# Modelling the spatial variability of as-laid embedment for HPHT pipeline design

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Modelling the spatial variability of as-laid embedment for HPHT pipeline design

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ABSTRACT

Subsea pipelines are being designed to accommodate higher temperatures and pressures. Current modelling approaches that adopt constant lateral seabed resistance along the pipeline do not capture the high spatial variability in as-laid pipeline embedment from field observations, which strongly affects the lateral resistance. Ignoring spatial variability when designing pipelines with engineered buckles leads to higher predictions of axial force along the pipeline, with reduced likelihood of buckle formation. This can result in excessive mitigation measures being adopted, such as sleepers or counteract structures, which significantly increase project costs.

Spatial variability of pipeline embedment is not currently handled rationally in design because the understanding of the physical mechanisms that cause as-laid embedment, and methods for accurately predicting it, have only recently emerged. This paper illustrates how the influence of these physical mechanisms that drive embedment can be extracted from field survey data, and then modelled synthetically in design analyses. The impact of embedment variability and the resulting variation in lateral seabed resistance on the lateral buckling response is illustrated. The framework represents an improvement in the way geotechnical uncertainty and variability is handled in pipeline-seabed interaction analyses for use in pipeline design, and has already begun to be implemented in practice.

Keywords: pipeline embedment, pipeline design, HPHT, lateral buckling, modelling, spatial variability
1. INTRODUCTION

For pipelines laid and operated on the seabed, the pipe embedment has a significant impact on the lateral and axial seabed resistance (White and Cathie 2011). This in turn has a significant influence on the global behaviour of the pipeline during operation. Cycles of temperature and pressure cause expansion and contraction, which are affected by the pipe-seabed resistance. During design it is necessary to assess the likely pipe-seabed resistance, the resulting build-up of force in the pipe, and the potential for buckling to occur. Such buckling must not cause unacceptable strain or fatigue of the pipe.

The as-laid embedment of pipelines in soft soils, such as those found in deep water hydrocarbon-rich regions of the world, can be an order of magnitude higher than static embedment predictions would suggest, owing to dynamic lay effects such as soil softening and trenching (Cheuk and White 2011).

Methods for predicting as-laid pipeline embedment have improved over the past decade, due to new theoretical solutions for pipe-seabed penetration resistance (e.g. Randolph and White 2008a) and the use of as-laid survey data and detailed records of the installation process to provide calibration and benchmarking (Westgate et al. 2013). The global range of as-laid embedment along an entire pipeline can now be predicted with higher confidence. However, the local spatial variation in embedment and its effect on lateral and axial seabed resistance is not usually quantified in pipeline design. Instead, uniform resistance is assumed to apply over the entire pipeline length. Accounting for the local variability in embedment offers the potential to improve the realism and reduce the uncertainty in pipeline design (White et al. 2014).

For example, realistic modelling of spatial variability can improve pipeline design by (i) attenuating the influence of extreme variations in shallow or deep pipe embedment, by imposing them only over short lengths of pipeline rather than needing to assess the impact if they exist over the whole pipeline and (ii) by taking advantage of local fluctuations in embedment where they are beneficial, for
example by capturing the possibility of buckles occurring at locations of low lateral resistance rather than adjacent zones of high resistance. This possibility is generally beneficial for design because low lateral resistance leads to lower bending strain in the buckled pipe.

1.1 Geotechnical Variability and Uncertainty in Lateral Buckling Design

Pipe-soil interaction (PSI) parameters, i.e. ‘friction factors’ and their associated mobilisation displacements, are used in structural analysis calculations to assess the response of a subsea pipeline to thermal and pressure-induced expansion and contraction. Low values of seabed resistance reduce the stability of the pipeline, which can lead to excessive axial expansion or the formation of lateral buckles at locations where sufficient axial force has built up to cause an out-of-straightness feature to develop into a buckle. High values of seabed resistance increase the compressive forces generated in a pipeline, reducing the axial expansion. However, if a buckle does occur, it has a tighter curvature than if the lateral resistance was lower, leading to higher strain in the pipe.

Because of these complex interactions, there is no single conservative value of pipe-seabed resistance to assess the competing limit state conditions of the pipeline-structural system. Instead, it is necessary to determine the potential range of end expansions and the strains in the buckles by considering ‘friction factors’ that have been calculated using the full range of the relevant pipeline and soil input properties that may occur over the entire pipeline route. This results in low estimate (LE), best estimate (BE) and high estimate (HE) design values of each PSI parameter, which can be utilised as a statistical distribution.

This LE to HE calculation approach captures both epistemic (global) uncertainty and aleatoric (local) variability. Epistemic uncertainty represents the range in a parameter that applies equally at all points along the pipeline. Aleatoric variability represents the range in a parameter that exists between different locations along the pipeline. The key difference between variability and uncertainty, as defined here, is that if properties were averaged out over a long pipeline length, the fluctuations due
to variability would average out to the mean value. In contrast, uncertainty could result in higher or lower soil resistance everywhere along the pipeline. Uncertainty and variability as applied to lateral buckling design are generally handled in the following manner:

- **Buckle initiation** assessments are generally performed probabilistically using the full range of each PSI parameter (i.e. LE to HE) in programs such as BUCKFAST or similar (Cosham et al. 2009, Rathbone et al. 2008a). Independent values of lateral resistance might be generated at intervals of approximately one buckle length in a simulation of the whole pipeline that is used to determine the likelihood of buckles forming along the pipeline. This approach implicitly assumes that the entire LE-HE range represents aleatoric variability. There is also no physically meaningful basis for selection of the length scale associated with the variability, i.e. adjacent values of soil resistance are uncorrelated, which may be different to the actual length scale of the spatial variability.

- **Buckle response** assessments are generally performed deterministically using a uniform value (LE, BE or HE) of each PSI parameter along the entire pipeline (or the length of pipeline between planned buckles) in a finite element analysis program. This approach implicitly assumes that the entire range represents epistemic uncertainty, and therefore does not account for the more realistic representation that the soil resistance will be spatially variable so the pipeline is subjected to lengths of lower or higher seabed resistance.

The overall process is more detailed, and some projects handle geotechnical variability and uncertainty in a more sophisticated way. Best practices are defined by the relevant industry guidelines such DNV RP-F110 (DNV 2007) and the SAFEBUCK JIP Guideline (Atkins 2015).

### 1.2 Sources of Spatial Variability in Pipeline Embedment

Pipeline embedment in fine-grained soils depends on many factors, which often include variability and/or uncertainty:
• Pipe properties, specifically the weight, diameter, coating roughness, and bending stiffness, which are generally fixed along a given pipeline section and therefore have low variability and uncertainty;

• Soil strength, specifically the tendency for the undrained shear strength to change from intact to remoulded due to disturbance caused by the lay process, and the subsequent recovery of the strength during reconsolidation;

• Lay process, specifically the type of lay vessel (J-lay, S-lay, reel lay) and the associated construction activities and rate of progress, which may be intermittent due to cycles of welding, coating and pipeline payout, as well as downtime events due to weather or other delays;

• Sea state conditions, specifically swell, waves, wind and currents, and how they interact with the vessel to transfer pipeline motions from the lay ramp to the touchdown zone at the seabed; and

• Pre-commissioning events, specifically the time prior to pipeline flooding, which can significantly increase the bearing pressure of the pipeline and result in additional pipeline embedment and/or changes in the strength of the surrounding soil.

A pipeline is a long linear feature and each factor can have a different effect at each location along the pipeline. This means that a single pipeline represents many realisations of each factor and allows epistemic uncertainty and aleatory variability to be defined as global and local respectively. It is important to understand whether the various influences on the embedment are predominantly uncertainty or variability. The factors from the list above that can include a significant degree of variability along a pipeline are summarised in Table 1, and generalised into three categories of geological, anthropogenic and metocean factors. Included in this list are the typical relative length scales for each factor, representing the length over which there will be a correlation between the
degree of influence. Soil properties such as strength have natural variability, and therefore can have low correlation between adjacent locations. Conversely, the sea state changes slowly over the course of hours or weeks, and therefore has a high correlation over the timescale relevant to pipe laying, which translates, via the vessel lay rate, into a high correlation along the pipeline.

Some of these length scales can be predicted in advance of pipeline installation, or even measured (in the case of some geological factors) or controlled (in the case of the pipeline construction), and therefore geotechnical and pipeline engineers have an opportunity to account for these variations in pipeline design.

1.3 Objectives and Focus

The objectives of this paper are to show that:

1. Spatial variability inherently exists along subsea pipelines due to a multitude of factors, each of which can be rationalised based on a real physical mechanism (e.g. sea state, lay method, soil conditions);

2. Spatial variability can be simulated, explicitly accounting for each influencing factor; and

3. Capturing spatial variability in pipe-soil interaction analysis can improve the realism of pipeline design analyses, illustrated here by the reduction in lateral seabed resistance acting on initiated buckles.

This paper does not address pipe embedment variability due to scour and sediment mobility, which is generally more important for coarse-grained soil in shallower water, but can also occur in fine-grained soil in deepwater (e.g. Clukey et al. 2007). However, the same principles apply to the impact of sediment mobility, and can have significant beneficial impact on pipeline design (Bransby et al. 2014).
2. FIELD OBSERVATIONS AS-LAIRED EMBEDMENT

As-laid embedment data from two field surveys in soft fine-grained soils are presented. The two cases comprise sites with different geographic locations, water depths, soil conditions, lay vessel characteristics, and metocean conditions. The global statistics of the as-laid embedment of each pipeline have been back-analysed in detail previously (Westgate et al. 2010a, 2010b, 2013). The survey data are used to illustrate different approaches for narrowing the range of pipe-soil resistance for a particular design check, which comprise (i) averaging over a length scale, or (ii) filtering across multiple length scales.

2.1 Summary of Field Conditions

A summary of the pipeline properties and lay conditions for each survey is provided in Table 2. Both pipelines were laid in the empty condition. A small hybrid S-lay/J-lay vessel with a stern-mounted lay ramp was used at Site A, while an intermediate size J-lay vessel with a gimbaled mid-ships lay ramp was used at Site B, both of which are detailed in Perinet and Frazer (2007). The different lay ramp geometry between the two vessels strongly affected the transfer of vessel motions to pipeline motions at the touchdown zone (Westgate et al. 2010a, 2010b).

The pipelines were relatively light, with empty bearing pressures, $W'/D$, ranging from about 0.5 to 1.5 kPa. The seabed at the touchdown zone was subject to dynamic variations in the vertical pipe-soil contact force due to the sea state. This range has been quantified using numerical simulations of the lay process with the offshore modelling software OrcaFlex. This program includes a non-linear seabed model to capture changing vertical seabed stiffness during cyclic loading (Randolph and Quiggin 2009). The dynamic amplification factors ($V_{dyn}/V_{max}$), averaged over the touchdown zone length, ranged from just over 1 up to values of 2, with peak values over a shorter length scale being significantly greater than 2 (Westgate et al. 2010b).
The surface seabed soils comprised soft fine-grained sediments. Strength testing was performed using cone penetrometer and mini-vane shear testing at Site A, and cyclic T-bar testing at Site B. The ranges in soil strength parameters provided in Table 3 are based on linear fits to the available data within the upper 0.5 m of the seabed.

The as-laid pipe embedment profiles, w/D (normalised by pipe diameter), derived from ROV cross-profiler data, are shown on Figure 1. The data was obtained at irregular spacing, varying from 1 to 3 m for Pipe A and from 0.82 to 0.98 m for Pipe B. Pipe A embedment has a mean $\mu = 0.37D$ and standard deviation $\sigma = 0.11D$, while Pipe B embedment has a mean $\mu = 0.22D$ and standard deviation $\sigma = 0.05D$.

Some of the measured local variation could be due to general noise in the raw data, but this effect is considered minor relative to the global variation along the route. Without independent measurements of the seabed profile, or repeated surveys immediately after each other, it is not possible to quantify the noise in the raw data. We have therefore conducted our interpretation without any attempt to remove the measurement error from the survey results. This approach does not affect the overall conclusions from our study, but it is an effect that should be considered if survey data is used in practice in the same way.

Four different length scales ranging from the raw data (1-3 m spacing) up to 1000 m averages are included in the plots to better illustrate local and global trends, as well as the duration over which the installation was completed using the average lay rate for each line. The data have been filtered to remove free spans, locations of midline structures, and areas where the vessel was halted due to weather-related or mechanical downtime. The KP values for each line have been adjusted to account for this filtering process to avoid gaps in the data.
2.2 Predictions of As-Laid Embedment

Research by the authors and others has shown that use of the fully remoulded undrained shear strength to account for dynamic lay effects in a static vertical pipe bearing capacity analysis provides a satisfactory approach to assessing the as-laid embedment of pipelines in fine-grained soils (Westgate et al. 2010b). This approach is based on existing plasticity solutions for pipe penetration in fine-grained (undrained) soils (Randolph and White 2008a, Merifield et al. 2009), and incorporates catenary overstress effects (Randolph and White 2008b). This process has helped to validate simple models to predict as-laid pipeline using field measurements of remoulded soil strength (Westgate et al. 2010b).

This approach can be employed deterministically or probabilistically. Deterministic calculations use combinations of soil strength parameters, e.g. LE intact strength gradient with HE soil sensitivity, and vice versa, to determine the widest range in pipe embedment. Probabilistic calculations, using a Monte Carlo approach, allow the full variability in soil strength parameters (and by extension the variability in lay conditions) to be captured naturally, assuming the inputs are uncorrelated (or partially correlated, if desired) (White and Cathie 2011).

A comparison of these two calculations approaches – deterministic and probabilistic – is shown on Figure 2 for each pipeline. These were performed based on the methods stated above using the pipe properties and lay conditions from Table 2 and soil input parameters from Table 3. As indicated on Figure 2, the predicted embedment using the deterministic approach bounds the field data very well, while the probabilistic approach (with soil strength and sensitivity being uncorrelated) also captures the overall shape of the distribution, allowing more flexibility in the selection of a design range and the associated likelihood of occurrence. More refined approaches that explicitly assess the degradation in strength and consider combined loading effects are available (Cheuk and White 2011 Westgate et al. 2013).
While these calculation approaches capture the range in embedment along an entire pipeline, they fail to quantify spatial variability effects.

2.3 Local Embedment Variability

Systematic assessment of variability can narrow design ranges of pipe-soil resistance, and one simple way to explore the potential influence of variability is to examine the change in embedment and pipe-soil resistance when averaged over various lengths that are relevant to different aspects of design, which are illustrated on Figure 3. The entire set of as-laid field data contains the widest range in embedment due to effects mentioned above (section A, as shown on Figure 3). However, buckle initiation occurs over a relatively short length of pipeline (section B), perhaps 10 meters or so, and therefore the pipe will ‘feel’ the average soil resistance over that length (that is, the pipe will respond as if subjected to a 10 m-averaged profile of the true pipe-soil resistance). During lateral buckle expansion, the buckle also lengthens (section B to section C), and the relevant averaging length for a check of whether a buckle is tolerable may be an order of magnitude larger, i.e. a 100 m length. As the pipeline feeds into the buckle axially, the relevant length for assessing axial pipeline feed-in is typically another order of magnitude larger (section C to section D), linked to the virtual anchor spacing (VAS) along the pipeline.

Figure 4 shows the reduction in the range of pipeline embedment for each averaging length compared to the range for the raw data, for the field data used in this paper. The LE ($P_5$) and HE ($P_{95}$) values are tabulated in Table 4. By considering a 10 m averaging length (relevant to the initiation of buckles), the HE embedment reduces by ~10%, while the LE embedment increases by ~40%. This contrasting effect indicates that regions of low embedment are typically short and isolated, whereas regions of high embedment have a longer length scale. This simple process of narrowing of global range in embedment through averaging length, and by extension lateral seabed resistance, can be beneficial in design.
3. SIMULATING EMBEDMENT VARIABILITY

While length averaging of field survey data indicates the potential for narrowing embedment design ranges, to incorporate this in design for a pipeline which is not yet laid (so embedment survey data is not available), requires a method to predict the local variation in embedment along a pipeline. This section sets out a methodology to achieve this. Firstly, spectral analysis is performed on survey data, which leads to a basis to link these observations to the various factors that influence pipeline embedment. Secondly, the reverse process is performed in a simple manner, which provides a practical tool to generate synthetic profiles of pipeline embedment, and the resulting impact on buckling behaviour is illustrated.

3.1 Spectral Analysis of Survey Data

Spectral analysis techniques can be used to quantify the variation in as-laid pipeline embedment, by considering the observed embedment variation as a composite with several influencing factors (Table 1), each with a different length scale and magnitude for a given pipeline and site-specific condition. Fast Fourier Transform (FFT)-based spectral analysis can be used to extract individual signals from a composite waveform, such as done for seabed topography by Lindenbergh et al. (2006). However, the length scale of variation in embedment can change along a pipeline due to changes in the driving mechanism, and determining a reliable spectral density function from an FFT analysis can be difficult. In addition, non-uniform spacing of the source data precludes standard FFT-based harmonic analysis.

A least-squares method, valid for unevenly spaced data, was therefore used to fit a series of sinusoids to the embedment variation measurements along the two pipelines A and B. The following steps were performed for each dataset:

1. Define a table of frequencies (or wavelengths) to represent the low frequency (long wavelength) component(s) of the data, selected to range from 100 m to 20 km wavelengths in
this case. By limiting the analysis to low frequencies (equivalent to wavelengths longer than
100 m), a considerable amount of noise and high-frequency information is omitted.

2. Use the frequencies (or wavelengths) to further define a table containing a pair of sine and
cosine coefficients for each wavelength.

3. Perform a least-squares fit of the sinusoids to the data, extract the coefficients, and calculate a
spectral power for each wavelength.

4. Define an approximation of the contribution \( f \) of the low frequency (long wavelength)
components from the data, capturing the first few terms of the Fourier series (mean plus six
harmonics), where:

\[
f = \mu + \sum_{i=1}^{6} \left[ a_i \cos \left( \frac{2m\pi x}{L} \right) + b_i \sin \left( \frac{2m\pi x}{L} \right) \right]
\]  

(1)

where:

\( \mu \) = mean value of embedment;

\( a \) and \( b \) = coefficients for \( i^{th} \) term;

\( m \) = frequency (equal to the reciprocal of the wavelength); and

\( L \) is taken equal to 1 km.

Six harmonics have been considered in this analysis since this is sufficient for illustrative
purposes. However, additional terms could be included to increase accuracy but at the
expense of additional computational effort.

5. Define a second table of de-trended data by removing the low frequency (long wavelength)
component \( f \) evaluated at each of the horizontal coordinates, and then defining a table to
represent the high frequency (short wavelength) components of the data, selected to range
from 5 m to 2 km in this case, allowing for some overlap with the low frequency end.
Spectral power density plots calculated using this approach for Pipe A are shown on Figure 5. There is clearly a strong component at the very long wavelength (low frequency) range (Figure 5a), with a significant peak density occurring at approximately 5.5 km wavelength and some spectral leakage into neighbouring wavelengths between about 3 and 8 km. Beyond that, there are some comparatively very small peaks at shorter wavelengths around 670 m, 400 m, and 295 m. The long wavelength Fourier series and least-squares trends are shown on Figure 6a. After removing the long wavelength component $f_A$ from the data (Figure 6b) and repeating the analysis, the spike at 670 m is now a major feature (Figure 5b). The cluster of spikes between 25 m and 100 m is obvious but less distinct because of its width. Several other distinct spikes occur for various wavelengths ranging from about 5 m to 15 m.

The spectral power plots for Pipe B are shown on Figure 7. Again, there is a strong component at the very long wavelength range between approximately 1 and 10 km (Figure 7a). Beyond that, significant peaks also occur at 110 m, 170 m, and 385 m. The long wavelength Fourier series and least-squares trends are shown on Figure 8a. After removing the long wavelength component $f_B$ from the data (Figure 8b), and repeating the analysis, the spike at 2 km is now a major feature, with a cluster of spikes down to about 500 m (Figure 7b). Distinct spikes also occur around 25 m, 50 m, and 100 m, as well as several other weaker spikes at various wavelengths down to about 6 m.

It is apparent from the least-squares analysis that there are four general components of embedment variability in the two datasets:

1. The first component is the long wavelength component ranging from about 3 to 8 km for Pipe A and from 1 to 10 km for Pipe B. This component represents the sea state effect, which for Pipe A was shown to be a governing factor in the observed pipeline embedment based on detailed back-analysis (Westgate et al. 2010a). Pipe B was laid in deep water from a lay vessel that minimized sea state effects (Perinet and Fraser 2007), so the sea state influence is less distinct.
2. The second component comprises intermediate wavelengths, ranging from approximately 300 to 700 m for Pipe A and from approximately 100 m to 400 m for Pipe B. This may be due to geological effects, for example the frequent pockmarks along Pipe A, laid in the Witch Ground area of the North Sea (Dando et al. 2007), but there may have been other contributing factors.

3. The third component comprises shorter intermediate wavelengths, ranging from 25 to 100 m for Pipe A and from 25 to 50 m for Pipe B. While it is uncertain from pipe-lay records what the exact pipeline construction sequence was, this component of variability is inferred to represent the stop-start welding and payout process during laying. Distinct peaks at 25 m and 50 m represent a double or quadruple pipe section, respectively, being constructed with each welding and offloading cycle.

4. Finally, there is a fourth component comprising very short wavelengths, less than 10 to 15 m for both pipes. This component may represent natural soil variability, as it is too short to be linked to any metocean-based. Alternatively, it could be associated with anthropogenic processes such as the intrinsic out-of-straightness of the manufactured pipe joints and their alignment during welding into the pipeline.

3.2 Numerical Simulations of Embedment Variability

Four factors influencing the as-laid embedment have been identified from the survey data for the two pipeline cases. For the second component comprising an intermediate wavelength associated with the geological features such as seabed pockmarks, ripples or anthropogenic factors, it is difficult to determine the level of influence of this component and link it to a specific soil or pipelay parameter used in a forward analysis of as-laid embedment. Furthermore, this component may not exist to any meaningful degree for featureless seabeds and uniform pipelines. Therefore, only three factors have been considered for constructing simulated profiles of as-laid embedment, each of which could be
considered to be inherently present for typical pipelines installed from a lay vessel. These comprise
(i) the metocean variability from the sea state (represented as the range in dynamic amplification
factor, $V_{\text{dyn}}/V_{\text{max}}$), the anthropogenic variability from the lay method (represented as the range in the
degree of soil remoulding – none to full – across the full range in measured soil sensitivity, $S_t$), and
(iii) the natural soil variability (represented as the range in intact undrained shear strength, $s_u$). The
embedment variation along the pipeline can then be written as the sum of these different influencing
factors:

$$\left( \frac{\Delta w}{D} \right)_{\text{Total}}(x) = \left( \frac{\Delta w}{D} \right)_M(x) + \left( \frac{\Delta w}{D} \right)_L(x) + \left( \frac{\Delta w}{D} \right)_S(x)$$  (2)

where:

$x$ is the position along the pipeline;

$(\Delta w/D)_M$ is the component of embedment affected by sea state, or metocean conditions;

$(\Delta w/D)_L$ is the component of embedment affected by the lay method; and

$(\Delta w/D)_S$ is the component of embedment affected by the soil heterogeneity.

The degree of influence of each of these factors on the overall embedment variation can be assessed
through deterministic calculations of undrained pipeline embedment using various extreme values of
each input parameter in Table 2 and Table 3, based on the methods presented in Randolph and White
(2008a, 2008b) and Merifield et al. (2009). This was done for each line, with the LE and HE
calculated embedment w/D, and resulting amplitude $A$ (equal to half the difference between the HE
and LE embedment) for each factor, shown in Table 5.

Each of the influencing mechanisms in Equation 2 was simulated using a sinusoidal waveform,
consistent with the spectral analysis. The wavelength $L_N$ and the amplitude $A_N$ for each cycle $N$ were
randomly sampled from a uniform distribution between low estimate (LE) and high estimate (HE)
values (Table 6). This basis for selecting the wavelengths represents a simplification of the spectral

analysis results, and the amplitude was based on the difference in embedment calculated in Table 5. The variation in embedment, $\Delta w/D$, for a given influencing component, along the length $x$ of each pipeline was taken as:

$$
\left( \frac{\Delta w}{D} \right)_x = A_N \sin \left( \frac{2\pi x}{L_N} \right)
$$

(3)

such that overall variation in embedment $w/D$ along each line was calculated as:

$$
\frac{w}{D}_x = \mu + A_{M,N} \sin \left( \frac{2\pi x}{L_{M,N}} \right) + A_{L,N} \sin \left( \frac{2\pi x}{L_{L,N}} \right) + A_{S,N} \sin \left( \frac{2\pi x}{L_{S,N}} \right)
$$

(4)

where $\mu$ is the mean global embedment.

An example deterministic simulation of the composite variation in embedment for Pipe A, showing the impact of the individual mechanisms, is shown on Figure 9. The axis scales differ to allow visual assessment of the variability effect for each mechanism. Each individual factor is presented in terms of its effect on the pipeline embedment, symmetrically distributed around a zero mean value. As indicated, the example simulation captures the general pattern of observed embedment variation from Figure 1a. A similar set of plots is shown on Figure 10 for Pipe B for comparison to Figure 1b. Improved matches could potentially be obtained by considering additional mechanisms, or by optimisation through a Kriging process (Krigge 1951), fitting specific points on the individual components from the survey data to predicted values.

Due to uncertainties in the potential variability of these influencing factors for a real pipeline, multiple realisations of these simulations can be performed, with each scale length and amplitude sampled probabilistically based on a selected distribution. Table 7 shows the stochastic parameters (mean and standard deviation) of scale length and amplitude for each mechanism considered in the deterministic analysis. These were used in a Monte Carlo analysis to calculate 100 different realisations of pipeline embedment variability. For each simulation, a fixed scale length value and
amplitude value for each mechanism was sampled from the mean and standard deviation, using normal distributions for each.

The resulting distribution in embedment across all 100 realisations for each pipeline are shown on Figure 11. As indicated, the simulated and field-based distributions compare well. The range in scale length and amplitude can of course be refined as information on sea state, lay vessels, and seabed conditions become available for a given site.

### 3.3 Impact on Lateral Seabed Resistance

In reality, it is actually the variability in pipe-soil resistance that is averaged in the structural response of the pipeline, not the embedment itself. The two quantities are not linearly related due to the non-linear effects of pipe embedment and soil strength on lateral resistance. However, if the spatial variation in pipe embedment is known then the spatial variation in lateral resistance can be determined.

The variation in lateral seabed resistance along each pipeline shown on Figure 12 was calculated using the soil parameters from Table 3 and the variation in as-laid pipe embedment from Figure 1. The best estimate soil parameters were used, in order to isolate the impact that the variation in pipeline embedment has on lateral resistance (noting that the embedment itself was predicted using a range of soil strength and sensitivity).

For the purposes of this illustrative example, the lateral resistance, specifically the peak, or breakout value, \( H_{brk} \), was calculated using the very simple approach described in Bruton et al. (2006):

\[
H_{brk} = 0.2W' + \frac{3}{\sqrt{s_{u-int}/\gamma}} \left( \frac{W}{D} \right) \tag{5}
\]

More accurate methods are used in design, such as those based on theoretical failure envelopes for shallowly embedded pipelines (Merifield et al. 2008, Randolph and White 2008a), but for the purposes of illustration the simpler approach is adequate.
The raw data values from the embedment surveys were averaged over a 10 m scale length to represent the minimum length scale over which the resistance is mobilised by a pipeline during formation of a lateral buckle (Figure 3). Stiffer pipelines of course could have longer mobilisation length, and vice versa. Also shown are the LE ($P_{5}$) and HE ($P_{95}$) values, typically used in a deterministic structural buckling analysis.

A simple approach to check for buckle susceptibility is by using the Hobbs infinite mode solution to calculate the critical buckling force, $P_{\text{Hobbs}}$ (Hobbs 1984):

$$P_{\text{Hobbs}} = 3.86 \sqrt{\frac{EIH_{\text{brk}}}{D}} \tag{6}$$

The critical buckling force profile for each pipeline is shown on Figure 13.

The axial driving force that causes buckles increases along the pipeline at a rate equal to the axial friction, $T = \mu W'$, with $\mu$ taken as 0.5 for both pipelines, representing a typical value accounting for stress history and embedment ‘wedging’ effects (White and Randolph 2007). This sets a constraint on the locations at which the buckling force can ever be reached. The axial force can never build up sufficient to trigger buckles at locations with high $P_{\text{Hobbs}}$ because the corresponding axial force profile will exceed lower values of $P_{\text{Hobbs}}$ on adjacent lengths of pipeline. The effective, or ‘conditional’, buckling force profile can be determined by filtering the calculated $P_{\text{Hobbs}}$ profiles, taking at each point (i) the minimum of the calculated buckling force or (ii) the force that could be mobilised at that point when a buckle at an adjacent location would trigger. As shown on Figure 13, when spatial variability is taken into account, the average potential buckling force is only slightly greater than the $P_{5}$ (LE) value that was calculated ignoring variability, for the parameters used in these synthetic embedment analyses.

This analysis represents a new method to quantify how much a pipeline is able to find a weak location to initiate a lateral buckle due to the spatial variability in embedment. The reduction in the
buckling force is created by the spatial variability, and for higher variability over shorter length scales, the reduction is greater.

To explore the generality of this observation, a Monte Carlo analysis was performed in which 100 synthetic embedment profiles were used to calculate 100 simulations of lateral breakout resistance profiles and critical buckle force profiles. For each simulation, the intact soil strength used in the lateral resistance calculation was allowed to vary between the LE and HE values (Table 3) using the same random variable value that was used to model the embedment variation due to strength heterogeneity. Conditional $P_{H_{brk}}$ profiles were then generated following the methodology described above, and were used to back-calculate the lateral resistance using Equation 6. The resulting distributions in $H_{brk}$ for each pipeline, based on 100 realisations with varying embedment and soil strength, are shown on Figure 14. Included in these plots are the conditional and overall distributions based on the field data, using the observed variation in embedment and best estimate soil properties.

The simulated conditional distributions in lateral resistance are lower than the overall distribution, and are comparable to the conditional distributions from the field data (but conservative, in the sense that the effect of spatial variability is underestimated rather than exaggerated). While the agreement is reasonable, some of the components in the spectral analysis have been overlooked. If the full spectrum had been used to generate the synthetic profiles, then perfect agreement would emerge. However, selection of the three components in Table 7 represents a practical simple approach that can be used in forward design, and does not require site specific field survey data to be provided.

Overall, this shows that the simplified spectral approach used to generate synthetic embedment profiles in the present analysis provides a good representation of the effect of variability on pipeline buckling, and the lateral resistance experienced by the buckles that form. This new approach can be refined in various ways as more survey data is reviewed, to improve our understanding of the influences on variability. Also, in a design scenario it is possible that survey data may be available
(from similar nearby pipelines, for example), in which case the full spectrum of embedment from those lines can be used to generate the synthetic embedment data for design.

Other techniques may be preferred for generating the embedment profiles, such as random fields simulated using the Local Average Subdivision (Fenton and Griffiths 2007), and existing approaches for incorporating this form of variability into pipe-soil interaction analysis have been proposed (e.g. McCarron 2015).

The use of only the conditional lateral resistance range can lead to significant cost savings in planned buckle mitigation if the expected variability can be captured at the design stage (Westgate and White 2015; Bransby et al. 2015), and is similar to consideration of other variability effects such as horizontal out-of-straightness (e.g. Rathbone et al. 2008b) or sediment mobility and pipeline self-burial (e.g. Roberts and Taavale 2014). This approach could be extended to other design checks using appropriate averaging lengths as illustrated in Figure 3.

4. CONCLUSIONS

This paper has proposed a simple approach for simulating as-laid pipeline embedment variability, and by extension, the variability in lateral seabed resistance. Averaging of the embedment and therefore the lateral resistance on the proper length scale accounts more accurately for portions of the pipeline that may have some movement, thereby limiting the axial forces that that could lead to the critical buckle force due to restraint caused by portions of the pipeline with high lateral restraint. Proper spatial averaging will better identify the more compliant zones than averaging over longer length scales. This spatial averaging approach can reduce the conservatism inherent in the usual handling of geotechnical variability in subsea pipeline design, particularly in relation to planned buckling to relieve expansion loads caused by temperature and pressure.

As-laid embedment data from two field surveys have been presented, covering different geographical regions, water depths, and lay conditions. Influencing mechanisms within the observed variability in
pipeline embedment have been extracted using spectral analysis. This spatial variability was then used to derive profiles of lateral seabed resistance and buckling force along each pipeline, which were filtered to account for local reductions in neighbouring locations. The results demonstrated the conditional distributions of buckle force and lateral resistance that arise because of the pipe being able to ‘find’ weak zones of soil resistance created by the spatial variability. These insights are used to define a new method to generate synthetic profiles of pipeline embedment which provides a basis to improve the realism of pipeline design by capturing the influence of spatial variability on the pipeline response.

While the study is limited to these two case histories, spatial variability is inherent to pipeline installation due to the stochastic nature of the sea state, variations in lay rate linked to pipeline construction processes, and natural variability in soil conditions. Unplanned buckles continue to occur in practice, and it is unclear whether these are solely due to the spatial variability in resistance being overlooked in design, or whether there are other mechanisms such as the horizontal or vertical out-of-straightness not being appropriately considered. Further back-analyses of field measurements of as-laid embedment together with back-analysis of operating pipelines would help explain this and lead to improved confidence in the incorporation of spatial variability in design.

The end goal is a rational approach to the generation of pipe-seabed interaction parameters that can interface with the various types of pipeline analysis used to assess the likelihood and tolerability of buckles, taking realistic account of spatial variability. Exploiting the ability of a subsea pipeline to work with variability in this way – by finding weaker zones of pipe-seabed resistance rather than reacting against the assumed uniform seabed conditions – may lead to savings in hydrocarbon development costs by reducing or eliminating buckle initiation and control structures along HPHT pipelines.
5. REFERENCES


Randolph, M.F., and White, D.J. 2008a. Upper bound yield envelopes for pipelines at shallow embedment in clay, Géotechnique, 58(4), 297-301


List of Tables

Table 1. Sources of variability in as-laid embedment and associated length scales
Table 2. Pipeline properties and lay conditions
Table 3. Soil conditions
Table 4. Ranges of pipeline embedment for different averaging lengths
Table 5. Calculated amplitude of embedment for each mechanism
Table 6. Deterministic parameters used in example embedment simulations
Table 7. Stochastic parameters used in probabilistic embedment simulations

List of Figures

Figure 1. As-laid field survey embedment data
Figure 2. Comparison of field data with embedment predicted by deterministic and probabilistic approaches
Figure 3. Relevant characteristic length scales for different HTHP pipeline design aspects
Figure 4. Effect of averaging length on design ranges in embedment
Figure 5. Least-squares spectral power density distributions for Pipe A
Figure 6. Best fit Fourier series and least-squares approximation to Pipe A embedment data
Figure 7. Least-squares spectral power density distributions for Pipe B
Figure 8. Best fit Fourier series and least-squares approximation to Pipe B embedment data
Figure 9. Example simulation of as-laid pipeline embedment for Pipe A
Figure 10. Example simulation of as-laid pipeline embedment for Pipe B
Figure 11. Observed versus simulated distributions in pipe embedment based on 100 Monte Carlo realizations
Figure 12. Calculated lateral breakout resistance profiles using 10 m averaged as-laid embedment profile and BE soil properties
Figure 13. Calculated critical buckling force profiles using 10 m averaged variable lateral breakout resistance profiles (vertical scales for each pair of graphs is identical)
Figure 14. Collated distributions of simulated conditional breakout resistance compared to overall range
Table 1. Sources of variability in as-laid embedment and associated length scales

<table>
<thead>
<tr>
<th>Source</th>
<th>Basis</th>
<th>Examples</th>
<th>Length scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>geological</td>
<td>soil heterogeneity</td>
<td>soil strength, soil unit weight</td>
<td>very short</td>
</tr>
<tr>
<td></td>
<td>sediment deposition</td>
<td>sediment runoff</td>
<td>long</td>
</tr>
<tr>
<td></td>
<td>seabed features</td>
<td>sand waves, furrows, pockmarks, iceberg scars</td>
<td>moderate</td>
</tr>
<tr>
<td>anthropogenic</td>
<td>lay activities</td>
<td>PLET/ILT installation, mechanical downtime</td>
<td>short</td>
</tr>
<tr>
<td></td>
<td>lay method</td>
<td>J-lay, S-lay, reel lay</td>
<td>short</td>
</tr>
<tr>
<td></td>
<td>pipeline design</td>
<td>anode connection, buckle arrestors, ITP field joints</td>
<td>varies</td>
</tr>
<tr>
<td>metocean</td>
<td>sea state</td>
<td>swell, waves, wind, currents</td>
<td>very long</td>
</tr>
</tbody>
</table>
## Table 2. Pipeline properties and lay conditions

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Diameter</th>
<th>Submerged pipeweight, W' (kN/m)</th>
<th>Bending stiffness, EI (MN-m²)</th>
<th>Lay angle, φ (deg)</th>
<th>Water depth, z_w (m)</th>
<th>Significant wave height, H_s (m)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>0.39</td>
<td>0.22</td>
<td>36.6</td>
<td>68</td>
<td>~140</td>
<td>0.3 to 4</td>
</tr>
<tr>
<td>B</td>
<td>0.50</td>
<td>0.37</td>
<td>46.9</td>
<td>84-86</td>
<td>~1300</td>
<td>0.7 to 2.5</td>
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</table>
Table 3. Soil conditions

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil type</th>
<th>Undrained shear strength gradient, ( k_{su-int} ) (kPa/m)</th>
<th>Soil sensitivity, ( S_t ) (-)</th>
<th>Soil submerged unit weight, ( \gamma' ) (kN/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>silty clay</td>
<td>2.4 to 15</td>
<td>2 to 4</td>
<td>~7.5</td>
</tr>
<tr>
<td>B</td>
<td>high plasticity clay</td>
<td>12 to 24</td>
<td>3 to 5</td>
<td>~3</td>
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</table>
Table 4. Ranges of pipeline embedment for different averaging lengths

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Case</th>
<th>Raw</th>
<th>10 m</th>
<th>100 m</th>
<th>1000 m</th>
</tr>
</thead>
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<td>LE (P₅₀)</td>
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<td>0.26</td>
<td>0.27</td>
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<tr>
<td></td>
<td>HE (P₉₅)</td>
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<td>0.50</td>
<td>0.47</td>
<td>0.47</td>
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<tr>
<td>B</td>
<td>LE (P₅₀)</td>
<td>0.14</td>
<td>0.16</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>HE (P₉₅)</td>
<td>0.31</td>
<td>0.28</td>
<td>0.26</td>
<td>0.25</td>
</tr>
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</table>
Table 5. Calculated amplitude of embedment for each mechanism

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Factor</th>
<th>Case</th>
<th>$s_{u,int}$</th>
<th>$S_t$</th>
<th>$\gamma'$</th>
<th>$V_{dyn}/V_{max}$</th>
<th>w/D</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sea state</td>
<td>LE</td>
<td>10</td>
<td>3</td>
<td>7.5</td>
<td>1.0</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HE</td>
<td>10</td>
<td>3</td>
<td>7.5</td>
<td>3.0</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lay method</td>
<td>LE</td>
<td>10</td>
<td>1</td>
<td>7.5</td>
<td>2.0</td>
<td>0.22</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HE</td>
<td>10</td>
<td>4</td>
<td>7.5</td>
<td>2.0</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil heterogeneity</td>
<td>LE</td>
<td>15</td>
<td>2</td>
<td>7.5</td>
<td>2.0</td>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HE</td>
<td>2.4</td>
<td>4</td>
<td>7.5</td>
<td>2.0</td>
<td>0.60</td>
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</tr>
<tr>
<td>B</td>
<td>Sea state</td>
<td>LE</td>
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<td>4</td>
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<tr>
<td></td>
<td>Lay method</td>
<td>LE</td>
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<td>0.09</td>
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<tr>
<td></td>
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<td>HE</td>
<td>20</td>
<td>5</td>
<td>3</td>
<td>1.5</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil heterogeneity</td>
<td>LE</td>
<td>24</td>
<td>3</td>
<td>3</td>
<td>1.5</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HE</td>
<td>12</td>
<td>5</td>
<td>3</td>
<td>1.5</td>
<td>0.30</td>
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</table>
Table 6. Deterministic parameters used in example embedment simulations

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Case</th>
<th>Sea State</th>
<th>Lay Method</th>
<th>Soil Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Length, $L_M$ (m)</td>
<td>Amplitude, $A_M$ ($\Delta w/D$)</td>
<td>Length, $L_L$ (m)</td>
</tr>
<tr>
<td>A</td>
<td>LE</td>
<td>3000</td>
<td>0.00</td>
<td>25</td>
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<tr>
<td></td>
<td>HE</td>
<td>8000</td>
<td>0.16</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>LE</td>
<td>1000</td>
<td>0.00</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>HE</td>
<td>10000</td>
<td>0.06</td>
<td>50</td>
</tr>
</tbody>
</table>
Table 7. Stochastic parameters used in probabilistic embedment simulations

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Case</th>
<th>Sea State</th>
<th>Lay Method</th>
<th>Soil Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Length, $L_M$ (m)</td>
<td>Amplitude, $A_M$ (Δw/D)</td>
<td>Length, $L_L$ (m)</td>
</tr>
<tr>
<td>A</td>
<td>Mean</td>
<td>5500</td>
<td>0.08</td>
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<tr>
<td></td>
<td>Standard Deviation</td>
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<td>Mean</td>
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<td></td>
<td>Standard Deviation</td>
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<td>0.02</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Figure 1. As-laid field survey embedment data
Figure 2. Comparison of field data with embedment predicted by deterministic and probabilistic approaches
Figure 3. Relevant characteristic length scales for different HTHP pipeline design aspects
Figure 4. Effect of averaging length on design ranges in embedment
Figure 5. Least-squares spectral power density distributions for Pipe A

(a) Low frequency components

(b) High frequency components
Figure 6. Best fit Fourier series and least-squares approximation to Pipe A embedment data

(a) Low frequency component and trendline

(b) Remaining high frequency data
Figure 7. Least-squares spectral power density distributions for Pipe B
Figure 8. Best fit Fourier series and least-squares approximation to Pipe B embedment data
Figure 9. Example simulation of as-laid pipeline embedment for Pipe A
Figure 10. Example simulation of as-laid pipeline embedment for Pipe B
Figure 11. Observed versus simulated distributions in pipe embedment based on 100 Monte Carlo realizations
Figure 12. Calculated lateral breakout resistance profiles using 10 m averaged as-laid embedment profile and BE soil properties.
Figure 13. Calculated critical buckling force profiles using 10 m averaged variable lateral breakout resistance profiles (vertical scales for each pair of graphs are identical)
Figure 14. Collated distributions of simulated conditional breakout resistance compared to overall range