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Analysis of microtunnel jacking forces in alluvium and glacial till in Mullingar, Ireland

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ABSTRACT

The number of successful microtunnelling drives completed in Ireland is growing rapidly. However, current jacking force predictions rely on experience from the UK and beyond, often gained through work in soils with a small range of particle sizes. Irish soils have particular characteristics that can affect their behaviour; for example, Irish glacial tills are frequently well-graded, with a wide range of particle sizes from clay to gravel. Jacking force relationships developed for more uniform soils may not be appropriate in these conditions. This paper aims to address these issues by presenting jacking force records for microtunnel drives constructed using three different slurry shield microtunnelling machines in two different soil types during sewerage pipeline construction in Mullingar in the midlands of Ireland.

1. INTRODUCTION

In recent times, there has been a considerable growth in the application of microtunnelling and pipe jacking to the construction of utility pipelines in Ireland (especially for waste water) and this has reduced disruption to towns and cities (Curran et al., 2010). In parallel, some publications have emerged which have collated Irish experiences of microtunnelling. Risk management procedures used in the construction of microtunnel drives in the historic town centre of Drogheda have been described by Bateman (2008). McCabe et al. (2012) have advised on appropriate Gaussian settlement trough width and volume loss parameters for Irish glacial tills, with estimates of these parameters dependent on whether the fine or coarse fractions of the till is dominant. Furthermore, Curran and McCabe (2011) and Reilly (2011) have analysed jacking force records for drives in glacial tills, soft clays and estuarine silty sand.

This paper discusses data from a number of microtunnel drives which took place during a recent sewerage improvement scheme in Mullingar, a regional town in the midlands of Ireland. Two drives in very soft ground, where ground conditions were the main motivating factor for using a trenchless solution, are discussed in addition to four drives in firmer glacial tills, where a desire to minimise disruption to surface infrastructure, including streets, rivers and a railway embankment, created a compelling case for using trenchless technology. These case histories are novel in that two microtunnelling systems in two soil types are reported. In particular, it is hoped that the investigation of jacking forces in glacial till will add to the scarce literature available on the challenges of microtunnelling in highly heterogeneous soils.

2. PIPE JACK DESIGN

Three different Tunnel Boring Machines (TBMs) and pipes of two different internal diameters (ID) were employed in three non-contiguous areas of pipe jacking in Mullingar town. Details of each drive, including the reference numbers of starting and finishing shaft, machine type and corresponding external pipe diameter, depth to tunnel centreline (z_0), length of drive and indicative soil type are presented in Table 1. The two Herrenknecht machines (AVN 1200 and 1800) were of the remote-controlled slurry-shield type fitted with a 'mixed' head (incorporating both scraping teeth and cutting discs). The Iseki Crunchingmole TCM 2160 was also fitted with a mixed head to deal with soft silty material and medium dense gravel. The cutting heads of the Iseki and Herrenknecht machines are shown in Figure 1. Pipes were standard steel banded concrete jacking pipes, of ID 1200mm and 1800mm. Bentonite lubrication was provided to each drive through an automatic bentonite dosing system fitted to every third or fourth jacking pipe. Dosage rates were adjusted by site personnel to suit the conditions.

Table 1 - Drive data

Drive Ref.	Date	Machine	TBM external dia. (mm)	z_0 (m)	Length (m)	Soil type
MH 2-1	Nov 2008	TCM 2160	2160	4.3	88	Alluvium
MH 2-3	Jan 2009	TCM 2160	2160	4.8	125	Alluvium
MH 9-11	July 2009	AVN 1800	2150	3.4	216	Glacial till
MH 13-11	July 2009	AVN 1800	2150	3.4	117	Glacial till
MH 21-22	Sept 2009	AVN 1200	1505	4.1	47	Glacial till
MH 23-22	July 2009	AVN 1200	1505	3.9	62	Glacial till

Figure 1 – Mixed ground heads - Iseki TCM 2160 (left) and Herrenknecht AVN1800 (right)

3. GEOLOGICAL SETTING

Mullingar is located on the River Brosna, a tributary of the Shannon River. Underlying the region are the dark shaly limestones of the Lucan Formation, known locally as "Calp". Glaciation has been the dominant contribution to the Quaternary geology of the area, which is primarily limestone- and shale-based glacial till (Finch, 1977) with isolated regions of fluvial deposits.

The ground types encountered on the drives discussed below have been divided into two primary classifications as shown in Table 1: glacial till and alluvium.

The glacial tills encountered are highly variable, as shown by the range of particle sizes plotted in Figure 2, a characteristic shared with many of the glacial lodgement tills encountered in Ireland. Local soil types encountered ranged from soft silty gravel to stiff black boulder clay with abundant cobbles and boulders. Standard Penetration Test N-values varied widely, from N=3 in the softest material to N=55 in the stiffer clays. Cone penetration tests carried out between MH 9 and 11 indicate a mixed geology at the tunnel depth, ranging from medium dense sand at MH 9 (cone frictional resistance less than 50kPa and cone penetration resistance less than 16MPa) to soft to very soft clay in the middle of the drive (cone frictional resistance less than 5kPa and cone penetration resistance less than 1MPa).

To the south of Mullingar, large depths of very soft alluvial/lacustrine deposits are located along the floodplain of the River Brosna (Finch, 1977). These are locally known as “marl”, composed primarily of soft silty sands and sandy silts, with shells and traces of organic material. The range of particle sizes encountered is shown in Figure 2. These deposits extend up to 17.5m below ground level, although dense sands and gravels were encountered during the latter stages of the drive MH 2-3. Cone penetration testing showed penetration resistances less than 3MPa and frictional resistance less than 10kPa, increasing to a penetration resistance of 20MPa and frictional resistance of 100kPa near MH 3.

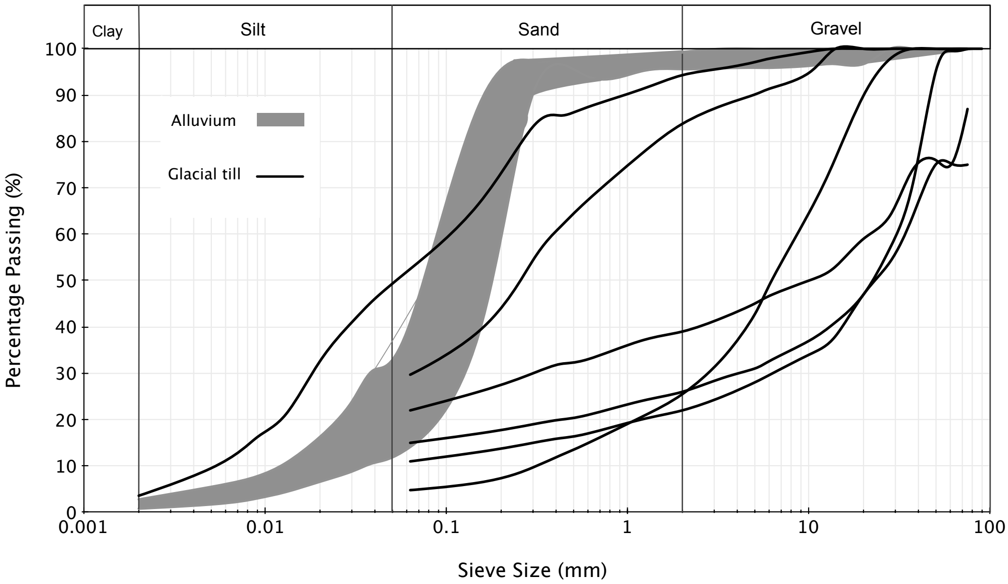

Figure 2 – Particle size distribution for all drives.

4. INTERPRETATION OF JACKING FORCES

4.1 Measurement of jacking forces

For drives MH 2-1 and 2-3, data concerning the jacking forces were recorded manually by the Iseki TBM operator using information from the various sensors and measuring devices on-board the TBM and relayed to the operator station. Jacking force data were recorded every 625mm, or four times per pipe length. For the other drives, jacking force data were acquired automatically from the TBM on-board computer system, with data recorded every 200mm of advance at a minimum, and an average jacking force computed for each pipe length. The differences between manually and automatically recorded jacking forces are discussed below.

4.2 Face resistance force, P_F

The face resistance force, P_F, is the resisting force encountered by the cutting wheel of the TBM shield as it advances through the ground. It is due to forces required to break up the ground and crush harder particles, slurry pressure supplied to the face and the resistance at the face due to the area of steel in contact with the ground (see Figure 1). In the case of the drives in sandy silt, MH 2-1 and 2-3, a face resistance sensor in the drive train measured the face resistance force, $P_{F(measured)}$, directly. In the other cases discussed in this paper, the face resistance force must be deduced from the overall jacking force. A method proposed by Pellet-Beaucour and Kastner (2002) to determine $P_{F(difference)}$ is preferred, in which the difference between the lower and upper bound jacking force envelopes is averaged over the length of the drive. This method is appropriate because:

(i) The local variations of total jacking force are generally linked to the face resistance.

(ii)The minima of the total jacking force correspond to very low face forces.

4.3 Frictional or skin resistance force, P_S

The frictional resistance force, P_S tends to make up the larger part of the total resistance to the jacking force. As the length of drive increases, so does the overall frictional resistance. Equation 1 proposed by Stein et al (1989), in which it is assumed that the entire soil mass exerts a radial stress on the entire surface of the pipe, has been found suitable for the drives discussed in this paper:

$$P_S = M\pi D_P L \qquad [1]$$

where M is the skin resistance, D_P is the external diameter of product pipes and L is the length of the pipeline. It is intuitive that values of M will be highly dependent on soil type, and this is borne out in the literature (Pellet-Beaucour and Kastner, 2002, Stein et al., 1989). Values of M quoted for conditions similar to those here range from 0.5 to 30 kPa. Clearly with such a wide range of values, local experience and careful judgement are required when making estimates of likely jacking forces required in future projects.

4.4 MH 2-1 and 2-3

Drives MH 2-1 and MH 2-3 were carried out in a greenfield site. Plots of the average jacking force recorded per pipe, showing the measured face resistance pressure and the best-fit lines to the total jacking force envelope used to determine the skin resistance are shown in Figure 3 and 4 below. Direct measurement of face resistance force was possible during these drives, and plots of face resistance pressure (face resistance force divided by the area of the face) are shown on the figures.

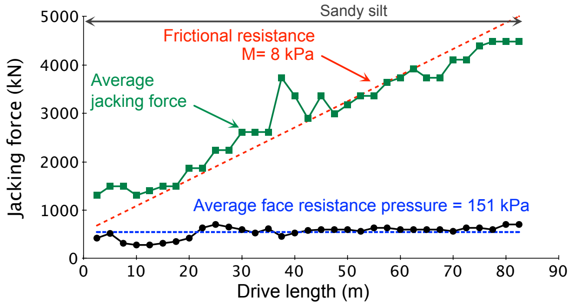

Figure 3 - Jacking force plot MH 2-1

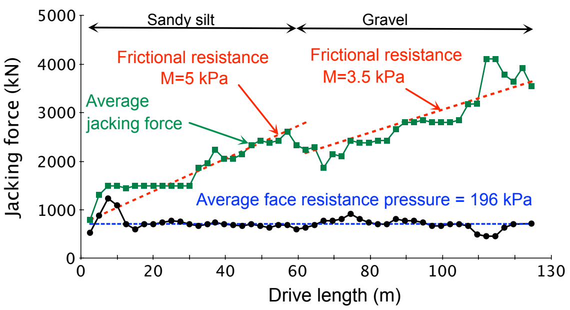

Figure 4 - Jacking force plot MH 2-3

In the case of MH 2-3, the drive enters more gravelly ground at approximately 60m. This is accompanied by notable drop in total jacking force while measured face resistance pressure remained constant. Clearly the drop in force must be explained by reduced frictional resistance force due to the stronger ground being better able to support itself and hence allowing the overcut zone remain open.

4.5 MH 9-11 and 13-11

Drives MH 9-11 and 13-11 crossed under a road, a river and a railway embankment. The decision to install this section of pipeline produced large savings in indirect costs to the scheme. As shown in Figure 5, Drive MH 9-11 began in stiff clay, but finished up in much softer material, as evidenced by SPT and CPTu tests and observations of the tunnelling arisings. The same pattern was observed during drive MH 13-11, as indicated in Figure 6. The jacking force envelopes in Figure 5 and 6 reflect this, with lower jacking forces evident in the softer materials. As direct face pressure measurement was not possible in these drives, the interpreted average face resistance pressures for each drive are shown.

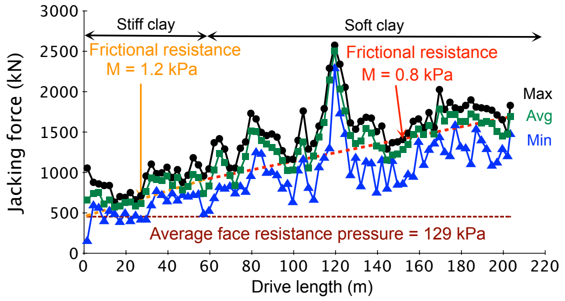

Figure 5 - Jacking force plot for MH 9-11

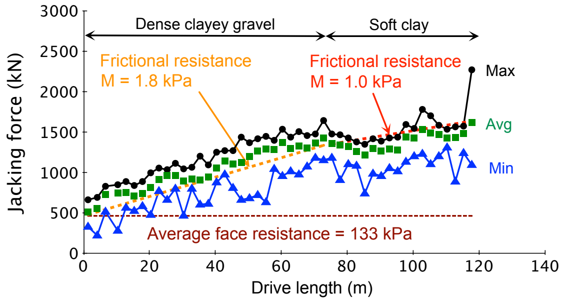

Figure 6 - Jacking force plot for MH 13-11

4.6 MH 21-22 and MH 23-22

Drives MH 21-22 and MH 23-22 were beneath streets in the town centre. The jacking force envelope for each drive is presented in Figure 7 and 8 below. There is notably higher variation in jacking force towards the end of drive MH 23-22, most likely due to the presence of boulders when tunnelling towards reception shaft MH 22. Boulders were found to slow down the TBM dramatically, as evidenced by the decrease in penetration rate towards the end of the drive shown in Figure 10. In contrast, Figure 9 shows the penetration rate increasing towards the same reception shaft. A possible operational reason for this is that the contractor chose to pre-grout the ground between MH 21 and 22, immobilising the boulders and allowing the TBM to crush them more efficiently.

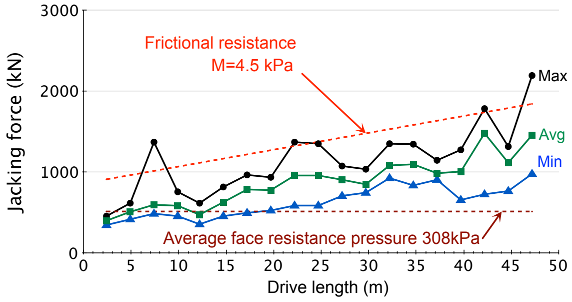

Figure 7 - Jacking force record MH 21-22

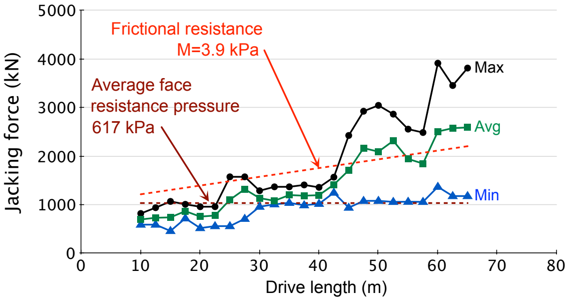

Figure 8 - Jacking force record MH 23-22

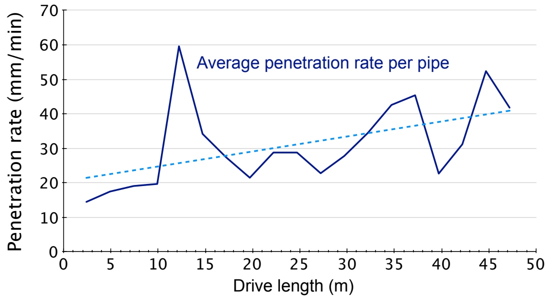

Figure 9 - Penetration rate drive MH 21-22

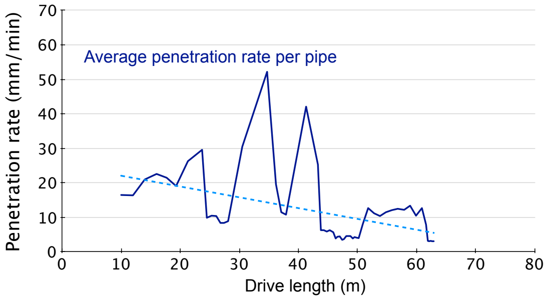

Figure 10 - Penetration rate drive MH 23-22

5. FACTORS AFFECTING JACKING FORCES

5.1 Soil properties

The relevant interpreted skin friction stresses and face pressures for each drive are summarised in Table 2. The skin friction stress is plotted against face pressure in Figure 11 as a convenient means of considering the relative effect of the different ground conditions, using the same microtunnelling method. The two sets of data are quite distinct in this context. The following conclusions can be drawn from Figure 11:

(i) The face pressure of 150-200kPa in alluvial conditions compare well with an average face pressure of 160kPa reported in silty sand conditions in Co. Dublin (Reilly, 2011).

(ii) There is a large difference in face pressure between the soft and stiff glacial tills. The presence of boulders has had an influence on the face pressure in the latter case.

(iii) The stiff glacial tills also provide a greater skin friction stress (M=4-4.5 kPa) than the soft till (M<1.5 kPa).

(iv) Skin friction stresses and face pressures in the stiffer glacial till are broadly consistent with corresponding values at Kilcock reported by Curran and McCabe (2011).

(v) Skin friction stresses tend to be higher in silty sand than glacial till, again consistent with findings by Reilly (2011).

It is acknowledged that M also depends on pipe surface finish and lubrication, but these can reasonably assumed to be the same for all the drives reported in this paper. Face pressure can also be said to be operator dependent, but two or more TBM operators were engaged for each drive and any such influence is considered to average out over time.

Table 2 - Summary of face and frictional resistances for each drive

Drive Ref.	Machine	Face pressure, σ_F (kPa)	Friction resistance, M (kPa)	Soil type
MH 2-1	TCM 2160	151	8	Alluvial silt
MH 2-3	TCM 2160	196	3.5-5	Alluvial silt
MH 9-11	AVN 1800	129	0.8-1	Glacial till
MH 13-11	AVN 1800	133	1-1.8	Glacial till
MH 21-22	AVN 1200	308	4.5	Glacial till
MH 23-22	AVN 1200	617	3.9	Glacial till

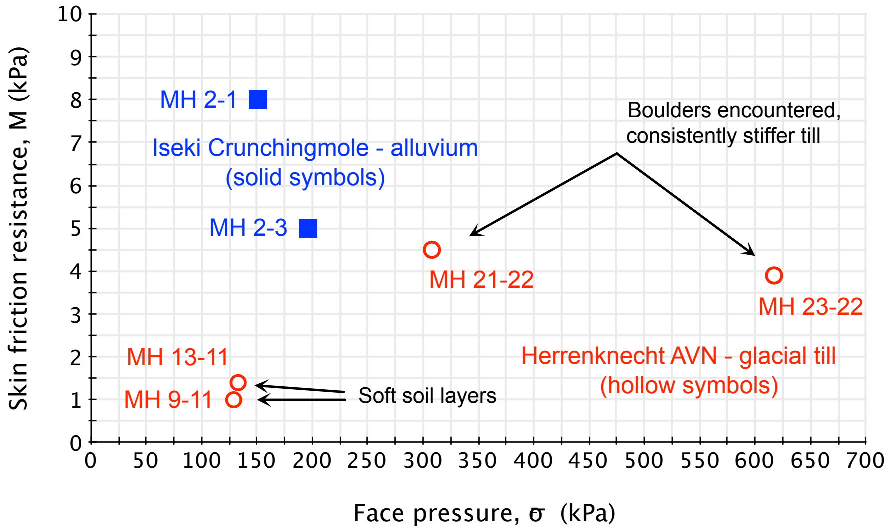

Figure 11 - Frictional resistance plotted against face resistance for each drive

5.2 *Stoppages*

Once the TBM is stopped, the bentonite lubricant injected into the overcut can dissipate to the surrounding soil. This may allow the soil mass settle onto the pipes, requiring a greater jacking force to restart movement. Figure 12 and 13 below indicate where these overnight stoppages occurred in each case, showing the effect of each stoppage on the maximum jacking force per pipe. MH 2-1 was driven in 8 to 10 hour shifts, with overnight stoppages from 14 to 16 hours, while MH 2-3 was driven continuously for 24 hours per day apart from one overnight stop for mechanical repairs.

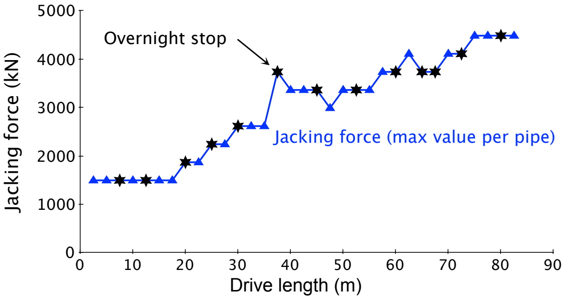

Figure 12 - Overnight stoppages, MH 2-1

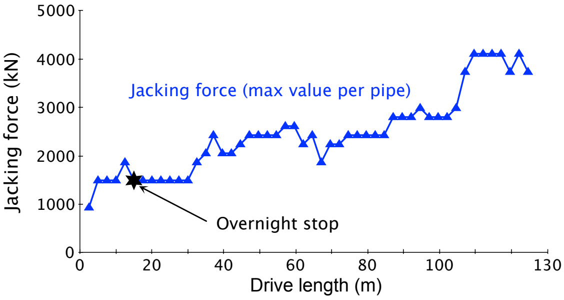

Figure 13 - Overnight stoppages, MH 2-3

5.3 *TBM deviation from line*

In addition, as documented above, to stoppages affecting the jacking force, deviation of a drive from the desired line can also affect the jacking forces. MH 2-1 suffered a sustained deviation from line of up to 270mm, which the TBM operator had to fight to regain for the majority of the drive. In contrast, and possibly due to continuous 24 hour working, the maximum deviation from line recorded during MH 2-3 was only 137mm. The deviation from line during MH 2-1 contributed to over 60% higher overall jacking forces over an equivalent length in equivalent materials (e.g. at 60m the jacking force shown in Figure 12 is 3750kN for drive MH 2-1, whereas at the same location from drive MH 2-3 it is approximately 2300kN as shown in Figure 13). Clearly, efforts taken to minimise deviations are worthwhile, including moving to 24 hour working to prevent the heavy TBM settling in soft soils during stoppages.

5.4 *Operator influence*

As mentioned above, the drive parameters for the drives using the Iseki TBM were recorded manually by the operator, whereas parameters were recorded automatically for the other drives. This is an area where the influence of the operator can be seen. In particular, the Iseki drive records (Figures 3 and 4) contain one distinct jacking force value per pipe, whereas the Herrenknecht drive plots (Figures 5 – 8) contain a wide jacking force envelope, with three values presented per pipe. This jacking force envelope shows the variation through the drive better, whereas the manually recorded entries have been interpreted by the TBM operator, and are therefore already “best fit” lines, limiting further scope for analysis.

6. CONCLUSION

Six different microtunnel drives using three different TBMs and in quite different and varied soil conditions but all within 1.5km of each other, have been discussed. The following conclusions are be drawn:

(i) The drives in glacial till led to lower values of frictional resistance than the drives in the soft alluvial materials. This may be due to the higher shear strength of the till materials allowing the overcut to remain open, while the softer soils are more likely to collapse onto the jacking pipes, increasing the frictional resistance.

(ii) In glacial till conditions, face resistances recorded were very varied, ranging from 120kPa to 620kPa. Some of this variability is attributed to the varying proportions of boulders in the drives. In the case of the drives in alluvium, the face resistances recorded were in line with experience elsewhere.

(iii) A plot of frictional resistance against face resistance is a useful framework for comparing data in different ground conditions.

The effects of stoppages, TBM deviations from line and operator influence have been explored. It is hoped that further work will allow more conclusions be drawn from experience on this interesting scheme.

7. ACKNOWLEDGEMENTS

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