 / M8 in Laois and M6 Athlone exhibit fine contents in excess of 60% are likely to have been deposited from melt water.

The range of SPT N values is from 2 to 90 with average values per location varying from 4 to 55. Four locations have unusually low ranges of SPT N less than 12 which are less commonly observed in Irish till deposits. These include the M9 MSA Kilcullen, M7/M8 Co. Laois Ch 22+800 to 22+950m and the M6 Athlone site. The proportion of these soft till sites in part reflects a bias in relation to settlement monitoring being preferentially performed on sites with poor, compressible glacial till deposits. Settlements observed are typically less than 80mm with the one exception of 95mm occurring at M9 MSA site. The constrained modulus M is calculated directly from the observed settlement, embankment loading (height x fill density, $\gamma$ assumed = 20 kN/m$^3$) and till layer thickness.

Correlations for Drained Vertical Modulus $E'_{\nu}$

The vertical Young’s Modulus $E'_{\nu}$, derived from the field data is rarely less than 7 MPa in soft tills or higher than 80 MPa in very stiff deposits such as Dublin Boulder Clay. Modulus is broadly correlated to SPT N with ratios of $E'_{\nu} / N$ varying between 0.5 and 1.5MPa but some sites with low PI having $E'_{\nu} / N$ around 3 MPa. The relationship between $E'_{\nu} / N$ and PI for Irish till sites is plotted on Figure 3 which includes the data for four Canadian till sites republished by Stroud & Butler (1975) plus their suggested design line. There is some evidence for $E'_{\nu} / N$ being correlated to PI and a trend line for the Irish sites is shown with the following relationship, however the scatter should be noted:

$$E'_{\nu} / N = 9.452 \ (\text{PI})^{-1.007} \ \ \ \ \ \ \ \ \ \ (\text{Eqn} \ 3)$$

The trend line predicts $E'_{\nu} / N$ ratios of 0.46 MPa to 0.93 MPa for PI in the range of 20 to 10%, which are around half of the ratio suggested by Stroud and Butler from field correlations from Canadian sites and granular till deposits and closer to those derived from lab data. A comparison of constrained modulus $M'$ derived from field measurements with those from laboratory tests for sites...
found that an average ratio of $\frac{M_{lab}}{M_{field}} = 0.81$ which could be improved to 0.97 by correcting the $M_{lab}$ for the proportion of gravel over 5mm in size using equation 4 such that:

$$M_{\text{lab corr}} = \frac{M_{\text{lab}}}{(1 - \text{Gravel fraction > 5mm})}$$  

(Eqn 4)

An exceptionally high modulus was observed for the Dublin Port Tunnel which had a very deep till profile of over 30m and an effective stress loading due to dewatering resulting in an extremely high $E'_v$ value of 553 MPa. The vertical strain level measured at the Dublin Port Tunnel site was around 0.02% which compares to typical vertical strains of 1 to 2% in the other embankment and footing test case histories. This explains the very high modulus observed at the site and reinforces that the field modulus of glacial soils is highly non linear and strain dependant.

**Correlations for Coefficient of Consolidation $c_v$**

The coefficient of consolidation $c_v$ was derived from the field settlement – time history by assessing time for 95% consolidation to occur from the midpoint of loading and then back calculating the equivalent $c_v$ parameter assuming double drainage of the cohesive till layer thickness. In the case of M9 MSA Kilcullen site where vertical drains were installed the back calculation was made assuming Barron’s equation. Field $c_v$ values typically range from 10 to 40 m$^2$/year and compare well to values discussed earlier for Irish tills. $c_v$ is broadly correlated to $N / PI$ with ratios of $c_v(PI) / N$ varying between 4 and 15 m$^2$/year. The relationship between $c_v$ and Liquid Limit (LL) for Irish till sites is plotted on Figure 4 which includes the correlation from NAVFAC (1982) for virgin compression which the trend line closely matches, but the scatter in data for LL below 25% is large.
4 Conclusions

For embankment heights of up to 9m and cohesive till thicknesses of up to 10m, embankment settlements rarely exceed 60mm when constructed on Irish glacial till foundations soils. Exceptions can occur in untypical soft till sites with SPT N values of less than 12 or in higher plasticity tills (PI >20%) but even in these unusual cases, observed settlements did not exceed 100mm. Sites with these characteristics may require ground improvement by use of surcharge loading or possible vertical drainage dependent upon the construction programme constraints.

Irish glacial tills exhibit vertical modulus generally ranging from 7 to 80 MPa which is loosely correlated to SPT N and PI (refer to equation 3). The ratio of $E'_v / N$ generally varies between 0.5 and 1.5MPa and is lower than observed in Canadian tills but $E'_v$ is similar to reported values for UK tills.

Consolidation appears to occur rapidly under most embankment loading scenarios, in practice rarely exceeding 6 months. Derivation of coefficient of consolidation $c_v$ is not straight forward due to the influence and uncertainty of high permeability layers within cohesive till deposits. Based on the limited data obtained, values for $c_v$ from 10 to 40 m$^2$/year seem typical for Irish tills and the correlation of $c_v$ to Liquid Limit given in Figure 4 may have useful application for preliminary design.

Acknowledgements

The authors would like to acknowledge the National Roads Authority, Clonmel Enterprises Ltd., Celtic Roads Group Portlaoise, DirectRoute (Limerick) Limited, Graham Construction Limited and Colas-Roadbridge JV, for their kind permission to publish the data contained within this Paper. The views expressed in this paper are the sole views of the authors and do not represent the views of the organizations named above or Roughan & O’Donovan.

References


