

# **ON THE BEHAVIOUR OF PIPE-CLAMPING MATTRESSES TO ARREST PIPELINE WALKING**

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## **ABSTRACT**

A novel solution to mitigate pipeline walking, namely the use of pipe-clamping mattresses (PCMs), was first developed for the Malampaya project. Comprising a hinged concrete structure designed to clamp onto a section of pipeline, and supporting (post-installed) ballast weight that is transferred directly to the pipeline, PCMs are potentially a highly efficient alternative to more traditional solutions such as rock dump or concrete mattresses.

The original PCM geotechnical design was based primarily on analyses extrapolated from pipeline-seabed interaction, supported by a standard suite of classification and interface tests. Physical model testing was not performed. While observations (taken since installation) show that the PCMs have effectively mitigated pipeline walking in the seabed conditions at Malampaya, their performance in other soil types has not been investigated.

To provide further evidence on the effectiveness of PCMs in other soils types, and investigate their performance over time, a series of centrifuge tests was performed in a soil sample representative of deep-water Gulf of Mexico conditions. In each test, a model representing the PCM was installed on the pipeline section, which was then subjected to cyclic axial displacement. Settlement of the pipeline-PCM system, as well as changes in axial resistance, were directly measured and are reported in this paper.

**Keywords:** Pipeline walking, stabilisation, Gulf of Mexico clay, centrifuge modelling

## **INTRODUCTION**

Subsea pipeline walking is well recognised in the literature e.g. Carr et al. (2006), Bruton et al. (2010). The phenomenon is caused by cyclic expansions and contractions driven mainly by heating and cooling, and where frictional resistances at the seabed create a bias for axial movement of a pipeline in one direction over the other. Over a number of start-up and shutdown cycles, walking can cause significant cumulative axial displacement leading to potential failures at connections to pipeline end termination facilities and manifolds.

Pipe clamping mattresses (PCMs) are a relatively new concept developed by Shell, proposed as a novel solution to mitigate pipeline walking and as a cost-effective alternative to rockdump and more conventional concrete mattresses. The PCM may be plainly described as comprising two identical (mirrored) reinforced precast concrete slabs. The slabs are joined by structural wires (installed internally prior to concrete pouring) to form a hinged assembly running axially along the pipeline. The PCM features lifting points used to manoeuvre it over the top of the pipe for installation. By capitalising on the hinged assembly, the PCM naturally clamps onto the pipe during lowering, using its self-weight at a high leverage. The clamping surfaces feature a ~25 mm rubber layer (to assist clamping action) and drainage holes in the concrete slabs to promote faster consolidation. Following PCM deployment, a reinforced precast concrete log mattress is lowered and installed over the PCM, with the weight delivered to the outer extremities of the PCM so as to maximise leverage and the clamping effect.

PCMs have been used for the Malampaya deepwater gas project as reported by Frankenmolen et al. (2017). The pipeline had been designed around 1996 with no special provisions to prevent walking. It later transpired that walking was occurring, reaching about 28 mm displacement per shut-down and restart cycle, reportedly accumulating to 1.8 m at the Pipeline End Structure. In response, the PCM concept was developed, designed and trialled, leading to 15 No. PCMs being installed over 5 pipe joints in 2015 – each having a dry weight of around 16 tons and dimensions of 4 m (along the pipe) by 2.75 m (see Fig. 1). Monitoring subsequently showed that the PCMs had been effective at stopping the walking behaviour.



**Figure 1. Pipe-clamping mattress (Frankenmolen et al, 2017)**

### WHY CENTRIFUGE MODELLING?

The success of the technology for the Malampaya project has led to interest in its application for other soil types and pipeline configurations. The current centrifuge testing campaign was aimed at better understanding (and quantifying) the following two aspects:

- Friction – The capacity is governed by friction between PCM, pipe and seabed. Testing investigated whether this resistance could be estimated from conventional interface tests only, and how drainage and consolidation hardening affect the available friction.
- Settlement – PCMs are designed to clamp onto the pipeline and remain fully connected through the operating life. Soft soils may lead to high PCM settlements, and the testing investigated whether this could lead to ‘unclamping’ of the PCM.

Centrifuge modelling is an effective way to address the above knowledge gaps as consolidation processes operate much faster than for the equivalent prototype case. This allows long-term field scale events (in this case the ‘whole life’ loading histories of PCMs in fine-grained soils) to be replicated within a practical test period.

Note that while this paper introduces testing in one soil type only, this research is part of broader commercialisation activities by Shell and the licensee of the technology (Subcon), and has developed into a multi-operator test campaign that will be fully reported in due course.

### MODEL AND SOIL SAMPLE DETAILS

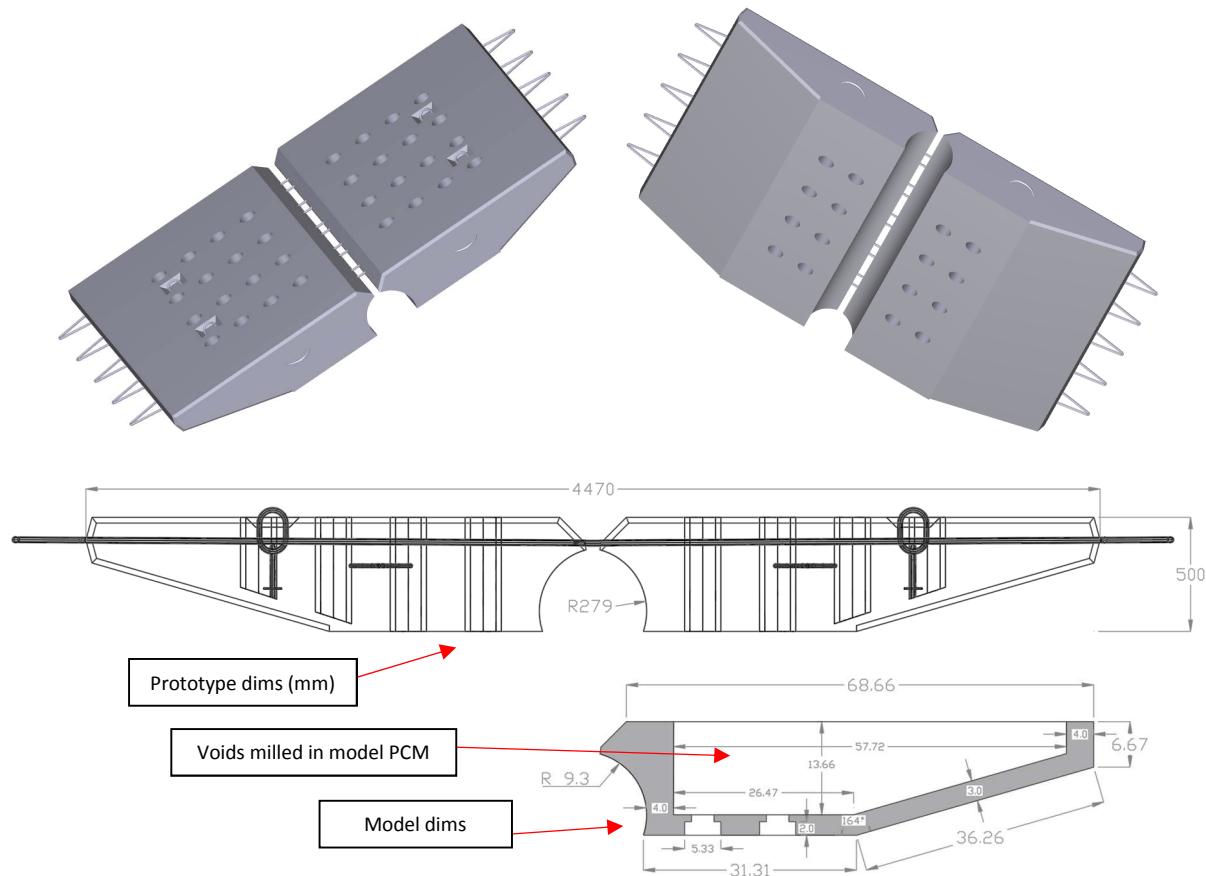
Centrifuge testing (at 30g) was carried out at the National Geotechnical Centrifuge Facility at UWA in late 2019 using the 10 m diameter beam centrifuge (Gaudin et al. 2018).

#### ***Clamp, log mattress and pipeline models***

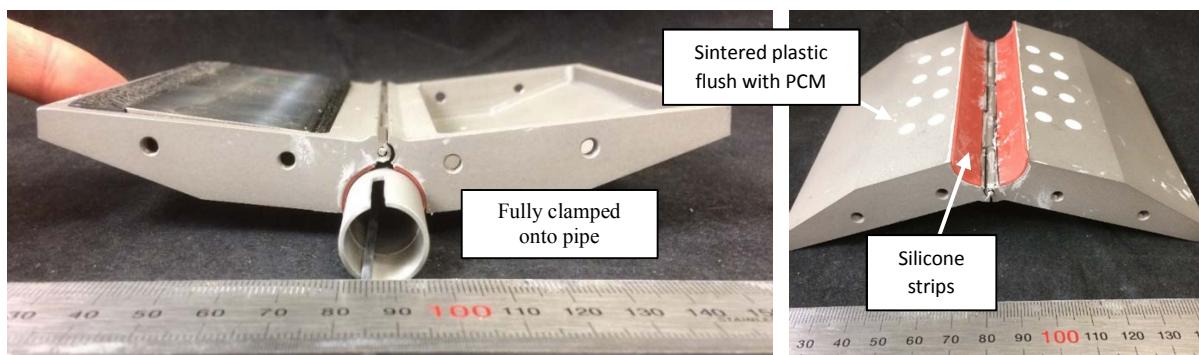
The model was based on a variant of a PCM currently being used on an industry project. In prototype units, the lower clamp is roughly 4.5 m wide and 3.5 m long, with a submerged weight of 74.6 kN. The upper log mattress adds a further 94.5 kN in submerged weight.

A model clamp was fabricated from aluminium with the dimensions shown on Fig. 2, and was sand blasted along external surfaces (those in contact with the soil) to ensure a rough interface. Voids were included in the model PCM to allow for variations in submerged weight (via different inserts), achieving a range of 42 kN (light) to 78 kN (normal). Photos of the model PCM and inserts are presented in Fig. 3. The model included a loose butt hinge to allow clamping around the model pipeline, with silicone strips used to ensure a good connection. Like the prototype, the model featured drainage holes at its base, achieved (in the model) via sintered porous discs that were fitted into 2 mm thick circular recesses in the drainage holes.

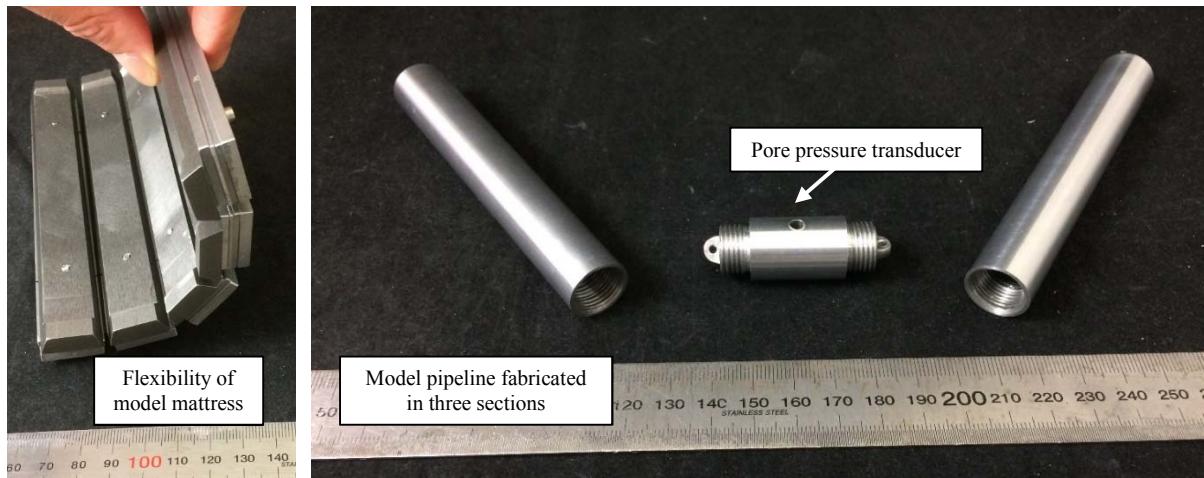
The model log mattress, comprising five 'logs' fabricated from aluminium with a trapezoidal cross-section, was designed to have submerged weight varying from 50 kN (light) to 97 kN (normal). The model mattress is shown in Fig. 4.



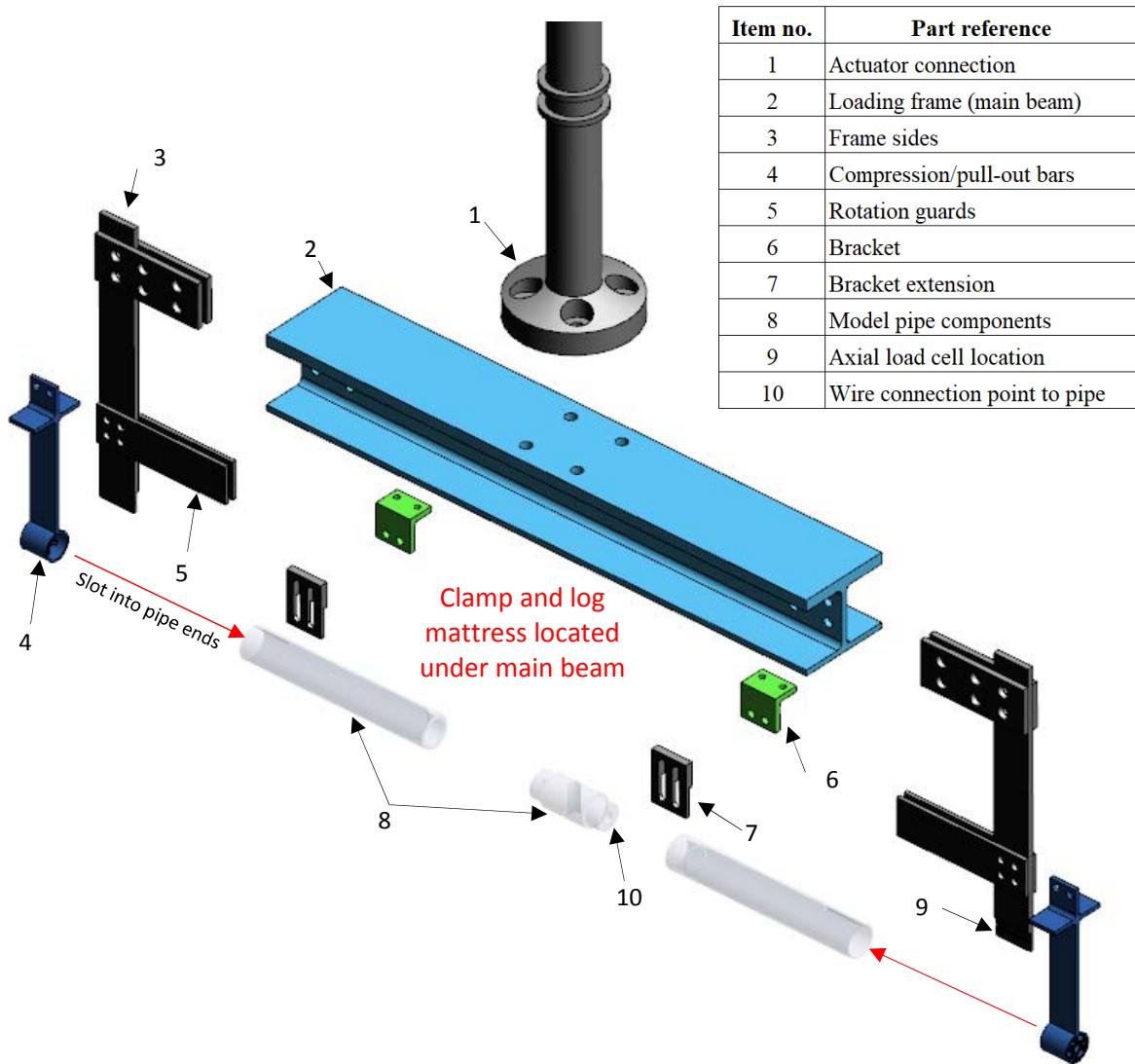
**Figure 2. Model designed to replicate field conditions**



**Figure 3. Photographs of model clamp**



**Figure 4. Photographs of model log mattress and pipe**



**Figure 5. Pipeline loading apparatus and components**

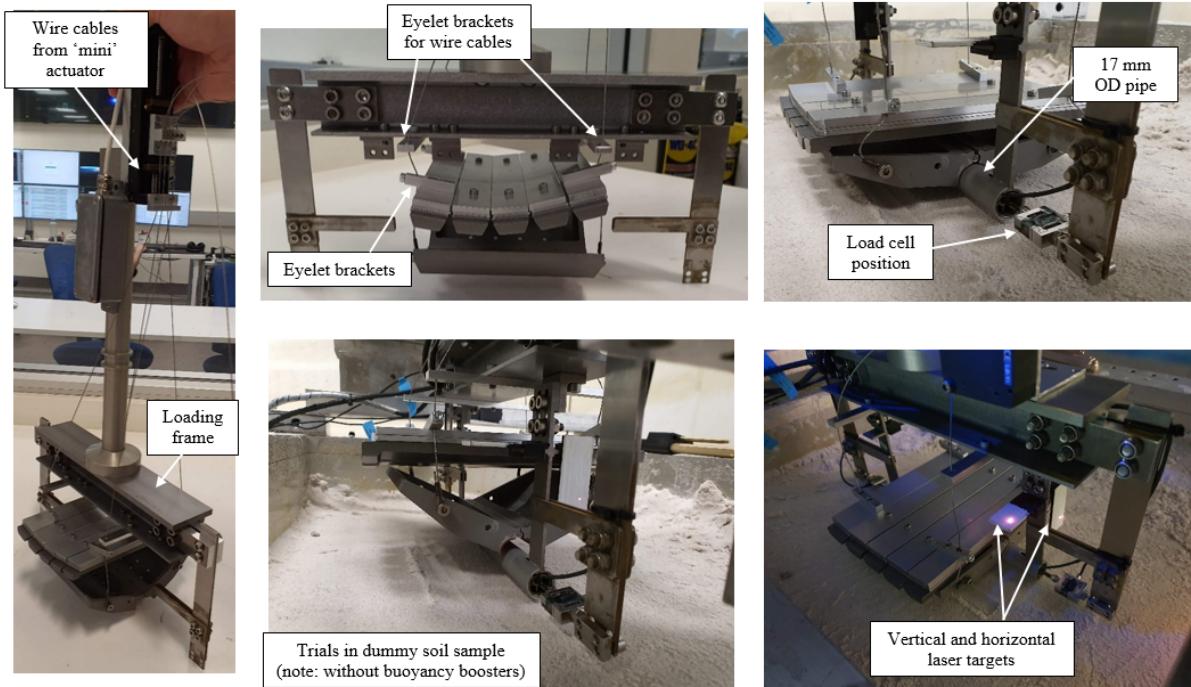
The model pipeline was fabricated from aluminium with an outer diameter ( $D$ ) of 17 mm simulating a flowline with  $D$  of around 0.51 m (including the rough outer coating). Two model pipes were fabricated (from aluminium) with lengths of 11 $D$  (short) and 22 $D$  (long), with both

pipes open at the ends to minimise end bearing resistance during axial movements. Fabricated in three sections (Fig. 4), the central section was solid, and included a pore pressure transducer at the pipe invert to measure the development and dissipation of excess pore pressure during testing, as well as load attachment points to translate axial movements from the loading frame to the pipe (see below). The two end sections had a wall thickness ( $t$ ) of roughly 1 mm in an attempt to match the in-situ submerged weight, with buoyancy ‘boosters’ (3D printed hollow plastic boxes lacquered to ensure they were watertight) attached to the pipeline to offset any difference in the model and in situ submerged weight. This arrangement achieved submerged weights (prototype) of approximately 1 kN/m and 0.7 kN/m for the short and long pipe respectively.

### Test arrangement

The apparatus is shown in Fig. 5. The loading frame, connected to the actuator via an adaptor, comprises an I-beam with an assortment of detachable members. These members included elements to allow the pipe to be pushed (and cycled) into the seabed to the target depth (these are removed prior to testing to ‘free’ the pipeline); a frame to apply axial displacement to the pipe via a stainless steel wire cable that incorporated a small load cell; and guides to stop the pipe rotating, while not creating additional friction. Non-contact (laser) displacement sensors were used to measure the axial displacement and pipe settlement. The position of the vertical axis of the actuator (and hence the I-beam) was controlled through a feedback loop, to ensure the axial load applied to the pipe remained horizontal (as the pipe settled).

Fig. 6 shows a mock-up of the apparatus at 1g. Four wire cables were connected to a secondary linear actuator. These allowed the PCM to be suspended in an open (unclamped) position over the pipeline, prior to lowering in-flight.

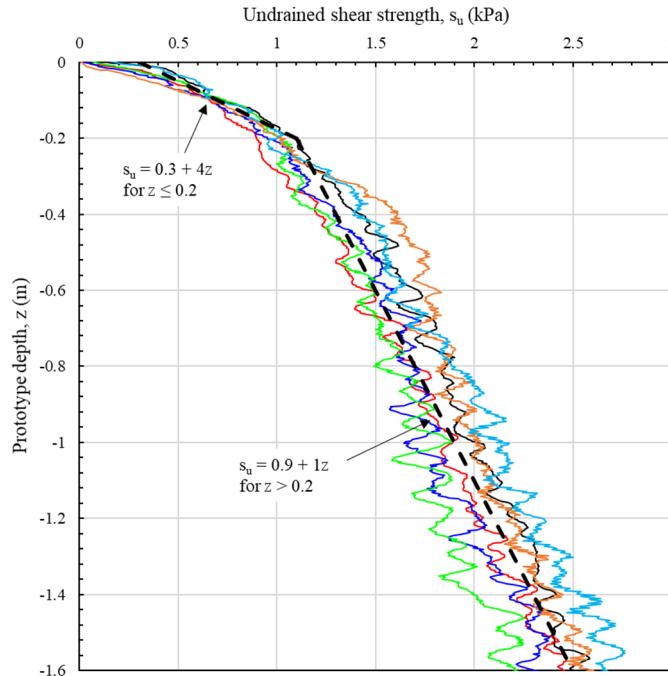


**Figure 6. Apparatus setup on laboratory floor (and in trial sample)**

### Soil sample

The soil sample used in this test programme was a reconstituted deepwater clay from the Gulf of Mexico. The clay was first mixed as a slurry, before being placed into a rectangular strongbox (0.39 m width  $\times$  1.3 m length  $\times$  0.225 m depth) that included a base drainage layer.

The slurry was initially consolidated in a consolidation press on the laboratory floor to a pressure of around 5 kPa, after which corner drains were installed (linking the base drain to the free water above the sample surface). The samples were then transferred to the centrifuge where a surcharge plate was placed on the sample surface to create roughly 6.7 kPa surcharge at 30 g. Settlement of the sample was monitored and the surcharge plate removed once consolidation was considered complete. The sample was allowed to swell (at 30g) to the final test condition, with T-bar testing performed before and after PCM testing to assess the soil strength (Fig. 7).



**Figure 7. Undrained shear strength profiles as determined by T-bar testing**

## EXPERIMENTAL PROGRAMME AND PROCEDURES

The tests were designed to address the knowledge gaps previously outlined by:

- Quantifying the short and long-term (hardened) friction coefficients.
- Quantifying settlement and the behaviour of the clamping arrangement.

The experimental programme performed on this sample comprised five model tests covering variations in consolidation periods, changes in clamp and log mattress weight, and different model pipe lengths.

In each case the pipe was pushed to an initial embedment of 0.3D into the sample, with 10 vertical cycles (between mudline and 0.3D) applied at a displacement rate of 0.5 mm/s, sufficient to achieve an undrained response in this soil. The centrifuge was then ramped down to remove the tension/compression supports (thus releasing the pipe), before being immediately ramped back up to 30g and left for an extended period (roughly 2 months prototype time) to fully dissipate any excess pore pressure around the pipe. The centrifuge remained at 30g for the rest of the test.

After allowing for pore pressure dissipation, each PCM test comprised the following two main stages (annotated data from a typical PCM test is provided in Fig. 8):

- Stage 1: An initial series of ‘pipe only’ cycles was first performed with the pipe displaced forward and backward by 0.5D for 15 cycles. Individual cycles occurred at weekly

(prototype scale) intervals, with only a brief pause between forward and backward movements.

- Stage 2: The PCM clamp was then lowered onto the pipe, followed by a brief (1 week) pause, after which the log mattress was lowered onto the clamp. After a pre-determined pause period (ranging from 1 week to over 1 year), Stage 2 involved cyclic ‘packets’ of axial movement, with each packet comprising four small cycles (sweep of 0.125D) followed by one large cycle (sweep of 0.5D). Approximately 2 weeks was allowed between individual cycles. The intent of this was to closely represent actual pipeline conditions in terms of short and long periods of shutdown, or small and large swings in temperature, during operation.

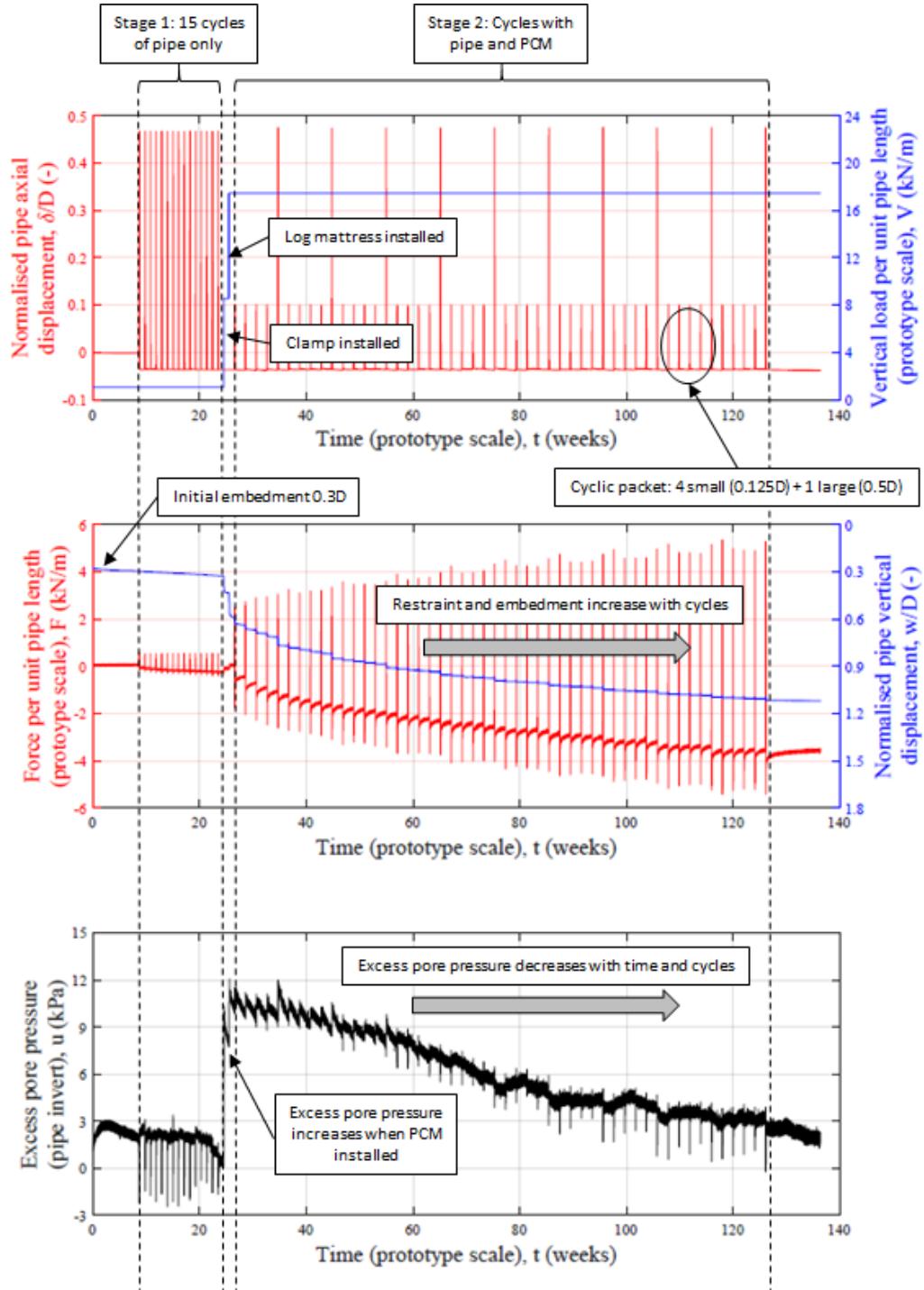
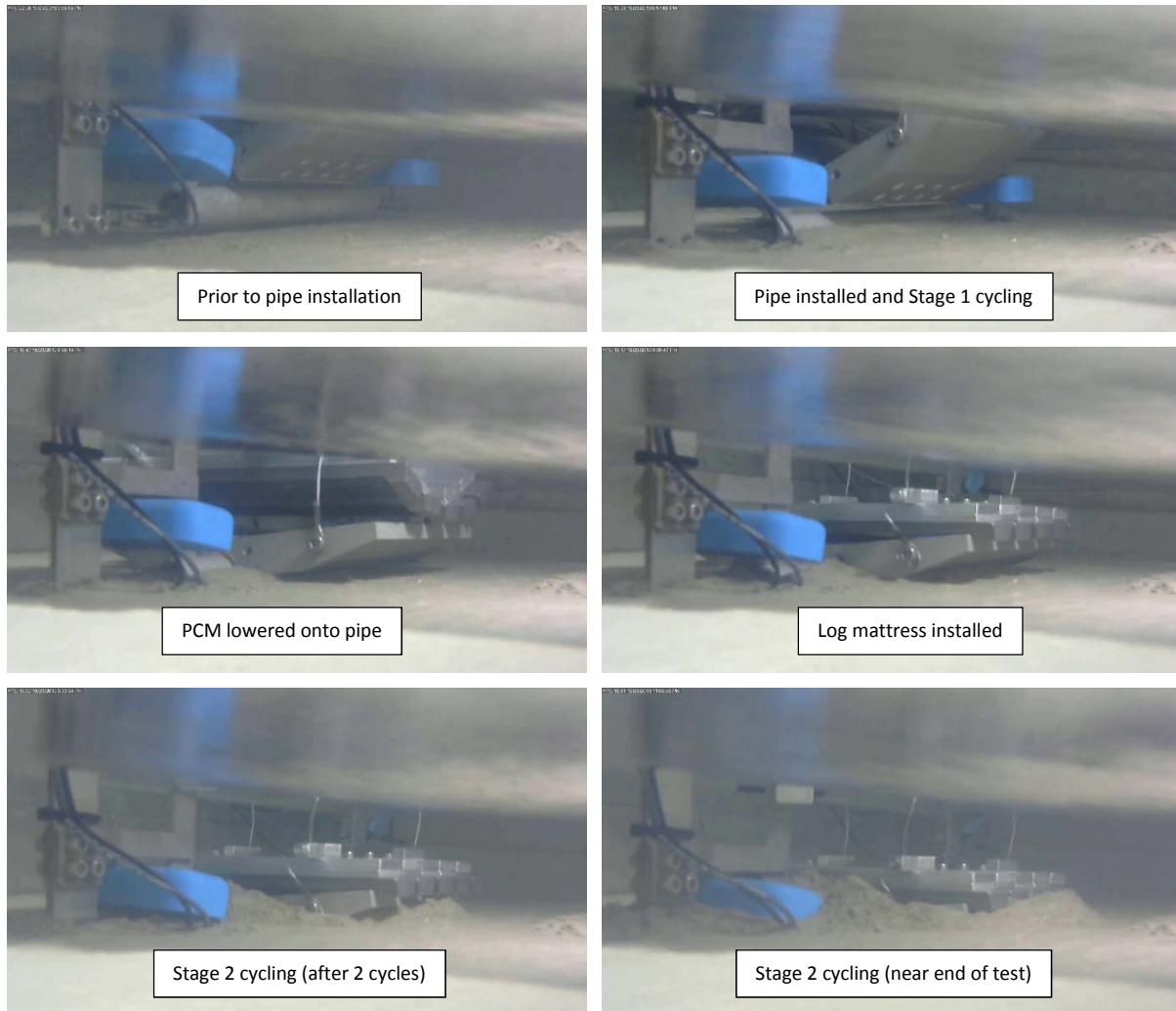


Figure 8. Typical PCM test results

Photographs taken during a test are provided in Fig. 9, illustrating the test stages and showing progressive embedment of the pipe and PCM. Note that the settlement from this test on an isolated length of pipe is greater than would occur for a PCM on a real pipeline. This is due to the support provided by bending stresses in the adjacent pipe, and longitudinal sharing of the vertical load. Testing with the longer pipe and lighter PCM was performed specifically to explore this.

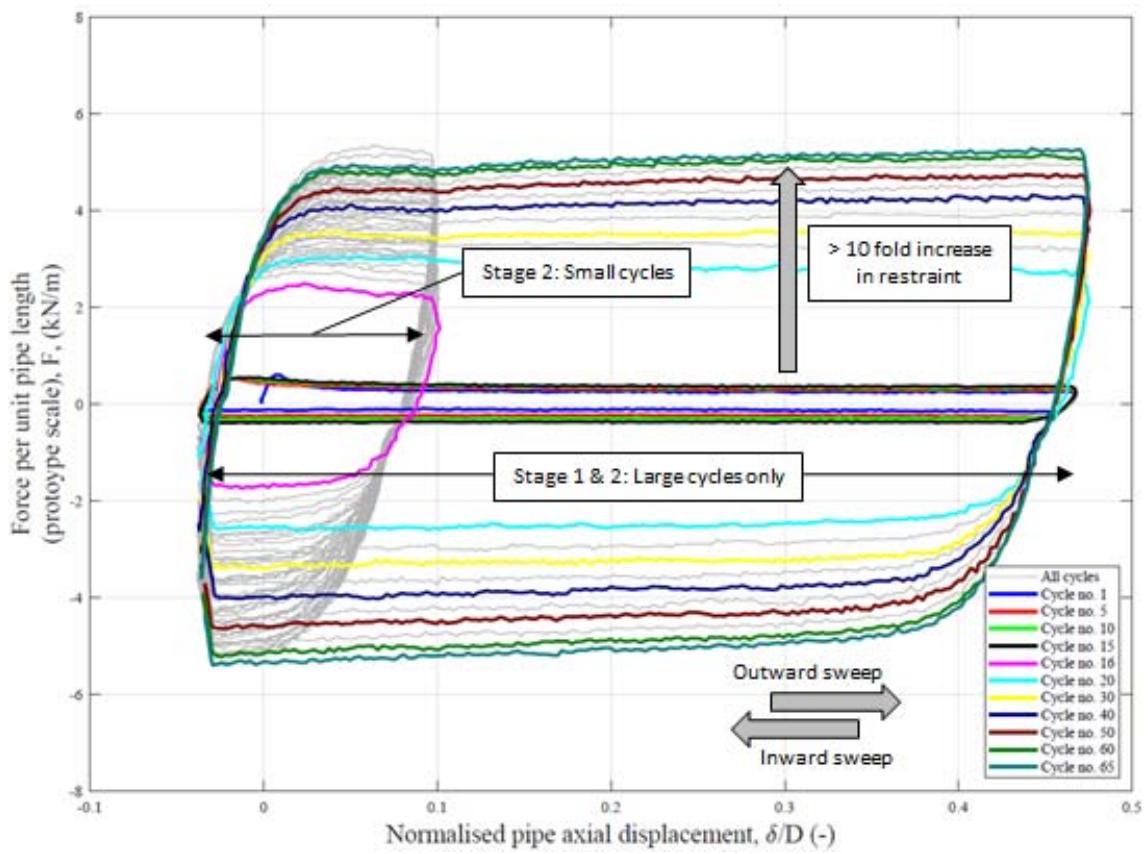
The test results help to quantify potential embedment, and despite this being significant in this soil, there was no indication that the clamp ‘unlocked’. Evidence for this comes from the axial resistance of the PCM-pipe system, which remained high and steady while the settlement accumulated, while video observations did not reveal any relative axial movement between PCM and pipe.



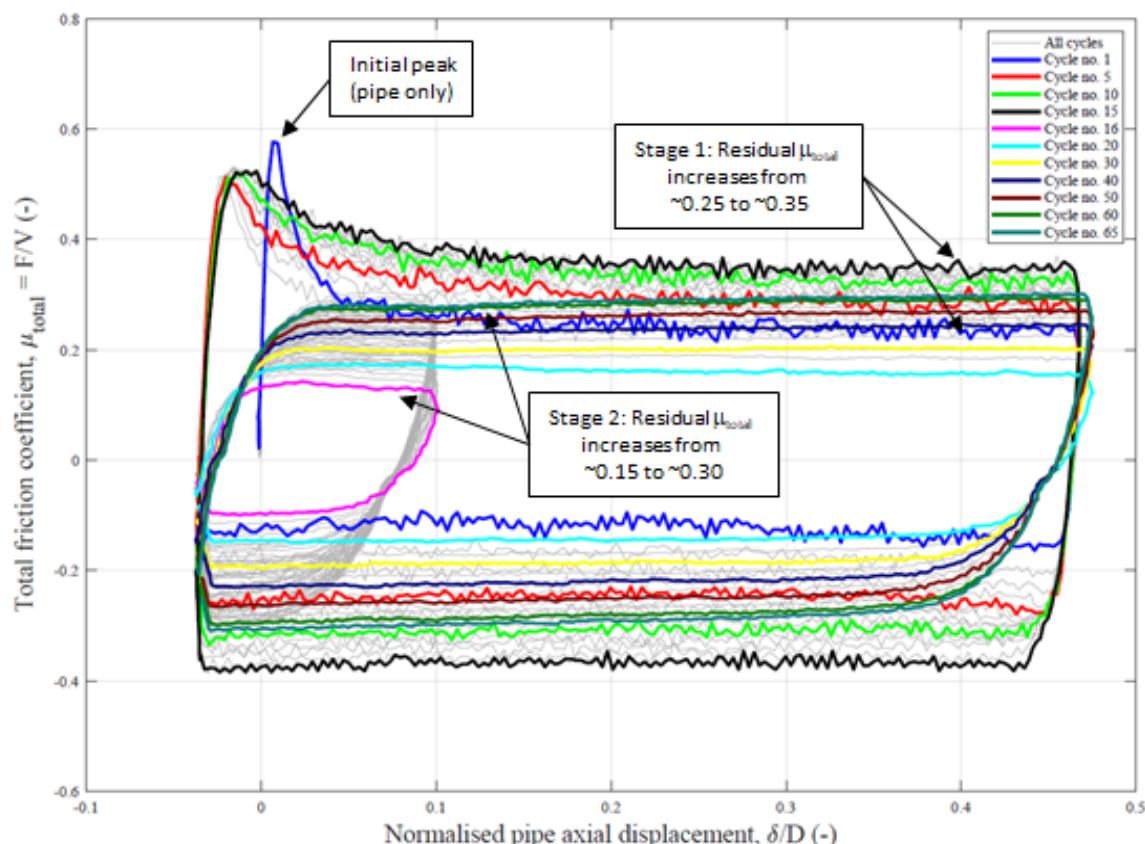
**Figure 9. Typical photographs from each test stage**

## SELECT RESULTS AND DISCUSSION

The axial resistance versus axial pipe displacement from the first completed test is presented in Fig. 10, and is typical of all tests performed. In this case, a ‘light’ PCM configuration was used, along with the short pipeline. Only a short (1 week) pause was allowed between lowering of the log mattress and the start of Stage 2 axial cycling, with a further 2 week pause between each ‘pipe plus PCM’ cycle.



(b) Total axial resistance against normalised axial displacement



(b) Total friction coefficient against normalised axial displacement

Figure 10. Observed axial resistance against axial displacement

In Fig. 10, the axial resistance represents the force required to move the model, while the total friction factor ( $\mu_{\text{total}}$ ) is the measured axial resistance divided by the submerged weight of the model(s) – which is the pipe weight alone for the first 15 cycles, and the pipe plus PCM weight for the later cycles. Some initial observations from the test data are as follows:

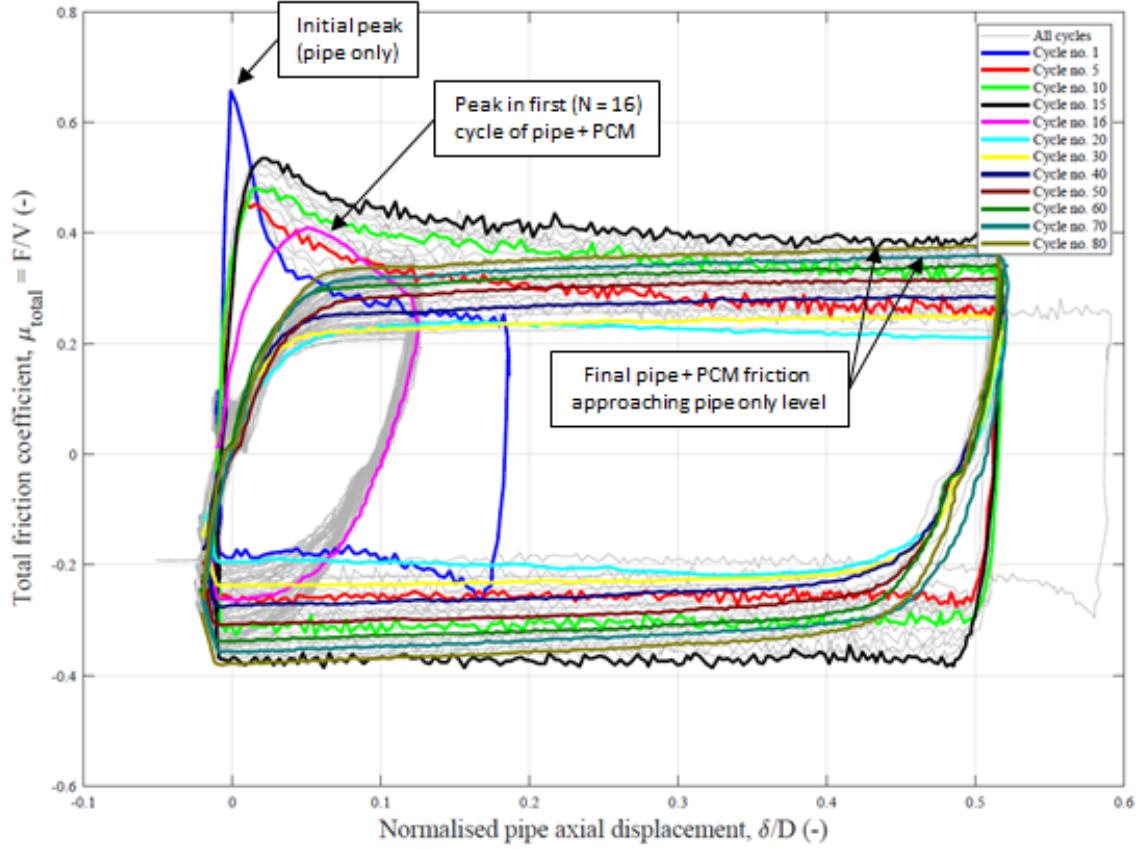
- Evident in Fig. 10a, the addition of the PCM increases the axial restraint by over an order of magnitude, from around 2.5 kN (for the ~5.5 m long pipe) to over 30 kN for the combined pipe plus PCM system.
- The Stage 1 (pipe only) cycles show an initial peak at the start of the cycle, followed by strain softening behaviour to a constant resistance (termed ‘residual’). There is no peak during the return half of the cycle, indicating that the peak in resistance between cycles is generated by the 1 week pause period. The residual value of  $\mu_{\text{total}}$  gradually increases with cycles from approximately 0.25 to around 0.35, reflecting consolidation hardening in the fine-grained Gulf of Mexico soil, as observed in previous similar model tests on other soils (e.g. Smith & White, 2014). Laboratory testing is currently ongoing to compare the observed values to friction coefficients measured (for instance) with interface shear apparatus.
- After the PCM is installed, a relatively low value of  $\mu_{\text{total}}$  is initially observed, in this case equal to approximately 0.15 at the end of the first (0.125D) movement. With further cycling the friction factor rises to an almost stable value of around 0.3, but remains less than the pipe only friction factor. The difference in the residual friction factor between the final pipe only and pipe plus PCM cycles is thought to be due to a combination of (i) the pipe-only friction being enhanced by a wedging effect, which enhances axial resistance by 20% typically (Smith & White, 2014); and (ii) the effect of pore pressure, which is slower to dissipate under the PCM due to longer consolidation times. There may also be an influence of combined bearing-sliding failure under the PCM (compared to pure sliding beneath the pipe), while the effect of stress level on interface friction may also be a factor.
- Pore pressure at the invert of the model pipe was measured throughout the tests (see Fig. 8) with significant excess pore pressure observed during the initial packets of pipe plus PCM cycling. This suggests that there was only a modest increase in vertical effective stress prior to the initial cycle, leading to the low  $\mu_{\text{total}}$  observed. Over time, excess pore pressures dissipate and friction increases.

To further explore the effect of initial consolidation on PCM performance, Fig. 11 presents the result of an identical test to that presented in Fig. 10, with the exception of an extended period (roughly 1 year) of consolidation after log mattress installation and prior to cycling. Comparing with the data in Fig. 10, Cycle 16 (the first pipe plus PCM cycle) shows that allowing full consolidation prior to axial movement leads to a sharp increase in initial resistance. The friction coefficient then increases for both tests with further cycling, although the test with longer initial consolidation reaches a higher overall friction (approaching the pipe-only value).

## CONCLUDING REMARKS

A centrifuge test programme was undertaken to assess the performance of PCMs in a reconstituted deepwater Gulf of Mexico clay soil, specifically to enhance understanding relevant to design. This paper provides an overview of the models that were developed for the testing, and introduces some preliminary results.

Relatively large settlements were observed as a result of cycling, with pipe embedment exceeding 1D in all tests performed in this (soft) soil, and higher for larger PCM weights. However, no evidence of PCM slippage relative to the pipe (or clamp unlocking) was observed in any of the tests, and the observed friction remained high despite the embedment.



**Figure 11. The effect of consolidation (and cyclic hardening) after PCM installation**

The results suggest that the frictional response will increase (harden) with cyclic loading and consolidation, and that the response is slightly different between pipe and pipe plus PCM, but broadly leads to a 50-100% increase in axial resistance for each case. In this soil, the response for typical installation and operational timeframes is strongly dependent on dissipation of excess pore pressure generated during installation of the PCM. Any pore pressure remaining from PCM installation appears to result in lower initial restraint, which increases with time and cycling (with other factors having a smaller influence, i.e. combined failure, stress-level effects). Installation of the PCM ultimately leads to a (more than) 10 fold increase in total restraint for the section of pipe modelled.

A more comprehensive interpretation from this testing (and companion testing in other soil types) is in progress, including the results from laboratory testing, and will be reported in due course.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Bruton, D., Sinclair, F. and Carr, M. (2010). Lessons Learned From Observing Walking of Pipelines with Lateral Buckles, Including New Driving Mechanisms and Updated Analysis Models. Offshore Technology Conference, Houston Texas, USA, 3 –6 May 2010, Paper No. OTC 20750.
- Carr, M., Sinclair, F., and Bruton, D. (2006). Pipeline Walking-Understanding Field Layout Challenges, and Analytical Solutions Developed for the Safebuck JIP, Offshore Technology Conference, Houston Texas, USA, 1-4 May 2006, Paper No. OTC 17945.
- Frankenmolen, S., Ang, S.-Y., Peek, R., Carr, M., MacRae, I., White, D., and Rimmer, J. (2017). Pipe-Clamping Mattress to Stop Flowline Walking. Offshore Technology Conference. Houston, Texas, USA, 1-4 May doi:10.4043/27815-MS.
- Gaudin, C., O'Loughlin, C.D., and Breen, J. (2018). A new 240 g-tonne geotechnical centrifuge at the University of Western Australia. In Proceedings of the 9th International Conference on Physical Modelling in Geotechnics (ICPMG 2018) (pp. 501-506). CRC Press.
- Smith, V.B. & White D.J. (2014). Volumetric hardening in pipe-soil interaction. Proc. Offshore Technology Conference, Asia. Kuala Lumpur. Paper OTC-24856-MS