Mitigation of Lateral Buckling at an In-line Tee

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1. Abstract

A 16-inch gas export pipeline, installed in 2007, transports gas over 150 km from an FPSO to a platform in shallow water. The pipeline incorporates an in-line tee assembly (ITA) approximately 6 km from the FPSO for the future tie-in of a gas export pipeline from an adjacent field. The ITA is supported by a fixed mudmat foundation and is free to move and rotate on top of the mudmat.

During an as-built ROV survey conducted in 2009, free-spans were identified in the vicinity of the ITA, which were considered acceptable. A subsequent ROV survey in 2010, with the pipeline at full operating pressure showed that the ITA had rotated. Whilst the loading was considered acceptable, the rotation was a potential concern for the future tie-in connection at the ITA. Further detailed surveys conducted in 2012, in operating and shutdown conditions confirmed that a mode 2 lateral buckle was centred on the ITA; with the amplitude of the buckle increasing under operational loading. The rotation was estimated at 5.5° between operating and shutdown conditions.

Mitigation engineering was carried out to arrest movement at the ITA, in preparation for the future tie-in. A two-phased approach was used; firstly, to assess the level of restraint required and secondly to model physical restraints that could be implemented in a cost effective and timely manner. The influence of installation timing was also assessed for operating and shutdown conditions.

2. Abbreviations

FE	Finite Element
FPSO	Floating Production Storage and Offloading
GVI	General Visual Inspection
ITA	In-line Tee Assembly
LBL	Long Baseline
LTI	Lost Time Incidents
OMIR	Operation, Inspection, Maintenance and Repair
OOS	Out-of-Straightness
PSI	Pipe-soil Interaction
ROV	Remotely Operated Vehicle

3. Introduction

The aim of mitigation engineering was to develop a finite element model of the pipeline, calibrated against survey data. The model was used to conduct an integrity assessment of the pipe in its current configuration. The calibrated model was then used to develop mitigation measures to control the movement at the ITA and ensure the integrity of the pipeline for future operation. After installation of mitigation measures, the same model was used to confirm that the performance of the mitigation met operational requirements.

4. Buckle Matching

4.1. Review of Survey Data

A number of surveys have been performed since the pipeline was installed:

- April 2009: As-built survey, post hydrotest
- December 2010: Integrity monitoring survey, in the operating condition
- November 2012: Shutdown GVI and positioning survey
- December 2012: Operating GVI and positioning survey

An ROV with a wheeled undercarriage was used to conduct the 2009 and 2010 surveys. The two surveys conducted at the end of 2012 covered approximately 200m either side of the ITA using LBL measurements from a temporary array installed around the ITA. The maximum amplitude of lateral deflection between the two 2012 surveys, of 1.7m and 1.4m was recorded to the south and north of the ITA respectively.

The four sets of OOS data are presented in Figure 1. The data is rotated such that the lateral offset is zero at the ends of the chosen section. Small axial and rotational adjustments are made between the data sets to ensure alignment at the ITA (x = 200m), which rotates between operation and shutdown. The data shows good agreement between the buckle shapes in the 2010 and 2012 operational surveys (blue and red lines). The movements at each lobe between shutdown and operation in 2012 are marked and match those reported at the time of the survey.

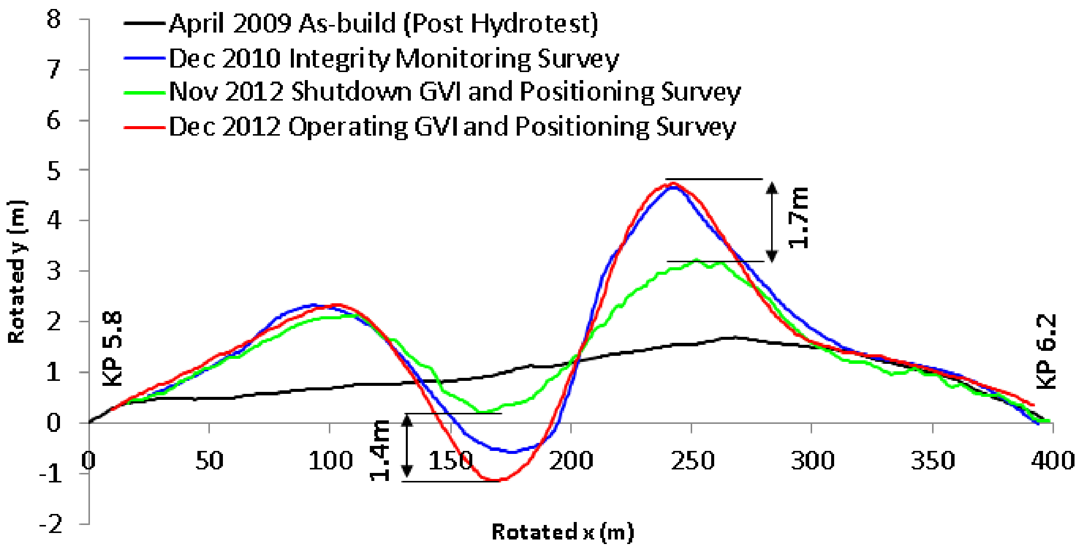

Figure 1 – Rotated coordinates at the ITA

4.2. Review of Operational Data

Continuous pressure and temperature readings were available from the start of operation. The data was used to determine the sequence of loading and the associated operating conditions prevailing at the time of the surveys, in order to calibrate the FE model. Table 1 summarises the operating and design data used in the FE Analysis.

Event / Date	Pressure (bar)[1]		Temperature (°C)	
	KP0	KP10	KP0	KP10
Hydrotest	237	237	4	4
As-laid Survey, April 2009	4.7	4.4	4	4
IM Survey, December 2010	143	141	35	10.5
Shutdown, March 2011	3.9	3.7	4	4
Operating (maximum conditions)	195	188	35	10.5
Shutdown Survey, November 2012	0.4	0.5	4	4
Operating Survey, December 2012	160	157	35	10.5
Design	215	215	47	10.5

Table 1 – Summary of operating data

[1] All pressures are referenced at MSL

The pressure and temperature data indicated that a number of shutdowns occurred between start-up and the last survey conducted (December 2012) prior to mitigation engineering, although these were mostly partial or minor shutdowns. Total indicated that two full shutdowns had occurred in March 2011 and November 2012. During these periods the pressure and temperature reduce to ambient conditions at the FPSO. The two full shutdowns were modelled to calibrate the model against the surveyed shape of the buckle at the ITA.

4.3. Review of Pipe-Soil Interaction

The soils in the vicinity of the field are described as very soft clay. Friction factors were available from previous design analysis conducted by others. Using data from site investigations, a review of the pipe-soil data was performed to provide confidence in the friction factors used in the analysis.

Pipeline embedment has a significant influence on the pipe-soil response. However, the embedment predicted in design did not compare well with that measured in operation. In Table 2, the HE and LE embedments in operation are based on the mean ± 2 standard deviations of the data provided from KP0 to KP6.5.

Embedment	Project Predicted empty	Project Predicted flooded	Post-hydrotest 2009 KP0 to KP6.5	In operation 2010 KP0 to KP6.5
HE soil	4%	7%	22%	25%
BE (average)	8%	15%	42%	49%
LE soil	12%	22%	66%	72%

Table 2 – Embedment comparison: design vs. operation

This discrepancy in predicted embedment was due to the use of simple embedment models in design that did not recognise the influence of the lay catenary on the soil strength, which is remoulded in the touchdown region[3], or the potential for subsequent reconsolidation prior to flooding[5]. The soils data from site investigations was reassessed, using current PSI models, and the calculated embedment matched field observations well. The calculated friction factors are compared to the design values in Table 3.

		Low Estimate	Best Estimate	High Estimate
Design Assessment	Embedment	7%	--	22%
	Axial friction factor	0.21	--	0.25
	Lateral friction factor	0.35	--	0.48
Revised PSI Assessment	Pipeline post-flood embedment	19%	43%	70%
	Axial friction factor	0.44	0.82	1.13
	Lateral breakout friction factor	1.01	1.75	2.93
	Lateral residual friction factor	0.44	0.72	1.16
	Total berm friction factor	0.44	1.21	2.66

Table 3 – Friction comparison: design vs. revised analysis

The revised high estimate friction factors are significantly higher due to the increased embedment.

4.4. Finite Element Analysis

4.4.1. Model Description

The FE model was constructed in Abaqus with 'pipe' elements used for the pipeline (Figure 2).

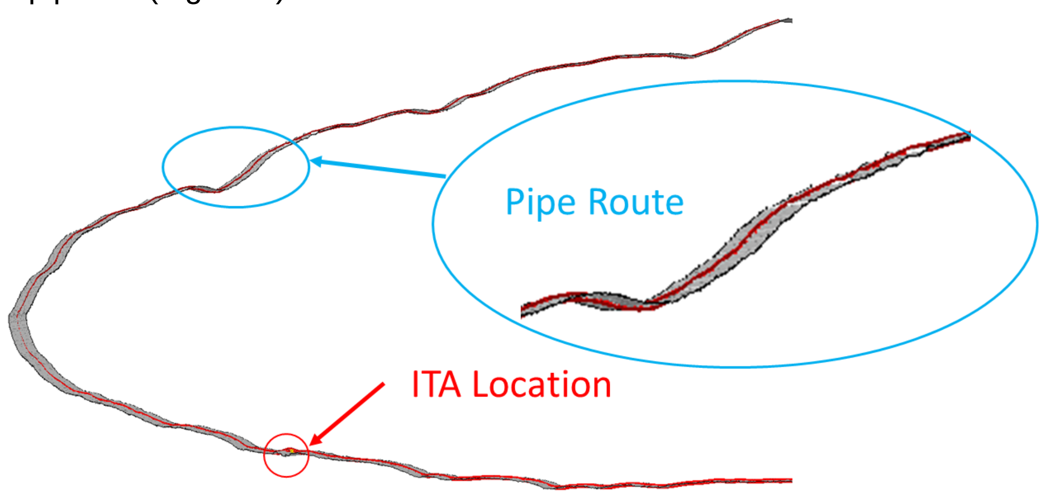

Figure 2 – FE representation of pipeline and ITA

The ITA structure was modelled approximately, ensuring that the pipeline was elevated to the correct height above the seabed and the submerged weight was correct. The model length of 12km included a 300m section upstream of KP0 to capture the tension imposed by the SCR. The seabed was modelled, using the pipe centreline bathymetry from the as-built survey, as a swept surface following the route of the pipeline, shown in Figure 2. The depth is constant perpendicular to the pipe.

The model accounts for material and geometric non-linearity, including a frictional model for pipe-soil interaction with different friction factors in the axial and lateral directions. The model also allows friction factors to be changed during the analysis. The lateral resistance was modelled using a tri-linear (breakout and residual) response. The ITA-mudmat interaction was modelled with a friction factor of 0.3 both axially and laterally.

Survey data showed the presence of significant berms where the pipe had moved between the operating and shutdown conditions (Figure 3). The formation of berms was modelled in the analysis by lateral springs that were created and removed with each cycle to replicate the true berm response. The berm resistance was calibrated to match the surveyed buckle amplitudes.

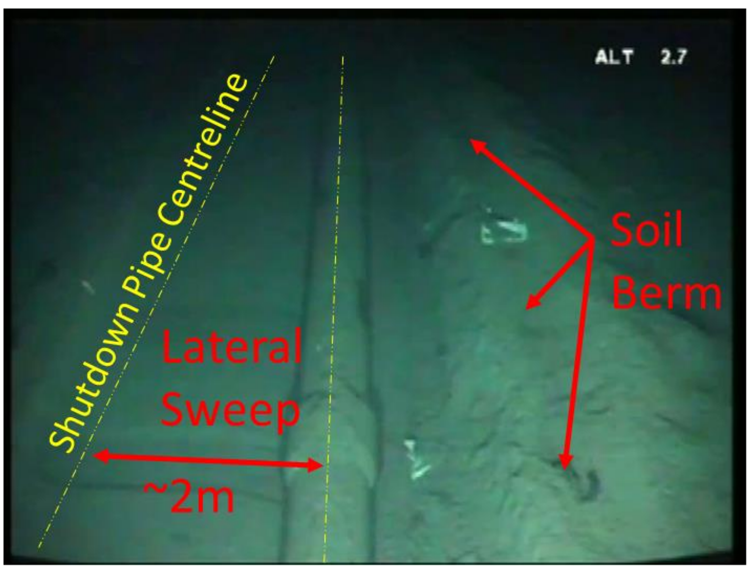

Figure 3 – Soil berms at extreme movement of the pipe

The as-laid geometry was captured by forcing an initially straight pipe into the surveyed shape, and then releasing it onto the seabed with the ITA in place. Upon release, the FE simulation smooths the survey data, providing the starting point for hydrotest and operational loads to be applied.

4.4.2. Results

Figure 4 shows a comparison of the survey data (solid lines) and the results of the best fit FE analysis (dashed lines). There are some small differences between the as-built OOS data and the smoothed FE analysis due to minor fluctuations in the survey data, which was of exceptional quality. The results from the FE analysis match well with each set of survey data, although there are slight differences in the peak displacement at the two main lobes of the buckle, which do not influence the overall response.

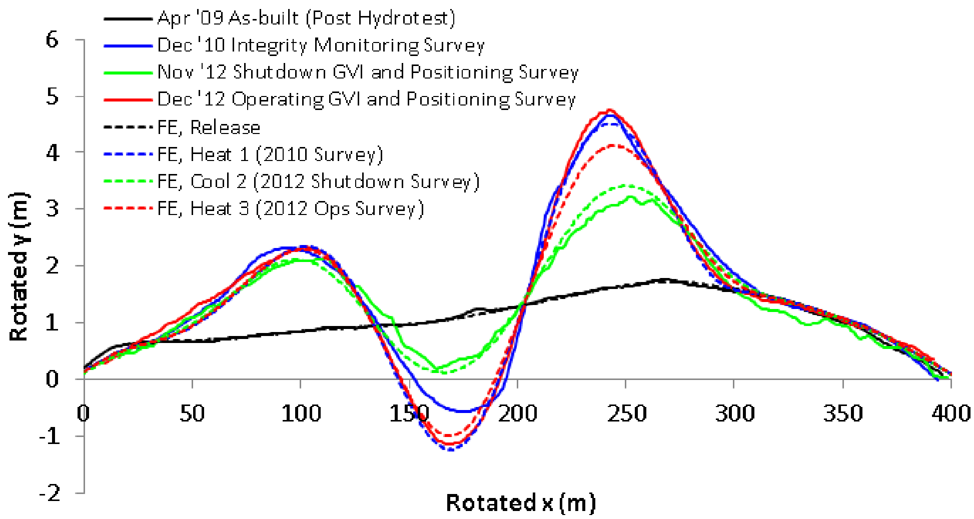

Figure 4 – Comparison of lateral shape

A number of cases were analysed, to ensure good agreement with the survey data. It was known from the OOS data that an additional rogue buckle had formed close to KP9; by varying the axial and lateral friction factors within the revised range of friction factors, the most likely combination was established that developed operating lateral buckles at KP6 (ITA location) and KP9. It was not considered necessary to take account of localised embedments or friction factors in the global model. However, with the BE axial friction factor, additional buckles formed to that observed; and with BE lateral friction the buckle at KP9 did not form (meaning that BE values appeared too high). Sensitivity analyses established a set of friction factors that best-fit the survey data, which in most cases are at or close to LE values (Table 4) but above the original design values (by others).

Buckle locations are generally in regions of lesser pipe embedment, so that low lateral resistances are probably more appropriate.

	Low Estimate	Best Estimate	High Estimate	Back Analysis
Axial friction factor	0.44	0.82	1.13	0.44
Lateral breakout friction factor	1.01	1.75	2.93	1.01
Lateral residual friction factor	0.44	0.72	1.16	0.53

Table 4 – Friction: back analysis

To control the cyclic growth of the buckle, soil berms are modelled. In the back-analysis, a total berm friction factor of 1.21 is adopted throughout. This was the BE total berm friction factor, based on the revised PSI assessment. This resistance is sufficient to constrain the growth of both buckles.

4.4.3. Integrity Assessment

The results of the FE analysis were used to perform an integrity assessment of the pipeline in its current configuration (i.e. before any mitigation measures were implemented). The stress and strain in the buckle throughout the analysis remained elastic, however for completeness three key limit states were assessed:

- local buckling (DNV-OS-F101 [1]),
- fatigue (DNV-RP-C203 [2]),
- plasticity (SAFEBUCK JIP [3]).

The governing limit state was local buckling due to internal overpressure, however the calculations showed that the loading in the buckle was acceptable in the current configuration. The fatigue damage accrued due to operational cycling (2 full shutdowns, Table 1) and the anticipated future cycling of the pipeline (shut-ins anticipated at both discharge and arrival points) was acceptably low. Since the stress and strain in the buckle throughout the analysis remained elastic, the plasticity limit state checks were met.

5. Quantify Required Restraint

Initial analysis was performed to understand the level of restraint required to restrain movement at the ITA. The analysis sought to address a number of factors:

- What restraint load is required, for mitigation applied with the pipeline shutdown or in operation?

- Is the load required to restrain movement reduced, if an additional lateral buckle can be triggered elsewhere?

5.1. Restraint Modelling

In the model, the lateral buckle was restrained, using simple lateral springs to prevent cyclic movement. Spring elements were included into the FE model and were distributed over the full length of the buckle at the ITA. The maximum load in the springs provides a simple measure of the required restraint.

Figure 5 shows the restraint required, with the pipe in the shutdown and operating conditions, to prevent movement on the following loading condition (either operation or shutdown). The results show some end effects (load spikes) at the ends of the modelled restraint. This could indicate that the coverage may be insufficient. However, the modelling here allows no movement under cyclic loading. In practice, small movements would be acceptable.

The results indicate that significantly higher restraint is required to prevent the buckle moving when the mitigation is applied in operation, because the buckle amplitude is larger; i.e. 6.6kN/m is required when the restraint is applied in operation, compared to 2.3kN/m required when the restraint is applied with the pipe shutdown.

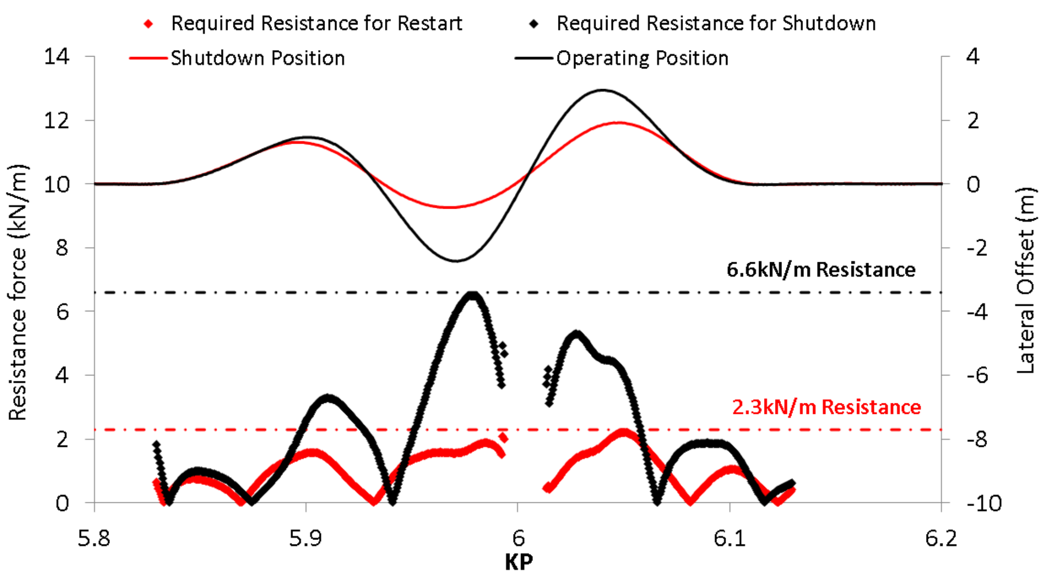

Figure 5 – Restraint mitigation

Additional analysis was conducted to determine whether triggering an additional lateral buckle close to the ITA would influence the restraint required to prevent movement of the pipe. A number of analyses were conducted where buckles were triggered at different locations away from the ITA. Only a buckle triggered within 1km of the ITA (at KP5) reduced the required restraint to prevent subsequent movement. However, the beneficial effect is limited and only effective if the buckle is initiated close to the existing lateral buckle (i.e. within 1 km). With this option, there will always be a concern that the additional buckle could fail to reform in the future which could result in a long-term increase in the required restraint load at the ITA. This option was not considered further.

The full-restraint analysis represents an idealised scenario, where a continuous distributed load is applied over a defined length; whilst something close to this may be achievable; this is an approximation of more practical discontinuous mitigation solutions. In addition, the assessment takes no account of the increase in axial resistance which would occur as a result of applying download to the pipe.

6. Mitigation Modelling

A workshop was held between Crondall Energy and Total to define options for mitigating the movement at the ITA. Two simple to procure and install options were carried forward for consideration:

- Concrete mattresses placed over the pipe, and
- Gravel bags placed adjacent to the pipe.

The mattress option was preferred, since gravel bags were unlikely to provide sufficient restraint to control the movement at the ITA. The gravel bag analysis showed that once any movement of the gravel bags occurred; on subsequent loading, they failed to provide sufficient resistance to further movement. In contrast, the mattresses were expected to provide increasing levels of constraint as the pipeline beds-in under the mattress weight. Consequently, only the results from the analyses including mattresses are discussed here.

6.1. Modelling Mattress Restraint

The segmented concrete mattress dimensions were specified as 2.5m x 6m x 0.3m. The total weight of one mattress was specified as 3.4Te, although much of this weight does not act directly on the pipe. In addition, as the pipe tries to displace laterally, it may slide underneath the mattress in preference to dragging and displacing the mattress with the pipe.

A literature review produced little information on either of the key concerns, and in particular no information was found on the resistance to lateral movement provided by mattresses. Such information is often considered proprietary by the suppliers.

A methodology was therefore developed based on an assessment of the lateral failure loads of a pipe sliding under a segmented concrete mattress and an assessment of the axial restraint provided by the mattress download.

Based on this assessment it was possible to demonstrate that the uplift resistance (download) provided by one mattress is approximately 1.9kN/m, provided 'arching' does not occur, which was considered unlikely in this scenario. 'Arching' is known to occur when a pipeline slides axially and embeds under a segmented mattress, which forms an arch over the pipe, reducing the download. Under lateral movement 'arching' is unlikely.

Calculating the lateral resistance provided by the mattress is more complex. The weight from the mattress contributes to the lateral resistance, but there is an additional contribution from the mattress draped around the pipe. The mattress segments can slide over the pipe as the pipe displaces laterally but the pipe must do work to lift each concrete element over the pipe and there is friction between the pipe and the underside of the mattress. The pipe will also embed more deeply under the overburden, increasing the passive soil resistance with displacement. An initial assessment based on the additional weight alone, with an initial mattress spacing of 4m (centre to centre) showed that the average lateral resistance provided by the mattresses would be lower than the 2.3kN/m resistance required to constrain ITA rotation.

The approach assumed a simple representation of friction, which in reality is likely to be significantly more complicated. Without further research work, it was decided, based on experience and analysis of the expected response, that the average lateral restraint provided by each mattress section (assuming a 4m spacing) would be at least 2.3kN/m. This includes for some bedding-in of the pipe on first load. This equates to each mattress (without spacing) providing a lateral resistance of 3.68kN/m. A schematic of the proposed mattress arrangement is shown in Figure 6.

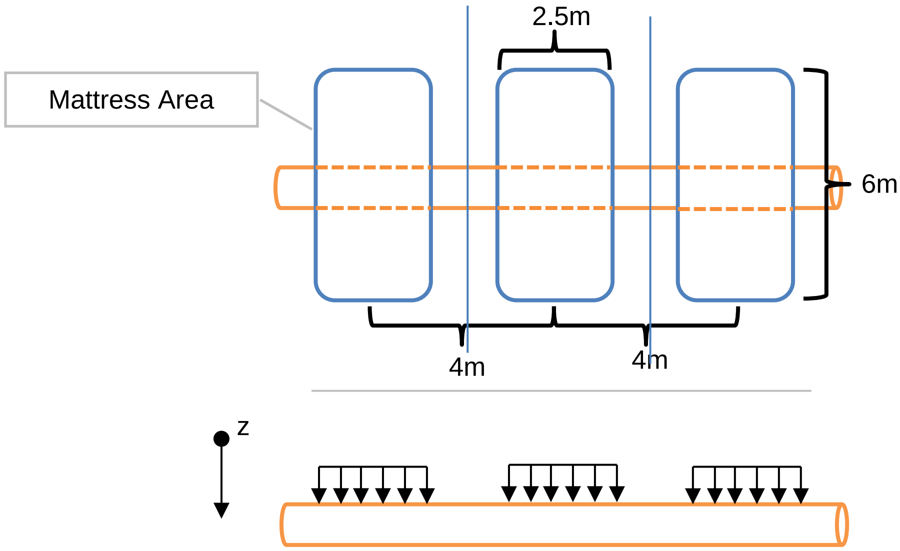

Figure 6 – Mattress modelling

6.2. Modifications to the Model

To include the effect of the mattresses in the analysis the 1.9kN/m download (per mattress) is applied, which represents the uplift resistance provided by the mattress, along with a local change in the axial and lateral frictions under the mattresses. The axial friction is modified based on the download provided by the mattress together with the additional friction interaction between the mattress and the pipe. The lateral friction is modified to provide an additional average lateral resistance of 2.3kN/m from the mattress.

Figure 7 shows a schematic of the mattress laid over the pipe. The figure shows the submerged weight of the pipe (W_{sub}) and the uplift resistance provided by the mattress (W_{add}) in addition to the pipe-soil frictions (μ_{ax_ps}, μ_{lat_ps}) and the assumed pipe-mattress axial (μ_{ax_pm}) friction.

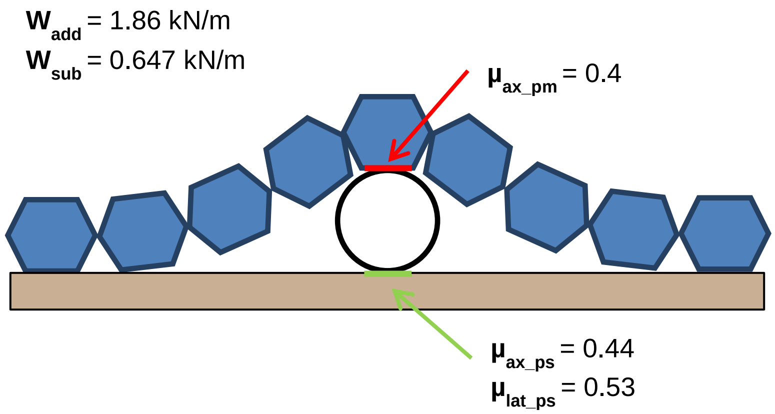

Figure 7 – Mattress friction interactions

To achieve the required lateral resistance (2.3kN/m), modifications to the pipe-soil friction factors were applied in the model over short lengths of pipe under the mattress (2.5 m). Accordingly, the axial friction factor was increased to μ_{ax}= 0.74 and the lateral friction factor was increased to μ_{lat}=1.61.

6.3. Analyses Conducted

A number of analyses were conducted to investigate the mattress mitigation. Sensitivities include:

- Effect of installation timing; i.e. mattresses installed with the pipe either in operation or shutdown.
- Mattress spacing; discontinuous 4m spacing or continuous edge to edge spacing.
- Length of mattress coverage;
- Length of the gap at the ITA.

In these analyses, following application of the mattresses, five design start-up shutdown cycles were applied, to confirm that the applied mitigation was sufficient to constrain the rotation at the ITA to less than 1°. This was a notional target allowable rotation, agreed with Total.

6.4. Results

The results from three of the analyses are presented here. These form the basis for the as-installed mitigation, described in section 7.

6.4.1. Restraints Applied in Shutdown

The initial restraint assessment identifies a peak restraint loading of 2.3kN/m is required to restrain movement at the ITA. A model was developed with discontinuous restraint applied across the buckle (4m spacing of mattresses), with an average lateral resistance of 2.3kN/m. The displaced shape from the assessment is shown in Figure 8.

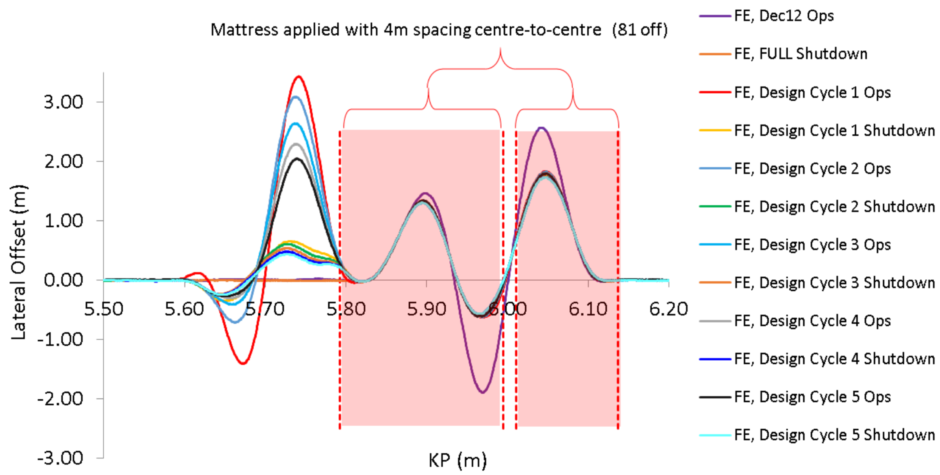

Figure 8 – Displaced shape, discontinuous restraint

The results show that the buckle is well restrained as a result of the mattresses; however, during the first heat up, post mattress installation, an additional buckle forms at the edge of the mattressed region. The buckle forms as a result of the increased axial force associated with the bank of mattresses, in combination with an out-of-straightness feature at around KP5.7. The formation of the buckle does not pose an integrity threat to the pipeline or ITA, however, its proximity to the ITA is undesirable.

Figure 9 shows the rotation at the ITA post mattress installation. The level of rotation is low throughout.

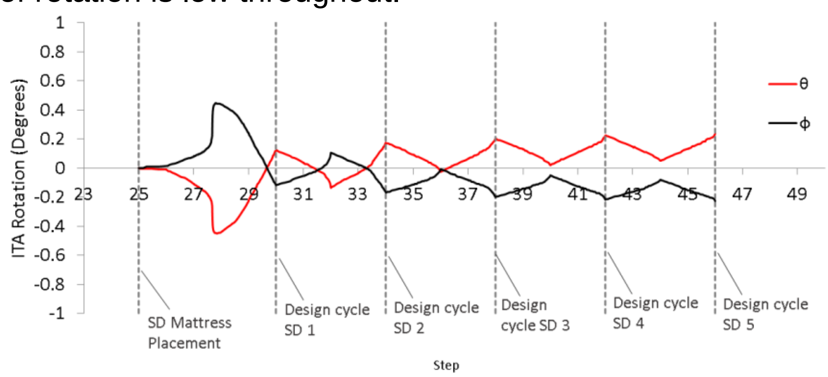

Figure 9 – Restraints applied during shutdown

The assessment confirms that applying an average restraint of 2.3kN/m provides sufficient rotational restraint at the ITA.

An additional case was considered in which the length of mattresses was increased (by 200m) to cover the OOS feature and stop the formation of the rogue buckle so close to the mattresses. In this case the movement at the ITA was again sufficiently restrained, although a rogue buckle again formed, this time at KP4.8.

Following discussion of the results with Total, the focus changed to installing the restraint in operation, since there was no planned shutdown in the coming period. Additional analyses were therefore conducted to develop a mattress scheme capable of restraining movement sufficiently at the ITA.

6.4.2. Mitigation Applied in Operation

The initial restraint analysis suggests that a restraint of 6.6kN/m across the buckle would be required to arrest movement at the ITA if the restraints are applied in operation. To develop a suitable mattress scheme, a combination of mattress spacing was investigated. 2.5m mattress spacing (i.e. no gap) was employed around the main buckle lobes where the required lateral restraint exceeded 2kN/m, elsewhere, a 4m mattress spacing was employed. Removing the gap between mattresses increases the lateral resistance to 3.68kN/m. The location of the mattresses upstream and downstream of the ITA are presented in Figure 10 below, where the pink shaded regions indicate a 4m centre-to-centre mattress spacing and the grey regions indicate a 2.5m centre-to-centre spacing (i.e. no gap).

The case has a mattressed length of 368m; 40 mattresses are applied without gap (20 upstream; 20 downstream), 67 mattresses are applied with a mattress spacing of 4m centre-to-centre (42 upstream; 25 downstream). The analysis assumes a small gap either side of the ITA; approximately 5 m upstream and downstream from the edge of the ITA.

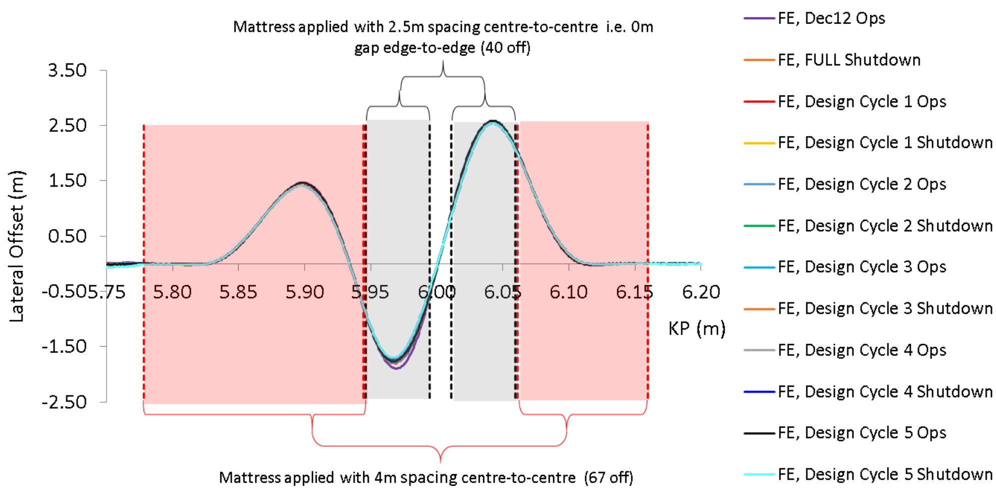

Figure 10 – Displaced shape, mix of continuous and discontinuous restraint

The figure presents the displaced shape of the pipe throughout, and shows that cyclic movement of the buckle arrests following mattress placement. However, smaller levels of displacement are indicated at the crown of the central lobe; KP5.97. Although small movements are indicated, they do not appear to cause significant rotation at the ITA. The results presented in Figure 11 show a maximum rotation of ~0.5° during each start-up shutdown cycle.

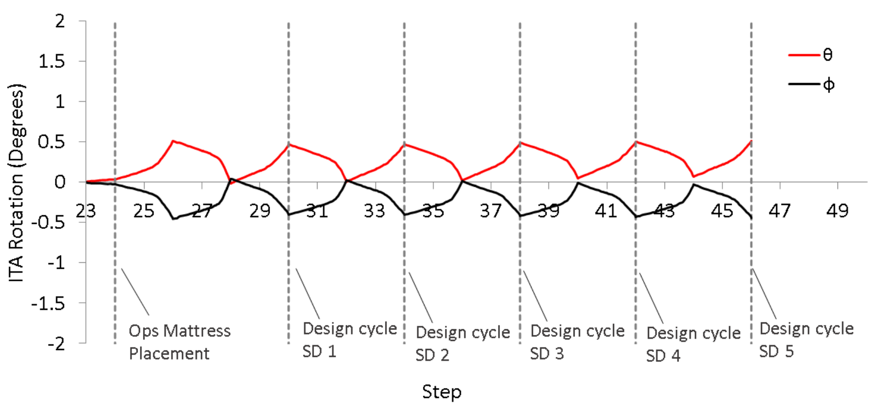

Figure 11 – Rotation, mix of continuous and discontinuous restraint

The assessment shows that, whilst applying the restraint in operation does not fully arrest the movement at the ITA, the continued rotation is acceptable.

6.4.3. Planned Installation Configuration – Applied in Operation

Prior to installation, Total were concerned that the gap between the mattresses and the ITA was too low and that applying mattresses to the pipe in the span may be detrimental to the connections on the ITA, as a result, an increased gap at the ITA was proposed (Figure 12).

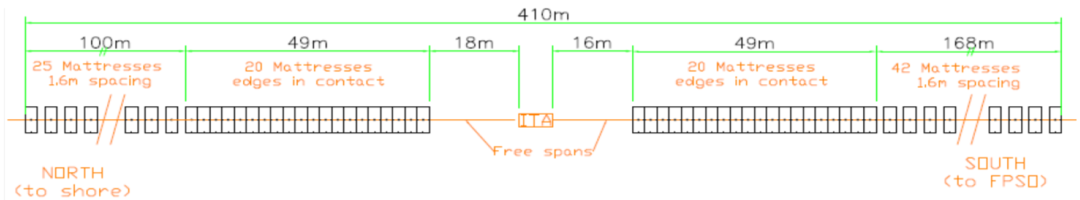

Figure 12 – Proposed and installed mattress configuration

The proposed mattress configuration was modelled. Figure 13 shows the displaced shape from the assessment.

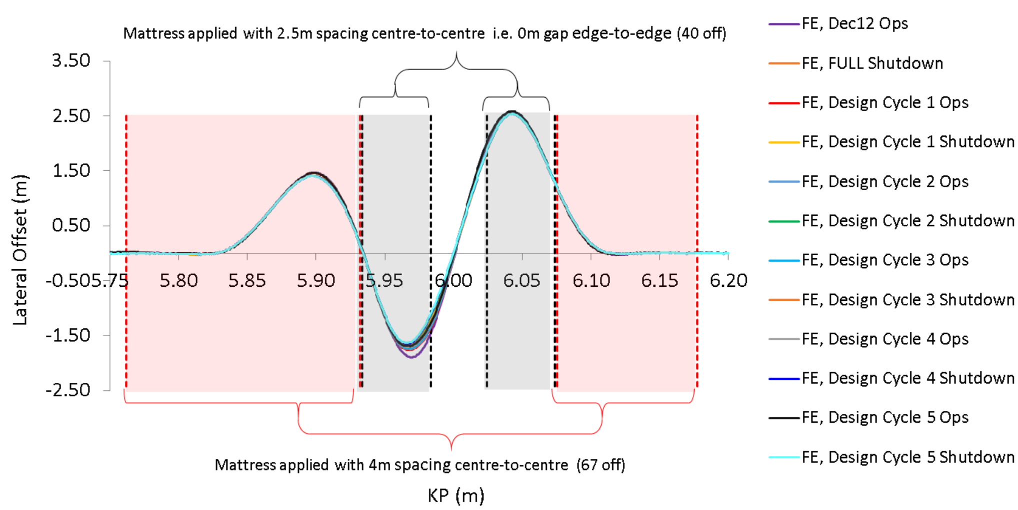

Figure 13 – Displaced shape, proposed mattress configuration

The results indicate that the buckle is well restrained despite the larger gap at the ITA. The rotation at the ITA is compared in Figure 14 for the original case, and the case with the increased gap at the ITA. The rotation is larger as a result of the increased gap, but this increase is small and the rotations remain acceptable.

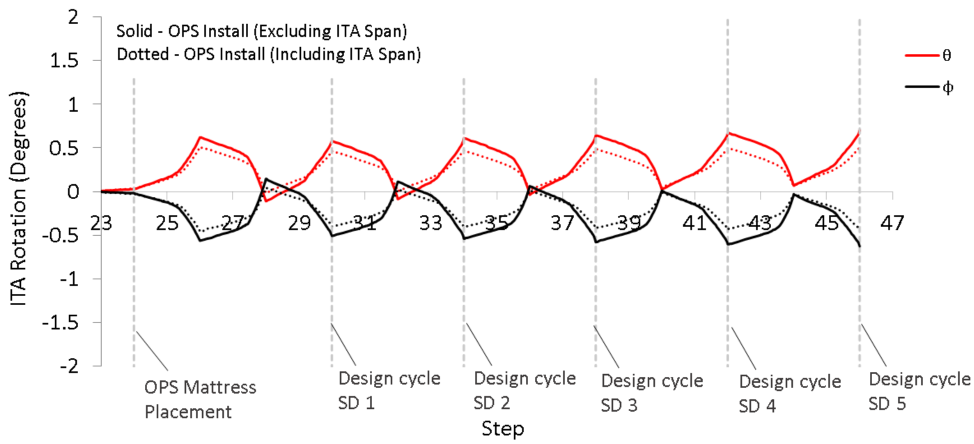

Figure 14 – ITA rotations, proposed mattress configuration

6.5. Summary of Mitigation Modelling

The analysis shows that successful mitigation can be achieved when the mattresses are applied during operation if continuous mattresses are applied to the main lobes of the buckle. Remote from the main buckle lobes, mattress spacing can be increased to save deployment costs/time.

7. Mitigation Installation

As the mattress installation had to be performed in operation, a real focus was brought to the dropped object study in order to define the minimum distance of the safe handling zone to achieve a failure probability below 10^{-7}.
A minimum distance of 185m was defined. The procedure for installation of the mattresses is summarised in Figure 15.

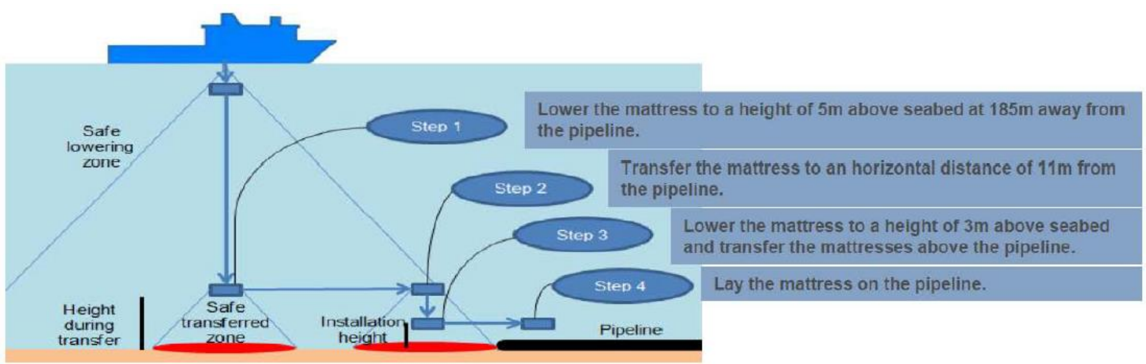

Figure 15 – Safe handling zone schematic

80 of the 107 mattresses were loaded on the Operation, Inspection, Maintenance and Repair Vessel (OIMR Vessel) deck, the remaining being sent offshore by supply vessel (Figure 16).

Figure 16 – OIMR Vessel deck arrangement

Installation started with the central mattresses for which a small overlap of the first row of concrete blocks was allowed. The actual mattresses width was 2.4m thus 1.6m edge to edge spacing was required between the remaining mattresses. Two beams were added to the lifting frame to be used as visual guides for this operation (Figure 17).

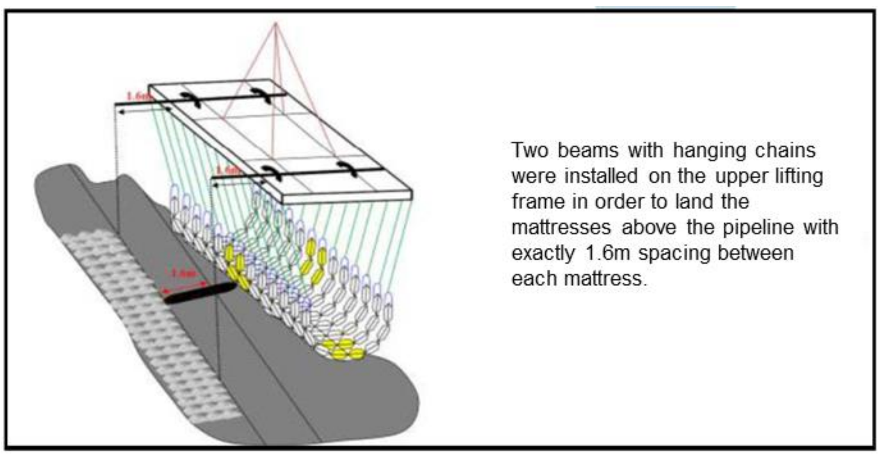

Figure 17 – Lifting frame with guides

Figure 18 shows a number of images from the mattress installation including those installed with a small overlap, and those installed with a 1.6m spacing.

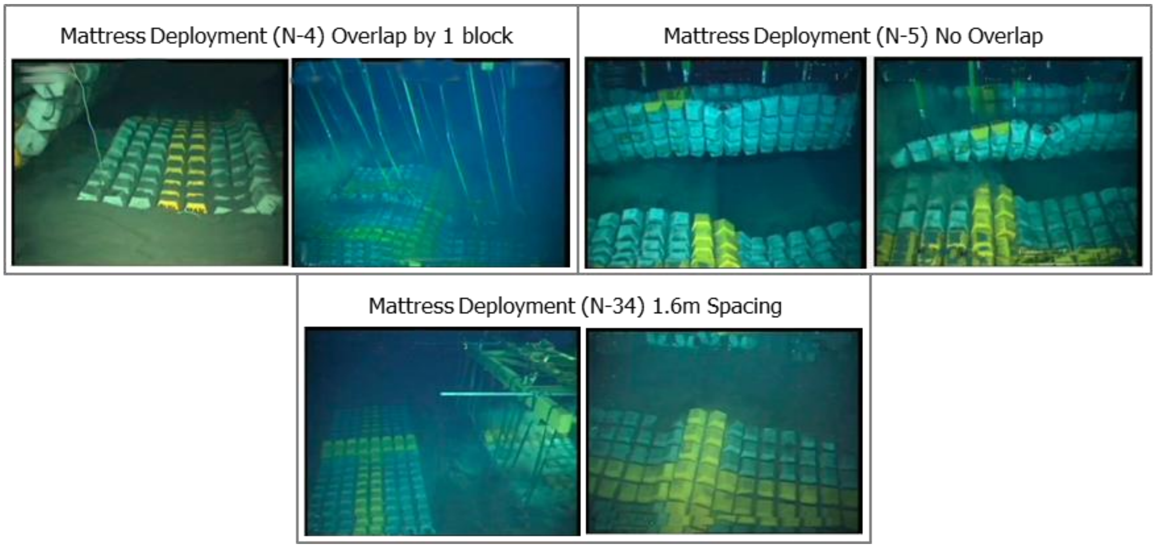

Figure 18 – Images from mattress installation

From the top right images, it was evident that the size of the soil berm present on one side of the pipeline prevented good coverage of the pipe by the mattress and thus may reduce the vertical load applied. However, it was anticipated that once the pipeline moved (during shutdown) the full weight of the mattress would be mobilised as the pipe beds-in. The impact on the mitigation efficiency is discussed in the following section.

The operation to install the mitigation was successfully completed well within the schedule and budget limitations and without any LTI.

8. Mitigation Performance

Following the mattress installation in April and May 2015 (with the pipeline in operation) the first full shutdown and restart occurred between February and March 2016. The rotation at the ITA was monitored by taking the headings from the ROV which docks onto the ITA; the pressure in the pipeline was also recorded at the same time from topside equipment. The data recorded is summarised in Table 5.

Monitoring Event Number	Rotation Monitoring Period	Initial Pressure (bar)	Final pressure (bar)	Initial Heading (°)	Final Heading (°)	Rotation (°)
1	16/02/16 to 24/02/16	171	103	249.47	250.39	0.92
2	24/02/16 to 24/02/16	103	93	250.39	250.49	0.10
3	24/02/16 to 09/03/16	93	7	250.49	251.37	0.88
4	09/03/16 to 11/03/16	7	153	251.37	250.72	-0.65
5	11/03/16 to 18/03/16	153	172	250.72	250.51	-0.21

Table 5 – ITA rotation monitoring

The table shows how the pressure in the pipe reduces from the operating pressure (~170 bar at monitoring event #1) to shutdown conditions (event #3) and increases back up to the operating pressure (monitoring event #5). It is assumed that over this period the temperature also reduces to ambient (4°C) and returns to the normal operating temperature (~20°C at the ITA location). The headings from the ROV were taken a number of times throughout the shutdown / restart cycle. From full operating conditions to the first shutdown since installation of the mattresses the ITA rotated 1.9 degrees. On subsequent restart, back up to the full operating pressure, the ITA rotated back by 0.86 degrees.

Images from surveys are presented in Figure 19 to the South of the ITA and Figure 20 to the North of the ITA. The images on the left were taken when the mattresses were installed in the operating condition in 2015; the images on the right were taken from the survey conducted with the pipeline in the shutdown condition on 9th March 2016. The images show how the pipe has moved underneath the mattresses.

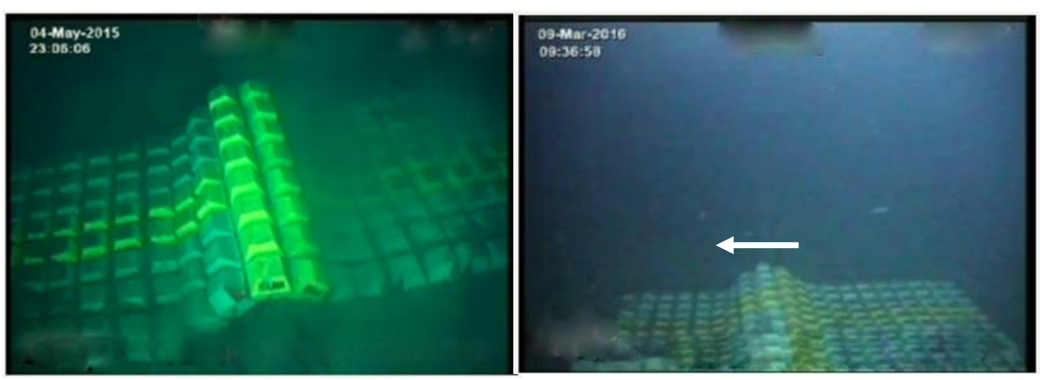

Figure 19 – South side of ITA – at installation and after shutdown

The pipe at the South side of the ITA (Figure 19) appears to have moved laterally by about two blocks (~0.6m). The pipe at the North side of the ITA (Figure 20) appears to have moved laterally by 2 or 3 mattress blocks (0.6m to 0.9m). These movements are in-line with the initial rotation observed at the ITA.

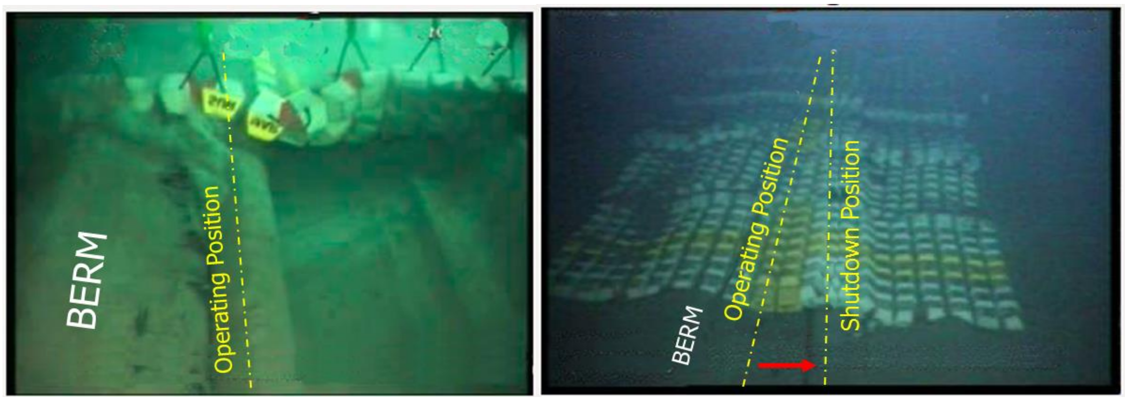

Figure 20 – North side of ITA – at installation and after shutdown

From the images and survey, it is clear that the full lateral resistance of the mattress is not active on first movement (first load), also the presence of the soil berm has initially prevented the mattress blocks from draping over the pipe effectively. It is not surprising that the initial rotation at the ITA is higher than that observed in the mitigation analysis but once the pipe had moved and bedded-in, the full restraint was expected to act on the pipe.

Further FE analysis has been completed to replicate the rotation measurements by reducing the lateral restraint provided by the mattresses on first load before the full weight is mobilised (Figure 21).

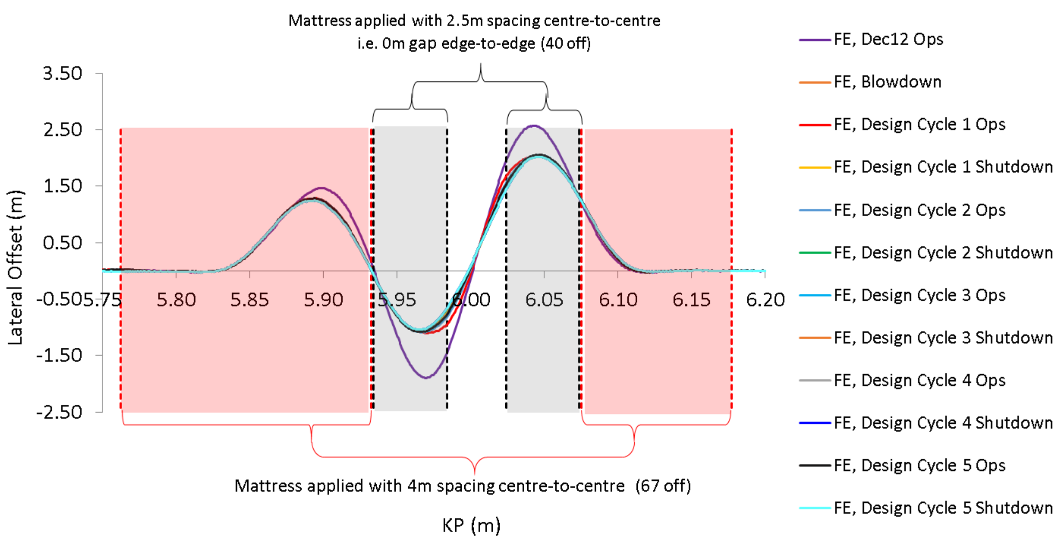

Figure 21 – Displaced shapes, response tuned to match observations

No out-of-straightness data is available to check whether buckling has occurred elsewhere; however, it is assumed that no additional buckles have been triggered, as predicted from the analysis. In the assessment, the lateral resistance from the mattresses is tuned such that an initial rotation of 2° was achieved on the first shutdown. On the subsequent restart and for the remainder of the analysed cycles, the full lateral resistance expected from the mattresses was applied.

The buckle shapes from the model are shown in Figure 21. The buckle shape shows a displacement of less than 1m at each of the two main buckle lobes; this is consistent with the observed movements of the pipe underneath the mattresses. The results also indicate that the buckle shape stabilises with future cycles as the full mattress resistance is mobilised.

The rotation at the ITA from the model is shown in Figure 22. The figure also shows the rotations measured from the surveys.

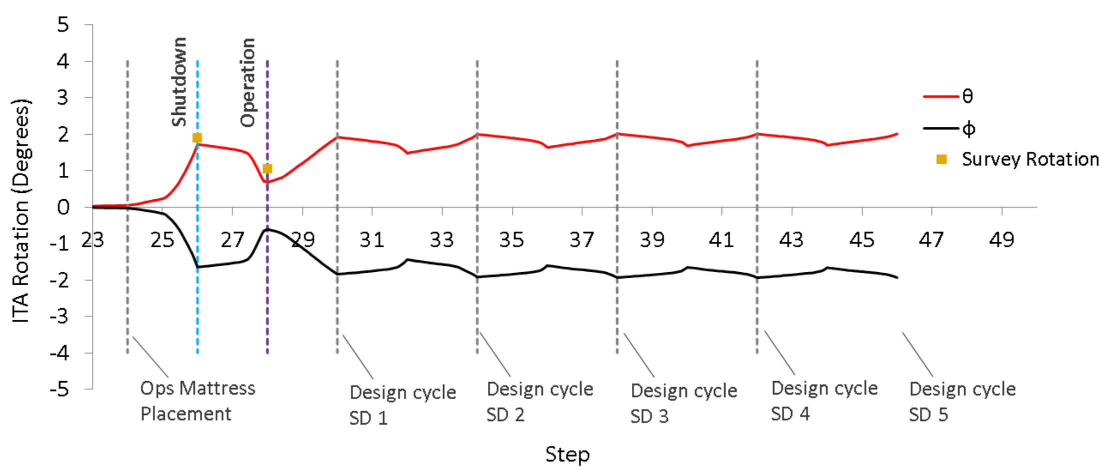

Figure 22 – ITA rotations, tuned model

The tuned model gives good agreement to the measured data (Survey Rotations) and predicts that the cyclic change in rotation is low (<0.5°) for future cycles. Any future measured data will help to confirm this finding.

9. Conclusions

- Pipeline structures should be designed to avoid buckling close to the structure. This can be done by: (1) preventing rotation at the structure; (2) reducing the axial force, by promoting buckling a short distance from the structure; (3) keeping OOS as low as possible and not laying an ITA on a route curve.

- Calibrated back-analysis, provides an excellent match to the response of the pipeline at the ITA and allowed the predicted PSI responses to be calibrated.
- Initial mitigation analysis, using fixed restraints was valuable in identifying the required restraint in operation and shutdown to fully restrain movement. This provided an excellent guide for detailed analysis and demonstrated that installing the mattresses at shutdown would require less restraint.
- Detailed analysis identified an appropriate mitigation scheme for applying mattresses to the buckle in operation. The analysis also demonstrated that applying the mattresses in a shutdown condition may induce additional buckles.
- Mattresses were installed in accordance with the proposed mitigation scheme, while in operation this was completed well within schedule and budget limitations and without any LTI.
- A review of post mitigation images show that on first load the pipe moves under the mattresses as the pipe beds-in, which was expected.
- Analysis confirms that the initial loading does not fully mobilise the mattress resistance, the soil berms under the mattress may have contributed to this.
- Subsequent loading after bedding-in, shows that the full restraint is mobilised and further analysis confirms this by replicating the response of the buckle after mitigation.
- The mitigation scheme is effective at reducing rotation at the ITA from 5.5° to less than 0.5°, which is less than the required maximum rotation of 1.0°.

10. References

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