

**Soil Nailing in Glacial Till:
a Design Guide Evaluation Based on Irish and American Field Sites**

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ABSTRACT

The French in-situ earth retaining system soil nailing began in 1970 and benefited greatly from that government's investment in the 1986 study 'Clouterre'. As such, French geology strongly influenced both practice and expectations world wide over the past four decades. Yet, recent studies in glacial till, a non-French soil type, have shown significant strength under-estimation using conventionally accepted design approaches. The paper reconsiders skin friction expectations for soil nail installations in glacial till. Installation at three glacial till sites (one American and two Irish) are examined in detail. Traditional British, French, and American design methods and parameters are applied. Conventional methods under-predicted capacity by more than 50%, thereby raising serious questions as to the appropriateness of such design guidelines in glacial tills. New correlations based on pile installation design are proposed.

INTRODUCTION

Soil nailing began as a French earth retention system in 1970. The approach uses long steel inserts to generate frictional resistance between the nail and the soil, thereby forming a coherent unit resistant to horizontal and vertical loads. Understanding of the technology grew following the French 1991 publication of 'Clouterre', which summarizes the entire soil nailing design and construction processes. Recent installations in Irish glacial tills indicated a strong conservatism by applying such correlations (Menkiti and Long 2008). In fact, soil nailing adoption in Ireland has lagged significantly behind other developed countries. In the United Kingdom (UK) more than 60,000m² of face area of soil nailing was installed in 2002 alone (CIRIA 2005), with huge growth having occurred in the 1990's especially for infrastructure projects. In contrast, Irish practitioners cite a paucity of expertise, lack of knowledge, protectionism related to older techniques, and inadequate design guides as reasons that Irish soil nailing usage lags (O'Dowd 2009). While several design guidelines exist [e.g. Clouterre (1991), England's Highways department HA68/94 (1994), BS8081 (1981), and CIRIA (2005)] none specifically addresses soil nail performance expectations in glacial tills.

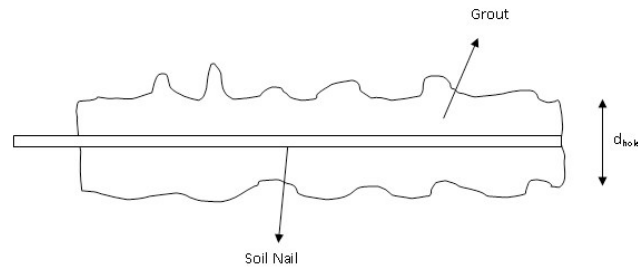


Fig. 1. Profile of embedded portion of soil nail.

The prominence of glacial tills in Ireland challenges the applicability of current design guides for the Irish context. Currently most work is conducted based on contractor experience, and little is known about long-term performance in such widely encountered tills as Dublin Boulder Clay (DBC). This paper investigated a more accurate means of predicting skin friction for soil nails in glacial tills.

BACKGROUND

DBC can stand at angles up to 80° in natural slopes for indefinite periods of time without additional support, despite having negligible cohesion (O'Dowd, 2009). The observed short-term stability has been attributed to the materials' very low permeability (10^{-8} - 10^{-10} m/s) combined with suction created during excavations (Menkiti and Long, 2008). This unique ability allows for greater excavation cuts in DBC than most materials; previously, Bruce and Jewell (1986b) noted that in over-consolidated clays cuts greater than the industry standard of 2m for granular soils were often observed. DBC, however, is variable and may include local sand/silt seams. According to O'Dowd (2009), Irish soil nailing first occurred in Cork in 1978. Initial Irish usage concentrated on slope stabilization and deep basements. The 1981 British Government's decision to require BS8081 (1981) for soil nailing design; thereby mandating full double corrosion protection, effectively ended Irish soil nail usage (O'Dowd 2009) until after the introduction of HA68/94 (1994) more than a decade later.

SCOPE

This project examines current practices in soil nailing in glacial tills with regard to establishing a further understanding of performance and best practice. Although there are a large number of factors influencing soil nail performance, the key interaction and the most difficult parameter to assess in design is skin friction, which is currently obtained from design guides or pull out tests on sacrificial nails. To investigate this issue, a four-pronged approach was taken: (1) data and information were gathered through personal interviews conducted with representatives of both of Ireland's soil nailing contractors, (2) a survey was issued to soil nailing specialists worldwide, (3) a review of design guides used for predicting skin friction was conducted, and (4) pull-out test results from two case studies in Dublin, Ireland and one in Washington, United States (US) were examined. The project compared the design codes, results obtained, opinions, and previous research conducted over the past 40 years to make recommendations as to which design guide most closely predicts the values of skin friction measured during a number of case studies in glacial tills.

METHODOLOGY

Interviews were held with both of Ireland's soil nailing contractors: P.J. Edwards's Geotechnical Consultants Ltd. and PHI Ireland Ltd. regarding Ireland's relatively slow soil nail adoption rate, perceptions about potential barriers, and challenges to soil nail installation in glacial tills. This informed the survey creation, which was sent to 22 soil nail contractors and designers worldwide representing the membership of the Soil Nailing committee of the Deep Foundation Institute (DFI); 6 responses were received. The aims were to inquire as to how frequently soil nailing was used, where, with what designs guides, and whether skin friction values used in design were considered conservative. Finally, data from three field sites dealing with skin friction in glacial till were evaluated and data from pile design in DBC (Gavin 2009) (Table 1). Three of the projects were located in or around Dublin Ireland and the fourth in the American state of Washington, where Vashon Till (VT) was present (Mitchell et al. 2007). All of the soil nails were drilled and grouted nails. Unfortunately Irish soil nails are rarely tested to failure due to cost.

Table 1 Soil Properties

Project	Menkiti and Long (2008) – DPT	O'Dowd (2009) - Trinity College	Mitchell et al. (2007)	Gavin (2009)
Soil Type	Glacial till (DBC)	Fill overlaying Glacial Till (DBC)	Glacial till (Vashon till - VT)	Glacial till (DBC)
Description	Very stiff to hard dark-grey slightly sandy clay with some gravel and cobbles zones	10 m of fill overlaying very stiff to hard dark-grey slightly sandy clay with some gravel and cobbles zones	Silty, gravelly sand to sandy clay ("hardpan"); cobbles and boulders; very dense to hard	Very stiff to hard dark-grey slightly sandy clay with some gravel and cobbles zones
Location	Dublin	Dublin	USA	Dublin
Friction Angle (ϕ')	32.5°	30°	45° *	32.5°
γ	20.5 kN/m ³	18 kN/m ³	20 kN/m ³	18 kN/m ³
C_u / SPT (N)	220kPa	Not available	SPT: 50 (HWA Geosciences 2007)	SPT: 20 to 80

*Based on typical SPT value of 50 and look as a well-graded sand and gravel (Smith and Smith 1998).

At the DPT (Dublin Port Tunnel) pull out tests were conducted to obtain skin friction values on sacrificial nails at varying depths across the height of the excavation generating ultimate and maximum skin friction 212-550kPa. (Maximum skin friction occurs where the nail and gout interface fail, as opposed to Ultimate skin friction where the soil and grout interface fail). Not dissimilarly, Mitchell et al. (2007) collected ultimate skin friction values 300-950 kPa in VT in Washington based on micropile installation.

At a soil nailed retaining wall at Trinity College Dublin (TCD) in fill overlaying DBC, to confirm assumed skin friction values proof tests to 150% of the design working load were performed on 5% of the nails in accordance with BS8081 (1989). TCD site exhibited a maximum measured skin friction of 70kPa at strains ranging from nearly 10% to 14%, at which point testing was discontinued. For the purpose of design, the contractors used conservative values of friction angle and bulk density (Table 1) [O'Dowd 2009].

Adapting Results

Developing dimensionless analysis to allow for relevant comparisons to be made between results was necessary for developing a better understanding of nail performance in Glacial Till. In particular, nail loads measured during testing on the TCD site was converted to skin friction values, which are independent of nail length and spacing. This conversion was necessary for comparing results from different sites. Nail load was converted to skin friction using eq 1 (Clouterre 1991).

$$q_s = \frac{T_f}{\pi L_e d_{hole}} \quad (\text{eq 1})$$

where q_s = skin friction (kPa), T_f = load in the nail (kN), d_{hole} = nail hole diameter (mm), and L_e = effective length of the nail (mm).

The TCD information is not as straightforward as the nails were not pulled to failure. Thus, it only gives an indication of how the nail performs up to 150% of its designed working load. To conduct dimensionless comparisons skin frictions calculated for the TCD site were compared with strain (ϵ) in the nail (eq 2)

$$\epsilon = s / L_e \quad (\text{eq 2})$$

where s = displacement at the nail head (mm).

Data collected from Gavin (2009) included results from SPT tests carried out in DBC's across the Dublin area. SPT (N) values can easily be converted to undrained shear strength (C_u) using eq 3 (Gavin 2009).

$$C_u = 6 N \quad (\text{eq 3})$$

Calculating Skin Friction

To compare actual performance and current design, the skin friction suggested by current design guides in use in Ireland was calculated. The design guides examined were: CIRIA (2005), HA68/94 (1994), and BS8081 (1989). While Clouterre is not used directly, most of the codes reference it and hence skin friction results suggested by Clouterre (1991) were also considered (Table 2). Using these design guides ultimate skin friction was calculated. In contrast, CIRIA (2005) details a number of methods for predicting skin friction all of which were used in the report (see Table 3). Table 3 shows values suggested for pull out resistance for Boulder Clay and Glacial tills.

Table 2 Clouterre Skin Friction

Soil	Limit Pressure	Skin Friction
Clay	200kPa	50kPa
Clay	2600kPa	125kPa
Sand	500kPa	50kPa
Sand	3000kPa	125kPa

Table 3 Information extracted and tabulated from Ciria (2005)

Source	Values
FHWA (1998 and 2003)	40–100 kPa
Pull out test data for DBC	177–235 kPa
Effective Stress Methods	As per HA 68/94
Undrained Shear Strength Methods	As per BS8081
Correlations with Pressuremeter tests	As per Clouterre

In Fig. the solid black squares represent soil values in DBC obtained from O'Dowd (2009) and the open circles represent values from Menkiti and Long (2008). Optimal values of skin friction were achieved using the highest bulk density and friction angle; however at low depths (around 2m) the effects of friction angle and bulk density on skin friction are minimal. For calculations according to BS8081 ($q_s=C_u.\alpha$) 2 values of alpha were considered ($\alpha=0.45, 0.75$), with α a 'fudge' factor to reduce shear strength to account for changes in the soil state (e.g. dilation) as piles are installed. As a result, α varies with soil and installation method; α for bored piles in stiff clay (DBC for instance) should be taken as 0.45 (Craig 2004). Gavin (2009) also suggested that α for driven piles in Boulder Clay span 1.0 at $C_u=80\text{kPa}$, to 0.45 when C_u exceeds 200kPa and that for piles in DBC α can be as high as 0.75 for bored pile design, contingent upon field verification. Fig. shows results of calculations using SPT (N) values taken from Gavin (2009) and converted to C_u values using eq 3.

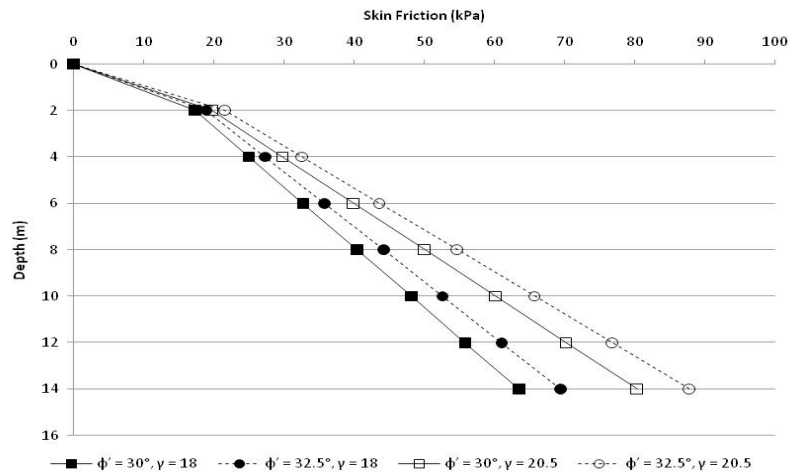


Fig. 2 DBC, HA68/94 Changing γ and ϕ

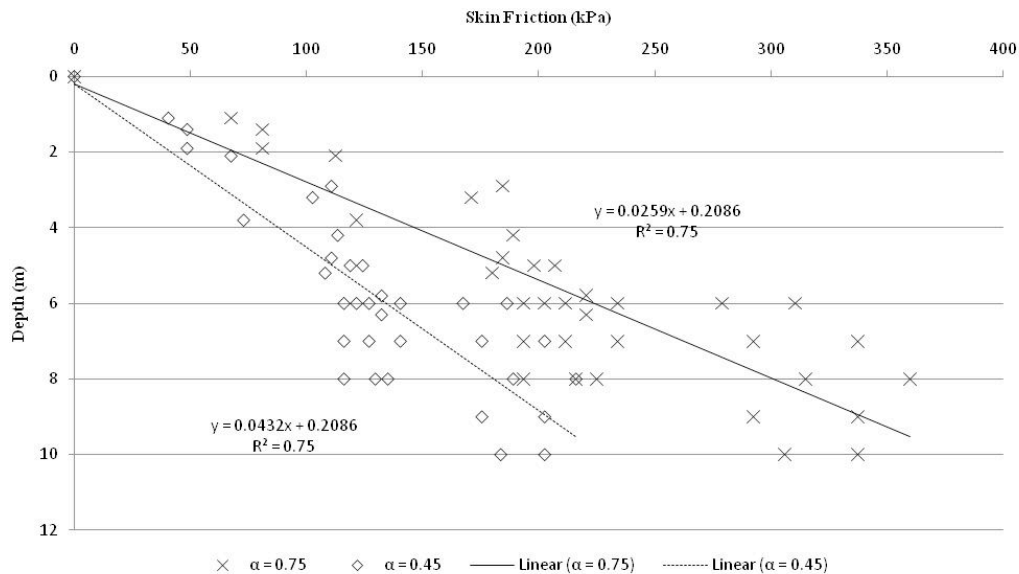


Fig. 3 DBC Skin Friction by BS 8081 ($\alpha=0.45, 0.75$) (C_u from Gavin, 2009a)

As shown in fig. 3, the skin friction predicted for DBC using HA 68/94 greatly underestimated the values obtained from Menkiti and Long (2008), by a factor of approximately four. The pull-out results predicted by CIRIA are extremely conservative compared to the field results reported by Menkiti and Long (2008) (Fig. 4). Skin friction from design guides CIRIA (FHWA) and Clouterre was also plotted and was found to be even more conservative (Fig. 4). The maximum value obtained from these design guides was for the upper limit of Clouterre (125kPa), which was well below the lowest ultimate skin friction (212kPa).

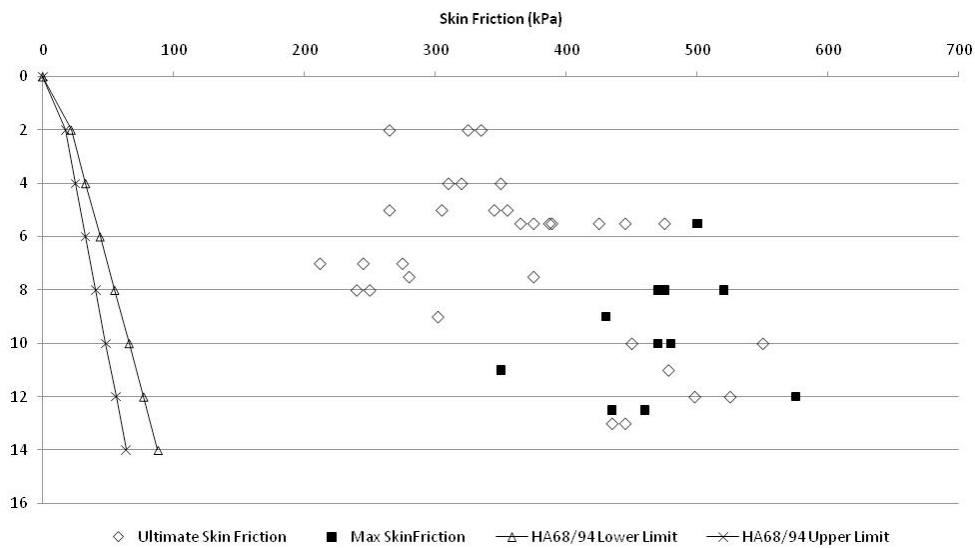


Fig. 4 DBC, DPT versus HA 68/94

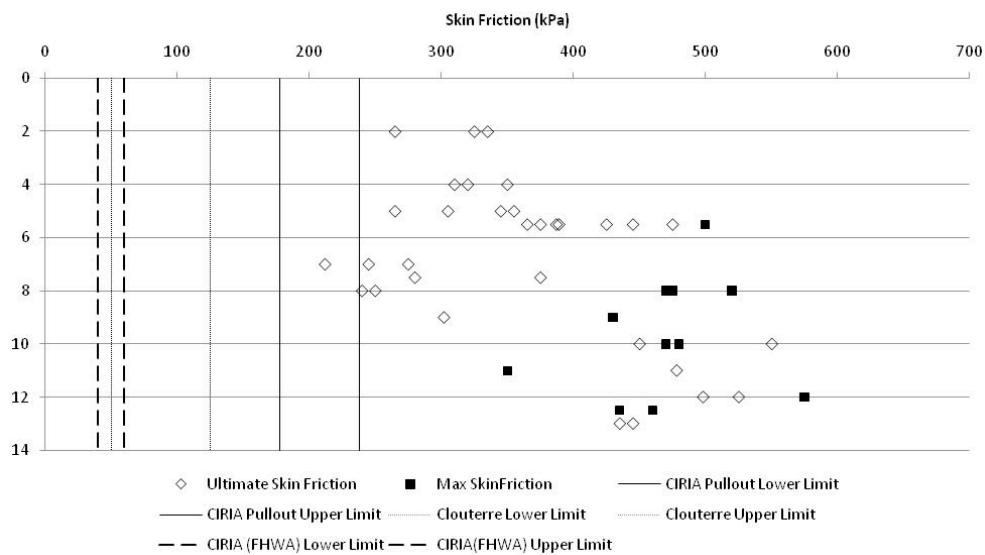


Fig. 5 DBC, DPT versus CIRIA pullout, CIRIA (FHWA), and Clouterre

Fig. 5 shows predicted skin friction values using the undrained shear strength method with $\alpha=0.45$ and 0.75 based on Gavin (2009). This is the first case where a clear correlation can be noticed between predicted and measured results.

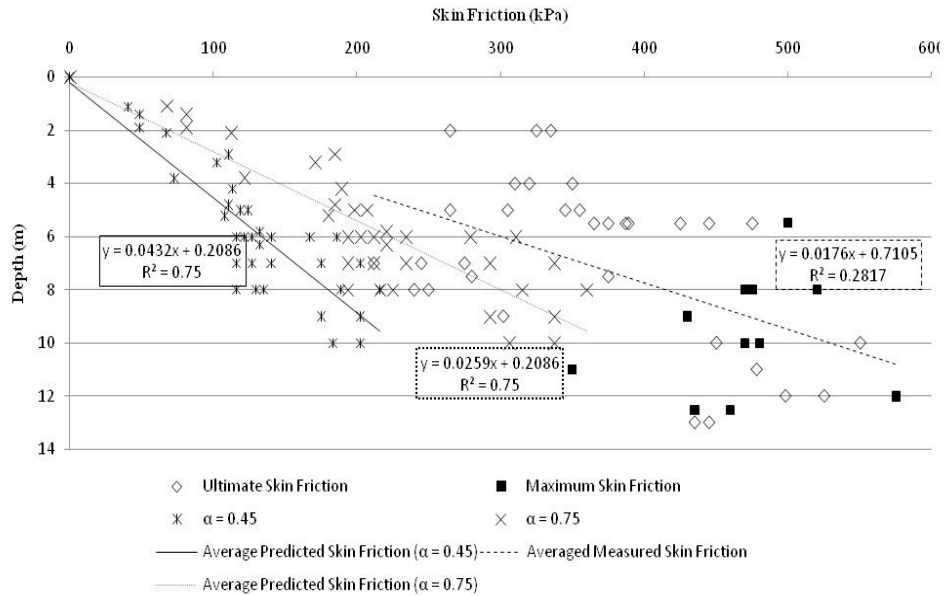


Fig. 6. DBC, DPT versus BS8081 Cu from Gavin (2009)

Trinity College Dublin Performance

The results of maximum skin friction for the TCD retaining wall were compared against that obtained from CIRIA, Clouterre, and HA68/94 (Fig.). The maximum measured skin friction of 72 kPa correlates well with the suggested skin friction of Clouterre, but these nails were not tested to a very high load. Correlations with BS8081 were not carried out here as the skin friction predicted using BS8081 (Fig.) was more than three times that recorded at the site.

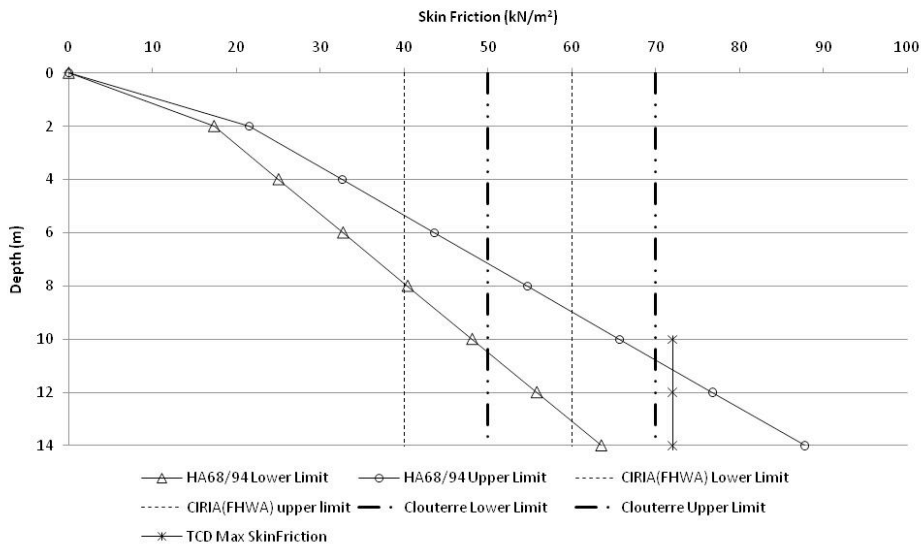


Fig. 7 DBC, TCD measured vs predicted

Vashon Till Performance

Fig. shows overly conservative skin friction results predicted in VT by HA68/94 (1994) and those suggested by Clouterre compared to results reported by Mitchell et al. (2007). Results are regularly underpredicted by at least half.

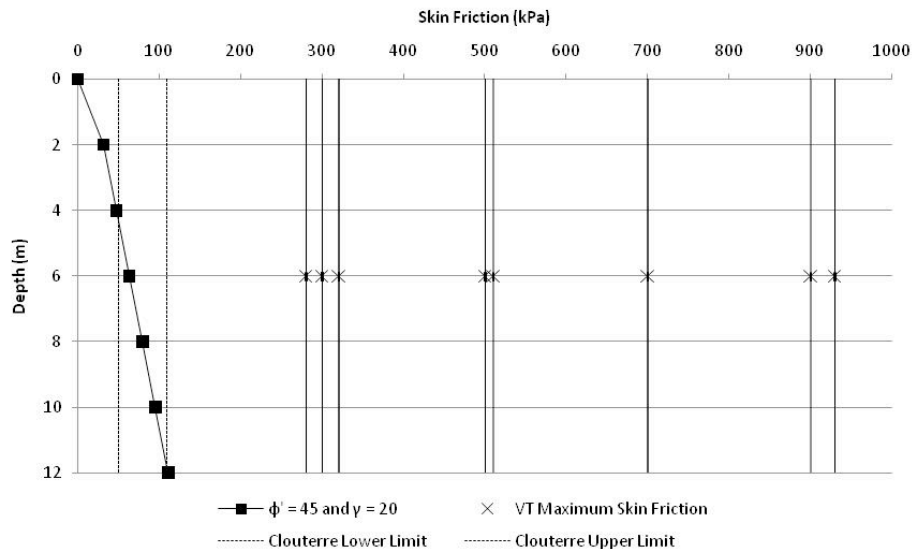


Fig. 8 VT HA68/94 and Clouterre vs skin friction Mitchell et al. (2006)

Summary

Table 4 summarizes the results of using the primary design guides (HA68/94, BS8081, CIRIA, and Clouterre) for glacial till. Where the nails were pulled to ultimate capacity, under prediction was by as much as four fold. Only at the TCD site, where the nails were not full stressed did HA 68/94, Clouterre and CIRIA provide reasonable correlations (Fig.). Undrained shear strength methods of predicting skin friction provide the closest match to the measured values of skin friction for DBC (Fig.), where a critical design value is α .

Table 4 Design Guide Performances

Design Guides	Project / Soil Type		
	DPT – DBC	TCD – DBC	VT
BS8081 (1989)	Satisfactorily predicts (α is key)	Inconclusive *	--
HA68/94 (1994)	Underestimates greatly	Satisfactory	Underestimates greatly
CIRIA (2005)	Underestimates	Inconclusive *	--
Clouterre (1991)	Underestimates	Inconclusive *	Underestimates

*Inconclusive results were obtained for some of

Table 4 particularly at the TCD site. In these cases it was not possible to make comparisons as the nails were simply not loaded sufficiently.

FURTHER ANALYSIS

The undrained shear strength method (BS8081) for predicting skin friction provided the most accurate results for ultimate skin friction (Fig.). A value of α as 0.75, only marginally underestimated the average skin friction in DBC. In contrast, the effective stress methods (Fig. and Fig. for DBC and VT respectively) greatly underestimated skin friction. Using a value of $\alpha=1.1$ [instead of the previously

proposed value of 0.75 (Gavin 2009)] provided the best fit between the predicted and measured results (Fig.).

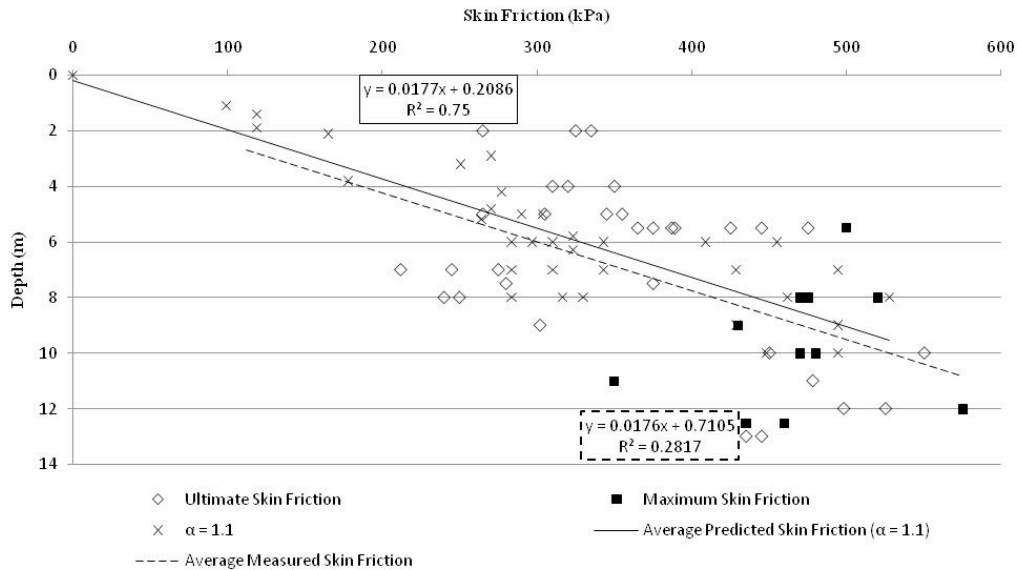


Fig. 9. DBC measured versus predicted skin friction ($\alpha = 1.1$, C_u from Gavin (2009))

Alpha values for piles are based on a displacement (s) over diameter (D) ratio of 5% (Fig.). Because of the comparatively small diameters and large lengths of soil nails. An s/D of 10% may be in the range of 10mm, and if of concern could be mitigated by pre-tensioning the top row of nails as suggested by Wolosick (1988).

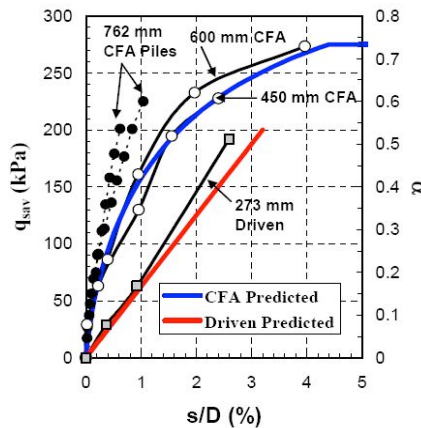


Fig. 10. Measured and Predicted pile skin friction, extracted from Gavin (2009).

Craig (2004) suggested that α values should not exceed 1.0 as this would imply more than the soil shear resistance was being mobilised. However a value of $\alpha=1.1$ could be justified in soil nails due to the irregularities created during the installation of the grout around the nails. These irregularities protrude into the soil potentially generating extra resistance shear strength of the soil through shear keys.

While the findings presented are extremely promising in terms of predicting skin friction of Glacial Till, it is important to remember that data sets for only one case study were considered in terms of assessing a new value of α for Glacial Till.

To substantiate the findings and significantly more data are needed, especially as α is an empirical value.

SURVEY RESULTS

Survey results showed the primary American design guide used was FHWA GEC 7, with 5 of the 6 respondents citing this document as a good reference, but even so 40% of those with experience nailing in Glacial Tills suggesting that current designs underestimate the pull out resistance. Additionally 83% of respondents noted that soil nailing design relies heavily on local experience, so it is likely that they have developed their own proprietary correlations for skin friction in the same way as has been done in Ireland (O'Dowd 2009).

CONCLUSIONS

Primary design guides (HA68/94, BS8081, CIRIA, and Clouterre) to predict the performance of soil nails in glacial till generate conservative results. As such, use of undrained shear strength methods (BS8081) is proposed to predict skin friction. Gavin (2009) suggestion of $\alpha=0.75$ would be better for nail design in glacial tills, and simple correlations based on one project showed that a value of $\alpha=1.1$ might be most appropriate for Dublin Boulder Clays. However since α is an empirical value further confirmation and verification is needed.

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