Advances in Understanding of Pipe–Soil Interaction in Lateral Buckles

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1. Abstract

For most on-bottom pipelines, lateral buckling induced by cyclic temperature fluctuations is virtually inevitable, and the design objective is to control the buckling process by initiating buckles in pre-determined locations.

In operation, lateral buckles cut a trench bounded by soil berms. Numerical simulation of this behaviour often employs significant simplifications, being based on horizontal sweeping under constant vertical load, with springs or other simplified models to represent soil berms. In reality, as the pipe moves laterally it displaces vertically. The apex of the buckle cuts a trench, inflection points form as the pipe moves, and vertical contact forces vary along the length of the lateral buckle. Furthermore, the soil berm restraint is load-controlled (or strictly speaking, pipeline-temperature-controlled).

The authors have developed a state-of-the-art modelling approach to simulate transverse pipe–soil interaction (PSI) on soft clay, using sequential limit analysis within multiple 2D slices of soil attached to a 3D structural model of a pipeline undergoing lateral buckling, running within existing Abaqus FEA software.

This approach has been used to simulate field examples to:

1. Compare predicted fatigue damage with traditional analysis methods, quantifying design conservatism.
2. Assess the response of soil berms, to identify more appropriate berm responses.
3. Model ‘heavy’ pipe, which traditionally requires mitigation such as buoyancy.

This modelling approach has the potential to become the software of choice for assessment of the most challenging pipelines. Giving realistic predictions efficiently and robustly, it has the potential to make significant savings on mitigation costs.

2. Introduction

In the offshore energy industry, subsea pipelines are vital components of the infrastructure for transporting hydrocarbons, operating at elevated pressure and temperature. The resulting tendency for axial expansion, combined with frictional restraint from the seabed soil, causes large compressive forces to build up. Since pipelines are relatively slender structural elements, they are susceptible to bar buckling: either upheaval buckling in the case of a buried pipe, which must be prevented; or lateral buckling in the case of an on-bottom pipe (laid directly on the seabed). Lateral buckling is usually encouraged to occur at regular intervals to relieve the compressive force and control loading in the lateral buckles. Indeed, controlled lateral buckling is often the only practical solution for pipelines operating at high temperature.

Lateral buckling is controlled by initiating buckles in pre-determined locations along the pipeline route, using triggers such as snake-lay, sleepers, buoyancy, or naturally occurring vertical out-of-straightness [1], to ensure that the predicted lateral displacements, bending stresses and (usually) plastic strains, are not excessive.

Operation of a subsea pipeline involves numerous shutdowns and restarts, that cause lateral buckles to cycle back and forth across the seabed. This motion is predominantly normal to the pipeline axis, and because the amplitudes involved are large – typically at least 10 or 20 pipe diameters – there is severe plastic distortion and remoulding of the near-surface seabed material, with soil being ploughed into mounds or 'berms' in front of the pipe (Figure 1), as the pipeline cuts itself into a trench.

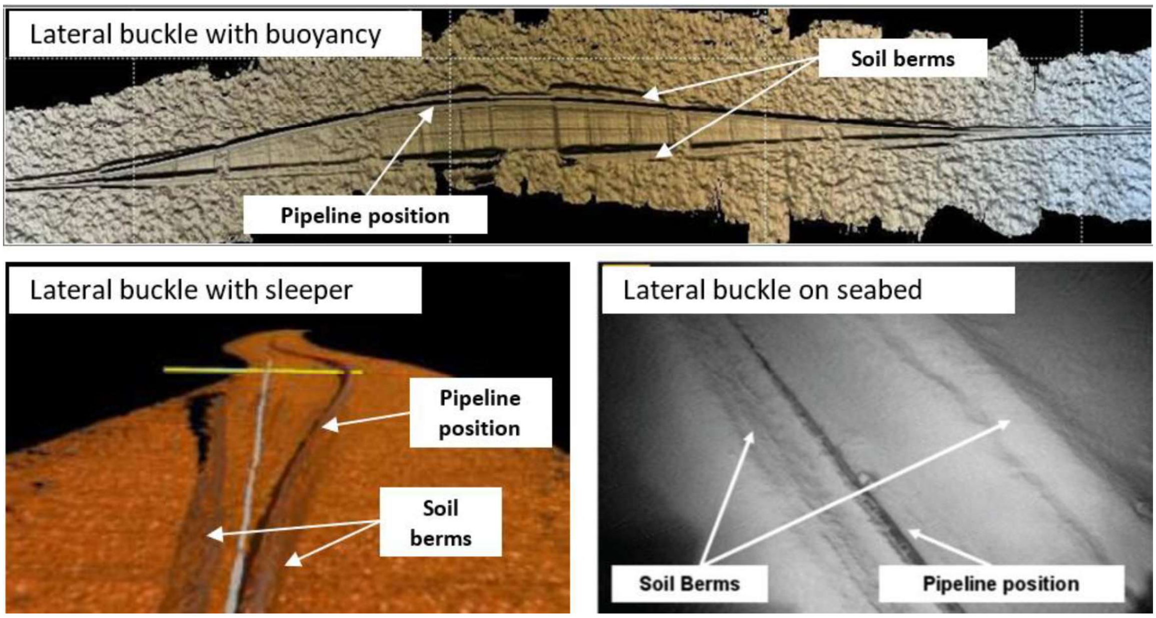


Figure 1 Lateral buckling of subsea pipelines showing soil berms [2] [3]

Direct numerical simulation of this behaviour (e.g. using FEA with 3D continuum elements for the soil) remains extremely challenging, and in practice greatly simplified PSI models are used. These simplified models ignore the vertical movement of the pipe as it displaces laterally, and hence fail to capture the particularly complex coupling between these two degrees of freedom. Finally, there is a significant component of cyclic axial movement as adjacent lengths of pipe feed into, and out of, a lateral buckle during restarts and shutdowns.

There is an opportunity now to develop new approaches that better capture this complex behaviour. Further, these predictions can be compared with survey data from existing pipelines, many of which have been in operation for over two decades. This has the potential to allow the industry to 'close the circle' on feeding operational experience back into design, and thereby simplify design solutions, with the possibility of reducing or avoiding expensive buckle-control mitigation options.

3. Current Design Approaches and Limitations

3.1. Current Design Guidance

The SAFEBUCK Joint Industry Project, summarised by Bruton & Carr (2011) [4] made major advances in the understanding and modelling of both axial and transverse PSI based on the extensive SAFEBUCK test database of large-scale (laboratory), small-scale (centrifuge) and in-situ tests [5], donated to the JIP by participants or carried out by the JIP. Lessons learned from detailed reviews of the test data to provide appropriate design guidance [6] were captured in the SAFEBUCK Design Guideline [7].

However, the lateral buckle cyclic response was only addressed at high level by bracketing the data on cyclic vertical penetration and resulting berm resistance. This design guidance resulted in a very wide range of cyclic berm resistances, and little guidance was given on the influence of the three-dimensional shape of a lateral buckle after many operating cycles. While many important lessons associated with PSI during lateral buckling were incorporated into SAFEBUCK Design Guidance and carried forward into the DNV recommended practice DNV-RP-F114 [8], the cyclic berm response guidance was not included by DNV.

3.2. Test Data Limitations

Most lateral PSI tests are based on the application of constant vertical load and prescribed displacement-controlled lateral cyclic sweeps of the pipe. Due to test bed limitations, lateral displacements in most of the SAFEBUCK PSI tests were limited to a few pipe-diameters (typically 3 to 5), significantly less than occurs in reality. Where vertical load or lateral amplitude was varied in the tests, these variations were guided by real pipeline behaviour. True load-controlled lateral displacement based on lateral buckle response was not feasible, as laboratory tests were based on a 2D slice model of a short segment of pipe, using vertical load control to represent the submerged weight of the pipe.

Such tests were unable to replicate the true load-controlled lateral response over many diameters of movement, nor could they account for the variations in vertical load that may occur as the lateral buckle digs itself into a trench.

3.3. Current Analysis Limitations

Many pipeline projects face a significant challenge to predict the full cyclic PSI response in 3D. Current numerical analyses often employ a rigid seabed model with axial and lateral pipe–soil friction factors, with springs or other simplified models to represent the expected soil berm response. This means that there is significant uncertainty in predicting the true cyclic response, leading to:

1. Conservative predictions of cyclic fatigue damage, with models that do not capture berm accretion over many cycles, or encroachment on the pipeline.
2. Lack of confidence in PSI predictions when the pipe is relatively heavy[1], such as PIP (pipe-in-pipe) or thick-walled pipe. This limitation has led to the extensive use of engineered buckling mitigation measures such as buoyancy modules to reduce the vertical load to achieve light pipe behaviour.

It is possible that the relatively expensive mitigation measures used to address these issues in design may not have been strictly necessary. This observation is backed up by data from integrity monitoring surveys of operating pipelines where on-bottom lateral buckles have experienced many shutdown cycles.

[1] 'Heavy' pipe behaviour during lateral buckling is typically observed when the dimensionless group $W/D.s_u$ is greater than about 2.

4. Development of a 3D Slice Model

The 3D slice model overcomes many current limitations in the analysis of cyclic PSI for a lateral buckle. Crondall Energy (CE) has been working with Oxford University to develop this state-of-the-art modelling approach for simulating transverse PSI, based on earlier work by Martin et al. [9], which proposed the use of multiple 2D (plane strain) slices of soil attached to a 3D structural model of a pipeline undergoing thermally induced lateral buckling.

This paper details further development and application of this software for soft clay typical of most deepwater seabed soils, in parallel with a review of some real cases of pipeline response observed in the field, to verify the predicted 3D response.

4.1. Multi-Slice Sequential Limit Analysis (MS-SLA) Model

This new approach uses a multi-slice (MS) model with sequential limit analysis (SLA) [10] in each soil slice. The slices are distributed along the length of the lateral buckle model, to capture the full 3D load–displacement response. Computational effort is significantly reduced by using a moving analysis domain that is focused on the localised region of soil that surrounds the pipe within each slice. The MS-SLA model includes the influences of increasing shear strength with depth and remoulding (softening) of the soil in the active berm. This model is linked with the software Abaqus, calling upon separate SLA instances that run in parallel, for each soil slice along the lateral buckle. An important aim of the model is to achieve high computational efficiency to minimise run-time; this is made possible by a number of innovative approaches within the slice modelling subroutine that achieve remarkable run-time efficiency.

A fully three-dimensional model of a lateral buckle is capable of assessing the cyclic response, including the cutting of a trench, the building of soil berms, and the subsequent influence on long-term cyclic behaviour within the lateral buckle. This 3D behaviour is strongly influenced by soil berm growth and berm encroachment into the trench as soil slumps or is dragged back into the trench by the retreating pipe (a mechanism observed in large-scale tests). The resultant redistribution of vertical contact force within the lateral buckle is also modelled, as the apex of the lateral buckle tends toward spanning in the deepest part of the trench, while the contact forces at the inflection points gradually increase, creating a fulcrum close to the supporting shoulders to each side of the lateral buckle.

4.2. Aims and Capabilities

This new approach provides a much greater focus on the interface between academic research and industry practice to understand this challenging behaviour, based on an unparalleled wealth of prior experience in pipe–soil modelling and lessons learned from numerous observations of pipeline behaviour in the field. The overall aim is to 'close the circle' on design through operational monitoring, to learn the lessons that come from decades of observing lateral buckling in subsea pipelines.

In particular this new approach can overcome several current model limitations by:

1. Modelling the accretion of soil into berms, resulting in encroachment on the lateral buckle that gradually reduces the cyclic amplitude and thus reduces the long-term fatigue damage. This cannot be predicted with current techniques, which are not able to model the potential encroachment of the soil berms.

2. Capturing the 3D shape of the lateral buckle, as the pipe cuts a trench that allows the most highly loaded apex of the lateral buckle to sink below seabed level, with a natural reduction in the vertical contact force as the lateral buckle is supported at its shoulders. This behaviour is particularly important for heavy pipes and influences load distribution in the lateral buckle, leading to a long-term stabilised response that cannot be predicted with current models.

3. Simulating the response of an established lateral buckle to an increase in operating temperature in late life. Current modelling approaches for this are uncertain, and the potential risk is that the pipe breaches the established soil berm, focusing high bending loads at the buckle apex. Modelling a lateral buckle in 3D allows the starting point for this risk to be properly assessed based on the established 3D shape of the lateral buckle and restraining berms.

4. Modelling the cyclic response of 'heavy' pipelines such as PIP systems or thick-wall (high pressure) pipelines. Previous work to address this limitation and simulate heavy pipe behaviour was extremely challenging and carries significant uncertainty [11]. Accurately capturing this type of PSI response is considered intractable with current models. The ability to predict the long-term cyclic response of heavy pipe could avoid the need for engineered initiators to control buckling using buoyancy modules. These are commonly added by design contractors to make the engineering solution tractable, at significant cost to the operator.

5. Cyclic Lateral Buckling Behaviour – Site 1

5.1. Input Data for Cases A and B

Overall outside diameter (D)	0.359	m
Operating submerged weight (W)	934	N/m
Axial friction factor (μ_A)	0.55	-
Pipe/soil interface roughness factor	0.25	-
Soil sensitivity	2.5	-
Soil unit weight	3.5	kN/m³
Initial embedment	28%	D
VAS (Virtual Anchor Spacing)	1200	m
Soil slices from 0 m (CL) to 100 m	5	m
Soil slices from 100 m to 600 m	20	m

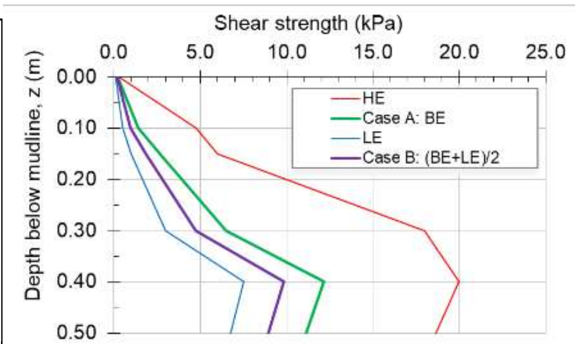


Figure 2 Pipe and soil data for Cases A and B

Case A is based on the BE shear strength profile at this site, while Case B is based on a strength profile midway between BE and LE (Figure 2). The analysis uses a half-length model symmetric about centre so only half of the 1200 m VAS length is modelled (X = 0 to 600 m). The model has no vertical OOS (out-of-straightness), and modest lateral OOS, sufficient to initiate buckling.

5.2. Case A – Berm Response Under Variable-Amplitude Temperature Cycles

Case A demonstrated that when a lateral buckle experiences an increase in the cyclic temperature amplitude, the soil berm at the extrados of the lateral buckle is displaced outwards by the pipe. In this case, the pipe does not rise up over or breach the berm, neither does the berm disappear. This response is an important point to address in simplified berm-spring modelling that has been known to incorrectly assume that the berm is 'lost' once the pipe 'rides though' the berm. In reality, the pipe does not breach the berm but displaces it outwards.

Case A also allowed modelling of the detailed large-displacement lateral response with variations in operating temperature (Figure 3). Intermediate soil berms deposited at lower operating temperatures were subsequently displaced outwards when the operating temperature was increased. Meanwhile the berm at the intrados of the lateral buckle encroached into the trench, limiting shutdown displacement. Lateral movement of the pipe at the apex of the lateral buckle is shown in Figure 3a, starting with an operating temperature of 48°C and an unload temperature of 4°C, before cycling three times to 42°C (lower operating temperature). Then, as shown in Figure 3b, the buckle is loaded three times to 68°C (increased operating temperature). The pipe positions at the extreme of each lateral displacement and the associated soil profiles clearly show the scraping action, the deposition of intermediate soil berms and the tendency for a slight reduction in amplitude during repeated cycles at a given temperature.

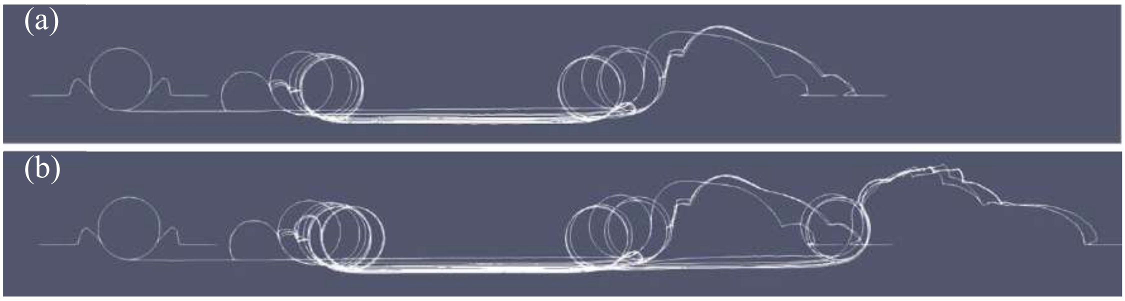


Figure 3 Case A MS-SLA displacements and berms at buckle apex
(a) 3 temperature cycles from 4°C to 48°C, then 3 cycles from 4°C to 42°C
(b) additional 3 temperature cycles from 4°C to 68°C.

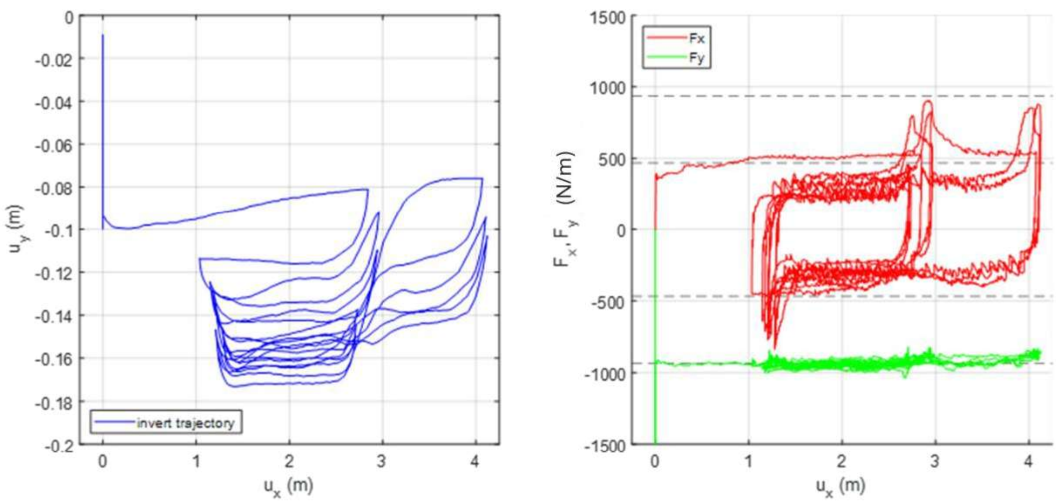


Figure 4 Case A MS-SLA displacement response and load response at buckle apex

The overall cyclic displacement and berm shape in the early cycles was well matched to field observations. The load responses (Figure 4, right) are remarkably similar to full- and small-scale PSI slice model tests, except that in this case the berm response is load-controlled and the amplitude clearly reduces with cycling, while lateral resistance at the berm is steady over several cycles, unlike displacement-controlled PSI tests. This analysis demonstrated that a future increase in operating temperature is acceptable.

5.2.1. Berm Encroachment

The evolution of the berms in the MS-SLA modelling of Case A, also discussed at SPT 2024 [12], confirmed behaviour observed in the field, where accretion of soil into the berms at the extremes of pipe displacement tends to reduce buckle amplitude as the berms encroach on the lateral buckles. This reduction of cyclic amplitude is translated into increased pipeline walking displacement. This walking mechanism has caused end expansion to exceed design limits on at least one system that was originally anchored to control walking, requiring retroactive anchoring mitigation.

5.3. Case B – Fatigue Under Constant-Amplitude Temperature Cycles

Analysis of the same system under repeated cyclic thermal loading (4°C to 42.2°C) was used to assess the influence of different berm modelling approaches. Not modelling soil berms is a well-known error, identified in 2005 as leading to non-conservative design [13] due to buckle relaxing. This approach is used to benchmark against current design practice in the following comparison of buckle shapes shown in Figure 7:

- [a] Prediction obtained using the new MS-SLA model.
- [b] Friction factor modelling with no berms – unrealistic relaxation of buckle.
- [c] Simple expedient of adding relatively strong berms with a total friction factor of 2 after the second cycle, which conservatively constrains buckle growth.
- [d] Increasing berm resistance with cycles for a less conservative approach using CE's berm growth assessment method, based on SAFEBUCK data.

It is clear from this comparison that the MS-SLA approach 'relaxes' least, with increasing berm encroachment on the intrados of the buckle that reduces the cyclic displacement and subtly changes the buckle shape.

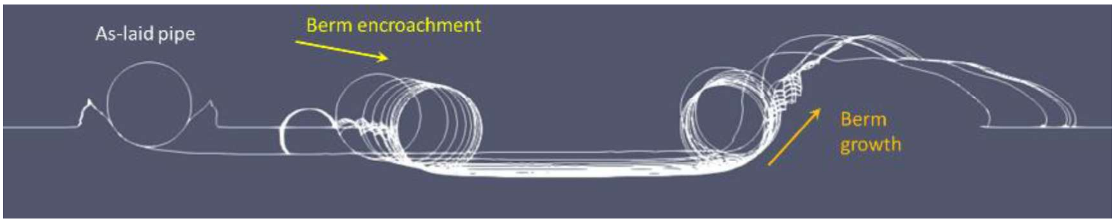


Figure 5 Case B MS-SLA displacements and berms at buckle apex

It is interesting to observe the folds of soil within the berm generated by cyclic encroachment (Figure 5) and the shape of the trench, which is also evident from offshore surveys of the pipeline that this analysis is based on (Figure 6).

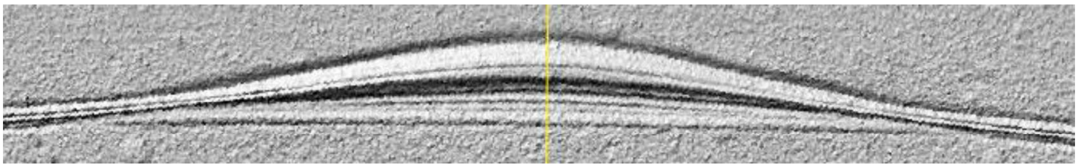
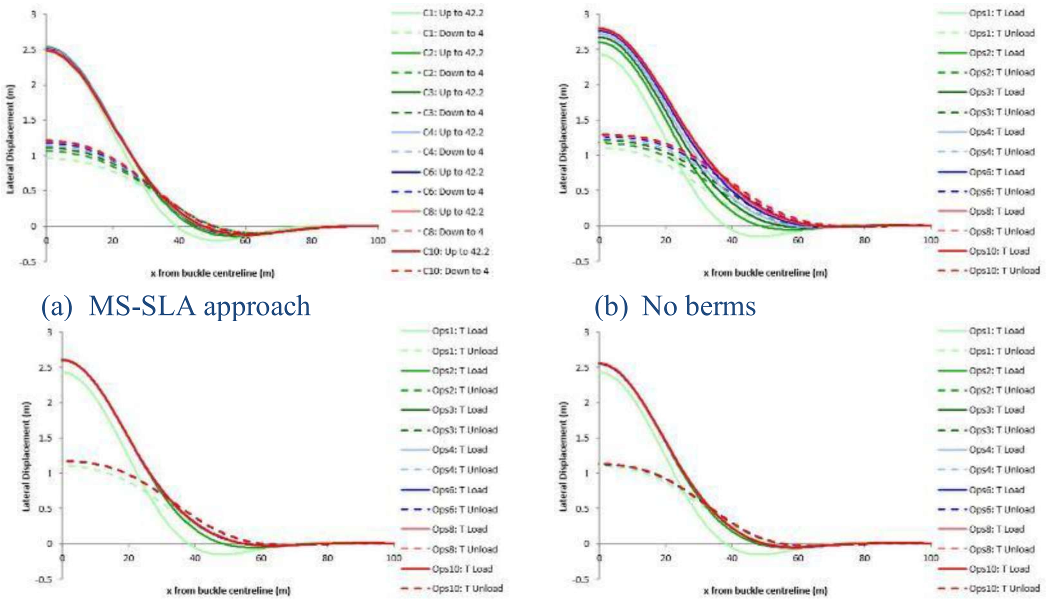


Figure 6 Case B High resolution survey of the lateral buckle after some years in operation

The influence on cyclic stress is clear in Figure 8, which for no berms shows a non-conservative reduction of stress range and fatigue damage (-13.5%), while applying strong berms on the 2nd cycle is conservative (+24.3%), and increasing berm strength less conservative (+13.5%). The influence on fatigue damage is marked, with the MS-SLA approach reducing fatigue damage significantly based on simple unity checks. Further thermal cycling is expected to further improve fatigue damage reduction.



(a) MS-SLA approach
(b) No berms
(c) Strong berms after 2nd cycle
(d) Increasing strength with cycles

Figure 7 Case B Buckle shape changes with cycles using different berm responses

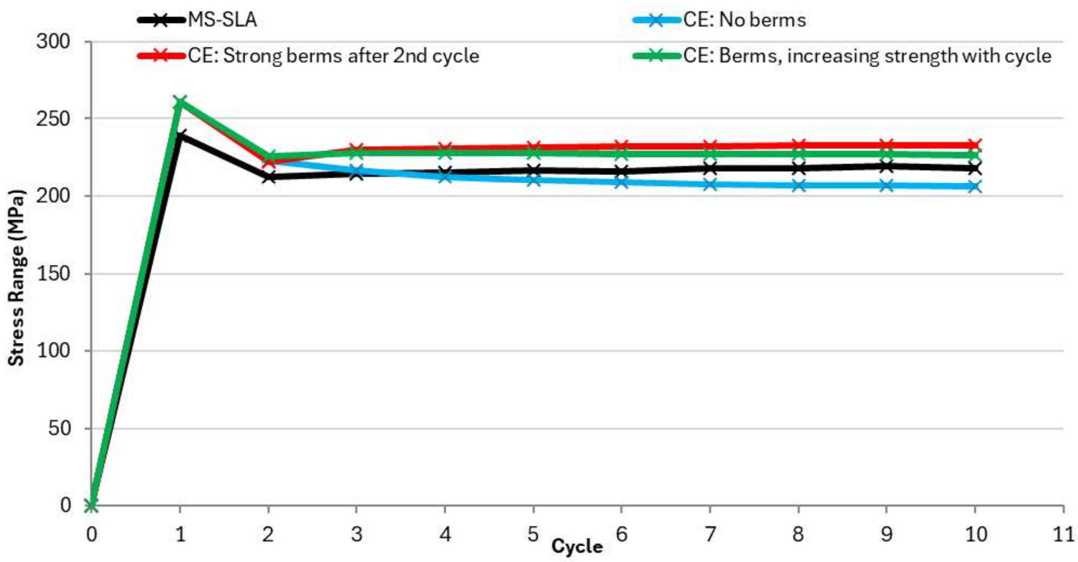


Figure 8 Case B Stress range with cycles using different berm responses

The MS-SLA cyclic load responses are shown on the right of Figure 9, where the dashed lines indicate the pipe weight (W) and half weight (W/2). Breakout and residual lateral friction factors for this case are well predicted by SAFEBUCK models at 0.5 (467 N/m) and 0.61 (570 N/m) respectively.

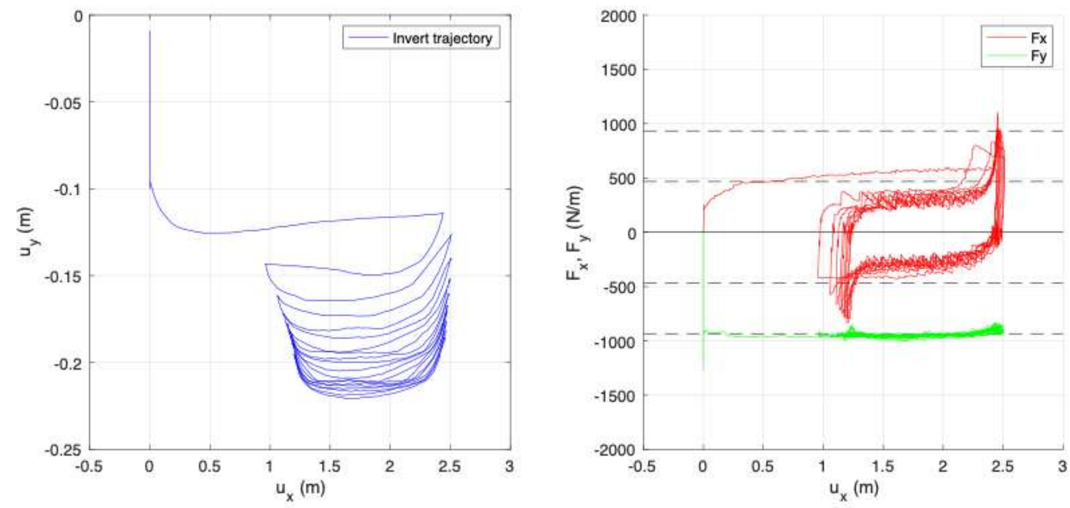


Figure 9 Case B MS-SLA displacement response and load response at buckle apex

Total berm resistances are not well predicted by the SAFEBUCK [7] cyclic model, which predicts a very wide range of resistance. This reflects the scatter in the underlying database, due to the range of pipe weights, diameters and different soil parameters in the test database. It is acknowledged in the guideline that the range in resistance may be too wide to provide an acceptable design basis, which is why designers often assume an average value, but it appears that can also be wide of the mark. CE has developed an improved model based on extensive test data but all these models are based on displacement-controlled tests. With the MS-SLA approach, the berm resistances in Figure 9 are based on load-controlled interactions with the berms, and in this case the berm resistances are closer to the lower bound of the range, shown in Figure 10 for a single shear strength profile with no model uncertainty.

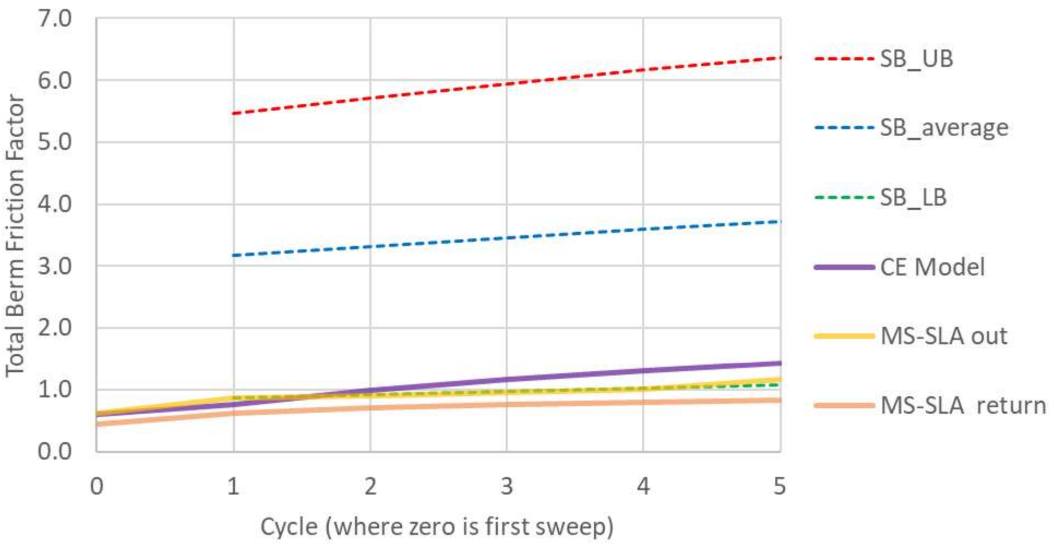


Figure 10 Case B Predicted berm resistance responses (as equivalent friction factors)

It is also worth pointing out from experience, that lateral buckle cyclic berm interaction is usually only critical to the design over the first few cycles, to establish a conservative fatigue assessment. Generating volumes of predicted berm resistances over hundreds of cycles is generally futile; although with the MS-SLA approach it is clear that more cycles (assuming there is no increase in the cyclic temperature amplitude) will result in more constraint from the berms and commensurately lower fatigue damage.

6. Cyclic Lateral Buckling Behaviour – Site 2

6.1. Input Data for Case C

Overall outside diameter (D)	0.324	m
Operating submerged weight (W)	1952	N/m
Axial friction factor (μ_A)	0.75	-
Pipe/soil interface roughness factor	0.5	-
Soil sensitivity	3.0	-
Soil unit weight	3.25	kN/m³
Initial embedment	50%	D
VAS (Virtual Anchor Spacing)	830	m
Soil slices from buckle ± 100 m	5	m
Soil slices beyond 100 m	20	m

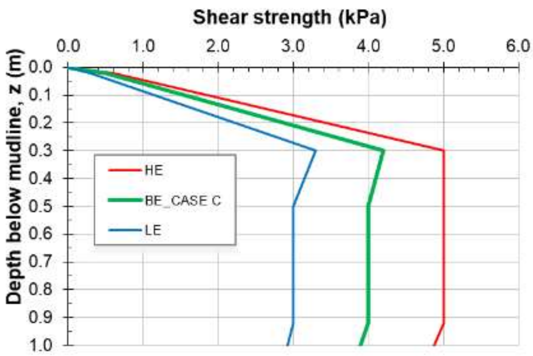


Figure 11 Pipe and soil data for Case C

Case C is based on the BE shear strength profile at this site (Figure 11). The lateral buckle was located at a natural vertical OOS feature and initiated at X = 330 m.

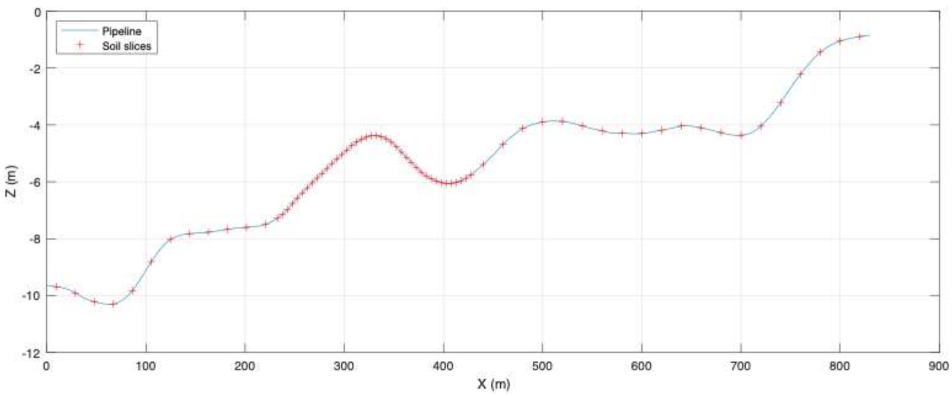


Figure 12 Case C Vertical out-of-straightness profile

6.2. Case C – Berm Response Under Constant-Amplitude Temperature Cycles

The first 10 cycles (all carried out with the same temperature range) clearly show the growth of the berm at the extrados and berm encroachment at the intrados of the lateral buckle (Figure 13).

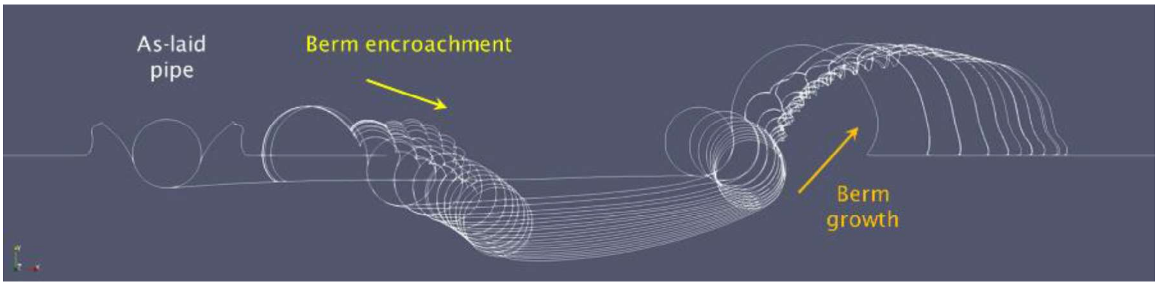


Figure 13 Case C MS-SLA displacements and berms at buckle apex

It is interesting to observe the folds of soil within the berm generated by cyclic loading and the shape of the trench, which is also evident from offshore surveys of the pipeline that this analysis is based on (Figure 14).

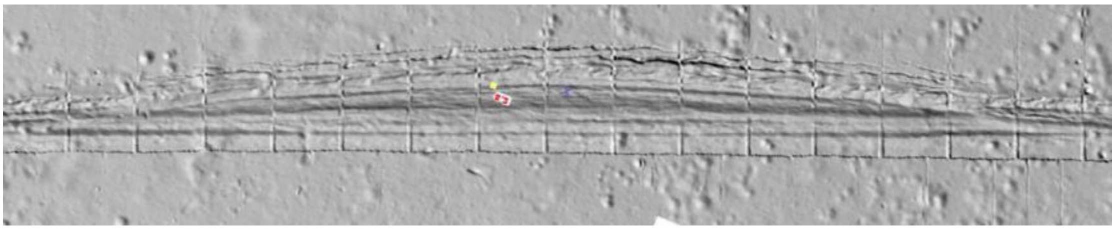


Figure 14 Case C High resolution survey of the lateral buckle after some years in operation

The MS-SLA cyclic load responses are shown on the right of Figure 15, where the dashed lines indicate the pipe weight (W) and half weight (W/2). After ten cycles the berm resistance is still increasing with each cycle, as the cyclic amplitude reduces.

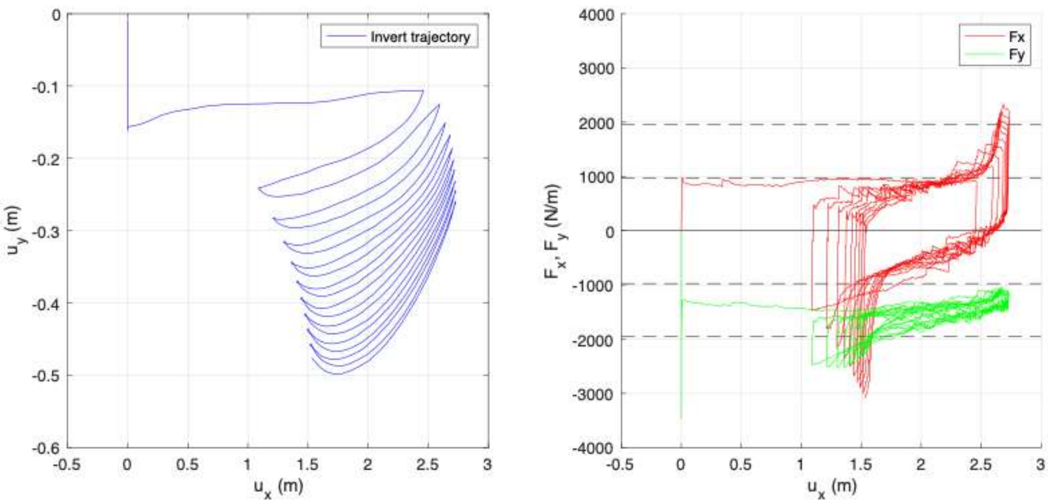


Figure 15 Case C MS-SLA displacement response and load response at buckle apex

Because this is a 'heavy' pipe, the breakout and residual lateral friction factors for this case are, as expected, not well predicted by SAFEBUCK at 0.67 (1307 N/m) and 0.78 (1529 N/m) respectively, compared with 0.51 and 0.48 in the MS-SLA model. However, in this case the 'heavy' pipe response, which typically shows increasing lateral resistance with displacement, is not as expected, because instead of diving the pipe is climbing during each outward sweep and the vertical contact force (in green) is reducing (Figure 15). The reason for this behaviour is the initial vertical OOS, which is encouraging the pipe towards upheaval, with reduced vertical contact force on heating and increased vertical contact force on cooling. While a traditional PSI model with friction factors could be set up to reproduce this behaviour, such a model is unlikely (without prior knowledge from a more sophisticated simulation) to be able to predict the cyclic response accurately for a heavy pipe. Once again, the total berm resistances are poorly predicted by the SAFEBUCK [7] cyclic model, while the CE model is closer but conservative. With the MS-SLA approach, berm resistances in Figure 15 are based on load-controlled interactions with the berms, and in this case the berm resistances are closer to the lower bound of the range, shown in Figure 16 for a single shear strength profile with no model uncertainty.

Integrity assessments of this buckle using friction factor modelling were calibrated to match the maximum curvature in the lateral buckle, but could not match the true observed shape of the lateral buckle or its cyclic behaviour. These could only be predicted reasonably by using the MS-SLA model.

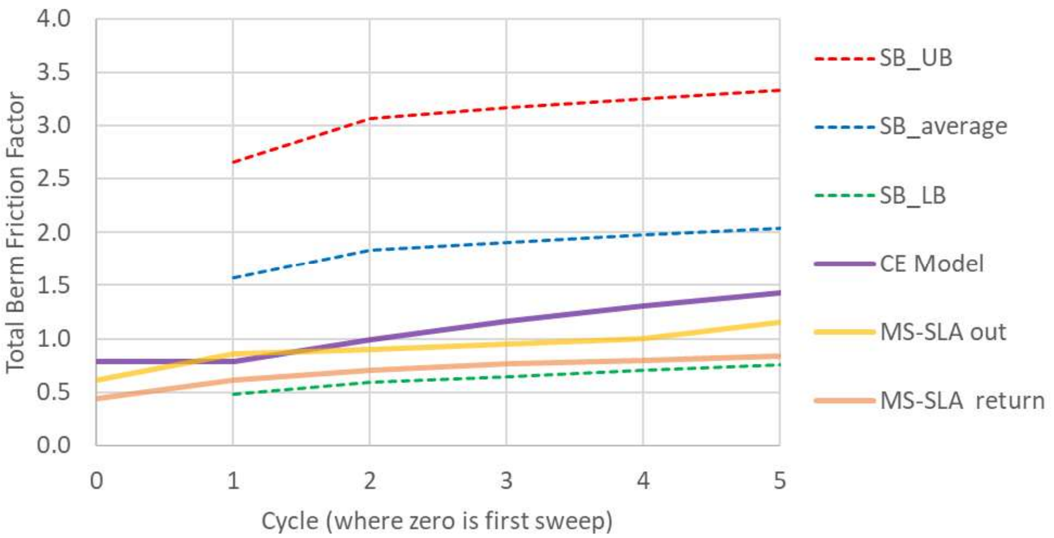


Figure 16 Case C Predicted berm resistance responses (as equivalent friction factors)

7. Conclusions

A better understanding of the cyclic response of lateral buckles and berm encroachment has come from full 3D PSI (pipe–soil interaction) simulations of a lateral buckle using a new MS-SLA (multi-slice, sequential limit analysis) modelling approach. In these analyses, 2D soil slices are distributed along the length of the structural pipeline model, to capture the full 3D load–displacement response.

The MS-SLA model includes the influences of increasing shear strength with depth and remoulding-induced softening of the soil in the active berm. It runs from within Abaqus and achieves remarkable run-time efficiency; made possible by a number of innovative approaches within the slice modelling subroutine, including a moving analysis domain that is focused on the localised region of soil that surrounds the pipe.

The analysis process is efficient enough for commercial use, and the results compare well with field observations of pipelines in operation for many years. This approach is recommended for detailed assessment of individual lateral buckles using VAS (virtual anchor spacing) models, to provide improved fatigue assessments, to simulate variable cyclic temperature ranges over the life of a pipeline, or to address heavy pipeline behaviour without needing to resort to costly mitigation measures such as buoyancy unless absolutely necessary.

8. Acknowledgements

The authors would like to acknowledge important contributions to the background of this paper from their colleagues in Crondall Energy and Major Operators whose operating pipelines have provided many important lessons.

9. Nomenclature

BE	Best Estimate
FEA	Finite Element Analysis
HE	High Estimate
LE	Low Estimate
MS	Multi-Slice
PIP	Pipe-In-Pipe
PSI	Pipe–Soil Interaction
SLA	Sequential Limit Analysis
VAS	Virtual Anchor Spacing

D	Outside diameter of pipe including coatings (m)
F_x	Lateral load in soil slice (N/m)
F_y	Vertical load in soil slice, upwards positive (N/m)
s_u	Undrained shear strength of soil (kPa)
u_x	Lateral displacement in soil slice (m)
u_y	Vertical displacement in soil slice, upwards positive (m)
W	Submerged unit weight of pipe (N/m)
X	Axial coordinate in finite element model
Z	Vertical coordinate in finite element model
μ_A	Axial friction coefficient

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