Development of a vertical embedded plate anchor (VEPLA) for pipeline restraint

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Pipeline walking, due to thermal expansion and contraction of seabed pipelines in operation, has been the subject of extensive research to understand when walking may occur, and the forces and movements generated. To date, the usual solution for pipelines at risk of walking is to place a large anchor at one end of the pipeline, or mid-line anchors installed to each side of the pipeline along the route. However, such anchors require pre-installed attachment points on the pipeline. A more elegant and efficient approach, demonstrated by recent research, is to install or retrofit distributed anchors on the pipeline at the most efficient location. Also, for many pipelines the potential for walking is unclear, and a solution which can be installed during the operational life of the pipeline is attractive, as part of ‘Wait and See’ strategy, based on the ‘Observational Method’.

To address these issues, the Vertically Embedded Plate Anchor (VEPLA) has been developed, as a modest capacity anchor that can easily be clamped to an existing or new pipeline. The concept utilises two plates, which are embedded by self-weight into the seabed and clamp onto the pipeline. A series of numerical studies and centrifuge tests have been performed to assess the efficiency of the solution and allow restraint capacity to be assessed. This paper describes the concept and discusses the research performed to assess the geotechnical operation of the anchor system.

1 Introduction

The operational cycle of subsea pipelines results in changes in temperature and internal pressure. Both factors can induce an axial load (effective force) in the pipeline that can overcome the axial restraint provided by friction of the seabed soils causing end expansion. In the case of surface laid pipelines, eccentricity in end expansion can result in axial walking, while the axial load can result in lateral buckling of the pipeline while in service.

The forces and restraint associated with lateral buckling of a pipeline has been extensively investigated by the SAFEBUCK JIP (see for example Bruton et al, 2011). The SAFEBUCK research project also included consideration of the axial forces and restraint of pipelines, but did not specifically consider solutions to mitigate pipeline walking. A more relevant project that specifically considered axial walking mitigation was the Anchoring Pipeline Technology (APT) JIP led by Crondall Energy.

The APT JIP reviewed the current state of the art in anchoring solutions and assessed a series of case studies considering pipelines that had experienced walking and back-analysed the observed displacements. In addition, the study assessed whether a large-capacity single point anchor or low-capacity distributed anchor solution might be more effective, and outlined some possible design solutions for distributed anchors.

This paper presents details of some follow-on work from the APT JIP undertaken by the authors to develop the concept of a vertical plate anchor embedded in the soil to provide axial restraint.

2 Pipeline walking

Many pipelines have experienced walking (stepwise ratcheting displacement along the axis of the pipe), which is caused by changes in the operating conditions during shutdown and restart and can lead to very large global axial displacements, leading to overloading of end connections.

The basic mechanisms that drive walking are well understood (Bruton et al, 2010), they include seabed slopes (exacerbated by liquid dropout at shutdown); tension caused by a steel catenary riser; or thermal transients (sudden heating or cooling of fluids during pipeline restart). However, accurately predicting the walking behaviour for real pipelines is very challenging because the magnitude and direction of walking can change with quite modest changes to the input parameters and inherent uncertainty in the design data. A significant investment in research and testing has greatly improved understanding of pipe-soil interaction (PSI) responses (Hill et al, 2012) but much uncertainty remains in predicting the long-term cyclic axial response associated with pipeline walking.

Many pipelines do not walk, but those that do can present significant integrity management challenges. The design approach varies significantly across the industry from pre-installed, to retrofit anchors of varying types.

The APT JIP was set up to improve the design approach and develop practical methods to mitigate pipeline walking. Part of that approach was to develop more efficient anchoring systems and adopt delayed or observation-based intervention wherever possible.

3 Current anchoring solutions

The most common form of anchoring a pipeline that will potentially walk is a single point anchoring solution. This has the advantage of being located at a single point, with the anchor capacity designed to resist the walking loads from the pipeline, with typical capacities of 50 to 350 tonnes. As many of the pipelines that are expected to experience pipeline walking are on deep water developments where soft clays are predominant, a suction pile is possibly the most common anchoring solution. As can be seen in Figure 1, the resulting anchor piles are large as the load application point is typically at the top of the pile. Experience of designing both pipeline walking piles, and FPSO anchor piles, where the load is applied at depth, indicates that the impact of top loading is to reduce the capacity by a factor of ten.

Figure 1 Example of suction anchor pile to mitigate pipeline walking (Jayson et al, 2008)

Other potential single point anchoring solutions include piled mud mats which are either placed in advance of pipelay or placed over and then clamped to the pipeline, and driven piles used to achieve the design axial resistance.

Distributed anchors are less common; however, pipeline clamping mattresses have been developed by Shell (Frankenmolen et al, 2017). These are concrete mattresses with a central hinge and designed to clamp the pipeline by self-weight as shown in Figure 2. An additional log mat is typically placed over the hinged mat to increase the overall weight and hence the friction developed at the pipe-soil interface.

The number of pipeline clamping mattresses deployed can be adjusted to achieve the required axial resistance, however the actual magnitude of the resistance achieved is subject to several variables, increasing the uncertainty in the available resistance. It is also necessary to allow a period of time for excess pore water pressures associated with placement of the mattress to dissipate, and the full load resistance to be achieved.

Figure 2 Example pipeline clamping mattress

4 Development of the VEPLA concept

The APT JIP considered a number of options for providing distributed restraints for pipelines. Some of the options considered included screw anchors placed to the side of the pipeline and connected to the pipeline by wire or chain, a fluke type anchor mounted on the underside of the pipeline which would open as the pipeline moved, and providing a surface to the pipeline which would provide drainage and increase pipe-soil frictional resistance.

However, the most promising concept proposed was a plate anchor placed in a vertical orientation to either side of the pipeline as shown in Figure 3. Some of the potential advantages identified for this concept included ease of placement with installation achievable by self-weight, predictability of axial resistance with the prime input being undrained shear strength, and capacity achieved effectively immediately. The initial concept comprised two plates designed to straddle the pipeline and then close around the pipeline, clamping the line in the process.

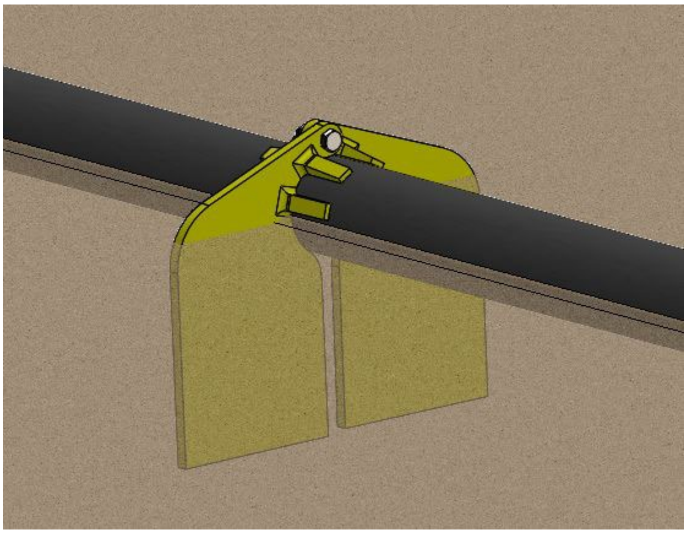

Figure 3 Initial concept of a vertical plate anchor (schematic)

Following the completion of the JIP, further work has been performed to both better understand the displacement resistance achievable and the develop the overall design and clamping concept. These factors are discussed in the following sections of this paper.

5 Application of anchors to mitigate pipeline walking

5.1 *Large capacity anchors*

Single large-capacity anchors use both fixed (bi-directional) or chained (unidirectional) attachments to the pile-head. The required capacity of a single uni-directional anchor is not significantly affected by its location along the pipeline. In contrast, depending on the pipe soil friction, a bi-directional anchor may require approximately double the design capacity when placed at the end of the pipeline, reducing to the capacity of a unidirectional anchor if located towards the middle. In extreme cases, where the walking rate is predicted to be high, it is essential to pre-install high-capacity anchors.

5.2 *Low-capacity anchor strategy*

The APT JIP used such traditional suction type anchors to provide a benchmark to assess new anchoring strategies, including low-capacity anchors placed at strategic points along the pipeline. This approach is already known to benefit long pipelines, where an anchor at one end can have little influence, over pipeline expansion at the other end. Also, if predicted walking rates are low, a ‘wait and see’ approach is more appropriate. Such cases are common and lend themselves to retrofitting low-capacity anchors that do not require attachment points to be pre-installed or large restraint clamps to be retrofitted to the pipe.

For low-capacity anchors, it was found more efficient to cluster a series of anchors at specific locations along the pipeline, typically close to the virtual anchors that form between lateral buckles where the cyclic movement is less. This approach reduces the total anchoring capacity required, although anchor spacing has to be carefully considered in design.

5.3 *Advantages of low-capacity anchors*

Low-capacity anchors appear to have the advantage over much larger suction pile anchors, for the following reasons:

1. Being placed along the pipeline, the overall capacity can be significantly less than a single large capacity anchor at the pipeline end.
2. Lateral buckles are protected from the very high tensions that can occur with a single anchor, and walking is stabilised more quickly.
3. Walking rate is much reduced even if the total capacity is insufficient to fully arrest walking - more anchors can be added later.
4. When total capacity is sufficient, cyclic movement is reduced allowing the pipeline system to stabilise quickly and walking is arrested in a short number of cycles.
5. The relatively small size of low-capacity anchors enables them to be installed as part of an inspection, maintenance and repair operation and without the need for specialist construction vessels.

5.4 *Types of low-capacity anchor*

Two feasible generic low-capacity anchor types were evaluated:

1. Deadweight (bi-directional) anchors; including pipe clamping mattresses, where the full anchor load is generated at small pipe displacements in both directions.
2. Slot (unidirectional) anchors; including vertical plate anchors with a hardening response, where the anchor mobilises passive soil resistance. Movement generates a ‘slot’ behind the anchor, so that some reverse movement is required to generate load in the opposite direction.

Slot-type anchors are compliant (yielding as load is applied) and act coherently, by allowing some axially displacement until all the anchors engage. They then work in unison, as uni-directional anchors, which ultimately require less overall capacity than deadweight anchors.

6 Horizontal capacity calculations

To provide an initial estimate of the physical size of plate anchor that would be beneficial for pipeline restraint and the number of units that may be required, calculations based on p-y curves for pile design were developed (see e.g. DNV-RP-C212). These considered a range of physical sizes and a typical undrained shear strength profile of 2kPa + 1.3 kPa/m depth. The results of this analysis for plates with an overall width of up to 3.0 m and 2.0 m depth are required.

The results of this analysis are shown in Figure 4 and indicate that an ultimate capacity of almost 100 kN is available from a pair of plates of the larger size considered. Given that a typical axial restraint requirement from a pipeline is in the region of 500 to 1000 kN, this would suggest that the required restraint could be achieved with between 7 and 15 VEPLA units with allowance for suitable factors of safety. These would be positioned over a length typically between 100 and 200 m. This was considered a viable number and encouraged further, more detailed verification.

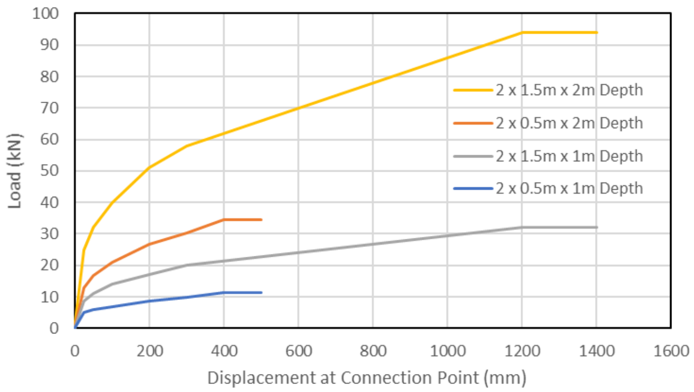

Figure 4 Initial concept verification of a vertical plate anchor based on p-y curves

7 Model testing (1g)

While the simple analysis discussed above gave an indication of the unidirectional ultimate capacity, the cyclic axial loading of an operational pipeline results in a series of load reversals. To address this initial 1.g model testing was performed using a plate with an embedded depth of 50 mm and a width of 120 mm with a 20 mm gap to represent the clearance over the pipeline as shown in Figure 5.

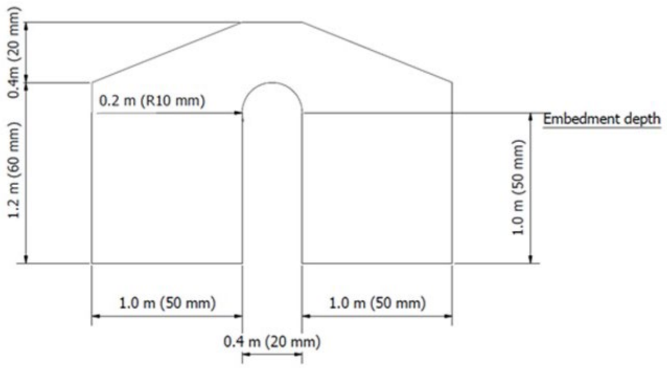

Figure 5 Test plate dimensions (showing centrifuge prototype scale and model scale in brackets)

The soil sample was prepared from slurried Speswhite kaolin with 120% moisture content. The clay was then consolidated in a 0.5m diameter chamber with drainage to top and bottom and an applied stress of 30 kPa. On completion of consolidation, lab vane and mini T bar tests were performed which indicated a consistent undrained shear strength of 3 kPa with minimal increase with depth.

The test configuration, showing the consolidated sample and the installed plate connected to a lateral actuator is shown in Figure 6.

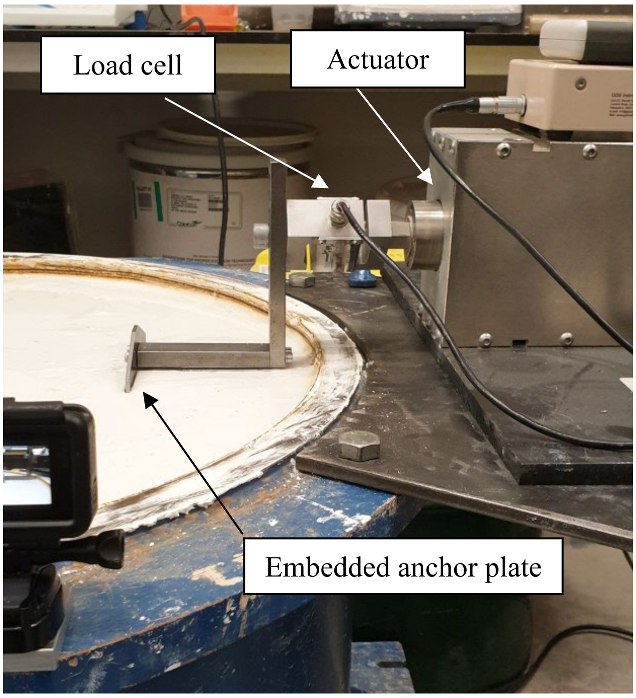

Figure 6 Loading configuration of VEPLA anchor in consolidated clay test bed (1g). (anchor is shown as installed and prior to loading)

Four tests were performed in the chamber, two to determine the ultimate monotonic capacity, and two cyclic tests to assess repeat loading, as might be expected to be experienced by an operational pipeline. Two tests were performed in the top of the sample, and then the sample was turned upside down, and two tests were performed in what was the base.

The results of the monotonic tests are shown in Figure 7 with the ultimate capacity correlating closely to the results of the p-y based analysis (shown in Figure 4 when the results are scaled to full size.

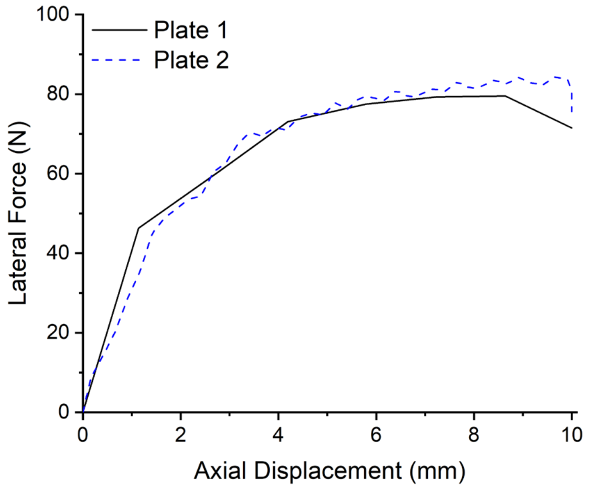

Figure 7 1g monotonic unidirectional results

The second phase of testing considered cyclic loading with a maximum lateral load equivalent to 50% of the ultimate monotonic load. These results showed further consolidation occurring within the clay allowing a degree of continuing displacement under the working load (Figure 8).

An interesting observation was the clear gap which developed behind the plate (Figure 9), suggesting that the plate largely returned to its original position with little resistance. However, there was also a concern that this could be due to the clay being effectively over consolidated because of the consolidation process.

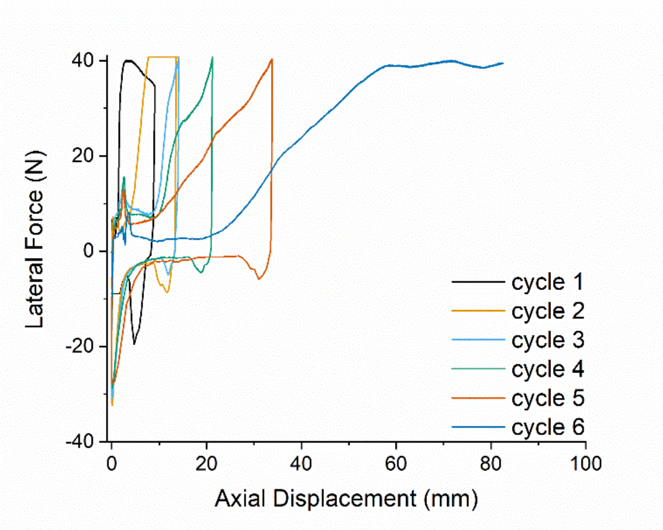

Figure 8 Cyclic load test result at 1g

While the 1g testing did give some encouraging results, it was concluded that the results would be more reliable if performed by centrifuge and that this would give an improved understanding of the behaviour of the clay around the plate including consolidation under load and the effect of gapping if still apparent with a more realistic strength profile of a normally consolidated soil.

Figure 9 Gapping behind plate

8 Centrifuge testing

A series of two centrifuge samples were prepared with two tests being conducted in each sample box. The samples were prepared from Speswhite kaolin mixed to a slurry with a water content of 120%. Once slurried, the sample was transferred to the centrifuge test box and the centrifuge spun at 20g to achieve normally consolidated clay. The consolidation phase typically occupied 72 hours (40 months at prototype scale).

Characterisation of the box sample was undertaken by a combination of T-bar testing and vane testing. To avoid disturbing the sample for the vertical plate tests, these tests were carried out after the plate tests. The model anchor plates were installed at 1g using an Instron UTM and lateral testing of the VEPLA was undertaken in-flight using a purpose-built lateral actuator. The results are presented as Figure 10 and show good correlation between T-bar and vane tests. The resulting profile at prototype scale is approximately 0 kPa + 0.5 kPa/m While this strength profile is softer than a typical deep-water clay this was considered acceptable for the purposes of this testing and the results could be factored by strength ratio to provide realistic results.

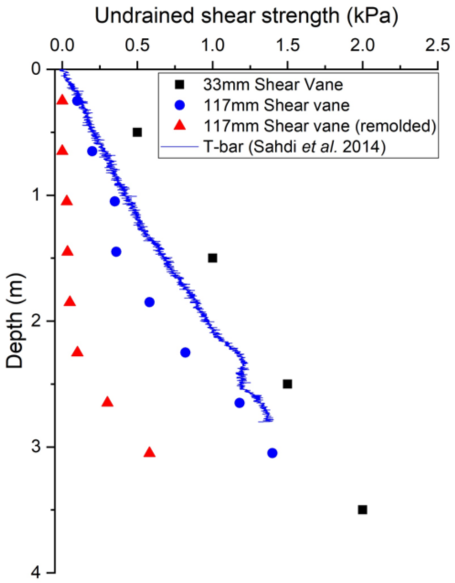

Figure 10 Undrained shear strength v depth (centrifuge tests, prototype scale)

Testing was performed using the same plates as used for the 1g tests as they neatly correlated to a size of 1.0 m embed depth by an effective width of 2.4 m.

The first test performed was a simple monotonic test taking the soil to failure at a loading rate of 20 mm/min (model scale, and effectively undrained conditions) to determine the ultimate lateral resistance using a continuously increasing load to final displacement as shown in Figure 11.

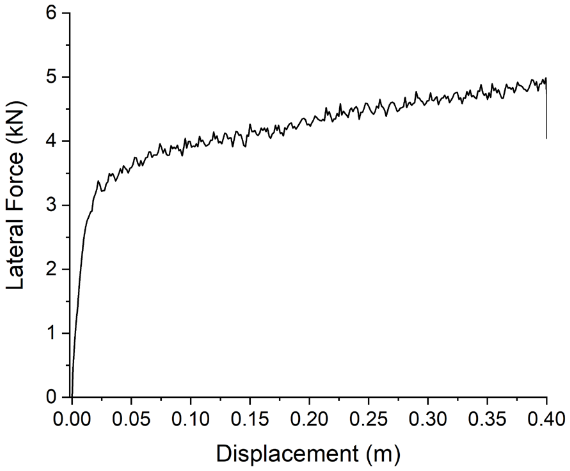

Figure 11 Monotonic lateral push centrifuge test result (prototype scale)

From the 1g results, it was evident that the consolidation of the clay, when loaded horizontally made a significant contribution to the overall capacity / displacement of the anchor. For the cyclic testing phase the ultimate capacity was halved (i.e. the maximum load applied was 50% of monotonic capacity) to more closely replicate design conditions where the pipeline would be expected to load up the anchor to a value with continuing displacement occurring as the clay consolidates in front of the anchor. This load may then pass through several cycles of reversal and reapplication.

The results of one of these load tests is presented as Figure 12. For the tests, the loading sequence was to apply approximately 2.6 kN (at prototype scale) and maintain this load for a scale period of 30 days. At this point the load was reversed and the anchor returned to its original position and the process repeated. For each load cycle, load was held constant until consolidation displacement ceased.

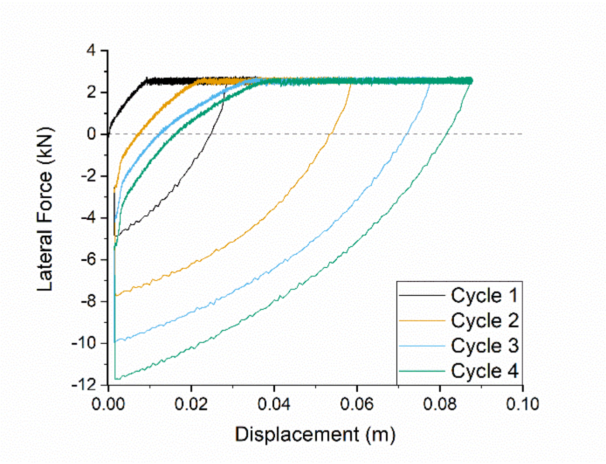

Figure 12 Cyclic load test result (prototype scale)

The consolidation stage can be seen in Figure 12 as an increasing ultimate displacement experienced during each load cycle, and with an increasing displacement with each cycle. However, a key factor is the small magnitude of the ultimate displacement. At prototype scale, this is less than 0.1 m. This small displacement will be beneficial in engineering a pipeline walking solution.

Returning the anchor to its original position resulted in appreciably higher resistance being experienced than on the primary loading direction. This is considered to be due to the collapse of the clay on the reverse side of the anchor due to its exceptionally low strength. This aspect merits further investigation as a more typical in situ strength profile may have sufficient strength to stand vertically for at least a short time.

9 Comparative finite element analysis

Due to time constraints for the centrifuge tests, a maximum of four cycles were applied in a test. To further the analysis of the VEPLA anchor, a series of comparative Finite Element Analysis (FEA) simulations were conducted. The Modified Cam Clay constitutive model was used in Plaxis 2D to model the properties of the kaolin clay used in the centrifuge and 1g tests. The boundaries of the model were the same as those for the centrifuge test, vertical boundary of 2.0m from the base of the anchor and a lateral boundary of 12.5 m (prototype scale). The properties of the clay can be seen in Table 1 (Robinson, 2019), The shear strength of the soil with depth matched the values obtained through shear vane tests (0 kPa + 0.5 kPa/m) (Figure 10).

Table 1: Soil properties used for MCC constitutive model in Plaxis 2D (Robinson, 2019)

Property	Value
γ_{sat}	13.47 kN/m^3
$e_{initial}$	2.65
λ	0.1680
κ	0.02100
M	0.8510
Plastic limit	32.5 %
Liquid limit	65 %

To ensure the parameters used in the FEA were indicative of the soil used in the model scale testing, the monotonic lateral capacity of the anchor was initially determined and compared with the centrifuge results (Figure 13). Once this had been conducted and a good agreement had been reached, the cyclic loading regime from the centrifuge tests was applied to the plate. This consisted of loading the plate to 2.6 kN and maintaining the load for a set period of time before reversing the position of the plate to its original location and repeating the process.

Ten cycles of loading were applied to the plate, in order to determine the minimum number of cycles required to reduce any incremental displacement, such that it has effectively stopped creeping forward from cycle to cycle (Figure 14).

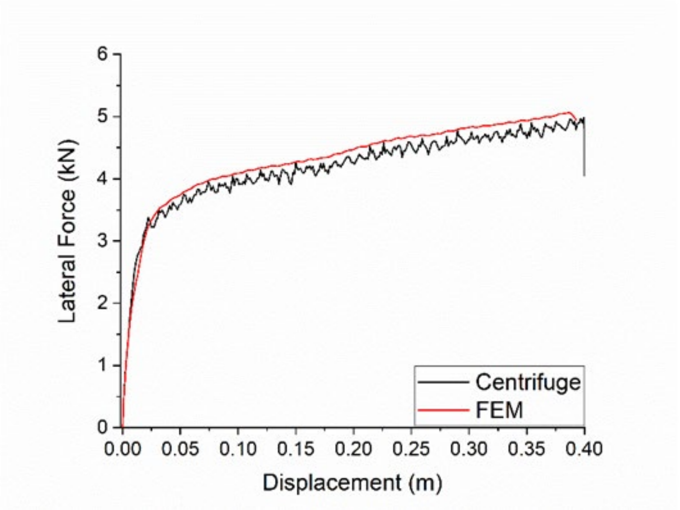

Figure 13 Comparison of the monotonic capacity determined through FEA and centrifuge modelling (prototype scale)

From the simulation it can be seen that for the first four cycles the FEA is able to match the results of the centrifuge experiments and after eight cycles of loading there is minimal increase in displacement from the additional cycles of loading. This suggests after minimal cycling the anchor is able to restrict the movement of the pipe to a predictable amount, and thus limit its ability to walk. The testing and analysis also show that simple FEA modelling can be used to predict realistic behaviour in clay soils at low strength.

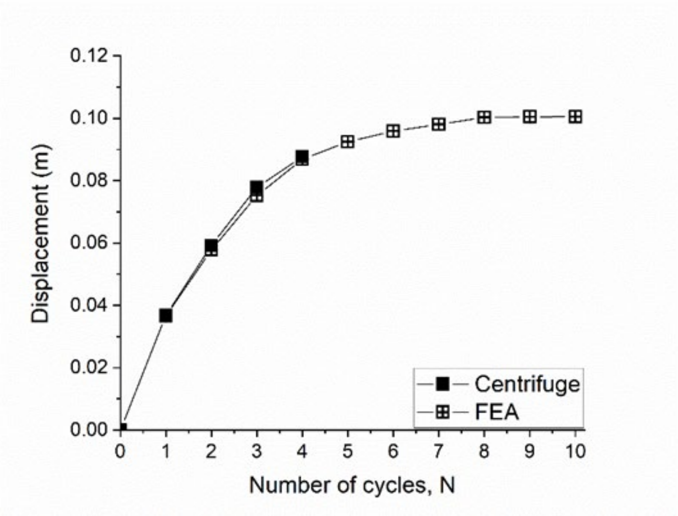

Figure 14 Comparison of peak displacement per cycle for centrifuge testing and FEA simulations (Prototype scale)

10 Practical design considerations

Consideration has also been given to practical design aspects. It was considered important that the anchor could be placed by simple craning into location with a support ROV. The anticipated configuration of the anchor is shown in Figure 15. To achieve alignment of the anchor over the pipeline, two sets of plate pairs are planned, rigidly connected by a spacer bar such that the pipeline effectively acts as a guide and ensures they penetrate into the soil perpendicularly to the pipeline.

Figure 15 VEPLA configuration shown over a mock-up pipeline prior to penetration

To achieve penetration of the plates, the weight of the anchor pair can be easily adjusted to ensure full penetration is achieved. Once in place, a single lead screw closes the lower jaw pair around the pipeline and with the upper jaw, all three jaws act at 120°. Thus the pipeline is clamped in a manner similar to a three jaw chuck, as shown in Figure 16 with a helical spring providing the clamping force. The spring provides both a simple visual indication of the clamping force applied, and ensures any creep in the clamping system or pipeline coating is compensated for. Production units will include re-engineering of the long lead screws to make them more compact and snag free. The clamping stress will be a function of the shear to be transferred through the anchor, and in practice will be of a similar order to the shear force on each clamp. The actual stress can be managed by adjusting the size of the clamping pad.

Figure 16 VEPLA concept model shown clamped to a pipeline mock-up

11 Conclusions and recommendations for application

This paper has summarised some of the issues around pipeline walking and suggested a possible solution to this problem in the form of a vertically embedded plate anchor system (VEPLA). The system is seen to have several advantages over existing technologies including:

- The system is scalable according to project requirements by simply adjusting the size of the anchor plates or number of individual units utilised.
- VEPLA units can be added to a live pipeline if required and the resistance achieved is mobilised immediately on installation with consolidation displacement being managed by the physical size of the anchors. Installation while in operation has the advantage that some previous walking displacement can be recovered.
- Design can be achieved rapidly using readily available strength parameters and simple exiting analysis techniques or FEA simulation.
- Installation can be achieved by most IMR vessels with no requirement for large crane capacities associated with construction vessels.
- The design is based around simple steel fabrication with no complex parts or precisely machined components. This allows for high local content where this is desirable.
- VEPLA would have independent cathodic protection, and can easily be electrically isolated from the pipe.

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13 References

Bruton, D.A.S., Carr, M. Overview of the SAFEBUCK JIP. Offshore Technology Conference. OTC 21671 May 2011.

Bruton, D.A.S., Sinclair, F., Carr, M. Lessons Learned From Observing Walking of Pipelines with Lateral Buckles, Including New Driving Mechanisms and Updated Analysis Models. Offshore Technology Conference. OTC 20750 May 2010.

DNVGL-RP-C212 (2017) Recommended Practice - Offshore Soil Mechanics and Geotech Engineering

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, OTC 27815. vol. 4, Offshore Technology Conference. pp. 2669-2683

Hill, A.J., White, D., Bruton, D.A.S., Langford, T., Meyer. V., Jewel. R. & Ballard. J.C. A New Framework for Axial Pipe-soil Resistance Illustrated by a Range of Marine Clay Datasets. Offshore Site Investigation and Geotechnics. P367 Sep 2012.

Jayson, D., Delaporte, P. Albert, JP., Provost, ME. Bruton, D., Sinclair, F. 'Greater Plutonio Project – Subsea Flowline Design and Performance'. Offshore Pipeline Technology Conference. Feb 2008.

Robinson, S. (2019) Rate Effect Behaviour of Different Clays from High Speed Triaxial Element Testing. PhD thesis, University of Dundee, UK.

Sahdi, F., Gaudin, C., White, D. J. and Boylan, N. (2014) 'Interpreting T-bar tests in ultra-soft clay', International Journal of Physical Modelling in Geotechnics, 14(1), pp. 13–19. doi: 10.1680/ijpmg.13.00012