OMAE2015- 42119

AN INTEGRATED NUMERICAL APPROACH TO DESIGN OFFSHORE PIPELINES SUSCEPTIBLE TO LATERAL BUCKLING

F. Van den Abeele
Fugro GeoConsulting
Brussels, Belgium

F. Boël
Fugro GeoConsulting
Brussels, Belgium

D. Hayes
Atteris Pty Ltd
Perth, Australia

D. Scales
Atteris Pty Ltd
Perth, Australia

ABSTRACT

Lateral buckling is a global response to excessive compressive axial force due to thermal and internal pressure loads which when combined, exceeds the initiating Euler Buckling force and overcomes the lateral friction force reacting against a pipeline laid on the seabed.

According to DNV-RP-F110, the integrity of a pipeline susceptible to buckling can be assured by either restraining the pipeline, thus sustaining large axial compressive forces, or releasing them through a combination of pipeline displacements; lateral buckles. Buckling may be rogue in nature or engineered at predetermined locations, either of which must demonstrate compliance to DNV OS F101. Engineered lateral buckles are a cost effective way to manage for example HP/HT pipelines as opposed to the construction of restraint designs. However, uncertainty in the initial buckle formation process and buckle behaviour may reduce design reliability; resulting in an increased level of redundancy in a buckle management system.

This paper presents the vision of an engineering tool aimed at providing an integrated single model environment which enables straightforward engineering analysis, with application to all phases of design, and providing support to operations. Verification of buckling forces and post-buckling configurations is undertaken through comparison with Hobbs and Kerr analytical models and validated against ABAQUS.

INTRODUCTION

As most 'easy' oil and gas reservoirs have been developed, generally in shallow waters, offshore oil and gas installations move into more remote locations, e.g. deeper waters and challenging geology.

Hence, there is an increased demand to access high pressure (HP) and high temperature (HT) formations. As a consequence, the loading. As a consequence the loading exerted on pipelines and flowlines is increased.

In this paper, an engineering tool is presented based on a *one model* methodology ensuring that development from an early concept design through Front End Engineering Design (FEED), detailed design and into the operations phase is undertaken in a congruent and concise manner. Additionally, utilisation of one model throughout the design lifecycle will ensure that model development time is minimised and engineering is streamlined ensuring that Operators receive an assured design within an economical timeframe. Furthermore, by utilizing a single engineering tool throughout the design and operation stages, any assumptions that have been made within the design stage (aimed at minimizing CAPEX) are transferred to the operations team and can be incorporated within their ongoing strategies to minimize OPEX.

Assurance of the engineering tool is provided through verification against both analytical models and ABAQUS numerical models. Limitations within the numerical engine behind the finite element analysis (FEA) are identified. As these limitations can impact some specific lateral buckling scenarios, they will be addressed within future releases of the engineering tool.

LATERAL BUCKLING FOR OFFSHORE PIPELINES

HP/HT pipelines under operation are exposed to increased compressive axial force due to the thermal and internal pressure loads, when these loads are combined and they exceed the initiating Euler Buckling force and overcome the lateral frictional restraint from the seabed then a lateral buckle will form [1-2].

Lateral Buckling is a global pipeline response resulting in large lateral displacements and corresponding stresses and strains within the pipeline and as such to ensure integrity of the overall pipeline system needs to be considered within the design phase and managed if necessary.

The earlier that lateral buckling can be identified as a risk and a Buckle Management System (BMS) defined then the lower to the overall cost of ownership will be for the Operator. Thus, the design procedure should ensure that rapid analysis of a multitude of options is undertaken to determine the critical parameters within the lateral buckling process and any resulting Buckle Management System.

Furthermore, if a Buckle Management System is required, then it dictates early investigation and definition to allow non-critical path procurement and contracting of the necessary equipment and installation method. The *one model* approach will also allow efficient post start-up verification of the BMS and allow operations to have confidence in the delivered solution.

BUCKLING MANAGEMENT SYSTEMS

If the pipeline to be installed is susceptible to lateral buckling and it is determined that rogue buckling is unacceptable then a BMS is required to ensure compliance of the pipeline system with the relevant standards (for instance DNV-OS-F101 [3] or DNV-RP-F110 [4]). BMSs take two main forms [4]:

1. Restraining
2. Initiating

Restraining the pipeline will ensure that no lateral buckles can form and that the axial compressive forces are maintained within the pipeline. The design of restraining BMSs entails ensuring that both lateral and upheaval buckling will be prevented within all design conditions.

Initiating BMSs work by ensuring lateral buckles are formed at prescribed locations along the pipeline such that the stresses and strains induced within the lateral buckles comply with code requirements. Therefore, the design procedure needs to ensure that the installed buckle initiators are spaced such that buckles form within acceptable limits due to the high probability of a sufficient number of buckles forming at prescribed buckle sites.

Current design methodologies will be briefly presented and discussed in the next section of this paper.

Rock Dumping

Rock dumping of a pipeline is a technique used for restraining the pipeline either along its entirety or within smaller sections in which lateral buckling is deemed unacceptable.

Restraining of the pipeline requires the construction of a suitable rock berm which is designed to resist both pipeline upheaval and lateral buckling. In addition, the rock is also required to be self-stable during hydrodynamic events to prevent degradation of the berm, thus reducing its capacity to mitigate buckling. This aspect of the design will influence the rock particle size, which in turn is influence by the availability of rock material, and constraints dictated by the installation vessel specification and installation technique.

Rock dumping along pipelines is a common construction activity, although relatively expensive due to the requirement of specific marine vessels. However, rock dumping is predominately used for pipeline protection and/or stabilization. Therefore, when used in combination with other functional requirements such as these, this method for restraining the pipeline will become more cost effective.

Snake Lay

Snake lay is the process of installing a pipeline on the seabed with a predefined horizontal out of straightness (OOS) as presented in Figure 1.
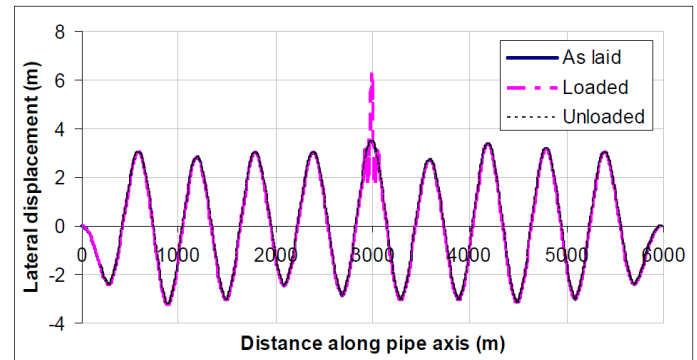

Figure 1: Shallow amplitude snake lay [5]

The induced horizontal OOS reduces the pipelines capacity to resist lateral buckling as presented by Matheson et. al. [6], and the reduced critical buckling force P_{cr} for a pipeline with submerged weight W in a bend radius R under lateral soil friction μ_{LS} is given by

$$P_{cr} = \mu_{LS} \, W \, R \qquad (1)$$

Copyright © 2015 by ASME

Snake lay relies on a defined level of lateral OOS to be imposed on the pipeline as it is laid. It is therefore important that pipeline installation lay tolerances are tightened at points of defined OOS to ensure these are constructed. Should lay tolerances not be tightened in the pipeline specification, there is a risk that the OOS is not installed.

Furthermore, it should be noted that snake lay provides a global definition for the lateral out-of-straightness. However, due to pipeline installation tolerances at the location of buckle initiators, localized OOS may be more severe than nominal OOS considered during design (either lateral, vertical or combined). Therefore, sensitivity of OOS should be considered during the design phase to allow for increased curvature.
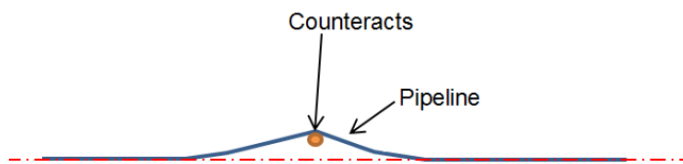
Seabed Sleepers

Sleepers are pipe joints that are installed perpendicular to the pipeline and typically have a low friction surface applied to them to reduce lateral friction forces.

A combination of the vertical OOS and low lateral resistance; both from the low friction surface of the pipeline-sleeper interface but also from the spanning section of the pipeline, result in a reduced critical buckling force.
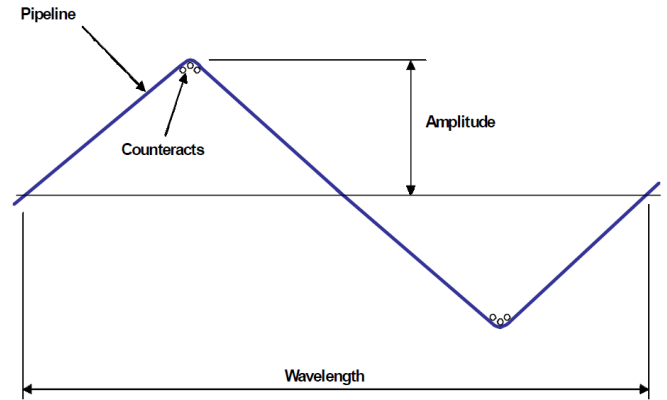
Due to the vertical OOS it is important that span effects either side of the sleeper are accounted for within the design of the individual buckle initiators.

Zero Radius Bend

Zero Radius Bends (ZRBs) are a variant of the sleeper option by the addition of a lateral counteract for the pipeline to be installed around thus allowing a smaller bend radius to be achieved than that from soil restraint alone, i.e. snake lay. Furthermore, by utilizing the sleeper and counteract, an OOS is induced in both horizontal and vertical directions resulting in a low critical buckling force.

Figure 3: Zero Radius Bend [5]

The requirement to install the pipeline over the sleeper location whilst also ensuring that it is installed around the counteract, dictates the need of careful installation of the pipeline within the vicinity of the ZRB. As a result, the lay rate at ZRBs is typically reduced.

Sleepers with imposed lateral displacement

A more recent modification to the sleeper design is the use of a sleeper with a lateral displacement ram installed. The pipeline is installed over the sleeper with no requirement to install any lateral OOS using pipelay vessel positioning. Once the pipeline is installed, tooling is deployed to actively slide the pipeline laterally to a predetermined level of OOS. The pipeline is then restrained on the inside of the deflection and the tooling is retrieved. This procedure would then be performed at all buckle initiation sleepers prior to start-up.

Figure 4: Sleeper with Imposed Lateral Displacement

Figure 2: Use of counteracts

CURRENT METHODOLOGIES

Analytical Approach

The main body of analytical work associated with lateral buckling was produced by Kerr [7] and extended later by Hobbs [1-2]. Kerr's work was based on lateral buckling of railway tracks induced by thermal loads and Hobbs extended the methodology to pipelines including pipelines with restraints

The premise of Hobbs' method is the use of a pipelines effective axial force (EAF) and the corresponding critical buckling force of the pipeline. If the EAF exceeds the critical buckling force then a lateral buckle will theoretically occur. For a fully restrained, closed-ended pipeline, the effective axial force F_e is the sum of the forces due to axial elongation, internal and external pressure (including end effects) and the temperature gradient ΔT [8]

$$F_e = T_{res} + (1-2\nu)(p_e A_e - p_i A_i) - EA\,\alpha\Delta T \qquad (2)$$

with T_{res} the residual lay tension and α the coefficient of thermal expansion for steel. If the ends of the pipeline are free to move then the EAF at the end points is based on the axial frictional resistance μ_{ax} to movement until the EAF reaches the fully constrained EAF at the virtual anchor point. The axial frictional resistance from each end is given by

$$S_{fr} = \mu_{ax} W x \qquad (3)$$

where x the is the axial distance from the free end. Figure 5 shows the EAF for a pipeline that reaches full constraint between $0.4 \le x/L \le 0.6$.
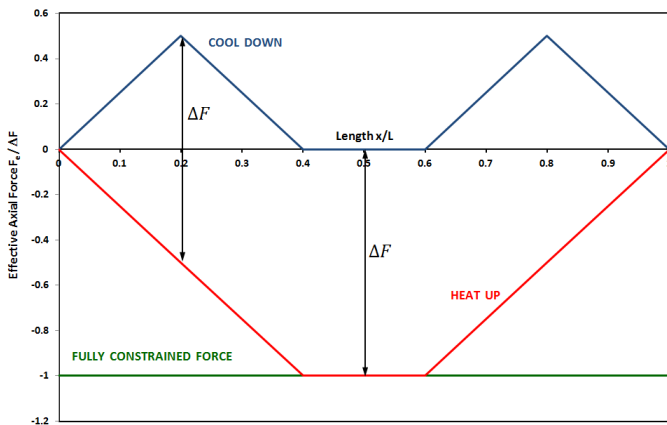

Figure 5: Effective axial force for fully constrained pipe [9]

Hobbs defined the critical buckling force based on the buckle length given by

$$P_0 = P + k_3\,\mu_{lat}\,WL\left[\sqrt{1 + k_2\,\frac{AE\mu_{lat}WL^5}{(EI)^2}} - 1\right] \qquad (4)$$

where

$$P = k_1\,\frac{EI}{L^2} \qquad (5)$$

is the reduced axial force within the buckle and μ_{lat} is the lateral friction factor. In addition, Hobbs [1-2] defines an analytical solution for the post-buckle amplitude

$$\hat{y} = k_4\,\frac{\mu_{lat}W}{EI}\,L^4 \qquad (6)$$

In equations (4)-(6), $k_i(i = 1..4)$ are the constant for lateral buckling modes derived in [2].

More recently the HOTPIPE JIP and SAFEBUCK JIP have established a number of analytical solutions for lateral buckling and axial walking, which will be discussed further in the next sections.

HOTPIPE and DNV-RP-F110

The HOTPIPE JIP was established by Statoil to develop a guideline for the design of HP/HT pipelines and to increase the overall knowledge surrounding the global buckling phenomenon that had been observed at this time.

The HOTPIPE JIP was concerned with the generation of simplified analysis procedures to allow the rapid analysis of the post-buckling response of a pipeline for both single buckle models and global (multiple) buckle models. Structural reliability methods were utilised to assist in calibration of the partial safety factors. Typically a Load Controlled (LC) approach has been followed due to the primary focus of the JIP being large diameter trunklines. Although the LC approach is not strictly valid for lateral buckling, for large diameter pipelines it is generally considered a more appropriate methodology due to the large wavelength buckles which typically form.

The outcomes of the HOTPIPE JIP were incorporated into the Det Norske Veritas (DNV) Recommended Practice for global buckling in 2007 [4]. Currently DNV are updating the Recommended Practice to incorporate outcomes from both SAFEBUCK and industry learnings. This is due for release in Q2 2015 [10].

VISION AND METHODOLOGY IMPLEMENTATION

In comparison to the through life project cost, engineering is a relatively small proportion of the overall economics. However, during the CAPEX phase of a project, delivery is fundamental to its success. With changing global economics and increased pressure to deliver solutions which are technically assured to be safe and reliable, yet also reduce CAPEX, engineering budgets are constantly under scrutiny. Therefore, increased efficiency and minimization of effort is key to meeting project expectations. Buckle Management Systems typically will also require ongoing performance monitoring through life to ensure integrity limits of the pipeline defined during design are not exceeded. Invariably, there is also an engineering cost associated with this phase too.

The partnership of CAPEX and OPEX project phases is also key to the transfer of design risk through to Operations for thorough asset management. To this end, the drive for more efficient and robust engineering to reduce cost, without compromising safety and quality, has led to the vision of a *one model* engineering tool to be developed. The main advantage of such an approach is that it can capture the actual stress state and corresponding mechanical response of the offshore pipeline during its entire design life: from the installation induced stresses, over hydrotesting, subsequent heating and cooling, hydrodynamic loading, and operational conditions that change during the life of the hydrocarbon reservoir.

Engineering is an iterative process, which typically evolves through the design phases as new or more detailed input data becomes available. Hence, the ability to enhance design models which reflect the phase of engineering (concept, FEED or detailed design) right through to operations, is an attractive prospect. Such a flexible and versatile *one model* approach allows reducing the workload, as it limits the requirement for re-work or additional developments. This staggered modelling approach hence allows reducing the engineering budget and compressing the corresponding project schedule.

Moreover, if this vision were to be realized, the gains in efficiency could be traded for increased assessment efforts to improve certainty of the correct BMS method selection. Also, enhanced analysis enables to reduce the risks associated with the response of the BMS. Such analyses hence assist in realizing increased asset availability and minimizing operational risks (e.g. costly remediation programs or loss of production due to a poorly designed BMS).

In this paper, the SAGE Profile software suite for offshore pipeline analysis [9] is used to explore and implement the proposed vision. This tool can be used to predict the mechanical response of an offshore pipeline after installation, and during the subsequent operational phases. A comprehensive overview of the engineering tool is given in [9].

Application of the tool to on-bottom roughness and free span analysis is demonstrated in [11-12]. Simulation of pipeline walking due to thermal gradients and sloping seabeds has been addressed in [13-14], and the prediction of susceptibility to upheaval buckling is tackled in [15]. In this investigation at hand, we want to illustrate how such a numerical analysis tool can be used to predict lateral buckling, and design appropriate mitigation measures, pursuing a *one model* approach. This does avoid the need to implement different finite element models for each purpose, e.g. installation, thermal expansion, free span analysis or in-service buckling.

The simulation results, presented in this paper, are benchmarked against analytical equations and finite element analyses performed with the general purpose Abaqus software.

VALIDATION AND VERIFICATION

For the validation and verification plan, seven scenarios of pipelines prone to lateral buckling have been identified. These different scenarios are summarized in Table 1.

Table 1: Case Matrix

Case	B.I. Location [km]	Lateral OOS [m]	Sleeper Height [m]	OD [mm]	wt [mm]
1	-	-	-	767.4	33.7
2	5	0.5	-	767.4	33.7
3	5	0.5	0.25	767.4	33.7
4	5	0.5	0.5	767.4	33.7
5	5	0.5	0.75	767.4	33.7
6	5	0.5	0.5	508.0	23.0
7	5	0.5	0.5	324.0	15.0

- The first case is a perfectly straight pipeline with a length of 10 km, installed on a flat seabed in a water depth of 500 m. This base case scenario is introduced to confirm that the finite element models can correctly capture the unbuckled effective axial force described by Hobbs [1-2].

- The second case is similar as the base case, but with an imposed lateral out of straightness of 0.5 m to trigger a lateral buckle.

- In Cases 3-5, a seabed sleeper is introduced as a rigid object on the seafloor, and a sensitivity analysis is performed to assess the influence of the sleeper height. For the results, presented in this paper, the sleeper contact is assumed to be frictionless.

- Both Case 6 and 7 are similar as Case 4, but with a different pipeline (i.e. different outer diameter and wall thickness).

Table 2: Pipeline Data

Parameter	Unit	Value
End restraints	[-]	Free
Pipeline length	[km]	10
Water depth	[m]	500
Steel grade	[API]	X65
Young's modulus	[GPa]	207
Poisson Ratio	[-]	0.3
Thermal coefficient	[1/°C]	1.17E-05
SMYS	[MPa]	450
SMTS	[MPa]	535
Steel density	[kg/m³]	7850
R.O. α	[-]	1.30
R.O. N	[-]	20.46
Coating thickness	[mm]	2.5
Coating density	[kg/m³]	900
Content density	[kg/m³]	350
Axial friction	[-]	0.7
Axial mobilization	[mm]	5
Lateral friction	[-]	0.7
Lateral mobilization	[mm]	5
ΔT	[°C]	60
$\Delta p = p_i - p_e$	[MPa]	30

The pipeline model is 10 km in length, and the common pipeline data is shown below. The pipe is simulated by discretizing the entire pipeline into sections of finite length, where an element length of 4m has been selected. These sections are represented by Bernoulli beam elements with 12 degrees of freedom, bounded at either side by nodes. The distributed mass of the pipe (including content and coatings) is lumped at these nodes. A similar model is implemented in Abaqus, where PIPE31H elements have been used, which are particularly suitable to model long, slender pipelines with a thin-walled circular cross section. Orthotropic friction is included in the contact algorithm to allow distinguishing between axial and lateral friction.

All cases, presented in Table 1, were simulated with a transient dynamic (explicit) solver, using an integrated numerical approach:

1. First, the laydown process was simulated to capture the stress distribution after the installation process.
2. Then, the lateral imperfection was introduced by imposing a prescribed out-of-straightness and/or introducing a sleeper as a frictionless, rigid cylinder on the seabed.
3. Finally, the operational pressure and temperature profile are gradually ramped in.

RESULTS AND DISCUSSION

Figure 6 compares the effective axial force profile for both SAGE Profile 3D (SP3D) and Abaqus for Case 1, where a straight pipeline on a perfectly flat seabed is filled with a hot and pressurized fluid. The EAF profiles closely align, and reflect the state of a pressurized pipeline which does not buckle.
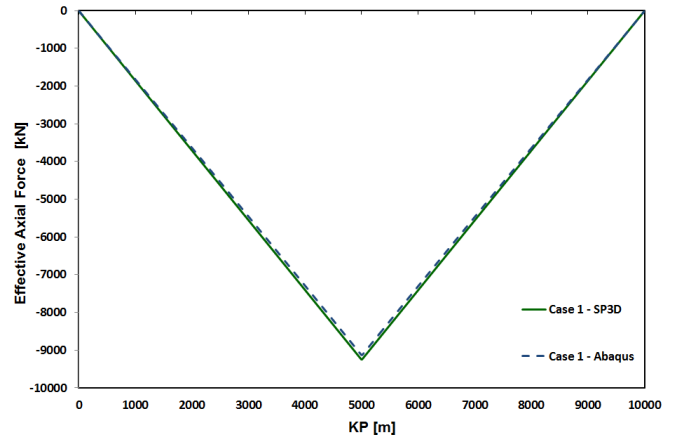

Figure 6: Effective axial force profile for unbuckled Case 1

When introducing an out-of-straightness by imposing a lateral displacement of 0.5 m at KP = 5 km, the pipeline *does* buckle during the operational phase. In Figure 7, the effective axial force at the apex is shown vs. the corresponding lateral displacement. The SP3D and Abaqus runs predict similar results, and agree well with the (theoretical) Hobbs curve.
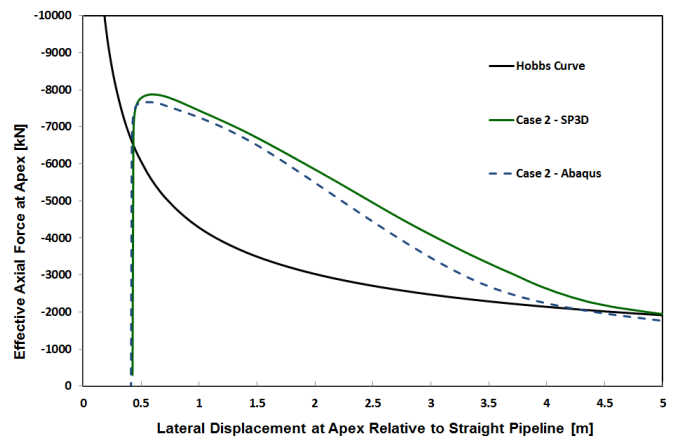

Figure 7: EAF vs. lateral displacement at apex (Case 2)

In Case 3, a seabed sleeper is introduced as a frictionless, rigid body, in addition to the initial OOS of 0.5 m. The combination of both lateral and vertical OOS triggers a mode three buckle, as clearly shown in the post-buckling configuration of Figure 8.
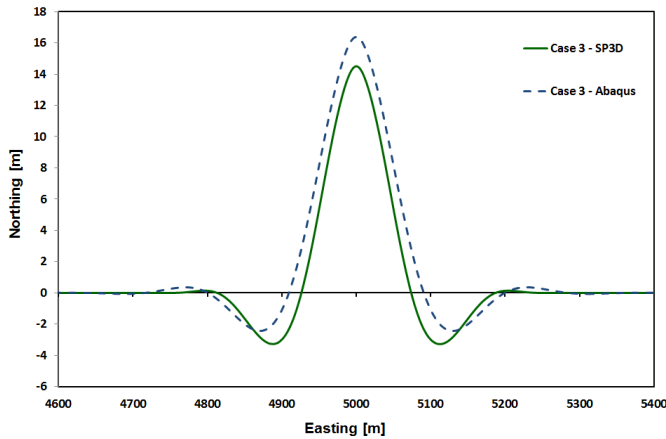

Figure 8: Post-buckling configuration (Case 3)

Cases 4 and 5 provide a sensitivity analysis on the sleeper height. Figure 9 demonstrates that the predicted curvature in the vicinity of the buckle apex closely matches for both explicit solvers used in this investigation.
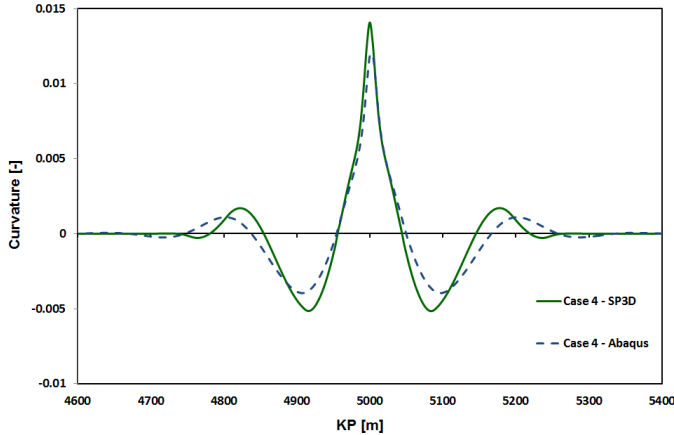

Figure 9: Pipeline curvature (Case 4)

In Figure 10, the predicted post-buckle configuration is shown for different sleeper heights, i.e. varying from 0 m (Case 2) up to 0.75 m (Case 4). For each case, the prescribed lateral OOS was fixed at 0.5 m. Whereas the configuration without seabed sleeper gives rise to a mode 5 buckle, the presence of a seabed sleeper tends to trigger a mode 3 buckle. Unsurprisingly, the buckle amplitude is more pronounced for increasing sleeper height.
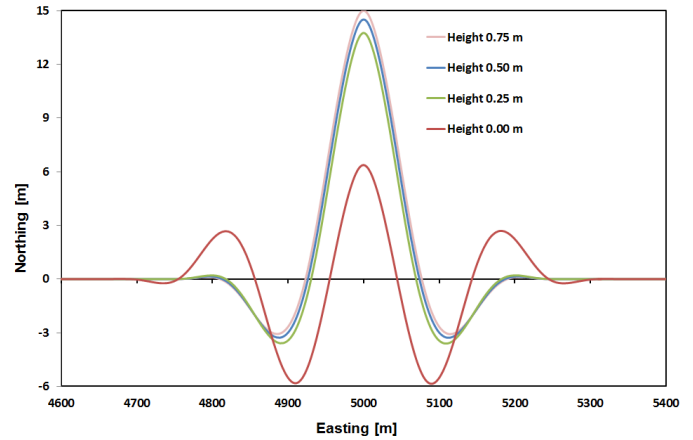

Figure 10: Influence of sleeper height on buckle formation

Case 6 is similar to Case 4 (i.e. a sleeper height of 0.5 m with an imposed lateral OOS of 0.5 m), but with a pipeline with outer diameter OD = 508 mm and wall thickness wt = 23 mm. A snapshot of the post-buckling configuration in Virtual Reality rendering is provided in Figure 11, clearly indicating that this configuration produces a mode 3 lateral buckle as well.
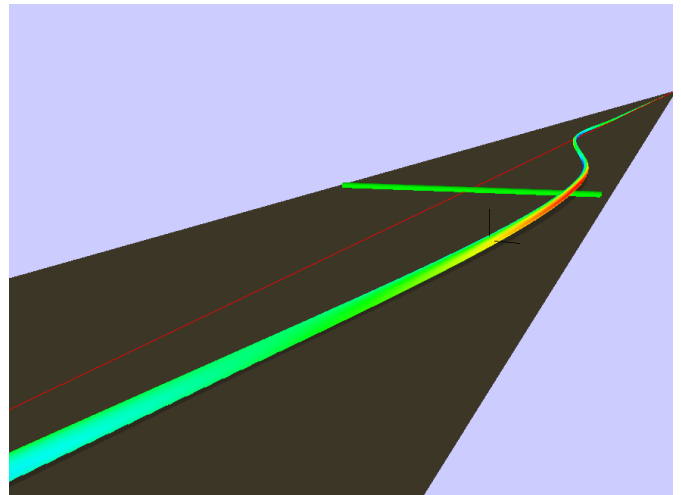

Figure 11: Post-buckling configuration (Case 6)

Cases 4, 6 and 7 allow comparing the influence of pipeline diameter and wall thickness when the operational conditions and the initial imperfections are fixed (i.e. a sleeper height of 0.5 m with an imposed lateral OOS of 0.5 m). For each pipeline, the effective axial force profile is shown in Figure 12, and compared to the corresponding critical force that would produce a mode 3 buckle. While the ratio of diameter over wall thickness is similar ($D/t \sim 22$) for the selected pipelines, the magnitude of the buckling force is significantly different. All three scenarios give rise to an engineered lateral buckle.
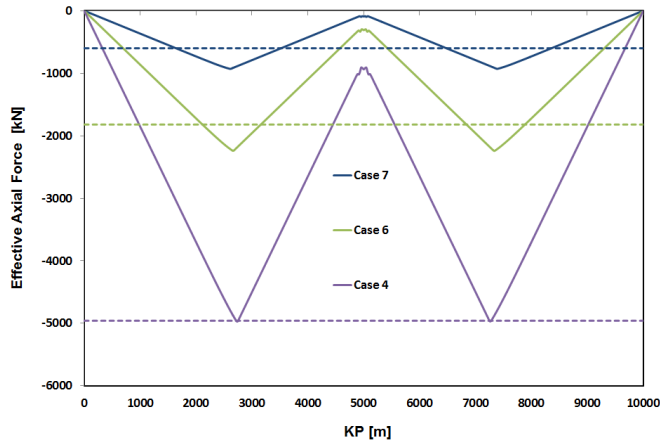
Figure 12: EAF profiles for different pipelines

The combined loading unity check for load controlled conditions (LCC) as per DNV-OS-F101 [3] is shown in Figure 13. Calculation of LCC/DCC values, taking into account the subsequent load patterns experienced by the pipeline (e.g. installation, hydrotesting, hydrodynamic loading, operational temperature and pressure profile, lateral buckle formation, …) provide a means of evaluating the proposed BMS. This endorses the strategy to pursue an integrated numerical approach for the design of offshore pipelines which are susceptible to lateral buckling.
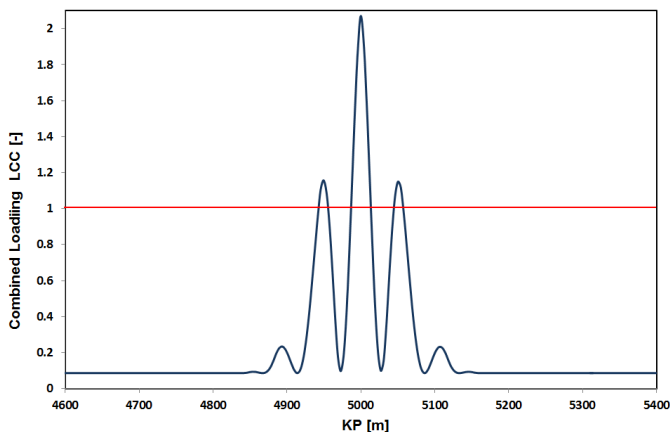
Figure 13: Limit state (LCC) for buckled pipeline (Case 7)

The main limitation of the proposed engineering is the constitutive material modelling of the pipeline steel, which is currently limited to non-linear elasticity (e.g. Ramberg-Osgood curve fit for strain hardening). As a result, the tool presented in this paper can reflect the (non-elastic) hardening of the steel material, although it fails to capture permanent deformation when the operational temperature/pressure is removed. As this limitations constrains the accuracy and predictive ability of the tool for some specific lateral buckling scenarios, pipeline plasticity will be addressed within future releases of the engineering tool.

CONCLUSIONS

In this paper, the vision of an engineering tool is presented, aimed at providing an integrated single model environment which enables straightforward engineering analysis, with application to all phases of design, and providing support to operations.

The main advantage of such an approach is that it can capture the actual stress state and corresponding mechanical response of the offshore pipeline during its entire design life: from the installation induced stresses, over hydrotesting, subsequent heating and cooling, hydrodynamic loading, and operational conditions that change during the life of the hydrocarbon reservoir.

For pipelines prone to lateral buckling, the *one model* approach will allow efficient post start-up verification of a proposed Buckle Management System and allow operations to have confidence in the delivered solution.

In this paper, different scenarios for lateral buckling were presented and simulated. Verification of buckling forces and post-buckling configurations has been undertaken through comparison with Hobbs and Kerr analytical models and validated against ABAQUS.

REFERENCES

[1] Hobbs R.E., In-Service Buckling of Heated Pipelines, Journal of Transportation Engineering, vol. 110(2), March 1984

[2] Hobbs R.E. and Liang F., Thermal Buckling of Pipelines Close to Restraints, Proceedings of the 8th Offshore Mechanics and Arctic Engineering Conference, OMAE, 1989

[3] Det Norske Veritas, Offshore Standard: Submarine Pipeline Systems, DNV-OS-F101, October 2013

[4] Det Norske Veritas, Recommended Practice on Global Buckling of Submarine Pipelines – Structural Design Due to High Temperature and High Pressure, DNV-RP-F110, October 2007

[5] Harrison G.E., Brunner M.S. and Bruton D.A.S., King Flowlines: Thermal Expansion Design and Implementation, Proceedings of the Offshore Technology Conference, OTC-15310, May 2003

[6] Matheson I., Carr M., Peek R., Saunders P. and George N., Penguins Flowline Lateral Buckle Formation Analysis and Verification, Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering, OMAE2004-51202, June 2004

[7] Kerr A.D., Analysis of Thermal Track Buckling in the Lateral Plane, ACTA Mechanica, vol. 30

[8] Fyriliev O. and Collberg L., Influence of Pressure in Pipeline Design – Effective Axial Force, Proceedings of the 24th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2005-67502, June 2005

[9] Van den Abeele F. and Denis R., Numerical Modelling and Analysis for Offshore Pipeline Design, Installation and Operation, Journal of Pipeline Engineering, pp. 273-286, Q4 2012

[10] Marley M., Merge between SAFEBUCK and DNV-RP-F110 – Benefits and Challenges, AOG 2014, Perth, Australia, February 2014

[11] Van den Abeele F., Boël F. and Hill M., Fatigue Analysis of Free Spanning Pipelines subjected to Vortex Induced Vibrations, Proceedings of the 32rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2013-10625 (2013)

[12] Van den Abeele F., Boël F. and Vanden Berghe, Structural Reliability of Free Spanning Pipelines, Proceedings of the 10th International Pipeline Conference, IPC2014-33552 (2014)

[13] Ballard J.C., Van den Abeele F. and de Brier C., Influence of Axial Pipe Soil Response on Pipeline End Expansion and Walking, Proceedings of the 6th Pipeline Technology Conference, Ostend, Belgium (2013)

[14] Birdas M., Srinil N. and Van den Abeele F., Assessment of Pipeline Walking with Coupled Triggering Mechanisms by Finite Element Approach, Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2015-42101 (2015)

[15] Yonatan P.H., Van den Abeele F. and Ballard J.C., Numerical Simulation of Upheaval Buckling using Intelligent Backfill Soil Springs, Offshore Pipeline Technology Conference OPT2015, Amsterdam (2015)