Investigation into the Dynamic Effects of Lateral Buckling of High Temperature / High Pressure Offshore Pipelines

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ABSTRACT

A subsea pipeline laid onto a flat seabed will buckle laterally from a combination of pressure and temperature due to the pipeline's 'out-of-straightness'. The pipeline will tend to buckle laterally due to horizontal imperfections associated with the pipeline laying process, and the horizontal frictional restraint force is less than the pipeline submerged weight. The lateral buckling may take place as a dynamic 'snap' if the out-of-straightness, or imperfection, in the pipeline length is small. The pipeline 'snap' will result in dynamic motion. Seabed soil friction factors, in both axial and lateral directions, are also parameters which govern the lateral buckling, beside the size of the initial out-of-straightness. All of these parameters will influence the lateral buckling, and under which conditions dynamic buckling behaviour can occur. This paper investigates the influence of these different parameters and their effect on the onset of dynamic buckling.

INTRODUCTION

A pipeline may buckle laterally as seabed friction builds up frictional force to resist the axial expansion as depicted in Figure 1. The axial expansion is due to the internal operating pressure as well as the raised pipe wall temperature in relation to the seabed ambient temperature. The compressive axial force, set up by the seabed friction, is commonly referred to as the 'effective axial force'. The size of the initial out-of-straightness is an important parameter which governs the lateral buckling response. In practice, a pipeline laid on a seabed will have lateral imperfections arising from the laying vessel's motion during pipelay; thus, the pipeline will buckle only in the lateral direction when the effective axial force reaches the critical buckling load. Buckling will also tend to occur, in the lateral direction, as the frictional forces are less than the submerged weight. The critical buckling load represents the maximum compressive axial load that the pipeline can sustain.

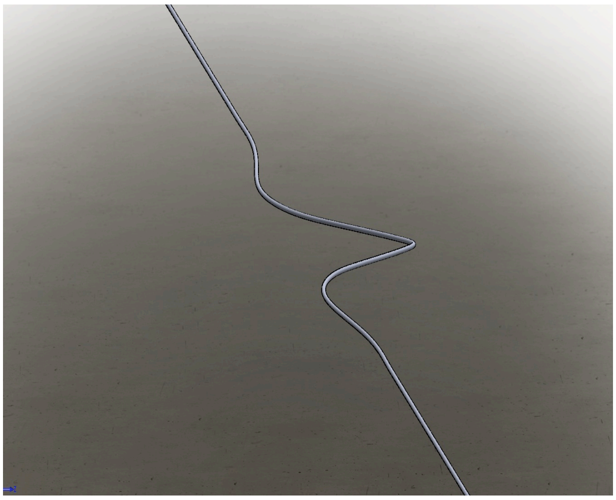

Figure 1. Buckled Pipeline on a Flat Seabed

Pipeline buckling can be seen as a structural instability and classified into one of two categories: bifurcation buckling or limit load buckling. In bifurcation buckling, the deflection under compressive load changes smoothly from one direction to a different direction (e.g. from axial shortening to lateral deflection). In limit load buckling, the structure attains a maximum load without any previous bifurcation. That is, with only a single mode of deflection. Snap-through buckling is an example of limit load buckling.

For small initial imperfections, the buckling may be expected to occur as a dynamic snap Snap-through is characterised by a visible and sudden jump from one equilibrium configuration to another for which displacements are larger than in the first. See Figure 2 for a simplified schematic of a bifurcation and limit load buckling scenario.

A subsea pipeline snap-through can take place as the pipeline pressure and temperature is increased to reach the critical buckling load. The loadings applied to a subsea pipeline are shown in their most simple form in (a) in Figure 2. As stated, this type of loading will undergo bifurcation buckling under simple boundary conditions and no snap-through will occur. Subsea pipelines boundary conditions, however, are generally due to the friction between the surface of the pipeline and seabed which creates a non-linear boundary condition when the lateral force exceeds the static co-efficient of friction. It is this non-linearity of the pipeline soil friction interaction which creates a loading scenario which can cause dynamic snap-through buckling [Pi & Bradford, 2008].

For a large initial imperfection, lateral buckling will go through a gradual deflection. There are two competing approaches which can be used to assess lateral buckling behaviour for a pipeline resting on a flat seabed, namely:

- Non-Linear Static Analysis.
- Non-Linear Dynamic Analysis.

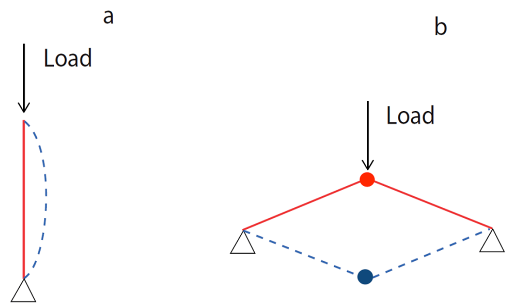

Figure 2. Buckling Schematics: (a) Symmetric Bifurcation (b) Snap-Through Buckling

Static analysis is more widely used by pipeline engineers. There are different non-linear solution methods implemented in commercial multi-purpose finite element software. These solutions can be used to simulate the buckling and post-buckling behaviour. In static analysis, the internal operating pressure and operating temperature are applied to a pipeline with an initial out-of-straightness. The shortcoming with this method lies in: a) large number of iterations which might be required to jump between two successive stable configurations; b) numerical difficulties involved in guiding the solution to pass limit-point instability. Also, static analysis does not take into account any of the dynamics of the response, i.e. the kinetic energy transfer during the response, and thus, does not properly asses the actual response.

Dynamic analysis, by implicit and explicit integrations, is available in commercial multipurpose finite element software. In dynamic analysis, the internal operating pressure and temperature are applied over a time interval with an initial out-of-straightness. The advantage of the dynamic analysis is predestined for pipeline snap-through problems. Furthermore, dynamic analysis may be required to determine axial and lateral velocities during buckle initiation. These velocities are to be used as an input for further soil laboratory tests.

The purpose of this paper is to investigate the limitations and merits of static and dynamic lateral buckling for a pipeline resting on a flat seabed with horizontal lateral out-of-straightness resulting from the pipelay. A series of numerical analyses are undertaken using ABAQUS. The paper considers a 36-inch export pipeline resting on a flat seabed and coated with concrete weight thickness which is required to achieve the on-bottom stability under the influence of hydrodynamic wave and currents. In the finite element analysis, the contribution of the coating on the pipeline's structural behaviour is only related to its contribution in the submerged weight.

BUCKLING BEHAVIOUR

In theory, a perfectly straight pipeline without any horizontal out-of-straightness or lateral imperfection will not buckle. In reality, a pipeline resting on a seabed will have an imperfection. The imperfection could be in the horizontal or the vertical direction. These imperfections could arise from:

- Uneven seabed: The presence of rock outcrops through the pipeline route can cause a vertical out-of-straightness in the pipeline. The pipeline can buckle in the lateral or vertical planes. The direction of the buckle depends on the resistance against movement in each direction as well as the level of out-of-straightness in each plane.
- Fishing: Fishing activities, in the vicinity of the pipeline route, can introduce lateral out-of-straightness as the result of the interference between the pipeline and the on-bottom trawl gears.
- Installation vessel motion during pipe installation: Lateral sway movement of the vessel during pipeline installation can introduce horizontal out-of-straightness in the pipeline.

However, this paper concentrates only on a pipeline laid on a flat seabed with initial out-of-straightness in the lateral direction. This initial out-of-straightness arises from vessel motion during pipeline installation. Therefore, the pipeline will buckle laterally rather than vertically at combinations of pressure, temperature and given initial horizontal out-of-straightness. This is, in part, because the lateral resistance in the horizontal direction is less than the submerged weight of the pipeline.

A pipeline will buckle when the effective axial compressive force reaches a critical load value. Then the pipeline will experience a large deformation into a new equilibrium shape in order to reduce the compressive load. At this stage, the pipeline is considered to have buckled. The load at which buckling occurs is called the critical buckling load or simply critical load. A pipeline's critical buckling is governed by the lateral friction factor, the pipeline unit submerged weight and the initial curvature of the initial lateral out-of-straightness.

[Hobbs, 1984] performed some experimental work in an effort to study the problem of offshore pipeline buckling. His work concluded that the pipeline can buckle into different lateral buckling mode shapes as illustrated in Figure 3.

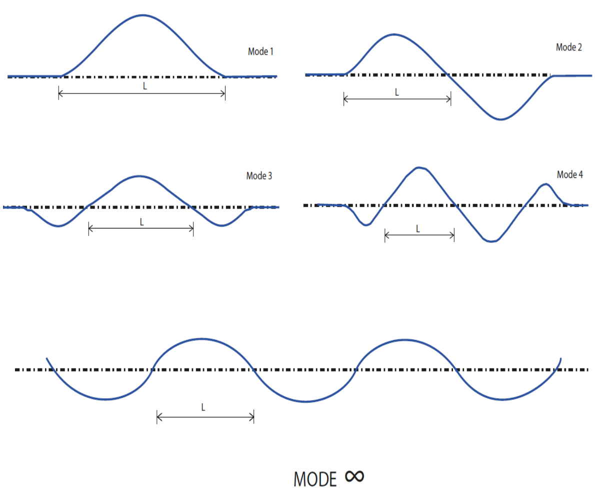

Figure 3. Lateral Buckling Mode Shapes

Figure 4 illustrates a typical mode-3 buckling mode shape. [Hobbs et al] indicated that mode-3 is considered the most critical mode in terms of minimum safe temperature rise. Additionally, several observations from finite element studies indicated that mode-1 initial imperfection shows a tendency to develop into mode-3 buckling mode shape. However, as the loading into the post-buckled section of the pipeline increases, mode-3 buckle will develop into a higher buckling mode. The formation of a mode-3 buckle is the result of a complex interaction between the soil resistance force at the centre of the buckle and the change in the effective axial force. The tendency to move into a mode-3 buckle instead of the lower mode-1 is due to the greater balance in the external horizontal force in the mode-3 shape.

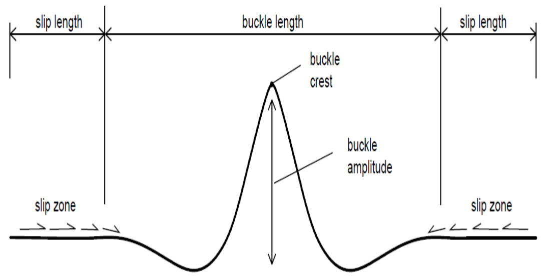

Figure 4. Mode-3 Buckling Regions

As can be seen from Figure 4, the lateral buckle region consists of a primary lobe and two secondary lobes on both sides. The length of the buckle is equal to the total length of the primary lobe and the two secondary lobes. The straight regions next to the secondary lobes are called slip zones. The slip zones continue to expand and feed into the buckle as the temperature increases further after the formation of the buckle. However, the axial feed into the buckle and the extent of the slip zones are governed by the soil resistance in the axial direction. Once the buckle is formed, the compressive force in the buckle drops as the buckle grows under the influence of any temperature increase. This increases the slip length and consequently causes more pipe length to feed into the buckle. More feed into the buckle jeopardises the integrity of the pipeline due to the increase in the bending moment. Figure 5 highlights a typical deformation response obtained from the dynamic analysis undertaken. In this case, the buckle shape is seen to change over time due to the increase in operating temperature.

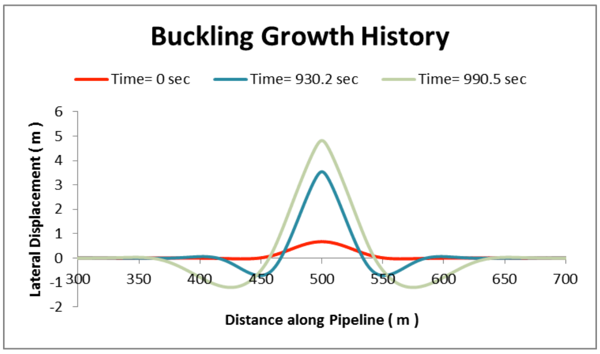

Figure 5. Lateral Deformation Response

THE NEED TO LIMIT DEFORMATIONS IN A LATERAL BUCKLE

Once the buckled section loses its ability to carry any further axial load, it acts as a flexible point that absorbs any further expansion. Large expansion towards the buckled section may have detrimental effect on the pipeline integrity associated with the excessive deformation.

Excessive lateral deformation can lead to at least one of the following three failure modes:

1. Ovalisation: The cross-section of a pipe undergoes ovalisation at the crown of the buckle under the imposed deformation. Excessive ovalisation could prevent the passage of pigging devices required in the monitoring of the pipeline and consequently lead to an operational failure of the pipeline. In addition, the excessive ovalisation could drastically affect the flow capacity of the pipeline thereby influencing the functionality of the pipeline. An example of such a failure model is given in Figure 6, which shows an ovalised pipe under bending.

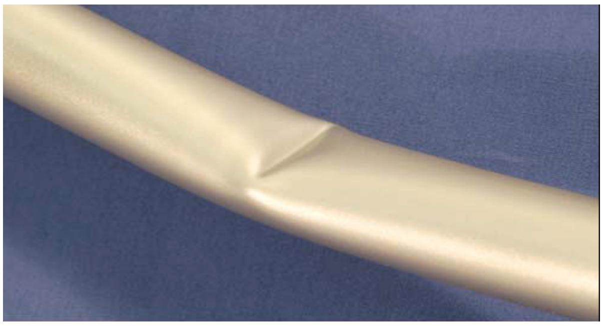

Figure 6. Example for Ovalisation Failure Mode under Bending (Kyriakides et al)

2. Rupture: This failure mode can take place when a pipe's cross-section exhibits an outward bulging. If the pipeline's cross-section becomes too inflated at an outward bulge buckle, high-tensile hoop stresses take place in the pipe wall and consequently the pipeline material can rupture. Figure 7 shows a ruptured pipeline under excessive bending moment.

Figure 7. Example for Rupture Failure Mode under Bending (Palmer)

3. Fatigue/Fracture: Cyclic loading due to shut-in/ shut-down as well as the daily fluctuations in pressure and temperature may result in fatigue of the pipeline girth weld located at the buckle crest. A lateral buckle tends to move back towards its original configuration under repeated shutdown conditions; thereby, causing larger axial stresses than in a non-buckled pipeline. The pipeline designer has to account for the low cycle fatigue of girth welds under the influence of hoop and axial stresses. As the longitudinal cyclic loading induces local hardening followed by fracture near the crack point leading to the development of the crack length as presented in Figure 8.

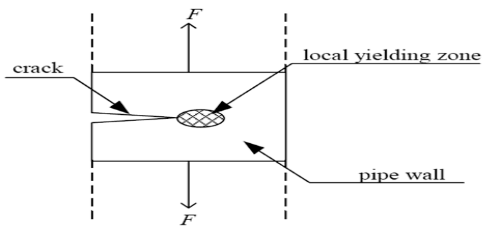

Figure 8. Local Yielding Zone at Crack Point

ANALYSIS

This section details all the modelling aspects as well as the numerical analysis procedure utilising commercial multipurpose finite element software 'ABAQUS'.

NON-LINEAR SOLUTION METHODS

There are different non-linear solutions implemented in ABAQUS that can be used to model the buckling and post-buckling behaviour of offshore pipeline under the influence of operating pressure and temperature.

Newton Method (with artificial damping): The static analysis is undertaken using the Newton Method with artificial damping. This solution is applicable for load and displacement loading, relatively stable, highly dependent on the user selected stabilisation factor. However, the analyst has to keep in mind that the dissipation energy due to artificial damping—the dissipation energy represents the energy taken out of the system—has to be as small as possible to reduce the influence on the results. Despite this, the non-linear and incremental/iterative technique is quite effective with respect to the computational costs.

Implicit Integration: The dynamic analysis is undertaken using the implicit Hiller-Hughes-Taylor operator for integration of the equation of motion. The implicit Hiller-Hughes-Taylor operator has the advantage of being unconditionally stable. However, the accuracy of the solution remains dependent on the time step size. Furthermore, the default time integrator of 0.05 is used which provides slight numerical damping.

MATERIAL MODELLING

Consequences of lateral buckling in pipelines always involve material non-linearity associated with plasticity or yielding. For the ABAQUS non-linear analysis, the material should be defined precisely in terms of the stress versus strain relationship. Figure 9 highlights the true, non-linear, stress-strain curve used in the analyses.

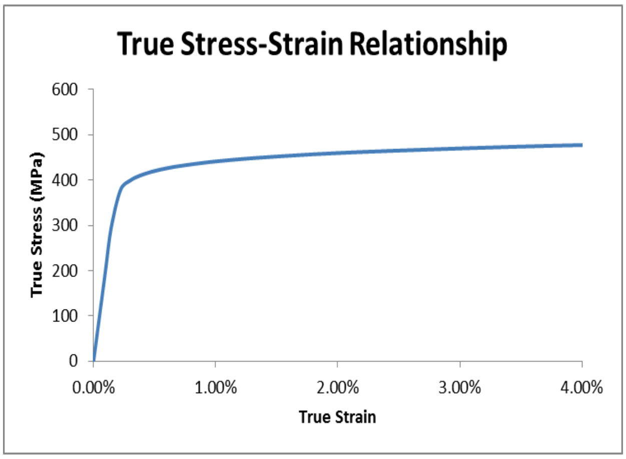

Figure 9. True Stress-Strain Curve

PIPE SOIL INTERACTION

In buckling assessment, the friction resistance between a pipeline and the soil has a significant impact on the lateral buckling behaviour of the pipeline. Lateral frictional resistance affects buckling behaviour by controlling the initial curvature, or out of straightness, at which the buckle initiates.

Also, lateral frictional resistance influences the subsequent post buckling behaviour as it controls the curvature of the buckle as it grows. In fact, it is the non-linearity of the soil friction that allows for dynamic snap through buckling to occur.

Alternatively, even axial frictional resistance controls the level of axial feed-in into the buckle.

A tri-linear response is used in the finite element models for the lateral resistance between the pipeline and the soil as shown in Figure 10. Three lateral friction responses are used in this assessment in order to investigate the influence of the break –out mobilisation distance (the displacement required for the static friction to initially be overcome, see Figure 10) on the snap-through behaviour of the selected pipeline. The values of the three responses used in the assessments are highlighted in Table 1. It should be noted that breakout mobilisation of response-1 is smaller than that of response-2, which means that the soil used in response-1 is much stiffer than the soil in response-2. In other words, more energy is required for the pipeline until the breakout is reached.

Table 2 outlines the bi-linear axial friction properties used, as illustrated in Figure 11.

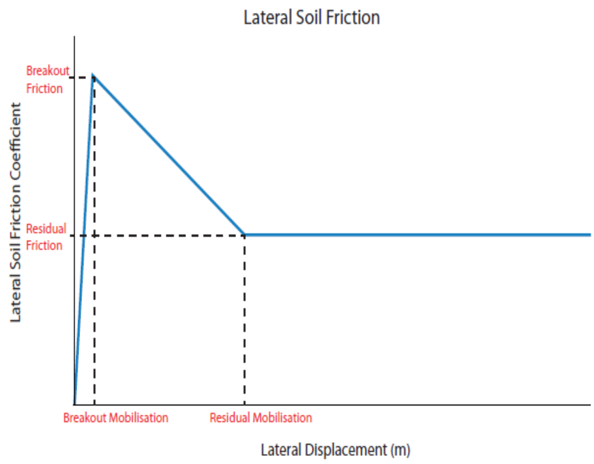

Figure 10. Example for Tri-Linear Response-Lateral Friction Factor

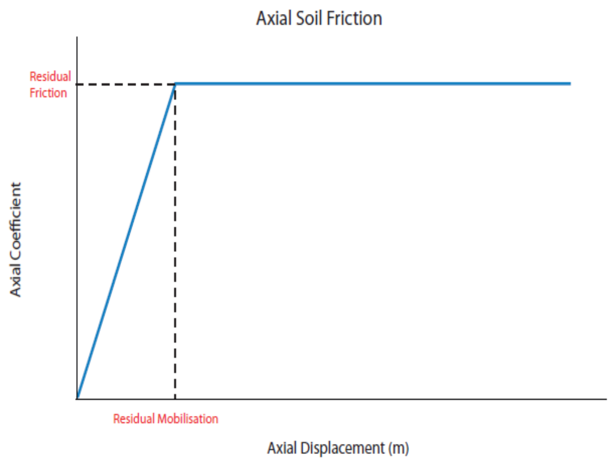

Figure 11. Example for Bi-Linear Response-Lateral Friction Factor

Table 1. Lateral Friction Coefficients

Parameter	Unit	Value
Soil Response-1		
Breakout- Lateral Mobilisation Distance	m	0.107
Breakout- Lateral Friction Co-efficient	--	1.3
Residual - Lateral Mobilisation Distance	m	0.3
Residual- Lateral Friction Co-efficient	--	0.8
Soil Response-2		
Breakout- Lateral Mobilisation Distance	m	0.215
Breakout- Lateral Friction Co-efficient	--	1.3
Residual - Lateral Mobilisation Distance	m	0.3
Residual- Lateral Friction Co-efficient	--	0.8
Soil Response-3		
Breakout- Lateral Mobilisation Distance	m	0.107
Breakout- Lateral Friction Co-efficient	--	0.95
Residual - Lateral Mobilisation Distance	m	0.3
Residual- Lateral Friction Co-efficient	--	0.8

Table 2. Axial Friction Coefficient

Parameter	Unit	Value
Axial Mobilisation Distance	m	0.003
Axial Friction Coefficient	--	0.4

SEABED MODELLING

The seabed is modelled as a flat rigid surface. Contact pairs are used to mimic the interaction between the pipeline and the seabed.

INITIAL HORIZONTAL OUT-OF-STRAIGHTNESS

Figure 12 illustrates the initial horizontal out-of-straightness considered in the finite element simulations:

- A sinusoidal shape with an amplitude of 0.7, 1.6 and 3 m is used with a wavelength of 100 m.

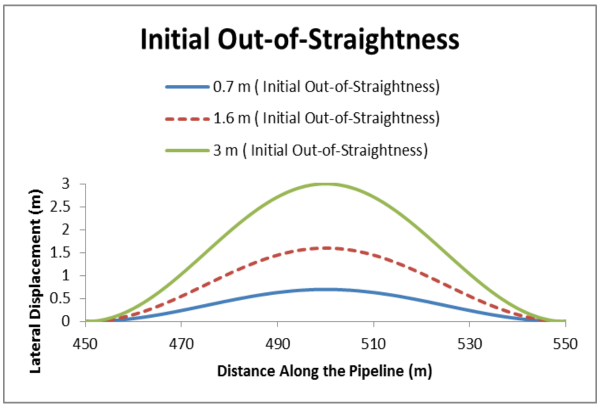

Figure 12. Initial Horizontal Out-of-Straightness

MODEL LENGTH

Figure 13 shows a lateral buckle formed near one pipeline end. The drop in the effective axial force results in the pipe to feed into the buckle. Outside the buckle, the force is greater than the force in the buckle. This produces an isolated buckle, anchored at each end (Carr et al, 2003). The model length used in all the finite element runs is selected as 1000 m. This length represents the section of the pipeline between two virtual anchor points as shown in Figure 13.

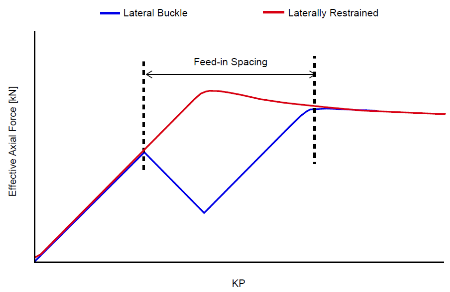

Figure 13. Illustration of Virtual Anchor Spacing

PIPE ELEMENT

Pipe element 31 is used in the finite element analyses. This element is 2 nodal 3-D beam in space. This element accounts for hoop stresses from internal/external pressure, effective force as well as detailed integration of the bi-axial material response around the pipe circumference. The finite element models considered have 32 integration points around the circumference. The element length is selected as 0.5 m in the region of the buckle in order to yield good results in this critical area. Away from the buckle region, a longer element of 2 m is used. This is used to reduce the computation time of the run.

MODEL BOUNDRY CONDITION

The model's boundary conditions are modelled as fixed in both axial and lateral directions.. This follows from the definition that at both end of the VAS the pipeline is axially fully constrained due to the soil friction.

SEQUENCE OF LOADING

The following load steps are employed in the finite element model:

1. Apply external pressure.
2. Lay the pipeline on a flat seabed with horizontal OOS.
3. Fill the pipe with product and apply internal operating pressure.
4. Apply operating temperature.

The residual lay tension, associated with the installation process, is ignored in the calculations.

INPUT DATA

The input data used in this paper is shown in Table 3.

Table 3. Input Data

Parameter	Unit	Value
Pipe Outside Diameter	inch	36
Wall Thickness	mm	25
Steel Density	kg/m^3	7850
Concrete Weight Coating Thickness-Heavy Pipe	mm	80
Concrete Weight Coating Thickness-Light Pipe	mm	40
Concrete density	kg/m^3	3400
Pipe Contents Density	kg/m^3	340
Pipe Unit Submerged Weight-Heavy Pipe	kN/m	6.6
Pipe Unit Submerged Weight-Light Pipe	kN/m	3.5
Operating Temperature	°C	60
Operating Pressure	bar	180
Seabed Ambient Temperature	°C	10
Water Depth	m	50

RESULTS

Eight different results runs were undertaken with the finite element model, to compare the effect of four different parameters on the dynamic snap through buckling of the pipeline. The eight results cases are given in Table 4 and Table 5, with the four parameters of pipe weight, breakout lateral mobilisation distance, lateral out of straightness and breakout lateral friction factor being compared respectively.

RESULTS SET 1: PIPELINE WEIGHT

The first set of results compare results run of ID1 and ID2, see Table 4 and Table 5. These results are compared to see the effect of the pipe weight on the dynamic buckling. Results case ID1 and ID2 also use the following initial lateral out of straightness and friction configurations:

- A sinusoidal shape with an amplitude of 0.7 m and a wavelength of 100 m.
- Tri- linear lateral friction response-1.
- Bi-linear axial friction response.

Figure 14 and Figure 15 show the effective axial force at the buckle crest as the temperature of the pipeline is increased and buckling occurs. As the temperature increases, the pipeline gains energy; and, once the potential energy reaches a minimum value, the pipeline will snap through, shown by the sudden decrease in effective axial force. This buckle and snap-through behaviour occurs when the axial forces reach the critical buckling force. From viewing these figures the following conclusions can be made:

- For the same pipe, the static analysis yields approximately the same critical buckling forces as the dynamic analysis.
- For all cases, the dynamic overshoot for heavy pipelines is clearly more than that in lighter pipes.
- Lighter weight causes the pipeline to buckle at lower temperatures.
- After the dynamic jump-out, the pipeline exhibits snap-back behaviour. The pipeline then oscillates around two stable equilibria as shown in Figure 15. Damping causes the oscillation to die out.

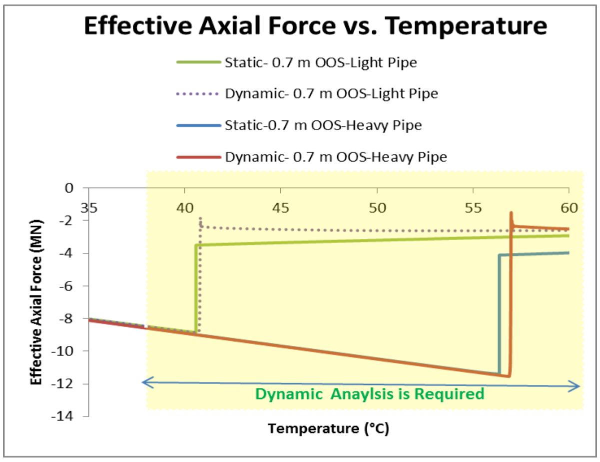

Figure 14. Effective Axial Force versus Temperature

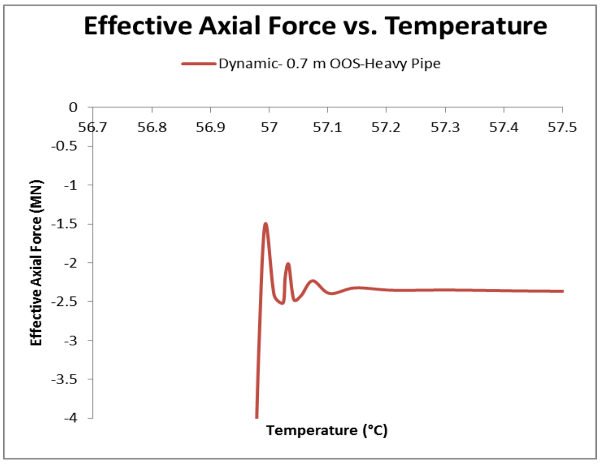

Figure 15. Effective Axial Force versus Temperature for Dynamic Case using 0.7 m OOS for Heavy Pipe during Snap-Through

Figure 16 shows the lateral displacement at the buckle crest as a function of temperature. If the temperature is increased beyond that shown in the figure, the static and dynamic response can be shown to converge. This results in a difference due to the dynamic buckling effects only resulting in differing values around the on-set of buckle region. This result means that the static analysis methods would be sufficient to model the response of the pipeline, unless the buckling occurs close to the maximum design / operating temperature or the pipeline was operated around the buckle zone. From Figure 16 the following conclusions can be made:

- For the same pipeline, lateral displacement can be seen to begin at approximately the same temperature for both static and dynamic analyses.
- The heavy pipeline buckles at higher temperature compared to the lighter one.
- The extent of dynamic overshoot in the lighter pipe is less than that in the heavy pipe.
- For the same pipeline, the dynamic analysis predicts larger lateral displacement. The difference is due to the high inertia effects induced in the dynamic analysis associated with the sudden jump resulting from the snap-through.

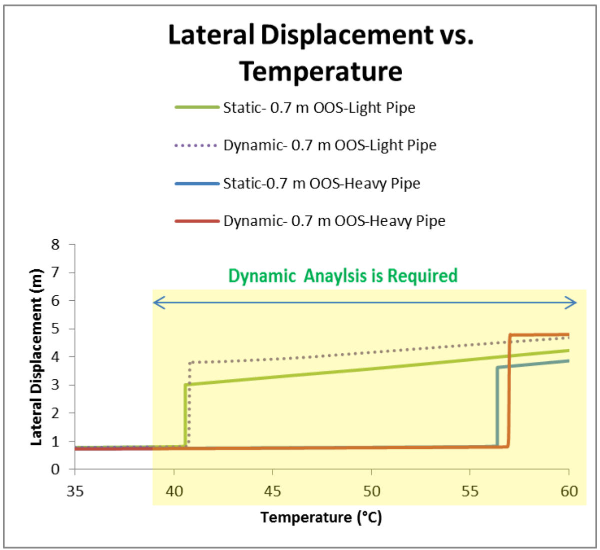

Figure 16. Lateral Displacement versus Temperature

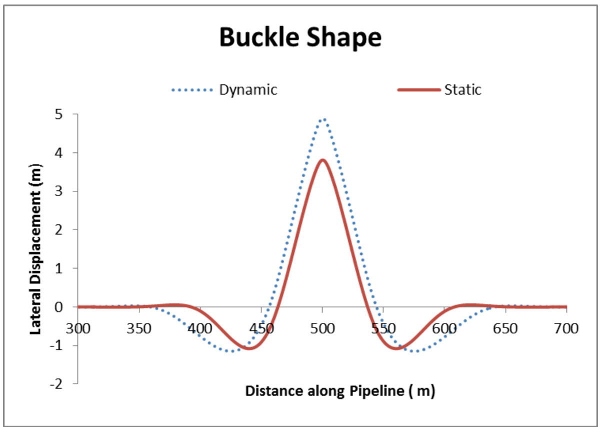

Figure 17. Buckle Shape for Static & Dynamic Cases @ Maximum Operating Temperature- Heavy Pipe

Figure 17 shows the final lateral displacement shape of the heavy pipeline for static and dynamic analysis methods. This figure highlights well the difference in the buckle shape which can occur if the dynamic effects are not considered.

Finally, Figure 18 displays the curvature of the pipeline at the buckle crest vs. temperature. The curvature is directly proportional to the stress/strain in the pipeline and thus is critical in the evaluation of a suitable pipeline design. The general shape and trend of curvature response is similar to that of the effective axial force shown in Figure 14. It can be noted that the dynamic overshoot acts similarly to a highly damped single degree of freedom spring-mass-damper system subjected to a step load. Based on the results presented in Figure 18, the following conclusions can be made:

- For the same pipeline, the curvature predicted by the dynamic analysis is higher than that calculated using static analysis.
- The curvature determined for the pipeline with a lighter coating is significantly smaller than that for the pipeline with a heavy coating.
- For the heavy pipe, the dynamic load factor is approximately 31 %.
- For the light pipe, the dynamic load factor is approximately 33%.

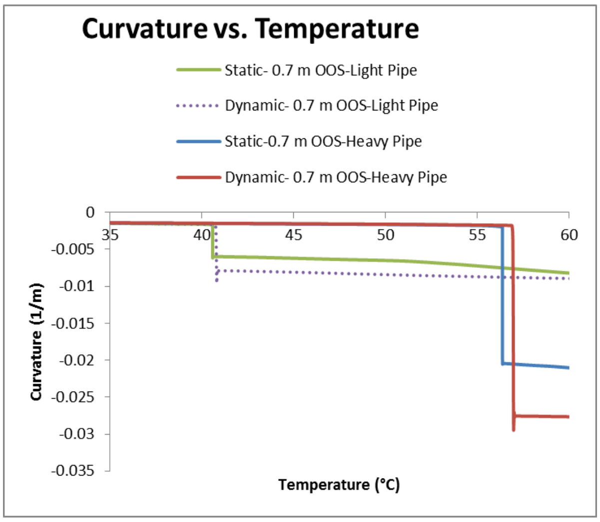

Figure 18. Curvature versus Temperature

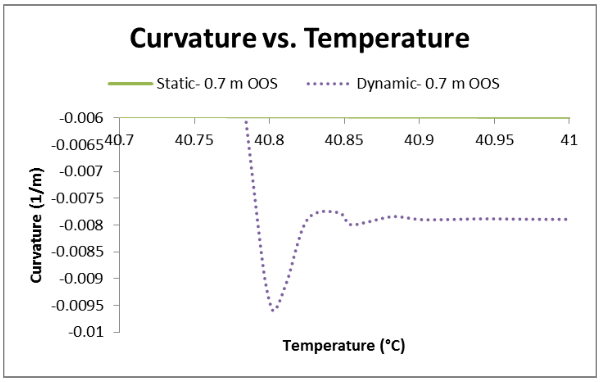

Figure 19. Curvature versus Temperature for Dynamic Case using 0.7 m OOS for Heavy Pipe during Snap-Through

Looking closely at Figure 19, it is noticed that the spring back effect relaxes the curvature at the buckle crest.

Figure 20 illustrates the lateral and axial velocities for the light and heavy pipeline configurations. The magnitude of the lateral velocity is directly related to whether there is any significant difference between static or dynamic analysis. Obviously, if the lateral velocity is very small, the kinetic energy will also be negligible and the response will be quasi-static and the difference between both static and dynamic analysis methods should be negligible.

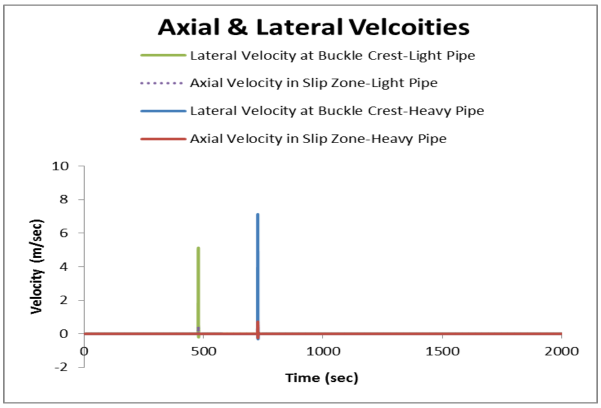

Figure 20. Lateral and Axial Velocities for Cases Considered in Set 2.

The lateral velocities are measured at the buckle crest, and the axial velocities are measured at point located in the slip zone.

The results presented in Table 4 and Table 5 and Figure 20 shows that the lateral velocity of the pipeline with heavy coating is higher than that in the light coating. This is as expected as the snap-through, for the heavy pipe, occurred at a higher temperature than the light pipe. In case of the heavy pipe, the amount of energy stored was higher than the energy stored in the light pipe.

It can be concluded that lateral velocity depends on temperature in which the pipeline will snap. This in turn, depends on the initial curvature of the horizontal out-of-straightness as well as the weight of the pipe. As expected the results case where a higher lateral velocity is experienced, there is a greater difference between the static and dynamic results.

For the axial velocity: The maximum axial velocities seen are 0.72 m/sec and 0.44 m/sec respectively. These velocities could be considered as relatively high axial sliding velocities that can arise during the initial buckle formation process, which is the critical event when peak bending strains are established. Rapid axial movement may lead to undrained conditions in the soil. Undrained conditions then, in turn, can produce a lower axial friction.

RESULTS SET 2: LATERAL BREAKOUT MOBALISATION DISTANCE

The following results compare two different friction model mobilisation distances, results case ID3 and ID4, to investigate their effect on the dynamic buckle response. The results presented use the following out of straightness and friction models.

- A sinusoidal shape with an amplitude of 0.7 m and a wavelength of 100 m.

In both configurations, the following soil combinations are used:

- Tri- linear lateral friction response-1 / Bi-linear axial friction response.
- Tri- linear lateral friction response-2 / Bi-linear axial friction response.

For brevity, the plots of the results will only be shown for the curvature and pipeline velocity. The maximum values for effective axial force and lateral displacement can be found in Table 4 and Table 5.

Figure 21 presents the effective curvature at the buckle crest versus temperature. It can be seen again from Figure 21 that the pipeline buckled at a higher temperature in the case of using a small lateral breakout mobilisation distance, compared to the large mobilisation distance. In this case, the pipeline needs more energy to overcome the soil resistance.This is because the soil with a small mobilisation distance is stiffer than the soil with high mobilisation (Please refere to the pipe soil interaction section).

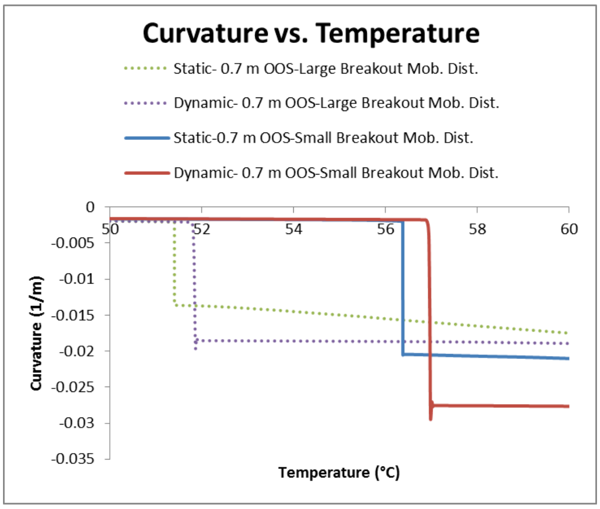

Figure 21. Curvature versus Temperature

Figure 22 illustrates the lateral and axial velocities for the two pipeline configurations considered in the results case ID3 and ID4. The smaller breakout mobilisation distance results in larger pipeline dynamic buckling velocities, as shown in Figure 22, and thus it also results in larger differences between the dynamic and static curvature shown in Figure 21.

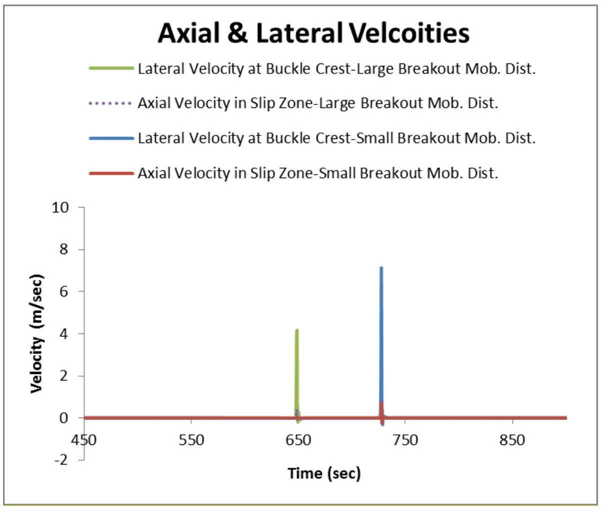

Figure 22. Axial and Lateral Velocities for Cases Considered in Set 2.

RESULTS SET 3: HORIZONTAL OUT OF STRAIGHTNESS

Results in this section are shown for three different OOS models, being results cases ID2, ID5 and ID6. A sinusoidal shape with amplitudes of 0.7, 1.6 and 3 m over a wavelength of 100m was used for the three respective OOS models.

In all configurations, the following soil combinations are used:

- Tri- linear lateral friction response-1 /Bi-linear axial friction response.

Figure 23 illustrates the effective axial force at the buckle crest versus temperature.

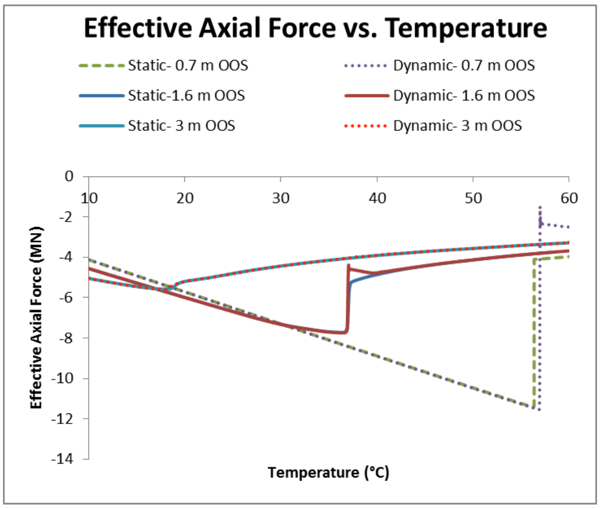

Figure 23. Effective Axial Force versus Temperature

It can be seen from Figure 23 that:

- The severity of the snap-through is reduced with the increase of the initial out-of-straightness
- The severity of the snap-through increases with the temperature at which the pipeline buckles at.
- For 3m initial out-of-straightness, the pipeline does not snap but rather it deflects smoothly.

It can be seen from Table 4 and Table 5 that the static and dynamic anaylses yields the same results for large initial displacement. In other words when the pipeline deflects smoothly. Also, it is clear the severity with the snap reduces with increasing the initial out-of-straightness.

Figure 24 illustarted the axial and lateral velcoities for the cases considered in results Set-3.

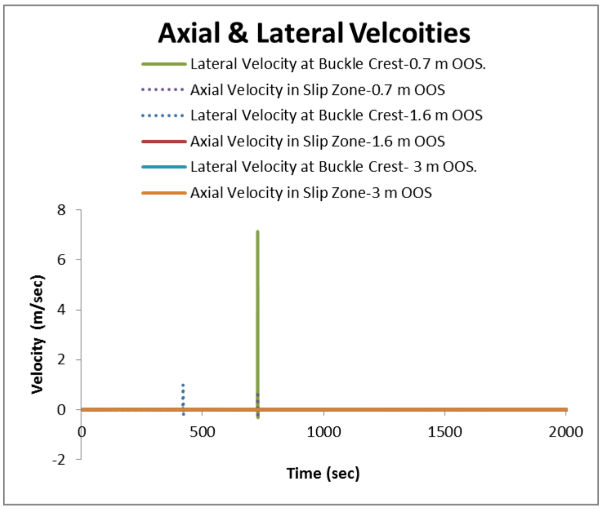

Figure 24. Axial and Lateral Velocities for Cases Considered in Set 3.

RESULTS SET 4: BREAKOUT LATERAL FRICTION RESPONSE

Results are shown for two different friction response models being results cases ID7 and ID8. The following out of straightness and a trilinear lateral friction model is used:

- A sinusoidal shape with an amplitude of 1.6 m and a wavelength of 100 m.

Figure 25 shows the effective axial force of the two friction models vs. temperature. From this figure and the results presented in Table 4 and Table 5 it indicates that reducing the breakout friction factor reduces the dynamic effects of the pipeline buckling.

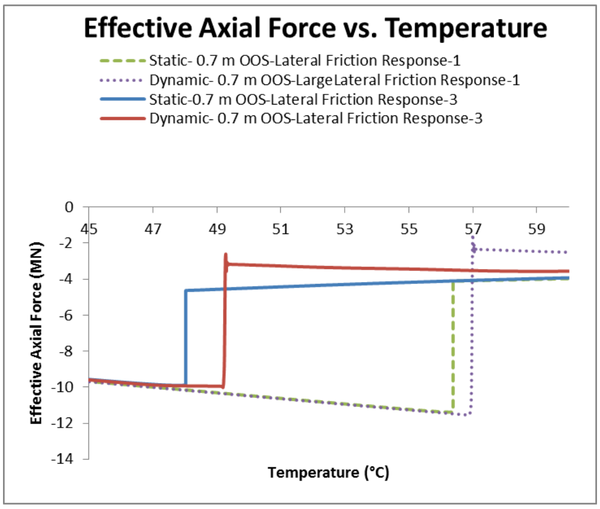

Figure 25. Effective Axial Force versus Temperature

CONCLUSIONS

The work in this paper presented the finite element modelling results of a comparison between the static and the dynamic anaylsis for a 36-inch laterally buckled pipeline. The results indicted the following:

If the static analysis shows that the buckling occurs close to the maximum design/operating temperature, then there might be considerable dynamic effects associated with the snap-through behaviour. This snap-through behaviour cannot be captured by the static analysis. Snap-through buckling is followed by oscillation around an equilibrium position. This vibration behaviour is similar to the response of a highly damped single degree of freedom system under a step load. The difference between the dynamic analysis and the static results is highly related to the lateral velocity of the pipeline and thus the kinetic energy of the system during buckling. It is this kinetic energy which is unable to be modelled with a static analysis and dynamic analysis must be performed to evaluate the impact of the sudden dynamic jump on the integrity of the buckle.

If the static analysis shows that buckling occurs at a low temperature in relation to the maximum design/operating temperature, then the snap-through behaviour will not be the maximum stress/strain experienced by the pipeline and a static analysis will yield appropriate results.

Based on the results in this paper, the snap-through behaviour of dynamic buckling in a subsea pipeline environment is dependent on various factors. The effects of pipe weight, break out friction distance, out of straightness and maximum friction factor were analysed and shown to have the following relationships to dynamic buckling.

- Pipe Weight

  The heavier pipe weight had greater dynamic motion, thought to be due to the increased kinetic energy from the weight which would be in the system during motion.

- Breakout Lateral Mobilisation Distance

  Smaller breakout distance had greater dynamic motion, with the smaller breakout distance acting in a similar manner to the effect of a smaller out-of-straightness (OOS) before dynamic buckling.

- Lateral Out-of-Straightness

  Smaller OOS had greater dynamic motion, the smaller OOS creates a system which has a more severe limit state (larger difference between equilibrium positions)

- Breakout Lateral Friction Factor

  Larger maximum friction factor had a greater dynamic motion. With a larger maximum friction factor more potential energy can be stored in the system before snap through occurs when the force increases above what the friction forces can hold and thus is transfer to a greater kinetic energy and more dynamic motion.

The work undertaken in this paper does not consider the effect of the hydrodynamic coefficients, such as drag, added mass and inertia, on the buckling response. However, the effect of the hydrodynamic coefficients will be covered in further publications.

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Table 4. Curvature/ Lateral Displacement Results during the on-set of Buckling

Run Case ID	Run Case	Comparison Effect	Curvature (1/m)			Lateral Displacement (m)		
			Static	Dynamic	DLF (%)	Static	Dynamic	DLF (%)
ID 1	0.7m OSS Light Pipe	Pipe Weight	0.006	0.009	33	2.92	3.83	23.8
ID 2	0.7m OSS Heavy Pipe		0.02	0.029	31	3.43	4.54	24.4
ID 3	0.7 OSS Large Mobilisation Distance	Breakout Lateral Mobilisation distance	0.013	0.019	32	3.34	4.22	20.8
ID 4	0.7 OSS Small Mobilisation Distance		0.020	0.029	31	3.43	4.54	24.4
ID 5	1.6m OSS Heavy Pipe	OSS	0.007	0.008	12.5	3.07	3.48	11.8
ID 6	3m OSS Heavy Pipe		0.006	0.006	0	3.07	3.07	0
ID 7	0.7m OSS Friction Response 1	Breakout Lateral Friction	0.020	0.029	31	3.43	4.54	24.4
ID 8	0.7m OSS Friction Response 3		0.014	0.016	14.3	2.96	3.87	23.5

Table 5. Critical Buckling Force/ Lateral and Axial Lateral; Velocities Results during the on-set of Buckling.

Run Case ID	Run Case	Comparison Effect	Critical Buckling Force (MN)			Lateral Velocity (m/s)	Axial Velocity (m/s)
			Static	Dynamic	DLF (%)	Dynamic	Dynamic
ID 1	0.7m OSS Light Pipe	Pipe Weight	-8.83	-8.85	0.23	5.99	0.43
ID 2	0.7m OSS Heavy Pipe		-11.38	-11.55	1.47	7.06	0.72
ID 3	0.7 OSS Large Mobilisation Distance	Breakout Lateral Mobilisation distance	-10.23	-10.29	0.58	4.16	0.41
ID 4	0.7 OSS Small Mobilisation Distance		-11.38	-11.55	1.47	7.06	0.72
ID 5	1.6m OSS Heavy Pipe	OSS	-7.72	-7.74	0.26	0.99	0.05
ID 6	3m OSS Heavy Pipe		-5.59	-5.59	0	0.02	0.001
ID 7	0.7m OSS Friction Response 1	Breakout Lateral Friction	-11.38	-11.55	1.47	7.06	0.72
ID 8	0.7m OSS Friction Response 3		-9.90	-10.01	1.1	3.82	0.37