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# FLEXIBLE RISERS LIFETIME EXTENSION: ADVANCED ANALYSIS TECHNIQUES AND RISER IN-SERVICE MONITORING

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## ABSTRACT

The demand for the lifetime extension of flexible pipes is increasing due to the need to extend the lifetime of the existing production fields. There have been many challenges with the lifetime extension of flexible pipes after the end of the initial design service life due to the inherent conservatism with the common analysis approach, safety factors and operation beyond the design limits. A lifetime assessment should be performed on flexible risers for re-qualification during the original design life if the design envelope is exceeded or there is a need for lifetime extension. Hence, a systematic approach for lifetime assessment execution is established to determine the integrity level of the flexible risers and define the recommended actions required, such as mitigations, repairs or monitoring to maintain an acceptable risk for the required extended service life based on consistent methodology. The primary objective of this paper is to present a riser integrity management field-proven technology to monitor the riser's behaviour in-service in addition to the advanced analyses guidelines to form a basis for the lifetime extension of flexible risers. The primary objective for the integrity management is to manage and control the risk of failure by detecting failure at an earlier stage when preventive action can be taken to avoid failure propagation. In addition, it is demonstrated that the primary hot-spots for the dynamic behaviour and fatigue life assessments of the flexible risers are primarily in bend stiffener regions and the touchdown zone (TDZ) due to large tension fluctuations caused by vessel motions and cyclic movement in the TDZ. Therefore, analysis techniques have been developed in two primary areas: advanced bend stiffener modelling using pipe-in-pipe (PIP) to model the sliding friction and the bend stiffener/flexible pipe's annular space and flexible pipe–seabed interaction modelling using a non-linear seabed model. Therefore, the flexible riser's lifetime extension assessment will be based on more reliable models that reflect the realistic and dynamic behaviour of the flexible risers. Consequently, these advanced analysis techniques can be used for new designs or lifetime extension of flexible pipes.

## INTRODUCTION

The number of flexible pipes in operation has been increasing for more than 40 years due to the increasing demand for energy and new field developments, as well as the need to extend the lifetime of the existing fields. Flexible pipes have been essential for subsea developments worldwide since the early 1970s and for Norwegian oil and gas production facilities since 1986. In Norway, the accumulated number of dynamic flexible risers has increased from 30 to 270 from the early 1990s to 2005[1]. There were 326 flexible risers in operation accumulated in 2013[2].

In the early 1970's, TechnipFMC pioneered the flexible pipe technology, which has gained prominence as an engineering solution with high levels of reliability and quality, even in the world's harshest and deepest offshore environments. The flexible pipe consists of unbonded layers of polymeric layers and steel reinforcing wires, which are helically wound and partly consist of complex shapes. Each layer has a specific function during the operation of the flexible pipe. Flexible pipelines have a high radial and longitudinal stiffness but relatively low bending stiffness and low allowable bending radius because of their unbonded layers construction[3].

There are two major types of flexible pipes: rough bore pipes where the innermost layer is an internal carcass and smooth bore pipes where the innermost layer is a plastic tube. The left part of Figure 1 shows the layers of a rough bore pipe and a typical smooth bore pipe architecture is presented on the right side. A typical rough bore flexible pipe's cross-section from the inside to the outside layers consists of a stainless steel carcass, a polymer pressure sheath, a pressure armour (Zeta) layer, anti-wear tapes, tensile armour layers, high strength tapes and an external sheath. The flexible riser cross-section essentially depends on the polymer layers to provide sealing and the metallic layers to provide strength.

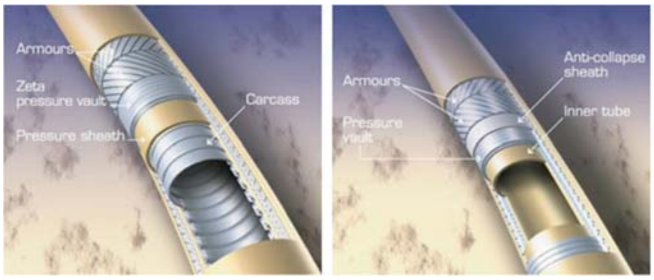


Figure 1: Unbonded flexible pipe structure

Flexible risers are utilised in challenging conditions with high pressure, high temperature, enormous variation in operating parameters and high dynamic motions. The main objective of this paper is to present the potential approaches and methodologies to be used for the lifetime extension of a flexible riser in addition to the riser integrity management to monitor the riser's behaviour. The lifetime assessment should be performed for flexible risers for re-qualification during the design life if the design envelope or operational conditions is exceeded or there is a need for lifetime extension. The purpose of the lifetime evaluation is to determine the integrity level of the flexible riser and define the recommend actions required such as mitigations, repairs or monitoring to maintain an acceptable risk for the required service life.

First, a systematic approach for the lifetime assessment execution is presented to provide a systematic process to determine the flexible pipe integrity level and provide risk criticality. Then, this paper discusses the global analyses modelling techniques to reduce the inherent conservatism, due to the modelling simplification, within the existing riser global models. In the next step, this study presents the riser integrity management technologies for lifetime extension to ensure the safe operation and control the risk of failure for the flexible pipe. It is proven that employing the monitoring systems and the advanced modelling and analyses techniques enables us to evaluate the flexible pipe dynamic behaviour and fatigue assessment with better accuracy and maximise the potential for lifetime extension.

The main hot-spots for the dynamic behaviour and fatigue life assessments of the flexible risers are primarily in the bend stiffener region and the touchdown zone (TDZ) due to large tension fluctuations caused by vessel motions and cyclic movement in the TDZ. Therefore, realistic modelling of the dynamic behaviour in these regions can enhance the accuracy of the lifetime extension of the flexible risers and reduce the inputs' inherent conservatism used for the local fatigue analysis. Analysis techniques have been developed in two main areas: advanced bend stiffener modelling using pipe-in-pipe (PIP) to model the sliding friction and the bend stiffener/flexible pipe's annular space and flexible pipe–seabed interaction modelling using a non-linear seabed model.

Integrity management is essential for flexible pipes and should be a continuous process implemented in the pre-service phase, i.e., the engineering design, manufacturing, and installation, as well as in-operation during service life. The main objective for integrity management is to manage and control the risk of failure. Fatigue failure may be detected at an earlier stage when preventive action can be taken to avoid propagating failure. The in-service integrity management is the main tool which can enhance the lifetime extension for flexible risers and ensure that the pipe operates within the design envelope. Therefore, this paper presents our techniques and field-proven technology for in-service integrity management. Overall, only with advanced interaction global modelling and riser in-service monitoring can one have confidence in the global analysis results and safe operating conditions.

## NOMENCLATURE

| | |
|---|---|
| *AE* | Acoustic emission |
| *a, b* | Power law parameters. |
| *CEA* | French research organisation |
| *D* | Pipe outer diameter. |
| *DTS* | distributed temperature sensing |
| *E* | Pipe eccentricity. |
| $f_b$ | Soil buoyancy factor. |
| *FDS* | Flooding detection system |
| *FEA* | Finite element analysis |
| $f_{suc}$ | Suction resistance ratio. |
| $K_{max}$ | Normalised maximum stiffness. This is the pipe-soil stiffness normalised by the ultimate net-bearing pressure. |
| *MEMS* | Microelectromechanical systems |
| *PIP* | Pipe-in-pipe |
| *S-N* | Stress-life curve approach. |
| $S_i$ | Denotes the applied stress level [MPa]. |
| $S_{oi}$ | Nominal stress range [MPa]. |
| $S_{u0}$ | Shear strength of soil at the seabed level [kN/m$^2$]. |
| $S_{ug}$ | Shear strength gradient [kN/m]. |
| *TDZ* | Touchdown zone. |
| *V* | Vertical seabed reaction force [kN/m]. |

 

| | |
|---|---|
| $z$ | Embedment depth of pipe below the seabed [m]. |
| $\gamma'$ | Submerged unit weight of soil [kN/m$^3$] |
| $\lambda_{rep}$ | Re-penetration parameter. |
| $\lambda_{suc}$ | Suction decay parameter. |
| $\mu$ | Sliding friction factor. |
| $\rho_{soil}$ | Saturated soil density. |

## FLEXIBLE PIPE LIFETIME EXTENSION FRAMEWORK

The flexible pipe lifetime extension and assessment requires additional detailed engineering guidance as there is currently a gap in the existing standards, guidelines and recommendation practices in terms of detailed engineering guidance, assessment codes and acceptance risk of failure. However, the equipment review form has been described in the NORSOK Standard U009 and Y002 [4, 5], which may be used as the basis for the lifetime extension process. TechnipFMC has set multiple evaluations and investigations for flexible pipe systems as well as each individual layer for the unbonded flexible pipe to form the framework for the following fundamental phases:

### Phase 1: Gap Assessment and Analysis

The gap analysis is to be performed with original rules and criteria to identify if the original design is still acceptable with respect to our latest criteria such as API 17J[3]. It is recommended that the gaps identified are evaluated for criticality and risks to ensure the right priority is given to the implementation measures.

### Phase 2: Design Envelope

This phase is to confirm that the flexible pipe and system configuration is in-service according to the design envelope and the limitations specified in the design premises. This can be achieved through the riser integrity management to record the floater motions, environmental metocean, historical pressures and temperatures and fluid composition in the bore and annulus including the measurement of $H_2S$ and $CO_2$ molecules. However, this is highly dependent on phase 1 because if there is no gap between the original and current design practice and the flexible pipe is performing within the design limitation then the flexible pipe integrity is sustained with confidence. Phase 2 output can be further used as a basis for the extended lifetime evaluation.

### Phase 3: State-Of-The-Art Service Life Modelling

It is important to review the inherent conservatism with the current service life model and use recent state-of-the-art approaches and numerical methodologies that are validated using FEA, testing or direct measurements of the flexible pipes. The advanced analysis techniques can provide better accuracy for service life assessment. The common used conservative degradation models and uncertainties associated with these models highlight the need to answer the question: What is required to improve these models?

### Phase 4: In-Service Monitoring, Testing and Inspections

Flexible pipe in-service monitoring, testing and inspection provide accurate data for the current status and detect the failure mode at a very early stage which allows the implementation of mitigations actions to avoid failure propagation. These monitoring systems includes temperatures, pressures and wire curvature measurements, annulus testing, vest monitoring systems, and etc. The measurements and testing results can be used to monitor the flexible pipe accumulated degradation. The monitoring systems can be used temporarily for inspection or be permanently mounted on the flexible pipe to monitor its behaviour during operation.

The following sections discuss the adopted approaches and methodologies as well as the in-service monitoring technologies which may be used as part of Phase 3 and Phase 4.

## METHODOLOGIES ADOPTED FOR MODELLING AND ANALYSIS

The methodology adopted for the modelling and analysis shall reflect the realistic dynamic behaviour of the flexible risers to reduce the inherent conservatism with the common approach and enhance the new designs as well as the lifetime extension of flexible pipes. This can be achieved by comparing the results of computer-aided analyses and testing or through the validation of the results by using the Finite Element Method.

### Bend Stiffener Modelling

The bend stiffener region is proven to be a hot spot for the ULS and FLS in global dynamics and local analyses due to high curvature range which is challenging for flexible pipe lifetime extension. Therefore, the bend stiffener model should reflect the realistic behaviour between the bend stiffener and the flexible riser. The common approach for bend stiffener modelling is to model the bend stiffener as an attachment at the top-side of the flexible pipe and this is considered to be conservative. This is because the resulted curvature in the bend stiffener is conservatively considered for the flexible pipe.

Therefore, it is recommended to perform the global ULS and FLS dynamic analysis for flexible pipe lifetime extension by using a realistic approach to model the behaviour between the stiffener and flexible pipe. The Pipe-In-Pipe (PIP) is an improved model for the bend stiffener/flexible pipe and it captures the realistic interaction behaviour of the flexible pipe inside the bend stiffener. The annular space between the bend stiffener and flexible riser and the sliding friction is included in the modelling.

Several commercial programmes are available to perform the global analysis of risers subjected to environmental conditions. The latest version of these programmes offer the capability to model a pipe-in-pipe (PIP) system. With this capability, it is possible to model the gap between a riser and a bend stiffener leading to a better representation of the hanging configuration. The validation of the PIP modelling is investigated with two commercial software, i.e., OrcaFlex® 10.0[6] and Deeplines® 5.0[7], which are general 3D non-linear time domain FE programmes specifically suited for the analysis of riser systems.

Both bend stiffener modelling approaches are considered in this study: the conventional approach for bend stiffener modelling as an attachment at the top side of the flexible pipe, see Figure 2 and the advanced approach to model the bend stiffener/flexible pipe interaction as a PIP, see Figure 3.

The line contact model specifies the relationship between the flexible pipe and bend stiffener as two distinct lines. The flexible pipe “contained line” is represented by the “penetrating line”. When the penetrating line nodes are within the length of the “containing line”, the penetrator will contact the inner surface of the containing line, i.e., bend stiffener. The inner surface of the containing line is the only contact surface. The containing line “bend stiffener” is represented by the splined line, see Figure 4.

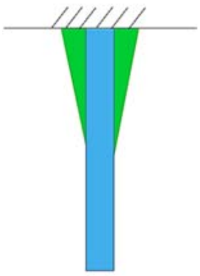

Figure 2 Schematic for conventional approach, attachment stiffener modelling

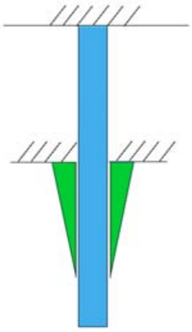

Figure 3 : Schematic for bend stiffener/flexible riser interaction as Pipe-in-Pipe Modelling

The splined line has a smooth spline curve fitted between the line nodes. These splines represent the line as a smooth, deformable cylinder for contact, allowing strain. Therefore, splines can deflect to pass through the nodes. The penetrator interacts with the splined line by contact with a flexible cylindrical elastic solid whose axis follows the spline.

The main challenge of using the advanced PIP model is to correctly handle the contact between the riser and the bend stiffener. Each commercial software used its own algorithm to handle the contact. Therefore, contact numerical parameters can be quite different for each software. However, the numerical parameters mainly aim to set a contact stiffness between the two parts. This contact stiffness should be sufficient enough to avoid the penetration of the flexible riser in the stiffener. However, using high contact stiffness can induce convergence issues.

Therefore, a correct set of parameters should be carefully chosen to reach both convergence and a correct representation of the contact. Trying to derive the contact stiffness from physical properties (material properties of the riser and the stiffener, for instance) is generally bad practice and can lead to wrong results. The approach chosen is then to fix a maximum penetration criteria and then to iterate on the contact parameters until this criterion is respected while achieving convergence.

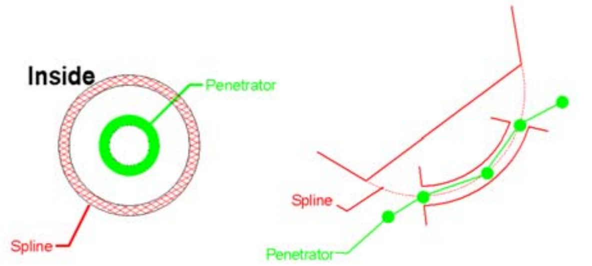


Figure 4: Pipe-in-pipe line contact

Figure 5: Abaqus FEA Model

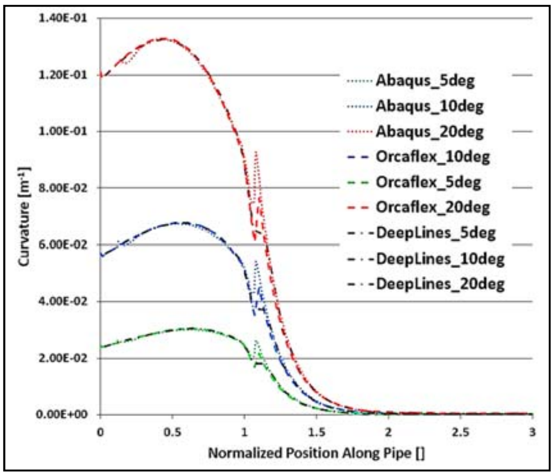


Figure 6: Classical modelling results

To validate the proposed methodology, a full 3D finite element analysis model of the configuration was built. The commercial FEA code Abaqus 6.14[8] was used for this study. In this model, the bend stiffener is fully represented by solid elements and the beam elements with contact surface are used for the riser. This model was checked against a physical full scale test with as-built dimensions and then used to assess the curvature of the riser under the stiffener tweaking different parameters such as the gap between the two parts. The Abaqus model results were thus taken as a reference and compared to the global dynamic analysis results from OrcaFlex® and Deeplines®.

The conventional bend stiffener modelling, see Figure 6, and the advanced PIP approach, see Figure 7, are compared for different load cases. All software products provide similar results. For OrcaFlex® and Deeplines®, the contact parameters were chosen to limit the penetration of the flexible line in the stiffener to a chosen criterion. Several iterations on the parameters were necessary to identify the maximum penetration allowed to be sufficiently close to the Abaqus results. The consistency of the simulations validates the methodology.

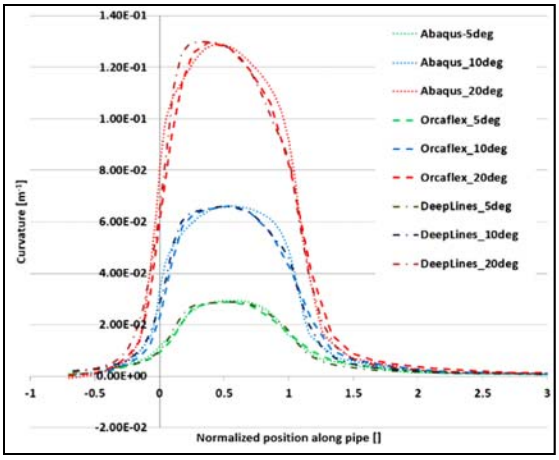


Figure 7: Advanced modelling

## Touchdown Zone

A flexible pipe attached to a floating platform at its upper end encounters oscillations in and near its Touchdown Zone (TDZ) which results in an interaction with the seabed. The motions of the floating platform can induce severe riser responses especially for a free hanging configuration, which must be predicted as accurately as possible to determine the dynamic behaviour and fatigue performance of the flexible pipe in the TDZ. Therefore, it is important to develop better modelling of the flexible riser-soil interaction mechanism to provide a realistic technique to predict the dynamic response and structural behaviour of the flexible riser in the TDZ. This section discusses the significance of the flexible riser–seabed interaction.

The demonstrated riser-seabed interaction models cover both the vertical and lateral riser motion on the soil. The lateral soil resistance of a partially embedded pipeline should be modelled at the design or re-qualification stage to determine the effect of the soil berms on the pipe movement and stability on the seabed. One of the principal factors in lateral movement modelling is the ability to model lateral movements with cyclic motions[9]. The most common riser models that model the seabed with rigid or linear surfaces disregard the nature of the trenching development process into the seabed and the passive soil resistance to the riser's lateral movement in the TDZ.

### Description of Pipe Embedment

For flexible risers, the TDZ is one of the critical fatigue hotspots due to the interaction between the flexible riser and seabed. The riser–seabed interaction is an essential key factor that should be considered in the strength and fatigue assessment for flexible riser analysis. How to precisely model this interaction response is still an issue and has been a hot field for research. Current riser–seabed interaction modelling approaches the seabed as a rigid or linear elastic model with friction coefficients appointed in the axial and lateral directions relative to the axis of the flexible riser. However, the linear seabed model does not simulate the actual behaviour of the seabed. Therefore, several studies have recently focused on load/deflection (*V-z*) curves for the response of the riser–seabed interaction, where *V* stands for the resistance force of the soil and *z* stands for the vertical penetration of the flexible pipe. Researchers determined the empirical equations for (*V-z*) curves from experiments. Flexible pipe penetration is defined as the depth of penetration of the pipe invert (bottom of pipe) relative to the undisturbed seabed as shown in Figure 8. Pipe penetration affects the riser pipe–seabed contact area, which subsequently affects the axial and passive soil resistance against the riser. Consequently, the passive soil resistance influences the lateral breakout force. The heave of seabed soil during embedment increases the local penetration of the flexible pipe by raising the soil surface level against the shoulders of the pipe.

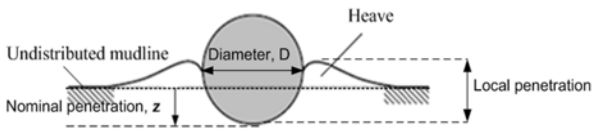


Figure 8: Initial penetration of the flexible pipe

### Non-Linear Soil Model Approach

Recent pipe–soil interaction models are too simplified to simulate the interaction between the seabed and flexible riser. The non-linear seabed model is more sophisticated than the common linear model in that it models the non-linear hysteretic behaviour of the seabed in the vertical direction, including the soil suction effects. Randolph et al. [10] introduced a mathematical non-linear model of the seabed vertical reaction force experienced by a pipeline in contact with the seabed, which is established on a hyperbolic secant stiffness formulation, such as those indicated by Bridge [11] and Aubeny [12]. The soil stiffness will vary along the TDZ within a non-linear soil model depending on the amplitude of the cyclic displacement. The model is implemented in OrcaFlex and uses data such as the pipe diameter, the seabed soil shear strength profile with depth and the soil density. As shown in Figure 9, there are four different penetration modes in this seabed model: not in contact, initial penetration, uplift and re-penetration. Different formulas are utilised for the initial penetration, the uplift and re-penetration, with the function parameters updated each time a penetration reversal happens. This set of modes enables the model to capture the hysteretic behaviour of the seabed soil response and the increasing penetration of the pipe under cyclic loading in the vertical plane. The model was validated against laboratory and field-scale experiments with reasonable accuracy. The typical *V-z* curve pattern, see Figure 10, of the pipe–soil interaction are produced by laboratory model experiments of vertically loaded horizontal pipes in weak sediment [13]. If the riser pipe continues to experience oscillatory loading movement, the *V-z* interaction curve will repeat the loop enclosed by the path 1-2-3-1 under the assumption of a non-degradation model. The non-linear model is particularly suitable as it models the vertical pipe–soil interaction on soft clay according to dynamic aspects more accurately than a linear seabed model.

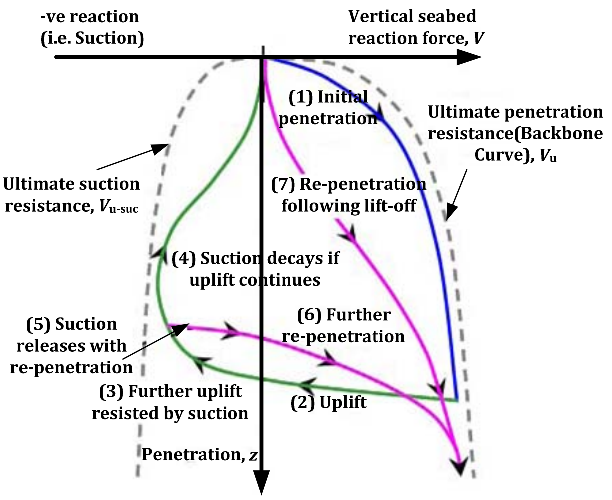


Figure 9: Soil model characteristics for different modes[10]

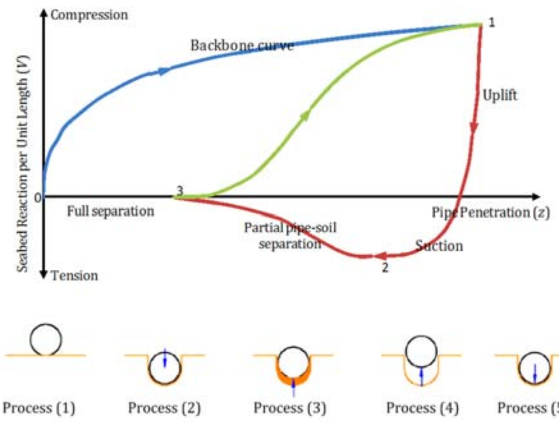


Figure 10: Depiction of typical *V-z* behaviour

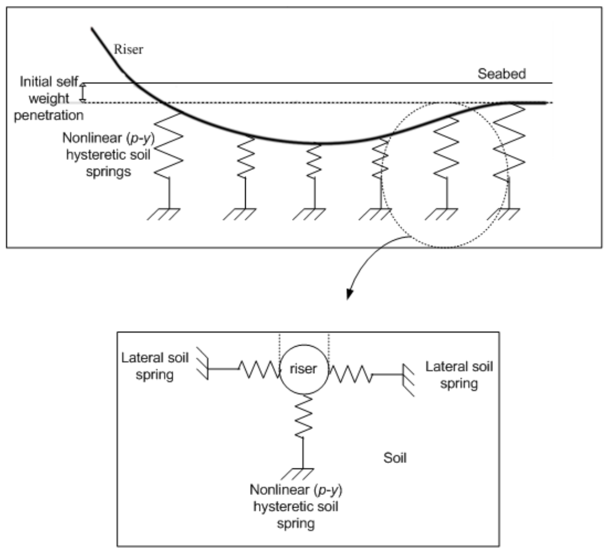


Figure 11: Schematic for riser-soil model with hysteretic nonlinear soil springs

## Pipe-Seabed Interaction Modelling

The pipe–seabed interaction response characteristic is a highly non-linear phenomenon. It is important not to restrict the modelling of this interaction to a linear seabed model approximation and the riser analysis techniques must be improved by refining the riser–seabed interaction [14]. Pipe–seabed interaction modelling should involve vertical and lateral soil responses to the cyclic loading oscillations of the flexible riser in the TDZ, which can cause trenching and dynamic embedment of the flexible pipe into the seabed. The pipe–seabed interaction problem and modelling technique based on the adopted approach presented earlier are shown in Figure 11.

## Numerical Implementation

Many fresh discoveries of deepwater fields are in regions where soft clay is detected. The typical range of shear strength, $S_{u0}$, of seabed soft clay is from 1.2 to 3.8 kPa at seabed level, and the shear strength gradient, $S_{ug}$, ranges from 0.8 to 2.0 kPa/m[15]. A non-linear seabed model has been implemented in OrcaFlex, as it models the dynamic behaviour of the vertical pipe–seabed interaction on soft clay more precisely than does a linear seabed model. The non-linear penetration resistance is established in a power law expression for the nominal bearing factor, $N_c = V / DS_U$, where $V$ is the vertical force per unit length, $D$ is the riser diameter and $S_U$ is the undrained shear strength at the catenary pipe invert (bottom of the outer surface of the pipe), expressed by Aubeny et al. [16] in the following way:

$$N_c \approx a\left(\frac{z}{D}\right)^b \quad \textbf{(1)}$$

where $z$ is the riser penetration into the seabed. Fitted values of the power law expression, a and b, rely on the relative roughness of the pipe-soil boundary and the strength profile with depth $\eta$, $\eta = S_{UG}D/S_{U0}$. Values of the power law coefficients, $a$ and $b$, in Eq. (5) provide a reasonable fit to the numerical results in the range of $0 \le \eta \le \infty$ and are shown in Table 1.

Table 1 Power law coefficients

| Boundary | $z/D \le 0.5$ | $z/D \succ 0.5$ |
|---|---|---|
| Smooth | a = 4.97, b = 0.23 | a = 4.88, b =0.21 |
| Rough | a = 6.73, b = 0.29 | a = 6.15, b = 0.15 |

The normalised secant stiffness, $K_{\max}$, is the pipe-soil stiffness normalised by the ultimate net bearing pressure at that depth and is a measure of the effective stiffness since the last reversal in penetration or since penetration started; the factor is defined in the following way:

$$K_{\max} = \frac{\text{Pipe - soil stiffness}}{\text{Ultimate net bearing pressure}} = \frac{\Delta V/\Delta z}{(V_u/D)} = \frac{\Delta V/\Delta z}{N_c(z).S_u} \quad \textbf{(2)}$$

with typical values for soft clay in the range of 150 to 250 [11]. The non-linear soil model parameters are discussed by Randolph [10].

Seabed stiffness degradation due to cyclic oscillations has an influence on the behaviour of flexible risers in the TDZ and especially on the hydrodynamic performance of flexible pipes. After the seabed soil approaches its maximum strength throughout the applied cyclic loading, the seabed soil tends to lose strength and stiffness with the increase in plastic embedment during cyclic oscillations. The seabed soil stiffness degradation mechanism comprises stiffness reduction presented in uplift, suction, and separation as well as a re-penetration process. Seabed soil degradation must be involved in the soil modelling efforts to capture dynamic cyclic loading in the response of the flexible riser. The degradation of soil stiffness with cyclic loading is best captured by the non-linear seabed model.

The pipe–seabed response in the TDZ follows the general characteristics of nonlinear soil behaviour illustrated by Randolph (2009) and asymptotic merging of the limiting resistance curves $V_u(z)$ and $V_{u\text{-}suc}(z)$. The penetration parameter $z$ for the ultimate resistance limits increases for penetration motion and decreases for uplift motion. The ultimate penetration and suction resistance asymptotic limits are given by $V_u(z) = N_c S_U(z) D$ and $V_{u-suc}(z) = -f_{suc}.V_u(z)$, respectively, where $S_U(z) = S_{U0} + S_{UG}z$ is the undrained shear strength at penetration z [10].

## Dynamic Riser-Seabed Response

The seabed soil's non-linear response is modelled using a hyperbolic approach and the model parameters are listed in Table 2. The dynamic pipeline-seabed contact resistance, expressed as seabed resistance/$D$, is shown in Figure 12. The initial penetration of 0.01$D$ corresponds to a local seabed contact force of 2.42$D$ (hence a secant stiffness of $k_{stiff}$ = 2.42/0.01 = 242 kPa). The maximum envelope of the pipeline profile increases to approach a penetration of 0.8$D$ during the cycles of vertical motion. The seabed resistance's maximum envelop approaches a local maximum of 19.4$D$ (nearly eight-times the static value of 2.42$D$) compared with seabed resistance with a value of 4.7$D$ kPa and 76$D$ kPa when linear and rigid seabed are employed respectively, while the minimum seabed resistance/$D$ "soil suction resistance/$D$" approaches a value of -9.84$D$ kPa.

Table 2 Non-linear soil model parameters

| Parameters | Symbol | Value |
|---|---|---|
| Pipe diameter | $D$ | 0.273m |
| Mudline shear strength (median range) | $S_{u0}$ | 2.6 kPa |
| Shear strength gradient (median range) | $S_{ug}$ | 1.25 kPa/m |
| Saturated soil density | $\rho_{soil}$ | 1.5 t/m$^3$ |
| Submerged unit weight of soil | $\gamma'$ | 7 kN/m$^3$ |
| Power law parameter | $a$ | 6.15 |
| Power law parameter | $b$ | 0.15 |
| Normalised maximum stiffness | $K_{\max}$ | 200 |
| Suction ratio | $f_{suc}$ | 0.7 |
| Suction decay parameter | $\lambda_{suc}$ | 0.6 |
| Re-penetration parameter | $\lambda_{rep}$ | 0.3 |
| Soil buoyancy factor | $f_b$ | 1.5 |

Figure 13 presents the calculated cyclic response in the TDZ during simulated cyclic motion. The non-linear hyperbolic model, which experiences a delay in rejoining the preceding maximum resistance during re-penetration, produces an incremental embedment of the flexible riser from an initial penetration of 0.16$D$ to a maximum value in excess of 0.8$D$ at an arc length of 1445 m. The non-linear soil model captures, as shown in Figure 13, the varying soil stiffness and soil cyclic degradation, allowing for the re-penetration, uplift and suction effects. The dynamic cyclic motions of the flexible pipe within the TDZ increase the flexible pipe's embedment beyond that produced by the static load. The results show evidence of the dynamic flexible pipe's penetration behaviour under cyclic loading. The seabed stiffness degradation due to cyclic oscillations has a significant influence on the behaviour of the flexible riser in the TDZ and especially on the flexible riser's dynamic behaviour. After the seabed soil approaches its maximum strength during the applied cyclic loading, the seabed soil tends to lose strength and stiffness with the increase in plastic embedment during the cyclic oscillations.

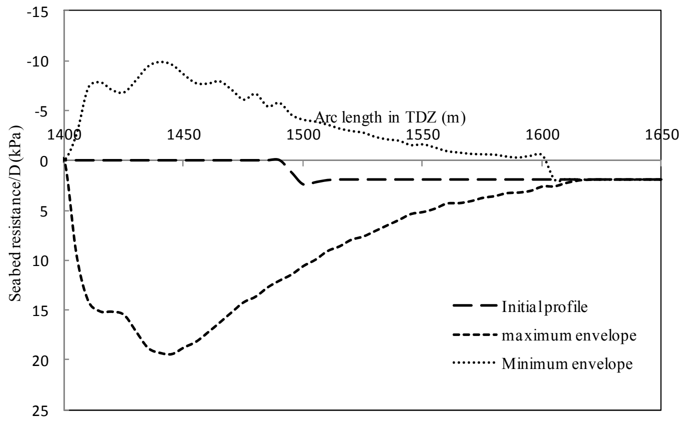


Figure 12: Dynamic pipe-soil contact resistance in far load case

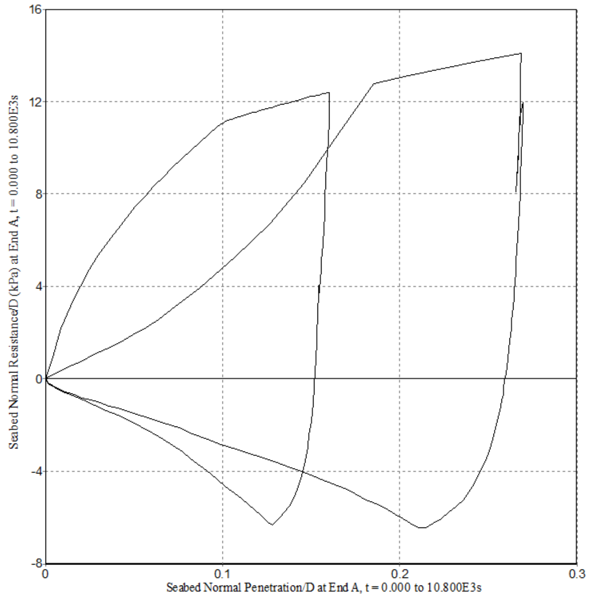


Figure 13: pipe–seabed interaction hysteresis response in the TDZ

The pipe–seabed interaction analysis allows for the effects of physical phenomena such as soil suction forces and lateral and vertical seabed stiffness on the flexible riser's performance to be identified and quantified for manufactured flexible pipes and lifetime extension purpose. The non-linear soil model characterises the variation (i.e., degradation) in soil stiffness during the dynamic riser–soil interaction as the seabed soil tends to lose strength and stiffness with an increase in embedment during cyclic oscillations after the seabed approaches its maximum strength during applied cyclic loading. The TDZ response, which involves the degradation of the seabed soil stiffness due to cyclic loading, is addressed by the analyses performed in this study.

The influence of the gradual embedment of the riser into the seabed and development of deep trenches on flexible pipe fatigue performance in TDZ should be investigated through the use of a hysteretic non-linear seabed model for flexible pipe lifetime extension. Gradual deepening of the trench, under random loads and cyclic motions can affect the fatigue damage assessment the TDZ.

## FLEXIBLE RISER INTEGRITY MANAGEMENT

Offshore fields are becoming increasingly complex due to remote locations, increased water depth, harsher meteocean conditions, or difficult fluids (hydrates, wax, HT/HP, sour services) leading to higher constraints applied on the offshore structures and more specifically on seabed-to-surface liaisons. In these conditions, it is paramount to mitigate human, environmental and technical risks, to protect valuable assets, to limit damages and to enable sustainable development.

TechnipFMC has developed a fully integrated package of services and solutions by combining state-of-the-art devices for inspection and monitoring to capture the most appropriate information. The proper management of these information can be performed through digital platform and dedicated performance monitoring software, engineering expertise for a proper interpretation, and skilled offshore technicians who are able to perform inspections and repairs.

There are several qualified monitoring systems with an objective to enhance the maintenance condition of the flexible risers while the operational cost is reduced through the automation and simplification of the inspections and offshore mobilization. The adapted solution should be selected based on the potential failure modes of the flexible riser and its ancillaries, that are depending on the riser characteristics, type of application and configuration. TechnipFMC has in-house the expertise to propose a fit-for-purpose strategy to monitor the relevant data and assist in the interpretation by using the digital services in accordance with API 17B and Sureflex. The following main cases can be considered:

### Case 1: Bend Stiffener Region Surveillance

The topside dynamic and hot-spot area, i.e. bend stiffener region, is linked to the fatigue of the pressure/tensile wires and/or polymer sheath ageing. The fatigue life of flexible risers is usually very crucial to ensure the flexible pipe integrity. TechipFMC has created a monitoring solution, i.e. Morphopipe. This monitoring system is embedded in the riser to insure its robustness and fully redundant for reliability purpose. It makes it fit for purpose for specific Norwegian and arctic conditions. Morphopipe solution will specifically provide real-time valuable data to detect the abnormal bending; e.g. bend stiffener integrity issue due to unexpected metocean or vessel response, torsion behaviour; e.g. due to armour wire breakage, compute the actual cumulated damage and monitor the temperature in the flexible pipe.

If the fatigue corrosion phenomenon is also identified as a risk, then the surveillance of the riser annulus condition is recommended. The flooding detection system (FDS) is fully qualified and field-proven technology which can give real-time valuable information regarding the water presence and location of the external sheath damage if any.

Furthermore, the armour wires' integrity can be monitored during the initial or extended service life by using the AE clamp. AE clamps can be used to detect any single wire break before any contagion to other armour wires and then insure a proper optimization of the riser uptime while remaining constantly in safe conditions.

### Case 2 Flexible Riser's Subsea Regions Surveillance

TechnipFMC has a qualified solution, i.e. distributed temperature sensing (DTS) solution being used as a flooding detection system (FDS) and also able to give a mapping of the riser appurtenances, such as bend stiffener, buoyancy modules and tether presence, to detect any slippage and to provide indications for flexible pipe embedment in the TDZ as well as touchdown point stability. This is especially suitable for wave riser configurations as commonly used in Norway.

These monitoring solutions are briefly described in the following paragraphs.

#### Flooding Detection System

The FDS is based on the monitoring of temperature along the full length of the riser. This can be done by a single optical fibre that using DTS technology. The measurement is performed by a laser pulse injected in the optical fibre and analysed by an optical interrogator unit converting a simple communication fibre into a long range distributed temperature sensor.

Figure 14: FDS implemented in risers with tubes integrated in armour layer

The optical fibre will be integrated in the Flexible risers by water jetting deployment inside a micro steel tube which has been installed during the manufacturing process of the pipe. TechnipFMC has qualified a unique fibre jetting technology allowing the deployment of a bare optical fibre in a few millimetres tube on more than four kilometres. the fibre is integrated in the riser is an ultra-resistant Inconel tube with no intermediate connection in the full optical loop from surface junction box (JB) back to the JB and even in case of accelerated ageing the fibre is replaceable at any moment, see Figure 14. The FDS will analyze thermal events such as:

- Cold spots generated by breach in external sheath
- Temperature transition generated by water level in annulus

Table 3: Flexible pipe integrity management and global riser surveillance

| N° | Area of interest | By DTS+FDS | By Morphopipe | By AE clamp |
|---|---|---|---|---|
| 1 | Corrosion and corrosion fatigue modes | **Y** | N | N |
| 2 | Dynamic loads and fatigue | N | **Y** | N |
| 3 | Tensile wire breakage | N | N | **Y** |
| 4 | Curvature and torsion | N | **Y** | N |
| 5 | Bend stiffener presence | **Y** | **Y** | N |
| 6 | Plastic sheath ageing | **Y** | **Y** | N |
| 7 | Marine growth | **Y** | N | N |
| 8 | Hydrate | **Y** | N | N |
| 9 | Buoyancy sliding | **Y** | N | N |
| 10 | Vertical anchor integrity | **Y** | N | N |

| | | | | |
|---|---|---|---|---|
| 11 | Touch down zone stability | **Y** | N | N |
| 12 | Cold/hot spot riser trenching | **Y** | N | N |

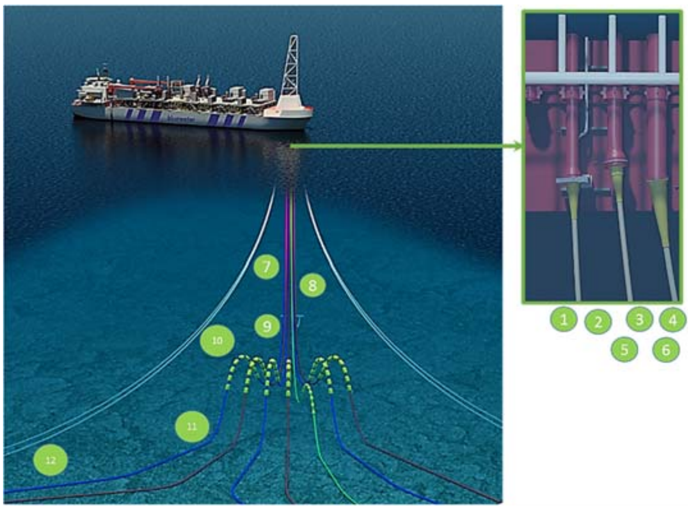


Figure 15: Flexible riser's monitoring and integrity management for all the locations across the riser's length

Those thermal anomalies will be revealed by the significant temperature gradient between bore temperature and the seawater temperature. In addition to Flooding detection, annulus temperature will also be affected by local changes in the pipe insulation, FDS can also be used for buoyancy module surveillance and bending stiffener surveillance as both generate insulation patterns visible on the DTS recordings. The main advantages of the FDS monitoring, see Figure 15 and Table 3, are as follows:

- The use of optical technologies which are intrinsically safe, non-sensitive to electromagnetic noise, long term measurement drift and humidity.
- A sensor integrated in the pipe for an optimal sensitivity and strong robustness to offshore environment
- A monitoring methodology allowing real time analysis and immediate event interpretation.
- A distributed monitoring solution covering the full length of the risers all allowing to asses most of the integrities issue of operating flexible pipes.

## Acoustic Emission Clamp

The AE Clamp is based on acoustic emission. This technology has been used for years in integrity assessment of steel structures and has demonstrated its efficiency for industrial applications. By equipping a loaded structure with a number of acoustic emission sensors, information can be gathered regarding the active damage process in the structure (e.g., micro-cracks and corrosion). Good examples of this type of application are the monitoring of pressure vessels, chemical reactors or storage tanks. These monitoring processes are now normalised (ASTM, EN) and can replace pressure tests in some applications.

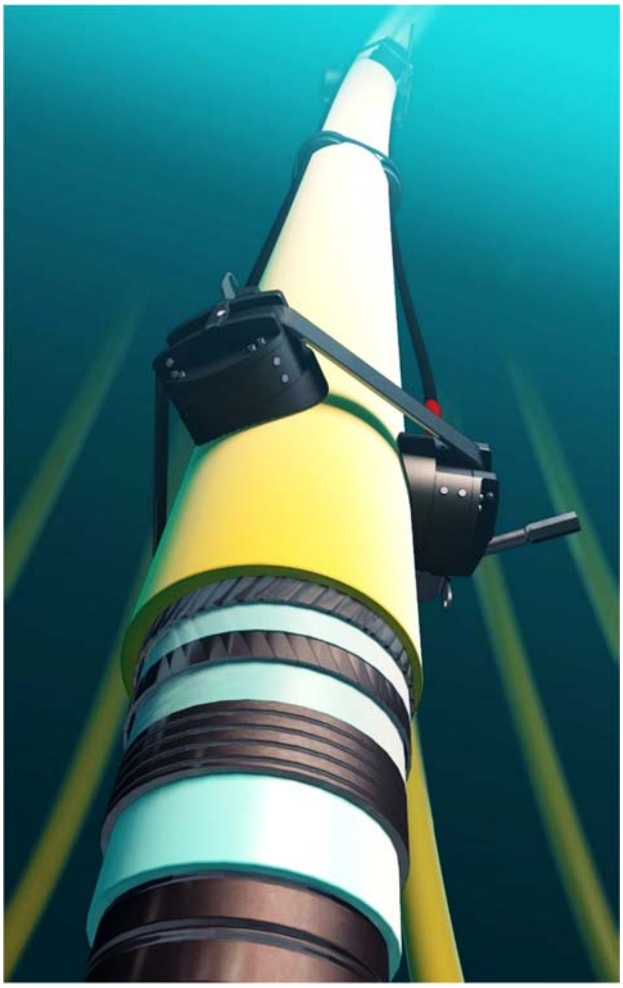

Figure 16: AE clamp on subsea flexible riser

For flexible risers monitoring, the fundamental principle consists of detecting the energy released by a tensile armour breakage through the acoustic emission waveform using the installed sensors, see Figure 16. The technology was chosen because it directly measures the signal of the breakage and is not significantly affected by other phenomena. In the case of alarm detection, the recorded waveform can be analysed by experts to confirm the diagnosis. The main challenge of applying this well-known technology to flexible risers monitoring is related to the offshore operational environmental constraints and to the specificity of the unbonded multi-layer structure of a flexible riser.

TechnipFMC's expertise in flexible risers has been necessary to design a system compatible with the riser behaviour under dynamic and thermal loadings while being harmless to the pipe that we intend to secure. An extensive laboratory expertise in acoustic emission monitoring has been acquired internally, through Cybernetix, providing the opportunity to develop a very useful customised algorithm detection methodology taking into account the composite layers' specificity. The efficiency of the system was demonstrated by several full scale tests where only acoustic emission had the sensitivity to detect every armour break without being saturated with false alarm calls.

The success of these tests motivated TechnipFMC to develop an offshore version: first break detection combined with strong false alarm call discrimination is the key element of an armour break monitoring system. The operator can then decide to decommission the endangered riser with the level of safety and confidence given by a fully reliable warning system. The objective was to develop a subsea system that can be left without maintenance for the riser service life.

AE Clamp, the resulting product, has been designed to fit with the harsh offshore environment requirements once clamped onto the riser and aims at monitoring the first 20-30 metres from the topsides (top end-fitting area including the bend stiffener). The system has been designed to be retrofitable, meaning installable offshore on an operating riser with a limited impact on the platform operations. The installation scenario and mounting process have been qualified to ensure optimal acoustic sensing performances whether carried out by rope access or divers.

Various possible offshore configurations led TechnipFMC to consider all types of demanding scenarios (Subsea, Aerial Balcony, I tube, etc.): aerial specific elements such as ATEX certified equipment and subsea requirements such as marine growth exposure and capacity to fit in confined spaces. A full-scale comparative demonstration convinced an operator to further develop the system in real offshore conditions, allowing us to install a demonstrator on a 25-year old riser, see Figure 17. The installed system has now been working for months with 100% availability rates and has demonstrated its good algorithm performances as no false alarm call has occurred.

## Morphopipe

Morphopipe is the result of the collaboration between the CEA (French research organisation) and TechnipFMC. This new product uses MEMS accelerometers and is based on the pioneering works of shape capture developed in the CEA labs. Morphopipe monitors the three-dimensional shape of the riser, and enables fatigue re-assessment [17]. The ability to detect one-time extreme events as well as to provide valuable data for cumulated fatigue re-assessment over time will improve safety and will potentially extend the lifetime of pipelines. The relevant zone of measurement is located under the bend stiffener, as it is a very dynamic zone, see Figure 18. Because this area is not accessible during service life and often located around the splash zone, the product is embedded as a dedicated layer in full compliance with the riser design.

Figure 17: AE Clamp on top-side of flexible riser

This instrumented layer design and industrial process have been defined to fit a large range of riser applications without interfering with the core structure of the riser, see Figure 19. The Morphopipe layer is added externally during the riser manufacturing, and can be implemented in any fluid chemical characteristic and pressure, typically from the riser internal diameter of 4" and allowing storage in a reel or basket.

Monitoring of a 3D curvature, see Figure 20, requires the deployment of a sensors network as the curvature is a space-time parameter, implying that it depends on time and space. The estimation must be accurate with a high resolution and robust because this measurement is used for fatigue computation and alarm generation. In this way, a Morphopipe system is composed of chains of MEMS accelerometers positioned in the topside area of the flexible risers. These chains of sensors are all linked to a data acquisition unit, located at the control room, which centralises data coming from the distributed sensors network. Stored data are then processed to provide an estimation of the three-dimensional shape of the riser (curvature, torsion, deformed shape) continuously along the dynamic area of the riser.

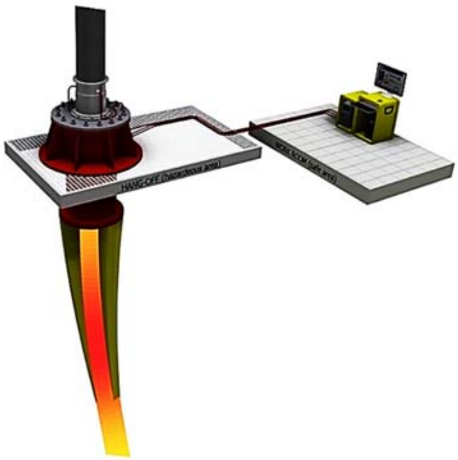

Figure 18: Schematic for Morphopipe system

Figure 19: Morphopipe instrumented layer

In addition to the above constraints regarding integration within the riser annulus and measurement performance, the monitoring system shall operate in subsea conditions for 25 years. As the embedded part of the monitoring system cannot be maintained or replaced, a strong focus has been set on reliability from the very beginning of the development project. The individual electronic cards have been designed to have a small failure probability rate. Furthermore, a strong redundancy in the system has been introduced. As a consequence, the accurate prediction of the curvature can be obtained with only a portion of the sensors. Moreover, the system will be deployed in a potential explosive atmosphere on platforms in several world areas.

Figure 20: Morphopipe test

## CONCLUSIONS

This paper presents a potential approach for flexible pipe re-qualification during the original design or if there is a need for lifetime extension. The flexible pipe lifetime extension requires additional detailed engineering guidance as there is currently a gap in the existing standards, guidelines and recommendation practices in terms of detailed engineering guidance, assessment codes and acceptance reliability target. In addition, it is important to adopt the state-of-the-art methodologies to improve the service life model as a part of the lifetime assessment execution to evaluate the flexible pipe's integrity level. The main contribution of this study is to adopt new methodologies, develop and apply advanced models for the bend stiffener/flexible pipe and non-linear pipe–seabed interactions using finite element modelling. Therefore, the reliable models for the bend stiffener region and seabed interaction reflect the realistic dynamic behaviour of flexible pipes and enhance the lifetime assessment accuracy.

The common industry approach for bend stiffener modelling in global analysis is to model the bend stiffener as an attachment to the flexible pipe and clamp at the top. This methodology is too conservative as it ignores the sliding friction and annulus space between the bend stiffener and flexible pipe. In addition, the clamp of the bend stiffener will generate high curvatures close to the bend stiffener base which can significantly increase the fatigue damage. Therefore, an advanced PIP modelling approach is used as an alternative to the common industry approach for bend stiffener modelling. The PIP model captures the interaction behaviour of the flexible pipe inside the bend stiffener as it models the sliding friction and the bend stiffener/flexible pipe's annular space. Therefore, the PIP model would improve the lifetime assessment of flexible pipes in the bend stiffener region as the resulted curvatures would be smaller than those deduced from the common standard stiffener model. The PIP modelling approach is validated by using FEA. This approach will provide accurate fatigue results removing excessive conservatism, maximising the potential for life extension.

The TDZ is one of the key locations where the fatigue damage occurs. The influence of soil stiffness, friction coefficients and suction effects can be reasonably significant on the dynamic and fatigue behaviour of the flexible risers. The sophistication of the interaction model depends on the type of analysis and accuracy required. Common riser analysis approaches employ either a rigid or linear elastic interaction surface to model the seabed and to simulate soil resistance to pipe penetration. A rigid seabed model generally gives a conservative result, since it is unyielding. Although the linear elastic contact is a better approximation of a seabed, however, it does not consider non-linear soil suction due to pipe–seabed interaction effects.

The improved pipe-soil interaction model combined with better prediction of soil stiffness and riser penetration enables us to obtain the global flexible riser dynamic performance in the TDZ more accurately. The pipe–seabed interaction analysis allows for the effects of physical phenomena such as soil suction forces and lateral and vertical seabed stiffness on the flexible pipe performance to be identified and quantified. The non-linear soil model characterises the degradation in soil stiffness during the dynamic riser–soil interaction as the seabed soil tends to lose strength and stiffness with an increase in embedment during cyclic oscillations after the seabed approaches its maximum strength during applied cyclic loading. The TDZ response, which involves the degradation of the seabed soil stiffness due to cyclic loading, is addressed by the analyses performed in this study. In this study, the vertical embedment of the flexible pipe in the TDZ was investigated. During the dynamic analysis, the seabed was modelled using a hysteretic non-linear soil model. The non-linear soil model captures the entity of varying soil stiffness and soil cyclic degradation, thereby allowing the re-penetration, uplift and suction effects. The investigation of soil stiffness degradation is influential in evaluating the structural dynamic performance and trench development in the TDZ.

This paper presents the flexible pipe in-service monitoring field-proven technology to monitor the riser's behaviour during operation. The main objective for the integrity management is to manage and control the risk of failure by detecting fatigue failure mode at an earlier stage when preventive action can be taken to avoid failure propagation. Furthermore, the in-service integrity management is the main tool which can enhance the lifetime extension for flexible risers and ensure that the pipe operates within the design envelope.

## ACKNOWLEDGMENT

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