On-bottom roughness analysis for repurposing of gas export pipelines in Brazilian coast

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Abstract. This work describes the on-bottom roughness analyses performed for the repurposing of two gas export pipelines in Brazilian coast for conditions out of original design premises, as well as the assessment of a lateral buckle identified in one of them. The main aspects of the employed methodology are presented, followed by their results. The importance of these analyses in a repurposing context is also discussed.

Keywords: on-bottom roughness, free span, lateral buckling, subsea pipeline, repurposing analysis.

1 Introduction

Submarine pipelines are designed and built supported by design bases that reflect the best information available regarding expected operation regime, fluid characteristics, environmental conditions, scientific knowledge, and engineering practice. Nonetheless, eventually operators and integrity managers face the need to operate in conditions beyond those considered in the original design. Both Brazilian regulation SGSS [1] and DNV-RP-F116 [2] address this scenario with the need for repurposing analysis, such as design verifications considering field data and operational history. Among those analyses, a new on-bottom roughness (OBR) assessment is required when changes on the pipeline accommodation loads on the seabed features are expected, as well as on free span distributions and characteristics, which may be due to changes in the content density, pressure, temperature or even seabed scour.

The reconfiguration of Espírito Santo Basin submarine gas export net will lead to changes in the operational parameters of several already installed pipelines and physical interventions in some of them. This work focusses on the OBR analyses for repurposing of two 12” gas pipelines of this system, herein referred as Pipeline A and Pipeline B, considering the presence of features found in surveys during operation.

Pipeline A, with wall thickness (WT) varying between 22-25mm, is planned to operate with an incidental pressure approximately 15% higher than considered in design, and under a more severe operational cycling regime. Pipeline B (WT between 16-21mm) will be cut and re-terminated to transport the production of new units and will operate with flow conditions different from the original project. In both cases, the analyses of survey outcomes showed features compatible with the occurrence of seabed scour. As an example, Figure 1 shows (left) one scour-caused span identified in Pipeline A and (right) examples of spans found in Pipeline B caused by scouring.

The reassessment of corrosion through inline inspection outcomes and new flow conditions led to a much more severe scenario for Pipeline B as originally considered, with a corrosion loss higher than twice the design value. The same did not happen in Pipeline A, for which the corrosion remains within below design limits.

Finite Element (FE) models were built incorporating as-built data, information gathered in inspection campaigns and monitored operational data to assess DNV-ST-F101 [3] design code checks regarding both strength and fatigue. Preliminary runs of Pipeline A model showed a potential to buckle along the first kilometers in the deeper section of the pipeline. Comparisons of the Deviation from Center Course (DCC) profiles in As-Laid (AL) survey and in a later one in operation (PIDR-1 2017) suggested a slight lateral buckle on the same region (see Figure 7), estimated to influence the loads along the first 3 km of Pipeline A. For that reason, and due to the locally very flat seabed, the first 3000m section was evaluated outside the OBR analysis scope in the lateral buckle assessment addressed in item 3.

This work focuses on the methodology applied and how the FE results were post processed to achieve the objective of the analyses as well as how difficulties, such as lack of information, were circumvented.

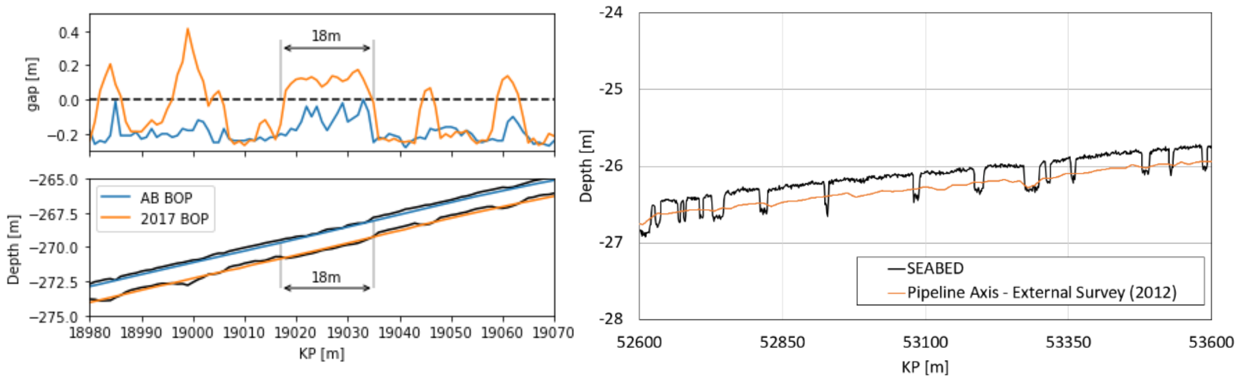

Figure 1. (Left) New free span (18m) caused by scour in Pipeline A close to KP 19; (Right) Examples of spans found in Pipeline B caused by scouring.

2 On-bottom roughness analyses

The purpose of OBR analyses in subsea pipeline design is to predict the loads resulting from the pipeline accommodation on the irregular seabed, as well as the distribution and characteristics of free spans. Parameters such as the residual lay tension, pipe-soil interaction (friction and penetration) and the sequence of operations (e.g. pipe laying, flooding, pressure test, emptying, operational cycling…) are taken into account. In a repurposing perspective, the analysis must ideally consider the best available data from construction, surveys and operational history, therefore reducing design uncertainties.

2.1 Methodology

The OBR analyses were performed in Fugro's SAGE Profile 3D®, an explicit FE software capable of simulating non-linear response due to pipe bending, soil interaction response (bearing capacity, and axial and lateral frictional resistance), and large deformation. The pipeline is modelled by Euler-Bernouli beam-column elements accounting for internal and external pressure effects. The interaction with the seabed is modelled by lumped non-linear springs in vertical, axial and lateral directions, activated whenever contact is detected. The pipe laid configuration along the route is achieved through an optimized routine in which the full length of the pipeline is not simulated, but only a smaller section close to the touch-down point (TDP).

The models considered survey bathymetric profiles, lay tension profiles from pipelay field procedures and all artificial supports placed along the routes during construction. Artificial free span supports along the routes were represented with imposed displacements and/or restrictions in the relevant nodes, following their positions according to surveys.

Pipe-soil interaction is usually governed by pipeline section characteristics (weight and diameter), soil properties and lay tension. Semi-empirical correlations based on soil samples along the pipeline routes were used to estimate the embedment in original design, but repurposing analyses may consider reassessed parameters based on field observations. Multi-linear vertical reaction (R) VS penetration (δ) curves were adjusted to delimited sections. Aiming to reproduce the embedment depths observed in survey and still preserve the design estimates, the original reaction curves were corrected by an "offset" in positive embedment direction, introducing a first segment defined by the pair (δ_m, w_s) where w_s is the submerged weight and δ_m is the average embedment along the section. This approach is motivated by the fact that the pipeline penetration on seabed is mostly governed by the installation operation. During the pipeline installation the load concentration on the TDP, along with the seabed swepping and disturbed by the pipeline dynamics, results in embedment depths higher than those predicted only by the static weight load. The adjust is exemplified in Figure 2 (left).

Prior to full-length model runs, some sensitivity analyses were carried out in order to verify element size influence on the results on a limited section (1500m long) of Pipeline A. Element lengths of 4m, 2m and 1m were tested, and very small differences were observed in Effective Axial Force (EAF) and Bending Moment (BM) profiles, see Figure 2 (right). Meshes with 1m and 2m elements were able to capture some oscillations in bending moment that were missed by 4m mesh approximately at KP 23250m. For Pipeline B, the adopted discretization level was the same employed in the OBR analysis of the original project. For both pipelines A and B, element sizes of 2 m or shorter were used.

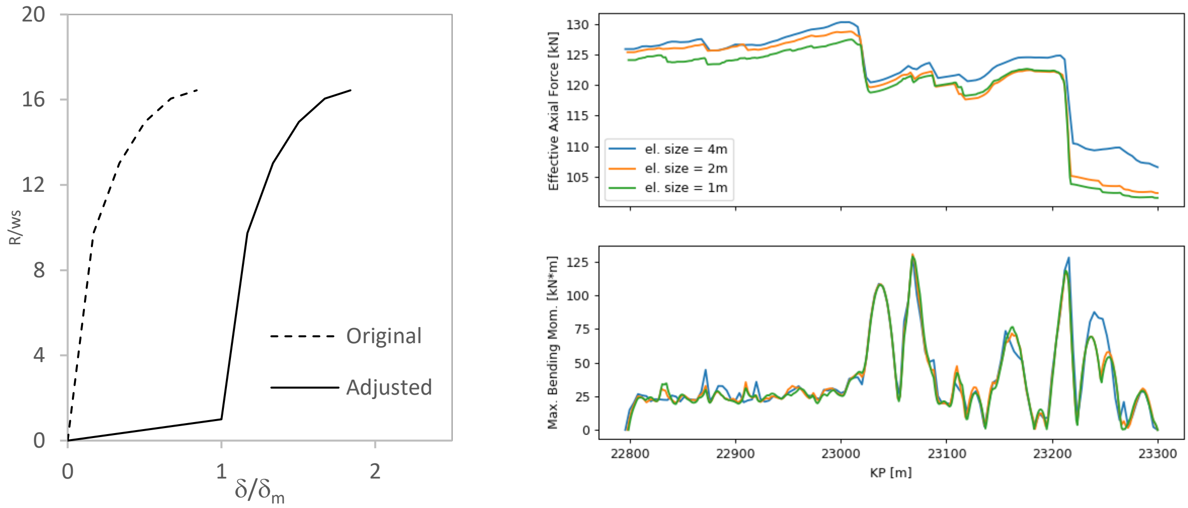

Figure 2. (left) Pipe-soil vertical reaction curve correction; (right) sensitivity analysis on element length.

Both pipelines were laid empty. After laydown and application of supports, the internal fluid pressure, weight and temperature were applied in a sequence that best suited the pre-commissioning and operational history and the expectance for future operation. A typical sequence comprises pipeline flooding, application and removal of hydrostatic test (HT) pressure, inertization with N_2 (assumed similar to empty in terms of pressure and submerged weight), multiple operational scenarios, incidental condition and shutdown. This sequence was straight-forwardly applied for Pipeline A. For Pipeline B, the adopted approach consisted of first simulating the pipeline behavior before the cut and re-termination for obtaining nodal results at the KP corresponding to the cut. These results were applied as boundary conditions (displacements and rotations) of a second model representing the pipeline after cut. So, the typical load sequence was applied twice, but the new flow conditions were applied only in the second model.

The section loads obtained in each scenario were checked against ref. [3] LCC (combined load local buckling criteria for Load Controlled Conditions), which addresses both local buckling and plastic collapse failure modes under the combination of BM, EAF, internal and external pressure.

The differences in longitudinal stress between key scenarios were used to calculate the fatigue damage in the girth welds due to operating loading using traditional S-N approach . For Pipeline B, only the pressure cycles history was considered since the pipe temperature in the section of interest was in equilibrium with the external seawater temperature according to the design premises. Pressure cycles histogram was built from monitored data using the rainflow method. The stress concentration factors due to girth welds were calculated applying Eq. 2.10.1 of DNVGL-RP-C203 [4]. It was considered the S-N curve F-1 in seawater with cathodic protection from DNVGL-RP-C203 [4] with an additional knockdown factor of 4.

For both strength and fatigue assessments, internal corrosion was considered as smooth and uniform, i.e., local stress concentration due to sharp corrosion features were out of scope of this OBR analysis. However, operators shall observe that the evaluation of significance of sharp and/or deep corrosion defects is mandatory for repurposing analysis of pipelines presenting such features.

2.2 Results

The pipeline profile resting on the seabed as well as the corresponding section loads (EAF and BM) along the pipeline route were obtained in all scenarios of interest. A good agreement was found between FE deformed configurations and survey results. As shown in Figure 3 and Figure 4, the FE models were able to reproduce the free spans, the embedment and the deformed shape along the route, indicating that the efforts on the pipeline are adequately captured.

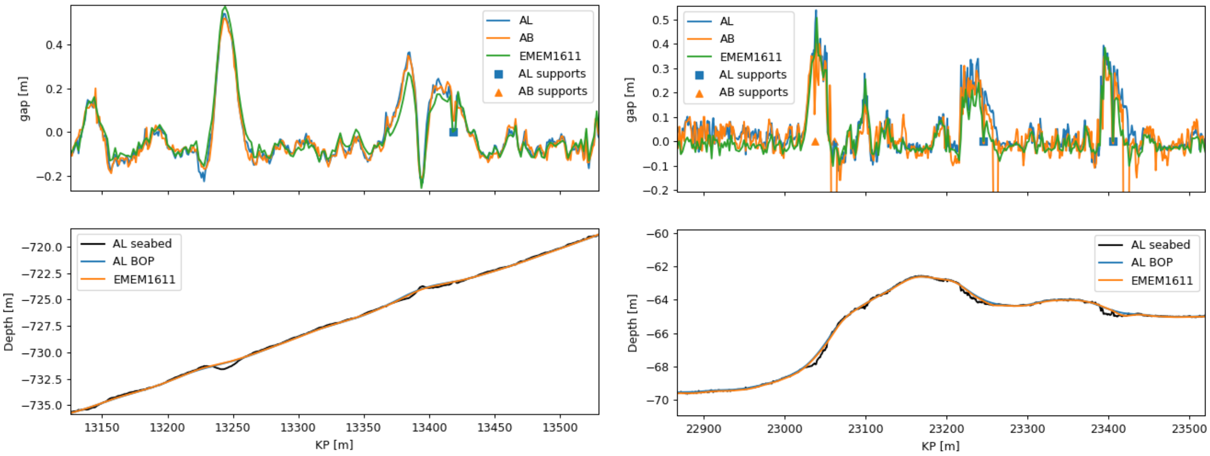

Figure 3. Pipeline A accommodation on seabed: comparison pipe-seabed gap and depth in FE (EMEM1611 - empty condition) and As-Laid (AL) and As-Built (AB) surveys.

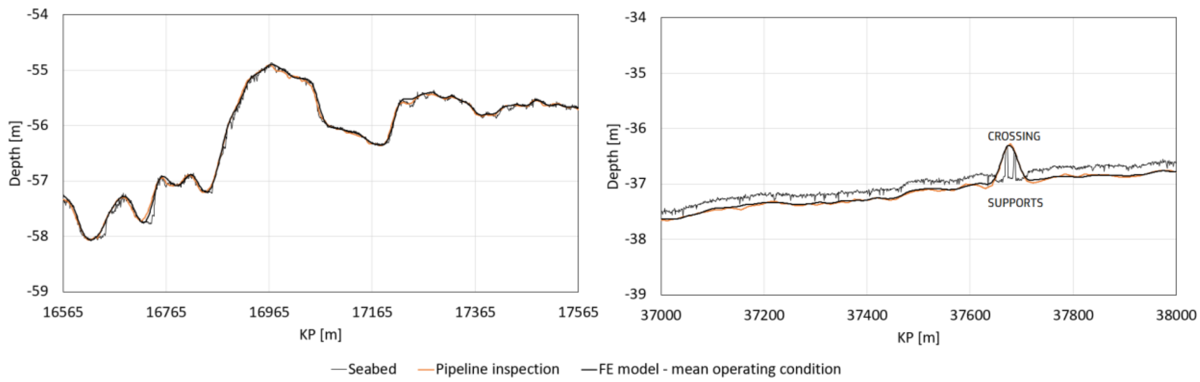

Figure 4. Pipeline B accommodation on seabed: comparison between periodic external inspection survey and FE results in two different locations.

LCC checks were within DNV limits for both pipelines. Some relevant results for Pipeline A are shown in Figure 5. It is evident from the 1st columns of graphs that different scenarios lead to the most critical results along the pipeline. The highest BM values occur in KP 13-25 approximately, where the seabed is most irregular. The highest LCC values coincide with the highest BM locations, nonetheless, a consistent increase in LCC is noticed from KP=20 towards KP=0 (deepest section) observed in scenarios OMEM3411 and OMEM3611. These scenarios consider zero internal pressure, ergo the LCC is governed by collapse due to external pressure. The graphs in the 2nd column show the effect of the increase of two spans due to scour in BM and LCC values in the most critical scenario. Although the LCC is well below the acceptable, these results show the need for constant monitoring of scour action once it is detected.

Analogously, some relevant results for Pipeline B are presented in Figure 6. The maximum BM takes place at the crossing (KP 37.6, see Figure 4 RHS) and maximum LCC between KP 16.5 and 17.5 (see Figure 4 LHS). Pipeline B resulted in more severe ratios than Pipeline A, which can be traced back to the lower WT and higher corrosion loss.

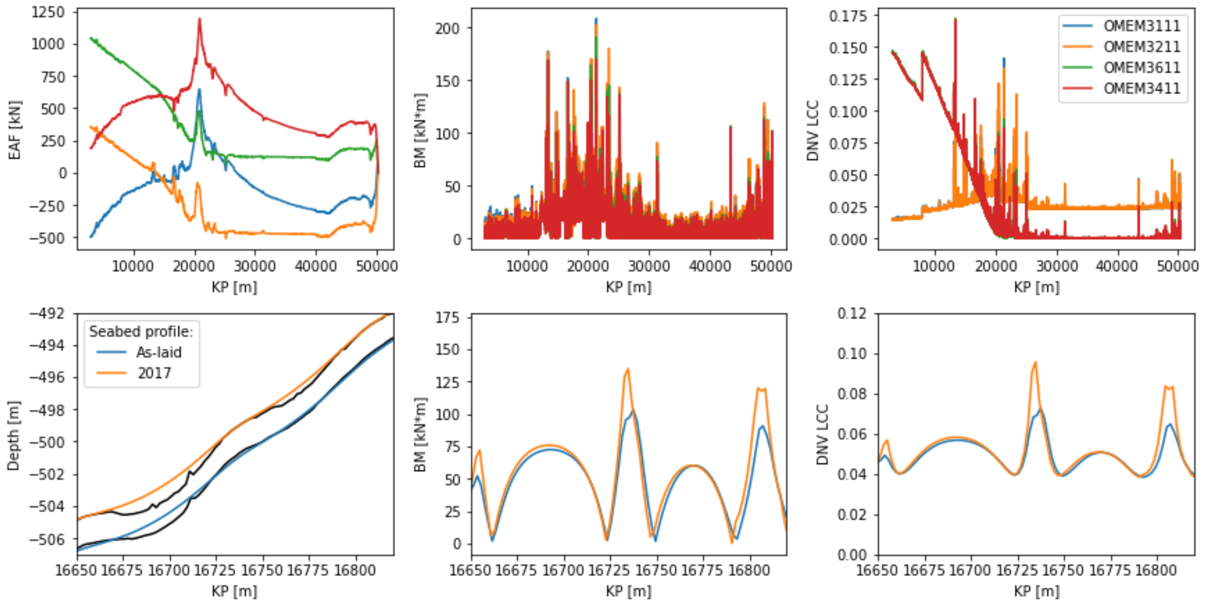

Figure 5. Pipeline A results. 1st column: EAF, BM and DNV LCC profiles in most critical EF analyses steps; 2nd column: free spans increasing due to scour and differences in BM and LCC in most critical scenario.

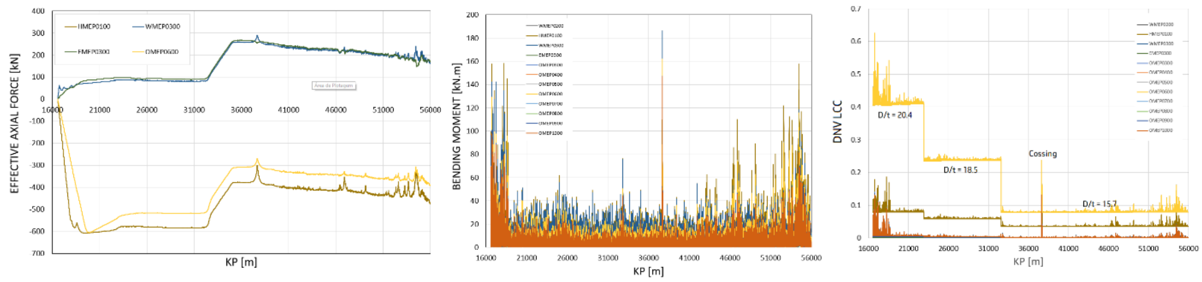

Figure 6. Pipeline B results. EAF, BM and DNV LCC profiles.

3 Lateral buckling analyses

Lateral Buckling in exposed pipelines on seabed should be analyzed for purpose [3]. The locations predictability of the buckles during pipeline visual inspections is an important and extremely challenging activity that is part of global buckling assessment. Herein, a methodology has been elaborated to identify pipeline lateral displacements, calibrate friction factors based on its movements and check the pipeline limit states [5] within a lateral buckle with a short numerical Virtual Anchor Spacing (VAS) model, considering also predicted conditions for future pipeline operations.

3.1 Buckle mapping from survey data

Fledermaus® software was used to visualize 3D bathymetric survey data from Pipeline A section where the buckle indication was found. Several 1m-spaced cross-profiles were traced from KP 1.5 to KP 1.7, long enough to capture the pipeline and the seabed features (marks and soil berms) that indicate previous movement. The seabed features illustrate a buckle-shaped pipeline lateral displacement from KP 1.55 to KP 1.66 (110m length) with amplitude about 2.6m centered in KP 1.61. This lateral displacement can indicate a global buckling behavior, for which the pipeline limit states must be checked, requiring calibrated friction factors in this region. The calibration process is addressed below.

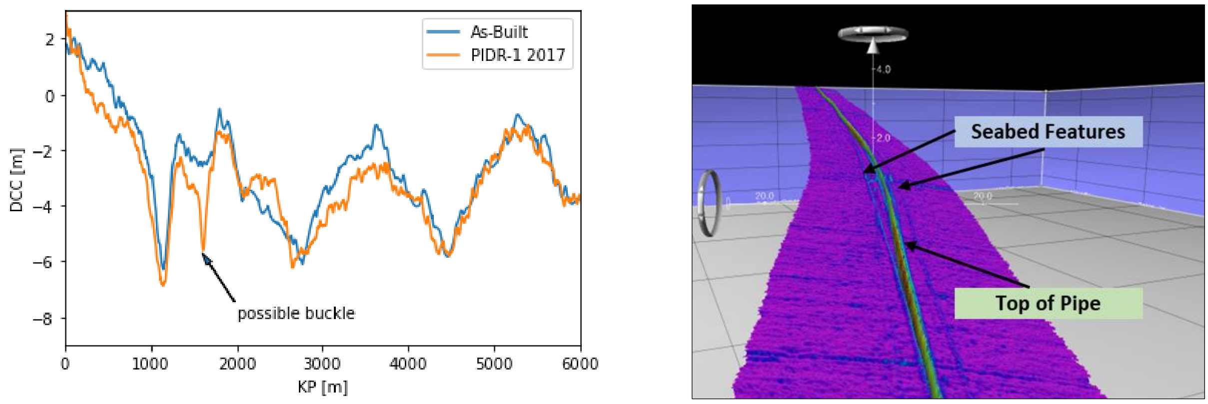

Figure 7. (left) Indication of lateral buckle in Pipeline A from major localized difference between AB and PIDR-1 2017 survey DCC profiles; (right) 3D view of the lateral buckle in Fledermaus®: soil varying between purple and blue, pipeline in green.

3.2 Friction factor calibration

FE analyses were performed using the Abaqus® v6.20 software aiming to obtain lateral pipeline displacements coherent with the mapped berms. The pipeline and the pipe-soil interaction were modeled with PIPE31H and PSI34 elements, respectively. Elastic-perfectly-plastic material and even seabed were considered. An initial sinusoidal out-of-straightness (OOS), centered in KP 1.61 [6] with 166m wavelength, 1m amplitude and 681m curvature radius was introduced with application of lateral displacements. As boundary conditions (BC), a Lower Estimate (LE) PLET resistance was considered in KP 0.0. Only a short pipeline section (8km long) was modelled [7], but long enough so that no influence of the second end was observed on the results.

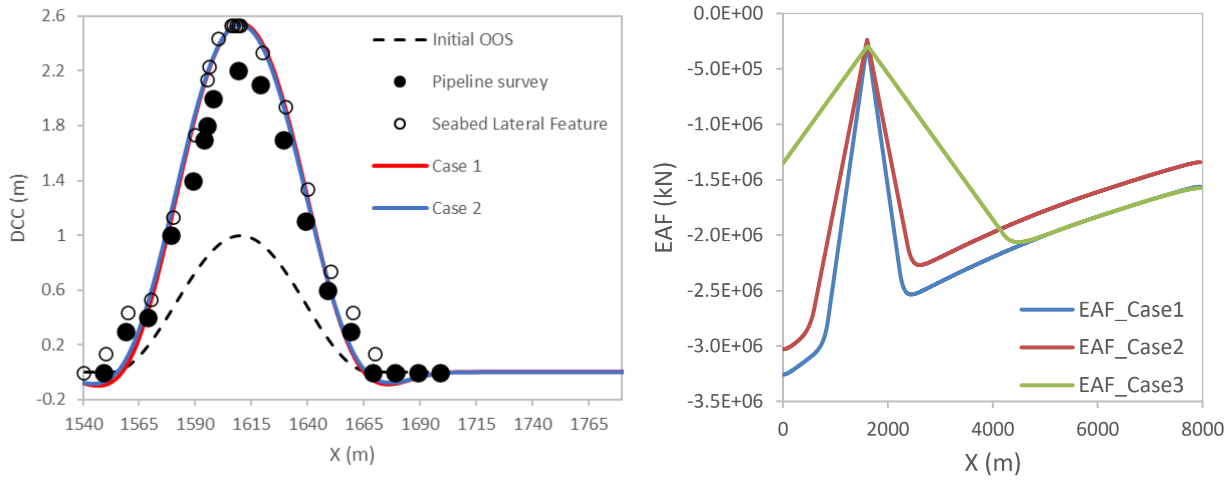

Figure 8. (left) Friction factors calibration results; (right) EAF distribution in Global Buckling Analyses

A similar step sequence as in OBR analyses was considered. The calibration runs used operational parameters coherent with the survey execution. For resistance checks, extreme parameters were considered.

Due to residual lay tension variation, two calibrations were done for the extreme values (minimum and maximum) of this parameter. Figure 8 (left) exhibits the results. The calibrated lateral displacement was slightly different in comparison with lateral seabed features. The main reason is the symmetric initial OOS used in the model, while the observed seabed features was asymmetrical.

3.3 Lateral buckling analysis results

The last part of lateral buckling analysis was to evaluate the limit state checks for further conditions predicted for the pipeline operation. Following ref. [3] criteria, the checked failure models were local buckling, fracture, fatigue axial strain and cyclic plasticity. For lateral buckling analyses, the models used the same load steps of the calibration friction factors analyses but with incidental pressure and design temperature profiles along the pipeline route. The pipeline was analyzed by sections according to design and calibrated soil resistances. The initial OOS was the same used in the previous item. For classified information purpose, the friction factors used in FEM (Abaqus® PSI34 package) aren´t shown. The analyzed cases had the same properties except the friction factors and residual lay tension. Case 3 used lower estimate axial friction factors and upper estimate lateral friction factors from pure geotechnical reassessment, Case 1 and Case 2 used the FE-calibrated friction factors obtained from item 3.2.

The EAF distribution in each case is exhibited in Fig. 8 (right). According to reference [5], global buckling is a structural response to a high compressive EAF (see Fig. 8 values) and may imply failure modes (ref. [5]) that were checked: Displacement control condition (UC_{DCC}), uniform strain capacity (UC_{USC}), cyclic plasticity ($UC_{Plasticity}$) and longitudinal strain limit ($UC_{fracture}$).

The limit states verifications were fulfilled in all analyzed cases, in accordance with refs. [3] and [5]. The Case 3 presented the most critical condition. In accordance with ref. [5], lower axial friction factors (Case 3) yield higher axial feed-in than others (Cases 1 and 2). The lateral frictions factors in Cases 1 and 2 are lower than Case 3. The results demonstrated that axial pipe-soil interaction is a more relevant parameter than lateral one and provided for the pipeline more axial feed-in, longitudinal strain and longitudinal stress range in Case 3. This behavior explains Case 3 checks values higher than other cases.

4 Conclusions

The use of survey data to feed FE models and engineering analysis for two submarine pipelines in a repurposing context was demonstrated. Originally motivated by operational changes, for both pipelines the analyses of survey results found occurrences not anticipated in design that had to be addressed, namely the action of scour (Pipelines A and B) and the lateral buckle (Pipeline A).

The OBR analyses conducted for Pipelines A and B repurposing led to acceptable results with respect to DNV criteria [3], as well as the lateral buckling assessment in Pipeline A deepest section.

Fatigue assessment due to vortex-induced vibration (VIV) in the free spans and the thermomechanical cycling at the lateral buckle are still on-going and were not addressed in this work.

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