An Improved Model for the Prediction of Pipeline Embedment on the Basis of Assessment of Field Data

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Summary

This paper reviews the current methodology for assessing pipeline embedment against field data, in which underprediction of pipeline embedment could be critical to design integrity.

Pipeline embedment is a fundamental input to the assessment of pipe/soil interaction (PSI), which is the largest uncertainty faced in the design of pipelines subject to lateral-buckling and walking phenomena. However, pipeline embedment is notoriously difficult to predict because of the inherent uncertainty of the installation process. Improving the prediction of pipeline embedment is critical to reducing the range of predicted PSI responses in design.

A current project has compared high-quality observations of pipeline embedment from an earlier phase of the same field development against predicted embedment with more-recent, high-quality soil data from parallel pipeline routes, including fully remolded soil strength from cyclic penetrometer testing. While current design approaches were underpredicting embedment levels, leading to a potentially nonconservative design, this updated methodology provided a much-improved match to actual embedment data. The revised model was verified successfully against measured levels of pipeline embedment and is now being used for the design of future pipelines in the area, with improved certainty and easing of the design challenge.

One important principle behind this new approach is to define the operative soil strength on the basis of the reconsolidation of the remolded soil beneath the weight of the empty pipe during the intervening period between laying and flooding. Having demonstrated that the soil around the pipe becomes fully remolded during installation, one can show that the additional embedment that can occur upon flooding needs to be assessed with an operative strength from reconsolidation, rather than the intact strength, which is current practice. This paper also provides current equations that improve the prediction of embedment greater than one-half diameter by proposing methods to take account of the increasing buoyancy with depth, the reducing influence of heave mounds, and the modified penetration resistance at deeper embedment. The methodology presented in this paper has the potential to improve assessments of embedment and avoid PSI responses that are not conservative on future developments.

Introduction

Verification of embedment-prediction models against existing pipelines is recommended frequently because of the known uncertainties surrounding installation dynamics and pipe/soil interaction (PSI), particularly where the PSI response is critical to the design of future pipelines in the same vicinity. Pipeline embedment influences both axial and lateral resistance, and these PSI responses are usually the most-significant uncertainty in the design of pipelines laid on the seabed. The case history presented in this paper shows that this approach is invaluable and provides a significant contribution to good design practice.

Two existing export pipelines of significantly different overall pipeline diameter and submerged weight were laid along the same route, in the same soils. These pipelines might have been expected to reach quite different levels of embedment following installation and flooding, and current models for predicting embedment (described in the following) confirmed this; yet, the final levels of embedment were relatively similar and deeper than those that would be predicted with current practice. This is clearly a concern because higher levels of embedment generally lead to higher levels of resistance from the soil, which is often the most-challenging design case in the assessment of lateral buckling (Bruton et al. 2007). This finding has therefore provided an excellent opportunity to modify and calibrate embedment models for use in defining PSI responses on current projects.

An assessment of the embedment mechanisms during installation and post-installation flooding has led to a modified methodology supported by geotechnical principles that provide a much-improved correlation between predicted and measured embedment levels for these pipelines. This new approach is recommended for prediction of pipeline embedment levels on current projects.

This paper addresses some important revisions to current embedment models:

- Improved modeling of penetration resistance because of buoyancy, heave mounds, and bearing capacity at embedment levels greater than one-half diameter, which is a concern in weaker soils.
- Improved modeling of the likely operative shear strength at the time of pipeline flooding, to account for the level of strength regained because of reconsolidation of the soil under the weight of the empty pipe.

In this assessment, one can assume that sufficient time (2 to 4 months) has passed to achieve a relatively high level of reconsolidation. Further work is required to quantify the likely increase in operative strength with time because the duration between installation and flooding is potentially an important input to the final pipeline embedment. Indeed, this methodology confirms that insufficient time between installation and flooding can result in excessively deep pipeline embedment.

Pipeline-Embedment Model

Definition of Pipeline Embedment. Nominal pipe embedment (w) is defined as the depth of penetration of the invert (bottom of the pipe) relative to the undisturbed seabed (usually termed “far” embedment), as shown in **Fig. 1.** Penetration of the pipe increases the local embedment of the pipe (usually termed “near” embedment) by raising the soil surface against the shoulders of the pipe. While heave mounds are observed frequently in pipeline surveys

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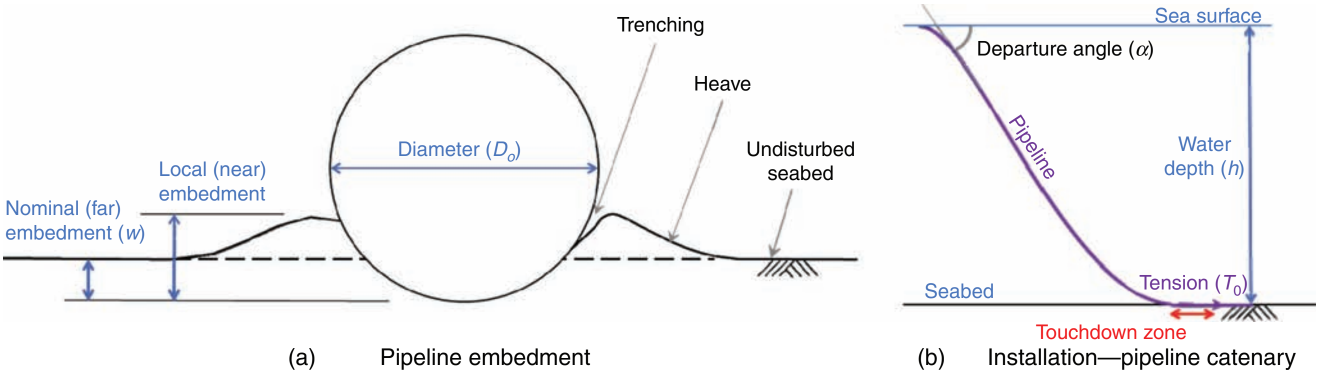

Fig. 1—Pipeline embedment and lay catenary touchdown zone.

following installation, it is also possible to observe "trenching" (or gapping) on each side of the pipe because of lateral touchdown dynamics. Field observations over time reveal that heave mounds and trenching tend to dissipate with time. Therefore, although high levels of local embedment may be present initially, this should not be relied upon to provide additional restraint or thermal insulation in the longer term. The conventional definition of embedment used in pipeline design is therefore the "nominal" pipeline embedment, which is usually normalized by the overall pipeline diameter (D_o).

Previous Publications and Research. A previous SAFEBUCK joint-industry-project (JIP) publication by Bruton et al. (2006) referenced the original plasticity solutions by Murff et al. (1989) to give a simple expression for predicting pipeline embedment on the basis of limited test data:

$$\frac{w}{D_o} = \frac{S_t}{45}\left(\frac{V}{D_o \cdot s_u}\right)^2. \quad (1)$$

This model recognizes the important influence of the soil sensitivity (S_t) on the definition of the reduction of intact shear strength (s_u/S_t), which is adopted later as the operative strength for as-laid embedment. However, Eq. 1 (and the other lateral-breakout and lateral-residual-response equations presented in that paper) have since been superseded by significant advances in the understanding of pipe/soil interaction (PSI). These advances are based on extensive research carried out over the intervening years by the SAFEBUCK JIP [summarized by Bruton and Carr (2011)] and numerous offshore projects, such as those reported by Hill and Jacob (2008), Hill et al. (2012), and Langford et al. (2007).

Meanwhile, pipeline-embedment research culminated in a comprehensive review by Randolph and White (2008), who presented the current model to predict pipeline embedment, which expresses the limiting load (V) at a given penetration as

$$\frac{V}{D_o \cdot s_u} = a\left(\frac{w}{D_o}\right)^b + f_b\left(\frac{A_s}{D_o^2}\right)\cdot\left(\frac{\gamma' \cdot D_o}{s_u}\right). \quad (2)$$

This model is the basis for current embedment assessments. The first term of this expression is a bearing factor (summarized as N_c) that is based on the theoretical plasticity limit-analysis solution, where a and b are parameters that vary with soil type and pipe roughness. Rounded values of $a = 6$ and $b = 0.25$ are convenient for defining a suitable bearing factor for design (Randolph and White 2008). This bearing factor accounts for the increasing contact area of the pipe as it penetrates into the soil and defines the penetration resistance as a function of soil shear strength (s_u). The second term defines the influence of buoyancy in the surrounding soil, as a function of the soil submerged unit weight (γ'), where the buoyancy is enhanced by a heave factor (f_b) to account for the soil that rises up to each side as the pipe penetrates the seabed, where typically $f_b \approx$ 1.5 (Merifield et al. 2009). A_s is the area of pipe lying below the mudline level, defined by Randolph and White (2008) as

$$A_s = \frac{D_o^2}{4}\left(\begin{array}{l}\sin^{-1}\left\{\sqrt{4\left(\dfrac{w}{D_o}\right)\left[1-\left(\dfrac{w}{D_0}\right)\right]}\right\}\\ -2\left\{1-2\left(\dfrac{w}{D_o}\right)\sqrt{\left(\dfrac{w}{D_o}\right)\left[1-\left(\dfrac{w}{D_o}\right)\right]}\right\}\end{array}\right). \quad (3)$$

However, the limitation of this model is that it is not valid beyond one-half the pipe diameter (0.5D). To extend this model to greater depths of embedment, it is necessary to reassess

1. The equation for the area of pipe lying below the mudline level (A_s)
2. The heave factor (f_b)
3. The bearing-factor calibration parameters a and b

Pipeline Embedment: Improvement to the Buoyancy Term, Extended Beyond 0.5D_o. To extend the embedment assessment to penetrations beyond 0.5D, it is necessary to modify Eq. 3 for A_s to capture the increase in buoyancy (relative to the soil) from 0.5D to 1.0D embedment and beyond. It is assumed that the top half of the pipe is unlikely to be surrounded by water, and is instead increasingly surrounded by the remolded soil flowing around and falling back over the pipe. The following equation is proposed here, which is simpler to apply and accounts for the increased level of buoyancy at embedment levels up to and beyond 1.0D:

$$A_s = D_o^2\left\{\left(\frac{\theta}{4}\right)+\left[\left(\frac{w}{D_o}\right)-\frac{1}{2}\right]\cdot\sqrt{\left(\frac{w}{D_o}\right)\left[1-\left(\frac{w}{D_o}\right)\right]}\right\},$$

$$\text{for } w < D_o, \quad (4)$$

where $\theta = \cos^{-1}\left[1-2\cdot\left(\dfrac{w}{D_o}\right)\right]$ (θ is depicted in **Fig. 2**).

$$A_s = D_o^2\left(\frac{\pi}{4}\right), \text{ for } w \geq D_o. \quad (5)$$

Equivalent equations for A_s are also presented in a different form by Randolph and Gourvenec (2011).

Pipeline Embedment: Improvement to Heave Factor, Extended Beyond 0.5D_o. The buoyancy term in Eq. 2 includes a buoyancy heave factor (f_b) of 1.5 to account for the additional buoyancy

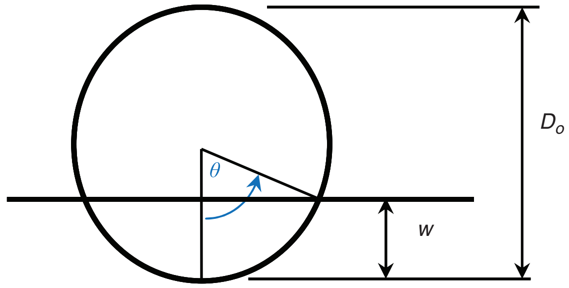

Fig. 2—Buoyancy-term nomenclature.

force caused by the heave mounds that form to each side of the pipe as the pipe penetrates the seabed, thus increasing the height of soil adjacent to the pipe (Merifield et al. 2009). This penetration resistance caused by buoyancy actually has two components:

- The buoyancy from the pipe immersed in the soil (accounted for by A_s)
- The negative buoyancy of the soil rising above the level of the surrounding seabed (accounted for by f_b)

However, the influence of the heave mounds on the buoyancy force is likely to reduce at deeper embedment levels (beyond 1.0D) because the heave-mound buoyancy factor (f_b) reduces to a value of 1.0. In reality, the influence of water entrained into the soil above the pipe could reduce the buoyancy force. However, by definition, f_b must converge to a value of unity at the depth at which the bearing factor reaches its "deep value," so that using a value of f_b = 1.0 at a shallower depth is conservative. In place of tests or finite-element analyses to define the heave factor for $w > D_o/2$, it is judged prudent to reduce the heave factor gradually from f_b = 1.5 at $w = D_o/2$ to f_b = 1 at $w \geq D_o$. Although the transition could vary considerably because of the uncertainty of heave-mound (trench-wall) collapse and flow-around mechanisms, a sinusoidal shape achieves a relatively smooth transition, as illustrated in **Fig. 3.** On this basis, a revised heave factor was proposed and illustrated in Fig. 3. Chatterjee et al. (2012) presents a more-detailed and -recent assessment of the heave factor (f_b) up to a depth of 1.0D, which also appears to confirm that the heave factor reduces with penetration depth, although this effect is not quantified.

$$f_b = 1.5, \text{ for } w \leq D_o/2. \quad (6)$$

$$f_b = 1.25 - 0.25 \cdot \cos\left[2\pi\left(\frac{w}{D_0}\right)\right], \text{ for } D_o/2 < w < D_o. \quad (7)$$

$$f_b = 1.0, \text{ for } w \geq D_o. \quad (8)$$

Pipeline Embedment: Improvement to Bearing Factor, Extended Beyond 0.5D_o. The bearing factor for a deeply penetrated pipe was based on tests carried out in kaolin at 1 g by Aubeny et al. (2008), where the bearing factor (N_c) was measured for embedment levels up to 5D, although the associated theoretical model neglects the weight of the soil that is raised up as the pipe penetrates into the seabed. On the basis of this test, a modification to the bearing factor, defined by modified values of the power-law parameters a and b, is proposed in **Table 1** to assess penetration resistance at deeper embedment levels.

The correlation with test data is reasonable; this model offers an improved fit to the data for embedment levels beyond 0.5D when compared with an extrapolated prediction, using the parameters proposed by Randolph and White (2008) for Eq. 2 in **Fig. 4** (identified in the legend as R&W extrapolated). This figure overlays the plot presented by Aubeny et al. (2008) with the modified bearing factor. In any case, the difference in bearing factor at deep penetrations is relatively small.

Uncertainty. The influence of uncertainty in the input parameters (s_u, γ', and S_t) is commonly assessed with the extremes of each value, which can be unnecessarily onerous. A more-pragmatic approach is to use first-order approximation of the combined probabilities, from which the high-estimate and low-estimate values are derived (Bruton et al. 2006). However, a more-rigorous approach is to combine the uncertainties with a probabilistic Monte Carlo analysis.

Conservatism in the Revised Embedment-Penetration Model. This revised embedment model is conservative because it is most relevant to the high-estimate embedment, and should err on the side of predicting slightly greater depths of embedment.

- The penetration resistance as a result of the bearing factor will probably increase more rapidly with depth than in the tests by Aubeny et al. (2008) because they were performed at 1 g, with a high overconsolidation ratio.
- The penetration resistance as a result of the heave-mound buoyancy factor should converge to a value of unity only at the depth at which N_c reaches the deep value by definition, so that using 1.0 at a shallower depth is conservative.

In summary, the current embedment model includes a number of improvements over earlier models and uses

1. Eq. 2, with bearing-factor parameters a and b, as given in Table 1
2. A_s, as defined by Eqs. 4 and 5

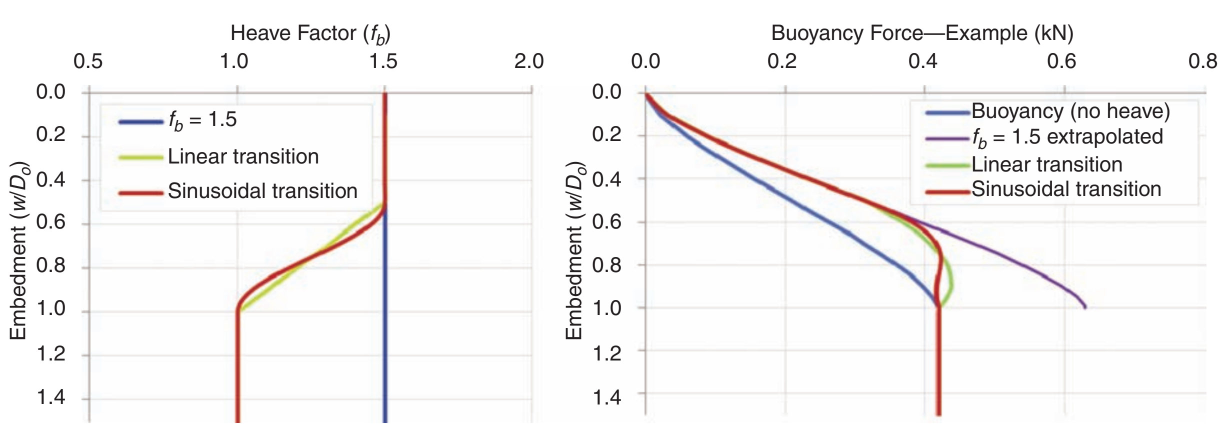

Fig. 3—Heave factor.

Pipe Depth of Penetration	*a*	*b*
$z/D_o \leq 0.5$ (current model)	6	0.25
$z/D_o > 0.5$	6.15	0.28
$z/D_o > 1$	6.15	0.26

Table 1—Proposed N_c power-law coefficients.

3. f_b, as defined by Eqs. 6 through 8, noting that recent work provides more detail on defining this factor (Chatterjee et al. 2012)

This model was used throughout the embedment calibration and is considered suitable for use on future projects for undrained embedment assessments associated with clay soils. Further research may well lead to improvements to some of these parameters. For completeness, this embedment-model review must now address the definition of the vertical load (V) and the associated operative shear strength (s_u).

Vertical Pipeline Load (V)

Pipeline embedment is based on the vertical PSI contact force (V) for three conditions:

1. The submerged weight of the pipe at installation (W_i'), usually empty (air-filled), but may be flooded with seawater[1], multiplied by a touchdown lay factor (k_{lay}) to account for the additional contact load in the touchdown zone.
2. The flooded submerged weight (W_f'), which occurs before hydrostatic testing and operation.
3. The operating submerged weight (W_o'), which is almost always less than the flooded weight.

The as-laid pipeline embedment usually exceeds predictions on the basis of the static self-weight alone. Two effects arise during the laying—the static vertical load induced by the laying process causing a force concentration in the touchdown zone, and the dynamics of the lay process arising from vertical and lateral catenary oscillations in the touchdown zone. These two influences are addressed in the following subsections.

Installation Parameters: Touchdown Lay Factor (k_{lay}). The touchdown lay factor ($k_{lay} = V_{tdz}/W_i'$) may be calculated by use of a simple catenary analysis on the basis of the horizontal component of lay tension (T_0), or the departure angle (α) and water depth (h) combined with the pipe composite bending stiffness (EI) and the submerged weight of the pipeline (W_i). There are two published methods to assess the touchdown lay factor or additional touchdown reaction.

Randolph and White (2008). On the basis of a linear elastic seabed response, if $T_0 > 3\lambda W_i'$, the stress-concentration factor k_{lay} can be estimated as

$$k_{lay} = 0.6 + 0.4\left(\frac{\lambda^2 \cdot k}{T_0}\right)^{0.25}, \quad (9)$$

where $\lambda = \sqrt{\dfrac{EI}{T_0}}$ and $k = \dfrac{V_{tdz}}{w}$.

Palmer (2008). On the basis of a rigid-plastic seabed response, the touchdown reaction can be derived by finding the depth at which the seabed-penetration resistance equals the required indentation reaction (V_{tdz}).

[1]The installation of a pipe flooded with seawater is unusual, but has benefits for pipelines with a low operating temperature because preflooding reduces the effective force in the pipeline, reducing pipeline expansion loads in operation. Flooded installation may also increase pipe embedment, thereby increasing axial and lateral resistance, although this generally has less influence on the expansion and buckling loads for such systems. For systems with higher operating temperature (such as production pipelines), the benefits of flooded lay are less perceptible.

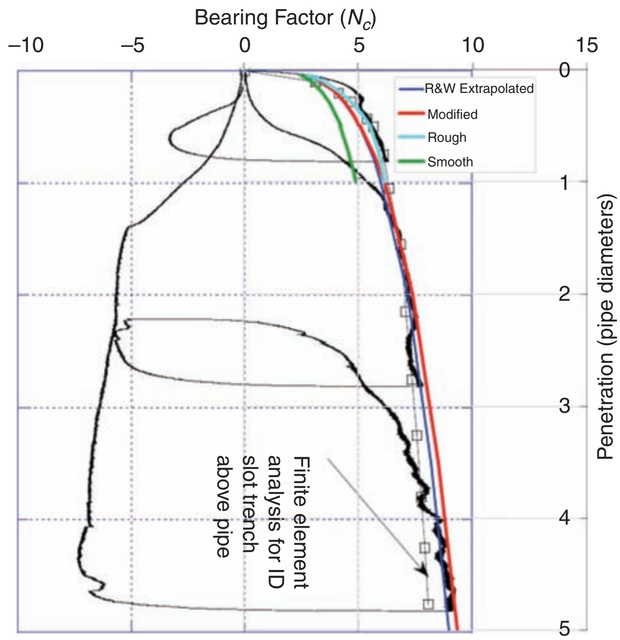

Fig. 4—Comparison of bearing factors with modified curve, after Aubeny et al. (2008).

$$\frac{w}{D_o} = \frac{EI \cdot W_i'}{2 \cdot D_o \cdot T_0^2}\left\{-m\left[\ln\left(1+\frac{1}{m}\right)\right]^2 + \frac{1}{1+m}\right\}, \quad (10)$$

where $m = \dfrac{V_{tdz}}{W_i'} - 1$. Both approaches require iteration until a compatible embedment and touchdown reaction is reached. The Palmer (2008) solution is more complex to apply, but provides a marginal (sometimes negligible) reduction in the value of k_{lay} and the resulting depth and range of embedment.

The touchdown lay factor increases in stiffer soils where the touchdown reaction is concentrated over a shorter length of pipe. In softer soils, where the reaction is spread over a long length of pipe, the touchdown factor can equal unity (no increased reaction). The touchdown factor can never be less than unity.

Operative Soil Strength During Installation

To assess embedment during installation, the touchdown dynamic motion in clay soils is accounted for with the fully remolded strength of the soil, which is now measured routinely by cyclic penetrometer tests (typically a T-bar or ball penetrometer), as described by Low et al. (2008). There are counteracting influences on the expected level of remolding because of water entrainment that would increase the sensitivity (further reducing the remolded strength) and the limited number of load cycles that occur in the touchdown zone, which may not be sufficient to fully remold the soil. However, the use of the fully remolded strength is straightforward and has been found by Westgate et al. (2010b) to provide a good fit to observed embedment.

It is clear from reviews of embedment data that the level of remolding during installation is affected by the installation-vessel type, lay rate, and configuration of the departure ramp or stinger for the installation conditions. Occasionally, a valuable and complete record of installation data, soil data, and embedment data for a pipeline is made available for review, allowing the influence of all these parameters to be assessed in detail (Westgate et al. 2010a). Shallow departure angles are normally associated with shallow water depths and generally require a higher lay tension. High lay tension is normally associated with an S-lay vessel (where "S"

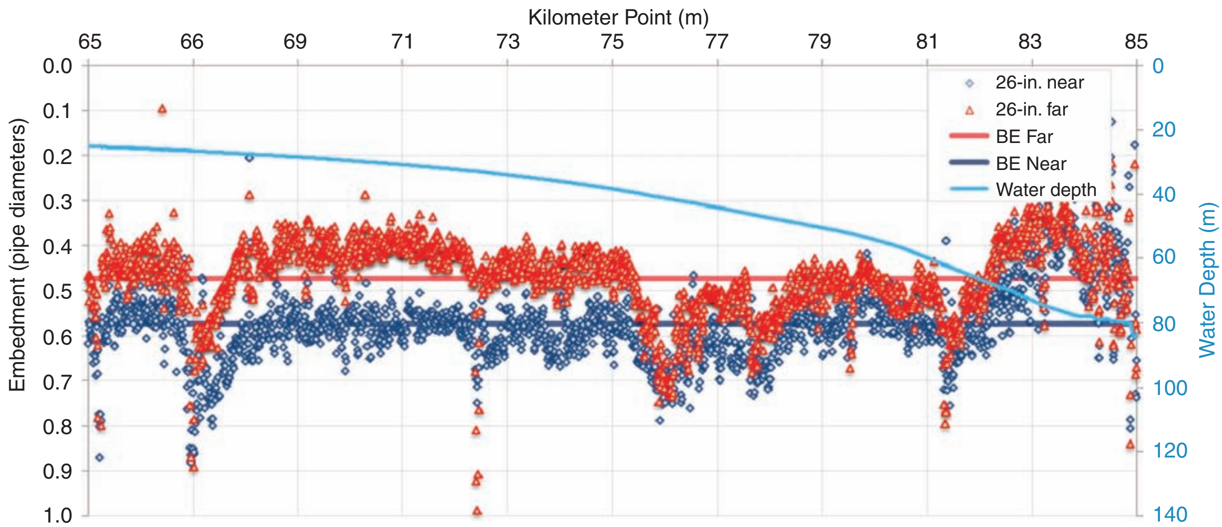

Fig. 5—26-in. pipeline—near and far embedment in early operation with best-estimate (BE) value more than 20 km.

describes the shape of the lay catenary) and tends to reduce the touchdown load, but introduces a higher level of soil disturbance, particularly at slow lay rates. There are some reservations about the embedment mechanism and level of soil disturbance in shallow water, where sideways motion of the pipe in the touchdown zone is more prevalent, causing trenching and higher-than-expected levels of embedment. Trenching is often evident in shallow-water-embedment data, as evidenced in a case study by Westgate et al. (2010b), and was present in embedment profiles from the case study presented in this paper for water depths less than 25 m.

Operative Soil Strength During Pipeline Flooding: Improved Approach

Although the soil around the pipe is assumed to be fully remolded during the installation process, the undisturbed soil-strength profile is used traditionally to define the penetration resistance when the pipeline is flooded. This implies that soil extending beneath the as-laid pipe has not been remolded by the installation process, or has recovered back to the intact strength. This existing approach was based on data from pipe/soil-interaction testing and comparison of predictions with measured embedment in deepwater fields. However, this approach does not correlate well with observed pipeline embedment for some very light pipelines that experience a significant increase in submerged weight upon flooding, typically large-diameter pipelines. Indeed, the existing methodology can severely underpredict pipeline embedment in such cases.

The following case study has confirmed that operative soil strength at the time of pipe flooding may be an important influence on the final embedment of large-diameter pipelines in clay soils. The case study shows that the zone of soil remolding may extend some distance below the installed pipeline and that this remolded soil will experience reconsolidation under the weight of the empty pipe in the period between installation and flooding of the pipeline. The operative shear strength of this soil beneath the pipe is then a function of the original soil strength, the load exerted on the soil, and the period of reconsolidation. This is illustrated by an assessment of embedment data from two pipelines, combined with recent high-quality soil data from a recent survey along the same pipeline route.

Case Study

Two existing export pipelines with markedly different pipeline diameters of 26 and 12 in. were laid along the same route, in the same soils. Current models for predicting embedment of these pipelines

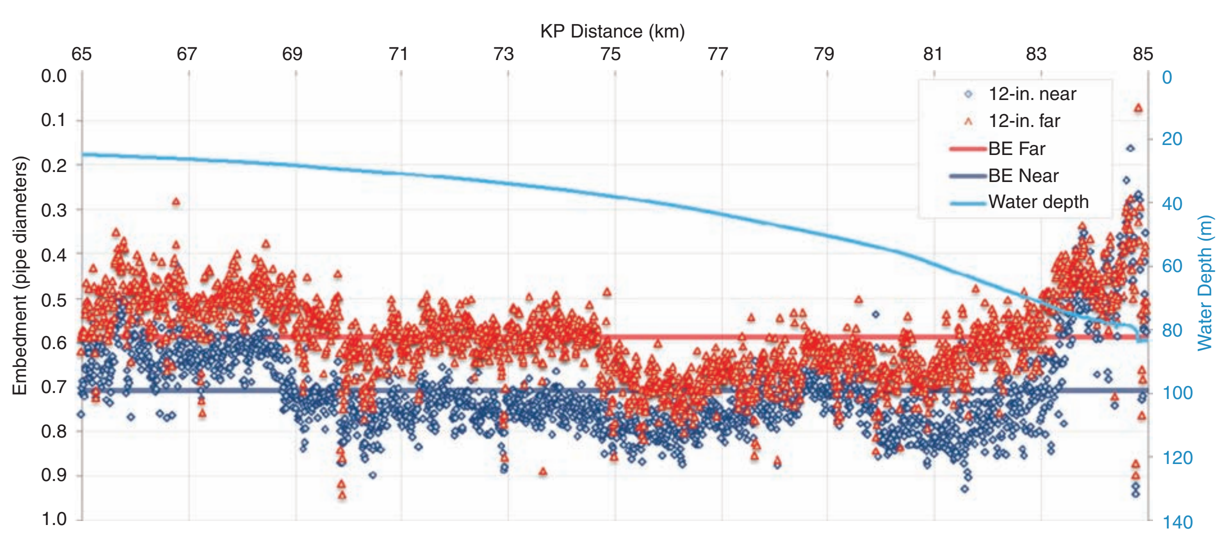

Fig. 6—12-in. pipeline—near and far embedment in early operation with best-estimate (BE) value more than 20 km.

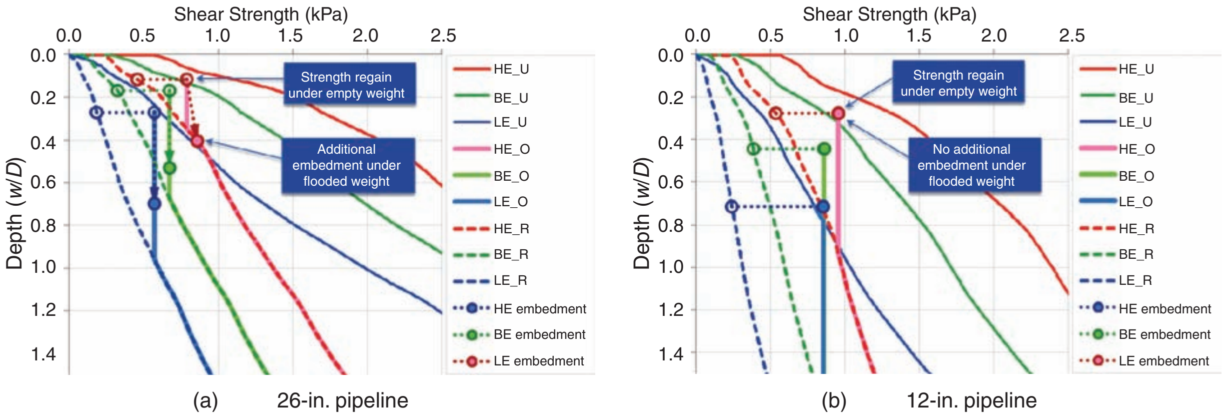

Fig. 7—Example showing high-estimate (HE), low-estimate (LE), and best-estimate (BE) values for undrained (U), operative (O), and remolded (R) shear-strength profiles.

severely underpredicted the embedment of the 26-in. pipeline. The causes of this discrepancy were assessed against high-quality observations of pipeline embedment in early operation and more recently acquired high-quality soil data from the pipeline routes, including cyclic-remolded-soil strength from penetrometer testing. This paper focuses on a 20-km section of the route of these two pipelines; the embedment data (smoothed to a 10-m gauge length for consistency) are shown in **Figs. 5 and 6** (for the 26- and 12-in.-diameter pipelines, respectively). There is scatter in these data because of installation upsets and some variation in soil properties and bathymetry along the pipeline route.

Base Case (Case 1): Undrained In-Situ Strength Case. The base case (Case 1) assumes that the undisturbed soil-strength profile (shown in **Fig. 7**) is used to define the penetration resistance upon flooding. In **Fig. 8,** which compares all the cases presented in this paper, the predicted embedment data (in dark purple) are compared with the actual embedment data (in turquoise), in which the high-estimate and low-estimate values are defined as +/– 1 standard deviation on the mean.

The underprediction of post-flood embedment for the 26-in. pipeline is excessive. A number of potential causes for this discrepancy were first eliminated, including the markedly different configuration of the pipelines **(Table 2),** which might have influenced the installation dynamics.

Excessive dynamically induced embedment was ruled out because these pipelines were installed under relatively benign environmental loading, and the touchdown amplification factor (k_{lay}) was equal to unity in most cases. Therefore, load amplification in the touchdown region is negligible.

High levels of soil remolding during installation were also ruled out by an assessment simulating increased soil sensitivity (causing greater reductions in remolded shear strength at installation). The as-laid submerged weight of the 26-in. pipeline is insufficient to overcome the buoyancy component of penetration resistance to reach recorded embedment levels. Also, if the remolded strength at installation were reduced, the 12-in. pipeline would reach a much greater embedment than that observed. It was concluded that dynamic load factors at installation are not likely to have caused the high as-laid and post-flooded embedment.

Fully Remolded Strength: Case 2. It was concluded that the increase in pipe weight upon flooding must have played a vital role in the final embedment of the larger pipeline. An assessment on the basis of the soil remaining in a fully remolded condition at the time of flooding did yield embedment levels closer to those observed, although the embedment of both pipelines was now overpredicted. Fig. 8 shows the overpredicted embedment (in green) for this fully remolded case (Case 2), compared with the actual embedment data (in turquoise).

It was also confirmed that the period of time between installation and flooding (2 to 4 months for the majority of the pipeline length) meant that the soil should have recovered strength because of reconsolidation before flooding.

The "operative" strength following reconsolidation of the soil is a function of the intact shear strength, the remolded strength following installation, and the vertical load exerted by the pipelines before flooding. Because the bearing pressure before flooding of the 12-in. pipe is greater than that of the 26-in. pipe and the drainage paths are shorter, the level of reconsolidation should be greater around the 12-in. pipe **(Table 3).** Therefore, the additional embedment following flooding would be commensurately less for the 12-in. pipe.

Strength Regain: Case 3. The following are proposed:

- The depth of soil remolding during installation could extend to some distance below the pipe invert.
- The soil around the pipe would reconsolidate after installation and before flooding, under the as-laid pipe weight.
- The level and rate of reconsolidation for the 12-in. pipe is likely to be greater because the bearing pressures are higher than those for the 26-in. pipe when empty, and the drainage paths are shorter.
- The duration between installation and flooding is sufficient to substantially reconsolidate the soil beneath the pipe.
- The additional embedment that occurs upon flooding would be less than in fully remolded soil, which should improve the alignment in predicted embedment for both pipelines.

Details of the Strength-Regain Model on the Basis of Reconsolidation Before Flooding. The calculation process for the strength-regain model is as follows:

1. The as-laid pipe embedment is assessed with the fully remolded strength (with the modified bearing-capacity model, defined earlier).
2. The post-laying reconsolidated soil strength beneath the pipe is defined by the normally consolidated shear-strength ratio for the soil (i.e., undrained shear strength divided by the effective overburden pressure).
3. The consolidation stress from the pipe weight is based on the vertical stress generated by the submerged pipeline weight and the as-laid bearing width of soil contact (D').

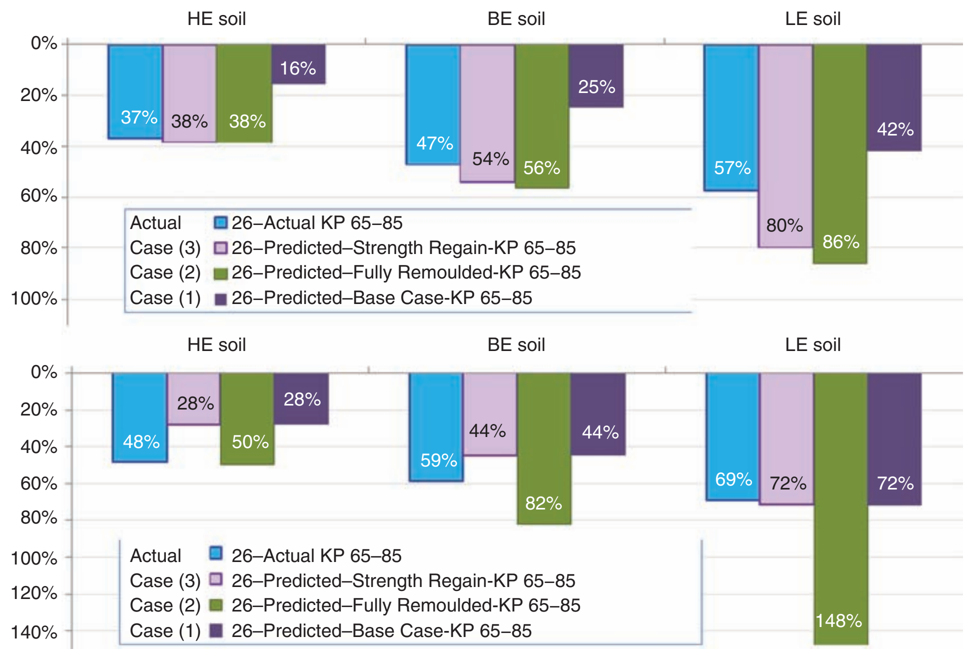

Fig. 8—Summary of results comparing different operational shear strengths at time of pipeline flooding.

Pipeline (in.)	Submerged Weight (kN/m)	Overall Diameter (mm)	Bending Stiffness (MN·m²)
26	≈1.3	744	≈500
12	≈1.2	409	≈45

Table 2—Comparison of overall diameter, submerged weight, and bending stiffness.

4. The operative reconsolidated soil strength is then the product of the normally consolidated shear-stress ratio and the vertical stress generated by the pipe. This operative reconsolidated shear-strength profile is assumed to have a constant value with depth, but is not allowed to fall below the fully reconsolidated strength at any given depth.
5. The post-flooding pipeline embedment is then assessed (with the modified bearing-capacity model).

The vertical effective stress because of the weight of the pipe is defined as

$$\sigma_V = \frac{w_i}{D'}. \qquad (11)$$

The chord length that defines the bearing area of soil contact is given by

$$D' = 2\sqrt{w\left(D_o - w\right)}. \qquad (12)$$

The reconsolidated operative shear strength is then defined by

$$S_{UO} = \sigma_V \cdot \left(\frac{s_U}{\sigma'_{vo}}\right)_{nc}, \qquad (13)$$

where $\left(\frac{s_U}{\sigma'_{vo}}\right)_{nc}$ is the normally consolidated shear-stress ratio, which for these soils was approximately 0.3. The measurement of the normally consolidated shear-stress ratio was available from project-specific pipe/soil-interaction testing.

Strength-Regain-Model Assumptions. There are some important assumptions in defining the operative reconsolidated shear-strength profile because there are counteracting factors to the definition of operative strength beneath the pipe. With increasing depth below the pipe, the download must increase because of the additional column of soil. However, the vertical stress component from the pipe also reduces as the total bearing area increases, thus reducing the surcharge with depth. These effects were investigated in some detail, but they counteract each other and introduce unwelcome complexity into the model. The use of a constant operative strength with depth (with cutoff to prevent it falling below the fully reconsolidated strength at any given depth) is pragmatic and is based on geotechnical principles. Although this approach does not capture all the uncertain influences on the operative strength, it is simple to apply, and ultimately provides a good fit to the observed data.

The simplification of using a constant operative strength with depth might be a concern if the additional embedment upon flooding was significant; however, in practice, the maximum pipe

	Empty, Submerged		Flooded, Submerged		Increase in Bearing Pressure From Empty to Flooded (kPa)
Pipeline (in.)	Weight (kN/m)	Bearing Pressure (V/D_o) (kPa)	Weight (kN/m)	Bearing Pressure (V/D_o) (kPa)	
26	≈1.3	≈2.0	≈4.4	≈5.9	3.6
12	≈1.2	≈3.2	≈2.0	≈5.0	1.8

Table 3—Summary of the increase in bearing pressures from installed to flooded weight.

penetration upon flooding is typically $0.3D_o$ and does not exceed approximately $0.5D_o$, which is considered reasonable.

It is also clear that the operative strength will increase with time, following installation. The assumption in this model is that the duration between installation and flooding (2 to 4 months) was sufficient to achieve full reconsolidation; the actual level of reconsolidation may be slightly less. Scaling of this reconsolidation time is necessary for shorter durations. Predicting consolidation times on the basis of in-situ field measurement of consolidation coefficients is an area for further research.

Results From Strength-Regain Model: Case 3. While current design approaches were underpredicting embedment levels, leading to a design that was potentially not conservative, this updated methodology provided a much-improved match to actual embedment data.

This strength-regain model significantly improved predictions of pipeline embedment, as shown in Fig. 8, which compares the predicted embedment following strength regain (in light purple) with the actual embedment data (in turquoise).

The range of embedment is slightly larger than that observed, which is conservative. Clearly, there is still room for improvement in predicting the best-estimate embedment, but much of the remaining uncertainty is associated with the installation process. This revised model was verified successfully against measured levels of pipeline embedment and is now being used for the design of future pipelines in the area, with improved certainty and easing of the design challenge.

These results confirm the assumption that, upon flooding, increased embedment occurs for the 26-in. line, while no additional embedment occurs for the 12-in. line. This is demonstrated for two example cases by plotting the operative shear strength at the pipe invert for each stage of the embedment process, overlaid on the in-situ and remolded strength profiles in Fig. 7, where the subscript "O" refers to the operative shear strength or the assumed strength profile at the time of flooding.

In each case, the initial as-laid embedment is calculated on the basis of the remolded strength, and then the strength regain is plotted at that embedment, followed by the calculated additional settlement once the pipeline is flooded. In addition, the reconsolidated strength is not allowed to fall below the fully remolded strength as the pipeline penetrates to a deeper embedment (seen in the high-estimate case in Fig. 7a).

Conclusion

Pragmatic improvements have been proposed to the modeling of embedment, which account for the influence of buoyancy, heave mounds, and bearing capacity at embedment levels greater than one-half diameter and that will assist in the prediction of pipeline embedment in weaker soils.

Industry guidance for embedment assessments assumes that the as-laid embedment should be assessed with the remolded soil-strength profile, and the potential for additional embedment on flooding is calculated with the intact soil-strength profile. However, this approach significantly underpredicted the embedment of a 26-in. pipeline, demonstrating that this model would not be conservative for design. A review of this methodology showed that a much improved fit to the embedment data is achieved for large-diameter lines if the remolded strength is used for the as-laid embedment, but an intermediate reconsolidated strength is used to assess the embedment during flooding.

The reconsolidated strength was estimated by considering the consolidation stress applied by the pipe in the as-laid empty condition. This model matched observed embedment levels reasonably well. A review of this model against large-diameter light flowlines with buoyancy provides a similar improvement in embedment predictions. However, the duration between laying and flooding has an influence on the enhancement of soil strength through consolidation, so good predictions of consolidation times can be important to ensure that the consolidation time (2 to 4 months in this case) is adequate before flooding. Insufficient time between installation and flooding of pipelines in the field may well result in excessive levels of embedment. This issue of the additional embedment on flooding could be critical to pipelines that experience a significant increase in bearing pressure when flooded, such as large-diameter gas pipelines or sections of pipeline with added buoyancy.

Nomenclature

a, b = calibration parameters, no units
D' = projected bearing area on soil per unit length of pipe, m
D_o = outside pipe diameter; over coatings (D_{oc} in SAFEBUCK), m
EI = pipe-composite bending stiffness, kNm^2
f_b = heave-mound buoyancy factor
h = water depth, m
k_{lay} = touchdown lay factor (during installation)
N_c = bearing factor
s_u = undrained shear strength, referred to pipe invert level, kN/m^2
s_{u_R} = remolded shear strength, referred to pipe invert level, kN/m^2
S_t = soil sensitivity
T_0 = horizontal component of lay tension, kN
V = vertical penetration resistance or vertical pipe load, kN/m
V_{tdz} = vertical reaction in the touchdown zone during installation, kN/m
w = depth of embedment at startup, m
W'_f = submerged weight when flooded, kN/m
W'_i = submerged weight at installation, usually the empty submerged weight, kN/m
W'_o = submerged weight in operation, kN/m
α = departure angle from the lay vessel, radians
γ' = submerged-soil unit weight, kN/m^3
θ = chord angle; defines pipe/soil-contact surface, radians

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