LATERAL BUCKLING DESIGN USING THE FRICTION DISTRIBUTIONS AT THE EXPECTED BUCKLES

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ABSTRACT

Operation at temperature and pressure of exposed subsea pipelines results in effective axial forces which may cause lateral buckling. To perform the lateral buckling design, the subsea pipeline industry typically uses a combination of Monte-Carlo simulations and finite element analysis. The Monte-Carlo simulations are used to determine the longest VAS that can be reliably exceeded (characteristic VAS), and FEA is used to determine the longest VAS with acceptable mechanical conditions (tolerable VAS). The lateral buckling configuration then needs to ensure that the characteristic VAS is less than the tolerable VAS along the whole pipeline.

This paper presents a methodology that can be implemented through the introduction of minimal changes to the recommendations of DNV-RP-F110. The methodology is based on a Monte-Carlo algorithm which determines the soil friction distributions of the expected buckles, and then an approach in which the tolerable VAS is in turn determined using these soil friction distributions of the buckles. The paper presents the application of the proposed approach to a case study to illustrate the significant impact this can have on the overall lateral buckling design. The Monte-Carlo algorithm used in this paper has been released under an open-source license to facilitate the implementation of this methodology by the industry.

NOMENCLATURE

BE	Best Estimate
CBF	Critical Buckling Force
CDF	Cumulative Density Function
DCC	Displacement Controlled Check
EAF	Effective Axial Force
ECA	Engineering Critical Assessment
FEA	Finite Element Analysis
HE	Highest Estimate
JIP	Joint Industry Project
KP	Kilometric Point
LE	Lowest Estimate
OOS	Out-of-Straightness
Px	x% Probability of Exceedance
PDF	Probability Density Function
SRA	Structural Reliability Assessment
STD	Standard Deviation
VAS	Virtual Anchor Spacing
Y/T	Yield to Tensile Ratio

INTRODUCTION

The lateral buckling response of surface-laid, subsea pipelines, in particular when engineered buckle triggers are not introduced, is highly sensitive to two parameters that have significant and unavoidable uncertainty at design stage: pipe-soil interaction and as-laid pipeline OOS.

In DNV-RP-F110 [Ref. 1] (hereafter referred to as F110), these inherent uncertainties are addressed through the concepts of characteristic and tolerable VAS. The former represents the length of pipeline feeding into a buckle with a certain probability of exceedance, while the latter is the maximum length of pipeline that can feed into a buckle without violating any of its limit states. The practical implementation of this approach is to ensure that the characteristic VAS is less than the tolerable VAS along the entire pipeline route.

The characteristic VAS can be calculated using either a probabilistic approach to predict buckle formation, or a combination of deterministic equations and conservative assumptions; this paper does not consider the latter method. The tolerable VAS is calculated using FEA. This involves finding the specific value of characteristic VAS, that combined with the rest of characteristic values used in the design, results in a buckle mechanical response matching its allowable resistance, i.e. unity check equal to 1. This methodology, which was in fact developed as part of the Safebuck JIP [Ref. 2, 3], calibrated the probability of exceedance of the characteristic VAS to achieve target probabilities of failure in line with DNV-ST-F101 [Ref. 4] (hereafter referred to as F101).

The use of the VAS concept as a simple proxy of the actual limit states, however, introduces the following inconsistency. In this approach, while the characteristic VAS considers the range of axial and lateral frictions under which buckles form, the tolerable VAS is based on onerous design combinations of the full range of geotechnical frictions. These two values of VAS are then compared without considering whether buckling is possible with the entire range of fictions. This inconsistency is also reflected in the way the approach was calibrated, as the VAS models used in the SRA calibration [Ref. 5] would have formed buckles with all (most) lateral frictions sampled from the complete geotechnical distribution.

This inconsistency results in an inaccurate quantification of uncertainty and a certain level of conservatism. In cases involving pipelines with moderate operating conditions and moderate OOS (e.g. nominally straight sections), the application of this approach leads to the introduction of engineered buckle triggers in pipelines designed to operate in similar conditions to others that have operated beyond their intended design life without the inclusion of such measures.

The industry has been aware of this limitation for some time and complementary tools and alternative advanced methodologies have been proposed by contractors such as Crondall and Intecsea [Ref. 6, 7]. However, these tools are not generally accessible, and comprehensive guidelines detailing these methodologies have not been published. Without widely available tools and an industry agreed methodology, it is challenging for projects to propose these methodologies to optimise the lateral buckling design of pipelines.

This paper presents a methodology that resolves the inconsistency of the characteristic versus tolerable VAS approach through the introduction of minimal changes to the recommendations of F110. The proposed methodology considers in the FEA, the VAS of buckles together with the axial and lateral frictions with which they form in the probabilistic simulations. The paper highlights the benefits of this methodology through a case study and discusses some key decisions on the sampling of the stochastic variables required for its implementation.

Additionally, the Python code used to perform the probabilistic analyses has been released with an open-source license with the intent of allowing the pipeline community to review, expand, and use it for the benefit of the industry. Access to the code can be provided upon request via email to the authors of this paper.

PROBABILISTIC ALGORITHM

The open-source probabilistic algorithm performs Monte-Carlo simulations to capture the VAS together with the axial and lateral frictions of the buckles that form in the simulations.

The algorithm divides the pipeline into elements and elements are grouped in sets of shared inputs such as pipe and soil properties. Three of the inputs are stochastic (residual axial friction, lateral breakout friction, and OOS factor), and all other inputs are deterministic. In each simulation, axial friction is sampled once per set, OOS factors are sampled once per individual element and two different options are considered to sample the lateral friction. All stochastic variables are considered independent.

The algorithm uses a simple buckle formation model that follows the recommendations of F110. The ratio of CBF to EAF is determined for all elements, the ratios are ranked and then the trigger of buckles is checked, in the ranked order, by checking if the elemental EAF exceeds the CBF. When a buckle forms, the EAF drops to a predefined post-buckling force over a predefined length.

In the algorithm, the CBF of each element is determined using the following equations:

$$S_{CR} = X_{NH} \cdot S_{char} \cdot \sqrt{\mu_L} \qquad \text{for nominally straight sections}$$

$$S_{CR} = X_{NB} \cdot \mu_L \cdot w \cdot R \qquad \text{for route curves with nominal bend radius } R$$

Where S_{CR} is the CBF, X_{NH} and X_{NB} are the OOS factors for nominally straight sections and route curves respectively, μ_L is the lateral breakout friction and w is the pipeline submerged weight. The term $[\, S_{char} \cdot \sqrt{\mu_L}\,]$ represents the Hobbs minimum force for the infinite mode buckle and the term $[\mu_L \cdot w \cdot R]$ represents the nominal buckling force for a long radius section with nominal bend radius R.

As shown in the previous equations, in combination with some basic mechanical parameters of the pipe cross section (which have limited uncertainty), the CBF is a function of the lateral breakout friction and the OOS of the as-laid pipeline, which have both significant uncertainty (at least before pipeline has been laid).

The sampling of the stochastic lateral friction and OOS factors, rather than CBF, and the extraction of the VAS together with the lateral frictions of the buckles that form in the simulations are the main differentiator attributes of this algorithm. The independent sampling of lateral friction and OOS factors is done to overcome the inconsistency between the frictions used in the characteristic and tolerable VAS approach.

STOCHASTIC VARIABLE SAMPLING

The probability distributions recommended in F110 for the critical or tightest OOS within a given reference length were determined by analysing as-laid OOS data from several pipelines. For straight sections, the distributions were defined with a reference length of 1km, while for route curves, the reference length was set as the lesser of 1km and the curve arc length. These distributions can be used to assess the formation of unplanned buckles.

The need for the concept of reference length for the OOS comes from the difficulty of defining OOS features as a discrete collection of events of known length, concatenated to describe the full length of a pipeline. Instead, it was decided to adopt a definition based on the weakest link within the OOS reference length.

In the algorithm, the OOS distribution is sampled at each element and is determined using the distribution of the reciprocal minimum to ensure that the distribution of the critical (tightest) OOS within all elements of the reference length remains unchanged (regardless of the element length used to discretise the pipeline):

$$F_{X_n}(X) = 1 - (1 - F_X(X))^{\frac{1}{n}}$$

$$f_{X_n}(X) \ = \frac{1}{n} \cdot f_X(X) \cdot \left(1 - F_X(X)\right)^{\left(\frac{1}{n} - 1\right)}$$

Where $f_X(X)$ and $F_X(X)$ are the PDF and CDF of the OOS factor at its reference length, $f_{X_n}(X)$ and $F_{X_n}(\mathrm{X})$ are the PDF and CDF of the elemental OOS factor, and n is the number of elementals within the reference length.

The probability distribution for the lateral breakout friction is determined from geotechnical assessments. In order to determine how to sample this distribution in the algorithm, it is important to understand the sources of uncertainty of this parameter. On the one hand, there is the uncertainty linked to the soil properties. On the other hand, there is the uncertainty related to the influence of the pipe lay process on the pipe embedment (the so-called Klay factor). For both sources, the uncertainty can be divided into two categories:

- General epistemic uncertainty: for soil properties, this would be the uncertainty on the properties of the soil type covering a certain area; for the Klay factor, the uncertainty on the installation conditions.
- Spatial variability: for soil properties, this would be the variability in soil properties along the pipeline (within area covered by the same soil type); for the Klay factor, the variability in installation conditions along the pipeline.

In the algorithm, a value of lateral friction is assigned to each element without applying any scaling effect. However, to account for the two different sources of uncertainty in this variable, two sampling approaches are considered: either the variable is sampled independently at each element, or it is sampled per OOS reference length and assigned to all the elements in the OOS reference length. The former is consistent with a case where spatial variability is significant within the OOS reference length. The latter is consistent with a case in which uncertainty is dominated by the general epistemic uncertainty within the OOS reference length. In the case study, these approaches are labelled as ‘Sampling per Element’ and ‘Sampling per OOS Ref. Length’, respectively.

The sampling of OOS factor and lateral friction as described above is done within the algorithm and used to calculate the CBF at each element. As such, there is no need to define a distribution for the CBF (with a given scale length), as it is done in the original F110 approach. It is interesting, however, to extract the distributions of CBF generated within the algorithm (with the two sampling approaches considered) to compare them and better understand the results of the case study.

The distributions of the CBF obtained from the two sampling approaches can also be derived mathematically. These two approaches assume that the OOS factor and friction distributions are independent at the sampling length of the friction distribution. Consequently, the resultant CBF distribution is in turn dependant of the element length and randomness approach used to sample the lateral friction. The PDF of the CBF distribution within the OOS reference length, calculated based on the selected sampling frequency of the lateral friction (n-times per OOS reference length), is calculated using the distribution of the product of two random variables:

$$f_{S_{CR_n}}(S_{CR}) \; = \int_{-\infty}^{\infty} f_{X_n}(X) \cdot f_\mu \left({}^{S_{CR}}\!/_{X} \right) \cdot \frac{1}{|X|} \, dX$$

$$f_{S_{CR}}(S_{CR}) \; = \; n \cdot f_{S_{CR_n}}(S_{CR}) \cdot \left(1 - F_{S_{CR_n}}(S_{CR}) \right)^{(n-1)}$$

Where $f_{S_{CR}}(S_{CR})$ is the PDF of the CBF at the OOS factor reference length, $f_{S_{CR_n}}(S_{CR})$ is the PDF of the elemental CBF, $F_{S_{CR_n}}(X)$ is the CDF of the elemental CBF, and $f_\mu(\mu)$ is the PDF of the lateral friction.

For the 1km long route curves in the case study in Table 1, these formulations are used to derive the CDF of the minimum CBF of an unplanned buckle within a 1km reference length, considering different number of elements (n) within the 1km length. In all cases, the OOS (scaled appropriately) and the lateral breakout friction (not scaled) are sampled once per element. The curves shown in Figure 1 illustrate how the CBFs reduce as the number of elements within the reference length is increased. This tendency can be easily explained. Since buckle formation is a weak link problem, the more times the lateral friction is sampled within the reference length, the more chances there are to find a low value of lateral friction and thus a low value of CBF.

In the figure, two curves are highlighted: the orange line, which corresponds to the case where the lateral friction is sampled once per km (labelled ‘Sampling per OOS Ref. Length’ in the case study) and the blue line, which corresponds to the case where the lateral friction is sampled 10 times per km (labelled ‘Sampling per Element’ in the case study, as 100m long elements are used in the case study). As shown in the figure, these two lines bound the range of scenarios reasonably well.

It should be noticed, that if the CBF distribution is derived by propagating uncertainty from OOS and lateral friction as suggested in the original F110 approach, the curve obtained matches the orange line.

Unless a dominant source of lateral friction uncertainty (epistemic or spatial variability) can be established for the specific pipeline considered, sensitivity analyses are required to capture this range of scenarios. This paper focuses on assessing the impact of the variability of the sampling of the lateral friction by considering the two scenarios defined by the blue and orange lines in Figure 1.

Sensitivities are also needed to address the uncertainty in the OOS distributions, but this is already identified in F110 and can be simply done by varying their mean and STD.

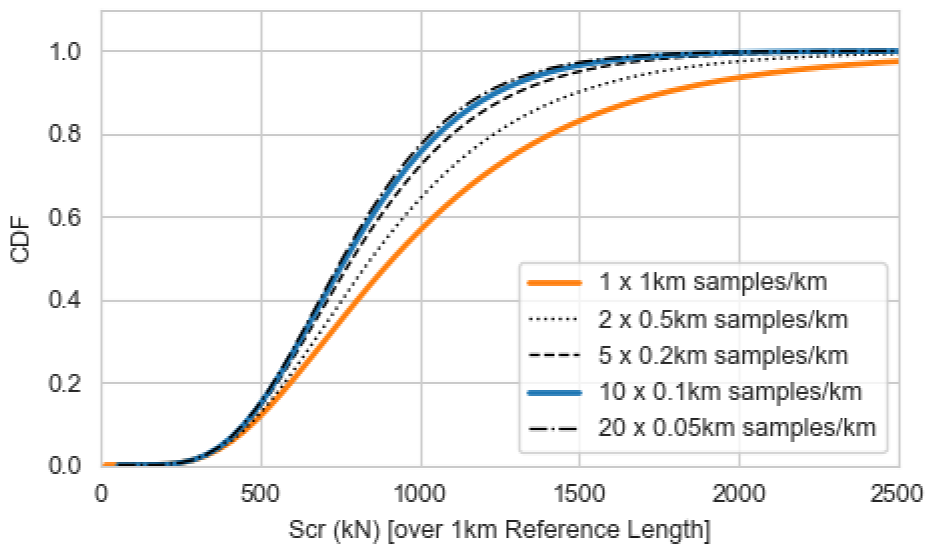

Figure 1 – Stochastic CBF Sampling Comparison within OOS Reference Length

FINITE ELEMENT VAS ANALYSES

The mechanical response of the lateral buckles identified in the probabilistic assessment is considered using VAS models run with Abaqus FEA software. These models specifically consider the isolated response of a lateral buckle with a specified length feeding into it, as described in F110.

In the models, constant pressure and temperature are considered over the whole VAS. These are conservatively taken as the values at the initial KP of the VAS, as to take values at the centroid of the VAS could lead to unconservative results in pipelines with non-linear temperature gradients.

The VAS analyses use a friction model with breakout and residual lateral friction values. The values in each VAS run are defined from the breakout value in the probabilistic run, assuming a linear correlation between the breakout and residual values.

Peak compressive and tensile strains are extracted from the analyses for limit state evaluation.

CASE STUDY

The impact of the proposed methodology on the lateral buckling design of a pipeline, and in particular on the possibility to allow uncontrolled lateral buckling, is illustrated using the deterministic and stochastic parameters presented in Table 1. The case study is based on a 25km long, 12” deep water pipeline with five curves along its length. The pipeline operates at high pressure (360bar) and moderate temperature (55˚C inlet).

Parameters

Parameter		Value
Outer Diameter		323.9mm
Wall Thickness		22.2mm
Material Grade		X65
Stress-Strain Curve	Luders Plateau	1.0%
	Yield Stress	450MPa
	Y/T	0.85
	Temperature Derating	As per DNV-ST-F101
Submerged Weight	Installation	788N/m
	Operation	1,330N/m
Pipeline Route	Length	25km
	Route Curves Location (km)	From 5.2 to 5.7, 6.7 to 7.2, 8.7 to 9.2, 15.0 to 16.0 & 20.0 to 21.0
	Radius of Route Curves	2km
	Ends	Free to Expand
Residual Lay Tension		0N
Water Depth		1,400m (Constant)
Internal Pressure	Installation	Empty
	Operation	360bar
Temperature	Installation	7˚C
	Operation	From 55 to 20˚C (Exponential)
Limit States	Tensile Strain Limit	0.4% Screening, or ECA if needed
	Compressive Strain Limit	0.88% (Factored)
Residual Buckle	Length	220m
	Effective Force	250kN (Compressive)
Axial Friction (Residual)	Distribution Types	Lognormal
	LE (P95)	0.30
	BE (P50)	0.40
	HE (P5)	0.55
	Reference Length	Sampled once per Soil Type
Lateral Friction (Breakout | Residual)	Distribution Type	Lognormal
	LE (P95)	0.40 | 0.50
	BE (P50)	0.80 | 0.70
	HE (P5)	1.60 | 1.10

Parameter			Value
	Reference Length		Element or OOS Reference Length
OOS Factor	Straight Section	Distribution	Lognormal
		Mean	1.260
		STD	0.330
		Ref. Length	1km
	0.5km Route Bend	Arc Length	0.5km
		Distribution	Lognormal
		Mean	0.560
		STD	0.168
		Ref. Length	0.5km
	1km Route Bend	Arc Length	1.0km
		Distribution	Lognormal
		Man	0.450
		STD	0.135
		Ref. Length	1km

Table 1 – Deterministic and Stochastic Parameters

Probabilistic Results (Characteristic VAS & Frictions of the Buckles)

In the case study, the pipeline is divided in 100m long elements. Probabilistic results are presented for two different sets of simulations: one where the lateral friction distribution is sampled once per element and another where it is sampled once per OOS reference length (e.g., the initial straight section between KP0 and 5.25 is divided in six OOS reference lengths: KP0 to 1, KP 1 to 2, KP 2 to 3, KP 3 to 4, KP 4 to 5 and KP 5 to 5.25. Within the same OOS reference length, different elements share the same lateral friction).

Results indicate that the pipeline buckles in all simulations, regardless of the lateral friction sampling approach. The total number of buckles along the pipeline remains relatively consistent, with the most likely number of buckles between 5 and 6. Across all simulations, the total number of buckles varies between 2 and 16.

However when results are grouped in 1km intervals along the pipeline route (Figure 2), noticeable differences are observed between the two sampling approaches in terms of both probabilities of buckling and characteristic VAS (determined as per F110 definition of the VAS exceeded in 1% of the simulations within a km, unconditionally on whether or not these simulations contain a buckle).

As anticipated (and consistent with the discussions around Figure 1), the probabilities of buckling presented in Figure 2 are larger when the lateral friction is sampled per element rather than per OOS reference length. Conversely, the characteristic VAS tends to be shorter in the former case.

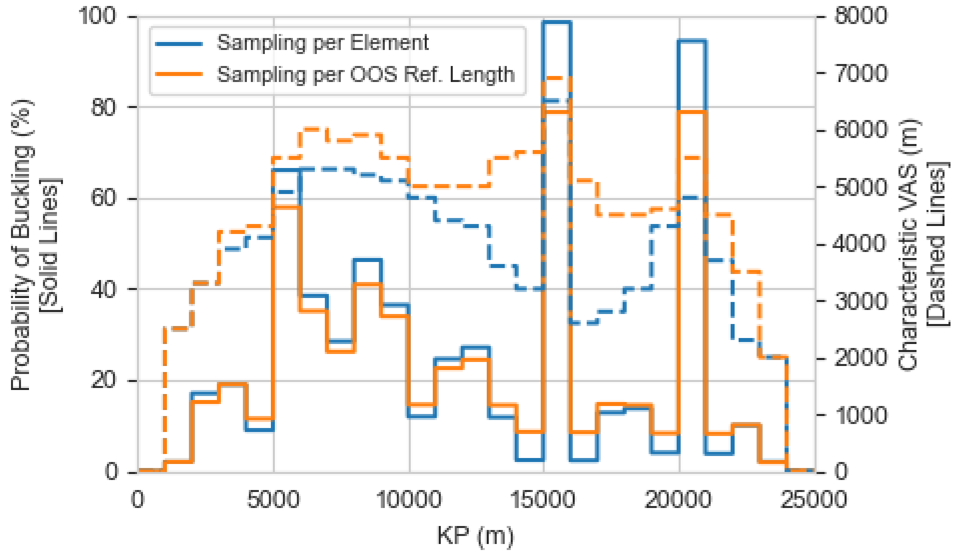

Figure 2 – Characteristic VAS and Probability of Buckling

Similarly, when the lateral breakout frictions of the buckles are grouped in 1km intervals along the pipeline, noticeable differences are observed between the geotechnical distribution entered as an input in the analyses (as shown in Table 1), and the friction distributions of the buckles that form in that km, in all simulations (calculated unconditionally on whether or not these simulations contain buckles).

To facilitate the comparison of friction distributions, Figure 3 presents the geotechnical and buckle lateral breakout friction distributions associated with the kilometre which has the largest probability of buckling along the pipeline route (from KP15 to 16). Within this kilometre, when the friction is sampled per element length, the mean and STD of the lateral friction distribution of the buckles are both about 40 to 50% lower than in the geotechnical friction distribution, and about 20 to 30% lower when the friction is sampled per OOS reference length. The differences between the blue and orange lines in Figure 3 clearly illustrate that the selected sampling method has a significant effect on the lateral friction with which lateral buckles form in the probabilistic assessment.

In fact, the lateral friction sampling method has an effect on the two key parameters that determine the mechanical response at a lateral buckle: the VAS length and the lateral friction. By sampling once per element (blue lines), both the lateral frictions at which buckles form, and their VAS length are reduced. If the assumptions on variability of lateral friction associated with the blue lines are not correct, this could lead to unconservative results.

The curves in Figure 3 also illustrate how the lateral friction distribution of the buckles, when the friction is sampled once per OOS reference length (orange line) tends towards the geotechnical friction distribution (green line) when the probability of buckling within a given km tends towards 100%. In the example shown in Figure 3, the probability of buckling within the km shown when the lateral friction is sampled once per OOS reference length is 79%.

It is also interesting to note that the lateral friction distribution of the buckles when the friction is sampled per element (blue line in Figure 3) tends towards a friction distribution that would be consistent with the distribution of the minimum CBF of the elements within that kilometre (blue line in Figure 1).

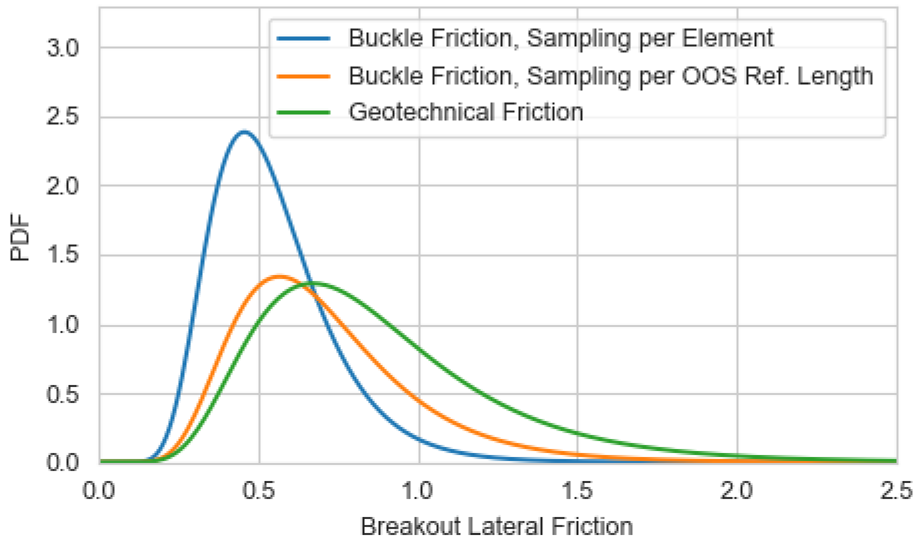

Figure 3 – Lateral Breakout Friction Distributions [Buckles between KP 15 and 16]

The same approach has been followed to define the axial friction distributions of the buckles. These distributions however are not presented in the paper as they are close to the geotechnical distributions within the fully restrained section of the pipeline; although, some differences are observed towards the pipeline ends where axial frictions are slightly larger due to their direct impact on the EAF profile. As these larger axial frictions contribute to reduce the axial feed-in into the lateral buckles, they can have a noticeable impact on the lateral buckling design in particular for short pipelines.

From the PDF of the lateral breakout friction of the buckles, it is possible to determine the frictions associated to a given probability of exceedance (the characteristic buckle frictions) for each km of pipeline.

As the methodology outlined in this paper tries to build on the original SRA [Ref. 5] performed to calibrate the F110 approach to be in line with the target probabilities of failure in F101, it is important to understand what was considered in that SRA to be able to select an appropriate (alternative) probability of exceedance to define the characteristic lateral friction.

The SRA calibration process consists of proposing definitions for the characteristic values for the main variables (axial friction, lateral friction and VAS). These definitions are then used to develop a design in which the characteristic VAS is equal to the tolerable one. The reliability of this design is then checked by performing an SRA (using Monte Carlo simulations) considering all the relevant limit states to determine the probability of failure. As part of the calibration, this process is repeated, adjusting the definition of the characteristic values, until the probabilities of failure achieved are consistent with F101.

At the end of this calibration process, the characteristic VAS was defined as the VAS exceeded in 1% of the simulations (or P1) and the characteristic lateral friction was defined as the friction with a probability of exceedance of 5% (or P5) from the original geotechnical distribution.

In simple terms, the probabilities of failures in the SRA are driven by cases in the Monte-Carlo simulations with values for the key parameters more onerous than their characteristic values. So, in the case of the lateral friction, the higher the probability of exceedance used to define the characteristic value, the higher the probability of failure of the proposed design would be.

It should be noted that in the approach taken to perform this original SRA for the calibration of F110 [Ref. 5], VAS models were run with high temperature and pressure and so buckles formed with all (most) lateral frictions sampled from the full geotechnical distribution. As such, and although it is not presented in this way in [Ref. 5], the calibration could be considered valid for a value of P5 of the buckle lateral friction distribution (blue and green curves in Figure 3).

In this paper, it is proposed to consider the characteristic lateral friction as the P1 value of the buckle lateral friction distribution. As detailed in the previous paragraph, this proposed methodology provides a certain margin and so remains consistent with the target probabilities of failure in F101. Indeed, the overall methodology is the same, but a more stringent buckle lateral friction (P1 buckle friction vs. P5 geotechnical friction) is taken to define the characteristic value and the buckle lateral friction distributions exhibit (at least in this example) very similar shapes to the lognormal geotechnical distributions used in the calibration SRA [Ref. 5].

Nevertheless, it is recommended to conduct an extension of the calibration SRA at some point to further support this finding and if possible, relax the definition of the characteristic lateral friction.

Figure 4 compares P1 buckle with P5 geotechnical lateral frictions along the pipeline route. The P5 of the geotechnical friction is a constant value of 1.6, whereas the P1 buckle frictions range between 0.47 and 1.13 and between 0.47 and 1.55 when frictions are sampled per element and per OOS reference length, respectively. As the selected definition of the P1 characteristic friction could lead to frictions larger than the P5 geotechnical friction used in the conventional approach, when the buckling probability tends towards 100%, it is proposed to cap it by the P5 geotechnical friction.

As discussed previously, the results in Figure 4 illustrate how more onerous results are obtained when the lateral friction is sampled per OOS reference length (orange curve) instead of per element (blue curve).

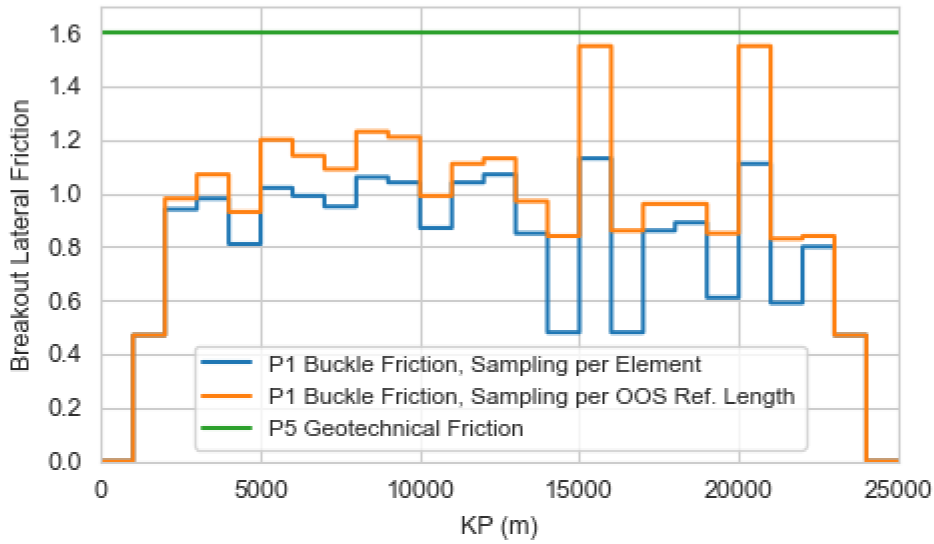

Figure 4 – Characteristic Lateral Friction Definition Comparison along the Pipeline

In order to provide additional insight into the results of the probabilistic run of the case study, Figure 5 presents a two-dimensional PDF of the pairs of VAS and lateral friction from all the buckles that form between KP15 and 16 (for the run in which the friction is sampled per element). In addition to the PDF contours, additional points are plotted to illustrate the pairs beyond the 1% probability of exceedance (referred to as outliers).

From these results, 1% of the points have friction above the P1 buckle friction (as expected), but only 0.03% of the points have frictions above the P5 geotechnical friction, as buckles are hardly triggered above this friction.

The figure also shows that 1% of the VAS and friction pairs are outside the F110 definition of characteristic VAS and lateral friction (orange outliers) and 1.8% are outside the new proposed definition of characteristic VAS and lateral friction (orange + red outliers). Although this shows an increase in points beyond the characteristic values, this does not imply an increase in the probability of failure (as per details above on the F110 SRA calibration).

The figure also shows that VAS and lateral friction are not correlated as there is no connection or signs of linear relationship between them.

A similar exploratory data analysis is presented in the next section to understand how many of these VAS and friction pairs do not comply with the relevant limit states.

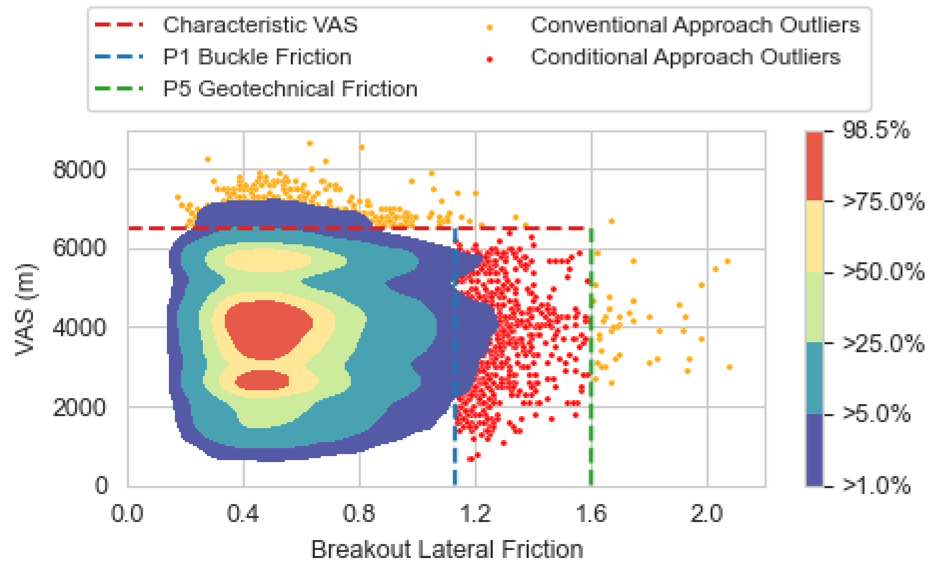

Figure 5 – VAS versus Friction [Buckles between KP15 and 16, Element Sampling]

FEA Results (Tolerable VAS)

As per F110 approach, the integrity of potential lateral buckles is assessed by running FEA VAS models with their characteristic values and comparing the mechanical response to the relevant limit states. This is equivalent to comparing those characteristic VAS to their tolerable VAS limits. This is done for each km of the pipeline.

The exercise is performed using the characteristic values presented in Figures 2 and 4, for the VAS and lateral friction respectively, considering two alternative approaches for the definition of the characteristic lateral friction:

- F110 definition of characteristic values, i.e. the P5 of the geotechnical distribution.
- Definition proposed in this paper, i.e. the P1 of the distribution of lateral frictions at the buckles that form in the probabilistic buckle formation algorithm.

For simplicity, these checks are only presented using the results of the probabilistic buckle formation algorithm run with lateral friction sampled per element (the blue curves in Figures above). This scenario has been selected as it maximises the improvements of the proposed methodology and so it illustrates more clearly the impact of the proposed change. Of course, in a specific case, the choice between sampling lateral friction per element or per OOS reference length will depend on the actual variability of the lateral friction and, if in doubt, the more conservative sampling by OOS reference length should be used.

In all cases, the definition of the characteristic values for the axial friction and VAS are taken as per F110 definition.

The results of these assessments are shown in Figure 6, where the peak compressive and tensile strains along the characteristic buckle at each km of the pipeline are plotted against characteristic resistance values (design values including partial safety factors) for the fracture and local buckling limit state. The results in the figure illustrate a very significant improvement in the results. Similar improvements are observed in the long-term mechanical responses (fatigue and ratcheting), but these are also not presented to keep the discussion focused.

The key conclusion of this comparison is that whereas with the F110 approach lateral buckling mitigations would need to be introduced over 17km of this pipeline, with the approach proposed in this paper, no mitigations are required at all (except conducting an ECA and possibly tightening slightly the weld acceptance criteria over 3km of the pipeline). This improvement would lead to significant cost savings.

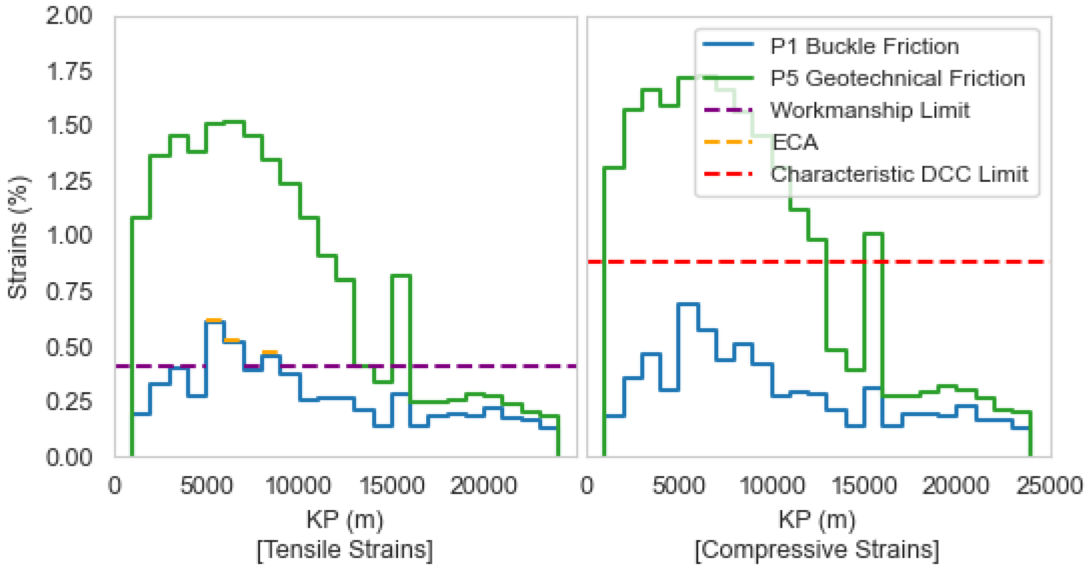

Figure 6 – Characteristic Strains vs Characteristic Resistance for Short Term Limit States

Additional Discussions

The cost savings achieved from the new proposed approach are in line with the probabilities of failure in DNV-ST-F101 (as per discussion on the F110 SRA calibration above).

Nevertheless, to further illustrate the results of the probabilistic assessment, the data exploration presented in Figure 5 is complemented by running FEA VAS models for the critical buckles to illustrate whether their mechanical conditions are above or below the characteristic resistance. The results of these assessments are presented in Figure 7, where the data points (buckles) failing the characteristic allowable value for the DCC are highlighted in red.

The results are presented for the buckles initiating between KP3 and 4. This is a section where, as shown in Figure 6, the F110 approach indicates that the design is not acceptable (characteristic strain approximately double the characteristic DCC resistance), but the new proposed approach indicates that the design acceptable (characteristic strain approximately half the characteristic DCC resistance).

In the km presented in Figure 7, 0.8% of the simulations have buckles outside the F110 definition of characteristic VAS and lateral friction and 1.5% outside the new proposed definition of characteristic values. The number of simulations with buckles exceeding the characteristic DCC resistance, however, is only 0.16% (the red points in the figure).

It should be noted that in these 0.16% of simulations, it is the characteristic value of the DCC capacity that is exceeded, not the unfactored DCC capacity. The value of 0.16%, therefore, should not be compared to the allowable probability of failure in F101, but to the definition of a characteristic load, i.e. a value closer to 10^{-2} than to 10^{-4}. Based on this, the value of 0.16% found would be in line with the comfortable margin shown in Figure 6 between KP3 and 4.

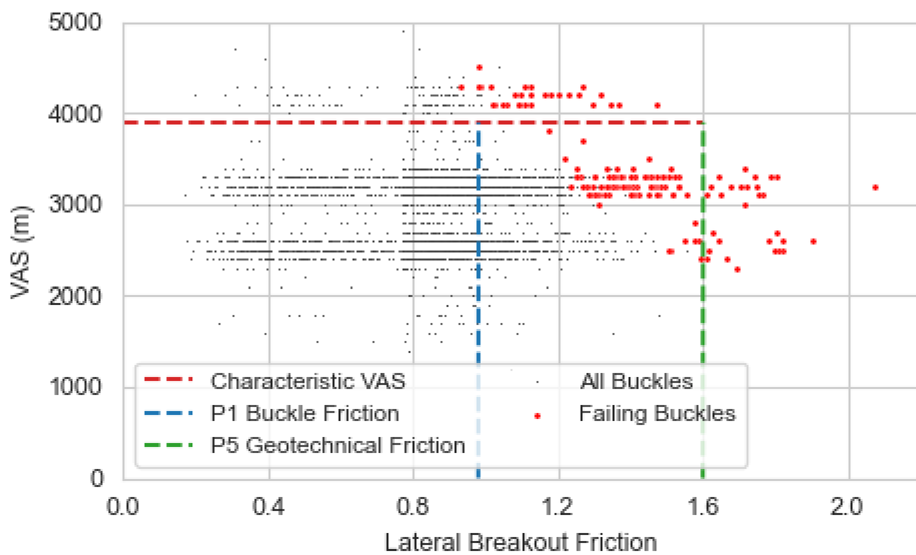

Figure 7 – All Buckles vs. Buckles with Compressive Strains >0.88% [VAS versus Friction, Buckles between KP3 and 4, Element Sampling]

From the peak compressive strain values at all buckles between KP3 and 4 (VAS and lateral friction of the buckles are extracted from the Monte-Carlo simulations and strains are then determined using the Abaqus VAS models), it is possible to develop the cumulative probability function for this variable, shown in Figure 8. The curve begins at 19%, as this this is the probability of buckling in this km of the pipeline in both lateral friction sampling approaches (see Figure 2).

The figure includes the result for the probabilistic buckle formation run in which lateral friction is sampled per element (blue line), which corresponds to the results in Figure 7. The results for the run in which lateral friction is sampled per OOS reference length is also included (orange line) to illustrate further the impact of the lateral friction sampling strategy on the results.

As previously discussed, the orange curve shows how more onerous results are obtained when the lateral friction is sampled per OOS reference length. In this case, the fraction of simulations where the peak compressive strain exceeds the characteristic DCC capacity increases to 0.38% (compared to 0.16% when sampling friction by element). This illustrates again the need to sample per OOS reference length, unless it can be proven that the variability in lateral friction is consistent with sampling per element.

Finally it is noted that when the exercise presented in Figure 6 is performed used using the results where the lateral friction is sampled per OOS reference length (i.e. determining the characteristic strain from the characteristic VAS and proposed characteristic friction), it is concluded that the buckles in the section between KP3 and KP4 are just over the limit for the DCC check (characteristic strain to characteristic DCC resistance of 1.04). Based on this, the new proposed approach would conclude that mitigation is required in this area. However, as noted above, when the CDF is developed for the strains in this area, only 0.38% exceed the characteristic DCC resistance, i.e. less than 10^{-2}. This result is in line with the argument that the new proposed approach is consistent with the target probabilities of failure in F101.

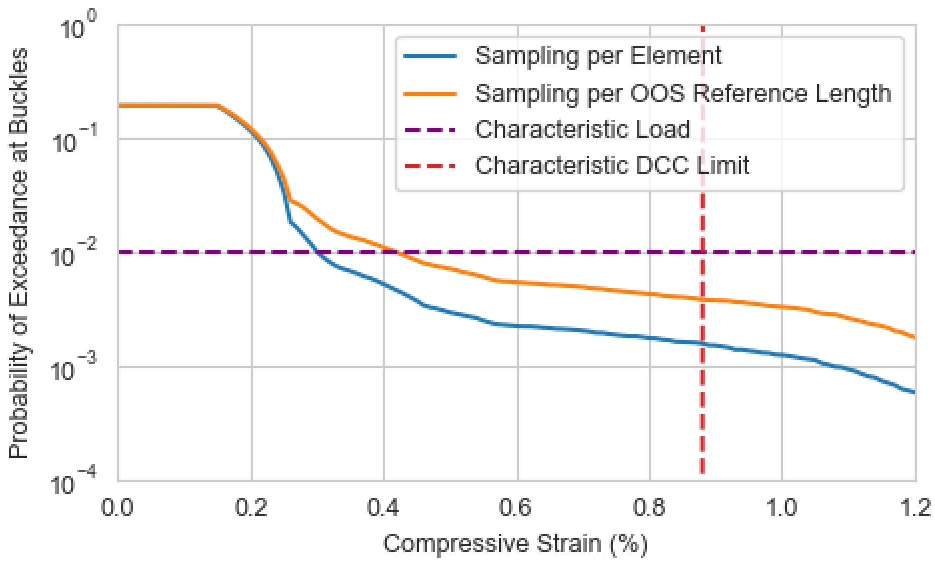

Figure 8 – Compressive Strain vs. Probability of Exceedance at Buckles [KP3 to 4]

CONCLUSIONS

This paper has introduced a methodology to address some of the limitations in the DNV-RP-F110 probabilistic lateral buckling assessment approach. The paper proposes the following modifications:

- In the probabilistic buckle formation algorithm, instead of sampling a distribution of critical buckling force, the breakout lateral friction and the OOS factor are sampled separately and combined to calculate the critical buckling force.
- This allows extracting, from the probabilistic buckle formation runs, not only a distribution of VAS lengths, but a distribution of the lateral frictions at which buckles form.
- The characteristic lateral friction that is used to assess the tolerable VAS is then defined as the value with a probability of exceedance of 1% from the distribution of lateral friction at buckles (for each km of pipeline), instead of the value with a probability of exceedance of 5% from the geotechnical distribution of lateral friction (as currently proposed in F110). For sections where the probability of buckling is very high and the P1 value of the distribution of buckles could be higher than the P5 value of the geotechnical distribution, it is proposed to cap the characteristic value by the P5 geotechnical friction value.

The paper argues that the proposed methodology complies with the target probabilities of failure in DNV-ST-F101. This is based on the selection of a more extreme value of the distribution of lateral friction (P1 vs. P5) and the way in which the calibration of F110 was performed.

The improvements of the proposed approach are illustrated by assessing a 12” uninsulated, deep-water pipeline, with a D/t of 15, a length of 25km, high pressure and moderate temperature of 55°C. The results of this case study show that whereas with the current F110 approach, lateral buckling mitigations are needed over 17km of the pipeline, with the approach proposed in this paper, no mitigations are required at all (except conducting an ECA and possibly tightening slightly the weld acceptance criteria over 3km of the pipeline). This improvement would lead to significant cost savings for this pipeline.

The separate sampling of lateral friction and OOS (instead of critical buckling force), introduces the question of how many times the lateral friction should be sampled over a certain length of pipeline. The paper considers two options: sampling at each element (typically 100m long) or sampling at each OOS reference length (typically 1000m long). These two options reflect the two types of uncertainty in lateral friction: general epistemic uncertainty and spatial variability.

The lateral friction sampling approach selected has a significant impact on the results of the assessments, with sampling at each OOS reference length producing more onerous results. The paper describes why this is the case and quantifies the effect through the case study. Based on this, for the assessment of a specific pipeline, the authors recommend the more conservative approach of sampling lateral friction per OOS reference length, unless it can be proven that the variability in lateral friction is consistent with sampling per element (due to high spatial variability).

The modifications described in this paper can be implemented with minimal changes to the approach presented in F110. Moreover, the Python code used to perform the probabilistic buckle formation runs, with the changes detailed above, has been released under an open-source license to allow the pipeline community to use the code together with the methodology presented in this paper. Access to the code can be provided upon request via email and it is the intention of the authors to encourage the pipeline community to review and adopt the code and to develop it further in a collaborative approach, for the benefit of the industry.

RECOMMENDATIONS

In the preparation of this paper, the authors have identified a number of aspects of the current methodologies that could be updated. The paper addresses some of those aspects through small modifications, but others remain. It is recommended that these aspects, listed below, are addressed before more complex approaches for lateral buckling design are considered:

- Review and update the OOS distributions, taking into account additional operational experience. This is particularly necessary for route curves and sleepers.
- Quantify the significance of spatial variability of lateral friction along a pipeline vs. the overall epistemic uncertainty to be able to propose how to determine the most suitable sampling method for this important parameter.
- Impact of the build-up of soil berms on the formation of lateral buckles in proximity of other existing buckles.
- Prediction of lateral buckling response using simplified VAS models in cases with non-uniform temperature gradients along the VAS length (and in particular when these profiles are non-linear), including the impact of this on the model shape expected to develop.

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