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Physical Modelling in Geotechnics

Pipe-jacking stoppages modelled using direct shear interface tests

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ABSTRACT: In long pipe-jacking drives used for installing utility pipelines, maximum jacking load requirements are usually governed by skin friction at the pipe-soil interface. In addition, field experience has shown that transient peaks in skin friction arise upon recommencement of jacking after stoppages; these stoppage durations can be short (due to the addition of a pipe to the string) or long (due to weekend stoppages or breakdowns) and constitute a risk for pipe-jacking contractors. In this paper, the problem is replicated in the laboratory using direct shear interface tests using a concrete specimen in one half of the apparatus and sand/bentonite mixtures in the other. Once critical state conditions were reached in these tests, stoppages of various durations (from 30 mins up to 2 weeks) were incorporated and the increase in shear stress upon recommencement of shearing was noted. From the experiments, there appears to be a threshold stoppage duration beyond which the skin friction increase appears to plateau, suggestive of a time-limited process within the bentonite. These skin friction data are shown to provide an upper bound to corresponding stoppage data from pipe-jacking drives in sandy ground conditions.

Keywords: bentonite, interface, pipe-jacking, skin friction, stoppages

1 INTRODUCTION

Pipe-jacking is now the preferred means of installing utility pipelines in urban areas, with some substantial jacked lengths achieved in recent times. For example, Ward & Burke Construction Ltd. have constructed approximately forty drives in excess of 500 m in length since 2013 in Ireland, U.K., Finland, U.S.A. and Canada. The total jacking force comprises the force at the tunnel boring machine (TBM) face and the shear force along the pipe-soil interface, with the latter usually dominant in longer drives, dictating the total force requirement (O'Dwyer *et al.*, 2018). Furthermore, field experience has shown that transient peaks in the skin friction (i.e. the shear force divided by the embedded pipe surface area) arise upon restarting jacking after a stoppage; these stoppages can be short (due to the addition of a pipe to the string, for example) or long (due to weekend work breaks or breakdowns). The selection of field data from the literature in Table 1 illustrates that longer stoppages give rise to greater skin friction increases upon restart in any one drive, representing increased risk for the pipe-jacking contractor. However, there is no consistency in the magnitudes of these increases across the variety of ground conditions represented in Table 1, although it is acknowledged that the type and extent of lubrication will also have an impact on these values. This hampers accurate prediction of jacking force requirements in pipe-jacking projects.

Table 1. Skin friction values reported in the literature for stoppages of various durations.

Ground conditions	Stoppage duration (h)	Skin friction increase (kPa)	Reference
Marl, sandy gravel marl	< 3h	0.8	Pellet-Beaucour & Kastner (2002)
	> 12h	2.2	
Sl. clayey fine sand	< 3h	0.7	
	> 12h	1.1	
Clay	< 1.5h	0.26	Curran & McCabe (2011)
	> 12h	0.30	
Gravelly clay	< 1.5h	0.8	
	> 12h	0.84	
Sand/gravel	< 1h	0.52	Cheng *et al.* (2017)
	> 12h	0.99	
Clayey sand	< 1h	0.44	
	> 12h	1.0	
Sand/silt	< 2	0.05	O'Dwyer *et al.* (2020)
	2–5	0.12	
	12–20	0.16	
	> 20	0.31	

An exclusive focus on the retrospective analysis of pipe-jacking drives as a means of improving our understanding of the relationship between skin friction and stoppage duration may have limitations, for reasons summarised by Sheil *et al.* (2020). The calibration of load cells used in conjunction with jacks in the launch shaft and the steering cylinders (and at intermediate jacking points, where present) is not routinely checked on working sites. Moreover, where steering cylinder forces (located just behind the TBM face, providing an indication of face force) are not measured, and therefore skin friction and face resistances cannot be separated directly, the widely cited Pellet-Beaucour & Kastner (2002) empirical method for separating these components can be used but is somewhat subjective.

Greater certainty in data quality can be achieved through laboratory testing. Interface shear testing has been used to measure the skin friction at typical pipe-jacking interfaces (e.g. Iscimen, 2004; Staheli, 2006; McGillivray, 2009; Shou et al., 2010). However, none of those studies has considered the impact of stoppages on interface behaviour. In this paper, direct shear interface tests with a concrete specimen in one half of the apparatus and either sand, a 1:1 sand/bentonite mix or bentonite in the other are reported. These tests cover the spectrum of overcut stability scenarios arising in practice; the sand-concrete interface is deemed to represent a collapsed overcut which is unlubricated, the sand/bentonite mix models a collapsed overcut with lubrication, while the bentonite-only case models an open lubricated overcut. Upon reaching critical state conditions, stoppages of various durations were imposed and the net increase in shear stress upon recommencement of shearing was noted. The results offer some new insights into the process underpinning the skin friction increases.

2 MATERIAL CHARACTERIZATION

2.1 Leighton Buzzard sand

A medium to coarse ‘2EW’ Leighton Buzzard sand was selected for the direct shear interface tests. The sand is sub-angular to rounded. It has a mean particle size (D_{50}) of 0.51 mm, and according to ISO 14688-2 (2017), the combination of its uniformity coefficient (C_u) of 1.81 and its coefficient of curvature (C_c) of 0.97 suggest that it is uniformly graded. Its specific gravity is 2.65.

2.2 Lubricant

Baroid Tunnel-Gel Plus, a bentonite slurry widely used in the pipe-jacking and microtunnelling industries, was chosen as the lubricant. A 5% slurry solution, corresponding to concentrations used in Ward & Burke Construction pipe-jacking drives, with pH measured as 9.3, was mixed at 500 rpm for 20 mins using a Stuart SS20 high speed stirrer; the speed was subsequently reduced to 100 rpm and was left to hydrate for 4 hours, following recommendations by Praetorius & Schoesser (2017). The Marsh funnel times fell in the range 10-20 mins, more consistent with Marsh funnel times on site (e.g. 38 mins quoted by Cheng *et al.* (2017) in clayey sand) than reported in other laboratory studies (e.g. 43 s in Reilly (2014); 130 s in Shou *et al.* (2010)).

Sand/bentonite combinations considered in this study were (i) sand only; (ii) 1:1 sand:bentonite and (iii) bentonite only. Both the bentonite (given its thixotropic nature) and sand were stored at approximately constant temperature and humidity (20ºC and 50% respectively) until time of testing in a laboratory with ambient temperature of approximately 19ºC.

2.3 Concrete

A concrete coupon was manufactured using a 30 MPa mix comprising 17 % CEM II cement, 14.6 % water, 32.8 % fine aggregate (≤ 2.36 mm) and 35.6 % coarse aggregate (≤ 8 mm) by mass. The coupon had a 59 mm square plan area and a thickness of 19 mm to ensure a snug fit within the bottom half of the direct shear chamber. The concrete surface roughness was measured using a Bruker's NPFLEX 3D optical profilometer in vertical scanning interferometry mode. This device has a vertical resolution of 3 nm and can measure up to 10 mm in height. Average surface roughnesses (R_a) of 10.3, 4.4 and 6.1 μm were determined for zones of 0.439 mm × 0.330 mm located at the centre and near two corners of the coupon. These values were a close match for R_a values for a section of a typical concrete jacking pipe (supplied by an Irish precast concrete manufacturer) using the same optical technique. The concrete coupon and an example surface profile are displayed in Fig. 1.

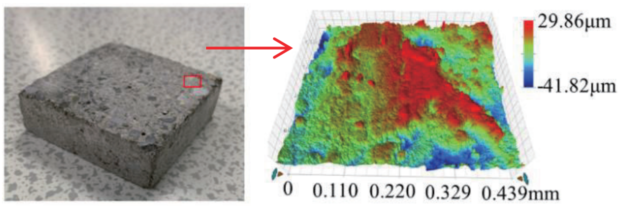

Fig. 1. Concrete coupon used for interface tests and topographical image of 0.439 mm × 0.330 mm zone.

3 DIRECT SHEAR INTERFACE TESTING

3.1 General

A 60 mm × 60 mm × 40 mm Wykeham Farrance apparatus was used to carry out the direct shear tests according to BS 1377-7 (1990). The shear force was measured using an *AEP Transducers* Type TS 0.5t load cell; horizontal and vertical displacements were measured using PY-2-F-025-S02M-XL0465 and PY-2-F-010-S02M-XL0465 transducers respectively, supplied by *GEFRAN*. All measurements were recorded using a *Controls Group* Geodatalog 8 data acquisition system at a rate of 1 Hz. Normal stresses of 50, 150 and 250 kPa were achieved by applying dead weights to the rigid steel top cap. For specimens containing bentonite, the consolidation process was monitored and was considered complete when the top cap displacement ceased. Sand and sand-concrete interface tests were conducted five times each to confirm repeatability. All tests incorporating bentonite were effectively replicates up to the point at which the stoppages were imposed.

3.2 Sand-only direct shear tests

For the sand-only tests, dry samples of 2EW Leighton Buzzard sand were placed in the apparatus following the steps in Miura *et al.* (1997); the sand was poured through a funnel with the tip in contact with the base initially, and then was carefully raised to minimise drop height. The surface was levelled before placing the perforated plate on top. This process created a loose sand sample with a dry density of 1.53 Mg/m^3 (relative density, D_r = 20±2 %). This relative density was chosen for consistency with that of the sand in the O'Dwyer et al. (2020) field pipe-jacking study. A shearing rate of 1 mm/min was chosen, recommended for sands by Bolton (1991) to ensure drained shearing.

3.3 Interface direct shear tests

To facilitate interface testing, the concrete coupon was placed in the bottom half of the shear box, ensuring that the top of the concrete was flush with the shear plane. The top half was filled with either sand only, a 1:1 sand/bentonite mixture, or bentonite only. The 1:1 sand/bentonite mixture was achieved by mixing 50 g of sand and 50 g of bentonite by hand in a container. Subsequently, 70 g of the slurry mixture was poured into the shear box, resulting in an initial density of 1.62 Mg/m^3. In the bentonite-only tests, a syringe was used to place the slurry directly on the concrete coupon, with an initial density of 1.1 Mg/m^3 achieved. Modified top and base plates were used to limit leakage in tests with bentonite. The plates and all contact surfaces were lightly greased to reduce friction and prevent bentonite leakage from the pre-defined failure plane. Filter paper was also placed between the perforated plate and the porous stone to prevent bentonite egress while allowing excess water to escape during the consolidation phase.

From direct shear tests on kaolin clay conducted at 0.05 mm/min (shown to be drained) and 1 mm/min, Doan (2019) showed that peak shear stresses normalised by normal effective stress (τ_{pk}/σ'_n) were rate dependent but critical state shear stress normalised by normal effective stress (τ_{crit}/σ'_n) were not. Assuming comparability of kaolin and bentonite based on their high clay contents, rate effects were also considered to be negligible in the bentonite, enabling the faster 1 mm/min rate to be adopted for the interface tests sheared to critical state in this study. Unless otherwise stated, shear stresses τ_{crit} were calculated as the mean of all values between 10% shear strain and ≈18%, to ensure critical state conditions had been achieved.

All tests incorporating stoppages were conducted at a normal stress of 50 kPa, reflecting the modest soil cover typical of microtunnel drives. In these tests, the motor was stopped at 12% shear strain upon verification that critical state conditions had been achieved. One of eight different stoppage durations was then imposed: 30 mins, 6, 24, 48, 75, 112/120, 150/163 and 333 hours, after which shearing resumed to ≈18% shear strain. Any consolidation occurring during the stoppage was also recorded.

Several methods for calculating the stoppage-induced increase in shear stress were explored. Ultimately the increase was determined as the difference between the shear stresses immediately before and the peak value immediately after the stoppage, in keeping with how real pipe-jacking drives are interpreted (e.g. O'Dwyer *et al.*, 2020); see example in Fig. 2 for the bentonite-only 75 hour stoppage case. A combination of stress relaxation and load fluctuations due to diurnal temperature variations arose during most stoppages; the example in the inset to Fig. 2 displays primarily the latter. Stress relaxation is a natural phenomenon in both sands (e.g. Lade, 2009) and clays (e.g. Oda and Mitachi, 1988) under constant strain. Phillips et al. (2019) and Phillips (2022) have also observed stress relaxation from instrumentation in concrete pipes during pipe-jacking stoppages. Therefore no correction for stress relaxation was applied. A 'Time Series Decomposition' approach was used to 'detrend' the shear stress values for temperature effects using Python programming; the full details are presented in O'Dwyer (2022).

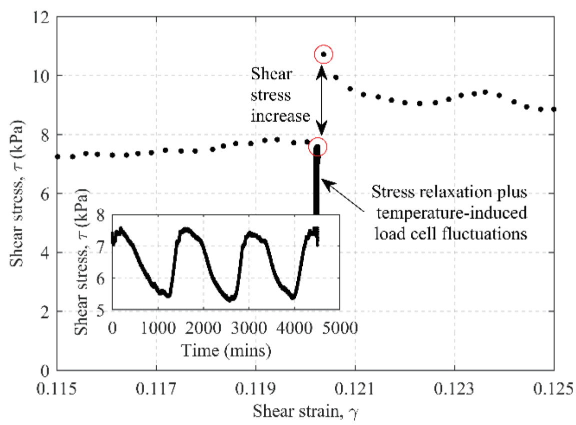

Fig. 2. Determination of shear stress increase upon restart of jacking after a 75 h stoppage; bentonite-only case

4 RESULTS

4.1 Sand and sand-concrete interface

The shear stress-strain relationship for dry sand is shown in Fig. 3 for normal stresses of 50 kPa, 150 kPa and 250 kPa, demonstrating excellent repeatability (coefficients of variation (COV) for τ_{crit} less than 3%). The average critical state friction angle (ϕ'_{crit}) from five tests was 33.3° (Fig. 4), slightly above the 31°-32°

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recommended by BS 8002 (2015) based on its angularity and grading. Values of 33°, 35.3° and 32° have been reported by Houlsby & Hitchman (1988), Lings & Dietz (2004) and White *et al.* (2008) respectively for Leighton Buzzard sand, the spread of values probably reflecting angularity and grading differences also.

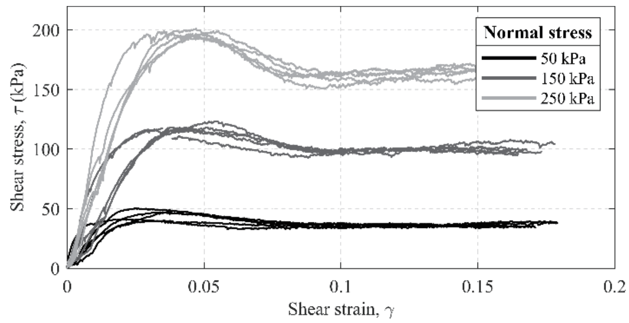

Fig. 3. Development of shear stress with shear strain for sand-only tests.

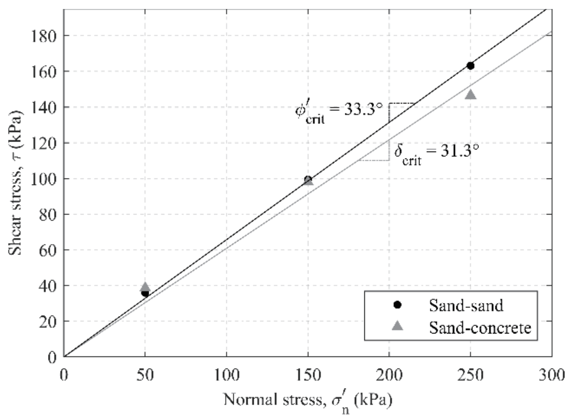

Fig. 4. Friction angle for sand and interface friction angle for sand-concrete.

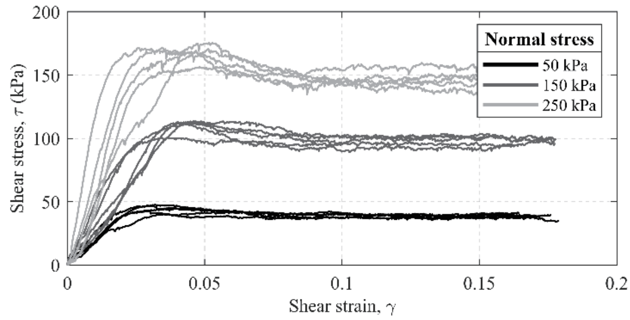

Fig. 5. Development of shear stress with shear strain for sand-concrete interface tests.

The shear stress-strain relationships for the sand-concrete interface are shown in Fig. 5, also showing strong repeatability (COV for τ_{crit} less than 4.1%). The relative differences between τ_{pk} and τ_{crit} are lower in the interface tests, in keeping with slightly reduced dilation evident from the vertical displacement measurements. The critical state interface friction angle δ_{crit} was determined (from the average of five tests) to be 31.3° (Fig. 4). The combination of the $\delta_{crit}/\phi'_{crit}$ ratio of 0.94 and the average R_a/D_{50} ratio of 0.013 is broadly in keeping with values for concrete interfaces presented by Knappett & Craig (2012) based on two separate studies; differences may be attributable to the techniques used to determine roughness.

4.2 Tests incorporating stoppages

All interface tests were conducted at a normal stress of 50 kPa. The specimens incorporating bentonite exhibited contraction and the absence of a peak stress. The mean and COV of τ_{crit}/σ'_n values averaged between 10% and ≈12% strain (just before the stoppages) were 0.39 and 8.6% respectively for the 1:1 sand/bentonite case, and 0.17 and 23.1% for the bentonite-only tests.

Final consolidation (vertical) displacements prior to shearing were 2.6–4.0 mm for the 1:1 sand/bentonite mix, and 2.9–5.2 mm for the bentonite-only mix. The extent of consolidation that had occurred by the end of each stoppage (ongoing in many cases) was relatively minor compared to the final values prior to shearing. On average, the ratio of consolidation that occurred during a stoppage to that prior to shearing was ≈0.02 for the 1:1 sand/bentonite mixture and ≈0.1 for the bentonite-only case. There was no relationship apparent between the amount of consolidation during the stoppage and the stoppage duration.

The relationships between the stoppage-induced shear strength increase and the stoppage duration are presented in Fig. 6. There are no time-related increases for the dry sand case, as would be expected for drained shearing. In general, the shear stress variation with stoppage duration data for the bentonite-only case plots slightly above that for the 1:1 sand/bentonite case. However, both sets of data are consistent in showing an increasing relationship between shear stress increase and stoppage duration up to ≈ 3–3.5 kPa after 5–6 days, after which the shear stress appears to plateau.

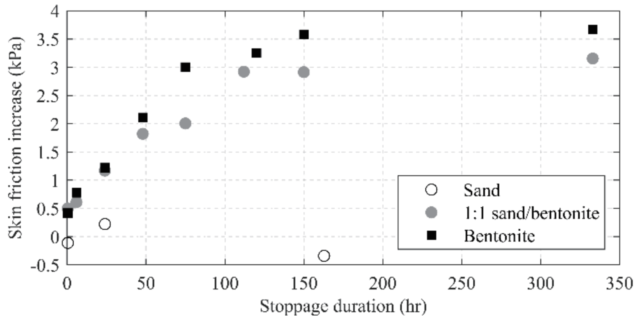

Fig. 6. Relationship between shear stress increase after stoppage and stoppage duration: direct shear data.

5 DISCUSSION

It is acknowledged that the magnitudes of shear stresses (τ_{crit}) alluded to in Section 4.2 exceed the values of skin friction measured in field drives, where values below 1 kPa are routinely achieved with modern automated lubrication systems (e.g. Curran & McCabe, 2011; Cheng *et al.*, 2017; O'Dwyer *et al.*, 2020). This is because jacking pipes are designed to exploit buoyancy from the lubricant within the overcut annulus, formed as a result of the TBM having a slightly larger diameter than the pipes. However, the primary focus here is on the magnitude of skin friction increases due to stoppages; their variation with stoppage duration modelled (Fig. 6) is believed to be representative of practice.

The shorter duration stoppage data are reproduced in Fig. 7, with the time axis plotted on a log scale due to the apparent skin friction intercept (at zero time) in Fig. 6. Also included are the skin friction increases quoted in Table 1 relevant to sandy soils (i.e. Pellet-Beaucour and Kastner 2002, Cheng *et al.* 2017 and O'Dwyer *et al.* 2020) superimposed. The arrow annotations on some field datapoints denote that the skin friction increases relate to stoppage durations less than or equal to (arrows pointing left), or greater than or equal to (arrows pointing right) those plotted. Error bars are used where a discrete time range is represented (with the point plotted at mid-range). The interface shear data shows good agreement with both the Pellet-Beaucour and Kastner (2002) and Cheng et al. (2017) field data. The fact that the O'Dwyer *et al.* (2020) plots lower reflects a highly effective lubrication strategy for that drive; those authors note that the volume of lubricant injected amounted to over six times the annular volume throughout the drive, which is over double the ratio recommended for tunnelling in sands and silts by Praetorius and Schoesser (2017).

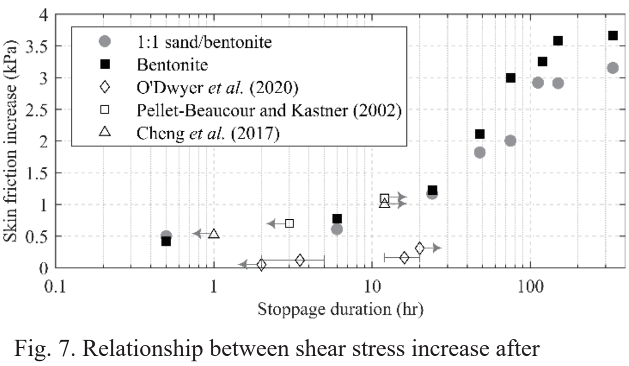

Fig. 7. Relationship between shear stress increase after stoppage and stoppage duration: direct shear and field data.

Various researchers have offered explanations for the increases in skin friction arising during a stoppage:

(i) Chapman & Ichioka (1999) proposed that there was potential for bentonite consolidation during longer stoppages, such as nights and weekends. While consolidation occurred during the stoppages in this study, the amounts were small and no correlation with stoppage duration was established.

(ii) Reilly & Orr (2017) highlight the role of bentonite pressure in reducing local effective stress on jacking pipes. The corollary, as suggested by Zhang *et al.* (2018), is that a reduction in bentonite pressure during a stoppage may cause the skin friction to increase, leading to cavity contraction, thereby increasing the effective stress acting on the concrete pipes. Such a decrease in pressure could also counteract pipe buoyancy (Choo & Ong, 2012). However, the significant lubricant pressures used in modern microtunnelling (e.g. Phillips 2022) means that this phenomenon is likely to be secondary.

(iii) In the context of stoppages, Zhang *et al*. (2018) also infer differences in the coefficients of static and dynamic friction. The time-dependent nature of the measured data in Fig. 6 would appear to oppose this explanation for these tests.

The time-dependent increase in skin friction in Fig. 6 may be a result of thixotropic strength gain within the bentonite. For example, using both a fall cone and shear vane, Shahriar *et al.* (2018) report an increase in thixotropic strength ratio (defined as the multiplier on initial strength) with time, plateauing after ≈150 hours. Noori *et al.* (2019) carried out triaxial tests on sand/bentonite mixtures in which an increase in undrained strength with time was observed up to 100 hours. The undrained strength showed a dependence on bentonite content, and exhibited a reducing rate of strength gain with time. There are clearly parallels between such trends and the interface shear data presented in Fig. 6. Research is ongoing at NUI Galway using a large-scale interface shearing facility incorporating a portion of a jacking pipe to consider further the mechanism behind the stoppage-induced skin friction increases (O'Dwyer 2022).

6 CONCLUSIONS

In this paper, direct shear interface testing has been used to model the effect of pipe-jacking stoppages on skin friction increases along pipe-sand/lubricant and pipe-lubricant interfaces. The maximum stoppage duration observed of 2 weeks was deliberately longer than typically arises in field situations. The maximum increases (≈ 3–3.5 kPa) were found to be small when benchmarked against critical state shear strengths, but could potentially represent very significant increases in jacking force requirements in field scenarios, where average skin friction values of less than 1 kPa are routinely achieved. The increases were dependent on stoppage duration up to 5-6 days, but appear to plateau thereafter, with only a mild effect of bentonite content noted. The results suggest that a temporal process, such as thixotropic strength gain in bentonite with time, may be behind the observed behaviour, but further research is needed to confirm the underpinning mechanism(s). The laboratory data presented appear to represent a (conservative) upper bound to corresponding stoppage-induced skin friction increases from three case histories presented.

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