Title	Analysis of jacking force data for microtunnels in glacial till at Kilcock, Ireland
Author(s)	Curran, Brien G.; McCabe, Bryan A.
Publication Date	2011
Publication Information	Curran, B.G. and McCabe, B.A. (2011) Analysis of jacking force data for microtunnels in glacial till at Kilcock, Ireland, Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering, Athens, Vol. 3, pp. 1627- 1632. DOI 10.3233/978-1-60750-801-4-1627
Publisher	IOS Press
Link to publisher's version	http://dx.doi.org/10.3233/978-1-60750-801-4-1627
Item record	http://hdl.handle.net/10379/6328
DOI	http://dx.doi.org/10.3233/978-1-60750-801-4-1627

Cite as:

Curran, B.G. and McCabe, B.A. (2011) Measured jacking forces during slurry-shield microtunnelling in a boulder clay at Kilcock, Ireland, *Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering*, Athens, Vol. 3, pp. 1627-1632.

Analysis of jacking force data for microtunnels in glacial till at Kilcock, Ireland

Microtunneliers dans les till de Kilcock, Irlande: Analyse des données d'effort de poussée.

Brien G. Curran
Ward and Burke Construction Limited, Kilcolgan, Galway, Ireland (formerly of the Department of Civil Engineering, National University of Ireland, Galway, Ireland)

Bryan A. McCabe[1]
Department of Civil Engineering, National University of Ireland, Galway, Ireland

ABSTRACT

Although the application of microtunnelling to pipeline construction has grown considerably in Ireland in recent times, there is very little published guidance on the jacking forces that might be expected in Irish ground conditions. In this paper, relevant experience from jacking records for a Sewerage Improvement Scheme project in Kilcock, Co. Kildare, Ireland is presented. Data from almost 0.9km of pipe-jacked tunnels constructed below the water table at depths between 2.4m and 4.4m in largely greenfield conditions are examined. Topics discussed in this paper include the separation of jacking force into friction and face components, lubrication and stoppages.

RÉSUMÉ

Bien que l'utilisation des microtunneliers dans la construction de pipeline a considérablement augmenté dernièrement, il existe très peu de publications concernant les efforts de poussée et au cas des sols irlandais. Cet article présente une expérience intéressante de relevé d'efforts de poussées pour un projet d'assainissement à Kilcock, dans le comté de Kildare en Irlande. Près de 900 m de galeries ont été creusées au tunnelier sous le niveau de la nappe à des profondeurs de 2,4 et 4,4m dans des sols vierges. Plusieurs sujets sont abordés dans cet article, notamment la séparation de la force résultant des efforts de poussée en une composante liée au frottement et une composante liée au front de taille, la lubrification et l'arrêt.

Keywords: Microtunnelling, jacking forces, glacial till, stoppages, lubrication

1 INTRODUCTION

Over the last few years, Ireland has witnessed considerable growth in the use of microtunnelling to construct pipelines for water, sewage and gas conveyance networks through a variety of soil and rock types [1,2]. Utility designers are starting to appreciate the technical reliability, environmental benefits and cost certainty afforded by microtunnelling and trenchless technologies in general.

A preference for slurry shield microtunnelling machines (Herrenknecht versions) has emerged in Ireland as they are most suited to the variable ground conditions commonly encountered. These machines have the option of various head arrangements; scraping teeth to shear softer soils, cutting discs to split rocks/boulders and a versatile mixed head (Figure 1) equipped with a combination of both. Openings in the cutter head allow the excavated material to enter a crushing cone, where any large rock, cobbles or gravel

[1] Corresponding Author.

pieces are reduced in size for transportation away from the head of the tunnel.

Water-based slurry is pumped to the head of the machine (at a pressure slightly in excess of hydrostatic groundwater pressure) where it mixes with the excavated material. The slurry mixture is then pumped back to the surface where the spoil is removed in the separation plant comprising a series of vibrating screens, hydrocyclones and centrifuges, from where the water is recirculated to the head of the machine. Tight control of the slurry pressure is paramount as it is used to support the excavated face and balances groundwater pressure. In highly permeable soils such as gravels, or where boulders are encountered, bentonite is added to the slurry to form a filter cake at the face to prevent the loss of slurry into the ground and an associated loss of face pressure.

Figure 1. Herrenknecht 'mixed head' used at Kilcock

Several successful utility projects have been completed in Ireland using slurry-shield microtunnelling [1,2]. Nevertheless, the relative recency of its application in Ireland has meant that there has been little published experience heretofore on the factors influencing jacking forces in indigenous soils. Jacking forces measured in soft ground conditions at two Irish sites, Howth and Downpatrick, have been reported very recently [2]. In this paper, jacking forces recorded at a glacial till site in Kilcock, Co. Kildare, Ireland are examined, with discussion on factors such as separation of friction and face contributions to the total jacking force, slurry properties, lubrication, stoppages and soil consistency.

2 SCOPE OF CONTRACT

Eleven individual microtunnel drives totalling almost 900m in length, constructed at Kilcock by Ward and Burke Construction Limited as part of the Lower Liffey Valley Regional Sewage Scheme, were monitored. Six of these drives were completed during April and May 2009; the remainder followed between January and April 2010. The drives were conducted in greenfield conditions, except for two which were performed beneath streets. Herrenknecht's AVN 600 tunnelling machine (780mm in diameter; to accommodate concrete pipes with 760mm external diameter and 600mm internal diameter) was deployed and equipped with a mixed head (Figure 1). The jacked length (L) and depth to the tunnel axis (z_0) are provided in Table 1 for each drive.

Table 1. Summary details of individual drives

Drive ID	L (m)	z_0 (m)	Soil type (at microtunnel face)
35-36	95	2.4-4.4	Dense gravel overlying stiff gravelly clay
35-34	105	4.3-4.4	Dense gravel changing to stiff gravelly clay
32-34	107	4.1-4.3	
32-31	107	4.0-4.1	Dense coarse gravel
30-31	114	3.7-4.0	Soft clay changing to dense gravel
30-29	90	3.8-3.9	Soft clay changing to very stiff gravelly clay
28-29	105	3.8	Gravely clay changing to sandy gravel
28-27	90	3.6-3.8	Stiff gravelly clay with occasional boulders
26-25	27	2.9-3.0	Firm gravelly clay
22-21	20	2.6-3.3	Soft peaty clay overlying dense sand
19A-38	35	2.9	Dense sandy gravel

The drive IDs in Table 1 are defined by the manhole numbers at the extremities, i.e. drive 35-36 was launched from manhole 35 and was received into manhole 36. Many drives share a manhole at one or other end.

Bentonite lubrication was used in all drives beyond a certain jacked distance; this was mixed in a batch plant and pumped through three ports behind the cutting head. The consistency of application of the bentonite was somewhat operator-dependent.

3 GROUND CONDITIONS

Kilcock is a provincial town (population over 4,000) situated in Co. Kildare to the east of Ireland where glacial till is the predominant sediment. Ground conditions, determined at the anticipated manhole positions, typically comprised firm to stiff brown and black glacial clay with medium dense to dense gravel layers, without any consistent pattern within the shallow depth range of the pipelines. Summary descriptions are provided in Table 1. Standard Penetration Test N values exhibit considerable scatter with depth (from N=7 to N>50), a tendency which has also been noted at other glacial till sites in the region, such as Mullingar [3] and in the Dublin area [4]. An indication of the spectrum of particle size distribution curves is shown in Figure 2.

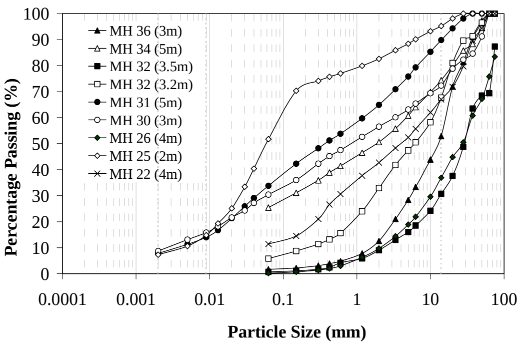

Figure 2. Grading curves for the Kilcock till

4 JACKING FORCE INTERPRETATION

4.1 Separation of jacking loads into skin friction and face components

Face load was not measured directly by the microtunnelling machine for the Kilcock drives, and in such situations, other means must be used to separate the skin and face loads from the total jacking load. Determination of the average jacking force variation with jacked distance from the 'raw' data, in addition to the minimum and maximum bound envelopes, is a necessary preliminary step and is illustrated in Figure 3 for drive 28-27.

The frictional load during jacking (i.e. dynamic friction) can be approximated from the minimum bound to the total jacking load [5], as shown in Figure 3. An alternative method for estimating shaft frictional load is based on the final jacking load once the machine has 'broken' into the reception manhole, when face load falls to zero. Five of the eleven drives have data of the latter type with adequate resolution for the two methods to be compared. The correspondence is strong (within 5% for four of the five), suggesting that either method is appropriate.

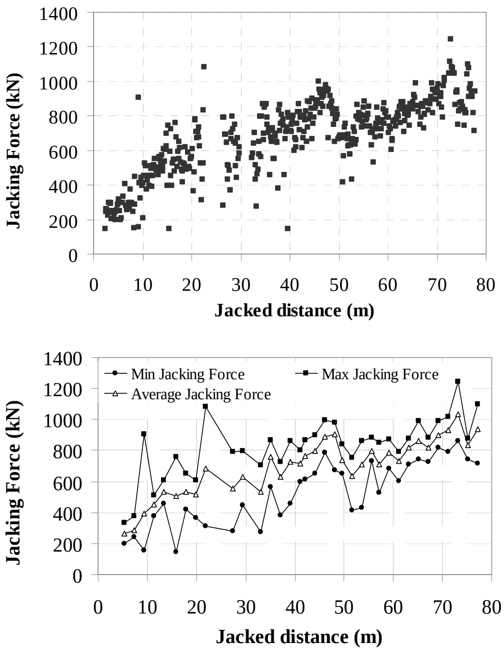

Figure 3. Jacking force data for drive 28-27: raw data (above), processed data (below)

Likewise, there are a number of approaches for estimating the face pressure. The authors' preference takes the average difference between the minimum and maximum bound envelopes to the total jacking force [5], as it is consistent with the corresponding approach for estimating friction. Alternatives are not as satisfactory; estimating face pressures over the initial few pipe-lengths after launch (when skin friction is low) is difficult as, with little control on steering, the driving style is cautious. High confidence in data resolution is required if face pressure is to be estimated as the drop in jacking load from just before to just after breakthrough, at the end of the drive.

4.2 Measured frictional stresses

Measured (lubricated) dynamic frictional stresses $f_{s,l}$ for Kilcock are shown in Table 2. For the purposes of this paper, frictional stresses are calculated assuming full contact area between pipe and the ground, as is used by many authors when comparing drives in different ground conditions or where different pipe diameters have been used. In this study, frictional stresses fall below or to the lower end of the 5-25 kPa recommended by the Pipe Jacking Association [6] as a guide.

In the dense gravels, $f_{s,l}$ values varied between 1.7 kPa and 4.0 kPa, while $f_{s,u}$ (unlubricated) values fell between 5.2 kPa and 8.4 kPa These values are generally consistent with the 2-6 kPa range reported in similar ground conditions [7]. Lubrication serves to reduce the frictional stresses by between 60–80%**.** In dense sand, one measured $f_{s,l}$ value of 2.6 kPa fall within the range of 1-7 kPa suggested by the same author [7].

For the drives in which stiff boulder clay was encountered, ranges of $f_{s,l}$ and $f_{s,u}$ are 0.5-7.8 kPa and 3.5-12.6 kPa respectively. These values are generally below or at the lower end of ranges recommended from other work of 3-18 kPa [7] and 5-18 kPa [8]. The reduction in friction of between 52–70% in stiff clay and 46% in soft clay indicates compares favourably with findings from research in others clays (43 – 47%; [5]).

4.3 Measured face stresses

Face stresses (f_f), obtained by dividing the face loads by the face area (diameter 760mm) and correcting for the 20kPa slurry pressure, are shown in Table 2. In the dense sandy gravel, f_f was equal to 473 kPa, within the range of 200–540 kPa observed elsewhere in sandy gravel [9].

The average f_f varied between 387 kPa and 663 kPa in stiff clay and 262 kPa and 386 kPa in soft clay. Again these values are within the range reported in clayey soils [9], between 180 and 350 kPa.

Table 2. Measured lubricated dynamic friction and face pressures

Drive ID	**$f_{s,l}$ (kPa)**	**f_f (kPa)**
35-36	2.2	537
35-34	1.7	620
32-34	2.1	451
32-31	1.7	656
30-31	1.9	298
30-29	0.5	387
28-29	4.0	315 (0-55m) 694 (55-105m)
28-27	3.8	644
26-25	7.1	663
22-21	2.6	262
19A-38	2	473

5 FACTORS INFLUENCING JACKING PROCESS

5.1 Slurry Water and Penetration Rate

During drive 30-29, penetration rates in the stiff clay were low. One of the causes identified was the saturation of the slurry water with clay particles; erosion of the face and transportation of excavated material is most efficient when combined with clean water. The findings of an investigative study are shown in Figure 4, in which the specific gravity of the slurry was determined and correlated with the penetration rate at 2m intervals over the course of jacking. The adverse effect of increased specific gravity on penetration rate is very clear.

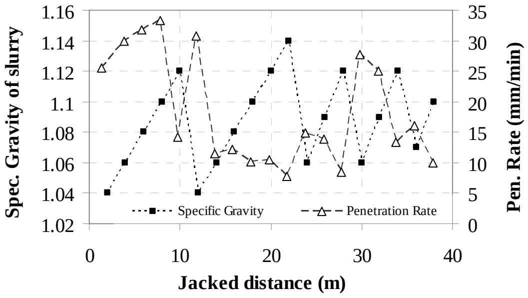

Figure 4. Influence of specific gravity of slurry on penetration rate

5.2 *Stoppages*

Increases in jacking loads following interruptions (i.e. the difference in load between the last thrust before a period of downtime and the first thrust at restart) was determined and plotted against the jacked length for each soil type encountered at Kilcock (see Figure 5). Stoppages were distinguished as short (<1.5 hours), usually owing to the addition of a pipe and other short breaks, and long (>12 hours), usually owing to overnight breaks in jacking. Relationships between the increase in jacking load upon restart and jacked length, for a given soil type and stoppage duration category, were found to be linear with coefficients of regression (R^2) values in excess of 0.7 in all cases.

An increase in jacking force of 0.62 kN/m (0.26 kPa) was inferred for stoppages less than 1.5 hours for the drives in clay with stoppages more than 12 hours requiring a slightly higher restart jacking load of 0.70 kN/m (0.30 kPa). The increase in jacking forces in the stiff gravelly clay was quite low as high stability ratios (defined as the ratio of the weight of the soil overburden to the undrained shear strength) in the range 0.35-1.9 allowed the excavation to remain open. The above relationships suggest that the length of the stoppage has some effect on the increase in jacking load in clay, as would be expected owing to elastic unloading and as a result of the dissipation of bentonite lubrication. The increases in frictional resistance fall well below those reported elsewhere [5] in gravelly clay, with 0.8kPa for stoppages less than 3 hours and 2kPa for overnight stoppages.

Increases of 1.95 kN/m (0.80 kPa) and 2.04 kN/m (0.84 kPa) were noted for stoppages less than 1.5 hours and over 12 hours respectively for the dense sandy gravel, showing that the length of the stoppage has little effect in this case. An increase of 2.2 kN/m was observed for stoppages less than 1.5 hours in sand (no overnight data for comparison). It is clear that the static friction (friction to be overcome at restart) is much greater in sands/gravels than in clays, but the linear nature of the plots in Figure 5 suggest that both can be predicted with reasonable accuracy.

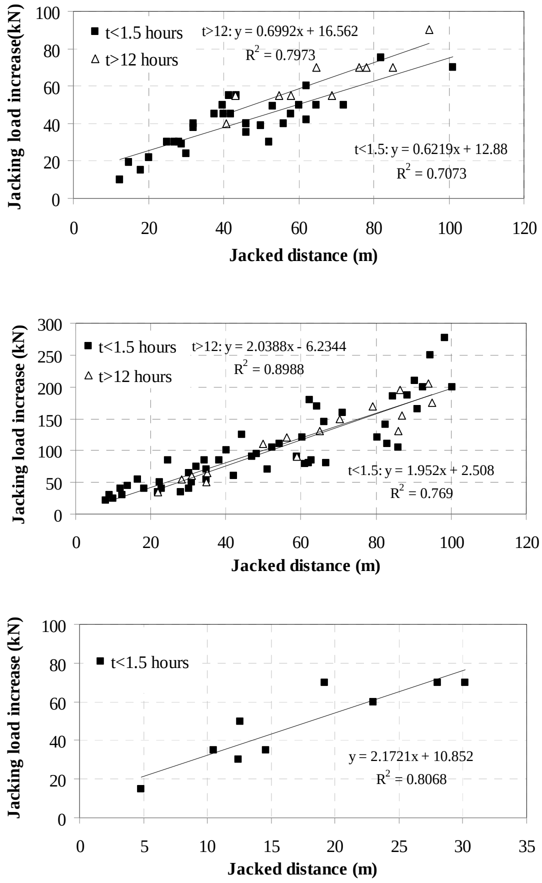

Figure 5. Linear relationships between static friction at restart and jacked length for (i) clay, (ii) gravel and (iii) sand for different stoppage lengths.

5.3 Soil Consistency

The lubricated frictional stress $f_{s,l}$ is plotted against SPT-N value in Figure 6 with distinction made between the various soil types at Kilcock. The SPT-N values derive from boreholes at the nearest manhole positions and therefore are a best estimate of ground conditions for the drive in question. There is an obvious trend of decreasing frictional stress with increasing SPT-N value for the data sets representing the stiff clay and dense gravel, and interestingly, both trends coincide well. Although this shows the potential to estimate frictional stresses from SPT-N values, caution is advised in the absence of further data to substantiate the observed trends. As acknowledged in Section 2, the consistency of bentonite application has varied somewhat in the drives.

There is no trend apparent between f_f values and SPT-N values.

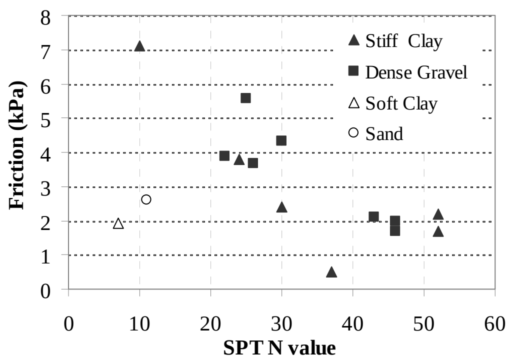

Figure 6 Effect of soil consistency with friction

6 CONCLUSIONS

This paper presents some key findings from a microtunnelling project in an Irish glacial soil. The dynamic friction measured in sand and gravel sections was greater than that noted in clay, due to the greater dilatancy of the soil and decreased efficiency of the overcut. The stable bore and reduced normal stresses on the pipeline contributed to the lower friction in clay conditions. The values for frictional stress suggested by the Pipe Jacking Association are quite conservative for this site. With correct lubrication, it is possible to construct microtunnels in excess of 100m long in glacial till.

Furthermore, the paper illustrates that the static friction required to restart after a stoppage varies linearly with jacked length and therefore lends itself to prediction. From analysis of borehole details, a general trend of decreasing frictional stress with increasing SPT-N value emerges. This is expected, especially in cohesive soils, as higher N values represent stiffer material and therefore allowing the excavation to remain stable. The analysis undertaken also demonstrates the influence of the specific gravity of the slurry on penetration rates in clay soils.

7 REFERENCES

[1] Curran, B.G., McCabe, B.A. and Ward, M. Microtunnelling – the future for pipeline construction? *The Engineers Journal*, **64** (1), (2010) 16-20.

[2] Reilly, C.C. Jacking force measurements at two microtunnelling projects in soft ground in Ireland, *Pipeline Industries Guild prize-winning paper*, (2011).

[3] McCabe, B.A., Orr, T.L.L., Curran, B.G. and Reilly, C.C. Settlement trough parameters for tunnels in Irish glacial tills, submitted to *Elsevier Tunnelling and Underground Space Technology*, (2011).

[4] Lehane, B.M. and Simpson, B. Modelling glacial till under triaxial conditions using a BRICK soil model, Canadian Geotechnical Journal, Vol. 37, No. 5, pp. 1078-1088

[5] Pellet, A.L. and Kastner, R. Experimental and analytical study of friction forces during microtunneling operations, *Tunnelling and Underground Space Technology*, **17**, (2002), 83-97.

[6] Pipe Jacking Association. A guide to pipe jacking and microtunnelling design, London, (2003).

[7] Stein, D., Mollers, K. and Bielecki, R. Microtunnelling: installation and renewal of nonman-sized supply and sewerage lines by trenchless technology method, Ernst and Sohn, Berlin, Chapter 10, (1989).

[8] Craig, R.N. Pipe-jacking: a state-of-the-art review, CIRIA Technical Note 112, (1983).

[9] Guilloux, A. The French National Report on tunnelling in soft ground, International Symposium on Underground Construction in Soft Ground, (2002).