INDEX OF REVISION

REV.	DESCRIPTION AND/OR REVISED SHEETS
0	THIS DOCUMENT REPLACES THE PREVIOUS TECHNICAL SPECIFICATION OF THERMO-MECHANICAL DESIGN (I-ET-0000.00-6500-940-P9U-003)
A	INITIAL ADJUSTMENTS AND ALIGNMENT WITH DNV-RP-F110
B	GENERAL REVISION AND ALIGNMENT WITH DNV-RP-F110
C	REVISION OF ITEMS 1.2.2 (REF. [5]), 1.4, 2.3 AND 5.1
D	GENERAL REVISION, MAINLY OF ITEMS 2.3, 4.1, 4.2.1, 4.3, 4.4.4 AND 6.2, AND INCLUSION OF ITEMS 2.5.8 AND 6.2.3

	REV. 0	REV. A	REV. B	REV. C	REV. D	REV. E
DATE	27/12/2017	14/08/2018	21/12/2018	20/05/2020	09/06/2023	
EXECUTION	ER48 / BXXG	ER48 / UP65	ER48 / BXXG	ER48	ER48	
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APPROVAL	CLZ2	CLZ2	CLZ2	CLZ2	CLZ2	

CONTENTS

1 INTRODUCTION

1.1 Scope

This Technical Specification establishes complementary requirements to the DNV-RP-F110 [1] and covers the scope of work, technical requirements and deliverables related to global buckling design of rigid subsea pipelines.

The contents of this Technical Specification cover only the following subjects:

- Load & end displacement;
- Global buckling, including lateral buckling (snaking) and vertical (upheaval) buckling;
- Route curve pullout;
- Buckle interaction and buckle stability;
- Pipeline walking.

CONTRACTOR shall consider that global buckling design includes all subjects listed above.

This Technical Specification describes the premises and methodology to be followed by the CONTRACTOR in global buckling design of subsea rigid pipelines, as well as makes reference to the codes, design guidelines and technical publications that shall be also considered by the CONTRACTOR.

This technical specification does not address all pipeline design and shall be complemented with a recognized pipeline design code.

This technical specification addresses specific issues associated with structural integrity of global buckling design. Design for limit states within this technical specification adopts DNV-ST-F101 [2].

Finally, this Technical Specification defines mainly all analyses of global buckling design that the CONTRACTOR shall perform and submit by technical reports for evaluation and PETROBRAS approval.

All deviations to this Technical Specification and other referenced specifications (Section 1.2) or attachments listed in the Contract shall be made in writing by TQF (Technical Query Form) and shall require written approval by PETROBRAS prior to executing the work.

1.2 References

The following documents were adopted as reference for this technical specification. Whenever the revision is not mentioned the last revision of such references is applicable.

1.2.1 Design International Codes

[1] DNV-RP-F110, Recommended Practice, Global Buckling of Submarine Pipelines, Structural Design Due to High Temperature / High Pressure.

[2] DNV-ST-F101, Standard, Submarine Pipeline Systems.

[3] DNV-RP-C203, Recommended Practice, Fatigue Strength Analysis of Offshore Steel Structures.

[4] DNV-RP-F109, Recommended Practice, On-bottom Stability Design of Submarine Pipelines.

[5] DNV JIP Lined and Clad Pipeline Materials - Phase 4, Guideline for Design and Construction of Lined and Clad Pipelines, Report No. 2017-3114, Rev. 1.

[6] DNV-RP-A203, Recommended Practice, Technology Qualification.

1.2.2 PETROBRAS Technical Specifications

[7] Alternative Flaw Acceptance Criteria of Submarine Rigid Pipelines and Risers Girth Welds, PETROBRAS Technical Specification, I-ET-0000.00-0000-210-P9U-005.

[8] Minimum Requirements for Buoyancy Modules for Flowlines and SLWRs, PETROBRAS Technical Specification, I-ET-0000.00-0000-250-P9U-002.

[9] Sleeper for Lateral Buckling Initiation, PETROBRAS Technical Specification, I-ET-0000.00-0000-250-P9U-001.

[10] Rigid Pipeline On-Bottom Roughness and Free Span Design, PETROBRAS Technical Specification, I-ET-0000.00-0000-940-P9U-002.

1.2.3 PETROBRAS Standards

[11] N-381 - Execução de Desenho e outros Documentos Técnicos em Geral.

[12] N-1710 - Codificação de Documentos Técnicos de Engenharia.

[13] N-2064 - Emissão e Revisão de Documentos de Projeto.

1.2.4 Technical Publications

[14] Carr, M., Sinclair, F. and Bruton, D., “Pipeline Walking – Understanding the Field Layout Challenges, and Analytical Solutions Developed for SAFEBUCK JIP”, Offshore Technology Conference, OTC2006-17945, May 2006.

[15] Palmer, A. C., Ellinas, C. P., Richards, D. M., Register, L. and Guijt, J., “Design of Submarine Pipelines Against Upheaval Buckling”, Offshore Technology Conference, OTC1990-6335, May 1990.

In case of disparity between the requirements of such references and those established in this document, the specifications of this document shall prevail.

1.3 Definitions

The following definitions are adopted in this technical specification:

2½D Analyses:	Pipeline analyses with all degrees of freedom (i.e. 3D) both modelled and analyzed in three dimensions, i. e., including curves in the vertical and horizontal planes, but with the seabed in the lateral direction modelled as flat.
Bathymetry Profile	2D profile determined by the sea level along a specific pipeline route.
Characteristic VAS	Virtual anchor spacing, i.e. distance between virtual anchor points along the pipeline length.
CONTRACTOR:	Company responsible for the global buckling design of subsea pipelines.
Effective Axial Force:	The combined axial action of the stress in the pipe wall and the internal and external pressure.
Global Buckling:	On-set of transverse instability of a significant length of pipe. The transversal instability could be in the vertical plane (upheaval buckling) or horizontal plane (lateral buckling).
Lateral Buckling:	Global buckling in the horizontal plane (the post buckling condition is sometimes also referred to as snaking).
Out-of-Straightness:	Pipeline initial geometrical imperfection. Lateral OOS refers to inherent initial imperfection due to pipeline lay process.
Pipeline Expansion	Pipeline movement axially, deflection in spans or displacement into one buckle.
Pipeline Walking:	Axial accumulation of displacement due to thermal and pressure cycle loads. Also known as axial ratcheting.
Pullout:	Route curve instability, i. e, lateral instability of pipeline route curve.
Rigid Pipeline:	A continuous pipeline composed of steel linepipes and used for transporting fluids.
Rogue Buckle:	Lateral buckles formed on the seabed where no trigger is employed, i. e., unintended or unplanned on-bottom buckles.
Seabed Bathymetry	3D surface determined by the sea level.
Subsea Equipment:	Subsea structures connected at the pipeline ends or in the middle of the lines, as PLETs, PLEMs and ILTs, for example.
Tolerable VAS:	Virtual anchor spacing which exactly match the governing design criterion.
Triggers:	Buckle initiators used to control lateral buckling phenomenon.
Upheaval Buckling:	Global buckling in the vertical plane (the post buckling condition is sometimes also referred to as vertical buckling).

1.4 Abbreviations

The following abbreviations adopted along this technical specification are presented below:

ALO	As-Landed Orientation
BE	Best Estimate (most likely)
C-Mn	Carbon-Manganese
CRA	Corrosion Resistance Alloy
ECA	Engineering Critical Assessment
FE	Finite Element
FEA	Finite Element Analysis
FJC	Field Joint Coating
HP/HT	High Pressure / High Temperature
ILT	In-Line Tee
KP	Kilometer Post
LE	Lower Estimate
N/A	Not Applicable
No.	Number
OOS	Out-of-Straightness
PLEM	Pipeline End manifold
PLET	Pipeline End Terminator
RC	Residual Curvature
RCM	Residual Curvature Method
RLT	Residual Lay Tension
SCF	Stress Concentration Factor
SMYS	Specified Minimum Yield Stress
SNCF	Strain Concentration Factor
TDP	Touch Down Point
TRF	Riser-Flowline Transition
UE	Upper Estimate
VAS	Virtual Anchor Spacing
VIV	Vortex Induced Vibration

1.5 Symbols

The following symbols are adopted in this technical specification:

Latin Characters:

A_s	Steel cross sectional area of the pipe steel
E	Young's modulus
I	Pipeline second moment of area
L_h	Virtual anchor length
R	Curvature radius of pipeline route
S_0	Fully constrained effective axial force
S_{end}	End reaction imposed on pipeline
$S_{\max}$	Maximum compressive effective axial force
W'	Pipeline submerged weight in the condition considered

Greek Characters:

β	Angle through pipeline curve
ΔT	Difference in temperature relative to the as-laid ambient temperature
Δ_x	End expansion
$\varepsilon_{l,nom}$	Total nominal longitudinal strain
μ_{lb}	Lateral breakout friction factor
μ_{ar}	Axial residual friction factor

2 DESIGN PREMISES

2.1 Scope of Design Analysis

2.1.1 General

CONTRACTOR shall perform at least the following analyses:

- Lateral Buckling Susceptibility;
- Upheaval Buckling Susceptibility;
- Load & End Displacement;
- Pipeline Walking Susceptibility;
- Curve Pullout Susceptibility;
- Lateral Buckling (VAS and Initiation Strategy);
- Lateral Buckling and Walking;
- Upheaval Buckling Detailed.

2.1.2 Basic Design

The scope of basic design shall comprise at least the following analyses:

- Lateral Buckling Susceptibility;
- Upheaval Buckling Susceptibility;
- Load & End Displacement;
- Pipeline Walking Susceptibility;
- Curve Pullout Susceptibility;
- Lateral Buckling (VAS and Initiation Strategy).

2.1.3 Detailed Design

All analyses listed in Section 2.1.1 above shall be performed in pipeline detailed design and follow the methodology defined in Section 3.

2.2 Design Standard and Recommended Practices

The pipeline shall be designed in accordance with DNV-ST-F101 [2] and others documents referenced in Section 1.2 of this Technical Specification.

The pipeline global buckling design shall be performed in accordance with DNV-RP-F110 [1] and complementary requirements of this Technical Specification.

In all cases, the latest edition of the relevant regulations, codes, standards, recommended practices, and guidance notes shall be used, unless noted otherwise.

2.3 Data for Global Buckling Design

Regarding global buckling design, the following information shall be included in pipeline design basis and soil interaction reports:

2.3.1 Pipeline Data

At least the following pipeline data and material parameters shall be presented:

- Nominal steel pipe outside diameter;
- Nominal steel pipe internal diameter;
- Nominal steel pipe wall thickness;
- Fabrication tolerance of steel pipe wall thickness;
- Pipeline length;
- Steel pipe material specification;
- Steel pipe density;
- Corrosion allowance;
- CRA material specification;
- CRA layer nominal thickness;
- CRA layer density;
- Coating material;
- Coating nominal thickness;
- Coating equivalent density;
- Cut back length;
- FJC material;
- FJC nominal thickness;
- FJC equivalent density;
- Field joint coating density;
- Pipeline nominal weights;
- Stress-strain curve;
- Safety class and design safety factors;
- Fatigue parameters (S-N curve parameters);
- SCF and SNCF.

The material parameters shall be presented in accordance with Table 3-2 from DNV-RP-F110 [1] over the temperature range applicable to design.

Pipe equivalent geometry and material properties shall be presented for pipelines with CRA internal layer.

2.3.2 Installation and Route Design Data

At least the following data along the pipeline route shall be presented:

- Subsea layout;
- Seabed bathymetry and water depth;
- Maximum seabed transverse slopes;
- Geometrical parameters, material properties, weights, arrangements and locations (KP and coordinates) of crossings;
- Buckle initiator (trigger) parameters;
- Subsea equipment information (locations, submerged weight and surface area in contact with soil);
- Maximum allowable loads at equipment connection;
- Locations and relevant characteristics of anchoring systems;
- Slack of anchoring systems;
- Pipeline installation tolerances at buckle initiator locations and away from buckle initiator locations;
- Pipeline internal pressure during installation;

- Internal fluid density during installation;
- Ambient temperature at seabed;
- Installation residual strains;
- Nominal, maximum and minimum bottom tension based on installation analyses;
- Pipeline residual lay tension;
- Riser tension at TDP location;
- Interface load at TRF location.

Note: The riser section between the TRF and the TDP shall be considered in global buckling design.

2.3.3 Operational Data

At least the following operational data shall be presented:

- Design lifetime;
- Description of all relevant predicted conditions (Hydrotest, Incidental, Design, Operational, etc.) for global buckling design;
- Hydrotest pressure profile, with associated temperature profile and fluid density profile;
- Incidental pressure profile, with associated temperature profile and fluid density profile;
- Maximum design temperature profile, with associated pressure profile and fluid density profile;
- Design pressure profile, with associated temperature profile and fluid density profile;
- Profile of maximum allowable operating pressure, with associated temperature profile and fluid density profile;
- Minimum operating pressure profile, with associated temperature profile and fluid density profile;
- Profiles of pressure, temperature, and associated fluid density for all relevant predicted scenarios, including commissioning, first operational loading, contingency, maintenance, etc., such as: leak test, first load (e.g., hot commissioning), pack-in, shut-in, bullhead, diesel circulation, etc.;
- Transient profiles of pressure, temperature, and associated fluid density for operational shutdowns and any other relevant cyclic events;
- Number of predicted cycles, as well as their time (in hours) of operational shutdowns (long and short, total and partial, etc.) and any other relevant cyclic events.

2.3.4 Environmental Data

At least the following key environmental conditions shall be presented:

- Seawater temperature;
- Seawater density;
- Marine growth;
- Extreme bottom current velocities with specified return periods and directions;
- Water depth and reference height for the current velocity measured above the bottom;
- Extreme bottom wave-induced flow velocities with specified return periods and directions;
- Peak horizontal and vertical load coefficients.

2.3.5 Soil Resistance and Stiffness Data

At least the following data regarding the interaction with soil shall be presented:

- Pipe embedment;
- Axial friction factors (breakout and residual);

- Lateral friction factors (breakout and residual);
- Lateral berm friction factors (cyclic response);
- Vertical soil stiffness;
- Equipment resistances;
- Associated mobilization displacements.

2.4 Design Loads

2.4.1 Operational and Design Loads

The global buckling design shall be based upon the design pressure and temperature; it shall be assumed that this design pressure and temperature shall not be exceeded during the life of the pipeline. The analysis shall take advantage of the gradients along the pipeline length. The pipe wall temperature shall be used in the analysis if this is available from the process simulations.

For calculation of the fatigue loads as well as in buckle interaction and pipeline walking analyses the pipeline operational pressure and temperature shall be employed.

The stress range developed depends upon the phasing between pressurization and thermal load. The analysis shall be based upon the following load cycle:

- Pressure-up;
- Heat-up;
- Pressure down;
- Cool down.

The application of operational cyclic loads shall produce the most onerous stress range associated with the change in operational conditions.

2.4.2 Environmental loads

The bottom current loads and wave-induced flow loads shall be taken into account in global buckling design in accordance with DNV-RP-F110 [1].

2.4.3 Load Combinations

All relevant load combinations shall be checked in accordance with DNV-RP-F110 [1].

2.5 Limit States Checks

2.5.1 General

The design shall demonstrate that the pipeline is fit for purpose for the entire life of the field, and fulfills all relevant limit state design checks as follow:

- Local buckling – combined loading criteria;
- Axial loading;
- Uniform strain capacity;
- Ratcheting / cyclic plasticity;
- Fatigue;
- Fracture;
- Liner wrinkling.

All other limit states relevant for pipelines not covered in this technical specification (pressure containment, hydrostatic collapse, etc.) shall be evaluated in accordance with DNV-ST-F101 [2] design code. The required approach to the remaining limit states is outlined in this Section; this approach shall be only intended for use in the assessment of the conditions in the buckled pipeline.

In addition to the key failure modes presented above, there are others failure modes that should be verified by the CONTRACTOR if considered relevant.

In addition to these limit states, the pipeline material properties shall be consistent with the high levels of imposed load following the requirements established in Section 2.3.1.

Along the design details relating to the limit state checks and the methodology that will be used to interpret these limit states shall be presented for PETROBRAS approval.

Besides the limit states specified below, design specific requirements shall be observed in regions such as crossings, free spans, etc.

2.5.2 Local Buckling – Combined Loading Criteria

The local buckling limit state shall be checked in accordance with DNV-RP-F110 [1], considering the seabed definition (even, moderately uneven or uneven).

2.5.3 Fatigue

CONTRACTOR shall fulfill the fatigue requirements defined by DNV-RP-F110 [1].

The fatigue life of the pipeline welds shall be checked in accordance with Recommended Practice DNV-RP-C203 [3]. Requirements defined in DNV-ST-F101 [2] and DNV-RP-F110 [1] shall also be fulfilled. The following points shall be considered:

- The welds shall be assumed to lie at the apex of the buckle;
- Knock-down factors shall be defined for specific project conditions.

The fatigue life defined in this Technical Specification refers only to stress range due to temperature and pressure variations during hydrotest and operational life, i. e., low cycle fatigue. Other possible sources of stress variations (VIV and laying process) shall be considered in specific reports to evaluate the cumulative damage when relevant.

2.5.4 Fracture

CONTRACTOR shall fulfill the fatigue and fracture requirements defined by DNV-RP-F110 [1].

Total nominal longitudinal strain $\varepsilon_{l,nom}$ shall be limited to 0.4% (including load factors and all strain concentration factors). The unity check shall be the ratio between the mechanical tensile strain at steel outer surface and the limit of 0.4% for the tensile strain.

Total nominal longitudinal strain shall be limited in CRA internal layer pipes and girth welds in order to avoid significant ductile tearing / fatigue crack growth and, consequently, the rupture of CRA layer. Engineering critical assessment (ECA) shall comply with PETROBRAS Technical Specification I-ET-0000.00-6500-210-P9U-005 [7].

2.5.5 Axial Loading

Buried pipeline design shall fulfills the axial loading limit state as defined by DNV-RP-F110 [1].

2.5.6 Uniform Strain Capacity

The imposed strain should not approach the uniform strain capacity of the material. The maximum nominal equivalent strain developed in the buckle shall not exceed the limitation defined by DNV-RP-F110 [1].

This check shall be based upon the nominal strain developed at the buckle; no strain concentration factor (SNCF) shall be considered in this design check.

2.5.7 Ratcheting / Cyclic Plasticity

The criteria defined in DNV-RP-F110 [1] shall be fulfilled.

This check shall be based upon the nominal stress developed at the buckle; no stress concentration factor (SCF) shall be considered in this design check.

2.5.8 Liner Wrinkling

The liner's bending strain shall be checked against the critical strain per liner wrinkling criteria as defined in Appendix C of DNV JIP Lined and Clad Pipeline Materials - Phase 4 [5].

3 DESIGN METHODOLOGY

CONTRACTOR shall adopt the design methodology outlined in DNV-RP-F110 [1] for the global buckling design.

In addition to the items presented in DNV-RP-F110 [1], CONTRACTOR shall assess load & end displacement, susceptibility to pipeline walking and route curve pullout. The following Sections present the methodology for all these items.

3.1 Load & End Displacement

The virtual anchor point shall be considered as the intersection point between the effective axial force in the pipeline for fully restrained condition and the build up in effective force due to axial friction. Thus, the virtual anchor length shall be determined using the following equation:

$$L_h = \frac{S_0 - S_{end}}{\mu_{ar}.W'} \qquad (3.1)$$

Where: S_0 is the fully restrained effective axial force as per DNV-RP-F110 [1];
S_{end} is the end reaction imposed on the pipeline;
μ_{ar} is the residual axial friction factor at the condition analyzed;
W' is the pipeline submerged weight at the condition analyzed.

It shall be noted that Equation (3.1) is not valid for a pipeline fully mobilized, i.e., where the restrained effective axial force is not reached.

Therefore, the end displacement considering flat seabed condition shall be obtained by the following equation:

$$\Delta_x = \int_0^{L_h} \frac{S_0 - S_{end}}{EA_s} dx \qquad (3.2)$$

Where: E is Young's modulus;
A_s is the cross sectional area of the pipe steel.

3.2 Route Curve Pullout

The initial assessment of curve pullout shall be undertaken using analytical models. The analytical models can be used to predict the lateral stability of the pipeline at a route-curve due to the effective axial force, lateral friction response and radius of curvature. The lateral stability of a curve can be guaranteed, at least in a preliminary approach, if the inequality below is satisfied:

$$|S| < \mu_{lb}.W'.R - \frac{EI}{R^2(1 - cos(\beta))} \qquad (3.3)$$

Where: β is the angle through curves along the pipeline route;
R is any curvature radius of pipeline route;
W' is the minimum pipe submerged weight per unit length during the condition analyzed;
μ_{lb} is the minimum breakout lateral friction factor during the condition analyzed.

The assessment of curve pullout shall be performed for the maximum tensile effective force $|S|$ during full shutdown and depressurization conditions. If susceptibility to curve pullout is indicated in any case, a detailed numerical assessment shall be performed. Curve pullout due to installation loads shall be evaluated in the appropriate design document.

Contribution of hydrodynamic forces shall be considered with similar approach which is defined for buckling susceptibility in Section 6.3.3 of DNV-RP-F110 [1], where it is relevant.

3.3 Lateral Buckling

Susceptibility to global buckling initiated by uneven seabed as well as buckling initiated by lateral imperfections (even seabed) shall be analyzed in accordance with DNV-RP-F110 [1].

The susceptibility of the pipeline to lateral buckling shall be checked by comparing the fully constrained force (incorporating end expansion effects where appropriate) against the critical buckling force. If the imposed force exceeds the critical buckling force, then the pipeline shall be designed for lateral buckling in accordance with DNV-RP-F110 [1].

The strategy to be employed for the design shall make extensive use of the VAS concept and finding robust technical solutions for on-bottom (rogue, unintended, or unplanned) and triggered (planned) buckles, in this case if buckle initiations are adopted.

The design procedure shall identify the tolerable VAS and ensure that buckles will form regularly enough to ensure this spacing limit is not violated. The design procedure shall be in accordance with Figure 3.1.

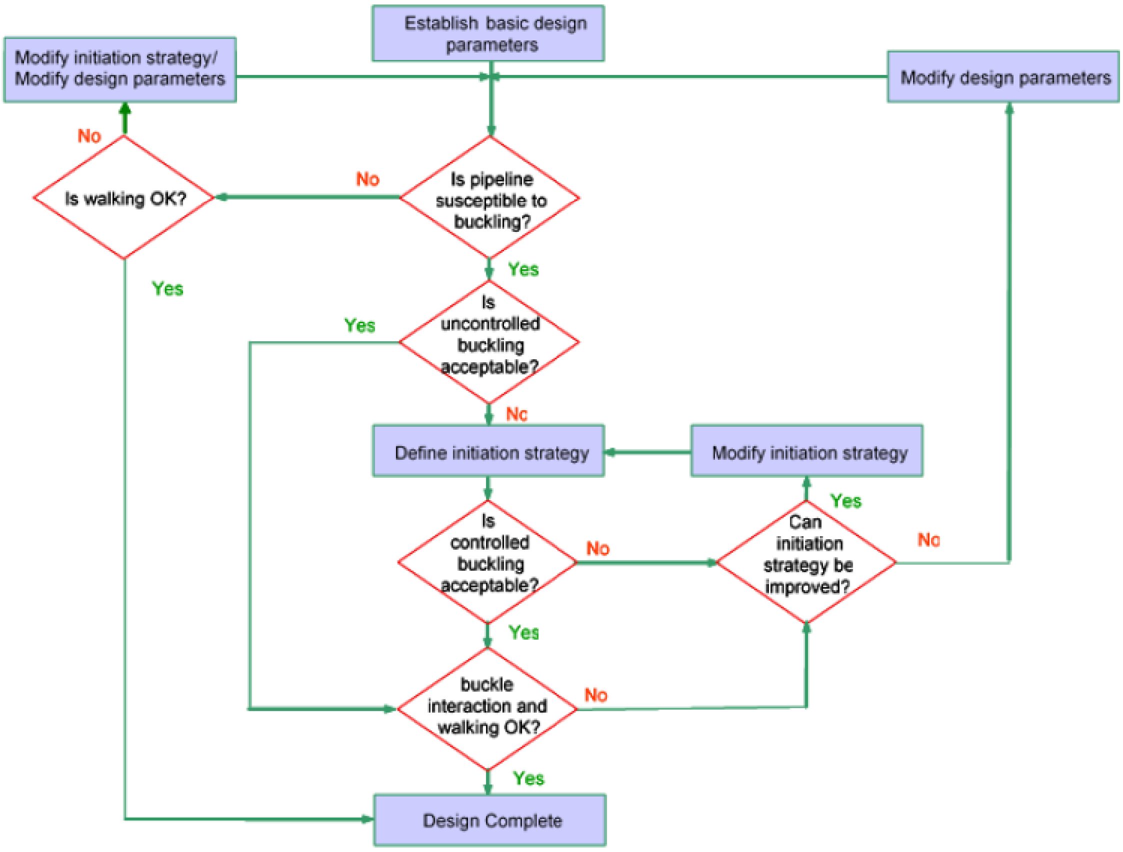

Figure 3.1 - Design Procedure for Lateral Buckling Design, as per DNV-RP-F110 [1]

3.4 Virtual Anchor Spacing (VAS) and Buckle Initiation Strategy

If the critical buckling force is exceeded, the loads in the buckle shall be calculated and checked against the relevant limit states. If the loads in the buckle are high enough to fail a limit state check, then the loads in the buckle shall be reduced by reducing the spacing between buckles. Repeating the calculation until all limit states are met leads to the Tolerable VAS.

The design procedure presented in Figure 3.2 shall be adopted to calculate Tolerable VAS as per DNV-RP-F110 [1].

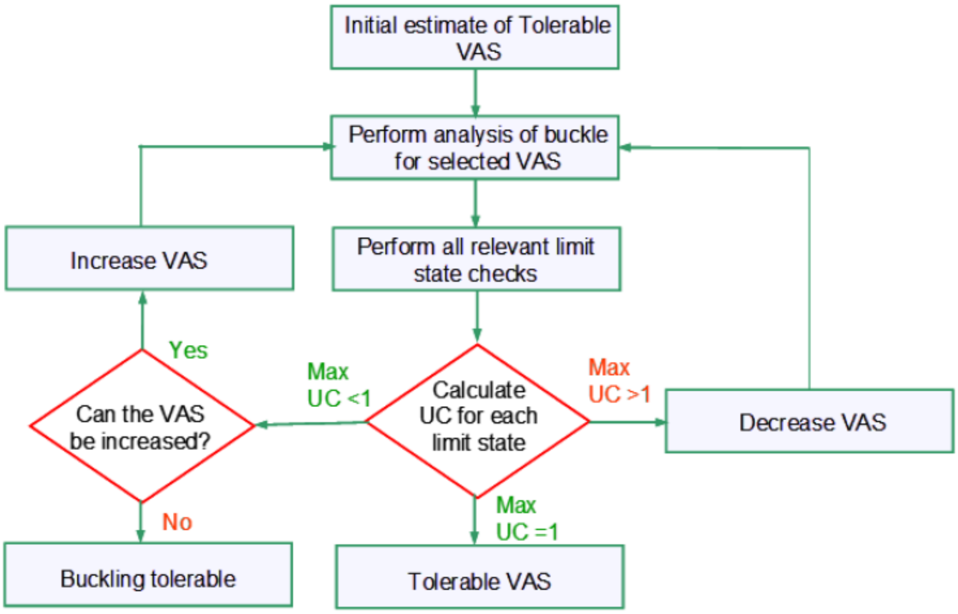

Figure 3.2 – Identification of Tolerable VAS, as per DNV-RP-F110 [1].

In addition to the definition of the Tolerable VAS, the Characteristic VAS defined in DNV-RP-F110 [1] shall also be calculated for unplanned buckles, planned buckles, and unplanned buckles which occur between planned buckles.

A robust buckle initiation strategy shall be engineered. Thus, the pipeline shall form buckles considering the Tolerable VAS and Characteristic VAS approaches. The out-of-straightness (OOS) uncertainty shall be considered and this shall be compatible to levels whereby the project can proceed with confidence.

A limit shall be defined to how closely the buckles can be guaranteed and this practical limit shall be incorporated in the overall design.

A buckle initiation strategy shall be selected. Details about these buckle initiators shall be observed and shall comply with the specific requirements described in Section 6.2.

3.5 Buckle Interaction

Once an acceptable lateral bucking strategy has been developed, then buckle interaction and pipeline walking shall be evaluated in order to ensure that undesirable cyclic behavior does not occur.

The cyclic expansion behavior shall be assessed including buckle interaction, buckle stability, route curve pullout as well as pipeline walking (see Section 3.6).

The buckle stability behavior shall also be analyzed for the entire pipeline route, including route bends, engineered buckles and rogue (unintended) buckles.

A FE model shall be employed to analyze in detail the interaction and buckle stability behaviors of the pipeline.

The behavior of the pipeline is acceptable if the displacements over the design life is within acceptable, the loads within any lateral buckle remain sustainable and route curve pullout does not occur.

3.6 Pipeline Walking

3.6.1 Susceptibility to Walking

CONTRACTOR shall assess the susceptibility to pipeline walking (axial ratcheting) due to seabed slope, riser tension and thermal transients using the methodology outlined in OTC 17945 [14]. In this assessment, minimum residual axial friction factor shall be adopted.

The pipeline walking analysis shall be also carried out for long pipelines where the lateral buckles essentially divide the pipeline into a series of short pipelines. Thus, this behavior shall be analyzed for any pipeline that adopts the buckle initiation solution [14].

3.6.2 Walking Detailed Assessment

A FE model shall be employed to analyze in detail the walking behavior of the pipeline.

The incremental displacement associated with each start-up cycle shall be evaluated. The most likely total displacement over the life of the pipeline shall be calculated based upon this incremental displacement and the design cyclic loads.

The design is acceptable if the total axial and lateral displacements over the entire life of the pipeline are below the design limits and all the limit state checks are met.

If the end connections or lateral buckles cannot tolerate the total displacement developed over the entire life of the pipeline, remedial measures to control the walking shall be required. In this case, guidance on suitable remedial measures shall be outlined (including required anchor capacity), but technical requirements for detailed designs of any remedial measures (for example anchoring) are not part of this Technical Specification.

3.7 Upheaval Buckling

A sufficient cover height shall be designed to prevent upheaval buckling and keep the pipeline in its original position in accordance with DNV-RP-F110 [1], following the design procedure presented in Figure 3.3.

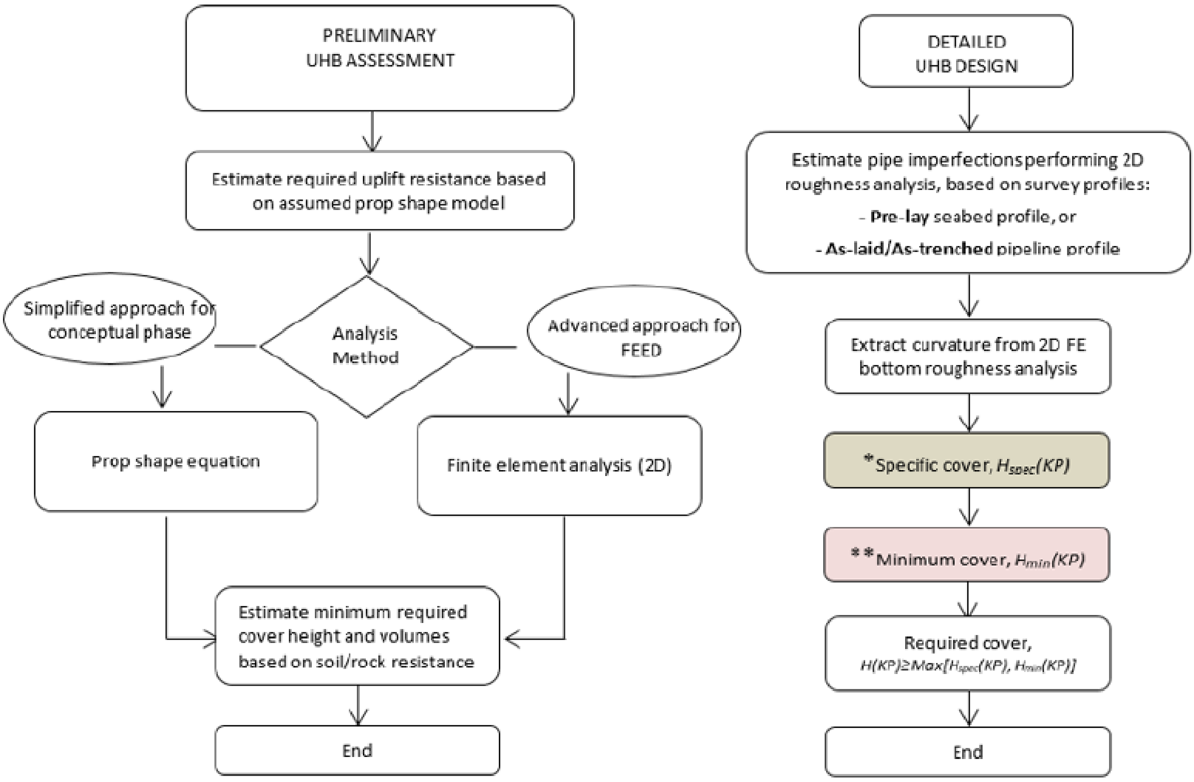

Figure 3.3 - Design Procedure for Upheaval Buckling Design, as per DNV-RP-F110 [1]

4 DESIGN ANALYSIS

4.1 Load Cases

The global buckling design shall comprise at least the analysis cases defined in DNV-RP-F110 [1].

CONTRACTOR shall consider the conditions of Hydrotest, Incidental, Design, Operational and any other relevant conditions (see Section 2.3.3) for definition of Load Cases in the analyses presented in following Sections (4.2 to 4.5).

Considering that the friction factor values are calculated from LE, BE and UE soil properties, the minimum friction factor represents the lowest nominal value obtained from LE, BE and UE soil properties. Similarly, the maximum friction factor represents the highest nominal value obtained from LE, BE and UE soil properties. The mean friction factor value shall be obtained from the BE soil property. Requirements on values and friction factor combinations are present in each specific analysis as described in following Sections.

Requirements of lateral OOS are present in each specific analysis as described in following Sections, where it is applicable.

CONTRACTOR shall estimate values of residual lay tension (RLT) based on installation analysis report and consider the BE of RLT in Base Case and the conservative extreme value (LE or UE) in Sensitivity Case in each analysis presented in following Sections.

CONTRACTOR shall estimate values of PLET reaction force based on equipment-soil interaction report and consider the BE of PLET resistance in Base Case and the conservative extreme value (LE or UE) in Sensitivity Case in each analysis presented in following Sections.

CONTRACTOR shall estimate values of riser tension at TRF based on riser interface loads report and consider the BE of riser tension in Base Case and the conservative extreme value (LE or UE) in Sensitivity Case in each analysis presented in following Sections.

CONTRACTOR shall define a conservative approach to consider the anchoring system slack, where applicable, in each analysis presented in following Sections.

CONTRACTOR shall present a Load Case matrix in table format for each analysis, including at least the relevant parameters, such as: case number (identification), analyzed condition (Incidental, Design, Operational, etc.), pipe-soil interaction resistance, lateral OOS properties, RLT, PLET resistance, riser tension at TRF and anchoring system slack.

4.2 Load & End Displacement and Walking Susceptibility Analysis

4.2.1 Load & End Displacement

CONTRACTOR shall determinate analytically the end expansion displacements using a MathCad spreadsheet adopting Equations (3.1) and (3.2) or numerically using FE model. CONTRACTOR shall consider the minimum axial resistances in order to lead to the maximum end expansion.

In addition, CONTRACTOR shall determinate the loads for both pipeline ends, in order to provide input data for other design analyses.

CONTRACTOR shall assess the load and end expansion at least for hydrotest, incidental, design and maximum allowable operating conditions. CONTRACTOR shall also assess any pipeline contraction displacement and associated load due to cooldown during full shutdown and depressurization conditions.

The pipeline submerged weight, contents pressure and residual lay tension may be considered constant along the pipeline.

Finally, CONTRACTOR shall determine and report at least the maximum predicted displacements as well as the maximum end loads in both pipeline ends for all analyzed conditions.

4.2.2 Susceptibility to Pipeline Walking

CONTRACTOR shall evaluate the susceptibility to pipeline walking in accordance with Section 3.6.1.

The susceptibility to walking shall be undertaken using analytical models or simplified FE models. The analytical models can be used to predict pipeline walking due to thermal transients, riser tensions and seabed slopes, and provide an initial indication of the severity of the walking design.

The number of operational cycles shall be considered in the walking assessment.

The pipeline walking assessment shall be based on two scenarios:

- Walking response of straight pipeline;
- Walking response between buckles.

A sensitivity analysis covering the range from the lower to higher values shall be undertaken to quantify the effect of following key parameters:

- Axial friction factors;
- Thermal gradients from transient flow assurance simulations;
- Seabed slope;
- Riser tension.

The results of the sensitivity study shall be used to quantify the severity of the pipeline walking behavior and define the cases to be analyzed using FE models.

Note: In susceptibility analysis to both route curve pullout and pipeline walking, Sections 4.3.2 and 4.2.2, respectively, CONTRACTOR shall consider the multiphase flow mechanism (effect of liquid holdup) only if is required by PETROBRAS, i. e., in cases when is representative and/or significant in terms of pipeline behavior.

4.3 Lateral Buckling and Curve Pullout Susceptibility Analysis

4.3.1 Susceptibility to Lateral Buckling

CONTRACTOR shall evaluate the susceptibility to lateral buckling in accordance with Section 3.3.

Susceptibility to global buckling initiated by uneven seabed shall be analyzed using FE models in accordance with Section 6.3.2 of DNV-RP-F110 [1] and shall be presented in on-bottom roughness report, fulfilling the requirements of PETROBRAS Technical Specification I-ET-0000.00-0000-940-P9U-002 [10].

Regarding buckling initiated by lateral imperfections (even seabed), beyond the conditions defined in Section 6.3.3 of DNV-RP-F110 [1], CONTRACTOR shall also evaluate the susceptibility to lateral buckling for hydrotest condition. Thus, CONTRACTOR shall also calculate the effective axial force based on hydrotest pressure and temperature and check against critical buckling force corresponding to the 1-year return period environmental condition, both for straight section (Equation (6.6) of DNV-RP-F110 [1]) and for route curve section (Equation (6.8) of DNV-RP-F110 [1]).

4.3.2 Susceptibility to Curve Pullout

CONTRACTOR shall evaluate the susceptibility to route curve pullout due to tensile force in accordance with Section 3.2.

Pipeline stability is not scope of this Section. However, it shall be observed that the stability of planned buckle initiation sites shall be analyzed as per Section 4.5.

4.4 VAS and Initiation Strategy Analysis

CONTRACTOR shall evaluate the Tolerable VAS, Characteristic VAS and initiation strategy of buckles in accordance with Section 3.4.

4.4.1 Tolerable VAS

CONTRACTOR shall determine the Tolerable VAS associated with rogue buckles and buckles at trigger locations using FEA considering flat seabed.

CONTRACTOR shall carry out the lateral buckling VAS analyses defined in Section 6.6 of DNV-RP-F110 [1]. CONTRACTOR shall assess the severity of any buckle that could form, evaluating the limit states stated in Section 2.5. Lateral buckling VAS analyses shall be presented indicating which limit state governs the tolerable VAS.

In all VAS analyses, CONTRACTOR shall adopt an initial geometrical imperfection (OOS) in VAS model. CONTRACTOR shall define the initial OOS considering minimum curvature radius and OOS amplitude approximately equal to 1m, ensuring buckle is formed and limit states can be checked.

The initial OOS definition shall be based on OOS data gathered for pipeline installation projects with similar characteristics of the current project (pipeline data, water depth, environmental and soil data, etc.) and shall be issued previously by TQF for evaluation Petrobras and approval. Given uncertainties in the initial OOS definition to be considered in lateral buckling VAS analysis, sensitivity analyses shall be performed to properly evaluate the criticality of this parameter.

CONTRACTOR shall present the Tolerable VAS for the on-bottom rogue buckles and also for the planned buckles.

4.4.2 Characteristic VAS

CONTRACTOR shall also determine deterministically the Characteristic VAS (Section 6.5.2 of DNV-RP-F110 [1]) adopting critical buckling forces and post-buckling effective axial forces from Tolerable VAS analyses.

CONTRACTOR shall present the deterministic Characteristic VAS for the on-bottom rogue buckles and also for the planned buckles.

If a planned buckling strategy is adopted, CONTRACTOR shall use the VAS model defining a minimum curvature radius in order to obtain the lower estimate of the critical buckling force for an unplanned buckle. This minimum curvature radius shall be based on previous projects considering only similar pipelines laid by same vessel that will lay the pipeline. Alternatively, the critical buckling force can be also calculated using analytical equation stated in DNV-ST-F110 [1].

4.4.3 Initiation Strategy

If necessary, CONTRACTOR shall develop a suitable initiation strategy, which ensures that the Characteristic VAS is smaller than or equal to Tolerable VAS.

CONTRACTOR shall carry sensitivity analyses taking into account Section 6.2 requirements in order to investigate the effect of buckle initiators characteristics. For example, when considering sleeper as initiation strategy CONTRACTOR shall evaluate at least the influence of its height and pipeline-sleeper friction. In case of adopted distributed buoyancy sections, CONTRACTOR shall evaluate at least the influence of the percentage of submerged weight reduction and their length.

CONTRACTOR shall indicate buckle initiator number and locations (KP) along the pipeline route. These locations shall be defined in order to avoid buckles at pipeline crossings, equipment and other restricted areas.

4.4.4 Initiation Strategy Robustness

CONTRACTOR shall verify the robustness of the buckle initiation strategy performing analysis using full-length 2½D numerical models and considering bathymetric profile along the pipeline route. All features along the route shall be considered in the FE models, such as free span rectifications, pipeline crossing arrangements, equipment, anchoring systems, riser tensions, etc.

Initially CONTRACTOR shall perform analyses for the pipeline with no buckle initiators considering the pipe-soil resistance combination that leads to the worst limit state check in VAS analysis. Afterwards CONTRACTOR shall carry out analyses considering the buckle initiation strategy outlined previously for the following pipe-soil resistance combinations: i) BE axial / LE lateral and ii) BE axial / UE lateral. CONTRACTOR shall assess the robustness of the buckle initiation strategy, evaluating the limit states specified in Section 2.5 and then if the Tolerable VAS is exceeded.

CONTRACTOR shall consider a lateral OOS distribution with the same characteristics (minimum curvature radius and OOS amplitude) adopted in Section 4.4.2. Lateral OOS can be represented by a sinusoidal horizontal distribution.

In order to demonstrate the robustness of the buckle initiation strategy, CONTRACTOR shall carry out two additional analyses for the most critical case identified, considering:

- An OOS distribution with minimum curvature radius of ten times previously adopted;
- An OOS distribution with minimum curvature radius shifted axially a quarter of wavelength initially adopted.

CONTRACTOR shall consider the temperature's transient profiles during heat up on the steps of the FE model in all aforementioned analyses until steady state profile is achieved.

In general, the results of the analyses shall demonstrate that the proposed initiation strategy is robust. The strategy shall ensure that the buckle spacing is below the acceptable spacing previously defined for buckles at the initiators and on-bottom.

Global buckling is not allowed in sensitive areas. Therefore, the initiation strategy shall also avoid buckles at these areas, such as crossings, free span rectifications and close to a mid-line tie-in location.

Alternatively, in order to demonstrate the robustness of the buckle initiation strategy, CONTRACTOR can propose to define the Characteristic VAS in terms of an exceedance probability in comply with Section 6.5.3 of DNV-RP-F110 [1] and to perform a reliability analysis in accordance with Appendix B of DNV-RP-F110 [1] for assessing the buckle formation.

In this last case, CONTRACTOR shall issue the reliability analysis scope and reliability model by TQF for evaluation and PETROBRAS approval.

4.5 Buckle Interaction & Walking Analysis

CONTRACTOR shall verify the global expansion, buckle interaction and stability, route curve pullout and pipeline walking behaviors performing full-length finite element analyses using 2½D numerical models and considering bathymetric profile. All features along the route shall be considered in the FE models, such as free span rectifications, pipeline crossing arrangements, equipment, anchoring systems, riser tensions, etc.

Since the bathymetric profile shall be incorporated in the analysis, CONTRACTOR shall provide a prediction of the pipeline spanning response. CONTRACTOR shall address the integrity assessment of the predicted spans in the specific span report, such as on-bottom roughness and fatigue analysis. This report shall be developed according to PETROBRAS Technical Specification [10].

CONTRACTOR shall perform an analysis for the entire pipeline considering the pipe-soil resistance combinations defined in Table 4-3 of DNV-RP-F110 [1], in order to evaluate pipeline walking. CONTRACTOR shall analyze an additional case considering the pipe-soil resistance combination BE axial / LE lateral, in order to evaluate buckle stability.

The influence of seabed bathymetry on buckle interaction, buckle stability and pipeline walking shall be evaluated, adopting for example a shifted pipeline route at the laying corridor. CONTRACTOR shall identify any severe bathymetric feature, which should be incorporated into the FE models, including, for example, relevant transversal seabed slopes.

For all these cases defined above, CONTRACTOR shall adopt lateral OOS only at buckle initiator locations, fulfilling the requirements defined in Section 6.2 for each initiator type.

The axial and lateral displacement response of the pipeline during cyclic loading shall be simulated until its behavior could be considered stable or the total number of cycles specified is reached. Additionally, independent of displacement stabilization CONTRACTOR shall consider at least ten complete operational cycles (full shutdown and restart) in all analyses performed.

CONTRACTOR shall assess the pipeline displacements related to aforementioned behaviors (global expansion, buckle interaction, buckle stability and walking), confirming that they are acceptable, as well as shall evaluate the limit states specified in Section 2.5 of the lateral buckles.

4.6 Upheaval Buckling Preliminary Analysis

CONTRACTOR shall determine the susceptibility to upheaval buckling for buried pipelines by calculating the maximum force profile in the pipeline and the uplift resistance. A pipeline shall be considered susceptible to upheaval buckling when the force exerted by it on the soil cover exceeds the vertical restraint against uplift movement.

CONTRACTOR shall obtain the effective axial force and the uplift resistance based on Palmer et al. [15] approach and shall follow DNV-RP-F110 [1] formulations and requirements, considering pre-installed design phase for buried pipelines.

4.7 Upheaval Buckling Detailed Analysis

CONTRACTOR shall carry out the upheaval buckling detailed analysis of buried pipelines in accordance with DNV-RP-F110 [1], considering the methodology, conditions, design process criteria and all requirements of this DNV recommended practice.

4.8 As-Built Global Buckling Design Analysis

4.8.1 Exposed Pipeline

After pipeline installation, CONTRACTOR shall perform full-length finite element analyses using 2½D numerical models (based on Section 4.5) and considering the following information, obtained both from as-laid and as-built surveys:

- Bathymetric profile;
- Pipe-soil penetration;
- Lateral OOS;
- Span rectifications;
- Crossing arrangements;
- Buckle initiators;
- Equipment locations;
- Any other feature that may influence pipeline behavior.

CONTRACTOR shall consider the requirements of Section 10.2 of DNV-RP-F110 [1] concerning the as-laid and as-built surveys.

CONTRACTOR shall consider in FE models a better estimative of RLT based on pipeline installation records.

Pipe-soil resistances as well as the interaction between the structures and the soil shall be reassessed based on the as-laid and as-built survey data.

This as-built global buckling design analyses shall be performed considering the reassessed pipe-soil resistance combination that led to the most critical results, in terms of limit state check, obtained from the previous analyses. CONTRACTOR shall demonstrate that the Tolerable VAS is fulfilled at buckle initiators and on-bottom buckles and global buckling is not predicted at sensitive areas, such as, crossings, free span rectifications and close to a mid-line tie-in location. CONTRACTOR shall also demonstrate that the response regarding buckle stability and pipeline walking fulfills the design criteria.

4.8.2 Buried Pipeline

After pipeline installation, CONTRACTOR shall perform an assessment in order to evaluate the pipeline behavior considering measured vertical imperfections and cover heights obtained during pipeline construction phase.

CONTRACTOR shall perform full-length finite element analyses considering the following information, obtained both from as-laid and as-built surveys:

- As-laid/as-trenched pipeline configuration;
- Actual cover height;
- Equipment locations;
- Any other feature that may influence pipeline behavior.

For the as-installed phase, CONTRACTOR shall demonstrate that the limit states presented in DNV-RP-F110 [1] are fulfilled.

5 MODELING REQUIREMENTS FOR FEA

5.1 Finite Element Model

Part of the global buckling design (Sections 4.4 to 4.8) shall be carried out by application of finite element methods. The finite element analysis shall be performed using the Abaqus software.

The FE models shall be able to represent the appropriate non-linearities including:

- Non-linear geometry response (large displacements and large rotations);
- Material non-linearity (plasticity);
- Non-linear pipe-soil interaction with uncoupled friction factors (anisotropic) in axial, lateral and vertical directions.

The pipeline shall be modeled using pipe elements able to represent the coupling of the internal pressure and the thermal expansion with the bending moment.

The element length in the buckle shall be small enough to identify the curvatures developed within the buckle. The maximum element length at the expected buckle location and in its vicinity shall be limited to one pipe diameter and the elements shall employ at least 8 integration points around the circumference.

It is not acceptable to apply equivalent loads in order to represent temperature and/or pressure loadings.

At least the following load steps shall be considered:

- Apply pipeline submerged weight and external hydrostatic pressure;
- Lay the pipeline on seabed;
- Include initial lateral OOS;
- Incorporate the stresses associated with the as-laid condition, such as: static residual lay tension, route bends and seabed bathymetry, where applicable;
- Set the as-laid conditions, e.g. equipment, anchoring, etc.;
- Flood the pipeline;
- Apply the hydrotest pressure;
- Remove the hydrotest pressure;
- Dewater the pipeline;
- Include pipeline internal content of analyzed condition (Incidental, Design, Operational, etc.);
- Apply the pressure profile of analyzed condition;
- Apply the temperature profile of analyzed condition;
- Remove the pressure profile;
- Apply the ambient temperature;
- Apply the operational cycles of restart and shutdown.

The minimum seawater temperature shall be obtained from Meteocean Data. CONTRACTOR shall consider this data in order to evaluate the difference in temperature relative to the as-laid ambient temperature (ΔT).

CONTRACTOR shall calculate pressure magnification factors based on Lamé's theory and apply these factors in FE models, in order to consider that the environmental pressure applied to the pipeline outside surface is increased due to the external coating.

The analysis shall take into account all relevant boundary conditions, such as:

- Bathymetric profile;

- Pipeline crossings and free-spans corrections;
- Spools pieces, connections, PLEMs, PLETs, ILTs, anchoring systems, etc.;
- Riser tensions;
- Lateral OOS due to laying process;
- Pipeline embedment.

These boundary conditions shall be considered in the appropriate load steps listed above.

In order to assess the fatigue and fracture limit states, a minimum of three full heat-up and shutdown cycles shall be modeled. If the soil modeling does not take into account the berm effects, the stress range to be considered in fatigue and fracture analysis shall be obtained from the first cycle.

The global buckling design shall employ two distinct types of FE model:
- VAS models;
- Full-length models.

The areas of application of each of these models are described in Sections 4.4 to 4.8 of this Technical Specification.

5.1.1 VAS Models

The VAS models shall represent a short length of pipe, where the ends of the models shall be fully restrained to represent the virtual anchor points.

The models shall be set up to assess on-bottom buckling such as that provided by lateral out-of-straightness (OOS) or initiation techniques like buoyancy modules and sleepers.

5.1.2 Full-Length Models

Full-length 2½D models shall be used to assess initiation strategy robustness, walking and buckle interaction in order to confirm the acceptability of the design, as defined in Sections 4.4.4 and 4.5.

These models shall represent the entire pipeline length including subsea equipment, bathymetric profile, pipeline crossings, anchoring systems, riser tensions, etc. The soil-equipment interaction shall be adequately modeled considering the equipment weight and soil resistance. If the length of the models is too large, the element discretization in regions where no buckles are observed may be coarser.

The numerical models shall incorporate at least the following features:
- The startup transient temperature profiles;
- A sufficient number of time steps to represent the restart/shutdown process and to capture the walking response.

5.2 Material Modeling

5.2.1 Stress-Strain Behavior

For welded pipes, the stress-strain curve to be adopted in analyses shall consider the hardening behavior based on material tests.

For seamless pipe, a perfectly plastic stress-strain curve using SMYS shall be adopted in analyses.

The cyclic plasticity is not acceptable in any case.

5.2.2 Temperature Dependence

The following material properties shall incorporate the detrimental effect of temperature:

- Yield stress;
- Young's modulus;
- Coefficient of thermal expansion.

5.3 Seabed Response

A three-dimensional surface shall be employed to model the seabed. The soil resistance shall be modeled using decoupled axial and lateral equivalent friction factors along with vertical stiffness.

5.3.1 Axial and Lateral Resistance

The axial and lateral pipe-soil interaction shall be modeled in FE model considering the non-linear axial and lateral force resistance curve.

For basic designs, the analysis can be based upon residual axial and lateral resistance, i.e., appropriate traditional bi-linear Coulomb friction models. For detailed design, the analysis shall employ the non-linear lateral resistance curve (breakout and residual).

The effect of soil berm resistance shall be incorporated where relevant.

5.3.2 Vertical Stiffness and Resistance

FE model shall employ the BE vertical force displacement response.

The vertical uplift resistance for upheaval buckling analyses of buried pipelines shall be considered in accordance with DNV-RP-F110 [1] recommendations.

5.3.3 Influence of Enhanced Embedment

A specific soil lateral resistance at regions of enhanced embedment such as span shoulders, close to sleeper and crossing locations shall be considered where relevant.

5.4 Stress and Strain Concentration Factors

Stress concentration factors (SCF) and strain concentration factors (SNCF), local and global, shall be considered on the limit states (local buckling, fatigue and fracture) in accordance with the requirements of DNV-ST-F101 [2].

Field joints, buckle arrestors, welding mismatches or any intermediate structure in the pipeline can introduce significant stiffness discontinuity and this shall be considered using SCF/SNCF in the evaluation of relevant limit states (Section 2.5). Moreover, local models shall be used in order to evaluate SCF/SNCF.

The effect of these discontinuities shall be incorporated into the design process.

5.4.1 Field Joints

The SCF/SNCF shall be calculated using FEA considering:

- Stress-strain properties of coatings (elastic modulus, Poisson's ratio and yield strength) considering design load and temperature effects;
- The length of the model shall be sufficient to avoid undesirable boundary effects due to application of design loads;
- Design loads shall be applied to the model boundaries faraway of the region of interest;
- Stress-strain concentration factor shall be evaluated by the ratio of peak to nominal strain in the region of interest.

A conservative approach shall be adopted in order to assess SCF/SNCF at field joint location. For example, the analyses shall consider the lowest stiffness of a field joint coating predicted for the project including the repair material.

5.4.2 Strength Mismatch at Welds

The following cases shall be analyzed in order to obtain the SCF/SNCF:

i. Base case with nominal pipe dimensions and specified minimum strengths, considering temperature de-rated;
ii. As (i) but incorporating strong-weak section due to pipe material/thickness variations.

The weak section incorporated in the model shall represent the most severe discontinuity which can be reasonably expected to occur at the crown of a buckle. An assessment shall be performed to identify the suitable level of strength mismatch.

The mismatch shall be achieved by modeling the adjacent pipeline as over matched; for example the yield stress of the main section of pipeline can be increased to give the required mismatch.

The location of the weak section relative to the buckle crown shall be carefully considered to identify the most onerous situation. For example, the girth weld between the weak section and nominal section can be at the crown, or the center of the weak section can be at the crown; the worst case shall be identified and assessed.

5.4.3 Buckle Arrestors

The loads developed in the vicinity of a buckle arrestor located at the crown of a buckle shall be identified and assessed. The assessment shall involve the following steps:

- Develop a FE model of the buckle arrestor;
- Calculate the bending response of the buckle arrestor and adjacent pipe under the maximum loads (pressure and axial force) developed at the crown of a lateral buckle;
- Identify the stress/strain capacity of the buckle arrestor;
- Identify suitable SCF/SNCF as a function of imposed nominal stress/strain.

The SCF/SNCF calculated in the analysis shall be applied to the stresses/strains calculated in the global buckling analysis and compared with the stress/strain capacity to confirm the integrity of the buckle arrestor. Where possible, buckle arrestor shall not be installed at buckle initiator's locations.

5.5 Installation Residual Strains (If applicable)

This Section is applicable only for the pipelines that will be installed by the reel lay and S-lay methods.

The effect of installation residual strains on operational behavior shall be evaluated and the results used in the global buckling models. The analysis shall involve relatively short pipe models. A full installation process (full reeling cycle for example) shall be imposed on the models, which shall then be subjected to operational loads. The results of this analysis shall be compared to the results from the same model without considered the installation process.

All installation process steps shall be considered in FE model and shall be employed to develop an estimate of the strain history induced in the pipeline. After this, the pipeline shall be laid on seabed and the following effects shall be considered in analysis:

- Effect on stress-strain response;
- Effect on expansion behavior;
- Effect on post-buckling configuration.

If the assessment of installation process shows that the operational response is significantly affected by installation process, then analyses shall be performed in the post installation condition. The initial conditions shall define the residual stress and strain developed at each location in the pipe due to the installation process.

6 MITIGATION MEASURES FOR EXPOSED PIPELINES

Mitigation measures shall be developed if end displacement, lateral buckling, pipeline walking and/or buckle stability are not acceptable, i.e. the design limit states (Section 2.5) and/or the design requirements in terms of maximum and accumulated displacements are not fulfilled.

The following issues may require restriction or control of pipeline expansion:

- Excessive end expansions;
- Pipeline walking;
- Route curve pullout;
- Instability of buckle due to load cycles;
- Global buckling.

6.1 Restrain Pipeline Expansion

If the option of restricting expansion is adopted, at least the following strategies should be evaluated:

- Trenching and backfilling;
- Rock dumping;
- Additional weight over pipeline (e.g. concrete mattresses stacks);
- Anchoring system;
- Stopper structures.

CONTRACTOR shall adopt the better strategy(ies) taking into account the project scenario.

Finite elements analyses defined in Sections 4.4 and 4.5 shall be performed for the adopted strategy and the key parameters of expansion restriction strategy shall be evaluated by sensitivity analyses.

6.2 Control Pipeline Expansion

In order to control pipeline expansion or buckle formation, only the following strategies can be assessed:

- Expansion spools;
- Intermittent rock dumping;
- Local weight reduction, such as distributed buoyancy sections;
- Vertical upset (e.g. single or dual sleepers);
- Zero-radius bends;
- Pre-bent or residual curvature sections.

Finite elements analyses defined in Sections 4.4 and 4.5 shall be performed for the adopted strategy and the key parameters of expansion control strategy shall be evaluated by sensitivity analyses.

CONTRACTOR should consider distributed buoyancy sections and sleepers as preferential control strategies based on PETROBRAS background in previous pipeline projects, taking into account PETROBRAS specification requirements [8] and [9], respectively.

When selecting one of the control strategy previously listed, except for distributed buoyancy sections and sleepers, CONTRACTOR shall present at bid stage a verification report issued by a third part company (CERTIFY AUTHORITY). This verification report shall confirm the track record and the chosen control strategy is field proven.

If selected control strategy had not been implemented successfully by CONTRACTOR in any previous project (either for PETROBRAS or any other operator) with similar characteristics of the current project (pipeline data, water depth, environmental and soil data, etc.), CONTRACTOR shall perform a technology qualification in accordance with DNV-RP-A203 [6]. Evidence documentation for proving that the selected control strategy had been properly implemented in previous project(s) shall be previously issued at bid stage for evaluation and Petrobras approval. Otherwise, a technology qualification shall be performed at the beginning of detailed design.

6.2.1 Distributed buoyancy sections

FE models at buoyancy sections shall adopt the same lateral offset (lateral OOS) which has been considered for on-bottom OOS in VAS analysis, Section 4.4.

A target submerged weight of the buoyancy sections shall be approximately 15-20% of the nominal submerged weight at operational condition. Moreover, the maximum spacing between two adjacent buoyancy modules shall be limited to one buoyancy module length.

The specification of the buoyancy sections strategy shall be presented comprising at least the following parameters in accordance with I-ET-0000.00-0000-250-P9U-002 [8]:

- Operational submerged weight at the buoyant sections;
- Length of individual buoys and length of buoyancy sections;
- Outside diameter of the buoyancy modules;
- Buoyancy modules geometry;
- All pertinent details, such as spacing between modules, number of distributed buoyancy modules in each buckle, etc.

The minimum requirements for buoyancy modules shall be in accordance with I-ET-0000.00-0000-250-P9U-002 [8].

In addition, CONTRACTOR shall address the stability assessment of the pipeline at buckle initiation locations in a specific stability report. This report shall be developed according to DNV-RP-F109 [4].

6.2.2 Sleepers

FE models at sleeper locations shall adopt a very small lateral offset (OOS with curvature radius greater than 10 times the value adopted for on-bottom OOS in VAS analysis, Section 4.4).

The lay corridor at sleeper location shall be defined considering the maximum lateral offset defined above and the accumulated pipe lateral displacements during overall operational life, in order to guarantee that the pipe stays over the sleeper. The lay corridor at sleeper location shall be longitudinally extended in order to ensure curvature radius greater than 10 times the value adopted for on-bottom OOS.

The numerical models shall consider pipe-sleeper friction factor obtained from experimental tests considering coatings and operational pipe-sleeper contact loads.

The specification of the sleeper strategy shall be presented comprising at least the following parameters in accordance with I-ET-0000.00-0000-250-P9U-001 [9]:

- Predicted effective sleeper height at operational condition, i. e., vertical upset provided by sleeper;
- Sleeper coating and friction factor between pipeline and sleeper;
- Total length of sleeper;
- Distance between sleepers in case double sleepers are selected.

In addition, CONTRACTOR shall address the free span assessment of the pipeline at sleeper locations in a specific free span report. This report shall be developed according to PETROBRAS Technical Speciation I-ET-0000.00-0000-940-P9U-002 [10].

Sleeper structure shall be designed in accordance PETROBRAS Technical Specification I-ET-0000.00-0000-250-P9U-001 [9], considering lay process, cathodic protection, foundation bearing capacity, structural analysis of components and lateral/longitudinal sliding stability.

6.2.3 Residual Curvature Sections

VAS FE models at locations of residual curvature (RC) sections shall adopt only the lateral offset of the sections themselves of RC, i.e., lateral out-of-straightness from pipe laying shall be not included in VAS FE models.

The spacing between two adjacent RC sections shall fulfill the DNV-RP-F110 [1] inequality of Xtrigger (buckle spacing) in order to prevent unplanned buckling between RC sections.

In addition to the documents of the global buckling design which are specified in Appendix A, CONTRACTOR shall issue for verification and Petrobras approval at least the following documents:

- Technical specification on “Initiation Strategy Using RCM”;
- Report on “RC Assessment at Tensioner Exit”, in order to evaluate the top tension and the risk of RC re-straightening at tensioner exit, defining the allowable sea state for installation of the RC sections;
- Report on “RCM Catenary Roll-Over Assessment”, in order to evaluate the RC roll-over in the sag bend, mainly the risk of excessive rotation in the sag bend;
- Technical specification on “RCM Acceptance Criteria”;
- Report on “Contingency Measure Analysis”;
- Procedure on “Contingency Measure Installation”.

The technical specification on the “Initiation Strategy Using RCM” shall be issued for verification and Petrobras approval, comprising at least the following parameters:

- Shape of the RC sections;
- Nominal residual strain of the RC sections;
- Residual strain tolerance of RC sections, defining minimum and maximum residual strains;
- As-landed orientation (ALO) angle of the RC sections;
- Length of the RC sections;
- Static and dynamic top tension as well as static and dynamic bottom tension during installation;
- Details of marking with a continuous line on the pipe to be done after tensioners in order to monitor the beginning and the end of RC sections and mainly the rotation of the pipeline once laid on seabed;
- Nominal as-laid lateral offset of the RC sections and minimum acceptable as-laid lateral offset;
- Maximum acceptable pipe embedment of the RC sections;
- Contingency (mitigation) measures for subsea correction of RCM.

A nominal residual strain of the RC sections shall be defined between 0.12 and 0.25% and the nominal ALO angle shall be equal to 90° for all RC sections.

The maximum acceptable ALO angle shall be demonstrated through FE analyses in “VAS and Initiation Strategy Analysis” (Section 4.4) report and shall not exceed 135°. This maximum acceptable ALO angle shall be adopted for defining the minimum acceptable as-laid lateral offset of the RC sections. Moreover, sensitivity analyses shall be performed with ALO angles of 0°. Thus, at least the following cases shall be analyzed in “VAS and Initiation Strategy Analysis” (Section 4.4) report: 0°, 90° (Base Case) and 135° (or the maximum acceptable ALO angle demonstrated as acceptable).

The maximum acceptable pipe embedment at RC sections shall be considered as the UE pipe embedment which has been predicted in pipe-soil interaction analyses, even if the minimum as-laid lateral offset is acceptable.

Moreover, an additional technical specification on the “RCM Acceptance Criteria” shall be issued for verification and Petrobras approval, comprising at least: methodology, RC acceptance flowchart, as-laid minimum lateral offset and as-laid maximum pipe embedment at RC sections.

If the as-laid RC configuration is not acceptable, based on the minimum acceptable as-laid lateral offset and/or on the maximum acceptable pipe embedment, CONTRACTOR shall have at least a contingency measure (e.g. subsea winch pull or sleeper installation) for mitigation of RC section configuration. The contingency measure shall be applied before pre-commissioning. This contingency measure shall be previously issued by an analysis report and an installation procedure for verification and Petrobras approval.

7 GLOBAL BUCKLING DESIGN DOCUMENTATION

7.1 Reports

CONTRACTOR shall issue for review and PETROBRAS approval at least the following reports presented in Table 7-1:

Table 7-1 - Global Buckling Design Reports

No.	Report Title
1	Load & End Displacement and Walking Susceptibility Analysis
2	Lateral Buckling and Curve Pullout Susceptibility Analysis
3	VAS and Initiation Strategy Analysis
4	Buckle Interaction & Walking Analysis
5	Upheaval Buckling Preliminary Analysis
6	Upheaval Buckling Detailed Analysis
7	As-built Global Buckling Design Analysis

Concerning the reports of Table 7-1, CONTRACTOR shall issue each report observing the details and the sequence describe in Appendix A, i.e., title, predecessor, minimum scope, methodology, specific requirements and calculation tools.

CONTRACTOR shall keep the consistence among all design documents and issue revisions whenever necessary.

CONTRACTOR shall issue all reports in accordance with the last revision of PETROBRAS standards [11], [12] and [13].

The review and approval by PETROBRAS of any document shall only indicate a general requirement and shall not relieve CONTRACTOR of his obligations to comply with the requirements of the Contract. Any errors or omissions noted by CONTRACTOR shall be immediately brought to the attention of PETROBRAS.

7.2 Result Presentation Requirements

All calculation and analysis results shall be supplied in metric units.

All notation, abbreviations and definitions employed shall be clearly defined.

Regarding the analytical calculations, CONTRACTOR shall present PTC Mathcad (version 15.0 preferentially) spreadsheets at least for the base and critical cases. The native editable Mathcad files used for the calculations shall be attached to the pdf report file. No hidden areas are allowed on the Mathcad files.

Regarding the FEA, CONTRACTOR shall furnish the input (.inp) and output (.odb) Abaqus native digital files at least of the base and critical cases.

CONTRACTOR shall present in the "VAS and Initiation Strategy Analysis", in the "Buckle Interaction and Walking Analysis" as well as in the "As-built Global Buckling Design Analysis", reports from Table 7-1, at least, the following graphic results:

- Effective axial force along pipeline model;
- Lateral displacement and effective force at the center of the buckle during first load as the pressure and temperature is increased;
- Axial and lateral displacements along pipeline model for the heat-up and shutdown cycles;
- Total bending moment at the buckle crown for the first heat-up and shutdown cycle;
- Total axial strain at the buckle crown for the first heat-up and shutdown cycle.

The limit state results (stresses, strains, and bending moments) of the analyses shall be presented in nominal values and also as a unity check defined as the ratio of the load to the resistance.

Concerning the "Buckle Interaction and Walking Analysis" and the "As-built Global Buckling Design Analysis" (Table 7-1), CONTRACTOR shall also report the displacements of each equipment along the pipeline route for all cases analyzed.

CONTRACTOR shall provide the database used to generate all graphics and limit state results in native MS Excel files attached to the pdf report file.

7.3 Recommendations for Pipeline Operation

CONTRACTOR shall fulfill at least all requirements stated in Section 11 (Documentation for Operation) of DNV-RP-F110 [1].

At the end of Report "As-built Global Buckling Design Analysis" (Table 7-1), CONTRACTOR shall present an as-built summary table informing at least the locations (KP), displacements and unity checks of all planned buckles, on-bottom rogue buckles, crossings, equipment, etc. along the pipeline route.

In addition, CONTRACTOR shall describe minimum recommendations for pipeline operation at the end of Report "As-built Global Buckling Design Analysis" (Table 7-1).

Regarding the pipeline start-up operation, CONTRACTOR shall describe recommendations for survey that shall be undertaken to confirm the design assumptions and outline the requirements for future integrity operational surveys.

APPENDIX A SUMMARY OF DOCUMENTATION REQUIREMENTS

No.	Report Title	Predecessor	Objectives	Methodology Section	Specific Requirement Section	Calculation Tools
1	Load & End displacement and Walking Susceptibility Analysis	N/A	To calculate load & displacement of pipeline ends; To assess the susceptibility to pipeline walking.	3.1 - Load & End Displacement 3.6.1 - Susceptibility to Walking	4.2.1 - Load & End Displacement 4.2.2 - Susceptibility to Pipeline Walking	Mathcad spreadsheets.
2	Lateral Buckling and Curve Pullout Susceptibility Analysis	N/A	To assess the susceptibility to lateral buckling; To assess lateral stability of pipeline route curves.	3.3 - Lateral Buckling 3.2 - Route Curve Pullout	4.3.1 - Susceptibility to Lateral Buckling 4.3.2 - Susceptibility to Curve Pullout	Mathcad spreadsheets.
3	VAS and Initiation Strategy Analysis	No. 2	To determine the Tolerable VAS; To determine the Characteristic VAS; To define the initiation strategy; To estimate the number of buckle initiators.	3.3 - Lateral Buckling 3.4 - VAS and Buckle Initiation Strategy	4.4 - VAS and Initiation Strategy Analysis	FE models to determine the Tolerable VAS, post-buckling effective axial force in the buckle and initiation strategy robustness analysis, and Mathcad spreadsheet to calculate the deterministic Characteristic VAS.
4	Buckle Interaction and Walking Analysis	No. 1 to 3	To evaluate buckle interaction and stability, route curve pullout and pipeline walking. To define the number of buckle initiators and its locations along the pipeline route.	3.5 - Buckle Interaction 3.6.2 - Walking Detailed Assessment	4.5 - Buckle Interaction and Walking Analysis	FE models in all analyses.
5	Upheaval Buckling Preliminary Analysis	N/A	To assess the susceptibility to upheaval buckling; To estimate minimum required cover.	3.7 - Upheaval Buckling	4.6 - Upheaval Buckling Preliminary Analysis	Mathcad spreadsheet to assess susceptibility to upheaval buckling and prop shape equation and FE models to assess upheaval buckling.
6	Upheaval Buckling Detailed Analysis	No. 5	To determine the required cover.	3.7 - Upheaval Buckling	4.7 - Upheaval Buckling Detailed Analysis	FE models in all analyses.
7	As-built Global Buckling Design Analysis	No. 4 or 6	To analyze the as-built pipeline profile; To confirm the results of the previous analyses; To describe recommendations for pipeline operation.	No specific methodology is prescribed. The suitable methodologies of the previous items shall be considered.	4.8 - As-built Global Buckling Design Analysis	FE models in all analyses.

Note: All limit states verification shall be performed using Mathcad spreadsheets.