Performance of 150 year-old railway slopes in glacial till: case study from southwest Ireland

Performance de talus de chemin de fer de 150 ans en till glaciaire : etude de cas dans le sud-ouest de l'Irlande

Paul Jennings
Applied Ground Engineering Consultants Ltd., Bagenalstown, Carlow, Co. Carlow, Ireland: pjennings@agec.ie

KEYWORDS: 150 year-old railway slopes, glacial till, slope stability, southwest Ireland.

ABSTRACT: A survey of railway slopes has been carried out on the Irish rail network. The survey findings for the southwest region of the rail network, which comprises about 600 soil slopes formed mostly in glacial till, showed few slope instability problems. Average slope inclination was 38° with an average height of about 5m. About 6% of slopes were found to have instability problems. Most major instability problems occurred on slopes with a history of failure with first-time major slope failures generally rare.

RESUME: Une étude de talus de chemin de fer a été effectuée sur le réseau ferroviaire Irlandais. Les résultats de l'étude pour la région sud-ouest du réseau ferroviaire, qui comprend environ 600 talus composé pour la plupart de till glaciaire, ont démontré peu de problèmes d'instabilité des talus. L'inclinaison moyenne des talus était 38° pour une hauteur moyenne d'environ 5m. Des problèmes d'instabilité existaient dans environ 6% des talus. La plupart des problèmes d'instabilité se sont produits dans le cas de talus avec une histoire d'échecs, des cas de premiers échecs majeurs étant généralement rares.

1 INTRODUCTION

As part of a programme of improvement and development of the Irish rail network, an inventory and assessment survey of earthworks infrastructure comprising all trackside man-made slopes was carried out.

The survey findings for the southwest region of the railway network are presented in this paper and are generally representative of the network as a whole. The survey included both soil and rock slopes, but for the purpose of this paper the findings of the soil slopes only are presented. Most of the soil deposits through which the railway slopes are constructed are glacially derived.

The southwest regional rail network, known as the Limerick Division, services the major urban areas of Limerick and Cork and the inter-connecting rail lines. Within the region there are some 750 railway slopes, of which about 600 are soil only slopes, totalling about 200 miles in length.

2 TOPOGRAPHY AND SOIL DEPOSITS OF SOUTHWEST IRELAND

The topography of southwest Ireland consists of wide valleys separated by high upland areas, which become more rugged and mountainous southwards. The main rail lines are within the valleys where the flat terrain results in earthwork slopes of generally less than 5 m in height. Further south, the rail lines encounter more rugged and mountainous terrain with the result that earthworks are more massive, with heights up to about 20 m.

Soil deposits in southwest Ireland, and in Ireland as a whole, are dominantly glacial deposits with in places a covering of peat and alluvium (Kilroe, 1907). Glacial deposits include a wide range of glacially derived sediment groups, of which till is by far the most prominent and wide-spread group.

Till is commonly encountered as a firm to very stiff well-graded gravelly sandy clay of low plasticity that usually contains a large proportion of coarse particles that can range up to boulder size.

3 SURVEY OBJECTIVES

The objectives of the survey were the assessment of the adequacy and condition of the existing trackside slopes with regard to essentially stability and safe clearances. The survey included slopes generally 3 m in height or greater.

The main elements of the survey comprised visual inspections of all slopes supplemented by a brief desk study of available information, with site investigation at a number of slopes.

The visual inspections were designed to achieve the target of surveying all slopes within the programme. The results of the surveys were initially included in a prioritisation scheme based on likelihood of failure (White Young Green, 2001). The prioritised slopes were latterly included in a network-wide prioritisation scheme based on quantitative risk analysis (Ross and Reid, 2001).

4 BACKGROUND

Historical review of railway construction in Ireland is given in O'Connor (1999). Most of the earthworks in the southwest region were constructed around the 1850s using the empirical design methods of the day. Work was generally carried out using manual labour and horse-drawn carts. Embankment construction relied on extracting the necessary soil from the nearest possible place, which was usually the nearest cutting. Placement of fill would have involved end-tipping of small volumes from horse-drawn carts with final shaping by hand. Compaction generally involved marching workers over the placed fill. The result would have been a generally poorly compacted but homogeneous fill material.

There are few available records of documented failures of earthworks, though a number of railway slope failures were provided by Iarnród Éireann, the Irish railway company. The documented failures cover the last 30 years. Reference to earlier failures, where they exist, is provided by anecdotal evidence or newspaper articles.

5 SURVEY FINDINGS

5.1 Typical Slope Geometry

Soil cuttings ranged in height from about 3 m to 20 m but are generally less than 5 m in height. Cut slope angles ranged mostly from about 20º to 45º, with only a few slopes recorded with steeper slope

angles. About 90% of all cut slopes are at a slope angle greater than 30°. A summary of soil cutting angles and heights is shown in Figure 1(a and b).

Embankments ranged in height from about 3 m to 8 m but were generally less than 5 m in height. Embankment side slope angles ranged from about 30º to 45º. About 92% of all embankments are steeper than 30°. Few embankments are steeper than 45º. A summary of embankment slope angles and heights is shown in Figure 1(c and d).

In general there is little difference in slope angle between embankment slopes and cut slopes. The average slope angle for all slopes is about 38°, with a height of about 5m.

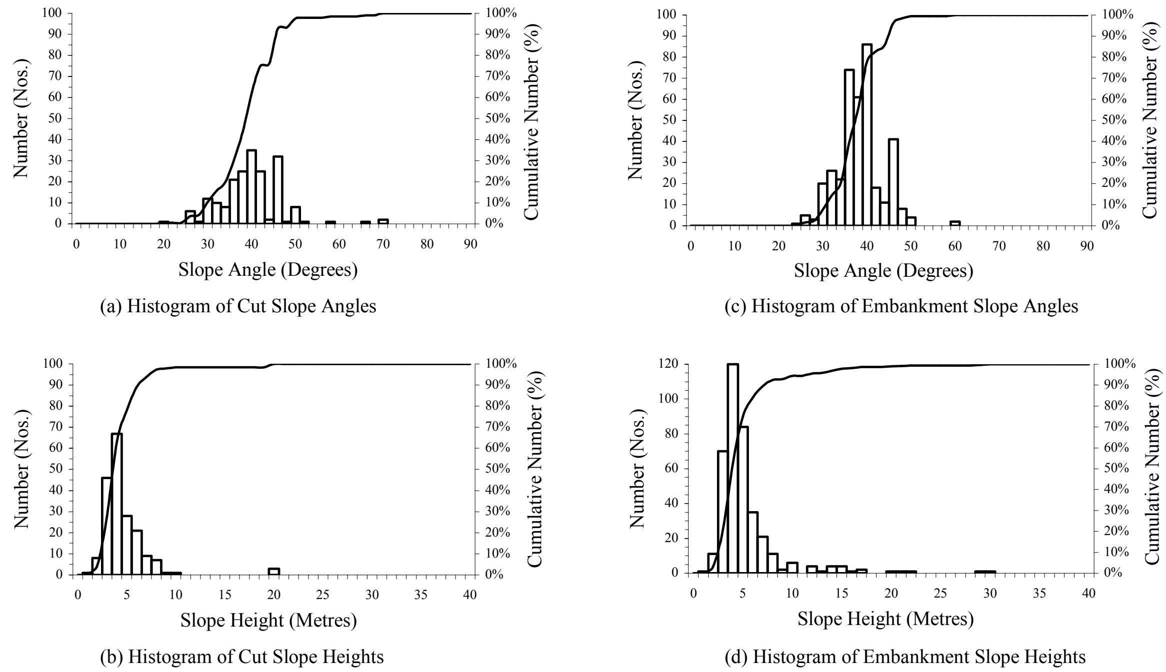

Figure 1: Histograms of Slope Angles and Heights

5.2 Earthworks Stability Problems Encountered

In general cut slopes experienced more stability problems than embankments by about 30%. The main types of earthworks stability problems encountered were as follows.

(1) Minor slope instability. This included small-scale shallow failure of generally less than 5 m^3 or minor indications of distress. Typical examples would include evidence of cracking, detachment of soil, severe erosion. This was the most prevalent type of instability and was identified on about 5% of slopes. Minor instability rarely represented a hazard to the track, and in most cases was considered a maintenance issue.

(2) Major slope instability. This involved near full-height failure of the slope, and was identified on 1% of soil slopes only. For most of the major unstable slopes, there was a history of failure. In general, first-time major instability appears to be rare. Postulated causes of major failures included typically rise in perched groundwater and softening of embankment cores.

(3) Foundation deformation. This comprised mainly creep settlement of peat below embankments. The passage of trains and re-ballasting of these embankments over time has perpetuated the settlement of the underlying peat to the present day. There were a limited number of these embankments within the survey area.

5.3 Identification of Critical Slopes

As part of the study, it was necessary to identify over-steep slopes which would have an unacceptably low Factor of Safety. This allowed critical slopes to be prioritised and a business case made for further investigation (see Perry et al., 2001). To identify critical slopes generalised soil strength parameters were assumed based on field descriptions, limited ground investigation and review of values conventionally adopted. These assumed values were then used to determine a stability index, which is basically an indicative Factor of Safety against slope failure, computed using simple stability charts.

Figure 2 shows a plot of slope angle versus slope height. Superimposed on the figure are the indicative Factor of Safety (FoS) =1.0 lines generated from the generalised soil strength parameters (ϕ'= 38° and c'= 1 kPa) for varying degrees of saturation. Where 0% saturation represents no groundwater within slope and 100% saturation represents groundwater surface coincident with slope surface.

Slopes showing signs of instability should be concentrated to the right of the FoS=1.0 lines, this is not the case. Unstable slopes show no correlation with either slope angle or height. One possible explanation for the lack of any correlation of failures is the heterogeneity of material within cuttings and the likely presence of site-specific destabilising factors. Using the generalised soil strength, a notable proportion of all slopes have an indicative FoS less than 1.0, even where there is no groundwater in the slope.

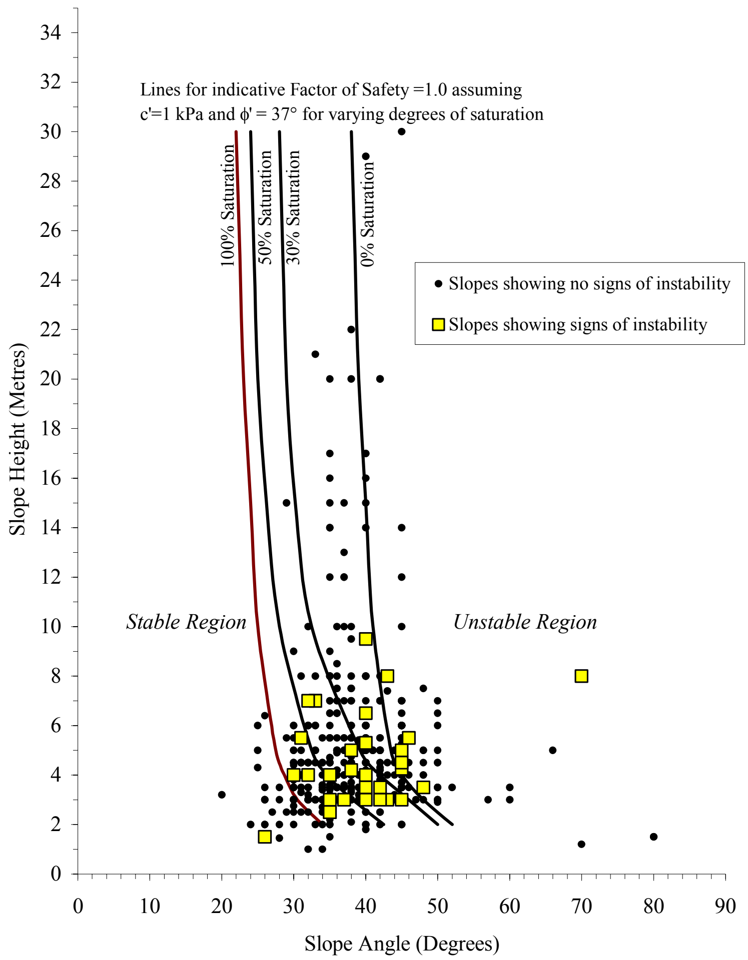

Figure 2: Slope Angle versus Slope Height

5.4 Comparison of Survey Findings with Current Earthworks Design

Slope survey data shows that about 90% of all slopes were constructed at slope angles in excess of 30° up to about 45° with very few slopes constructed at angles greater than 45°. Work in the United Kingdom on highway cutting slopes in till (Perry, 1989) showed that to limit failures then typically for a slope 5 m high the slope angle should be between about 16° and 27°. The results presented in this paper clearly indicate that the railway slopes remain stable at higher slope inclinations.

Based on the above, which has influenced current Irish practice in slope design in till, the railway slopes would be considered over-steep. Generally in Ireland most permanent cut and fill slopes in till would be constructed at slope angles of less than 30°.

Several likely factors for the seemingly over-steep slopes are as follows.

(1) Survey errors. Over-estimation of slope angle could arise from the railway practice of leaving spent railway ballast on slopes which results in localised steepening adjacent to the rail track.

(2) Unrecorded failures. There is an incomplete record of past failures, with reliable records available for only the last 30 years. It is known that large-scale failures did occur during or soon after railway embankment construction (Gregory, 1844). The generally dense vegetation cover on slopes would certainly mask some failures.

(3) Root reinforcement. The role of root reinforcement in stabilising particularly shallow instability has long been recognised (Greenway, 1987). Given that most surveyed slopes are densely vegetated, which includes a high proportion of 'woody' vegetation, there is likely to be some reinforcing effect.

(4) Effect of suction due to partial saturation. Recent work has demonstrated the effect of suction on the stability of glacial slopes (Springman et al., 2003), and the loss of suction has been postulated as a possible cause in a recent railway embankment failure (Gavin and Jennings, in prep).

Allowing for survey errors and unrecorded failures, there would still remain a large proportion of over-steep slopes that show no signs of instability. This suggests that the likely operating shear strength is higher than conventionally adopted, and that factors such as root reinforcement and suction effects are likely contributing to stability. Geomorphological evidence supports the presence of high operating shear strength with examples of till sea cliffs standing unsupported near-vertical with heights of about 30 m (Hanrahan, 1977). In the United Kingdom, Vaughan (1994) recorded natural till slopes in the north of England standing at 45°.

6 CONCLUSIONS

The following general conclusions are given.

(1) Railway slopes in southwest Ireland were constructed around the 1850s following generally empirical engineering rules. These rules appear to have restricted slope angles to 45° or less.

(2) The survey, which included some 600 railway soil slopes generally in glacial till, showed about 90% of all slope angles were between 30° and 45º with an average slope height of about 5 m.

(3) The survey showed little difference between slope angles for cut and embankment slopes. This indicates that the material is relatively insensitive to disturbance with little strength loss between in situ and re-moulded glacial till. However, cut slopes were found to have a greater proportion of instability compared to embankments.

(4) Within the survey only 6% of slopes showed signs of instability. Most instability was of a minor nature, comprising typically small-scale shallow failures. Few major instability problems were identified, and where present, generally occurred on slopes with a history of failure. First-time major failures on slopes were rare.

(5) Using generalised soil shear strength to determine indicative Factor of Safety of slopes shows that there are a notable number of apparently stable railway slopes with low Factors of Safety. This suggests that the operating soil strength is higher than conventionally adopted, and that factors such as root reinforcement and suction effects are likely contributing to long-term stability.

(6) Whilst the general findings indicate that glacial till is a relatively robust material, till is heterogeneous in nature and pre-existing localised instability problems, particularly in cuttings, may be present. This likely explains the higher proportion of instability in cut slopes compared to embankments and the generally random pattern of failure with respect to slope angle and slope height (see Figure 2).

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ACKNOWLEDGEMENTS

The author would like to thank Iarnród Éireann who commissioned and provided input to the survey. The opinions expressed here are those of the author and do not necessarily reflect those of Iarnród Éireann.