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STABILITY OF MAN MADE GLACIAL TILL SLOPES IN SOUTHWEST IRELAND

K.Gavin[1], J.F. Xue[1].and P.Jennings[2]
[1]*Department of Civil Engineering, University College Dublin, Ireland*
[2]*Applied Ground Engineering, Bagenalstown, Co.Carlow*

kenneth.gavin@ucd.ie

Abstract

Results from a recent survey of the condition of 150 year old man made slopes in glacially derived soils are presented. These show that embankments and cuttings which are built at angles higher than the angle of repose of the material remain surprisingly stable. The possible effect of negative pore pressures on stability is considered through a simplified analysis, which shows that such effects could explain both the observed stability of these slopes and also the occasional instances of instability that occur over a small proportion of slopes. Such failures are usually associated with heavy rainfall or drainage problems.

Keywords: Slope Failure, Glacial Till, Negative pore-water pressure.

Introduction

Ongoing development of the motorway network in Ireland involves the construction of a large number of cuttings and embankments through glacially derived material known as glacial till. Current practice for the construction of such slopes typically adopts a slope angle of 1(v) in 2(h) or ≈27°. Such practice is based, to a degree, on experience in the UK reported by Perry [1], and on the results of traditional field and strength tests on soil samples.

During the mid 1800’s a major programme of railway building was undertaken throughout Ireland, which necessitated the construction of a large number of man made slopes and fills. The majority of the earthworks, built predominantly in the 1850’s involved excavations in and reworking of glacial material. The Irish railway network in common with many throughout the world has a record of insufficient funding throughout its history. This has resulted in a situation where resources available to the network operator Iarnród Éireann (IE), have been largely spent on essential maintenance work only. As a first step in plans to upgrade the Irish railway network a survey inventory of earthworks (cuttings and embankments) was carried out. This inventory included location, geometrical details, visual inspection and in some cases ground investigation of these man made features.

This paper considers the details of the survey results from the southwest region in the context of current design practice in Ireland. Through back analysis of a recent failure consideration is given to the engineering properties of the glacially derived material which forms the slopes.

Geology of region

The topography of southwest Ireland consists of relatively wide flat valleys separated by high upland areas, which become more rugged and mountainous southwards. The main rail lines are generally located within valley floors, where the flat terrain results in earthwork slopes of generally less than 5m in height. In the south, within the more mountainous terrain, earthworks are more massive with heights up to about 20 m. The predominant soil type in the area is glacial till.

The extent of till deposits in Ireland has been determined by the extent of ice cover during glacial periods. There is some evidence of Ireland being affected by at least 2 major glacial periods in the last 500,000 years, McCabe [2]. The Musterian ice occurred between about 420 to 480 thousand years ago and covered the entire country, though areas along the Cork-Kerry border are considered to have been ice-free. The last glacial period, the Midland General Glaciation, came to a close about 13 thousand years ago. The ice developed and spread over much of the Midlands, though the southern advance of the ice was halted by high relief areas, such as the Wicklow Mountains. As such, most of the land surface of Ireland is covered in glacial deposits with in places a covering of more recent deposits such as peat and alluvium, Kilroe [3]. Glacial deposits include a wide range of glacially derived sediment groups, such as glaciolacustrine clays, glaciofluvial sand and gravel, and glacial tills, the latter of which is by far the largest group.

Within southwest Ireland, till is commonly encountered as an overconsolidated low-plasticity well-graded sandy clay matrix that usually contains a large proportion of coarse particles that can range up to boulder size. In situ strength of till is generally described as very stiff to hard.

Existing Cut Slopes and Embankments

The southwest regional rail network, known as the Limerick Division, services the cities of Limerick and Cork, and the inter-connecting rail lines extending as far north as about Portlaoise (See Figure 1). Within the region there are some 750 railway slopes of height in excess of 3m, about 600 of which are soil slopes with no evidence of bedrock outcrops. Most earthworks were constructed in the 1850's. Cuttings would have been excavated by hand and the excavated material used as fill in the construction of nearby embankments. Embankment construction would have involved end-tipping of small volumes of fill from horse drawn carts with final placement and shaping being done by hand.

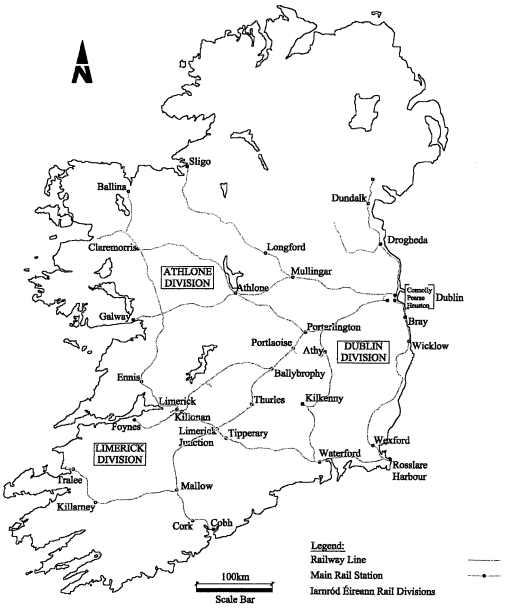
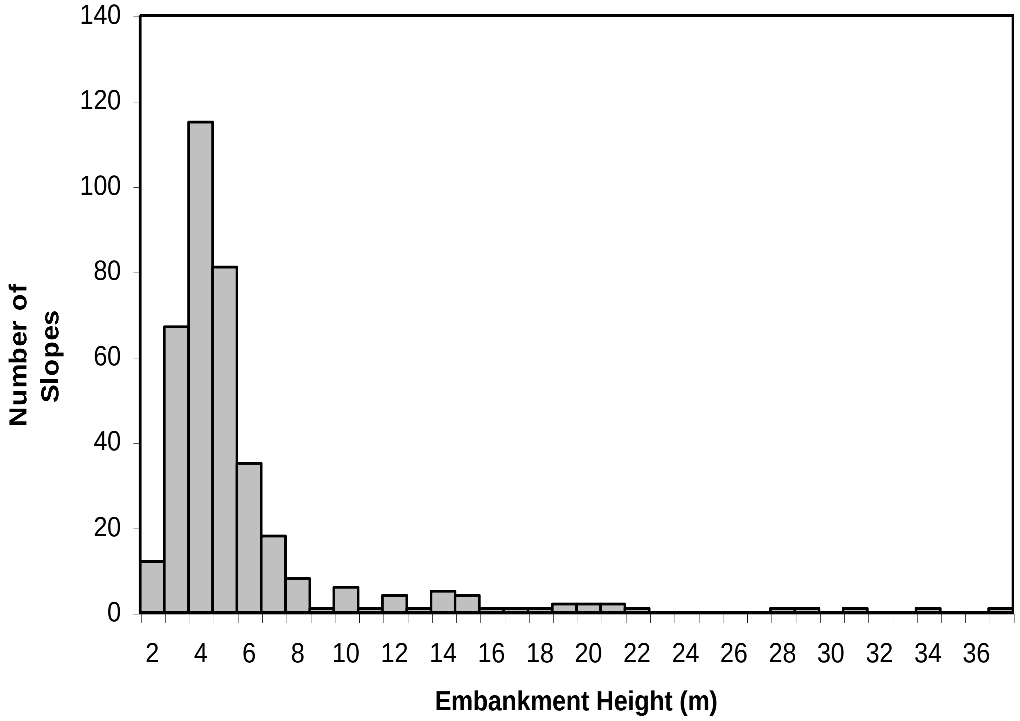


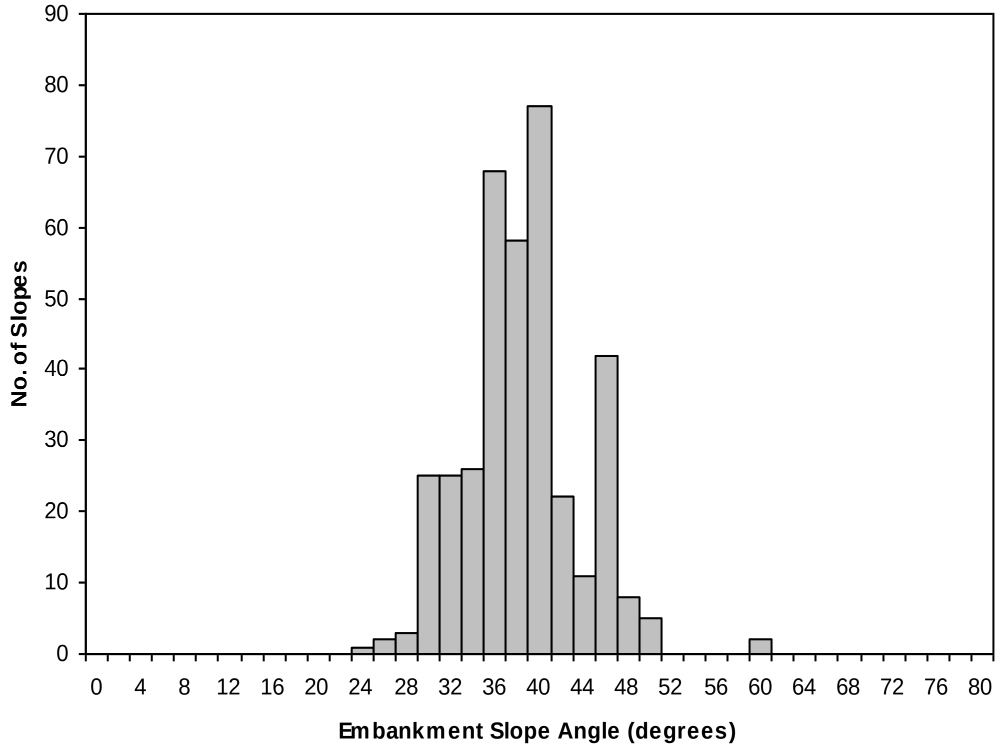
Figure 1 Map of Ireland showing Iarnród Éireann Network

The survey showed that embankments ranged in height from 3 to 30m, with a typical height of just under 5m (Figure 2a). The slope angle of embankments lay in the range 24 to 60 degrees, with 90% of slopes having a slope angle above 30 degrees (Figure 2b). Statistical data regarding the slope height and angles of cutting slopes reveals that slope angles adopted for construction of embankments and cuttings are remarkably similar.

Although survey work carried out to date has comprised mostly visual assessments and basic geometrical measurements, these investigations were carried out by experienced geotechnical engineers and revealed few signs of instability in cuttings or embankments. Two levels of instability were considered during these assessments, minor instabilities – consisting of small-scale shallow failures (with soil volume in the failed zone of less than $5m^3$), or other evidence of instability such as cracking, detachment of soil or severe erosion. About 28 of all slopes, or 5% of the total, were identified as having signs of minor instability. Only six slopes (≈ 1%) were identified which exhibited signs of major instability (recent or on-going near full height failures).



(a) Range of Embankment Height



(b) Range of Embankment Slope Angle

Figure 2. Survey details relating to Embankment Slopes

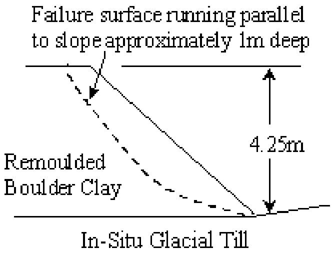


Figure 3. Shape of failure surface at Oola Embankment

Table 1 Ground Conditions at Oola Bank

Depth(m)	Stratum	SPT N (blows/300mm)
0 – 0.5m	Railway Ballast	-
0.5 - 4.25m	Remoulded Boulder Clay	-
4.25 – 9.25	Stiff Brown sandy gravely Clay with cobbles	35-44

A Case History - Oola Bank

Oola bank is an example of a typical embankment. Situated approximately 3km south of Limerick Junction (See Figure 1), the embankment is 4.25m high with a 45° slope. Oola bank has suffered two full height slope failures in recent history. The latest occurred in November 2000, following a period of heavy rainfall. A full height, shallow slip occurred, confined within the embankment slope (See Figure 3). A site investigation revealed that ground conditions at the site consist of remoulded boulder clay fill in the embankment overlying stiff sandy gravelly clay. Standpipes installed in two of the boreholes indicate that the water table level is approximately one metre below the toe of the embankment. A summary of the ground conditions and in-situ testing is shown in Table 1.

Standard Penetration Test (SPT) blow counts recorded in the stiff clay underlying the embankment typically ranged from XX to XX, such high SPT blow counts are typical for this glacial material. Particle size distribution curves show straight line grading curves associated with poorly sorted glacially derived material, with gravel and clay fractions of 30% and 15% respectively. Approximately 55% of the material passed the 425μm sieve. Index properties of this portion are given in Table 2. Hartford [4], examined the clay fraction of Irish glacial till and found the particles were predominantly rock flour, consisting of clay-sized particles of angular calcite and quartz, with negligible quantities of clay minerals.

Table 2 Index Properties of Glacial Till at Oola Bank

Property	**Average**	**Range**
Moisture Content (%)	17	14-21
Plasticity Index	16	(15-19)
Liquid Limit	32	(29-33)
Plastic Limit	15	(14-17)

Back Analysis of Slope Failure at Oola Bank

Design practice in Ireland assumes that undisturbed glacial till possesses some measure of cohesion, the cause of such an apparent cohesion value is normally attributed to cementation of the particles. However, recent research (Long pers. comm) has revealed that chemical bonding is absent in glacial till. Standard design practice would be to assume that for the analysis of embankment fills, any cementation would be destroyed during construction of the fill, and c' = 0 is assumed in design. Results of drained triaxial tests on very stiff/hard remoulded black glacial till, Farrell and Wall [5], and others, confirm such assumptions and indicate that the peak friction angle (ϕ'_p) is in the region of 37°, with constant volume friction angles (ϕ'_{cv}) of approximately 32°.

Adoption of these parameters in the analysis of slopes such as Oola Bank where the slope angle is 45°, inevitably returns a factor of safety below unity. Whilst such a result seems reasonable at Oola Bank it suggests a need for remedial works to be required on a large number of embankments. This is contrary to the findings of the visual survey which show that the vast majority of similar slopes remain stable.

Role of Suction in Embankment Stability

The construction process of all fills results in a material, which is a mixture of soil and water with air voids. Compaction during construction of the IE embankments, is likely to have been poor and therefore the proportion of air voids is likely to be high. Recent research, e.g. Fourie et al [6], Fredlund [7], Rahardjo et al. [8] & others has demonstrated the important role of soil suction on the stability of slopes, which exhibit shallow slope failures above the water table level.

The failure of such slopes generally takes the form of shallow (typically <2m deep), translational slides, which form parallel to the original slope surface. The mechanism of the slope failure has been described by Fourie et al. [6], Lumb [9] and comprises the downward migration of a wetting front (usually associated with rainfall), from the surface of the slope. The advance of water, causes a reduction (but not eradication) of near surface soil suctions. A residual suction (negative pore water pressure) has been shown to remain due to the existence of a capillary fringe just above the wetting front.

Typical residual negative porewater pressures values of 8kPa for coarse-grained soils increasing to 14 kPa for clays have been quoted by Pradel and Raad [10].

With respect to slope stability, the Factor of Safety (FOS) against failure is defined by the ratio of resistance to disturbing forces,

$$F = \int \tau_f dl / \int \tau dl . \qquad (1)$$

Forces on a slice of a slip surface are shown in the figure 4.

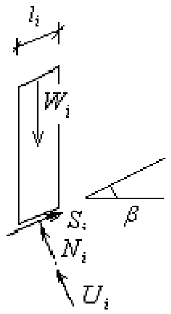


Fig 4. Forces act on a slice of the slope

From the equilibrium of force on the direction of S_i and N_i, F can be written as:

$$F = \frac{C + (\gamma h \cos^2 \beta - U_i) \tan \varphi'}{\gamma h \cos \beta \sin \beta} . \qquad (2)$$

where: C = cohesion

γ = total soil unit weight

h = vertical depth below ground level

U_i = porewater pressure

φ′ = constant volume friction angle

β = slope angle

Taking U_i as a constant, e.g. u_w, in the same layer:

$$F = \frac{C + (\gamma h \cos^2 \beta - u_w) \tan \varphi'}{\gamma h \cos \beta \sin \beta} \qquad (3)$$

When considering unsaturated slopes Fredlund et al. (1978), suggest that the shear strength of unsaturated soils should be:

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \qquad (4)$$

Considering $(u_a - u_w) \tan \phi^b$ as part of the total cohesion:

$$\tau = C + (\sigma_n - u_a)\tan\phi' \quad (5)$$

Where $C = c' + (u_a - u_w)\tan\phi^b$ is the total cohesion of unsaturated soils.

Where c' =effective cohesion,

u_a-u_w =matric suction of the soil,

ϕ'^b = angle indicating the rate of increase in shear strength relative to the matric suction,

Equation (3) can be rewritten as:

$$F = \frac{c' + (u_a - u_w)\tan\phi^b + (\gamma h\cos^2\beta - u_w)\tan\varphi'}{\gamma h\cos\beta\sin\beta} \quad (6)$$

The effect of suction on the stability of the slope at Oola bank can be considered by inserting a range of negative values of u_w into equation 6. The following soil parameters were used in the analysis, $c' = 0$, $\gamma = 20kNm^3$, $\beta = 45°$, $\phi'_{cv} = 34°$ and u_w was varied from 0 (no suction) to a maximum of -20kPa, which are typical of the range of measured negative pore pressures in this material. The highest uncertainty relates to the choice of a representative ϕ'^b value. To date there is no experimental work to quantify this parameter for Irish soils. Gan et al. (1988) (ref no.??) report tests on a glacial till, which indicate ϕ'^b varies from 7° at high suctions to 25.5° at low suction (0 to50 kPa). A ϕ'^b of 20° was adopted in the analysis.

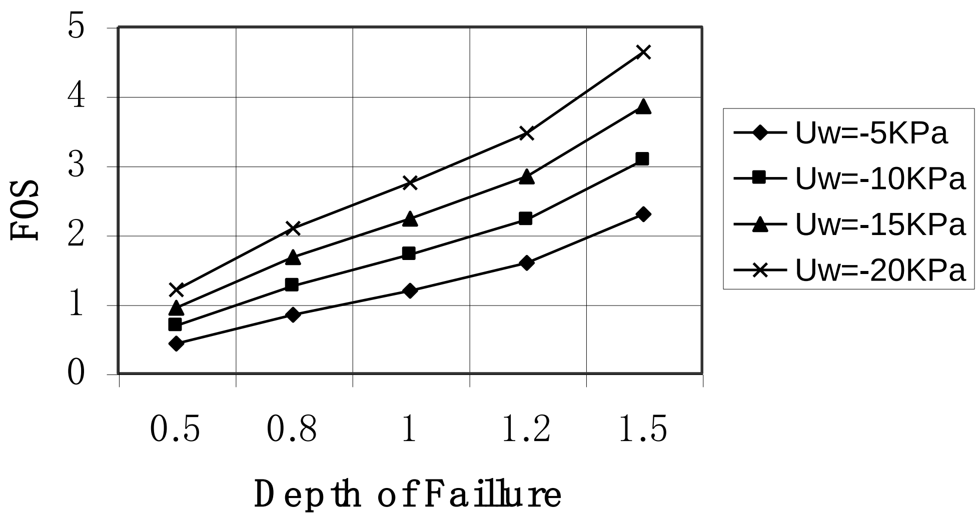


Figure 5. Effect of Suction on the stability of the embankment at Oola Bank

The results of the analysis assuming constant negative pore water pressure in the failed mass are plotted in Figure 5 as the variation in FoS against the depth of the assumed failure surface. The figure suggests that a planar failure surface (FOS < 1) would develop at a depth of 1m at Oola Bank if suctions in the near surface region of

the embankment fell to a level of –5kPa. This figure is compatible with quoted residual negative porewater pressures measured in other coarse grained soils.

Conclusions

A survey of one hundred and fifty year old man made slopes in glacial till suggests that slopes can stand at angles above their angles of repose for long periods of time. Such documentary evidence suggests that current practice for constructing these slopes at angles of 27° is conservative. It appears that due to the current volume of infrastructure development in Ireland savings both in terms of earthworks and land purchase could be achieved if higher slope angles could be adopted.

A simplified analysis was performed which considered the effect of small near-surface suctions on the stability of man made slopes and provided a possible mechanism for the observed robustness as well as insight into possible failure mechanisms of such slopes. Research work to quantify suction effects and assess their response to rainfall events is currently being carried out at University College Dublin (UCD) under the sponsorship of Iarnród Éireann.

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Reference system in text is mixed with reference numbers sometimes quoted. Need to sort out. Could also reference Jennings et al paper at last year Euro conf.

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