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Blackpool South Strategy project: analysis of pipe-jacking records

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ABSTRACT: In recent years, there has been an increased resort to microtunnelling/pipe-jacking as a means of constructing underground conduits (for water, sewage, gas and other utilities) to avoid on-street disruption in urban areas. In this paper, technical details of two 1200 mm internal diameter microtunnels in silty sand totalling 550 m in length are discussed; the microtunnels were constructed by Ward and Burke Construction Ltd. as part of the Blackpool South Strategy project. A general overview of the tunnelling process is provided, including the separation plant, jacking facilities and the bentonite supply process. The results show that the lubrication system was very effective at maintaining low skin friction levels, and that the pipe string was almost fully buoyant for the majority of the drive. Stoppages were shown to have a significant but transient effect on the jacking force; high jacking forces upon resumption of jacking after a stoppage return to 'baseline' levels after the length of one pipe diameter. Machine deviations did not appear to play a major role in increasing jacking forces for this particular project.

Keywords: Microtunnelling; Jacking force; Skin friction; Lubrication; Bentonite; Stoppages; Deviations.

1 INTRODUCTION

The rapid expansion of urban areas worldwide has resulted in a need to provide new and/or upgrade existing water, sewage, gas and other utility conveyance networks. Pipe-jacking has emerged as the preferred method of utility pipeline construction, as it avoids the on-street disruption arising from trenches constructed from the ground surface. However, the difficulty in identifying suitable intermediate shaft locations in urban projects means that long drives are often necessary; keeping jacking forces at manageable levels is a challenge in these drives. For example, excessive stress concentrations can give rise to spalling at the joints between pipes, potentially inducing pipe failure [1]. Intermediate jacking stations are cumbersome, however, and are generally kept to a minimum.

The total jacking load (F_{total}) consists of the resistance at the face (F_{face}) of the tunnel boring machine (TBM) and the frictional resistance (F_{friction}) between the pipe train and the surrounding ground. The frictional force is often the main contribution to the jacking load, especially in long drives [2]. The introduction of a lubricant into the overcut (the annulus formed on account of the TBM having a larger diameter than the pipes) is an efficient means of reducing the jacking force. The skin friction (τ , force per unit surface area of pipe) depends on the effective normal stress (σ'_n) from the soil on the pipe, the total effective weight of the pipe string (W_{eff}) and the angle of effective interface shearing resistance between the pipe and the soil, δ :

$$\tau = \left(\sigma'_n + \frac{W_{\text{eff}}}{\pi DL} \right) \tan \delta \quad (1)$$

where D is the pipe diameter and L is the embedded pipe string length. Lubrication has the effect of lowering δ . Additionally, if the pipe is buoyant in the lubricant, W_{eff} will be lower than the weight of the pipe W , and may be as little as

zero in a fully buoyant condition. A number of authors [1, 3-6] attest to the benefits of a properly-lubricated overcut. For example, τ values ranging between 0.1 kPa in well-lubricated drives to 4 kPa in moderately-lubricated drives were identified in four different drives in clay and gravel deposits [7].

Stoppages and deviations in steering also influence the jacking forces along a tunnel string [8, 9]. A study of microtunnels in glacial till in Ireland [10] found that stoppages in sands/gravels required a higher frictional force to be overcome upon recommencement of jacking than in clays. Furthermore, the stoppage duration had an effect on this jacking force in clay but not in gravel. Long stoppages in soft ground may allow the TBM to settle, resulting in deviations from the intended path. Deviations, irrespective of the cause, can increase the required jacking force. An analysis of data from microtunnels in alluvium and glacial till in Ireland [11] found that for two drives of similar length and ground conditions, the drive with the greater deviations overall required much greater jacking forces.

This paper provides an overview of some tunnelling aspects of the Blackpool South Strategy project, U.K. Following a brief description of the tunnelling process, data recorded (jacking force, deviations, bentonite injections) for two 1200 mm internal diameter tunnel drives are presented and analysed.

2 THE BLACKPOOL SOUTH STRATEGY PROJECT

The project site is located in Blackpool, U.K. The overarching purpose of the project is to improve bathing water quality along the seafront and mitigate the risk of flooding. This necessitated (i) an increase in the capacity of the sewer network, (ii) a reduction in the volume of surface water entering the network and (iii) an upgrade to the wastewater pumping station situated at Lennox Gate. The latter element

included the provision of a new storm-water holding tank to hold excess storm water until pumping back into the sewer network is possible. New pipework will connect this tank to the existing pumping station. A new surface water pumping station will pump surface water straight to sea.

The ground conditions comprise a layer of peat (1 – 2 m thick), overlying medium dense sand (2.6 – 4.4 m thick), in turn overlying silty sand. The water table was at a depth of 1.2 m in a borehole close to the reception shaft of Drive A.

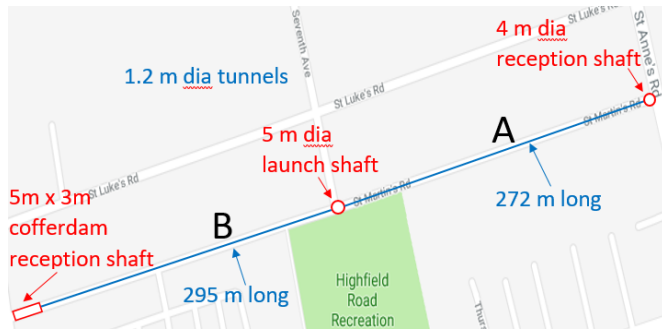


Figure 1. Location of tunnels and shafts at Blackpool site (adapted from Google Maps).

The locations of the two drives, A and B, referred to in this paper, are shown in Figure 1. These provide a sleeve for 700 mm internal diameter ductile water pipes which will transport excess stormwater from the holding tank to the outfall pipe at Harrowside, which will then feed the water out to sea.

3 TUNNELLING PROCESS

3.1 TBM, pipe and general details

A schematic of the tunnelling process, including TBM, jacking frame, separation plant, slurry feed and return lines and control unit, is provided in Figure 2.

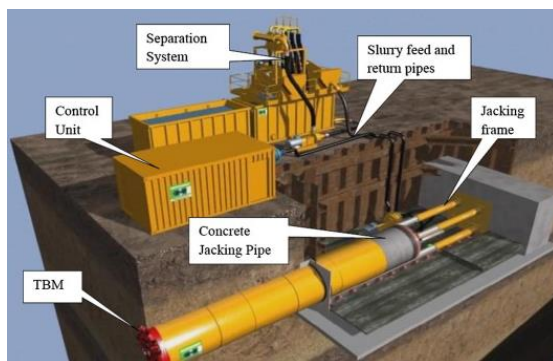


Figure 2. Schematic of the microtunnelling process (courtesy of Herrenknecht).

The TBM used at Blackpool was a Herrenknecht AVN 1200 (slurry shield), with a cutterhead diameter of 1515 mm and a machine lining outer diameter of 1505 mm. Each concrete pipe was 2.5 m long with an outer diameter of 1490 mm, providing an overcut 25 mm thick into which lubrication may be pumped.

A laser positioned on the back wall of the launch shaft and aimed at a target at the rear of the machine helped the operator

to direct the TBM. In general, ground conditions dictate how far the machine deviates from the intended line and what steering interventions are needed. For instance, the machine can change direction more easily in sandstone bedrock or cobble formation than in sand or clay deposits [12].

Drive A was 272 m in length, constructed in an east north-easterly direction with a gradient of -0.154 % and an initial launch invert depth of 7.61 m. Drive B was 295 m in length, constructed in a west south-westerly direction with a gradient of 0.347 % and an initial launch invert depth of 7.59 m (see Figure 1).

3.2 Jacking frame and intermediate jacking station

The jacking frame consisted of four hydraulic cylinders that push the machine and the concrete pipes through the ground. The hydraulic cylinders have a total stroke length of 3.52 m. The operator controls the speed at which the hydraulic cylinders advance the tunnel through the ground; this is dependent on torque, jacking forces, ground conditions and the steering of the machine. Figure 3 displays the main setup for the pipe jacking process with a concrete pipe in place for the recommencement of jacking.



Figure 3. Concrete pipe installed for jacking.

In the event that the jacking forces become excessive, recourse is made to intermediate jacking stations (interjacks), pre-installed partway through the drive. The interjack reacts off the pipes towards the launch shaft to advance the pipe train on the side of the reception shaft. The pipe string is therefore advanced in an 'inchworm' manner [13]. Each interjack consists of 10 hydraulic rams which are placed inside the tunnel at 100 m intervals. In this project, an interjack was placed in both tunnels but was not used as the total jacking force remained sufficiently low.

3.3 Separation plant

As the TBM advances, the revolving cutterhead excavates the soil material. During this process, water is pumped at high velocity to the head of the machine, where the soil material and water mix to form a slurry. This slurry is then pumped to the separation plant above ground, where the solid material is recovered from the slurry, before recirculation to the face of the machine in a closed system.

The separation plant consists of a primary shaker, a secondary shaker and a centrifuge. The slurry returning from the face of the machine passes through the primary shaker initially. The primary shaker comprises coarse screens that

only permit material finer than 4 mm to pass. The secondary shaker removes fine particles (greater than 20 μm). Finally, the mixture is pumped into a centrifuge which spins between 700 rpm and 2000 rpm. A flocculant is added to bind the fine silt particles together thereby aiding their removal; particle sizes greater than 1 μm are removed at this stage. The solid material that emerges from the shaker screens and centrifuge is subsequently dried by adding lime and removed from site.

3.4 Lubrication

Lubricant is pumped into the overcut to maintain tunnel stability and to reduce friction at the pipe-soil interface. For the Blackpool project, the first station was located in the pipe directly behind the TBM, with a further 19 stations positioned in ensuing pipes (one every fifth pipe) and one on the launch shaft wall. Each station comprised three lubrication ports (separated by 120°) situated at the midpoint of the pipe. A lubrication station arrangement is shown in Figure 4.

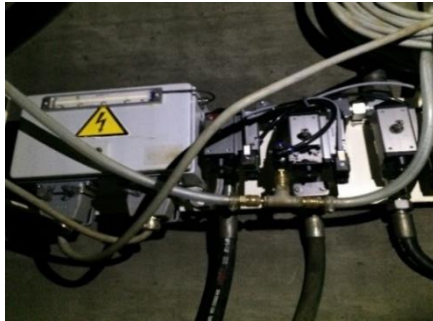


Figure 4. Lubrication station.

The bentonite lubrication system is volume-controlled; the volumes required for each station are calculated from the TBM advance rate and ground conditions [14]. The bentonite solution comprised Hydraul-EZ and water in the ratio 22.7kg to 400 l. Other additives included (i) soda ash to balance pH, (ii) MX polymer to prevent additional groundwater penetrating the mix, and (iii) torque reducer to promote lubrication and to reduce the potential for the pipeline to become jammed due to soil pressures exceeding that of the bentonite lubrication acting on the pipeline. When tunnelling in fine sands and silts, more lubricant is used than is required to fill the overcut. The extra lubricant seeps into the ground creating a filter cake that serves as a membrane or zone of low permeability to transfer the support pressure acting in the annular gap into the grain structure of the ground [15]. The typical volume administered in these ground conditions is 2.5 times the overcut volume [15], based on experience of monitoring on numerous pipe-jacking projects. The formation of a filter cake in sands and gravels requires more bentonite than in clays, due to differences in permeability.

4 MONITORING

4.1 Overview

The output data from the TBM was recorded at 200 mm intervals of jacked distance. Output provided by the TBM included jacking force, steering deviations, water circulation, feed and slurry line pump details, advance speed, cutting wheel revolution, slurry pressure in excavation, interjack

cylinder forces and bentonite injection volumes and pressures. The results presented in the following sections relate to Drive A only (with the exception of Figure 9), as findings are generally consistent between the two drives. Due to a technical issue with the data acquisition system, data were only recorded for Drive B beyond a jacked distance of 62 m.

4.2 Jacking force

As already mentioned, minimizing jacking forces is an important consideration during pipe jacking. From Figure 5, it is clear that the jacking force remained relatively constant throughout this drive, with an average of ~380 kN. Towards the end of the drive, the jacking force rose to over 1000 kN, as the TBM approached the concrete wall at the reception shaft.

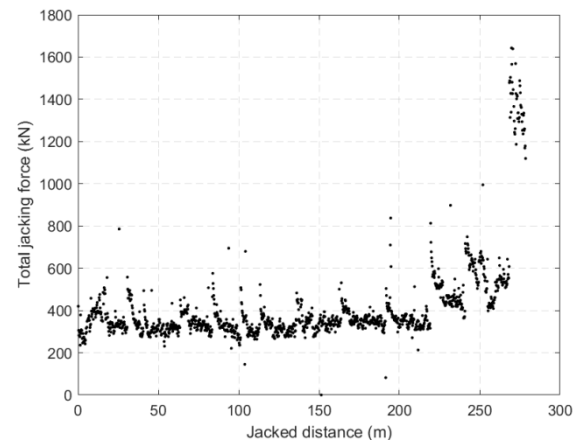


Figure 5. Development of total jacking force during Drive A.

Two separate methods of calculating F_{friction} are compared:

- Method A: The face pressure was calculated over the first 3 m of the drive (the length of the TBM) on the assumption that F_{friction} was negligible over that length [16]. This face pressure was assumed constant for the entire drive, enabling F_{friction} to be inferred.
- Method B: Based on the work of Pellet-Beaucour and Kastner [8], F_{friction} can be approximated from a trendline joining the minimum points on the total jacking load envelope, while F_{face} is taken as the difference between the minimum and maximum envelopes (data plotted at 10 m intervals in Figure 6).

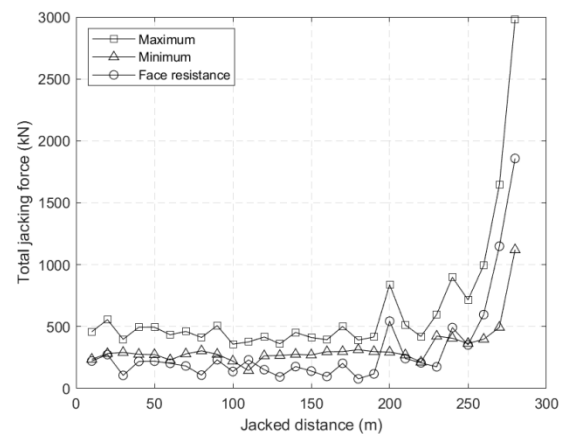


Figure 6. Maximum and minimum jacking force envelopes and face resistance for drive A

Skin friction is calculated by dividing F_{friction} by the developed surface area of all embedded pipes. Skin friction values calculated using these two methods are plotted against jacked distance in Figure 7. Using Method A, it takes ~35 m for the skin friction calculated to drop below 1 kPa, while it takes ~70 m for the skin friction to drop below 1 kPa using Method B. Average values beyond 100m are 0.27 kPa and 0.48 kPa for Methods A and Method B respectively.

It is interesting to note that if the slurry pressure recorded by the TBM is assumed to be numerically equal to the face resistance, the inferred skin friction is almost identical to that derived using Method B (Figure 7). Similar observations were made for Drive B. In practice, the slurry pressure is chosen to be slightly higher than hydrostatic ground water pressure. The match between slurry pressure and face pressure in this drive is perhaps fortuitous and/or specific to the silty sand, but suggests that the water pressure contributes significantly more than the active earth pressure to the face pressure. Had the machine been in clay, this slurry pressure would be lower than the face pressure, as the clay material at the face would not need the same level of support as the silty sand.

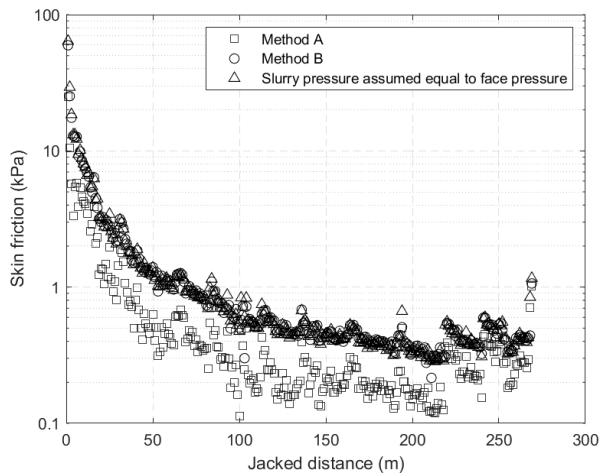


Figure 7. Methods of evaluating skin friction for drive A.

The constant face pressure method (Method A) is not a robust approach as the face resistance is likely to change throughout the drive. F_{face} calculated using Method B (also plotted on Figure 6), shows great variation with jacked distance, with an average value of 70 kN when the data are plotted at 1m intervals. This suggests that the value of F_{face} adopted (200 kN) at the start of the drive was too high, possibly due to careful driving style of the operator soon after launch.

Frictional resistances have been reported for sand of 2.8 kPa to 4 kPa without the use of lubrication [8] and 0.5 kPa – 2.5 kPa with lubrication [17]; the measured values reported here are at the lower end of these ranges, suggesting effective lubrication practice, which is explored further in Sections 4.3 and 4.4.

4.3 Lubrication

The volume percentage of bentonite pumped into the annulus is plotted (on a log scale) against jacked distance in Figure 8 for a selection of the 21 stations noted in Section 3.4. The distance of these stations from the TBM face is shown in the

legend (the position of Station 25 was fixed at the launch shaft).

Station 1 (immediately behind the TBM) is responsible for greater bentonite volume than any other individual station for most of the drive. The trailing stations pumped smaller volumes as their purpose was merely to maintain bentonite levels. For example, at the midpoint of the tunnel (135 m), Station 1 had produced 44% of the total volume of bentonite, Station 25 had contributed 13% and Stations 2 and 3 supplied 10.9% and 6.4% respectively. Therefore, these four stations contributed 74.3% of the total volume of bentonite at this position.

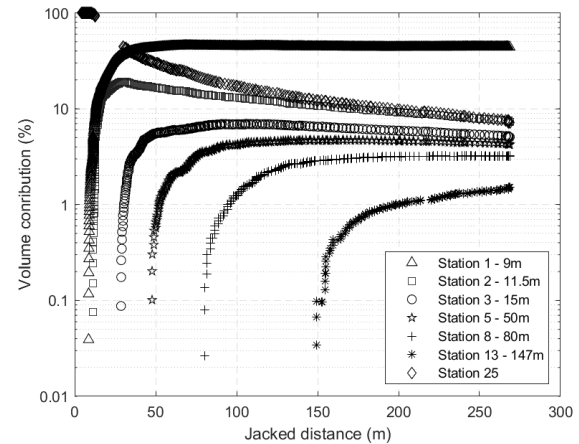


Figure 8. Percentage of total bentonite volume pumped from selected stations.

The development of bentonite volume normalised by the volume of the overcut during the drive is considered in Figure 9. It can be seen that the actual normalised bentonite volume for Drive A (~6.5 for most of the drive length) far exceeds the target of 2.5 recommended for filter cake formation [15]. The corresponding normalized volume for Drive B is lower at ~4.5 although the average skin friction values are virtually the same for both drives. Further research is required to assess whether there is a minimum or threshold normalized bentonite volume which enables minimum friction values to be achieved.

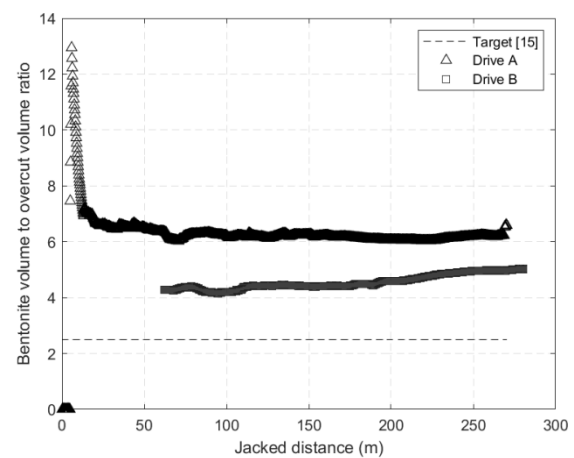


Figure 9. Normalised bentonite volume against jacked distance for both Drives A and B.

4.4 Pipe buoyancy

It is highly desirable for a train of pipes to be buoyant within its overcut, to help minimize the W_{eff} term in eqn (1). However, to the knowledge of the authors, pipe flotation has not been demonstrated using measured data. Making σ'_n the subject of Eqn (1) gives:

$$\sigma'_n = \frac{\tau}{\tan \delta} - \frac{W_{eff}}{\pi DL} \quad (2)$$

A value of 28.2° was assumed for δ , interpolated from data measured by Reilly and Orr [18] for a sand/rough concrete interface. In Figure 10, two extreme scenarios are presented: (i) full string weight (including TBM and power pack) assumed, i.e. $W_{eff} = W$, and (ii) $W_{eff} = 0$, i.e. the string is fully buoyant. It is clear that scenario (i) is incorrect as (impossible) negative values of σ'_n arise after a jacked distance of 37 m. The correct normal stress lies somewhere between the scenario (ii) data on Figure 10 and the $\sigma'_n = 0$ axis. This suggests that the pipe string is almost fully buoyant (on average over its length), if not fully buoyant.

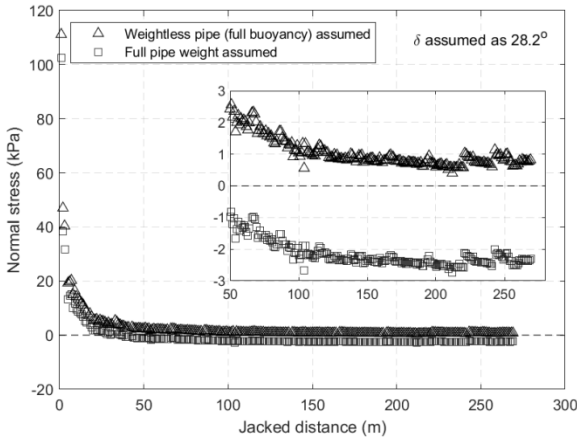


Figure 10. Demonstration of pipeline buoyancy

4.5 Stoppages

As the tunnel is advanced, small peaks in jacking force arise as a result of overnight and weekend stoppages, an example of which can be seen in Figure 11.

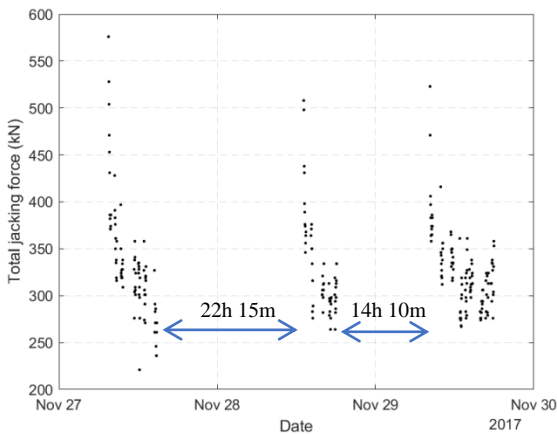


Figure 11. Influence of stoppages on total jacking force.

It appears that the initial peak in force upon resumption of jacking following a stoppage is reversed quickly. It can be seen in Figure 12 how the jacking force (normalized by the initial force upon recommencement of jacking) has reached baseline values over a length of little more than one pipe diameter.

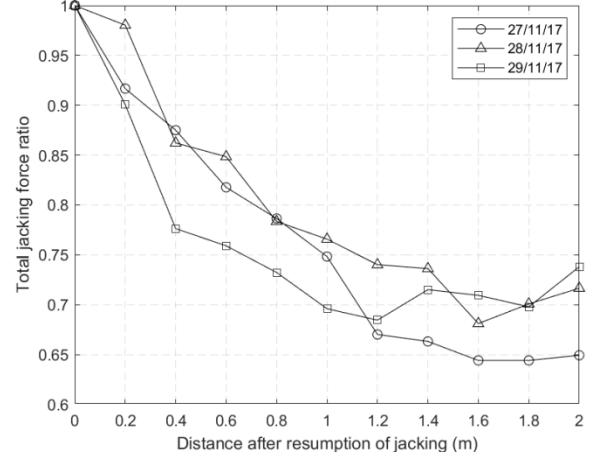


Figure 12. Jacking force ratio over one tunnel diameter for overnight stoppages

The increase in jacking force after different stoppage durations, t , are shown in Figure 13. Stoppage durations are categorised as follows: $t < 3$ h (pipe change and miscellaneous minor breaks), $10 \text{ h} < t < 20$ h (overnight stoppages) and $t > 20$ h (weekends). The jacking force increase is determined using the initial force after a stoppage minus the average jacking force calculated between one and two pipe diameters upon resumption of jacking. Results show that additional friction to be overcome is 0.22 kPa for short breaks, 0.30 kPa for overnight stoppages and 0.75 kPa for stoppages greater than 20 h. This suggests that the length of a stoppage dictates the increase in jacking force. Although the trend is similar to that reported by Curran and McCabe [10], values presented here are much lower in comparison.

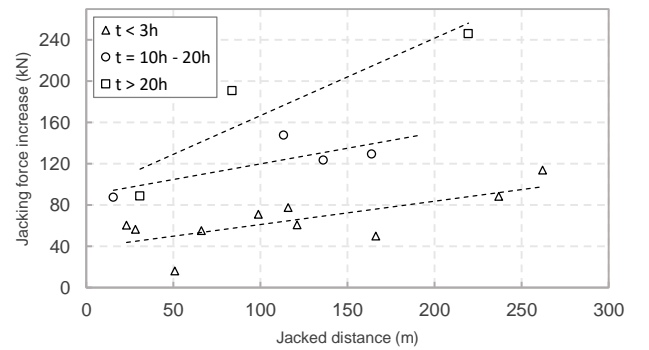


Figure 13. Influence of jacking force after stoppages

4.6 Steering deviations

The vertical and horizontal deviations from the laser line are recorded from both the back of the machine and at the drill head tip. With the articulated joint in the TBM used for steering, it is important to note that the drill head tip and rear of machine may not be on the same alignment (see Figure 14).

Horizontal deviations remain relatively low throughout the drive (<10 mm); only vertical deviations are shown in Figure 14 (over a selected length).

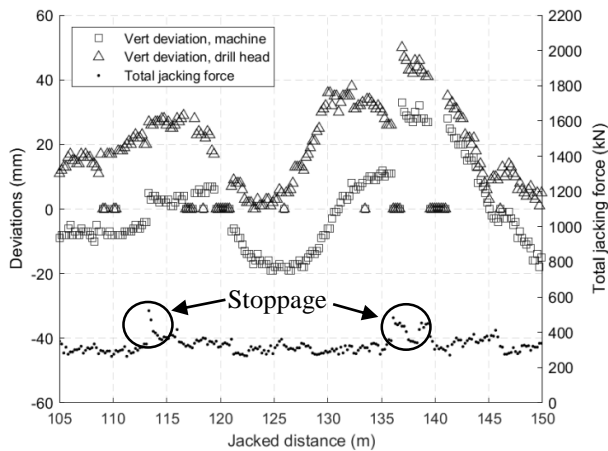


Figure 14. Deviations and total jacking force along tunnel.

For this silty sand site, steering deviations did not play a major role in the development of jacking forces. The small spikes in jacking forces, which align with deviations between 40 mm and 50 mm, are actually due to stoppages at these times.

5 CONCLUSIONS

This paper describes the microtunnelling process in the context of a recent UK project, including the jacking, lubrication and slurry separation processes. The results show that for the drives considered, the lubrication system proved very effective at maintaining low frictional forces, and the data suggest that the string was at least partially buoyant for the majority of the drive. The volume of lubrication used to achieve this exceeded minimum recommended amounts and efficiencies may be possible in this regard. Stoppages were shown to have a significant but temporary effect on the jacking force; high jacking forces upon resumption of jacking after a stoppage return to 'baseline' levels after advancing only the length of one pipe diameter. Machine deviations did not appear to play a major role in increasing jacking forces for this particular project.

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