# Analysis of Horizontal Out-of-Straightness Survey Data for use in Probabilistic Lateral Buckling Design

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## Abstract

The lateral buckling design of surface-laid, subsea pipelines can be optimised by using probabilistic design methods. In areas where the seabed has limited vertical unevenness, the key inputs used in these Monte Carlo simulations are the probability distributions for the pipe-soil interaction and for the lateral out-of-straightness (OOS).

For the pipe-soil interaction response, physical models have been developed based on experimental work and geotechnical principles and distributions can be predicted if adequate geotechnical data is available. For the OOS features however, it is not possible to make predictions based on engineering principles, since these features are the result of random deviations from the intended pipeline route during pipelay. Instead, for this parameter, the industry relies mostly on the empirical distributions that were developed by the Safebuck JIP, based on OOS data from pipelines installed before 2014. These distributions are currently presented in DNV-RP-F110 [Ref. 1].

The approach used in the Safebuck JIP to quantify OOS features consists in performing Finite Element analyses of sections of as-laid survey data to determine the axial force at which a buckle forms (with a certain lateral friction). The ratio of this force and the value predicted by a reference analytical equation (with the same lateral friction) represents the effect of the worst OOS feature in the section analysed. By repeating this process for many sections of survey data, distributions of OOS features can be developed.

This paper presents a modified version of the Safebuck approach to process OOS survey data and applies it to the data of pipelines installed as part of a TotalEnergies project.

The approach proposed considers a different scale length than the DNV-RP-F110 distributions, which simplifies the treatment of route curves and allows generating significantly more data from the available survey data.

Sensitivity analyses are also performed to evaluate the robustness of the approach to quantify OOS features, including the effect of the breakout and residual lateral friction and the mobilisation displacements considered in the FE analyses and the appropriateness of the reference analytical equations used in the processing of the FE results.

Based on these results, the paper proposes a detailed methodology to produce a systematic quantification of the OOS features, based on mathematical post-processing and Finite Element modelling of the survey data. The paper also discusses the creation of an industry-wide database of OOS data, intended to gradually improve the OOS distributions available for the design of new pipelines.

## Nomenclature

BE Best Estimate

| | |
|---|---|
| CBF | Critical Buckling Force |
| CoV | Coefficient of Variation |
| DHSS | Dual Head Scanning Sonar |
| DP | Dynamic Positioning |
| D/t | Diameter to Wall Thickness Ratio |
| FE | Finite Element |
| FFT | Fast Fourier Transformation |
| ILT | In-Line Tee |
| IMU | Inertial Measurement Unit |
| INS | Inertial Navigation System |
| IQR | Inter-Quartile Range |
| KP | Kilometric Point |
| LB | Lower Bound |
| LBL | Long Base Line |
| OD | Outer Diameter |
| OOS | Out-of-Straightness |
| PDF | Probability Density Function |
| ROV | Remotely Operated Vehicle |
| STD | Standard Deviation |
| UB | Upper Bound |
| UHB | Upheaval Buckling |
| USBL | Ultra Short Base Line |

## Introduction

The lateral buckling design of surface-laid, subsea pipelines can be optimised by using probabilistic design methods as detailed in Appendix B of DNV-RP-F110 [Ref. 1].

In areas where the seabed has limited vertical unevenness, the key inputs used in these Monte Carlo simulations are the probability distributions for the pipe-soil interaction and for the lateral out-of-straightness (OOS).

For the pipe-soil interaction response, physical models have been developed based on experimental work and geotechnical principles and distributions can be predicted if adequate geotechnical data is available.

For the OOS features however, it is not possible to make predictions based on engineering principles, since these features are the result of random deviations from the intended pipeline route during pipelay. For this parameter instead, it is necessary to define empirical distributions based on survey data of pipelines previously installed.

At present, the industry relies mostly on the empirical OOS distributions that were developed by the Safebuck JIP and are presented in DNV-RP-F110 [Ref. 1]. These distributions were developed from the survey data of 20 pipelines, including 434km of nominally straight sections and 182 route curves.

These distributions are more than 10 years old and so many kilometres of pipeline have been installed since they were developed. Moreover, it is expected that the quality of OOS surveys has generally improved. Finally, it is also considered that the methodology used to develop these distributions could be improved.

This paper only addresses the horizontal OOS introduced randomly during pipelay and does not consider the conditions at engineered buckle triggers or undulating seabeds.

## Objectives

The main objective of this paper is to present a methodology to systematically process OOS survey data, so that old data can be reprocessed and new data can be processed to derive more reliable distributions for use in probabilistic lateral buckling design.

The paper then presents the application of the proposed methodology to the OOS survey data of 12 pipelines with a total length of about 28km to illustrate the process and generate distributions that can be compared to the ones provided in DNV-RP-F110 [Ref. 1].

It also includes a series of sensitivity assessments to evaluate the robustness of the approach proposed to process the survey data and to quantify OOS. This includes the evaluation of different methods to smooth the survey data and an assessment of the influence of the lateral pipe-soil interaction response considered in the FE analyses and the appropriateness of the reference analytical equations used in the processing of the FE results.

Finally, the paper discusses an industry-wide database of OOS data, where anonymised OOS survey data could be shared with appropriate metadata, to allow the development of more reliable and specific OOS distributions for use in the design of new pipelines.

## Out of Straightness Features and Reference Length

Out of straightness features are the geometrical deviations from the design line that are required to trigger global buckling under axial compression. At the simplest level, a feature can be defined as the section between two inflection points along the pipeline. In practice, however, it is the profile of pipeline curvature over a certain length that captures the influence of the pipeline geometry on the critical buckling force. This may be the length between two inflection points, a fraction of this length or a certain concatenation of sections between inflection points. For each particular location, the length of influence will therefore be different, and in any case, it is difficult to define precisely all the individual OOS features along a pipeline.

In probabilistic lateral buckling assessments, the OOS along the pipeline need to be sampled randomly, based on a certain distribution of the expected values.

Since all features have different lengths and their lengths are difficult to define and capture in distributions, sampling OOS features is not really practical.

Instead, a practical approach is to discretise the pipeline into small segments and randomly sample a variable that represents the influence of the pipeline geometry over the segment on its minimum critical buckling force. This approach is used by probabilistic lateral buckling tools such as Buckfast [Ref. 4], Probe [Ref. 5] and BuckPy [Ref. 3].

It is clear that this variable depends on the length of the segment since, as the length of the segment increases, the probability that it includes OOS characteristics that will buckle at a low load also increases. This introduces the need for the concept of scale length in the definition of the OOS parameter.

The distributions currently available were developed for a scale length of 1000m. This means that they predict the minimum critical bucking force over a length of 1000m.

This cannot be used directly in probabilistic lateral buckling assessment, as the locations of buckles need to be predicted with more accuracy than 1000m. To address this, weak link theory is used to derive distributions applicable to shorter lengths.

The length of the segments into which a pipeline is discretised in probabilistic lateral buckling assessments is typically in the order of 100m. This is small enough so that two buckles would not be expected to develop within the length and consistent with the level of accuracy with which the locations of buckles need to be predicted.

This length is also large enough to contain the OOS features that trigger lateral buckles for most pipelines. For the example pipelines considered in this paper, it has been verified that all features triggering buckles had a length significantly shorter than 100m (the largest length of pipeline mobilised at the point of buckling was 49 m). This assumption may need to be confirmed for stiff, large diameter pipelines.

Since the reference length needed in probabilistic lateral buckling analyses is typically in the order of 100m, this paper proposes to develop OOS distributions for a scale length of 100m, instead of the 1000m used for the OOS distributions currently available [Ref. 1].

This selection presents the following advantages:

- It removes the need to scale the OOS distributions for use in probabilistic lateral buckling assessments (which is the only use of these distributions).
- It increases the number of data points that are extracted from processing existing OOS survey data by a factor of 10 and therefore allows producing distributions that are more statistically significant.
- This is particularly interesting for route curves, as inevitably shorter lengths of survey data are available for route curves.

  Moreover, not all route curves have a length of at least 1000m and so it is difficult to combine the statistics for route curves into a single distribution for that reference length. As a result of this, the distribution for route curves developed for the Safebuck JIP and presented in DNV-RP-F110 [Ref. 1] are defined for a reference length equal to the minimum of the curve arc length and 1000m.

  This complication disappears when a reference length of 100m is used.

In the results presented in this paper, a reference length of 100m is always used, except when the distributions are compared to the distributions in DNV-RP-F110 [Ref. 1], which are provided for a reference length of 1000m.

## Characterisation of Effect of Out of Straightness on Buckling Force

There have been several attempts at finding geometrical parameters that could capture the influence of OOS on the critical buckling load. These are discussed in [Ref. 2], where it is shown that no suitable parameters and analytical approach have been found.

Instead, the best approach currently available is the one that was proposed in the 2008 version of the Safebuck guidelines. This consist of introducing the OOS survey data along a certain length of the pipeline into an FE analysis and determining the axial force at which a buckle is triggered with a certain lateral friction.

This force can be compared to the value predicted by an analytical equation (with the same lateral friction) and the ratio of forces obtained. The analytical equations normally used are the Hobbs force for the infinite mode for nominally straight sections and the route curve stability equation for route curves (see [Ref. 1] for details).

These ratios of forces are referred to as $X_{NH}$ for nominally straight sections and $X_{NB}$ for route curves. Distributions of these coefficients capture OOS along pipelines.

The method proposed in this paper to analyse OOS survey data is based on the basic principles of this approach, with some variations in the pre-processing of the OOS survey data and the way the data is introduced into the FE analyses.

## Proposed Survey Data Processing

OOS surveys are performed to determine the as-laid geometry of a pipeline and to quantify its OOS. The survey techniques used for these types of survey try to minimise the error in the data but inevitably survey data has noise.

Before this survey data can be introduced into an FE analysis (as described in the previous section), the noise needs to be removed, as the pipeline will not be able to conform to noisy data without locking significant axial compressions along the pipeline and generating many areas with unrealistic plastic strains (if a model with material non-linearity is used).

This section defines the steps proposed for a standardised approach to prepare OOS survey data, for use in FE analyses to determine the values of $X_{NH}$ and $X_{NB}$.

### ***Step 1: De-Spiking***

The first step consists of de-spiking and correcting outliers in the OOS survey data cloud. This step is often performed by the surveyors, but it is worth ensuring that it has been done correctly to avoid numerical problems in the FE models. It is proposed to apply a Hampel filter to identify and replace outliers based on local statistical deviations.

The Hampel filter works by examining each survey data point with its 10 neighbouring points (5 on each side, for a total window of 11 points), computing the local median and median absolute deviation, and replacing points that deviate significantly from the median with the median value. The Hampel filter is more effective than mean-based filters, since the median is not as sensitive to outliers as the mean. Figure 1 illustrates this process.

### ***Step 2: Initial Noise Filtering***

Even after removing outliers, the survey data is generally too irregular to introduce in the FE model and requires some level of smoothing or noise filtering. As part of the tests performed in the development of this paper, two methods were assessed.

One simple approach could be to perform a Gaussian Kernel smoothing, as it is often done to smooth vertical OOS data for UHB analyses, where the data is two-dimensional, i.e. KP vs. top of pipe water depth.

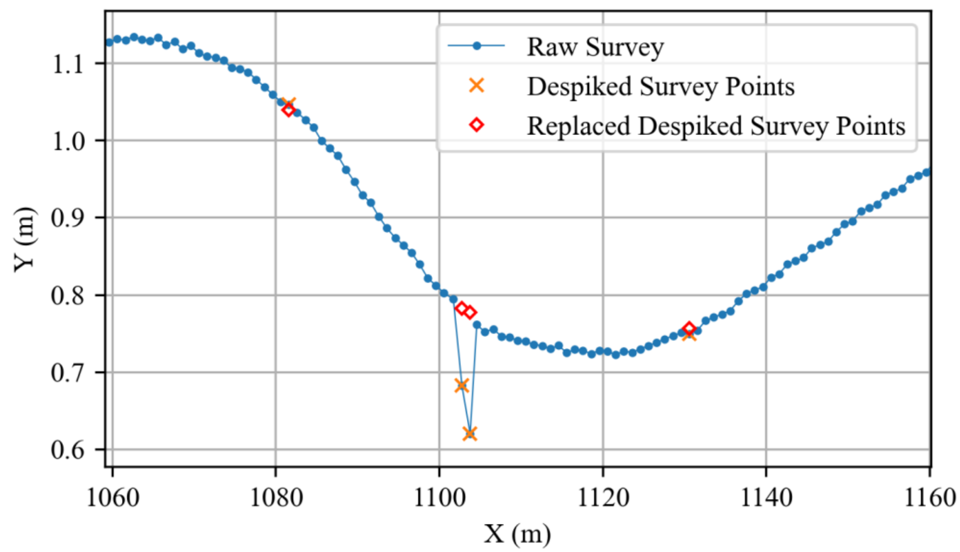


**Figure 1 – Illustration of De-Spiking Applied to Example Data Presented in Paper**

This approach requires selecting some parameters that have no physical meaning (i.e. band width and kernel size) and are therefore somewhat arbitrary. But the main drawback of this approach is its application to route curve areas, where the underlying geometry is not a straight line but a curve with a certain nominal radius.

In order to provide a smoothing method with physically meaningful parameters, FFT processing was considered. In this approach, the survey data is decomposed into sinusoidal harmonics with different wavelengths, therefore allowing noise to be removed through wavelength filtering.

The harmonics in the survey data that are potentially problematic have short wavelengths and either have negligible amplitude, in which case they do not influence the FE results, or have significant amplitude, in which case they affect the FE response but are physically unrealistic. By considering the bending stiffness of the pipe and the wave amplitude that is expected to have an influence on the results, the wave length below which the FFT signal is filtered can be determined. Although some subjectivity remains (and therefore sensitivities are needed), this provides a more objective way of smoothing the survey data.

A comparison the Gaussian versus FFT smoothing is illustrated in Figure 2. As shown in the figure, whereas the FFT filtering can selectively remove short wave length noise whilst preserving the long wave length trends, the weighted average in the Gaussian approach produces a less selective smoothing that can underestimate the size of the OOS features.

In order to apply an FFT filter, however, the data needs to be non-directional. This is possible in nominally straight sections, where KP vs. the deviation from the nominal straight line over a certain length can be used to apply the FFT filter. But this approach becomes a lot more cumbersome for route curves.

Since the geometrical parameter that determines the effect of the OOS on the critical buckling force is the profile of pipeline curvature, one option is to work with the profile of KP vs pipeline curvature.

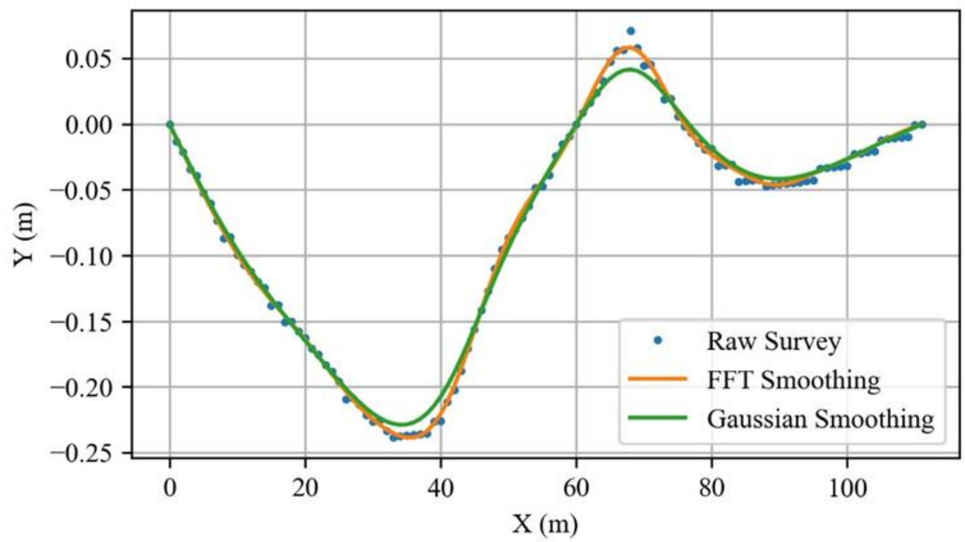


**Figure 2 – Example of Gaussian Smoothing vs. FFT Filter**

Working with the profile of KP vs pipeline curvature has the following advantages:

- It converts the data into a non-directional profile that is suited for FFT filtering and independent of the pipeline heading and whether the data is for a nominally straight section or a route curve.
- The FFT filter provides a method for a noise filtering with a more physical meaning than the alternative methods considered.
- The filtered curvature signal can be used to reconstruct the pipeline route.

  The pipeline route reconstructed from the unfiltered and filtered curvature profile is plotted together with the original survey data in Figure 3. It is clear that filtering the curvature signal can produce a certain drift in the pipeline route.

  However, when the data is plotted at a local scale (the scale at which the pipeline buckles and therefore the OOS features matter), the FFT filtered data provides a suitable smoothing of the survey data (as illustrated in Figure 4).

  It should be noted, however, that as discussed in the next section, the reconstructed route is not used in the FE analyses and it is shown in Figure 3 only to illustrate the effect of the FFT curvature filtering on the apparent pipeline route.
- One interesting advantage of the drift generated by the FFT curvature filtering is that it makes it more difficult to recognise the pipeline route and therefore it is a way of anonymising the survey data. This is an interesting feature for collating OOS survey data into a database shared across the industry to produce more accurate distributions. This is discussed at the end of the paper.

The approach proposed in this paper for the initial filter of the OOS survey data is an FFT filter on the KP vs. pipeline curvature signal. This method is used in the section below to process the OOS data from a series of installed pipelines. In the results, the logic to select the wave length cut off and the sensitivity of the results to this parameter are presented.

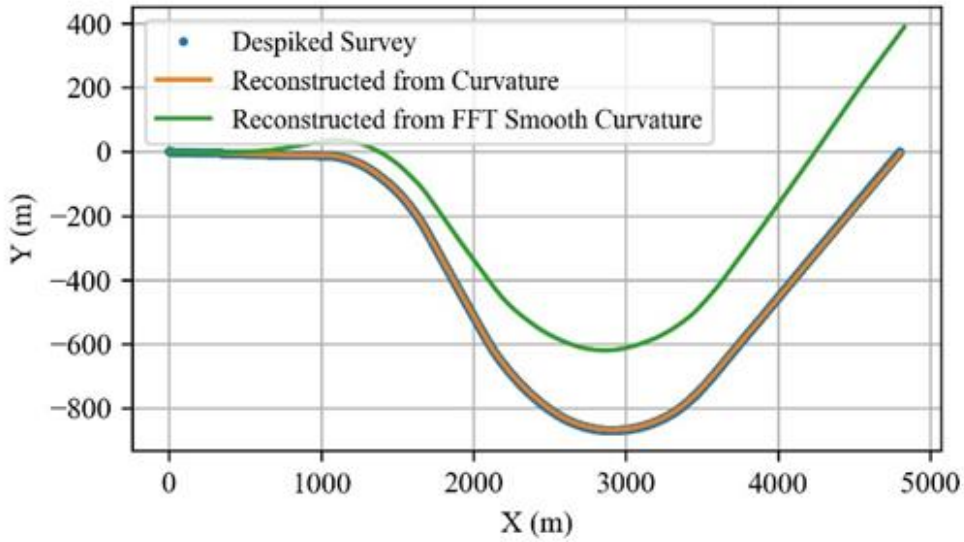


**Figure 3 – Illustration of Route Reconstructed from Curvature Profile with and without FFT Filter (at Overall Scale)**

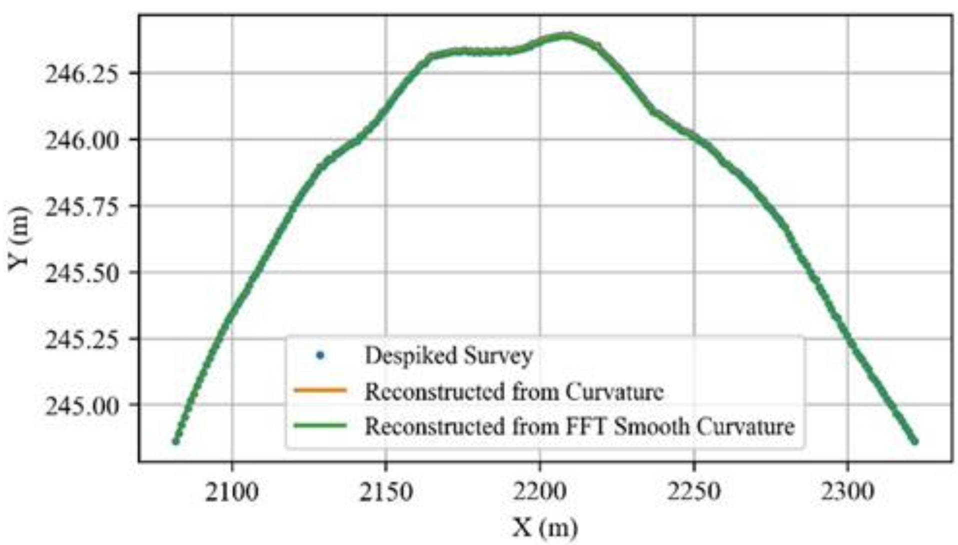


**Figure 4 – Illustration of Route Reconstructed from Curvature Profile with and without FFT Filter (at OOS Feature Scale)**

***Step 3: Finite Element Analysis Model***

The finite element model starts with a straight section of pipe elements representing the length of the pipeline considered plus an extra length of 300m either side of the model to avoid boundary effects. The central section representing the actual pipeline needs to be deformed to obtain the geometry of the smoothed survey data from Step 2.

The obvious way of imposing the smoothed survey data is by applying displacements in the Easting and Northing direction to the nodes of the pipe elements.

A more elegant, simple and robust way to achieve the same is by directly imposing the curvature profile obtained at the end of Step 2. This can be done by converting the curvature profile into a moment profile using the bending stiffness of the pipe, which can then be applied as the moment increment at each node of the pipeline model.

This deformed shape is then laid on a contact surface using the submerged weight of the pipe. Once contact has been established, the applied moments are released, and the pipeline relaxes to some extent, until sufficient lateral friction is mobilised to reach equilibrium. This relaxation constitutes the FE-based smoothing, which should be very small if the OOS data after Steps 1 and 2 is of good quality.

The model is then subjected to axial compression until a buckle forms, and the buckle force is converted to a value of $X_{NH}$ and $X_{NB}$ depending on whether the buckle forms in a nominally straight section or a route curve.

But in order to capture the $X_{NH}$ or $X_{NB}$ for all 100m long sections of the pipeline a series of FE analyses needs to be run. Two ways of addressing this have been considered.

***Option 1: Iterative Blocking FE Models***

One option to capture the $X_{NH}$ or $X_{NB}$ ratios for each 100m section of the pipeline consists of running iterations of the FE model in which the following sequence is implemented:

- The analysis is run until the compressive effective axial force at some point along the model is 10 to 20% lower than the maximum compressive effective axial force at any point along the model.
- The KP of the buckle in the analysis is defined as the point with the smallest effective axial compression at the end of the analysis.
- The area of influence of that buckle is defined as the length of pipeline either side of the KP defined in the previous bullet point until the lateral movement drops to a certain fraction of the movement at the buckle KP (typically 20%). The location of the buckle, its area of influence and buckling load are recorded.
- Another analysis is then launched, in which, after the smoothed survey shape has been imposed and relaxed, an additional restrain is imposed along the pipeline nodes in the area of influence of the buckle determined as detailed in the previous bullet point. This is achieved by restraining the ground nodes of ABAQUS PSI elements connected to the pipe nodes and free to follow the pipe deformation until that step. These PSI elements provide no axial resistance, but a very high lateral resistance with a very small mobilisation displacement.

This process is repeated iteratively, gradually restraining more sections of the pipeline, until at least one buckle has been triggered in each 100m section of the pipeline.

This process works well when the processed survey data at the end of Step 2 is of reasonable quality. However, if the quality of the data in sections of the pipeline is not sufficient and it has not been corrected by Steps 1 and 2 of the survey data processing, this can lead to sections of the model with significant compressions locked after relaxation. This occurs when geometry imposed is unrealistically sharp (if even not to the point of generating plastic strains) and can be kept in compression by the lateral friction. An example of processed survey data leading to these conditions is illustrated in Figure 8.

These effects are clearly unrealistic and make it impractical to run the iterative process described above in the cases where the quality of the data leads to these situations.

One option is to manually clean the section of the curvature profile generating the compression. This works, but it is a subjective process that is not systematic. Another option is to take the relaxed pipeline profile (the FE-based smoothed shape) and re-introduce it into the analysis. This removes the compressions, but as is illustrated later, over-smooths the data over the whole model and is not considered appropriate.

***Option 2: Rolling Window FE Models***

A more efficient way to avoid that small sections of bad survey data affect a significant section of the pipeline is to run the FE models in smaller sections. These models have a 100m long central length, instead of covering the full pipeline length (and the same 300m long section of undeformed pipe either side).

A series of models is created, in which the section of pipeline covered by the 100m long central section is gradually moved along the pipeline in steps of 10 to 20m, i.e. there is significant overlap between models, ensuring that all critical OOS features are captured near the centre of at least one model. Indeed, the same imperfection is often found to initiate buckling with the same force in several rolling window models.

In each model, the KP of the buckle and the buckling load are determined. The models where the buckle forms in the central part of the 100m long section are considered valid (as buckle formation is then not influenced by transition to the side sections where curvatures are not imposed). From the set of valid runs, the minimum buckling force in each 100m section of the pipeline is determined.

These models are efficient, have good convergence and short run times. Although more rolling window models are typically needed than full-length model restarts, the overall computational cost, particularly for long pipelines, is lower in the rolling window approach.

A comparison between the Option 1 and Option 2 approach is presented for the example data shown in the next section, which illustrates that both methods give very similar results, when the survey data is of reasonable quality and does not generate unrealistic compressions in the Option 1 models (see Figure 11). Because of the advantages detailed above, the approach proposed for the systematic processing of OOS data is Option 2.

***Step 4: Results Processing and Determination of $X_{NH}$ and $X_{NB}$ Ratios***

The minimum critical buckling force for each 100m long section is obtained from the Step 3 analyses. These forces are then converted into $X_{NH}$ and $X_{NB}$ ratios for the nominally straight and route curve sections of the pipeline.

In the processing of the $X_{NH}$ and $X_{NB}$ ratios, specific results can be discarded. This includes sections where the survey data does not have sufficient quality or sections with specific features that are not representative of nominally straight or route curve sections laid on the seabed, e.g. buckle initiators, crossings, ILTs, walking mitigations, etc.

Discarding these sections at this final stage is the simplest approach, as it does not require any manipulation of the data. It should be noted, however, that FFT signal processing is sensitive to the entire data set and therefore maintaining these features in the data can affect the FFT signal filtering, that should instead focus on the pipeline sections of interest. In all cases, it will therefore be necessary to perform some sensitivities on the effect of these specific sections on the data processing.

## Example Survey Data Processing and $X_{NH}$ and $X_{NB}$ Distributions

### ***Data Description***

The methodologies described in the previous sections are used to process the OOS survey data of a series of 12 pipelines with a total length of around 28km, including 6km of route curves, with nominal radii of between 1100m and 2000m. The relevant details of the pipelines are summarised in Table 1.

The as-laid OOS surveys for these pipelines were performed from an ROV with a wheeled undercarriage in contact with the pipeline for controlled navigation, travelling at an average speed of around 600m/h. The ROV was positioned using two solutions, LBL aided INS in areas of coverage within an array, and USBL aided INS. The pipeline position was obtained from a DHSS mounted on the ROV.

| **Parameter** | | **Value** |
|---|---|---|
| Pipe Data | Axial Stiffness | 5770 MN |
| | Bending Stiffness | 78400 kNm$^2$ |
| | Empty Submerged Weight | 1291 N/m |
| | Linepipe Material | X65 (450MPa) |
| Pipelay Method | | J-lay with DP vessel |
| Water Depth Range | | Deep water (>1000m) |
| Bottom Tension | | Low |
| Soil Type | | Very soft clay |
| Metocean Conditions | | Mild |

**Table 1 – OOS Survey Metadata**

### ***Characterisation of Effect of Out of Straightness on Buckling Force***

As detailed previously, the best approach currently available to characterise OOS along a pipeline is by using the $X_{NH}$ and $X_{NB}$ coefficients. However, it is still common for the peak curvature to be quoted as a suitable parameter to quantify OOS. But peak curvature alone cannot be used to characterise the effect of OOS on the buckling force. For example, the critical buckling force also depends on the buckle mode, which in turn is influenced by the initial shape of the pipeline, e.g. an OOS feature with a predominantly bowed geometry may buckle in a mode 1, whereas a wavier shape may promote a mode 3 buckle.

In order to illustrate that peak curvature alone cannot describe OOS and therefore capture the effect of the as-laid geometry of the pipeline on its critical buckling force, the extensive analyses performed with the OOS survey data used in this paper have been used to produce Figure 5. In the figure, the peak curvature in each 100m long section of the pipelines is plotted against the critical buckling load in that section (with a lateral friction of 1.0).

It is clear from the figure that although there is obviously some correlation between the two parameters, there is a very large scatter in the relationship, which confirms that peak curvature alone cannot be used to capture OOS.

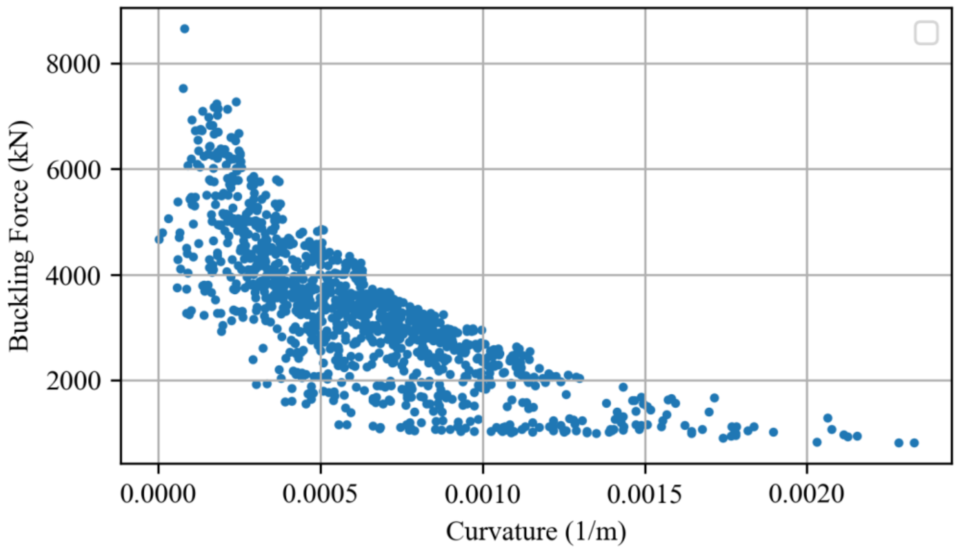


**Figure 5 – Peak Curvatures vs CBF along OOS Survey Data Assessed**

***Initial Survey Data Processing***

Once the data has been de-spiked, an initial noise filtering is applied by removing the components of the FFT of the KP vs. curvature signal below a certain wave length cut-off.

The sensitivity of the distribution of $X_{NH}$ obtained for one of the pipelines to the value of wave length cut-off is presented in Figure 6, which shows almost identical results. This demonstrates that the FE-based smoothing predicts essentially the same relaxed shapes with all the wave length cut-offs considered.

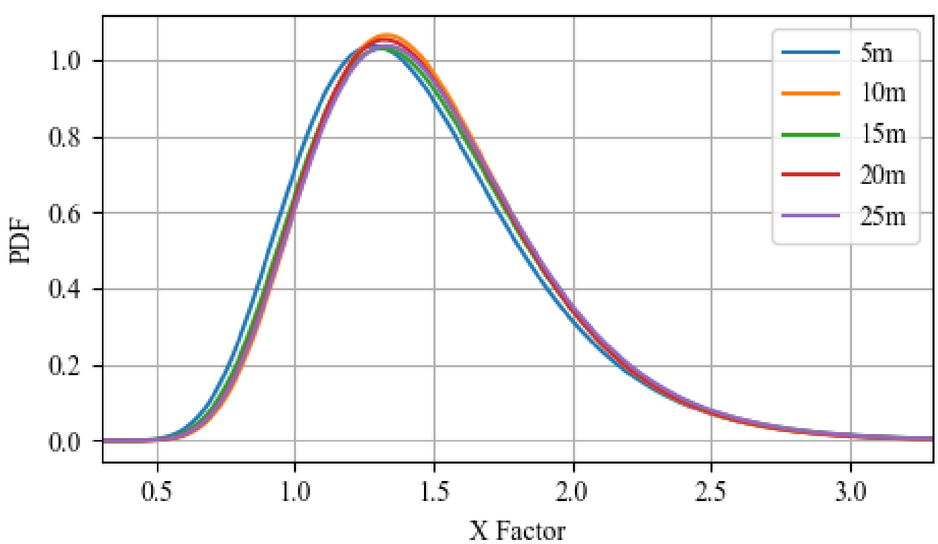


**Figure 6 – Effect of FFT Wavelength Cut-Off on $X_{NH}$ with 100m Reference Length**

Based on this, a wave length cut-off of 10m was selected for all pipelines, as this value removed all areas with stresses above yield and generally limited the stresses within the inter-quartile range (IQR) to around 50% of yield. Although similar relaxation behaviour is expected in general, it is recommended to include this type of sensitivity analyses whenever applying this methodology to ensure reliable $X_{NH}$ and $X_{NB}$ assessments.

***$X_{NH}$ and $X_{NB}$ Distributions***

The distributions for $X_{NH}$ and $X_{NB}$ over a 100m reference length from the analysed OOS survey data are summarised in Table 2 and illustrated in Figure 7. These results were obtained using 100m rolling-window FE models. The results in Figure 7 indicate a very good fit to lognormal distributions (the assumption typically considered in assessments).

| Parameter | Nominally Straight Sections | Route Curves |
|---|---|---|
| Effective length of Survey Data | 17.7km | 5.1km |
| Data Points, i.e. 100m sections | 177 | 51 |
| Mean | 1.85 | 0.83 |
| Standard Deviation | 0.63 | 0.19 |
| Coefficient of Variation (CoV) | 34% | 23% |

**Table 2 – $X_{NH}$ and $X_{NB}$ Distributions for 100m Reference from Example Data**

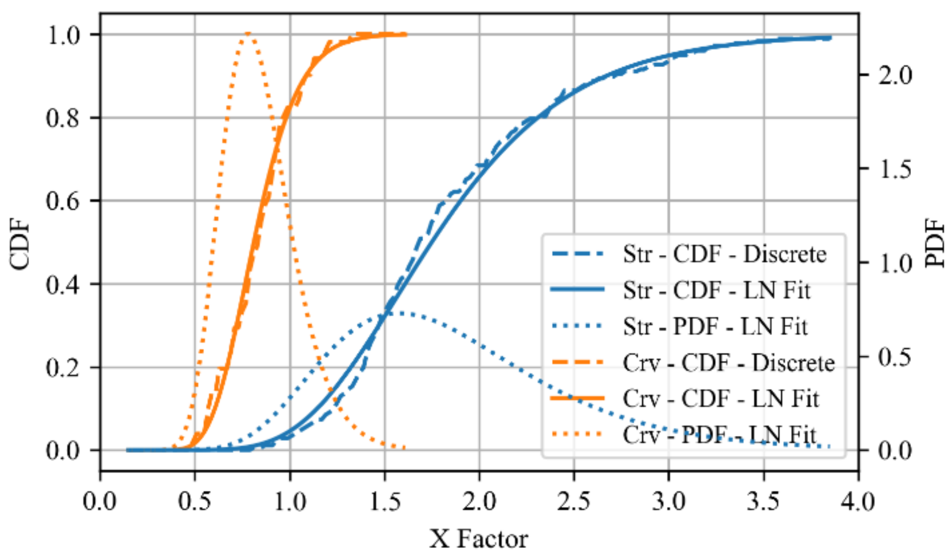


**Figure 7 – $X_{NH}$ and $X_{NB}$ Distributions for 100m Reference from Example Data**

***Difficulties in Applying the Option 1 FE Modelling Approach***

As noted previously, one of the disadvantages of the Option 1 approach for FE Modelling is that if the processed survey data has areas with insufficient quality, this leads to sections of the model with significant compressions locked after relaxation. An example of this is illustrated in Figure 8 for one of the pipelines analysed. The figure shows how significant compressions extend over a substantial length of the model. A zoomed view of the feature driving this effect is presented in Figure 9. The initial shape of this imperfection is unusually modal for an as-laid feature, and its origin might be linked to the proximity to a route feature such as an anchor or sleeper that distorted the survey quality and artificially introduced the anomaly.

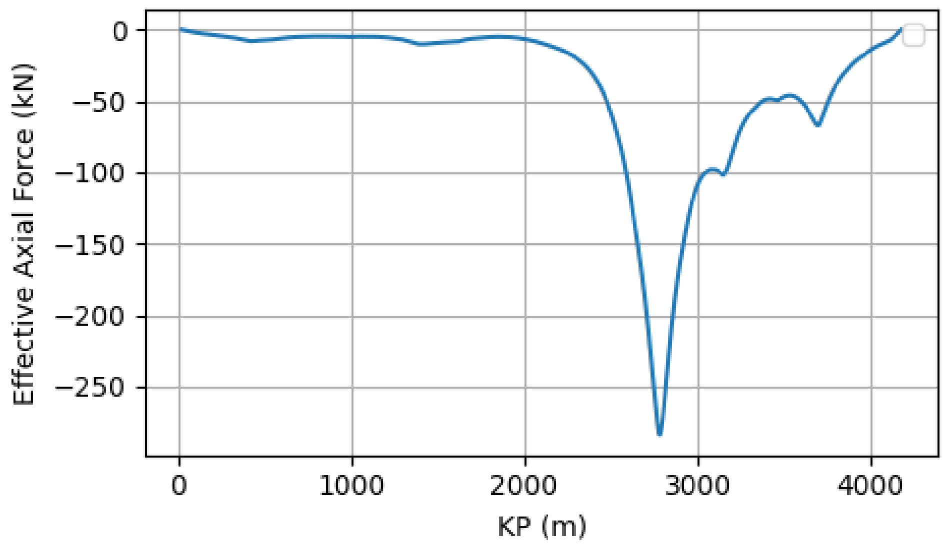


**Figure 8 – Example of Locked Compressions in the FE Model when using Option 1**

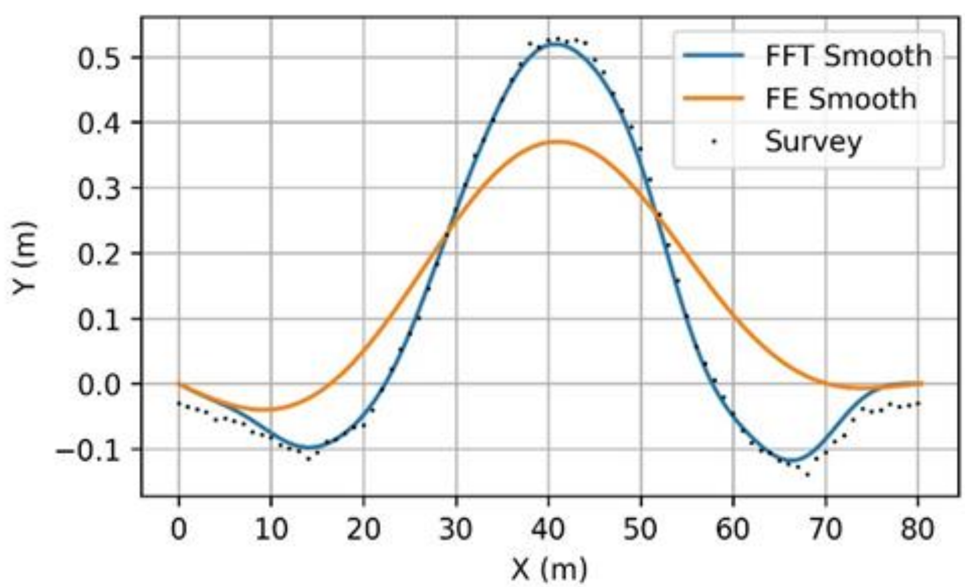


**Figure 9 – Imperfection Leading to Compressions, as Illustrated in Figure 8**

Adding a second step of FE-based smoothing removes the compression along the line. However, as illustrated in Figure 10, it leads to an overall increase in the critical buckling forces along the pipeline compared to results obtained using Option 2 FE.

For pipelines where there are no locked compressions in the Option 1 models, the results of Options 1 and 2 lead to nearly identical results, as shown in Figure 11.

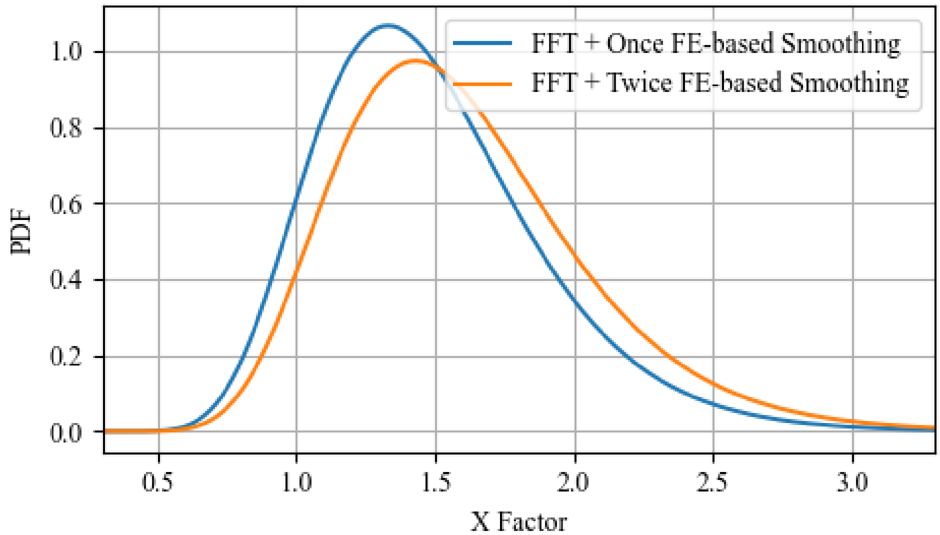


**Figure 10 – Effect of Second FE-smoothing in $X_{NH}$**

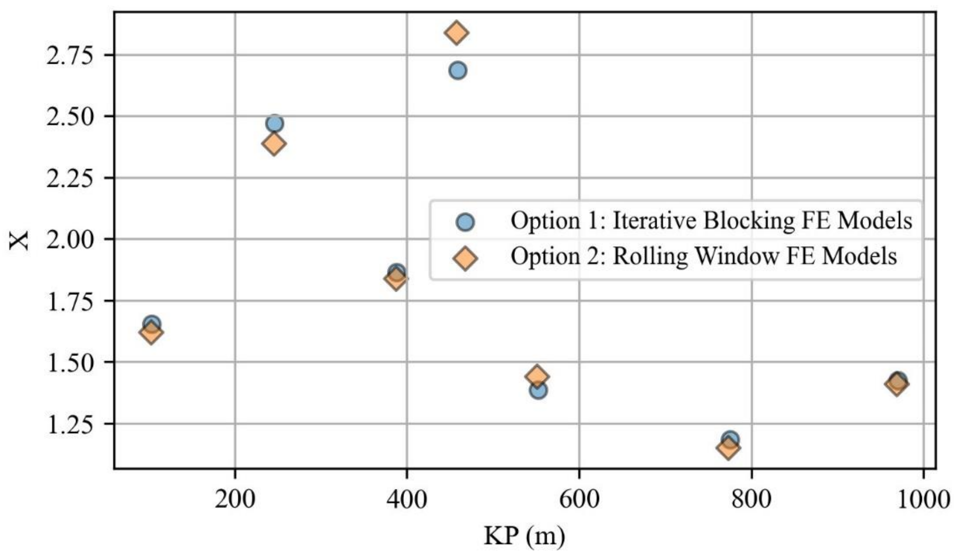


**Figure 11 – $X_{NH}$ & $X_{NB}$ from Option 1 and Option 2 Approach for one Pipeline**

***Comparison to DNV-RP-F110 Distributions***

The distributions of $X_{NH}$ and $X_{NB}$ for a 100m reference length obtained from the 28km of pipeline assessed can be converted to a reference length of 1000m using weak link theory as detailed in [Ref. 1] for comparison to the distributions presented in DNV-RP-F110.

The comparison is summarised in Table 3 and illustrated in Figure 12. The comparison shows general agreement, but with the following differences:

- The distributions from the data processed in this paper have significantly narrower distributions. This is consistent with the data belonging to a homogenous population and suggests the interest of developing families of OOS distributions for different types of pipelines and conditions (discussed later in this paper).

- The distribution for the nominally straight section is close to the LB distribution in DNV-RP-F110.
- The distribution obtained from the data in this paper for route curves has a significantly higher mean than presented in DNV-RP-F110.

| Parameter | Nominally Straight Sections | | | | Route Curves | |
|---|---|---|---|---|---|---|
| | Example | F110 | | | Example | F110 |
| | | LB | BE | UB | | |
| Mean | 1.06 | 0.93 | 1.26 | 1.58 | 0.57 | 0.45 |
| STD | 0.20 | 0.27 | 0.33 | 0.31 | 0.08 | 0.135 |
| CoV | 19% | 29% | 26% | 20% | 13% | 30% |

**Table 3 – $X_{NH}$ and $X_{NB}$ Distributions for 1000m Reference from Example vs F110**

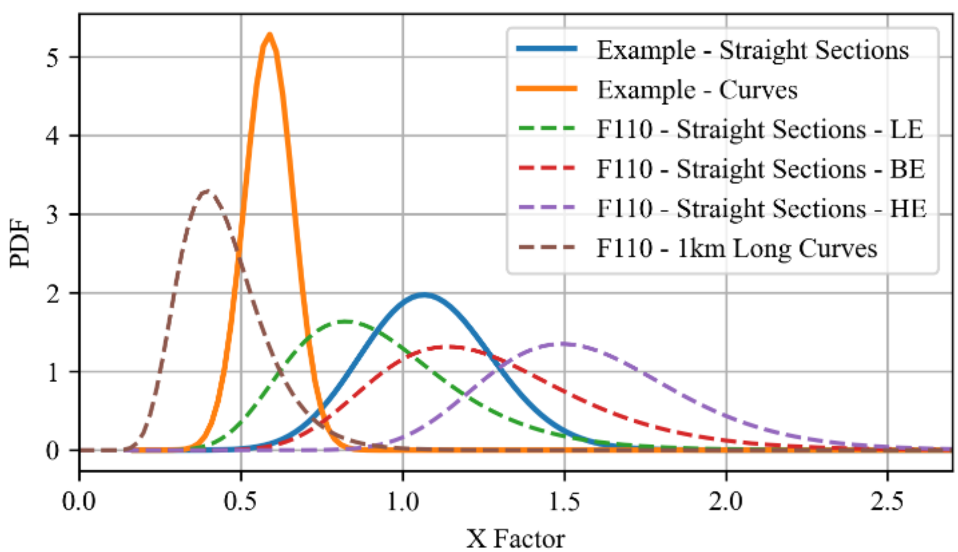


**Figure 12 – $X_{NH}$ and $X_{NB}$ Distributions for 1000m Reference Length from Example Data vs DNV-RP-F110**

## $X_{NH}$ & $X_{NB}$ Methodology Robustness

***Sensitivity to Lateral Pipe-Soil Interaction***

This section evaluates the independence of the values of $X_{NH}$ and $X_{NB}$, derived from the analyses described above, with regards to the parameters of the lateral pipe-soil interaction used in the FE models.

The sensitivity to the lateral breakout friction is illustrated in Figure 13 and Figure 14, which presents the values of $X_{NH}$ and $X_{NB}$ respectively from one of the pipelines in the example dataset. Each point in the figure represents one value of $X_{NH}$ or $X_{NB}$ from the analysis with a certain value of lateral breakout friction against the value of $X_{NH}$ or $X_{NB}$ for the same OOS feature but derived with a lateral breakout friction factor of 1.

The results show that instead of aligning along the 1:1 line, as would be expected if the results were independent of the breakout lateral friction considered, the points are scattered within a range of plus or minus 30% on both nominally straight and route curve sections (although the scatter is a bit smaller for route curve features).

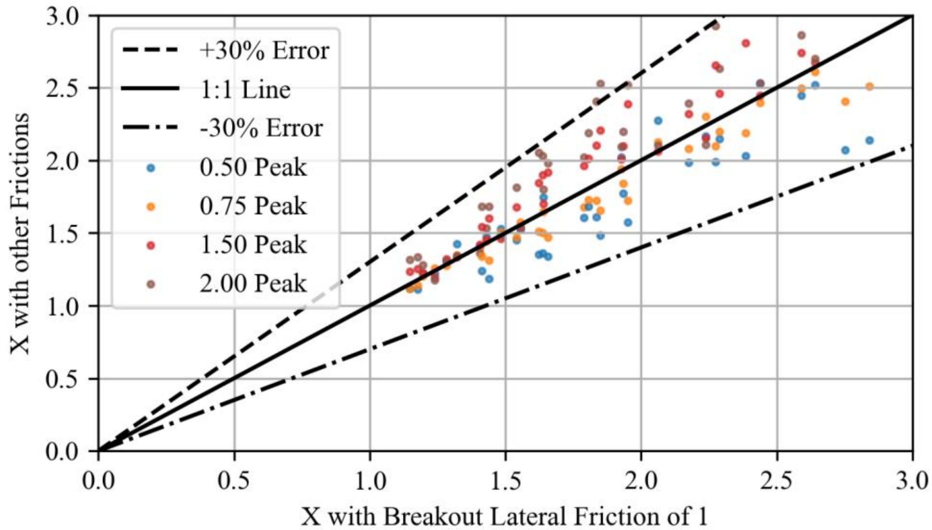


**Figure 13 – Sensitivity of $X_{NH}$ (Straight) to Breakout Lateral Friction in FE Model**

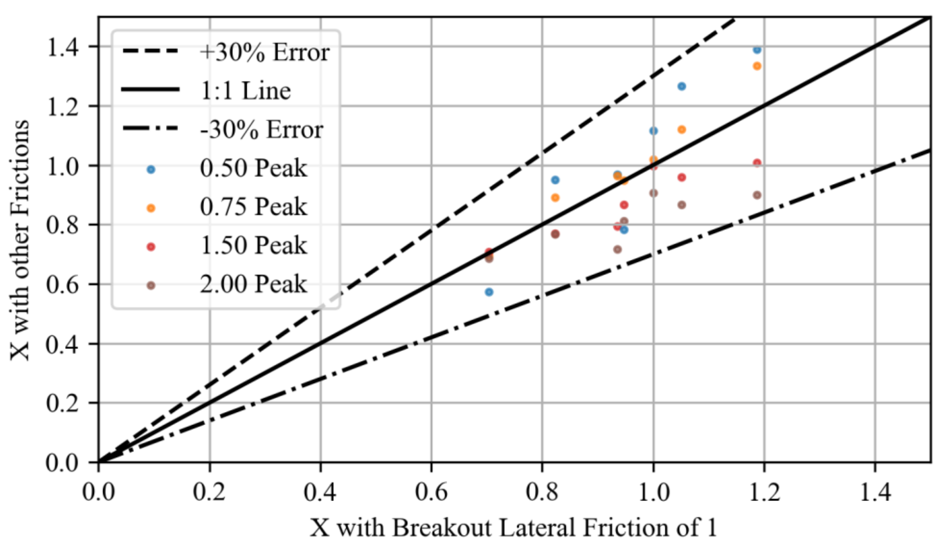


**Figure 14 – Sensitivity of $X_{NB}$ (Curve) to Breakout Lateral Friction in FE Model**

For OOS features in the nominally straight sections (Figure 13), it is noted that the orange and blue points (which correspond to runs with a friction lower than 1.0) tend to be below the 1:1 line, whereas the red and brown (which correspond to runs with a friction higher than 1.0) tend to be above the 1:1 line. This shows that the dependency of $X_{NH}$ to the lateral friction is not related to a relaxation of the OOS geometry in the FE model (as could be expected), but to the way in which features buckle with different values of lateral friction.

For OOS features in route curves (Figure 14), the opposite is observed, which could suggest that the scatter is due to relaxation of features in the FE models with lower lateral frictions or the non-proportionality of the reference equation to the friction (applicable for route curves) or square root of the frictions (applicable for straight sections).

Similar figures are presented to illustrate the sensitivity of the values of $X_{NH}$ or $X_{NB}$ to the lateral breakout mobilisation displacement (see Figure 15) and the lateral residual friction (see Figure 16) used in the FE models.

The results in Figure 15 show limited sensitivity for small values of the mobilisation displacement (between 0.5 and 5mm). For mobilisations of 20mm, however, this leads to a systematic reduction in the value of X, which reaches values slightly lower than -30%.

As was observed in the sensitivities to the breakout lateral friction, the results in Figure 15 show that a larger mobilisation displacement does not relax the OOS feature but instead, it increases the sharpness in the features, which then buckle at lower forces, i.e. a lower X.

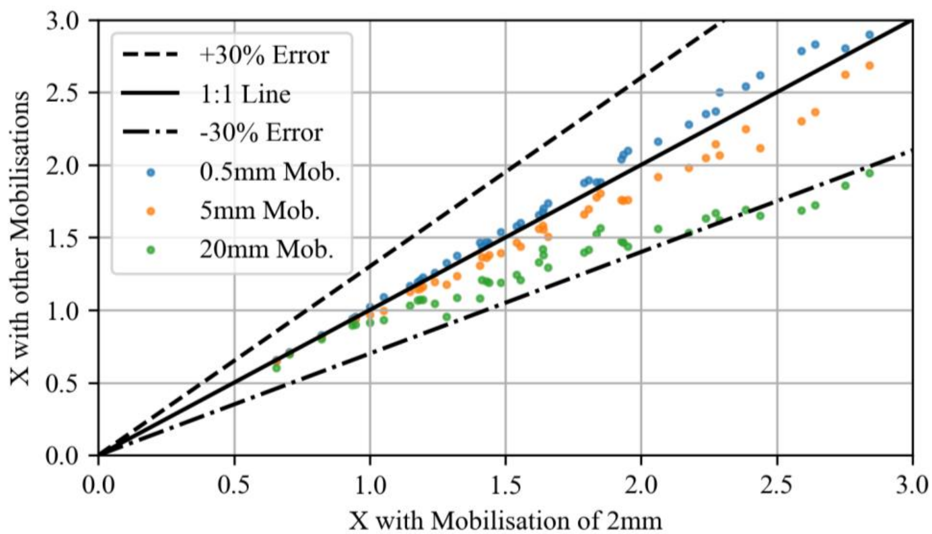


**Figure 15 – Sensitivity of $X_{NH}$ & $X_{NB}$ to Lateral Breakout Mobilisation Displacement**

In the sensitivities to the lateral residual friction shown in Figure 16, the breakout lateral friction factor remains 1.0, with a mobilisation displacement of 2mm, while the mobilisation of the residual friction is double that and the residual friction factor is varied. As for the previous parameters, these sensitivities show a dependence of the $X_{NH}$ or $X_{NB}$ values, with lower values obtained with the lower values of lateral residual friction.

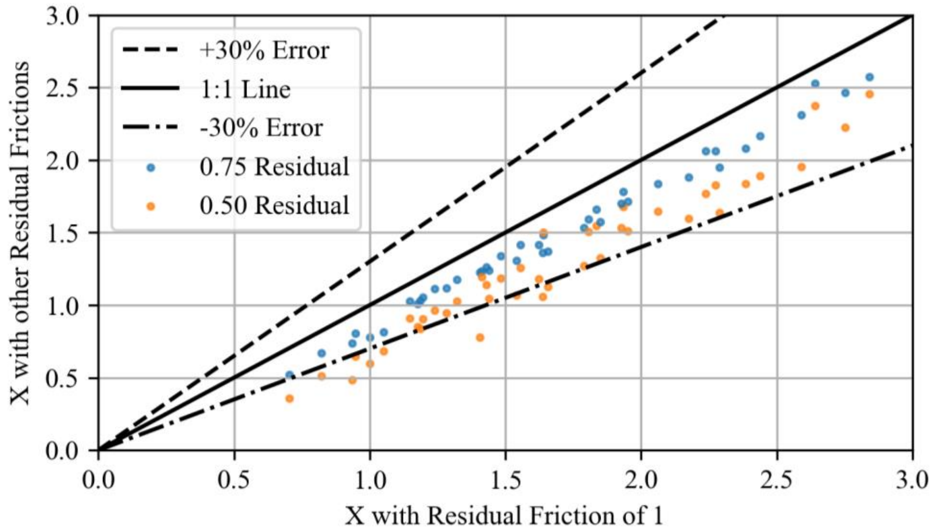


**Figure 16 – Sensitivity of $X_{NH}$ & $X_{NB}$ to Residual Friction Factor**

The approach currently used in probabilistic lateral buckling assessments is based on the hypothesis that the geometrical effect of OOS features on their critical buckling load can be characterized independently from the lateral friction model and the two parameters can then be sampled independently. The results of the three sensitivity assessments presented in this section challenge this hypothesis.

Although the dependency is not very severe, it is clear and non-negligible in some cases. Until alternative approaches are developed, this should be taken into account in design by considering additional sensitivities on the distributions of $X_{NH}$ and $X_{NB}$.

***Sensitivity to Reference Equation for $X_{NH}$***

The results in Figure 13 suggest that the scatter in the values of $X_{NH}$ with different values of breakout lateral friction may be because the reference equation used to determine the value of $X_{NH}$ from the critical buckling force in the FE models (Hobbs force for the infinite mode) is not suitable.

The sensitivity to the lateral breakout friction for a typical feature in a nominally straight section is illustrated in Figure 17. The results show that the critical buckling force is not really proportional to the square root of the lateral friction, as per the Hobbs force.

Different attempts were made to identify a better formulation for the reference equation, but a suitable alternative has not been identified at this stage.

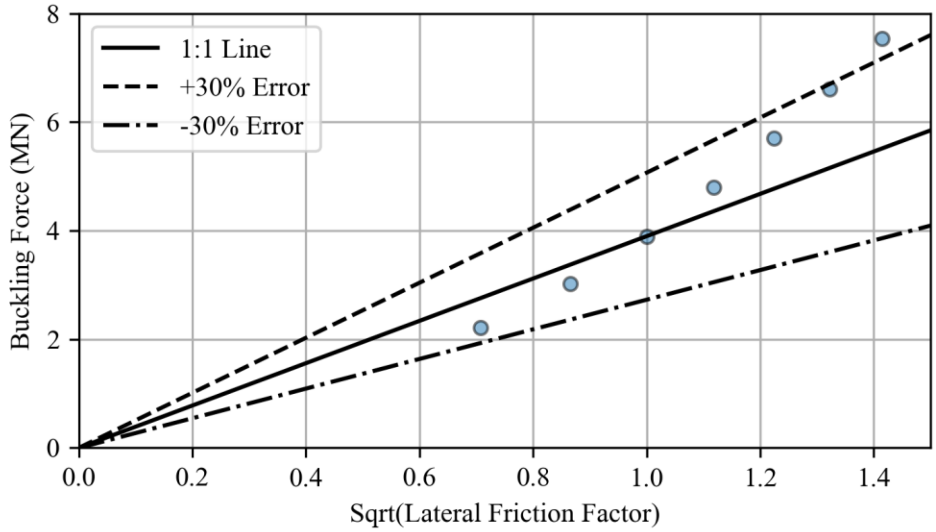


**Figure 17 – Sensitivity of Buckling Force ($X_{NH}$) to Breakout Lateral Friction for Typical OOS Feature**

## Industry Shared Lateral OOS Database

At present, distributions of lateral OOS can only be produced empirically from processing the survey data of installed pipelines. Accordingly, to be able to produce robust distributions, significant amounts of survey data are needed.

So far, the distributions available in [Ref. 1] were developed by the Safebuck JIP from an aggregated dataset containing different types of pipelines. In the development of these distributions, an attempt was made to identify families of data, but no clear patterns could be identified from the data available at the time. Based on this, it was only possible to propose three sets of distributions (LB, BE, UB), but without a link to the type of pipeline or installation method and therefore the distributions are meant to be used for all cases.

But it is clear that there have to be different families of OOS data, depending at least on the installation method. For example, it would be expected that pipelines laid with anchored barges will have more OOS than pipelines laid with DP barges and that deep water pipelines installed in J-lay with very low bottom tensions will have more OOS than shallow water pipelines installed by S-lay with high bottom tensions (in case of DP barges).

At present, it is not clear what the best way to group the data is, but it is clear that even more data will be needed to define different OOS distributions for different scenarios.

The approach presented in this paper significantly increases the data that can be extracted from OOS survey. But even with this approach, it will be difficult for any organisation to accumulate sufficient data to produce robust distributions for a range of scenarios.

Considering that OOS data does not contain details that are particularly sensitive or confidential, it seems that the data could be shared and aggregated between companies. Moreover, the approach proposed in this paper of working with KP vs. curvature profiles anonymises the data in a way that specific pipelines (and therefore Operating Company or Installation Contractor) are difficult to identify. Based on this, the following is proposed:

- Identify a mechanism to aggregate anonymous OOS data.
- Create a portal where the data can be added and where entities contributing data can access the data provided by the other contributors.
- Data to be provided in the form of KP vs curvature with the following metadata (as shown in Table 1 for the example presented in this paper):
    - Pipe bending and axial stiffness and empty submerged weight.
    - Type of installation method: S-lay, J-lay or Reel-lay.
    - Vessel positioning system: anchored or DP.
    - Water depth range: shallow waters (down to 100m), medium water depth (100 to 500m) or deep water waters (deeper than 500m).
    - Soil type: sand, clay, soft clay.
    - Bottom tension range.
    - Severity of metocean conditions: mild or harsh.

Once sufficient data with associated metadata has been added, the contributing entities will be able to process it separately or as a group and try to select better underlying equations to determine $X_{NH}$ & $X_{NB}$, identify data families and develop associated OOS distributions.

## Conclusions

This paper has presented a detailed methodology for processing OOS survey data in a systematic manner to develop distributions for use in probabilistic lateral buckling design.

The approach is based on the principle1s used in the Safebuck JIP to produce the distributions presented in DNV-RP-F110, with the following modifications:

- The distributions are developed for a reference length of 100m instead of 1000m. This produces richer data at the scale used in design.
- Methods to remove noise from the data are presented.
- The survey data is converted to KP vs. curvature for a more robust and streamlined processing.
- Rolling window analyses to capture the critical feature in each 100m section.

The approach proposed has been tested on the survey data of 12 pipelines with the same characteristics. The distributions of $X_{NH}$ and $X_{NB}$ obtained are generally consistent with those in DNV-RP-F110, but with lower CoV (possibly consistent with the data belonging to a homogenous population) and a higher mean for route curves ($X_{NB}$).

The sensitivities considered have identified that the values of $X_{NH}$ and $X_{HB}$ obtained from processing the OOS survey data are not completely independent from the parameters of the lateral pipe-soil interaction used in the FE models (as assumed in the current probabilistic lateral buckling assessment approach). The results have also questioned the reference equation to determine $X_{NH}$ (for features in nominally straight sections).

Alternative approaches have not been proposed in this paper, but in the meantime, it is recommended that these results are taken into account in design by considering additional sensitivities on the distributions of $X_{NH}$ and $X_{NB}$.

## Recommendations

From the results presented in this paper, the following is recommended for future work:

- Additional work is required to determine the best reference equation for processing $X_{NH}$ and $X_{NB}$ and address their dependency with the lateral pipe-soil interaction.
- If better solutions are not identified, it may be necessary to develop different distributions of $X_{NH}$ and $X_{NB}$ for different cases, e.g. for cases where the lateral breakout mobilisation displacement is high.
- Since the OOS data processing proposed is based on the KP vs. curvature signal, the feasibility of complementing external OOS surveys by IMU pig runs should be considered.
- A system of OOS data sharing between companies to aggregate large volumes of anonymised OOS data should be considered. This would enable developing more robust and scenario-specific OOS distributions to improve future lateral buckling designs.

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