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Dynamic Lateral Stability Analysis On Pipeline Under Operating Conditions

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ABSTRACT

The stability analysis of underwater pipelines refers to DNVGL RP F109 [3] (On-bottom Stability Design of Submarine Pipelines) and DNVGL RP F114 [2] (Pipe Soil Interaction) from 2017. The selection of analysis methods depends on the required level of detail in the design analysis. Dynamic analysis introduces more complexity in terms of numerical calculations and field conditions. It involves simulating the pipe's response to hydrodynamic loads, including random waves, steady currents, and soil resistance in the time domain to replicate extreme conditions realistically. The study's outcomes demonstrate that hydrodynamic forces analyzed through numerical methods in CFD software can be compared to analytical approaches outlined in DNV GL F109 and F114 with an error margin of less than 10%. The Maximum Lateral Displacement is measured at 86.49 mm, falling within the allowable displacement range of 0.5 – 10 times the pipe's outer diameter, as specified in DNV GL F109 & DNVGL F114 guidelines. The Von Mises Stress along the pipeline reaches 266.18 MPa, satisfying the 90% SMYS criteria stipulated in ASME B31.8 [2].

Keywords: *Pipeline Stability, Lateral Displacement, Von Mises Stress, Time Domain.*

1. INTRODUCTION

Indonesia has undergone dramatic changes in the development of its natural gas industry, where natural gas has significantly contributed to economic prosperity and reduced the country's dependence on oil. These conditions have prioritized Indonesia's natural gas industry in terms of supply and demand, infrastructure, pricing, regulations, as well as its prospects and optimization targets. According to the Energy and Mineral Resources sector in 2021 and its 2022 plans, showing a positive trend in optimizing and meeting the natural gas sector's needs [7].

Companies in the natural gas industry tend to utilize key production and distribution infrastructure such as subsea pipelines. Well-planned subsea pipeline designs can greatly enhance the resilience and longevity of pipeline networks [5]. PT. X, as a contractor specializing in the analysis and installation of subsea pipelines, is currently engaged in a project within the business area of a southeastern Sumatra block operator. The project involves exploring natural gas reserves in a field by drilling two gas wells expected to produce around 5.5 MMSCFD. Fluids from this platform will be transported to another platform for further processing through a 3 km pipeline.

Ensuring stability while the pipeline rests on the seabed is critically important for subsea pipeline structures. Subsea pipelines must be designed to withstand environmental loads and forces acting upon them so that they are deemed suitable during the installation planning phase and can perform effectively throughout their operational lifespan.
The interaction between ocean currents flowing through the pipeline and the combination of the pipeline's submerged weight with the friction coefficient between its surface and the seabed, along with the loads imposed on both internal and external parts, must be taken into account. There is also the potential for pipeline damage due to vertical and lateral movements caused by these loading factors.

Coulomb Friction theory explains the interaction between pipelines and soil to prevent lateral displacement. Until the 1970s, Coulomb Friction theory was the only method to estimate soil resistance against pipeline displacement due to hydrodynamic loads. Wagner et al [8] developed Coulomb Friction theory into an empirical model for pipelines, where total lateral resistance is assumed as the sum of Coulomb Friction and soil passive resistance components. Research indicates that design methods based on Coulomb Friction theory are often overly conservative.
In the analysis of subsea pipeline stability as referenced in DNVGL RP F109, there are three methods for lateral stability analysis: General Lateral Stability (GLS), Absolute Static Lateral Stability (ALSS), and Dynamic Lateral Stability (DLS). Dynamic analysis imposes more complex requirements, such as considering the pipeline's response to combinations of hydrodynamic loads from random waves, steady currents, and soil resistance in the time domain to simulate factual outcomes.

2. METHODOLOGY

The method used in analyzing the rigid pipeline structure in the on soil stability is dynamic analysis. The steps taken in this research can be explained as follows:

2.1 Literature Review

This study encompasses literature from books, journals, research papers, codes, and standards relevant to the issues addressed in this research. The literature focuses on the analysis of lateral stability of subsea pipelines, considering environmental influences such as currents, waves, and soil resistance using time domain analysis. Supporting analysis software such as Ansys Fluent and Ansys Mechanical [1], alongside several literature studies, serve as the guiding framework for this research.

2.2 Data Collection of Pipeline and Environment

For this study, data from PT. X's project and open-source metocean data were utilized. The pipeline data, along with environmental data, were obtained from PT. X's existing project records. The environmental data used encompass specifications of currents, waves, and soil. Given that the Java Sea's conditions involve enclosed waters, the JONSWAP wave theory was applied.

Table 1. Enviromental Data of Pipeline

Parameter		Unit	Value
Seawater Properties			
Density		kg/m	1025
Ambient Temperature		ºF (ºC)	77 (25)
Tidal and Surge Elevations			
Highest High Astronomical Tide (HHWL/HAT)		ft (m)	2.33 (0.71)
Mean Sea Level (MSL)		ft (m)	0.0 (0.0)
Lowest Low Astronomical Tide (LLWL/LAT)		ft (m)	-2.33 (-0.71)
Surge Level	1-year return period	ft (m)	0.16 (0.049)
	100-years return period	ft (m)	0.84 (0.256)
Wave Data			
Maximum Individual Wave Height, Hmax	1-year return period	ft (m)	12.11 (3.69)
	100-years return period	ft (m)	30.31 (9.24)
Period of Maximum Wave, Tmax	1-year return period	s	7.64
	100-years return period	s	10.18
Significant Wave Height, Hs	1-year return period	ft (m)	6.53 (1.99)
	100-years return period	ft (m)	16.34 (4.98)
Spectral Peak Period, Ts	1-year return period	s	5.07
	100-years return period	s	7.6
Current Data			
Surface Current Velocity	1-year return period	ft/s (m/s)	3.18 (0.97)
	100-years return period	ft/s (m/s)	5.84 (1.78)
Mid-Depth Current Velocity	1-year return period	ft/s (m/s)	1.58 (0.48)
	100-years return period	ft/s (m/s)	2.13 (0.65)
Near-Bottom Current Velocity	1-year return period	ft/s (m/s)	1.24 (0.38)
	100-years return period	ft/s (m/s)	1.36 (0.41)
Parameter			
Soil type		-	Very Soft Clay
Undrained Shear Strength		kN/m2	1.19
Dry unit Weight of Soil		kN/m2	6.24
Seabed Roughness		m	5×10^{6}
Soil Friction	Axial	-	0.2
	Lateral	-	0.2

In the analyzed project scheme, the pipeline spans 3,223 kilometers with a seabed profile ranging from a minimum depth of 23.92 meters to a maximum of 22.26 meters.

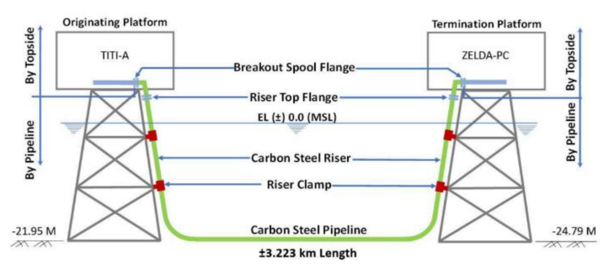

Figure 1. Pipeline Scheme

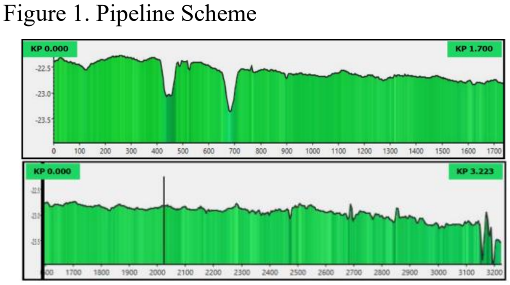

Figure 2. Contour of Seabed Profile

2.3 Analytical Calculation of Vertical and Lateral Stability

Vertical stability analysis was conducted to determine whether the weight of the pipeline, when in the air, can withstand its buoyant force when submerged in seawater. If the pipeline can resist buoyant forces and lay on the seabed, it can be considered stable. The table below presents the results of stability criteria calculations using a vertical safety factor stability (SF_v) value of 1.1, in accordance with DNVGL RP F109 Section 3.2 recommendations on "Vertical and Lateral Stability Method."

2.4 Modeling and Numerical Analysis of the Pipeline

Following the analytical calculations for hydrodynamic forces from currents and waves occurring at two depths along the pipeline route, the next step involves modeling using Ansys Design Modeler software. The geometry length is adjusted according to the desired review outcomes.

In addition to modeling, the analysis setup will include three outputs: hydrodynamic forces, lateral displacement, and von Mises stress, validated against respective standards and code checks.

2.5 Hydrodynamic Force Analysis of the Pipeline in Ansys Fluent

The hydrodynamic force calculations were conducted through two analyses: analytical and numerical. The prior analytical calculations serve as parameters in the numerical calculations, providing initial guess values.

After obtaining outputs as engineering data to determine the peak load of hydrodynamic forces acting on the pipeline, numerical calculations proceed to assess the effects of these forces.

As described in fundamental theory, hydrodynamic forces induce pipe reactions, notably horizontal movement (lateral displacement), which exerts the greatest load on the pipe during extreme sea conditions. The lateral displacement of the pipe will be evaluated against DNV F109 and DNV F114 standards.

Due to hydrodynamic loads, internal pipe pressure, and resulting movements or deformations, these factors collectively contribute to the pipe experiencing equivalent stress, known as von Mises stress. Verification of von Mises stress will be conducted in accordance with ASME B31.8 and DNV-OS-F10 codes and standards to determine if the pipe is subjected to overstress.

3. ANALYSIS AND DISCUSSION

3.1 Calculation of Submerged Weight and Vertical Stability on Specific Gravity Criteria

All In the submerged weight analysis, calculations begin with the dimensions and geometry of the pipeline. The pipe's weight is based on the nominal thickness of the steel wall and any coating layers. If metal loss occurs due to corrosion, erosion, and/or significant wear, the wall thickness must be reduced to compensate for the expected average weight loss. The pipe fill can be included with a minimum nominal mass density as per conditions. The total submerged weight value obtained is 578.931 N/m. Vertical stability is analyzed using predetermined specific gravity criteria.

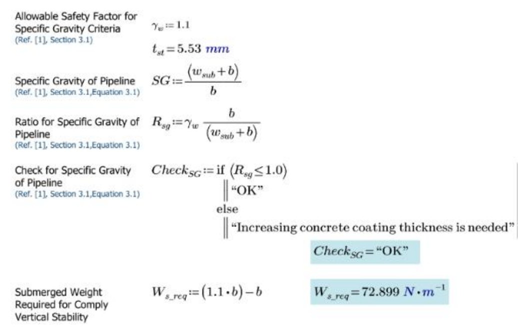

Figure 3. Vertical Stability Check Sheet in Water and Submerged Weight Required

The stability check due to normal forces (SG) remains within the "OK" category, indicating no need to increase the concrete thickness. The required submerged weight value Ws req = 72.899 N/m.

3.2 Wave Induced Parameter and Current Velocity

Wave-induced parameters are analyzed to obtain the current velocity impacting the pipeline perpendicular to its underwater direction. Oscillatory flow conditions induced by wave action at the pipeline level can be calculated using numerical or analytical wave theory. The wave theory must accurately depict conditions at the pipeline site, including effects from shallow water.

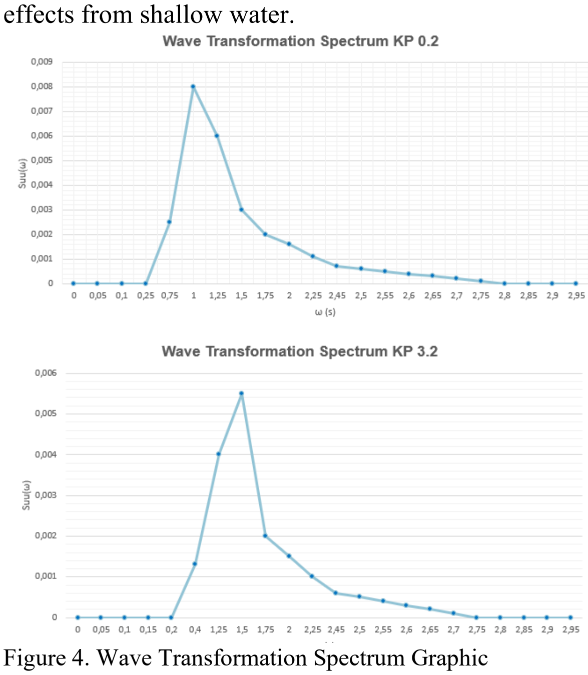

Figure 4. Wave Transformation Spectrum Graphic

Short-term, stationary, and irregular sea conditions can be explained by the transformation of the wave spectrum Shh(ω), representing the spectral density function of sea surface elevation and its effects on the wave-induced velocity spectrum at the pipe level at the two lowest and highest seabed elevations.

Submerged pipelines experience a stable current velocity flow, composed of analyzed components such as tidal currents, wind-induced currents, storm waves generated by currents, and density-driven currents (spectral density). Therefore, the average perpendicular current velocity above the pipe diameter is 1.46 m/s.

3.3 Pipeline-Soil Interaction

Subsea pipelines are subjected to various loads, as previously mentioned. These include environmental loads such as hydrodynamic forces from waves, currents, and various other loads and forces. These forces generate lift force, drag force, and inertia force, which can reduce pipeline stability.

Firstly, in calculating passive soil resistance, an initial penetration value is required. Total penetration comprises initial penetration, dynamic laying-induced penetration, and penetration due to the influence of currents and waves.

Table 2. Initial and Total Soil Penetration

Parameter	Kilometer Points	Notation	Value	Units
Initial Penetration	0.2	Zimin	27.318	mm
	3.2	Zimax	27.521	mm
Total Penetration	0.2	Ztmin	54.667	mm
	3.2	Ztmax	55.174	mm

Hydrodynamic loads can experience reduction due to the interaction between the pipeline and the soil. Analytical calculations are conducted to determine this reduction caused by the interaction. Subsequently, the calculation of soil passive resistance values follows, which will be utilized in assessing the lateral stability of the pipeline.

Table 3. Reduction Factor

Parameter	Kilometer Points	r_{perm}	r_{pen}	r_{tren}	r_{tot}
Horizontal	0.2	1	0.748	1	0.748
Reduction Factor	3.2	1	0.746	1	0.746
Vertical	0.2	0.7	0.896	1	0.627
Reduction Factor	3.2	0.7	0.894	1	0.626

Table 4. Soil Resistance

Parameter	Kilometer Points	Notation	Value	Units
Resistance Soil	0.2	Frmin	187.943	N/m
	3.2	Frmax	190.227	N/m

3.4 Hydrodynamic Loads and Verification of Vertical and Lateral Stability on the Seabed

The peak loads presented below are measured and analyzed using previous analytical methods, including horizontal components such as drag force and lift force, each with their respective coefficients. It can be observed that the influence and magnitude of the horizontal peak load (drag force) are greater.

Table 4. Coefficient and Hydrodynamic Peak Load Value

Parameter	Kilometer Points	Notation	Value	Units
Horizontal Peak Load Coefficient	0.2	Cymin	2.57	-
	3.2	Cymax	2.19	-
Vertical Peak Load Coefficient	0.2	Cxmin	2.09	-
	3.2	Cxmax	1.455	-
Horizontal Peak Load	0.2	Fymin	723.771	N/m
	3.2	Fymax	615.152	N/m
Vertical Peak Load	0.2	Fxmin	48.989	N/m
	3.2	Fxmax	334.794	N/m

Continuing with the following analysis, which provides absolute static requirements for the pipeline based on static equilibrium, ensuring that the pipe's resistance to movement is sufficient to withstand maximum hydrodynamic loads during sea conditions without experiencing significant lateral displacement.

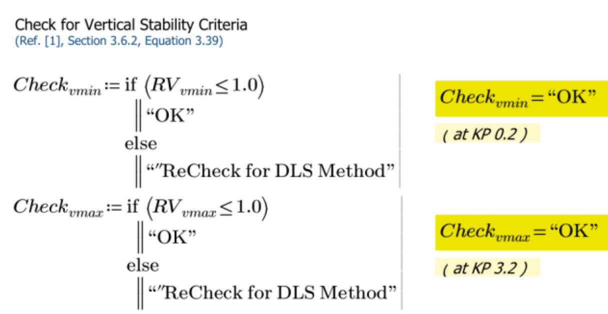

Figure 5. Check on Vertical Based on DNV F109 and F114

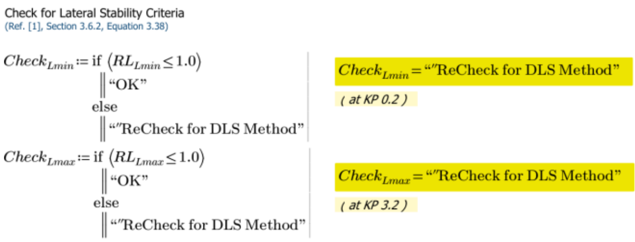

Figure 6. Check on Lateral Stability (bottom) Based on DNV F109 and F114

After conducting analytical calculations starting from the submerged weight of the pipe, pipe density, horizontal and vertical peak loads, and the passive resistance value of the soil, the lateral stability of the pipe must be rechecked using the Dynamic Stability Lateral (DLS) Analysis method.

3.5 Numerical Analysis of Hydrodynamic Forces and Validation

Following the analytical analysis, validation is carried out using numerical analysis to compare results according to DNV RP F109 Class standards. The modeling is performed using Ansys Fluent software. The geometry model and meshing process are set up accordingly, followed by the analysis setup.

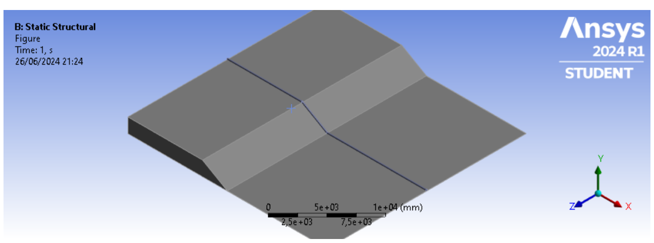

Figure 7. Geometry Model on Two Seabed Level of Pipeline

After conducting the analytical analysis, validation was performed using numerical analysis to compare the results according to DNV RP F109 Class standards. Ansys Fluent software was utilized for the modeling process, encompassing geometry modeling and meshing procedures, followed by the analysis setup.

The pipeline segment model was positioned at the lowest and highest pipe elevations, namely KP 0.2 and 3.2. After simulation, contour and streamline results of currents and waves were obtained using Ansys Fluent, along with values for drag (horizontal) and lift (vertical) forces.

From the numerical simulation results obtained using Ansys Fluent software, horizontal force (Fy) and vertical force (Fz) values were derived, as shown in the table below, and validated against the analytical analysis in Table 4.

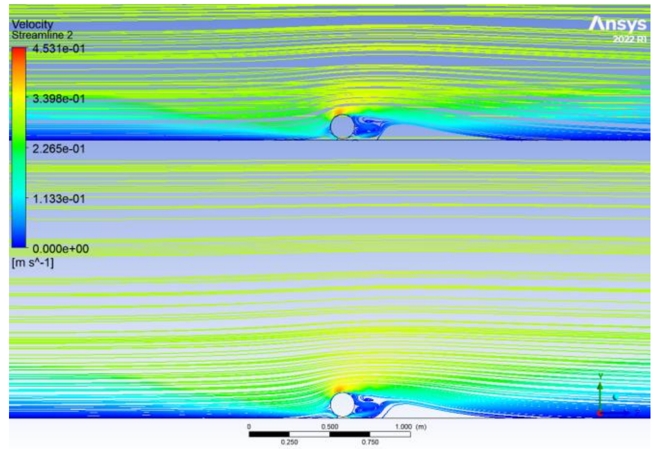

Figure 8. System Coupling on Ansys Workbench

Table 5. Comparison of Analytical and Numerical Results on Hydrodynamic Forces

Parameter	Horizontal Load	Vertical Load	Units
Analytical Analysis	408.40	669.461	N/m
Numerical Analysis	372.159	626.38	N/m
Error Value	9.27	6.51	%

Table 6. MAPE Category

Mape Parameter	Description
< 10%	Highly Accurate Forecasting
10-20 %	Good Forecasting
20-50 %	Reasonable Forecasting
> 50 %	Inaccurate Forecasting

3.6 Numerical Analysis of Hydrodynamic Forces and Validation

After setting up and obtaining the post-results from the CFD analysis, to derive displacement values and von Mises stress due to hydrodynamic loads on the pipeline, a fluid-structure interaction (FSI) analysis is conducted by linking the Fluent solution with a mechanical setup. This integration of the two solvers is referred to as system coupling.

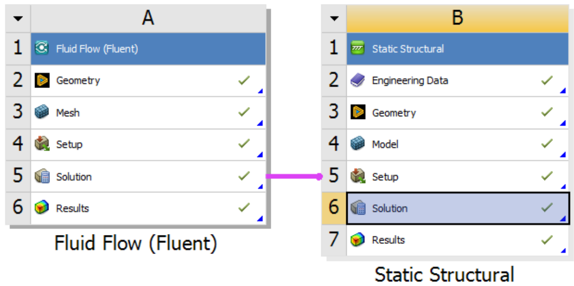

Figure 9. Streamline of Hydrodynamic Load Plotting

3.7 Dynamic Analysis of Lateral Displacement and Von Mises Stress with Validation

In addition to vertical stability analysis formed by hydrostatic loads and hydrodynamic force analysis as input for lateral pipeline stability, the pipeline structure must undergo dynamic lateral stability (DLS) analysis. This includes evaluating the equivalent stress (von Mises stress) occurring during operational extremes [6].

The initial setup begins with engineering data categorized into specific material or, upon closer inspection, subclasses. The classification material can be seen in Figures 10.

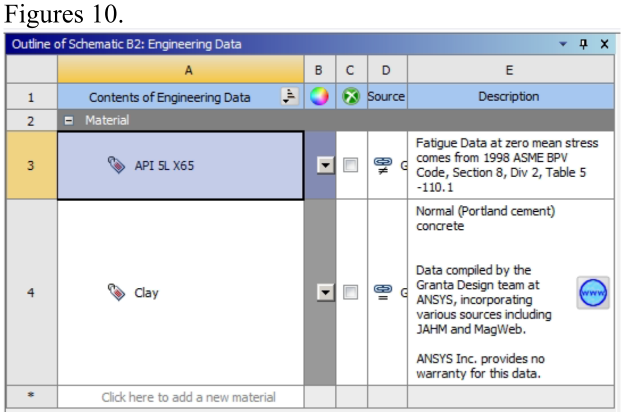

Figure 10. Material Setup for Pipeline and Seabed Configuration

Following the setup from engineering data and meshing, the analysis progresses to the setup phase in Ansys ADPL Static Structural. The aim of the static analysis is to determine displacement values from initial (0 mm) to maximum. Following this, Ansys Modal and Transient Structural solvers are utilized to derive frequency and time history outcomes

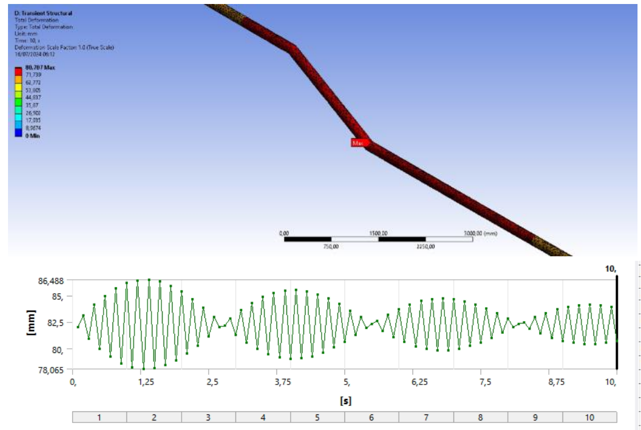

Figure 11. Maximum Lateral Displacement and Time History Result

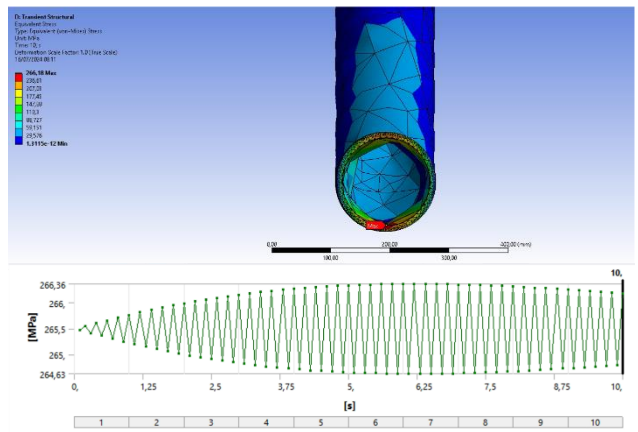

Figure 12. Maximum Von Mises Stress and Time History Result

The numerical analysis results for stress and displacement will be validated against the standards specified in DNV GL F109 and F114 for lateral displacement, while stress values will be validated against ASME B31.8 for allowable stress. The results will be deemed acceptable as presented in the following table 7.

Table 7. Von Mises Stress Result

Lateral Displacement Result	Criteria	Description
86.94 mm	84 - 1680.25 mm (0.5 - 10 x OD)	OK

4. CONCLUSIONS

From the results of the analysis and calculations regarding the subsea pipeline stability analysis in the previous chapter, the following conclusions can be drawn from the formulation of the previous issues:

1. The hydrodynamic forces analyzed using numerical calculations in CFD software and compared with analytical analysis according to DNV GL F109 and F114 yielded values that are nearly identical with an error rate of less than 10%.
2. The Maximum Lateral Displacement reaches 1.7539 cm, fulfilling the criteria of 0.5 – 10 times the pipeline OD according to DNV GL F109 & DNVGL F114.
3. The Von Mises Stress along the pipeline reaches 277 MPa, meeting the criteria of 90% SMYS according to ASME B31.8.
4. The Dynamic Lateral Stability Analysis method can directly ascertain the magnitude of lateral displacement and stress experienced by the pipeline, fulfilling applicable standards and codes while correcting results from conventional methods.

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