Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Measuring Axial Friction Factors in Fine-Grained Soil

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ABSTRACT: Axial seabed resistance plays a key role in the stability of surface-laid pipelines and cables, particularly in soft clays where consolidation and loading history influence resistance mobilisation. This paper presents centrifuge model tests using shallow penetrometers to investigate axial friction under low effective stresses – in the range 1-3 kPa – representative of pipe/cable-seabed conditions at shallow embedment. The test programme employed model pipes, toroids, and flat ring penetrometers in reconstituted Gulf of Mexico clay, with instrumentation to monitor vertical load, displacement, and pore pressure response. The results show that large changes in axial resistance and friction-factor – by a ratio of up to three – can emerge due to penetrometer geometry, shearing rate, and lay history, with distinct trends observed under episodic and continuous shearing. The study also highlights practical considerations associated with load control and interpretation at very low stresses when performing these novel tests. When performed with accurate control and interpreted appropriately, centrifuge shallow penetrometer testing provides a robust basis for characterising axial resistance relevant to pipelines, cables, and similar seabed infrastructure.

1 INTRODUCTION

1.1 Shallow seabed characterisation

The mechanical behaviour of the near seabed soil – i.e. the shallowest ~0.5 metres – plays a central role in the design of shallowly embedded subsea infrastructure such as cables and pipelines. Reliable assessment of seabed strength and consolidation response is therefore essential, as highlighted in recommended practice (e.g. ISO 2025; White et al., 2017).

In pipeline design, the seabed resistance to movement is commonly represented using friction factors, which express the mobilised resistance as a proportion of the pipeline's effective submerged weight per unit length, W'. These factors are not fixed material properties but outcomes of geotechnical evaluation, reflecting the combined influence of soil characteristics, pipeline geometry, installation conditions, and the nature of applied loading.

Separate friction factor values are typically adopted for axial and lateral motion, and both are sensitive to the sequence of prior loading and the timescale of the design event (White & Bransby 2018).

1.2 Aim of current study

The measurement of interface friction properties and pipe/cable-seabed friction factors remains an active area of research, driven by the large number of influencing geotechnical variables. Its relevance is evident from recent studies examining shallow penetrometer behaviour (e.g. Mohr et al., 2025; Singh et al., 2024).

This paper presents recent centrifuge tests aimed at improving methods for determining axial friction factors. The experiments use both pipe-like and flat shallow penetrometers and were conducted in soft clay under low effective stresses, requiring precise control of the very small applied loads achievable in the centrifuge environment.

2 WHY THE CENTRIFUGE?

2.1 Laboratory element testing

Friction properties are often characterised using interface shear box testing. These tests isolate the soil–structure interaction on flat surfaces, eliminating geometric effects such as wedging that occur with non-planar interfaces like pipelines or cables (White

& Randolph 2007). As such, the resulting measurements yield an interface friction **coefficient** rather than a friction **factor**, and careful interpretation is required to translate these laboratory results into practical design parameters.

Recently, Lehane & Liu (2013) and Mohr et al. (2025) suggested that the stress-dependence at low stress levels apparent in interface shear box data, incorporated into an expected trend in design practice, may be at least partly an artefact of the interface shear box apparatus itself due to sources of internal friction and load redistribution. This highlights a limitation of shear box testing and the need for further research into alternative test methods.

2.2 Shallow penetrometers at unit gravity

Shallow penetrometer testing has made valuable contributions to understanding friction, particularly using pipe-like geometries such as toroid and hemiball shapes (e.g. Yan et al. 2010, Schneider et al., 2020). These tests provide a straightforward way to probe the seabed under controlled vertical and rotational movement, offering a basis for interpreting fundamental soil properties and the interface shear strength at the penetrometer surface.

Nonetheless, when testing with small shallow penetrometers (e.g. a toroid of 25 mm diameter) at 1g, the effective stresses in the soil at the toroid invert are lower than those experienced at full scale around a cable or pipeline, which can influence the mobilisation of axial friction and soil consolidation.

2.3 Centrifuge testing

Full (or large) scale 1g tests have provided insights into axial pipe–soil interaction (e.g. Brennodden and Stokkeland, 1992; Paulin et al., 1998). However, such tests are often impractical for routine design work due to their large spatial requirements and the long consolidation times needed for fine-grained soils.

Centrifuge modelling has a long-established role in studying interface friction (e.g. Yan et al., 2010) and pipe-soil interaction (Gaudin & White 2009), and continues to attract global interest. For example, Rismanchian et al. (2019) and Satchithananthan et al. (2020) investigated lateral and axial friction respectively, using carefully designed and instrumented model pipe sections.

The centrifuge allows effective stresses to be scaled to prototype levels, while accelerating the long term consolidation processes that would otherwise accumulate over years of field operation. This enables realistic soil–pipeline interactions to be simulated rapidly at model scale.

Under these representative stress conditions, shallow penetrometers can capture interface friction behaviour, while reduced drainage paths permit field processes – such as installation or long-term settlement – to be reproduced within practical test durations.

3 TEST APPARATUS AND CLAY

3.1 Shallow penetrometers

Various shallow penetrometer types were used in this study, including pipe sections, toroids, and flat rings, with most components and the loading systems described in O'Beirne et al. (2023).

The primary tool was an open-ended model pipe section (Figure 1a) representing a prototype diameter *D* = 0.5 m and total length 6*D*. Larger diameter pipes were also tested, and removable end caps (Figure 1b) allowed comparison of open- and closed-ended configurations. Each pipe included an invert pore pressure transducer (PPT) to monitor excess pore pressure during installation, shearing, and rest.

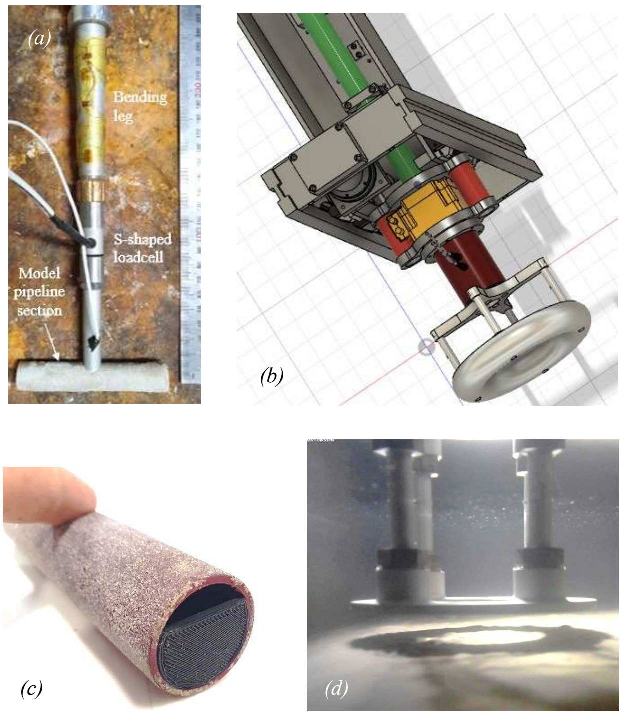


Figure 1. Shallow penetrometers with invert PPTs: (a) pipe fitted to instrumented bending leg, (b) toroid connected to vertical/torque loadcells on rotary actuator, (c) pipe with end caps, (d) flat ring before mudline touchdown

The toroid shared the same cross-sectional diameter (D) as the model pipe, with an average circumference of 12.6D. The flat ring tool had the same circumference but a 1.5D-wide contact surface, designed to eliminate wedging by causing planar soil-interface shearing.

Both the toroid and ring tools incorporated four underside PPTs and were linked via instrumented shafts measuring vertical load and torque.

3.2 Test facility and soil sample

Testing was performed in the 10 m diameter centrifuge at the National Geotechnical Centrifuge Facility at the University of Western Australia, which is described by Gaudin et al. (2018).

A reconstituted Gulf of Mexico clay was used to prepare two test samples (

a). The clay is entirely fine-grained (100% passing the 75 µm sieve) with a liquid limit of 94%, plasticity index of 66%, and specific gravity of 2.71. The soil was initially mixed to a slurry at a moisture content of approximately 130% and lightly overconsolidated at 37.5g in the centrifuge. All shallow penetrometer tests were then conducted at 31.25g, with the effective radius of the g-field set near the consolidated mudline height.

T-bar penetration tests were used to assess undrained strength. Results on

indicate a strength gradient, *k*, of approximately 1.75 kPa/m, based on a bearing capacity factor $N_{T\text{-bar}}$ = 10.5. Cyclic remoulding stages were included to estimate soil sensitivity, which was approximately 2.3.

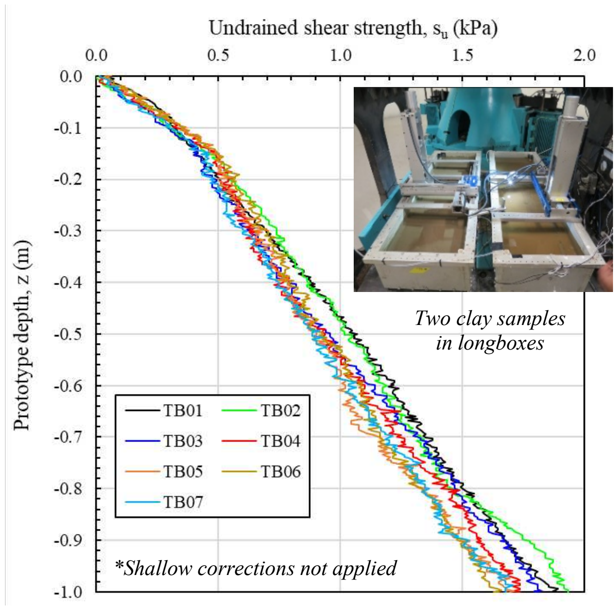


Figure 2. T-bar strength profiles in the shallowest 1m

4 TEST PROCEDURES

4.1 Stage 1: Lay simulation & dissipation

Lay conditions can strongly influence the available axial friction resistance, *T*, due to the generation of excess pore pressure and remoulding of the seabed soil caused by the lay process. Accordingly, various lay simulations were considered using the pipe-section and toroid penetrometers (Figure 3; Table 1 – Step 1 to 4). The structure of Table 1 was partly inspired by the presentation style adopted by White et al. (2022) when describing the different stages of a shallow penetrometer test when performed at 1g.

Three general installation procedures were examined in the clay sample: (a) installation with overpenetration, where *OPR* $(V_0/V_{axial}) > 1$, but with no consolidation period at V_0; (b) installation without overpenetration, where *OPR* = 1, and (c) cyclic installation, involving repeated penetration and retraction cycles prior to axial shearing.

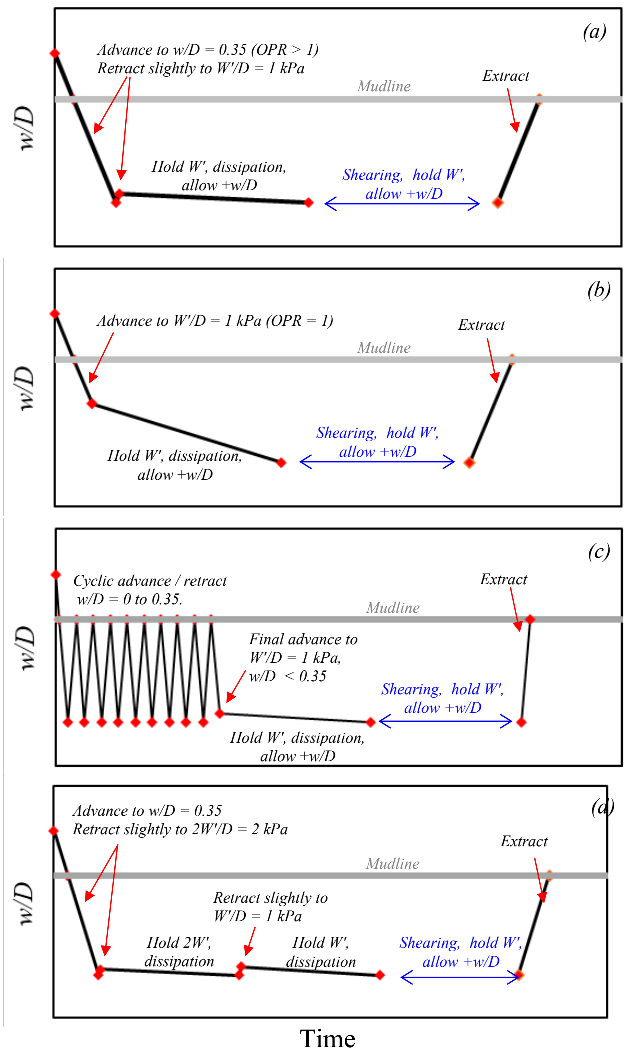


Figure 3. Lay simulations adopted

Additional test variants included a procedure that involved consolidation at twice the operating weight (Figure 3d), and a modified over-penetration case where the initial penetration depth was reduced to *w/D* = 0.175 (not shown).

The installation phase was followed by a dissipation interval during which the vertical load *W'* was held constant and the surrounding excess pore pressure was permitted to dissipate (Figure 3).

4.2 Stage 2: Shearing phase

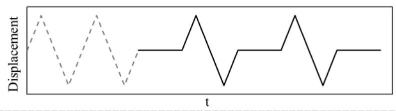
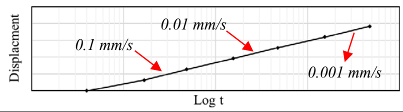
Shearing was applied using one of two approaches: episodic OR twitch-style (
Table 1, Step 5a OR Step 5b). During shearing, the vertical load *W'* was held constant under load control, so the penetrometer was free to embed.

Episodic shearing: A model-scale shearing rate of approximately 0.94D/min (0.25mm/s; 0.45°/s for rotational penetrometers) was adopted to maintain undrained conditions. Controlled consolidation periods were incorporated between shear increments. For the pipe-section tests, this occurred at the end of each ±1D axial cycle.

Twitch-style shearing: The shearing rate was varied over orders of magnitude, with continuous shearing and no consolidation holds.

In the pipe-section tests, prior to shearing two initial axial cycles (±1D, total travel 4D) were applied to 'clear' the local soil at the pipe ends, which otherwise can inflate the measured axial resistance, *T*. Other experimental studies have used pre-excavation of the soil at the pipe ends (e.g. Boylan et al., 2014) to avoid these end effects but this risks disturbing the in-situ stress state. This issue does not arise for the toroid and ring penetrometers, which have no ends and therefore may better represent part of a long pipeline or cable.

Table 1. Typical test procedure

Step	Controls/parameters	Procedure	End point or schematic
1. Sensor checks (in-flight)	v = 0.5 mm/s ax (or ω) = 0.25 mm/s (or 0.45 deg/s)	Sensor response to penetrometer displacement through water column. *PPT*s: check for hydrostatic response *V*: check response to buoyancy and g-field variations *Ax*: confirm negligible	Zero sensors at mudline (visual, underwater camera checks in-flight)
2. Lay simulation	v = 0.25 mm/s to target *w/D*	Vertical penetration to target *w/D* (typically 0.35). Options considered: (a) Monotonic – advance to *w/D*. *OPR* (V_0/V_{axial}) > 1, *OCR* = 1. (b) Monotonic – advance to target *W'*. *OPR* = 1. *OCR* = 1. (c) Cyclic – advance/retract 10 times, stop on final advance at *W'*.	Once relevant lay simulation complete
3. Unload	v = 0.25 mm/s to target *W'*	Only required for Option (a) in Step 2. Retract vertically (slightly) to target *W'*. Typical stress 1 kPa: approx. 1.54 N, 3.22 N, 4.83 N for pipe, toroid, ring respectively (model scale). Option to initially retract to 2*W'* to target *OCR* = 2. Refer to Step 4.	Immediately upon achieving target *W'*
4. Dissipate	Load hold at *W'*, allow embedment	Hold penetrometer under load control at target *W'*, allowing dissipation of excess pore pressure, Δu. If OCR 2 targeted, hold at 2*W'*, then repeat Steps 3 & 4 for *W'*.	When $\Delta u/\Delta u_0 \leq 0.1$ or set time interval limit
5a. ***Episodic*** shearing	Load hold at *W'*, allow for embedment ax (or ω) = 0.25 mm/s (or 0.45 deg/s)	Typical pipe section: Complete initial 'clearing' sweeps for trenches. Followed by undrained shearing with pauses between cycles for Δu dissipation.	
or 5b. ***Twitch*** shearing	Load hold at *W'*, allow for embedment ax (or ω) *VARIES	Typical toroid/ring: Varying rates starting from 0.25 mm/s (0.45°/s) incrementally reduced to 0.001 mm/s (1.8 x 10^{-3} °/s).	

v = vertical rate
ax = axial shear rate
ω = axial rotation rate
W' = vertical load / submerged weight
V and *Ax* = vertical or axial load
w/D = normalised embedment
PPT = pore pressure transducer
Δu = excess pore pressure
Δu_0 = excess pore pressure at Step 3
OCR = overconsolidation ratio
OPR = over penetration ratio
V_0 and V_{axial} = vertical load at installation and during shearing

5 KEY RESULTS AND DISCUSSION

5.1 Lay simulations

Control of the lay simulation at 31.25g was very good, as shown by the typical vertical displacement-load response given in Figure 4 (panels a to d correspond to lay cases in Figure 3a–d).

For the base case test, penetration to 0.35D produced a typical peak resistance of approximately 1.6 kN/m. The load was then reduced cleanly to the target operating submerged weight, *W'/D* = 1 kPa (*W'* = 0.5 kN/m), after which embedment continued to increase during consolidation (Figure 4a). The cyclic lay simulations showed a similar initial penetration resistance, which progressively reduced with cycling as the clay was remoulded. Resistance remained above the target W' (below roughly 0.3 *w/D*), requiring the final penetration cycle to be curtailed to target the correct load hold (Figure 4c).

In the *OPR* = 1 case, the system maintained good control at the very low load setpoint, though these small values approach the practical resolution limits of the load-control system (Figure 4b). For the simulation targeting a local *OCR* = 2, the sequence of pulling back to $2W'$, allowing consolidation, and then stepping down to W' produced the intended load path with consistent and stable control (Figure 4d).

Overall, the load histories demonstrate reliable achievement of the required penetration, unloading and load-hold stages across all lay simulations, providing a robust foundation for the subsequent axial-resistance interpretation.

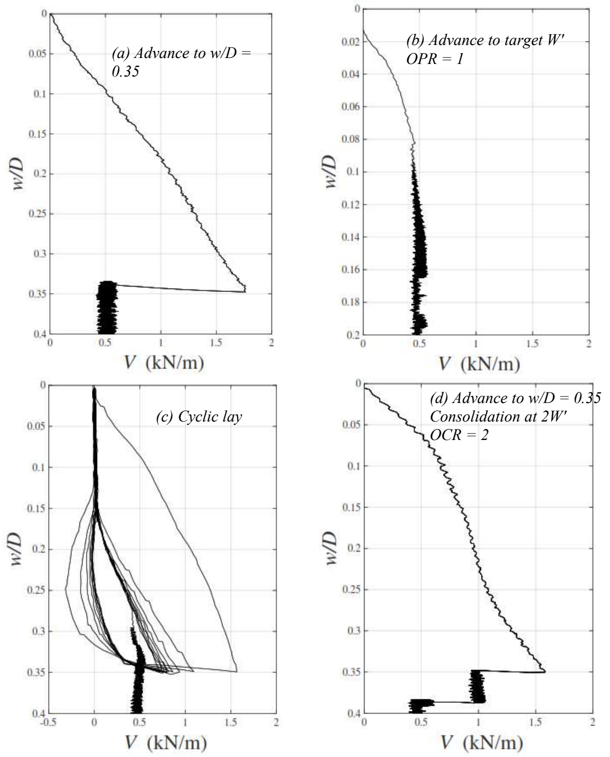


Figure 4. Lay data for pipe section

5.2 Shearing phase

Excellent control was achieved during shearing. Low vertical target loads were maintained with good stability, generally within about ±10% of the set load, even over extended hold periods with ongoing penetrometer embedment. An example vertical load hold during the shearing phase, targeting 1.54 N at model scale, is shown in Figure 5a.

The cyclic response from a pipe-section test is presented in Figure 5b. The format follows similar practice (e.g. O'Beirne et al., 2023), with initial clearing sweeps shown in black and subsequent cycles with intervening consolidation holds shown in blue. Breakout peaks after each consolidation phase are clear, highlighting an important consideration for pipelines or cables subjected to alternating periods of stationary load and movement.

Figure 6 presents shear data from twitch-style tests using toroid and ring shallow penetrometers. Initial breakout friction factors were slightly above 1 for the toroid and just below 1 for the ring. Both penetrometers exhibit a similar T/W' trend as shearing is sustained at 0.45°/s, approaching a lower bound (undrained) of approximately 0.35. As the shearing rate is incrementally reduced – with the penetrometer continuing to rotate in the same direction – the flat ring stabilises near T/W' = 0.5, whereas the toroid shows a higher stabilised T/W' value of approximately 0.65 at a rotation rate of 1.8×10^{-3} °/s.

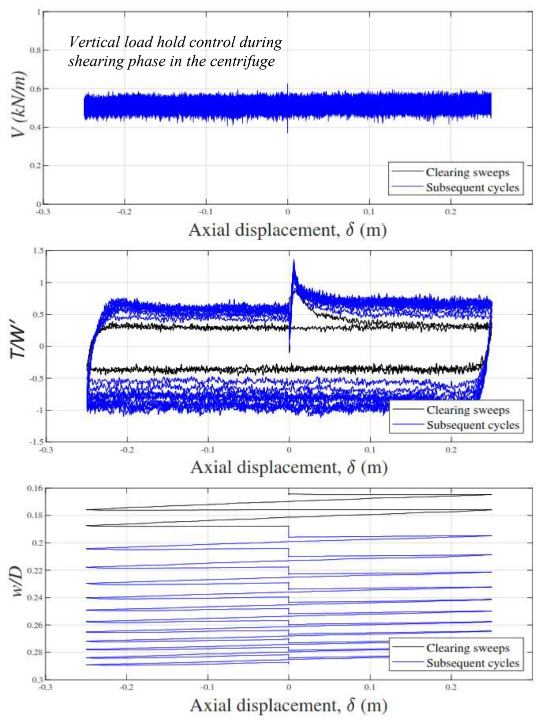


Figure 5. Shear data: (a) V–time, (b) T/W'–δ, (c) w/D–δ

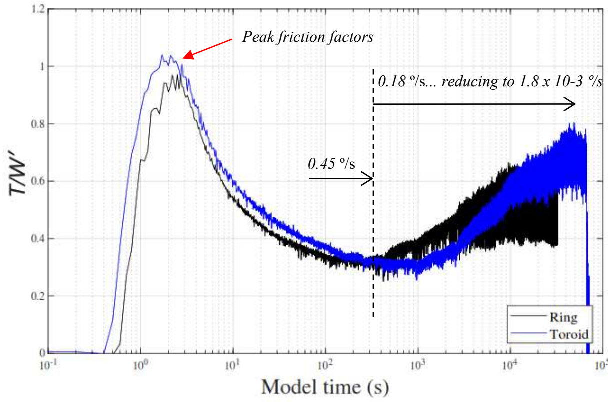


Figure 6. Twitch test: toroid and ring penetrometers

5.3 Practical testing considerations

Early tests in the soft Gulf of Mexico clay occasionally showed ongoing plastic embedment of the shallow penetrometers during the consolidation intervals, persisting well beyond the point at which excess pore pressures were expected to have fully dissipated. This behaviour can be partly attributed to the very low vertical model loads (refer to Table 1) targeted in the centrifuge environment and warrants consideration during interpretation.

Under such conditions, the location and boundary conditions of the vertical load cell are critical, and the load cell should be positioned as close as practicable to the penetrometer–soil interface. Several concurrent mechanisms may cause the *actual* vertical load acting at the penetrometer tip to evolve during testing, including:

- Soil infiltration into open-ended penetrometers (Figure 7) which increases apparent self-weight and can trigger additional embedment as the control system acts to restore the target load that acts in addition to the enhanced self-weight.
- Buoyancy effects associated with settlement, whereby increasing submergence of the shaft of the penetrometer reduces the effective self-weight below the load cell and therefore modifies the vertical load applied to the soil. Temporal variations in water column height would also disturb the applied vertical load due to the same effect.

Local g-field changes typical of centrifuge testing should also be considered, whereby continued settlement increases the local acceleration acting on the model and marginally increases its self-weight.

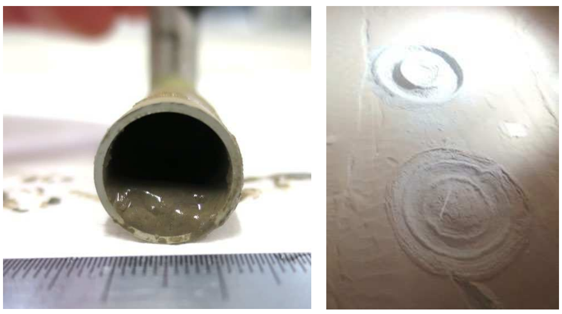


Figure 7. Post testing observations (a) Soil infiltration to model pipe and (b) footprints from toroid and ring tests

Accordingly, careful post-processing is required to determine the actual vertical load at the penetrometer tip, $W'_{actual}(t)$. Normalising the evolving axial resistance using this corrected load can yield a modified friction-factor trajectory and should be considered when interpreting the results.

6 CONCLUSIONS

Centrifuge tests using pipe, toroid, and flat ring penetrometers were conducted in soft clay to investigate axial friction mobilisation under low effective stresses relevant to shallow seabed infrastructure. Stable control of very low vertical stresses – in the range 1-3 kPa – was successfully achieved, enabling consistent interpretation of axial resistance during both episodic and continuous shearing.

The results demonstrate that changes in friction-factor with time are influenced by penetrometer geometry, shearing rate, and lay history, with sustained shearing approaching lower-bound undrained values and higher stabilised resistance observed at reduced shear rates.

The ratio between the highest and lowest friction factors seen in testing on the same soil sample is greater than three, highlighting the strong influence of the mechanisms explored in this study and the need for careful selection of friction factors in design.

Under such low-stress conditions, careful consideration of load measurement and post-processing is required to account for evolving vertical load at the penetrometer tip. When appropriately interpreted, centrifuge shallow penetrometer testing provides a robust framework for assessing axial friction relevant to pipelines, cables, and related seabed infrastructure.

ACKNOWLEDGEMENTS

The second author leads the Shell Chair in Offshore Engineering research team at UWA, supported by Shell Australia. The third author holds the Fugro Chair in Geotechnics at UWA, whose support is gratefully acknowledged. The fourth author acknowledges the support of the EPSRC Supergen Offshore Renewable Energy Hub (grant EP/Y016297/1).

The authors also gratefully acknowledge Dr Jinbo Chen (formerly Shell), Professor Robert Gilbert (University of Texas at Austin, USA), and Dr Ahmed Hussien (formerly University of Texas at Austin, USA) for their technical input during the planning, execution, and review of the test campaigns.

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