Retrospective Analysis of the Lateral OOS and Buckling Response of Operational Deep-Water Pipelines

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ABSTRACT

This paper examines the lateral buckling response of the pipelines in a deep-water field. This includes retrospective probabilistic analyses as per DNV-RP-F110, a review of the available survey data and a comparison of the predictions of the analyses with the actual observed responses. From the reviews of the data and the results of the comparisons, aspects of the design code that could be improved are identified and recommendations are made. The paper also reviews the published pipeline out-of-straightness data and makes recommendations on how to improve it for use in probabilistic lateral buckling assessments.

KEY WORDS: Pipelines; Lateral Buckling; Out-of-Straightness; Retrospective Analysis; Probabilistic Design; Survey Data; Mechanics.

NOMENCLATURE

CBF	Critical Buckling Force
DP	Dynamic Positioning
EI	Bending Stiffness
FE	Finite Element
LB	Lateral Buckling
NOD	Nominal Outer Diameter
OOS	Out-of-Straightness
PDF	Probability Density Function
PIP	Pipe-in-Pipe
Px	Value with an x% probability of non-exceedance
SP	Single Pipe
SLP	Sleeper
TDP	Touch Down Point
ZRB	Zero Radius Bend

INTRODUCTION

The lateral buckling response of surface-laid pipelines is very sensitive to the many out-of-straightness (OOS) features that are found along the actual, as-laid configuration of the pipeline.

Some of these are vertical features created by the seabed bathymetry. Some are deliberately introduced (either in the vertical or horizontal plane) as mitigations to trigger lateral buckles at specific locations. Both types of features can obviously be considered in the design.

But pipelines also contain many imperfections in the horizontal plane that are randomly introduced during pipelay. These are small deviations from the theoretical pipeline route that are unintended and therefore cannot be known or predicted at the design stage. For pipelines in reasonably flat seabeds, most OOS features (other than the mitigation measures) are generated in this random manner. This makes lateral buckling design a process with a lot of uncertainty.

One of the approaches used by the industry to deal with this uncertainty is to perform probabilistic lateral buckling assessments, using Monte Carlo simulations. This type of approach is described for example in DNV-RP-F110 (2021) and discussed in Ripoll et al. (2023).

Although the use of probabilistic assessments provides a way of addressing the uncertainty in the OOS features of the as-laid pipelines, it requires the definition of probability density functions for these features.

At present, the only published distributions of pipeline OOS are those in DNV-RP-F110. These distributions were developed in the context of the Safebuck JIP (Bruton and Carr, 2008; Cosham et al., 2009), using as-laid survey data from pipelines laid on flat or moderately uneven seabeds.

These distributions are discussed in the next section of this paper. It is worth noting, however, that in the guidance provided in DNV-RP-F110, it is stated that the data should be used ‘in the absence of more specific data’ and that ‘care should be taken in its application’.

Some installation Contractors are also collating survey data and trying to develop their own specific distributions.

In practice, however, since no other agreed data and post-processing methodology are available, probabilistic lateral buckling assessments tend to consider the OOS distributions in DNV-RP-F110. These assessments tend to predict high probabilities of unplanned buckling in route curves with industry standard radius of curvature. Moreover, when simple sleepers are used as buckle initiators, it tends to be difficult to ensure that unplanned buckles on route curves do not replace planned buckles at the sleepers. This is because the critical buckling force distributions for unplanned buckles within route curves and for simple sleepers typically overlap when the OOS distributions in DNV-RP-F110 are used.

In cases where unplanned buckles have to be avoided, this forces the designer to use buckle initiators with very low critical buckling forces, such as sleepers with pushing or pulling mechanisms or ZRBs; both of which are significantly more expensive than simple sleepers. The type of initiator needed, however, is very dependent on the OOS distributions used in the assessments, which, as noted above, are far from certain.

In order to assess the validity of the OOS distributions in DNV-RP-F110, the data available for the pipelines in a large, deep-water field that has been in operation for a few years has been assessed. This includes 21 flowlines, with a total length of 130km, including small diameter single pipes and heavy PIP pipelines. The data available includes positional and embedment data, collected during the as-laid and as-built surveys and in two additional surveys with the pipelines in operation.

The pipelines in this field were designed before the probabilistic lateral buckling methodologies were fully developed and before the OOS distributions currently in DNV-RP-F110 were generated. These assessments have now been performed as blind assessments using the DNV-RP-F110 OOS distributions, i.e. as they would be performed at design stage, before pipelay.

These probabilistic simulations are used to predict the number and locations of the buckles likely to develop. The anticipated number and positions of the buckles from this blind exercise are then compared with the actual number and locations observed in the available pipeline surveys. An analysis of the available survey data is also presented.

These assessments are conducted mainly to evaluate the validity of the OOS data presented in DNV-RP-F110 and to improve future designs.

The available survey data also includes pipe embedments along the pipeline routes. This parameter is correlated with the pipe-soil interaction, which is another aspect that brings significant uncertainty to lateral buckling design. The embedments recorded are assessed and compared to the values predicted in design. In the comparisons of the predicted and observed lateral buckling responses, the potential influence of the pipe-soil interaction design parameters is also considered. The spatial variability of embedment is also assessed.

End expansions recorded in operation are also compared to the predictions of the probabilistic lateral buckling assessments.

EXISTING INDUSTRY OOS DATA

OOS distributions are key to perform probabilistic lateral buckling designs. In this section, the limited data that has been published is reviewed and summarised.

It is important to note that it is difficult to measure the in-plane geometry of an installed pipeline with sufficient accuracy to capture its OOS features. Although we cannot comment on the quality of the data used to generate the distributions discussed below, some of the data from the project discussed in this paper illustrate how some regular as-laid and as-built surveys are not suitable to identify OOS features.

Safebuck JIP Data

Most of the OOS data that has been published was originally gathered and processed for the Safebuck JIP. Although this data was originally confidential and only available to the members of the JIP, the distributions generated from the data were incorporated into DNV-RP-F110 and so they are now available to the industry.

The first OOS distributions were proposed in 2004 and generated from the survey data of just 4 pipelines. At this stage, OOS was defined as the pipeline curvature, normalised by a reference length (proportional to the pipe bending stiffness and inversely proportional to the lateral soil resistance) and the distribution was defined for the maximum OOS feature over a 2km section for nominally straight sections of pipeline. For route curves, a distribution was created for the ratio of the minimum radius of curvature over the nominal value, using the very limited results of the survey data at the snake-lay crowns of 2 pipelines.

Although this is a convenient way of obtaining OOS results by simple post-processing of survey data, it was realised that peak curvature is not sufficient to capture the effect of the OOS on the axial compression at which a buckle is triggered.

A similar conclusion was reached by Rathbone et al. (2008), which considered alternative geometrical parameters to capture the effect of the OOS, such as the heading change (considering each OOS as a small snake-lay crown), but without convincing results.

A more cumbersome, but pragmatic approach was adopted from the 2008 version of the Safebuck guidelines. Instead of trying to identify the set of geometric parameters that fully define the OOS feature, the full survey data is used as the input of an FE analysis (with a certain lateral friction) and the axial force at which a buckle is triggered is recorded. This force can then be compared to the value predicted by an analytical equation (with the same lateral friction) and the ratio of forces captures the effect of the OOS. This ratio would depend to some extent of the lateral friction considered, but the sensitivities performed for the JIP suggested the sensitivity was sufficiently small to adopt this approach.

Although it requires FE analyses for all survey data, this is considered the best approach proposed to date to define horizontal OOS features.

Following this approach, survey data was processed for nominally straight sections, route curves and pipelines over sleepers, using as a reference the analytical equation of the Hobbs infinite mode, route curve stability and upheaval buckling respectively for each of the three cases.

For nominally straight sections and route curves, this introduces the need for a notion of reference length, as individual features are not identified but instead, the most severe feature in the reference length buckles in the FE model. In the analyses performed for the Safebuck JIP, the survey data was split in 1km long sections and so the reference length of the distributions generated is 1km for nominally straight sections and the minimum of 1km and the length of the route curve for route curves.

The OOS distributions that were presented in the last Safebuck guidelines and are now included in DNV-RP-F110 were generated from the survey data of 20 pipelines with a total length 434 km for nominally straight sections and 182 route curves. For sleepers, the distribution was developed from around 40 sleepers from one project.

The final version of the Safebuck JIP guidelines only provided one distribution for the OOS in nominally straight sections. The distribution was intended as a best fit for all the data available. But the data available showed significant variability in the distributions of the different pipelines; in particular for those with lower bending stiffness. When this was incorporated into DNV-RP-F110, three distributions were proposed instead, the Safebuck best fit, but also a lower bound and an upper bound. These distributions, together with the distributions for each of the pipelines for which data was available, are illustrated in Figure 1, taken from DNV-RP-F110.

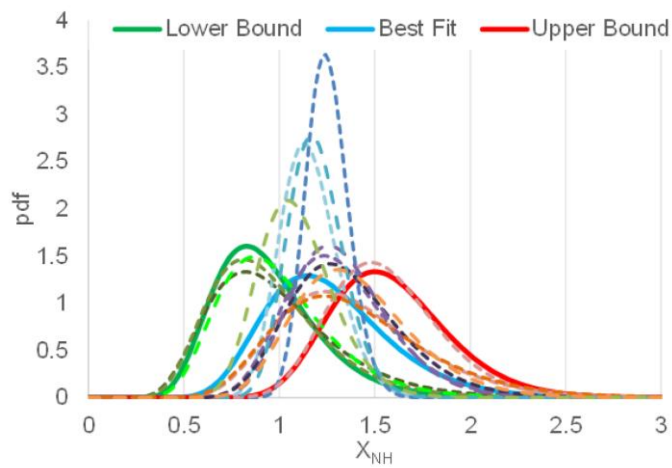

Fig. 1. Probability Distribution Function for X_{NH} (OOS parameter for nominally straight sections in DNV-RP-F110 (2021))

As shown in the figure, there is a significant spread and using only the best fit distribution could significantly underestimate the severity of OOS features for some pipelines. Although the RP (and indeed also the Safebuck guidelines) warn against the uncertainty in these distributions and recommend performing sensitivities, it is not unusual to see designs that only consider the original best fit distribution.

It would seem reasonable to expect that the OOS distributions would depend on a combination of bottom lay tension, type of pipelay vessel (DP vs. anchored) and metocean conditions during installation. But the data available does not allow identifying or quantifying these trends.

The Safebuck distributions were developed for pipelines laid on flat or moderately uneven seabeds. For this reason only 2D survey data was initially used to develop the OOS distributions. At a certain point, however, 3D survey data was included and is part of the data shown in Figure 1 and used to produce the distributions in DNV-RP-F110 (although these are still only valid for pipelines laid on flat or moderately uneven seabeds).

Whereas it makes sense to try and develop distributions for horizontal OOS features, it is not clear how incorporating into the data vertical OOS is appropriate, as this has to be very specific to a given location and not a random effect. It would seem more reasonable to have distributions that cover only horizontal OOS (generated from 2D) and to consider separately the vertical OOS, taking into account the bathymetry along each pipeline (possibly with a certain variability to cover the conditions within the pipelay corridor).

In the case of route curves, it is harder to produce distributions for each pipeline, as the number of curves in each pipeline is never sufficient. Instead, all route curves are combined to produce a single distribution, that is quite wide. Although this is probably the best that can be done with the data available, it could hide a situation with different distributions (as shown in Figure 1 for the nominal straight sections). It is then not possible to consider narrower distributions and perform sensitivities to the different distributions, which could produce different results for the probabilistic lateral buckling design.

Finally, both the data for nominally straight sections and for route curves only consider the worst OOS feature either within 1km or within the curve. This value was probably selected as it was expected that buckles would not form at closer spacing. However, as will be shown in the pipelines of the project described in this paper, buckles at closer spacing are not uncommon. It is not clear, if the DNV-RP-F110 distributions are suitable to capture these situations. It would be interesting to rerun the FE buckling analysis of the original data but with shorter section lengths and to compare the differences when the analytical reference length conversions are applied.

Saipem Data

Laye et al. (2019) presented an assessment of the Saipem OOS survey data, from 58 pipelines with a total length of 457km. This is indeed a significant set of data, comparable to the data used to develop the distributions in DNV-RP-F110.

Although this data is not publicly available, the details presented in the paper show that it has most of the necessary metadata to try and identify how the OOS data changes with the various parameters of a project, such as a pipelay vessel, bottom lay tension, pipe bending stiffness, soil conditions, etc. Indeed this is what the paper tries to do, using machine learning techniques.

The analysis suggests that more severe OOS features are encountered in areas with high pipe embedment and lateral pipe-soil friction. It also shows a correlation between the severity of the OOS features and the water depth (possibly due to the more prevalent use of J-lay in deep waters and S-lay in shallower waters, that will typically result in lower bottom lay tensions in deep waters). In general, both findings seem to match what could be expected and are both things that are currently not captured by the DNV-RP-F110 data and distributions.

In the processing of the survey data, the OOS features are described using peak curvatures (over 1km reference lengths, after a certain mathematical smoothing). This parameter is known to be inadequate to capture the effect of OOS features on the axial compression at which a buckle is triggered and so the results are not valid as such. However, the data set and some aspects of the data processing presented are clearly valuable and could be used to improve the DNV-RP-F110 distributions.

PROJECT DESCRIPTION

The pipelines considered in this paper were installed in deep waters, using a DP J-lay vessel, with a small residual lay tension. The seabed is mainly flat, with a soft clay surface layer, where the pipelines were expected to have a significant embedment.

The single pipes are uninsulated and have an operating inlet temperature and pressure of about 50°C and 300barg. The PIP pipelines have an operating inlet temperature and pressure of about 80°C 200 barg. The details of the pipelines in the field are summarised in Tables 1 and 2.

Table 1. Linepipe Data

Line	NOD	EI [MNm^2]	SW (empty/Op) [N/m]
SP01	12”	38	350 / 600
SP02			350 / 1100
SP03			
SP04			
SP05			
SP06			
SP07			
SP08			
SP09	10”	21	300 / 800
SP10			
PIP01	12” in 16”	158	2700 / 3300
PIP02			
PIP03			
PIP04			
PIP05			
PIP06	10” in 14”	94	2100 / 2500
PIP07			
PIP08			
PIP09			
PIP10			
PIP11			

Table 2. Pipeline Data

Line	Length [km]	Route Curve Radius [m]	LB Mitigations
SP01	32	2000	None
SP02	2.4	N/A	None
SP03	3.4	N/A	None
SP04	2.0	N/A	None
SP05	5.6	2000	1No 0.9m high SLP
SP06	5.4	2000	1No 0.9m high SLP
SP07	2.8	N/A	None
SP08	3.9	1400	None
SP09	22.1	1000 & 1500	5No 0.9m high SLP
SP10	10.4	1200 & 1500	2No 0.9m high SLP
PIP01	1.5	N/A	None
PIP02	2.1	N/A	None
PIP03	4.7	N/A	None
PIP04	3.4	N/A	None
PIP05	5.6	1500	None
PIP06	7.3	1500	None
PIP07	7.2	1500	None
PIP08	1.8	2000	None
PIP09	1.7	N/A	None
PIP10	1.8	N/A	None
PIP11	1.5	N/A	None

PROJECT SURVEY DATA ANALYSIS

The pipelines considered in this paper were surveyed before and after being pressure tested (as-laid and as-build surveys) and then twice once in operation; the first one shortly after start-up and the second one five years later. The data includes 100km of nominally straight pipeline and 18km of route curves.

OOS Features

An initial exploration of the positional survey data was conducted to try and extract OOS features and perform a statistical assessment. The comparisons of the different surveys however, highlighted the limited quality of the data, as illustrated in Figure 2, at least for the pre-operational data. Based on this, it was concluded that there was no point in conducting an FE OOS processing on the pre-operational data. Smoothing the data using mathematical methods without a physical sense was not considered reliable.

Processing of the post-operating data could be performed (excluding buckled areas), although this would have a limited value, as the results would be biased by losing the features where buckles ended up forming, and so this was not done either.

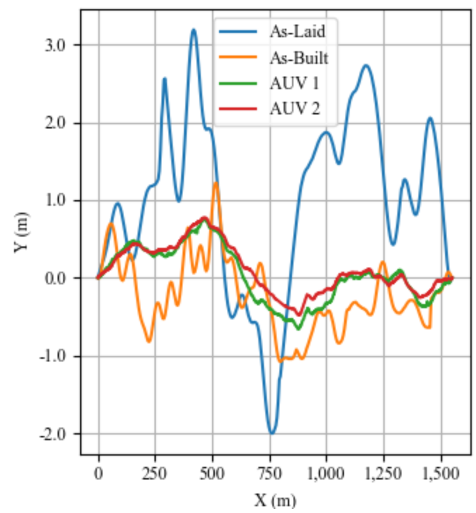

Fig. 2. Example of Survey Data with Insufficient Quality for OOS Identification

The good match between the two post-operating surveys confirms that it is possible to obtain good survey data. It is expected that the survey data used to develop the DNV-RP-F110 distributions and the Saipem data are of better quality than the pre-operation surveys of this project, as otherwise the distributions generated would have limited value.

Pipe Embedment

The pre-operation pipe embedments have been compared to the values predicted in design, using the seabed elevations adjacent to the pipe. When the values recorded along the routes of all the single pipes are grouped, it is found that the mean value is nearly double the best estimate calculated in design and the P95 value more than 50% higher than the P95 design value. The P5 value observed matches quite well the P5 design value. The values along the PIP routes match well the design P5, BE and P95 values.

These comparisons are made against the embedment predictions made using the formulations available at the time of the design, which have since then been improved, so there is no point in concluding about the accuracy of the design calculations. However, the underestimation in the pipe embedments for the single pipes could result in an underestimation in the lateral pipe-soil resistance, which could have an influence in the lateral buckling predictions of the blind analyses and their comparison to the observed responses in the next section.

The embedment along SP09 is shown in Figure 3, as a representative illustration of the values and variability observed along the pipelines in the field. If pipe embedment is considered as a proxy for lateral pipe-soil resistance, the figure illustrates the two types of uncertainty in this parameter: epistemic and spatial uncertainty. In this particular case, the actual value ended up mostly aligned with the high estimate prediction. On top of that, some spatial variability can be seen, as the values deviate from the mean observed value. These results suggest that, in this field at least, the uncertainty in lateral pipe-soil resistance is a combination of both types of uncertainty.

The significance of the type of uncertainty in lateral pipe-soil resistance in the context of probabilistic lateral buckling modelling is discussed in Ripoll et al. (2023), where it is shown this has a significant effect on the results of the analyses.

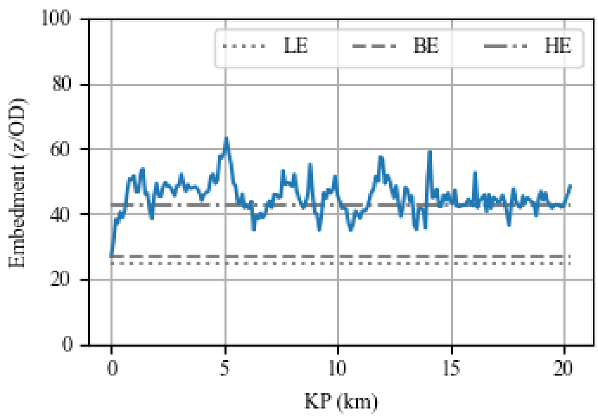

Fig. 3. SP09 Embedment (100m gauge length rolling average)

Details on the locations where buckle formed in operation are discussed after the probabilistic lateral buckling blind analyses are presented.

PROBABILISTIC LATERAL BUCKLING ANALYSES

Methodology

Probabilistic lateral buckling assessments were performed for the 21 pipelines presented in Table 1. The calculations were performed using Buckfast, the software developed for Safebuck (Cosham et al., 2009).

The assessments were performed as a blind exercise, i.e. without using any data gathered after installation, for the final design configurations, i.e. with the proposed lateral buckling mitigations where appropriate.

The Buckfast assessments considered one million Monte Carlo simulations. The critical buckling force distributions were derived using the formulations in DNV-RP-F110, with the design lateral friction distributions and the best estimate OOS distributions.

The CBF distributions for unplanned buckles on route curves and for planned buckles on 0.9m high sleepers for pipeline SP09 are presented in Figure 4. The distributions illustrate how unplanned buckles in the route curves are likely (even expected) to replace planned buckles on the sleepers.

It should be noted that some of the sleepers in this field were located within route curves. This is likely to have some effect on the force at which the buckles trigger (compared to sleepers on nominally straight sections). However since no formulation specific for sleepers in route curves is available, the standard formulation for sleepers in straight sections has been used.

From these Monte Carlo simulations, the probabilities of buckle formation along the pipeline routes are predicted. These results are then compared with the observed response of the pipelines in operation.

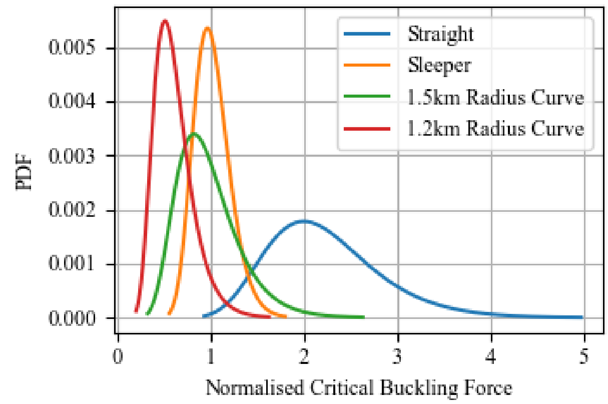

Fig. 4. PDF for the CBF for Unplanned Buckles in Route Curves and nominally straight sections and for Planned Buckles on Sleeper – Normalised by Mean of CBF at Sleeper

Blind Predictions and Comparison to Observed Pipeline Response

For the pipelines shorter than 3.9km, no buckles were predicted in more than 1% of the simulations and no buckles were observed. For the remaining pipelines, the number of buckles predicted by the blind probabilistic analyses are presented in Table 3 and the details of the buckles that actually formed are presented in Table 4.

For all the pipelines, the number of buckles observed is within the predicted range. In most cases, however, the mode (the most likely value) underestimates the number of buckles observed.

In general, the observed buckles developed in areas predicted to have high probabilities of buckling, but with some exceptions.

The results of the blind probabilistic analyses suggest a very poor reliability of the sleepers introduced in the design. As shown in Table 5, the probability of buckling predicted at the sleepers is very low (less than 40%). For sleepers located within route curves, the probabilities are even lower (between 1 and 5%).

This poor reliability anticipated for the sleepers is due to unplanned buckles on the route curves replacing the buckles at the sleepers (as discussed in the previous section and illustrated in Figure 4). In reality, however, all sleepers buckled as intended by the lateral buckling mitigation plan (100% success rate) and there was no replacement by unplanned buckles in route curves. This suggests that the CBF distributions for sleepers overestimate the actual response, in particular for sleepers in route curves.

Nevertheless, 29 unplanned buckles formed, 20 of them within route curves. Two examples of pipelines with a high number of unplanned buckles in route curves are presented in Figures 5 and 6.

Table 3. Number of Buckles Predicted in Operation

Line	Minimum	Maximum	P1	P99	Mode
SP01	1	26	4	17	12
SP05	0	4	0	1	1
SP06	0	6	0	2	2
SP08	0	4	0	1	1
SP09	2	20	4	10	7
SP10	0	10	1	4	3
PIP03	0	4	0	1	0
PIP05	0	6	0	2	0
PIP06	0	7	0	2	1
PIP07	0	8	0	2	1

Table 4. Number of Buckles Observed (in square brackets, number of buckles after hydrotest if different from operation)

Line	Planned		Unplanned		Total
	Straight	Curve	Straight	Curve	
SP01	0	0	6 [5]	4	10 [9]
SP05	0	1	0	0	1
SP06	0	1	0	3	4
SP08	0	0	0	2	2
SP09	2	3	2	4	11
SP10	2	0	1	5 [3]	8 [6]
PIP03	0	0	0	0	0
PIP05	0	0	0	1	1
PIP06	0	0	0	1 [0]	1 [0]
PIP07	0	0	0	0	0

Table 5. Buckling at Sleeper Locations

Line	Sleeper in Route Curve	Probability of Buckling Predicted	Observed Response
SP05	Yes	5%	Yes
SP06	Yes	2%	Yes
SP09	No	20%	Yes
	Yes	1%	Yes
	Yes	1%	Yes
	Yes	2%	Yes
	No	20%	Yes
SP10	No	25%	Yes
	No	40%	Yes

Figure 5 shows a case with several unplanned buckles forming within the route curve, in proximity of the planned buckle at the sleeper but without replacing it. The 4 buckles observed are within the range predicted (0 to 6).

Figure 6 shows a case with a large number of unplanned buckles, concentrating at the route curves. In this case, one of the unplanned buckles formed less than 1.5km from the pipe end, in the nominally straight section before the route curve (not too far from an ILT).

For this pipeline, although the observed number of buckles (8) is within the predicted range (0 to 8), Figure 6 shows how these buckles concentrate in the route curves and have developed in very close proximity. It is hard to tell if all these buckles formed at the same time or if the development of berms led to the adjacent buckles under higher temperature or pressure.

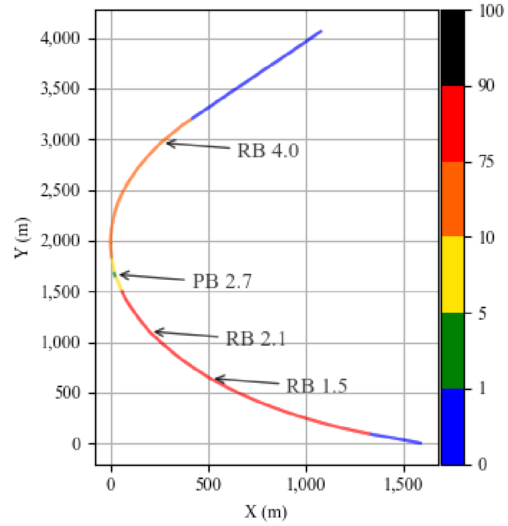

Fig. 5. Predicted Probabilities of Buckling along SP06 (colour scale) Together with Actual Buckles observed (RB – unplanned buckles, PB – planned buckles)

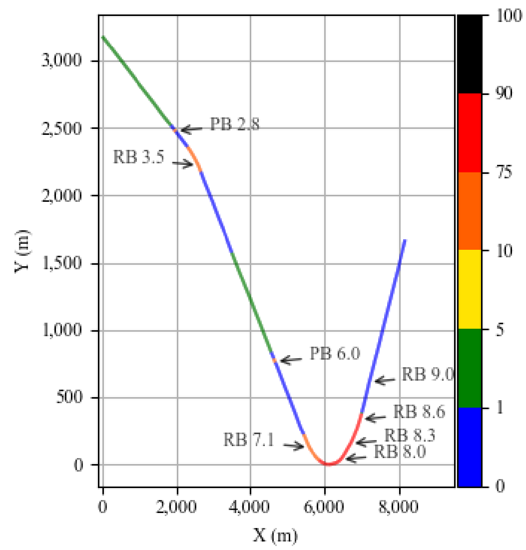

Fig. 6. Predicted Probabilities of Buckling along SP10 (colour scale) Together with Actual Buckles observed (RB – unplanned buckles, PB – planned buckles)

Based on these results, the following is suggested:

- The axial friction may be underestimated (buckles too close to the pipeline ends and some buckles in very close proximity – in some cases as close as 300m). As noted later, this could be supported by the measured end expansions.
- The post-buckling force used in the blind assessments (based on Hobbs formulation for a mode 3, with the lower bound lateral breakout friction) could underestimate the actual values. This would be consistent with the berms observed in some of the buckles and presented in the next section.
- The CBF distributions for nominally straight sections are probably

- overestimated (buckles observed in sections with low predicted probability of buckling). This would be consistent with the fact that only the BE OOS distribution was used in the predictions and confirms the importance of running sensitivities with the lower and upper bound distributions in DNV-RP-F110.
- The results obtained do not suggest that the CBF distributions for the route curves are underestimated (as suspected before this exercise was conducted). If anything, the distributions could be overestimated based on the number of unplanned buckles that have been observed along route curves.

Assessment of Available Field Data – Buckling Predictors

Once the blind assessments and comparison to the observed pipeline response had been completed, the pre-operation surveys were reviewed to look for parameters that could have predicted the locations where buckles formed in operation.

At these locations, there was no distinguishable features in terms of overall geometry or peak curvatures in the as-laid condition. For the curvature, this would be as expected. But the main problem is that the quality of the as-laid survey was not sufficient for this check.

It is interesting to note that the pipelines could be laid over sleepers located within route curves due to the low bottom lay tensions applied. It is hard to be certain due to the poor quality of the as-laid survey, but it would seem that in the section around the sleeper, the radius of the route curve is not maintained, but a certain overall OOS remains (probably more severe than at sleepers in nominally straight sections).

A review of the embedments at the locations where buckles formed when the pipelines were put in operation, indicates that these values were generally within the P25 to P75 of the measured values. This suggests that buckles did not form at locations where lateral friction was particularly low and therefore that spatial variability in soil properties was not a dominant factor in where buckles formed.

Assessment of Available Field Data – Buckling Configurations

As shown in Table 4, out of the total 38 buckles identified in operation, 34 formed during hydrotest.

A summary of the mode shapes of the buckles is presented in Table 6 for all the buckles identified in the field. The results indicate that all buckles ended up with a mode 3 shape (although it is hard to distinguish mode 1 and mode 3 shapes).

At two planned buckles within nominally straight sections, buckles initially formed into a mode 2 shape, but in both cases, these eventually re-arranged into a mode 3.

An example of a mode 2 and a mode 3 buckle over a sleeper is presented in Figure 7.

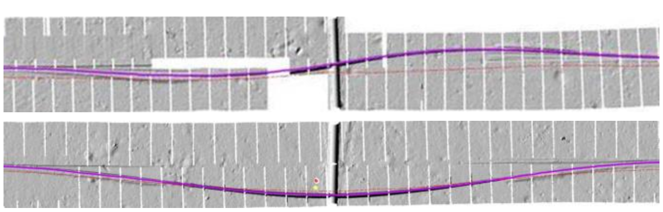

Fig. 7. Example of Mode 2 and Mode 3 over a sleepers

Table 6. Lateral Buckles in Operation

Line	KP	Location		Mode Shape	Berms
		Planned	Straight/Curve		
SP01	2.8	No	Curve	3	Data available not sufficient to determine
	5.9	No	Straight	3	
	9.1	No	Curve	3	
	10.5	No	Straight	3	
	14.4	No	Curve	3	
	19.4	No	Straight	3	
	23.4	No	Straight	3	
	25.0	No	Straight	3	
	27.3	No	Straight	3	
	29.1	No	Curve	3	
SP05	2.8	Yes	Curve	3	Yes at TDP
SP06	1.5	No	Curve	3	Yes
	2.1	No	Curve	3	Yes
	2.7	Yes	Curve	3	Yes at TDP
	4.0	No	Curve	3	Yes
SP8	1.4	No	Curve	3	Yes
	2.2	No	Curve	3	Yes
SP09	2.8	Yes	Straight	3	Yes at TDP
	5.7	Yes	Curve	3	Yes at TDP
	9.1	Yes	Curve	3	Yes at TDP
	9.8	No	Curve	3	Yes
	11.5	No	Straight	3	Yes
	13.2	Yes	Curve	3	No
	16.1	No	Curve	3	Yes
	16.5	No	Curve	3	No
	16.9	No	Curve	3	Yes
	17.7	Yes	Straight	2 - >3	Yes at TDP
	18.2	No	Straight	3	Yes
SP10	2.8	Yes	Straight	2 - >3	Yes at TDP
	3.5	No	Curve	3	Yes
	6.0	Yes	Straight	3	Yes at TDP
	7.1	No	Curve	3	Yes
	8.0	No	Curve	3	Yes
	8.3	No	Curve	3	Yes
	8.6	No	Curve	3	Yes
	9.0	No	Straight	3	Yes
PIP05	4.5	No	Curve	3	Yes
PIP06	4.5	No	Curve	3	Yes

Table 6 also reports the buckles where a significant berm is visible (defined as being higher than the top of pipe). As shown, most buckles have a berm higher than the top of pipe. Even for buckles over sleepers, berms are observed on the part of the buckles on the seabed. This widespread presence of berms is no doubt encouraged by the generally very high embedment along the pipelines. The presence of berms suggests that the post-buckling forces have been underestimated.

An example of one of the berms is presented in Figure 8.

Fig. 8. Example of Berm identified at Buckle Location

CONCLUSIONS

This paper has presented the retrospective analysis of the lateral buckling response of the pipelines in a deep-water field using the DNV-RP-F110 probabilistic method and compared the predictions to the observed response of the pipelines. The objective was to use the results of these comparisons to identify areas of improvement in the design code. Particular emphasis was placed on the OOS distributions required to perform the probabilistic assessments.

The OOS data and distributions that are publicly available have been reviewed and the method to quantify these features assessed. It is clear that peak curvature alone cannot be used to characterise OOS features. Instead, the most promising approach seems to be to use FE analyses on the survey data to quantify the severity of the features by determining the level of axial force at which they buckle.

In any case, it is clear that good quality surveys are required to be able to assess OOS features. Unfortunately, the pre-operation survey data available for the pipelines considered in this paper was not of sufficient quality to extract OOS features and develop OOS distributions for comparison against the ones proposed in DNV-RP-F110.

The observed response of the pipelines in operation shows a satisfactory lateral buckling response of all the pipelines in the field. Buckles formed at all planned locations where sleepers had been introduced and although a significant number of unplanned buckles formed (mostly within route curves), the conditions at all these buckles are acceptable.

However, some of the observed responses did not match the predictions of the retrospective analyses. From these disparities, the following is concluded:

- The DNV-RP-F110 CBF distributions overestimate the buckling loads at sleepers, in particular for sleepers on route curves.
- The DNV-RP-F110 CBF distributions do not underestimate the buckling loads at unplanned buckles in route curves (as suspected before this exercise was conducted). If anything, the distributions may overestimate the actual response.

The close proximity of some unplanned buckles and the observation of berms at almost all buckles suggest that the post-buckling force at buckles is underestimated in the retrospective analyses. Similarly, the axial friction may have also been underestimated.

The use of the best fit OOS distributions for unplanned buckles in nominally straight sections leads to underestimating the number of this type of buckles. This highlights the importance of running sensitivities to the lower and upper bound OOS distributions in DNV-RP-F110.

RECOMMENDATIONS

In order to continue improving lateral buckling designs, the following is recommended:

- Develop improved OOS distributions for nominally straight sections, route curves and sleepers (both in straight and route curves). The industry should collaborate to collate good quality survey data and define an agreed methodology to process the data required to define the OOS distributions (based on an FE approach as described in this paper). The data should be provided with all relevant metadata to assess the possibility of generating families of OOS distributions for more specific scenarios, i.e. pipelay method, severity of metocean conditions during pipeline, etc. This exercise should be performed using shorter reference lengths that considered in the DNV-RP-F110 data.
- Develop a methodology to consider the influence of the lateral soil mobilisation on the evolution of OOS features (from initial to buckle onset), as this can have an influence on the CBF.
- Develop a methodology to consider in the probabilistic analyses the interaction between the OOS features in the vertical plane (created by seabed bathymetry) and the lateral plane (created by pipelay process). This should be done by sampling independently vertical (large spatial variability dependant of the seabed roughness but small epistemic uncertainty) and lateral (as currently done) OOS along the pipeline route.
- For pipelines that are not designed to be completely stable, develop methods allowing to combine OOS distributions with the effect of hydrodynamic loading in the probabilistic assessments.

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