Probabilistic approach for lateral buckling analysis in Virtual Anchor Spacing (VAS) models of rigid flowlines subjected to High Pressures and High Temperatures (HP/HT)

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Abstract. This study deals with the main topics related to the phenomenon of thermomechanical buckling of rigid flowlines laid on the seabed. It focuses on the latest versions of DNV-ST-F101 [1] and DNV-RP-F110 [2]. Additionally, the study presents a probabilistic approach for lateral buckling analyses in Virtual Anchor Spacing (VAS) of rigid flowlines exposed on the seabed, subjected to High Pressures and High Temperatures (HP/HT) in deep-water environments. The methodology includes determining the probability curves of the parameters with the greatest influence on the analysis: Pipe-Soil Interaction (PSI), friction between the pipe and sleeper (buckling mitigator), and geometric imperfections (lateral out-of-straightness). This is followed by a Design of Experiment (DoE) analysis to create a matrix composed of a representative set of load cases to be simulated using the Finite Element Method (FEM). These simulations are performed using Abaqus to obtain the probability distributions of the effective Critical Buckling Force (CBF) and Post-Buckling Force (PBF). The tolerable VAS is determined through FEM analyses applied to a dedicated load case matrix to identify the most critical failure criteria. The results are post-processed to generate response surfaces and failure probabilities for each of these criteria using the Monte Carlo Method. Finally, a case study is performed to illustrate the probabilistic approach, which requires more simulation time than a deterministic method but offers more detailed probability ranges for lateral buckling responses, potentially reducing a project's overall cost. It can be used to assess the reliability of lateral buckling responses during the detailed design phase of subsea pipelines susceptible to lateral buckling.

Keywords: offshore rigid flowlines, HP/HT, lateral buckling, VAS, probabilistic approach.

1 Introduction

Lateral buckling analysis of rigid flowlines assesses the stability of subsea pipelines under compressive stresses from thermal expansion and operational pressures. This analysis ensures the integrity and reliability of flowlines, considering factors like thermal expansion, mechanical loads, pipe-soil interaction (PSI), and buckling mode shapes.

PSI significantly influences buckling behavior and amplitude by affecting axial displacement (feed-in) and lateral movement. Global buckling can induce local buckling, representing an Ultimate Limit State (ULS) per DNV-ST-F101 [1]. Finite Element Analysis (FEA) is used to model flowlines to predict lateral buckling under various conditions.

According to DNV-RP-F110 [2], the main goal of Virtual Anchor Spacing (VAS) analysis is to ensure the characteristic VAS is lower than the tolerable VAS, maintaining structural integrity by distributing the feed-in in a safe manner allowing the design criteria to be fulfilled, preventing catastrophic failure due to uncontrolled buckling. The characteristic VAS is the distance between virtual anchor points, determined through reliability assessment or a simplified deterministic approach. The tolerable VAS matches the design criterion, defined prostprocessing FEA results.

Bai et al [3] suggest using lateral buckling mitigation devices for High Pressures and High Temperatures (HP/HT) flowlines to ensure reliability and reduce stress, strain, and fatigue. Due to design uncertainties, a probabilistic approach can provide a cost-effective solution by reducing unnecessary conservatism.

This paper presents a probabilistic approach for lateral buckling VAS analysis of HP/HT rigid flowlines in deep-water using sleepers as mitigation devices. It models flowline horizontal OOS, non-linear axial and lateral PSI, and pipe-sleeper friction factor as stochastic variables. The approach aims to calculate the probability of failure due to lateral buckling, and optimize HP/HT flowline design, achieving less conservative results and potential cost savings through detailed FEA. This is confirmed though a study case at the end of the paper.

2 Probabilistic methodology for VAS analysis

According to DNV-RP-F110 [2], uncertainty must be quantified and either reduced to an acceptable level or addressed with a more robust design solution. The VAS lateral buckling probabilistic approach assesses flowline buckle formation using FEA models. As per Bai et al [3], it involves: Determining probability density functions of the stochastic input data (PSI friction curves, pipe/sleeper friction factor, horizontal OOS). Using a Design of Experiment (DoE) to create a Load Case Matrix (LCM). Running the LCM by FEA to obtain the CBF matrix responses. Conducting FEA to determine the tolerable VAS length. Using Monte-Carlo simulations to obtain the CBF probability density function from the CBF matrix responses.

2.1 Design of Experiment

According to Montgomery [4], Design of Experiment (DoE) is a systematic and statistical method used to plan, conduct, analyze, and interpret controlled experiments. It is used in various fields to understand the effects of multiple factors on a response variable. In this paper, factors like horizontal OOS, axial and lateral PSI friction factors, pipe-sleeper friction factor, and residual lay-tension are set in three levels: Lower Estimate (LE), Best Estimate (BE), and Upper Estimate (UE). The response variables are the CBF and fracture probability density function distributions for each load case that is run in an Abaqus FEA.

Resource availability is a concern when planning a DoE. A full factorial design with 5 variables at 3 levels each results in 243 LCs, which is resource-intensive. Therefore, a randomized design is used to minimize bias and ensure that results are not influenced by external variables. This data is then analyzed to identify significant factors, interactions, and build an equation model describing the system behavior.

2.2 Characteristic VAS

The deterministic characteristic VAS is given by analytical expressions defined in DNV-RP-F110 [2]. On the other hand, still according to DNV-RP-F110 [2], the probabilistic characteristic VAS is the one whose probability of exceedance is as defined in Tab. 1.

Table 1. Allowable exceedance probabilities for characteristic VAS.

	Unplanned buckles		Planned buckles
	Full pipeline length	Per km of pipeline	
Uncontrolled buckling strategy	10%	1%	n/a
Controlled buckling strategy	10%	1%	10%

DNV-RP-F110 [2] does not specify reliability requirements for planned buckling at engineered initiators, but high reliability of buckle initiation is generally needed to meet design method requirements (McCarron [5]). To define and use a probabilistic characteristic VAS, a structural reliability analysis of buckle formation must be performed per DNV-RP-F110 [2]. Sensitivity analyses should be conducted to understand the criticality of CBF distributions. Figure 1 shows the characteristic VAS reliability approach flowchart.

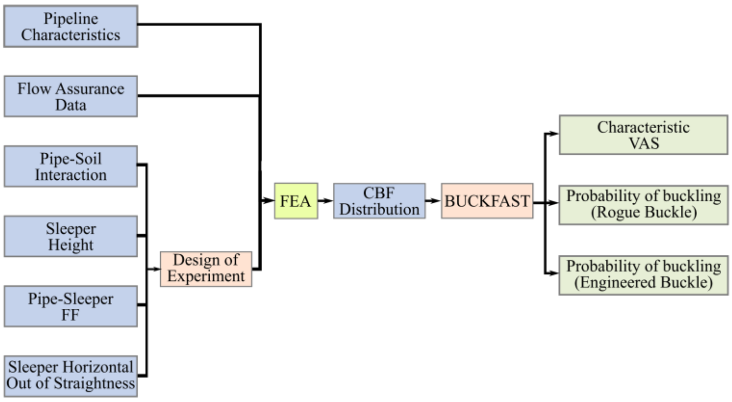


Figure 1. Schematic diagram of characteristic VAS reliability approach. Ref. [3].

2.3 Tolerable VAS

DNV-RP-F110 [2] defines tolerable VAS based on pipeline limit states that include local buckling, fracture, fatigue, or lateral displacement. It can be determined via an iterative process using VAS models or a single feed-in model.

The iterative process, applicable to all limit states, is depicted in Fig. 2. It shows a check on whether the tolerable VAS can be increased if the unity check (UC) is below 1.0. There is an upper limit for the tolerable VAS: for long pipelines it is typically related to the fully constrained effective axial force, while for short pipelines, it is usually half the pipeline length. If all UCs are acceptable at this upper limit, buckling is considered acceptable, and further calculation of the tolerable VAS is unnecessary.

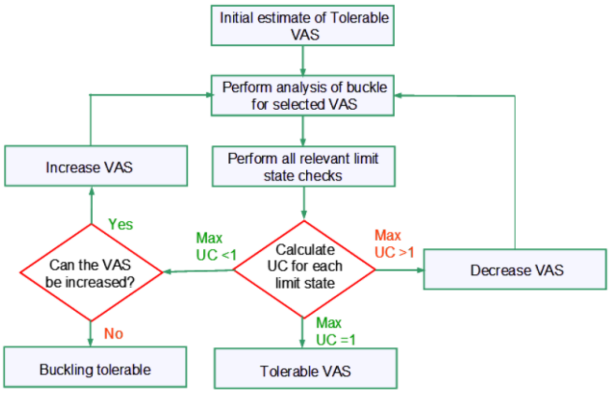


Figure 2. Design flow for identification of tolerable VAS. Ref. [2]

2.4 Limit states

Global buckling is not a failure mode, but can lead to failure modes like local buckling, fracture and fatigue. It can also lead to excessive displacements. Hence, after the global buckling categorization and combined loading check, the pipeline should be checked for other failure modes depending on the design methodology and the buckling response of the pipeline.

According to DNV-RP-F110 [2], pipelines on even or moderately uneven seabed without trawling interference should be checked for: local buckling displacement controlled (DCC), uniform strain capacity, ratcheting/cyclic capacity, fatigue, and fracture. Additionally, checks for excessive lateral (contact with other structures) and axial (walking and end expansion) displacements are required.

2.5 Critical buckling force distributions

In the probabilistic approach, the rogue buckle`s CBF distribution is based on the analytical formulation in the Appendix B of DNV-RP-F110 [2], while the engineered buckle`s CBF distribution comes from VAS FE analysis and DoE from the methodology`s first step. See also Vosooghi [6].

Although the mean of an engineered buckle`s CBF probability density function is lower than that for a rogue buckle in same conditions, there is an overlap between them that highlights the need for a probabilistic approach, as both types of buckles can occur in that range.

3 Case study

The VAS lateral buckling probabilistic approach FE model is presented through a study case of a 1.7 km long VAS flowline with a sleeper mitigator. This is done to illustrate the use of the described probabilistic approach, and to show its useful outputs that would not be obtained with a deterministic approach.

3.1 Main parameters

A typical multilayer rigid production flowline cross-section from deep water oil fields was selected. It is made of carbon manganese steel, internally mechanically lined with a corrosion resistant alloy (CRA). It is also coated with a 5-layer polypropylene (5LPP) coating.

The flowline wall-thickness was chosen at 1 inch because it can be both resistant to collapse and propagating buckling due to the high external pressure of deep waters and to resist bursting due to high internal pressures. Liner wall-thickness was conservatively chosen to resist wrinkling during reel-lay installation. Detailed cross-section properties are described in Tab. 2.

Table 2. Pipe properties.

No	Layer Description	Thickness mm	ID mm	OD mm
1	Alloy 625	4.0	195.2	203.2
2	Pipe SMLS 450 SFPD	25.4	203.2	254.0
3	5LPP Coating	42.3	254.0	338.6

The carbon manganese material steel is in accordance with DNV-ST-F101 [1]. Its mechanical properties can be seen in Tab. 3.

Table 3. Carbon manganese steel mechanical properties.

Symbol	Carbon Manganese Steel Properties	Value	Unit
E	Young's Modulus	206	GPa
ν	Poisson Ratio	0.3	.
SMYS	specified minimum yield stress	450	MPa
SMTS	specified minimum tensile strength	535	MPa

The pipeline is expected to be system pressure tested with seawater at 600 bar (measured in the deepest flowline section). It is considered that the worst flow assurance scenario is the one presented in Tab. 4.

Table 4. Density, pressure, and temperature conditions.

Symbol	Operation Parameters	Value	Unit
d	Content Density	690	kg/m^3
d_{water}	Seawater Density	1038	kg/m^3
P_{STP}	System Test Pressure	600	bar
P	Design Pressure	450	bar
T	Design Temperature	100	°C
T_{amb}	Ambient Temperature	4	°C
WD	Water Depth (7500ft)	2286	m

3.2 Stochastic data

In this methodology, in theory, all the input parameters could be considered stochastic. However, a huge number of analyses would become necessary. Therefore, only the most variable and difficult to predict are considered probabilistic. These are axial and lateral pipe-soil FF, pipe-sleeper FF, horizontal OOS, and RLT. Their values, for each level, are presented in Tab. 5.

Table 5. Stochastic Parameters.

Level	RLT	HOOS	$f_{sleeper}$	f_{xres}	f_{ybreak}
LE	70	0.1	0.1	0.28	0.67
BE	95	0.5	0.2	0.31	0.77
UE	110	1.0	0.3	0.35	1.31

All these input variables are modelled following lognormal distributions. The mean μ and the standard deviation σ, corresponding to each of these distributions, are in Tab. 6.

Table 6. Probability distributions.

Parameter	μ	σ
RLT	4.55	0.19
HOOS	-1.15	0.70
$f_{sleeper}$	-1.61	0.25
f_{xres}	-1.16	0.07
f_{ybreak}	-0.07	0.20

It is considered that the seabed is classified as even to moderately uneven. Typical deepwater soft clay PSI is assumed. The sleeper height is 1.0 m, and its diameter is 0.7 m. Detrimental effect of a sleeper settlement is also considered for tolerable VAS analyses.

3.3 FE model

The FE model is a 2.5D representation of the flowline VAS, which is defined symmetrically to each side of the sleeper. It was run in Abaqus using the element type PIPE31H. The element size is of 0.1 m in the first 75 m of pipe from the sleeper, and it increases gradually until it gets to the size of 1.0 m in a distance higher than 225 m from the sleeper. The general configuration of the model can be seen in Fig. 3.

The soil is modeled as a rigid body, with an analytical surface of the cylinder type. The contact pair with the pipe surface has a linear pressure-overclosure behavior. The pipe-soil friction is modelled with a user subroutine to separate the axial and the lateral friction factors.

The sleeper is modelled as a rigid body composed by rigid 3D elements of 4 nodes, i.e., element type R3D4. The pipe-sleeper surfaces interaction is defined as hard pressure-overclosure.

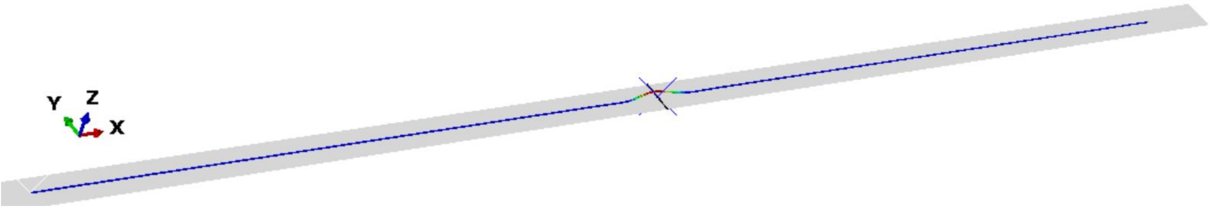


Figure 3. VAS FE model in Abaqus.

The analysis considers three types of nonlinearities: large displacements, material plasticity, and contact between surfaces. Thus, it is divided into a series of 14 numerical steps to account for the load history properly.

4 Study case results

4.1 Tolerable VAS

The FEA results were post-processed and checked against the following Unit Checks (UC): Displacement Controlled Check (DCC), liner wrinkling, uniform strain capacity, and fracture. To avoid a more complex fracture assessment determining maximum allowable size of weld flaws, the latter UC was defined according to Table 5-10 of DNV-ST-F101 [1] by limiting the axial tensile mechanical strain to 0.4%, i.e., fracture UC=1.0.

The flowline model was run for some VAS lengths to obtain the tolerable VAS. It was found that the longest VAS length that was below 1.0 for all UCs was 1700m. The maximum UC values found for this VAS length are present in Tab. 7. The maximum lateral displacement was 9.25m, sufficiently below half of the sleeper length, suggesting that sleeper end stoppers are not needed.

Table 7. Unit Check results.

DCC UC	Liner Wrinkling UC	Uniform Strain Capacity UC	Fracture UC
0.65	0.32	0.26	0.95

4.2 CBF Analysis

The overall effective axial force (EAF) along the flowline length for the highest CBF is shown in Fig. 4 (a). The CBF in this LC was 448.7 kN while the PBF was 169.1 kN (both compressive).

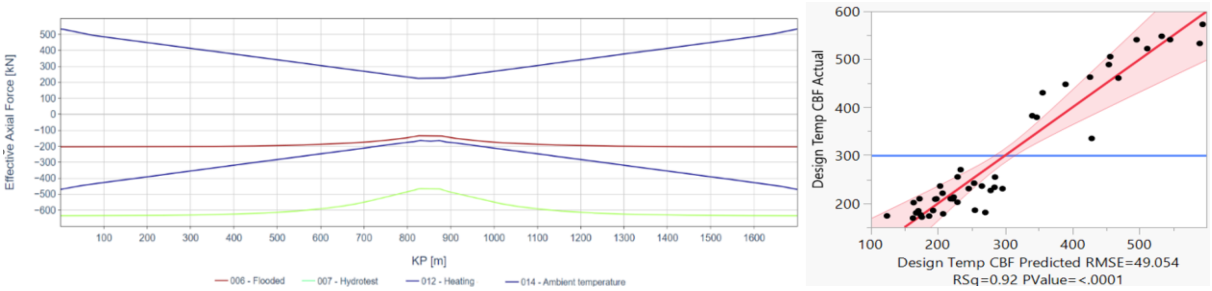
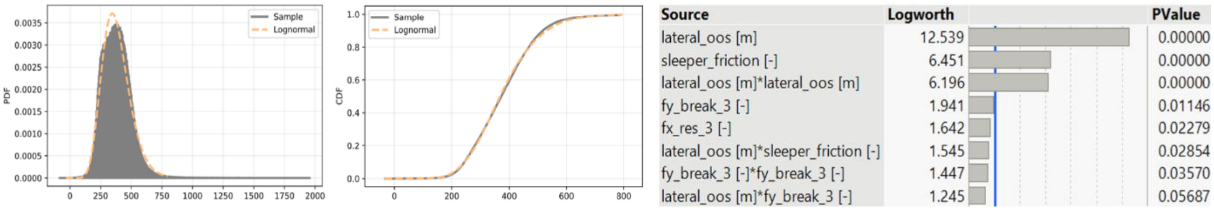


Figure 4. (a) Overall effective axial force along KP. (b) Actual by predicted plot of the CBF.

An LCM is selected through the DoE approach for the five stochastic input parameters with a load combination set of 50 cases with the Latin Hypercube technique. The evaluation of the results for the response surfaces shows that an LCM of 50 cases is enough to get accurate response surface equations for VAS lateral buckling.

These CBF results are used to create a simplified surrogate model of the CBF in function of the stochastic parameters. Testing the model had a sufficiently good performance with $R^2 = 0.92$, as it can be seen in Fig. 4 (b).

The Monte Carlo method was then performed for 1E06 samples. The resulting histogram fitted well with a lognormal distribution of mean $\mu = 6.23$ and standard deviation $\sigma = 0.218$. The probability curve fitting is shown in Fig. 5 (a).



Source	Logworth	PValue
lateral_oos [m]	12.539	0.00000
sleeper_friction [-]	6.451	0.00000
lateral_oos [m]*lateral_oos [m]	6.196	0.00000
fy_break_3 [-]	1.941	0.01146
fx_res_3 [-]	1.642	0.02279
lateral_oos [m]*sleeper_friction [-]	1.545	0.02854
fy_break_3 [-]*fy_break_3 [-]	1.447	0.03570
lateral_oos [m]*fy_break_3 [-]	1.245	0.05687

Figure 5. (a) Lognormal fitting for the CBF [kN]. (b) Significance of input parameters in the CBF response.

Another information that can be extracted is the significance of each input parameter in the CBF response. It is useful because it helps understanding which parameters have more influence on the results. Then the less significant input parameters can be treated as deterministic to reduce the number of simulations in a subsequent assessment. The obtained significance of the stochastic input parameters is shown in Fig. 5 (b).

4.3 Fracture UC distribution

The same probabilistic analysis made for CBF can be performed to other FE outputs. Using the same LCM one can create a surrogate model for the fracture UC, as in Fig. 6.

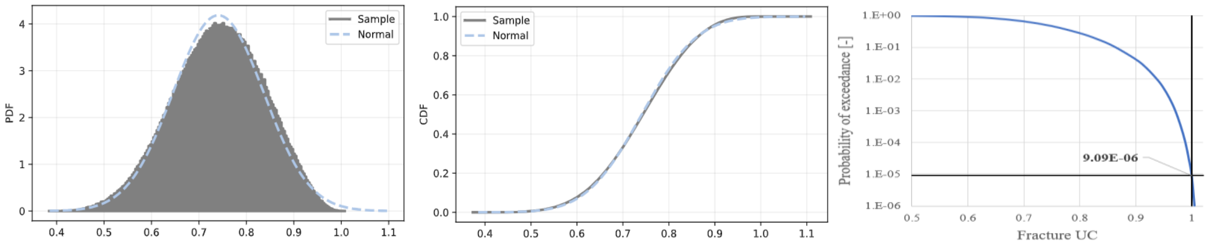


Figure 6. Normal fitting of the fracture UC and its probability of exceedance.

Figure 6 also shows the probability of exceedance of the fracture UC. The probability of exceedance of the unit check is 9.09E-06, which is far lower than the target failure probability of 1.00E-04. Considering this target probability, the fracture UC is 0.989. Thus, ECA and fracture assessments can be simplified according to DNV-RP-F110 [2].

5 Conclusions

The lateral buckling probabilistic approach presented through a study case shows that this methodology provides more detailed lateral buckling thermo-mechanical responses proving to be robust. This approach is becoming more feasible due to the availability and progress in computing technology. Even though it requires more simulation time compared to the deterministic approach, it can provide more detailed probability ranges for the lateral buckling responses, including parameters such as limit-states for post-buckle, buckle amplitudes for rogue and engineered buckle assessments.

The lateral buckling probabilistic approach can be used for a short full-length flowline or a flowline segment to prove whether uncontrolled lateral buckling is acceptable or to develop and refine lateral buckling mitigation measures until adequate probabilities of failure are achieved.

This approach could also be used for pipeline integrity management after the flowline survey, including as-laid flowline horizontal OOS and vertical OOS data to evaluate the buckle initiation and formation at the rogue lateral OOS location as well as sleepers or other mitigation devices.

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