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<td><strong>Author(s)</strong></td>
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<td><strong>Publication Date</strong></td>
<td>2016</td>
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<td><strong>Link to publisher's version</strong></td>
<td><a href="https://doi.org/10.13025/S85K5S">https://doi.org/10.13025/S85K5S</a></td>
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ABSTRACT: The ground conditions in the Terryland River Valley area present considerable site development challenges to geotechnical engineers. The soft soil formation consists of peat overlying very soft, highly compressible calcareous silt overlying slow draining organic silts and inorganic clays. These soil deposits are typical of those encountered in Limestone Basin regions throughout Ireland. NUI Galway has been involved in investigating these soils since the 1980s. The investigations at Terryland involved Cone Penetration Testing (CPT), shear vane and piston sampling plus laboratory testing. This paper summarises some previously unpublished data and places the results in the context of various published soil data from sites elsewhere in Ireland. The laboratory testing confirms that the design parameters for the soft soils in the Terryland River Valley are more onerous than for many other soft soil sites in Ireland.

KEY WORDS: calc tufa, marl, silt, clay, consolidation, compressibility

1 INTRODUCTION

The ground conditions along the Terryland River Valley, north of Galway City centre, have posed challenges for construction in the area over the last 30 years, as evidenced by the earthworks failure in Figure 1. The geotechnical characteristics of the Terryland River Valley deposits are presented in this paper with a view to providing a frame of reference for future developments on similar soft soil deposits. Particular emphasis is placed on 1-D compression behaviour.

The measurements presented are derived from adjacent ground investigations at Terryland for:
(i) a section of the N6 dual carriageway east of the Quincenntennial Bridge [1] (south zone and part of the north zone in Figure 2) and
(ii) both a piled embankment research trial and the Dún na Coiribe residential development (part of north zone in Figure 2).

2 GEOLOGY

2.1 Solid Geology

The bedrock at the test location is carboniferous limestone, generally pale to medium grey in colour, well-bedded, fossiliferous and medium-grained to coarse-grained. It is moderately strong to very strong with fractures which are closely-spaced to medium-spaced and at a low angle. The bedrock is part of the Visean Limestone formation of the Lower Carboniferous age which underlies much of Galway city and east Co. Galway [2].

2.2 Quaternary Geology

The Terryland River flows from the River Corrib (see Figure 2) and ultimately through a series of sinkholes into the sea, although the network of karst features between the sinkholes and the sea is not precisely known. During high tides, the direction of flow in the Terryland River can be reversed.

Some geotechnical characteristics of soft soil deposits along the Terryland River Valley, Galway

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Terryland River

Figure 1 Earthworks failure along the Terryland River Valley

Figure 2 Terryland River Valley and investigation areas

The soft soils in the Terryland River Valley are identified as alluvium or bogs on geological drift maps. A portion of the Terryland site was part of a lakebed until land reclamation works began in the 1850s. The lake was formed over glacial till, which was deposited over the limestone during the last Ice Age. The glacial till generally consists of well-graded sands, gravels and boulder clay [3].

The Quaternary geology comprises peat overlying calcareous soils, which in turn overlies lake deposits of silts. The top 0.2 m – 0.3 m of the peat is fibrous in nature, supporting the surface vegetation. The peat becomes more humified with depth, typically ranging from H5 to H7 on the Von Post [4] scale. During trial excavations, the peat below 0.3 m unusually had a yellowish colour (Figure 3) that turned black upon exposure to air. It is assumed that this peat was formed in anaerobic conditions implying that the water table did not fluctuate below this level.

The calcareous soil was formed as a result of calcium carbonate (CaCO₃) coming out of solution from the groundwater. Water originating from lime-rich strata saturated with CaCO₃ flowed upwards under artesian conditions at discrete locations through the underlying lake deposits. In reduced pressure conditions, the CaCO₃ emerged from solution and formed the calcareous deposit known as calc tufa or marl. Numerous bands of shells were deposited in the calc tufa as the bed of the lake was raised during the deposition process.

The lake deposits overlying the glacial till consist of green-grey organic silt containing numerous reeds and other organic matter, overlying blue-purple-grey inorganic clay. The organic silt was generally more laminated than the inorganic clay. The deposition of the lake soils followed by the formation of the calc tufa raised the bed of the lake sufficiently high to support the growth of reeds. This in turn gave rise to reed peat being formed in the upper strata [5].

**3 SITE INVESTIGATION AND IN SITU TESTING**

The site investigations at Terryland followed procedures established by NUI Galway based on previous experience of investigations in soft soils. Initially, a gouge auger was used to determine the nature and extent of the soft soil deposits. Next, piezocone tests were performed as they were quicker and easier to complete than shear vane tests or piston sampling (the fieldwork pre-dated the use of piezoballs in Ireland). Shear vane tests and continuous piston sampling were then carried out close to piezocone locations. Cable percussive boreholes were also carried out in the glacial layer. A description of the site investigation techniques and soil types encountered is provided.

### 3.1 Gouge auger

The gouge auger is a simple but very effective means of determining the stratification of soft soils. It consists of a 1 m long split tube, 30 mm in diameter, fitted with a detachable handle. It can sample soils to a depth of 15 m by adding a series of 1 m long extension bars. The stratification was determined by visual inspection of the recovered core. Portions of the core were removed for water content and Atterberg limit determinations.

### 3.2 Piezocone testing

The NUI Galway piezocone consists of a 60° cone with a cross-sectional area of 10cm² and the porous filter was located behind the cone tip. The piezocone was driven into the soil at a rate of 20mm/sec. The cone end resistance, pore water pressure and sleeve friction were recorded at 100mm intervals by a datalogger. The piezocone was held stationary at its maximum depth and the pore water pressure was recorded. In keeping with similar sites, the friction values recorded were very low and therefore are difficult to rely upon.

A representative variation of cone end resistance and pore water pressure with depth is shown in Figure 4. Uncorrected and corrected cone factors Nₖ and N₉₀ were typically found to lie in the range 5-12 and 6-12 respectively, with a small number of higher values [1]. A significant increase in pore water pressure is noted when the piezocone was held stationary, suggesting that a slightly artesian condition is present.

### 3.3 Shear vane testing

A Geonor H-10 (65mm x 130mm) shear vane was used at Terryland. The inferred profiles of undrained shear strength (cᵤ, without Bjerrum’s correction for plasticity index) with depth are shown in Figure 4. The corresponding corrected undrained strength ratios (cᵤ/σ₀’ where σ₀’ is the free-field vertical effective stress) are shown in Figure 5. This is attributed to drainage in the calc tufa during shear vane testing.

### 3.4 Continuous piston sampling

Continuous sampling was carried out using a Geonor piston sampler. Thin-walled aluminium sample tubes, 1.0 m in length and 101.6 mm in diameter, were driven into the soil using a tripod and winch reaction system. The leading edge of the tubes had a 30° cutting edge and the wall thickness was 1.75 mm, providing an area ratio of 7%. Once the sample tube had been extended fully, the operators waited approximately 15 minutes to allow any excess pore water pressures to dissipate before extracting the samples, which were up to 0.9 m long. The tubes were sealed on site with paraffin wax to prevent water loss. They were placed horizontally in a large box and carefully surrounded by polystyrene packaging to prevent excessive rocking that could disturb the microfabric of the very soft soils.
Once in the laboratory, the samples were stored horizontally to minimise the loss of water. When the samples were extruded, a split pipe was placed at the open end of the tube to support the sample. The sample was cut off using a thin nylon line and the tube was resealed at both ends with paraffin wax.

3.5 Cable percussive boreholes

Irish Drilling Limited carried out cable percussive boreholes at Terryland. The cable percussive method is a crude method of sampling soft soils as mixing can occur. In this case, it was used to determine the nature and extent of the glacial deposits. It was possible to chisel into the gravel until refusal of the Standard Penetration Test (SPT) occurred. Refusal was dramatic, indicated by the SPT hammer ‘bouncing’, and no further penetration of the SPT cone possible [7].

4 BASIC MATERIAL PARAMETERS

4.1 Stratigraphy and groundwater

The stratification across the test site was reasonably uniform although some minor variations in the depth to the glacial till were established. The interpreted layering is shown on Figure 4. The groundwater was generally at or close to the ground surface.

4.2 Water content, index tests and bulk density

The distributions of bulk unit weight, water content and Atterberg limits with depth are shown on Figure 4. The unit weight of the soils was determined from the specimens used for consolidation tests. The Atterberg chart (Figure 5) shows the calc tufa data plotting below the A-line as a silt of extremely high plasticity, whereas the green organic silt also plots below the A-line much further to the right. The blue inorganic clay plots just above the A-line as a high plasticity clay.

Figure 5 Atterberg chart

The natural water content of the peat varied from 660% to 1100%, while that of the calc tufa ranged from 120% to 260%. The green organic silt had water contents between 150% and 280% while the blue clay had a water content range of 70% to 80%. The plastic limit for the organic and inorganic soils was established using the rolling ball method. However, Baaker [8] suggested that the linear shrinkage method was more suitable for determining the plastic limit of calcareous soil so this method was preferred for the calc tufa. The liquid
limit was determined using the cone penetrometer test. The liquid limit results for the calcareous soils are typically about 100%, much lower than the natural in situ water content range. This is indicative of a structured or a slightly cemented silt. Sensitivity (the ratio of natural shear strength to remoulded shear strength) values ranging between 5 and 12 were found from fall cone tests carried out on undisturbed samples.

4.3 Sample Quality

The soft nature of the Terryland overburden soils meant that the recovery of quality samples was challenging. Sample disturbance was evaluated using methods proposed by Lunne et al. [9] and modified by Löfroth [10]. Lunne et al. [9] proposed that the volumetric strain required to recompress the specimen to the in situ vertical effective stress is a useful indicator of the degree of sample disturbance. Löfroth [10] carried out a study of sample disturbance effects for soft, Swedish soils and proposed a modified version to account for specimens with water contents up to approximately 150%. The boundaries between the sample quality classes have been extrapolated by the authors in Figure 6 to account for the higher water contents at Terryland; the figure indicates that the sampling was successful.

McCabe et al. [13] examined data from Terryland and elsewhere in Ireland and found that eqn (1) was also reasonably valid for clays and silts having higher water contents than 150%. However, the relationship typically overpredicted the measured \( C_C \) values for calcareous soils. A tentative relationship is proposed for calcareous soils based on data from Terryland and other calcareous silt sites in Ireland for \( 125% < w_N < 300% \) (Figure 9).

\[
C_C = 0.014(w_N - 22.7) ~~~~~~~~~~~~~~~~~~~~~ (1)
\]

5 ONE-DIMENSIONAL COMPRESSION BEHAVIOUR

A series of 75mm or 76mm diameter standard oedometer and constant rate of strain (CRS) oedometer tests were carried out on samples from Terryland. Plots of vertical effective stress against axial strain for standard oedometer tests are plotted in Figure 7 for the calc tufa and in Figure 8 for the organic silt. The typical loading sequence, following recommendations from Sandbaekken et al. [11], is 0.25, 0.5, 1.0, 1.5, 2.25, 4.5 and 9.0 times the free-field vertical effective stress \( \sigma_0 \).

5.1 Compression index

McCabe et al. [12] provided an empirical relationship between the compression index \( (C_C) \) and various indices for soft, compressible soils in Ireland in the water content range of 60 – 150%. The relationship between \( C_C \) and the natural water content \( (w_N) \) in eqn (1) was deemed to be the most reliable.

\[
C_C = 0.014(w_N - 22.7) ~~~~~~~~~~~~~~~~~~~~~ (1)
\]
5.2 Yield stress and tangent modulus

The Casagrande graphical construction for estimating the yield stress can be difficult to implement for Irish soils as many log stress versus strain curves can be very rounded without an obvious point of maximum curvature. The Janbu [14] method has been used on a number of Irish sites, e.g. [15, 16] to overcome this issue. The tangent modulus ($M$) is estimated from:

$$M = \frac{\Delta \sigma'}{\Delta \varepsilon}$$ .................................. (2)

The yield stress ($\sigma'_c$) can be inferred from the relationship between $M$ and the vertical effective stress $\sigma'$. There is a distinct break point as the soil structure is broken down before recompression of the soil occurs; this typically occurs at $\sigma'_c$. This is shown graphically in Figure 10. Some Swedish soils display a different relationship and the yield stress is determined in an alternative way. TK Geo [17] suggests that the soil deforms at a constant tangent modulus commencing at the yield stress before increasing at a stress $\sigma'_L$ (Figure 11). This is most likely due to the degree of structure in the soils, particularly in the Gothenburg region.

$$M = m p_a \left( \frac{\sigma'}{p_a} \right)^{1-a}$$ .................................. (3)

where $m$ is the modulus number, $p_a$ is the reference stress usually taken as 100 kPa and $a$ is a dimensionless stress exponent. The data from Terryland suggest that the modulus number $m$ typically varies between 4 and 7 for both the calc tufa and the organic silts. These values are shown in the context of Long’s [15] data for lower water content soils in Figure 15. The Terryland data indicate that the results are less sensitive to water content than the estuarine silts examined by Long [15]. The $a$ parameter in eqn (3) was typically zero for calc tufa which is in line with suggestions for soft soils [14]. Long [15] found that the $a$ parameter for many Irish soft soils was typically 0.25; the data for the green organic silt in Terryland are in keeping with these findings.

Figure 10 Classical Janbu tangent modulus versus stress model (image adapted from [14]).

Figure 11 Relationship between the vertical effective stress ($\sigma'$) and tangent modulus for Gothenburg clays [17]

The CRS tests carried out on the soils (Figure 12) have been analysed using the Janbu method (Figures 13 and 14). The data suggest that the initial tangent modulus $M_0$ is relatively low and it is difficult to determine the yield stress with this method. However, there appears to be a stress range corresponding to the stress range $\sigma'_c$ to $\sigma'_L$ where the tangent modulus $M$ is relatively constant, similar to the Swedish soils. Janbu [14] proposed that the constrained modulus could be characterised by a power function as follows:
Figure 14 Plot of $M$ versus stress with the Janbu power relationship for green organic silt specimen taken at 7.1m

Figure 15 Range of modulus numbers for Terryland and data from sites elsewhere in Ireland from [15]

6 CONCLUSIONS

In this paper, some NUI Galway experience of the ground conditions present in the Terryland River Valley area of Galway City is presented, intended as a frame of reference for geotechnical engineers dealing with similar soils. The soft ground investigations at Terryland were found to be particularly challenging. Some of the main conclusions from the investigation are:

(i) The geotechnical parameters for the calc tufa can vary significantly, as evidenced by the water content and Atterberg limit variation both with depth and across the site.

(ii) The CPT end resistances are very low (typically less than 300 kPa) and therefore the soft soils may be more suitable for investigation with a piezoball to develop greater resistance and resolution.

(iii) The soils are susceptible to sample disturbance, but good quality piston samples can be retrieved using well-maintained equipment used with sufficient care.

(iv) The empirical relationship for $C_C$ proposed by McCabe et al. [12] for soft Irish soils appears to be appropriate for the high moisture content silts and clays at Terryland, but overpredicts $C_C$ for the calc tufa. An alternative relationship is proposed for calcareous soils.

(v) The calc tufa is probably a weakly structured material with many similar characteristics to Swedish soils. The CRS tests suggest that the Janbu [14] method for determining the yield stress is not appropriate, while the method proposed by TK Geo [17] appears to be more applicable. This facet of the calc tufa behaviour is worthy of further investigation.

ACKNOWLEDGMENTS

The authors would like to acknowledge COFORD, Coillte Teo., O’Malley Construction Ltd. and Galway County Council for their generous financial support, in addition to staff and postgraduate students at NUI Galway who helped with laboratory and field testing.

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