DESIGN OF A DIGITAL TOOL FOR THE CONSTRUCTION OF SUBMARINE PIPELINES FOR THE TRANSPORT OF LIQUID HYDROCARBONS

DISEÑO DE UNA HERRAMIENTA DIGITAL PARA LA CONSTRUCCIÓN DE OLEODUCTOS SUBMARINOS PARA EL TRANSPORTE DE HIDROCARBUROS LÍQUIDOS

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ABSTRACT

This article entitled "Design of a digital tool for the construction of submarine pipelines for the transport of liquid hydrocarbons", exposes a tool consisting of two parts; the first part is focused on the design of the pipeline through a simplified analysis of an integrity management system and the second part to the stability of the pipeline under the practical standard DNV RP F109. These in order to be able to determine operational parameters to declare the pipeline as safe at an installation point or position. It should be noted that the tool aims to ensure the stability and operation of the pipeline throughout the productive stage of the field based on the operational problems given by conditions of the installation area or positioning of the pipeline, such as environmental conditions; waves, currents, temperatures of sea currents, corrosive environments and marine fauna, related to the design of the pipeline and its stability.

This tool was developed based on the methodology described in the article, which is composed by means of a bibliographic compilation of theory and equations worked together with visual BASIC and Excel, in order to obtain a good performance of any submarine pipeline that transports liquid hydrocarbons.

Obtained the results it will be possible to conclude which are the most suitable cases for the good operation of the submarine pipelines in a specific case, as also it will be possible to guarantee the utility of the tool, that is to say that for the validation of the tool the obtained results will be taken and they will be compared with an already existing case, where a percentage of efficiency will be determined

key words: Digital tool, Hydrodynamic Stability, Pipeline, Friction, Lateral displacement, HSP, Offshore, Thermal insulation.

RESUMEN

Este artículo titulado "Diseño de una herramienta digital para la construcción de oleoductos submarinos para el transporte de hidrocarburos líquidos", expone una herramienta que consta de dos partes; la primera parte está enfocada al diseño del oleoducto mediante un análisis simplificado de un sistema de gestión de la integridad y la segunda parte a la estabilidad del oleoducto bajo la norma práctica DNV RP F109. Todo ello con el fin de poder determinar los parámetros operativos para declarar la tubería como segura en un punto o posición de la instalación. Cabe destacar que la herramienta tiene como objetivo asegurar la estabilidad y operación del oleoducto a lo largo de la etapa productiva del campo en base a los problemas operacionales dados por las condiciones del área de instalación o posicionamiento del oleoducto, tales como las condiciones ambientales; olas, corrientes, temperaturas de las corrientes marinas, ambientes corrosivos y fauna marina, relacionados con el diseño del oleoducto y su estabilidad

Esta herramienta fue desarrollada en base a la metodología descrita en el artículo, la cual está compuesta por medio de una recopilación bibliográfica de teoría y ecuaciones trabajadas en conjunto con BASIC visual y Excel, con el fin de obtener un buen desempeño de cualquier tubería submarina que transporte hidrocarburos líquidos.

Obtenidos los resultados se podrá concluir cuáles son los casos más adecuados para el buen funcionamiento de las tuberías submarinas en un caso específico, como también se podrá garantizar la utilidad de la herramienta, es decir que para la validación de la herramienta se tomarán los resultados obtenidos y se compararán con un caso ya existente, donde se determinará un porcentaje de eficiencia.

PALABRAS CLAVE: Herramienta digital, Estabilidad Hidrodinámica, Tubería, Rozamiento, Desplazamiento lateral, HSP, Offshore, Aislante térmico.

INTRODUCTION

The oil industry has been characterized by its vital importance in the development of mankind and the economy, therefore with the passage of time has begun to implement different.

Alternatives for exploration and exploitation of hydrocarbons, in order to incorporate new reserves and ensure energy stability. In order to obtain these reserves, new challenges have been assumed, which have been strengthened in order to guarantee effective and profitable processes.

The search for new reserves gained strength in offshore operations since 1890, i.e. offshore platforms were installed for drilling and production of hydrocarbons [1], a few years later different countries opted to incorporate this practice, as in the case of Brazil, which in 2007 opted for offshore operations due to high demand and declining production on land, obtaining as a result a potential formation such as the Brazilian pre-salt [2].

Brazil as other countries took on this new challenge focused on the implementation of good practices and improvement of these practices, some of these practices have to do with the transport of hydrocarbons in deep water [3], which is relevant because of the utility provided by the pipelines for the transport of these fluids, it should be noted that these can suffer damage due to displacement in relation to a particular direction, which led to environmental damage, loss of time and additional costs [4].

Therefore, the tool will be based on the conceptual engineering of the construction of a subsea pipeline that originates from platform P52 and ends in a FSO, the hydrodynamic stability of the subsea pipeline will be analyzed against various environmental conditions to which each stage is subjected. [5]

METHODOLOGY

The development of the tool is subject to a bibliographic survey on the offshore industry in Brazil, pipeline sizing and application of the DNV-RP-F109 practice.

SUBSEA PIPELINE DESIGN

For the design of the pipeline, a simplified analysis based on the integrity management system is considered, focused on the identification of threats, impacts and solutions to mitigate future damage to the pipeline. This design considers the subsequent calculations:

Minimum diameter: For this calculation the friction coefficient must be considered which depends on the Reynolds number and Relative Roughness.

$$d = \sqrt[5]{7{,}658 \cdot 10 - 5 \cdot \lambda)/\Delta H}$$

λ= Coefficient of friction

ΔH= Height Difference (m)

Equation for the economic choice of the pipeline

$$no = \frac{Cc1 - \mathrm{C}c2}{\mathrm{C}e2 - \mathrm{C}e1}$$

Cc1: Costs of larger diameter pipe. ($ USD)

Ce1: Annual maintenance of the larger diameter pipeline. ($ USD)

Cc2: Costs of smaller diameter pipe. ($ USD)

Ce2: Annual maintenance of the smaller diameter pipeline. ($ USD)

Optimum pipe diameter: An optimum velocity must be considered for the calculation of the diameter; this is considered from the table titled as optimum velocities for non-viscous liquids in pumping lines.

$$d = \sqrt{(4 \cdot Q)/(\pi \cdot v)}$$

***V* =** optimum maximum or minimum speed (m/s)

Q= Flow rate (m^3/h)

Flow regime: This is derived from reservoir production, type of fluid transported and operating parameters.

$$Re = \frac{\rho \cdot v \cdot d}{\mu}$$

μ = Fluid viscosity (Cp)

ρ = Density of the fluid (Kg/m3)

v = Flow velocity (m/s)

Criteria for pipe thickness: These are considered by pipeline specifications.

$$tn \geq t + A$$

tn = Nominal thickness (in)

t = Design pressure thickness (in)

A = Tolerance (in)

Maximum Allowable Operating Pressure (MAOP): This calculation considers the zone where the pipeline will be positioned, the temperature of the transported fluid, the deformation and specifications of the pipeline.

$$MAOP\ (psi) = \left(\frac{2 * Sy * t}{De}\right) * F * E * T$$

Sy = creep at strain (psi)

t = Pipe wall thickness (in)

De = Outside diameter (in)

F = Design factor (AD)

E = Joint factor (AD)

T = Temperature factor (AD)

Pressure drops and load due to friction

$$\mathrm{HL} = 0{,}015\left(\frac{Ql^{1,85} * L}{d^{4,87} * C^{1,85}}\right)\ ;\ \Delta p(H\ y\ D) = 0{,}043 * HL; \Delta p(I) = 0{,}04335 * \Delta H * SG$$

HL = Head loss due to friction (ft)

L = length (ft)

d = Pipe diameter (in)

Q = Fluid flow rate (bpd)

C = Friction factor (AD)

∆p (H and D) = Pressure loss in downward and horizontal direction (psi).

∆p (I) = Pressure drop in inclined direction (psi)

Number of pumping stations per stage

$$\# \, BOMBAS = \frac{\Delta P \; total}{MAOP}$$

Thermal behavior

- ✓ Heat flow

$$q = \frac{\Delta T}{\sum R}$$

- ✓ Without insulation

$$\frac{q}{L} = \frac{2\pi(T_{\infty 1} - T_{\infty 2})}{\frac{1}{h_1 r_1} + \frac{in\,(\frac{r_1}{r_2})}{k_1} + \frac{1}{h_2 r_2}}$$

- ✓ With insulation

$$\frac{q}{L} = \frac{2\pi(T_{\infty 1} - T_{\infty 2})}{\frac{1}{h_1 r_1} + \frac{in\,(\frac{r_1}{r_2})}{k_1} + \frac{in\,(\frac{r_3}{r_2})}{k_2} + \frac{1}{h_2 r_3}}$$

- ✓ Outlet temperature

$$T\infty 1 = \frac{q * \left(\frac{1}{h_1 r_1} + \frac{in\,\left(\frac{r_1}{r_2}\right)}{k_1} + \frac{1}{h_2 r_2}\right)}{2\pi L}$$

q = Heat flux

∆T = Temperatura diferente

R = radius

L = duct length

T∞1 = Fluid temperature

T∞2 = Temperature of the medium

r1 = internal radius

r2 = external radius

h1= Heat transfer coefficient by convection of the fluid

h2= Heat transfer coefficient by convection of the medium

K1= Thermal conductivity of the pipe

K2= Thermal conductivity of the insulator

r3= radius of the insulator

1. HYDRODYNAMIC STABILITY OF THE PIPELINE

The analysis for pipeline stability considers the DNV RP F109 practical standard, which is a design standard for subsea pipeline bottom stability and by the acronym DNV referring to the classification, certification, verification and consultancy of subsea units. This practice considers the following methods mentioned below [6]:

Vertical stability in water: This method is focused on avoiding the buoyancy of the pipe in water, which contains a stability criterion that involves the submerged weight of the pipe and a safety factor of 1.1 in the case that the specific density of the pipe is greater than this [7].

Absolute static lateral stability: This method does not consider lateral displacements, in the horizontal hydrodynamic loads are less than the soil resistance, the method considers the following assumptions [8]:

1. The frictional force depends on the resistance components of the soil.
2. Linear wave theory must be considered for the calculation of the velocity and acceleration of the particles at the duct level.
3. The wave loads should be considered only one component and direction.
4. The practical standard and morrion formulation should be considered for the calculation of the loads.

Dynamic lateral stability analysis: This method aims to analyze the lateral displacement of the pipeline subjected to hydrodynamic loads from a combination of waves and currents in a design sea state.

Generalized lateral stability: This method allows for lateral displacements, which are produced by the action of oscillating wave spectra, and also contemplates two hypotheses.

1. It considers displacements of up to half of the diameter, considering the pipeline as stable.

2. It considers displacements of up to 10 times the pipe radius.

The practical standard DNV RP F109 considers the following calculations depending on the methods specified by the standard:

Total weight of the pipeline: This calculation considers areas and weight of each material that make up the pipeline.

$$Wt = Ws + Wi + Wp + Wc$$

Wt = Total weight of the pipe (N/m)
Ws = Pipe submerged weight per unit length (N/m)
Wp = Weight of anti-corrosion coating (N/m)
Wc = Weight of concrete layer (N/m)

Duct thrust per unit of length

$$b = \frac{\pi}{4} * D^2 * \rho w$$

D = Pipe outside diameter (m)
ρw = Fluid density (lbf/ft3)

Submerged weight of pipe per unit length

$$Ws = Wt - b$$

Criterion of vertical stability in water under the practical standard DNV - RP F109

$$\boldsymbol{\gamma w} * \frac{\boldsymbol{b}}{\boldsymbol{ws} + \boldsymbol{b}} = \frac{\boldsymbol{\gamma w}}{\boldsymbol{sg}} \leq 1$$

γw = Factor of safety

Sg = Specific gravity

Stability criteria and horizontal (y) and vertical (z) absolute static lateral safety factors under practical standard DNV - RP - F109

$$ysc_y * \frac{(FD + FI) + \mu * FL}{\mu * ws + FR} \leq 1{,}0 \qquad ysc_z * \frac{FL}{ws} \leq 1{,}0$$

$$ysc\_y = \frac{(\mu * ws + FR)}{Fy^* + \mu * Fz^*} \qquad ysc\_z = \frac{ws}{Fz *}$$

$ysc =$ Safety factor (AD)

FD = Drag style strength (N/m)

FI = Inertia force (N/m)

μ = Soil friction factor (AD)

FL = Lifting force (N/m)

FR = Passive Resistance Force (N/m)

Fy* = Horizontal hydrodynamic forces (N/m)

Fz* = Vertical hydrodynamic forces (N/m)

Factor of safety for 0.5D and 10D displacement for generalized lateral stability under the practical standard DNV - RP - F109: This method contemplates a significant weight parameter (L), a significant weight parameter required to lead to a virtually stable pipe (with displacements less than half a diameter) (L stable) and a weight required to obtain a lateral displacement of less than 10 times the diameter (L10).

$$y_{sc}(0{,}5D) = \frac{L}{L_{estable}} \qquad y_{sc}(10D) = \frac{L}{L_{10}}$$

2. IMPLEMENTATION OF THE TOOL

For the implementation of the tool, the formulas proposed by the duct design and stability under the DNV RP F109 practical standard are considered.

HSP: (Hydrodynamic stability of pipelines)

Logo:

Figure 1.
Logo representative of the tool.

Note. The image corresponds to the representative logo of the tool.

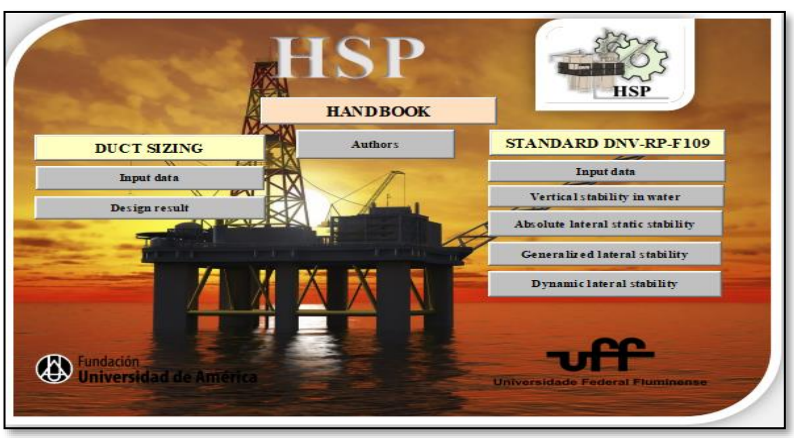
Programming: Visual Basic y Excel

Language: English

SECTIONS COVERED BY THE TOOL

Home: In the home tab the tool contains links to the manual, authors, sizing theory and stability with their corresponding input variables and results**.**

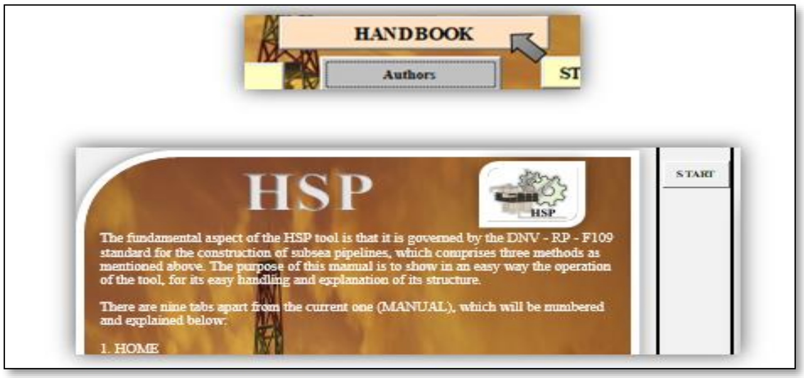
Figure 2.
Home tab of the tool.



Note. The image corresponds to the home tab of the tool.

Manual: This tab contains a summary corresponding to the authors of the tool**.**

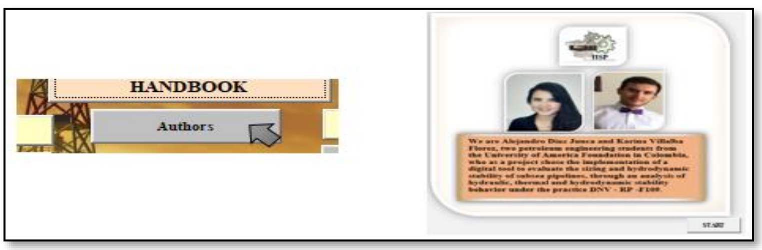
Figura 3.
Tool manual



Note: The image corresponds to the home tab linked to the manual corresponding to the tool.

Authors: This tab contains a summary of the authors of the tool.

Figura 4.
Authors of tools.



Note. The image corresponds to the home tab linked to the authors tab corresponding to the tool.

Sizing theory: In this tab you can view a summary of all the aspects of duct sizing.

Figura 5.
Duct sizing theory tab.

Note: The image corresponds to the duct sizing theory tab in the tool.

Input data for pipeline sizing: In this tab you can see the input variables corresponding to the pipeline design.

Figure 6.

Input variables for duct sizing in the tool.

Note: The image corresponds to the home tab linked to the pipe sizing layer data tab in the tool.

Theory on stability under the practical standard DNV RP F109: In this tab the theory corresponding to the methods contemplated in the standard will be displayed.

Figure 7.

Theoretical tab of the stability according to DNV RP F109 of the ducts in the tool.

Note. The image corresponds to the tab of the theory of duct stability in the tool under the practical standard DNV RP F109.

Inputs variables for sizing: In this tab you can enter the data corresponding to the parameters and costs of the pipeline, in addition to considering the variables for the calculation of optimum diameter, MAOP and variables corresponding to the thermal part of the pipeline.

Once the data tabulation is obtained, the data will be saved and will be directly reflected in the template and later the results corresponding to the duct design will be displayed.

3. REFLECTED RESULTS FOR DUCT DESIGN REFLECTED IN TOOL

1. Mínimum diameter:

Figure 8.
Results of the minimum duct diameter in the tool.

	MINIMUM PIPE DIAMETER
Graph	0,0339
	0,0145
	0,0162
	MINIMUM PIPE DIAMETER
	0,033922
	0,015636
	0,013883

Note. The image corresponds to the results of the minimum diameter obtained by the tool. obtained by the tool.

2. Optimum diameter:

Figure 9.
Results of the optimal duct diameter in the tool.

	FLOW RATE (Qn) m3/h	Diameter at minimum speed (dn min)	Diameter at maximum speed (dn min)	Average value of optical diameter
1	1102	0,883	0,624	0,754

Note: The image corresponds to the results of the optimum diameter obtained by the tool.

3. Fluid regime

Figure 10.
Results of the fluid regime in the pipeline.

Average diameter value (m)	FLOW RATES (Qn)	Flow velocity m/s	Reynolds number	Regime
0,754	1102	0,68629	65773,5065	TURBULENTO
0,124	30	0,68629	10852,2759	TURBULENTO

Note: The image corresponds to the results of the fluid regime obtained by the tool.

4. Criteria for pipe thickness

Figure 11.

Results in meeting pipe thickness criteria.

Sum of tolerances (A) ASSUMED	0,05	CRITERIA
Nominal thickness (tn)	0,51181	$t_n \geq t + A$
Design pressure thickness (t)	0,310713664	
Design pressure (Pi) ASSUMED	870	if it complies
Outside diameter (D) in	29,99994	

Note. The image corresponds to the results of compliance with the thickness criteria obtained by the tool.

5. Maximum operating pressure (MAOP)

Figure 12.

Results of the maximum pressure in the tool duct.

F	0,6
t	0,51181
E	1
T	1
SY	70000
MAOP	1433,07087

Note: The image corresponds to the results of the maximum pressure obtained by the tool.

6. Pressure drops

Figure 13.

Results of pressure drops in the tool conduit.

6	Determination of the pressure loss value in the pipeline											
	Absolute roughness	0,05	mm	coefficient (f)	0,01140							
	Fluid density	890	kg/m3									
	Viscosity µ	0,007	pa *s	Total duct length (	2583							
	CHANNEL WIDTH (w)	0,65	m									
	Average value of optical diameter (mm)	FLOW RATE (Qn) m3/h	flow velocity in the duct m/s	Reynolds number (Re)	e	Additional values (10/e)	Friction loss (Hf) m	Friction coefficient (f)	[v^2/2*g]	∑a	Hrl (m)	total pressure loss Hpt m
	0,754	1102	0,7	62295,4	0,066331	150,7580127	1,645144594	0,02000	0,024005914	5,78304	0,138827152	1,7840
	0,870	30	0,7	71899,3	0,057471	174	9,619508871	0,01929	0,024005914	5,78043	0,138764383	9,7583

Note: The image corresponds to the results of the pressure drop obtained by the tool.

7. Comportamiento térmico

Figure 14.

Heat loss and temperature results without insulation on the tool.

Heat transfer per meter q/L (w/m)	10513,00632
Full path heat transfer (w)	27155095,32
Inlet temperature T∞0 (°C)	34,42

Note: The image corresponds to the results of the heat and temperature loss by the tool. and temperature loss by the tool.

Figure 15.

Results of heat and temperature losses with insulation on the tool.

Heat transfer per meter q/L (w/m)	111,5531901
Full path heat transfer (w)	288141,8899
Inlet temperature T∞0 (°C)	30,04690049

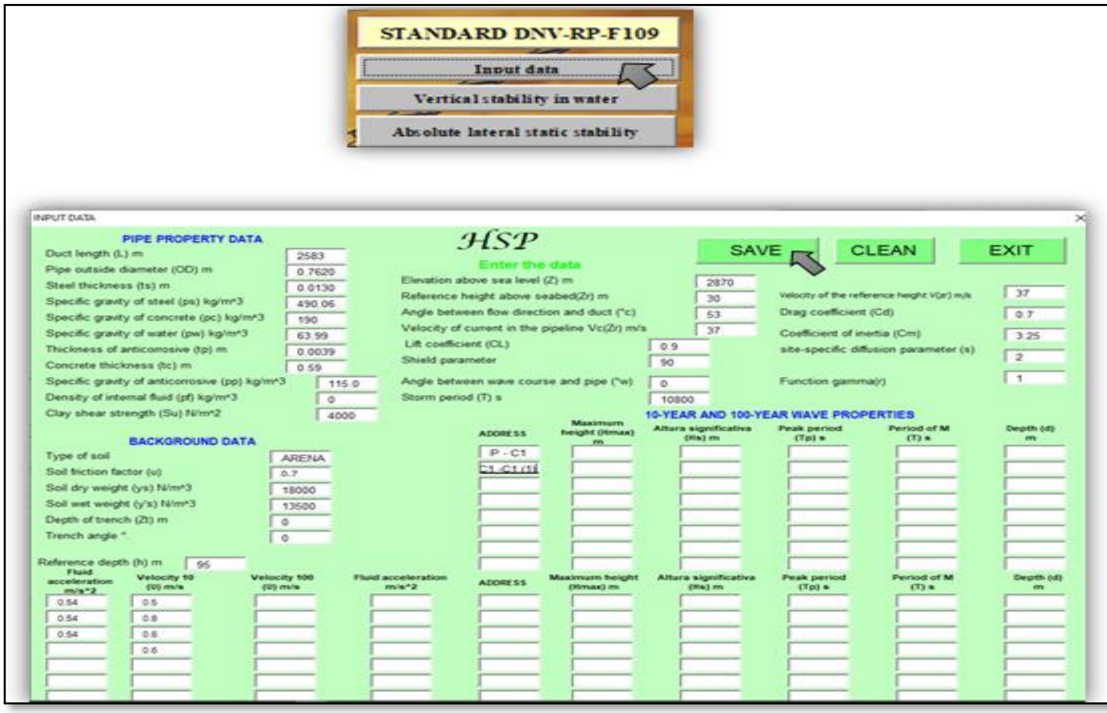
Note: The image corresponds to the results of the heat and temperature loss by the tool. of heat and temperature loss by the tool.

4. INPUTS VARIABLES FOR STABILITY UNDER PRACTICAL STANDARD DNV RP F109

In this tab you can enter the data corresponding to the pipe properties, background data, current properties, wave properties and you can choose the type of soil you want to work with.

Figure 16.

Input variables for the determination of pipe stability in the tool.



Note: The image corresponds to the input variables for the stability part of the pipe considered by the tool.

After having entered the input data, these will be reflected in the template and the criteria for each method contemplated in the standard will be calculated.

Results reflected for the method of vertical stability in water: In this tab it will be possible to demonstrate the compliance with the stability criteria to declare the pipe as safe.

Figure 17.

Result of compliance with the vertical stability criteria in water in the tool.

VERTICAL STABILITY IN WATER	0,094790576	$\gamma_w \cdot \frac{b}{w_s+b} = \frac{\gamma_w}{s_g} \leq 1,$

Note: The image corresponds to compliance with the criterion of vertical stability in water obtained using the tool. the vertical stability in water criterion obtained by means of the tool.

Results reflected for the absolute static lateral stability method: In this tab you can see the results of the criteria for the safety factor and vertical and horizontal stability, where you can make an analysis of the thickness of the concrete and thus comply with the specifications of the method for different sheets of water.

Figure 18.

Results of the variables considered by the method for different water layers and a single thickness in the tool.

ABSOLUTE STATIC STABILITY				
STATIC LATERAL EQUILIBRIUM	STATIC VERTICAL EQUILIBRIUM			
$\gamma_{sc\_y} \frac{(F_D+F_I)+\mu*F_L}{\mu*\omega_s+F_R} \leq 1{,}0$	$\gamma_{sc\_z} \frac{F_L}{\omega_s} \leq 1{,}0,$			
PARAMETER	SYMBOL	DATA	UNITS	
Vertical safety factor in water	Yw	1,1	AD	
Duct thrust per unit of length	b	30019,74735	kg/m	
Internal fluid area	Ai	0,43	m2	
Weight of internal fluid	Wi	0,00	kg/m	
Outer pipe area including casing	Ap	0,009383969	m2	
Anticorrosive coating weight	Wp	0,005536542	kg/m	
Concrete cover area	Ac	11,47803505	m2	
Weight of concrete layer	Wc	345816,7988	kg/m	
Steel duct area	As	0,030589688	m2	
Weight of steel pipe	Wsd	2377,109771	kg/m	
Total pipe weight	Wt	348193,91	kg/m	
Submerged weight of pipe per unit length	Ws	318345,28	kg/m	
Specific duct density	Sg	11,60	AD	
Hydrodynamic duct diameter	D	1,9498	m	
				10 YEARS
Drag style (FD) N/m	4,267	10,922	6,144	6,144
Inertial force(FI) N/m	51,214	51,214	51,214	0,000
Lifting force (FL) N/m	5,486	14,043	7,899	7,899
Vertical contact force between soil and fluid (Fc) N/m	318345,285	318345,285	318345,285	318345,285
Coefficient of force related to area (Ks)	0,025	0,025	0,025	0,025

START

CLICK TO CALCULATE CY* AND CI*

Note. The image corresponds to the results of the variables considered by the lateral stability method. Absolute statics obtained by the tool.

Figure 19.

Result of the vertical and horizontal safety factor for different sheets of water and a single thickness in the tool.

HORIZONTAL SAFETY FACTOR (Ysc_ y) SANDSTONES.	0,4289165	0,431771241
HORIZONTAL SAFETY FACTOR (Ysc_ y) CLAY	0,4132734	0,416024032
VERTICAL SAFETY FACTOR (Ysc_ Z)	1,396314858	1,400347714

Note: The image corresponds to the results of the vertical and horizontal safety factor obtained with the tool.

Figure 20.

Vertical and horizontal stability results for different water layers and a single thickness in the tool

Lateral static equilibrium for sandy soils	0,48064504	0,48859429
Lateral static equilibrium for clayey soils	0,20688112	0,16046452
Static vertical equilibrium	0,39566316	0,39566316

Note. The image corresponds to the results of the vertical and horizontal safety factor obtained using the tool.

Results reflected by the dynamic lateral analysis: In this tab you can see the results considered by the method, which are the basis for the analysis of lateral displacements and to define how to reduce them**.**

Figure 21.

Results of the variables considered by the dynamic method for different water layers and a single thickness in the tool.

START

DYNAMIC LATERAL STABILITY ANALYSIS								
Current conditions								
PARAMETER	SYMBOL	DATA	UNIT					
Current speed	V	37,59577074	m/s					
Short-term wave conditions								
YEARS	10							
Address	P - C1	C1 -C2	C1-C2	C1 -C2	C1 -C2	C1 - C2	C1 -C2	C2 -FSO
Spectral width parameters (α)	0,004906099	0,010850652	0,003562345	0,007527649	0,001770518	0,008634816	0,00436543	0,01335421
Gravity (g)	9,81	9,81	9,81	9,81	9,81	9,81	9,81	9,81
Short-term wave conditions								
Wave frequency (ω) s	0,445615979	0,519271513	0,541653906	0,521426167	0,480365849	0,458626665	0,51927151	0,44656612
Peak wave frequency (ωp)	0,445615979	0,519271513	0,541653906	0,521426167	0,480365849	0,458626665	0,51927151	0,44656612
Peak enhancement factor (Υ)	1	1,447329801	1	1	1	0,865074922	1	5
Spectral width parameters (σ)	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
JONSWAO wave spectrum (Snn(w))	7,698435255	11,46887327	2,106669814	5,384745126	1,908577289	10,15033176	3,18804419	103,664329
Wave number (k)	0,02111232	0,02782747	0,03014923	0,028045373	0,024102204	0,022194682	0,02782747	0,02118988
Water table depth (d)	1800	1700	1500	1000	500	200	120	95
Transfer function G(w	2,79161E-17	2,96064E-21	2,47905E-20	6,89084E-13	5,60887E-06	0,010832888	0,03687508	0,12147418
Espectro de velocidad inducido por onda (suu(w))	5,99948E-33	1,00529E-40	1,2947E-39	2,55688E-24	6,00427E-11	0,001191156	0,00433501	1,5296684
k*d	38,00217602	47,30669933	45,22384508	28,04537275	12,05110191	4,438936441	3,33929642	2,01303826
Spectral momentum of order n (Mo)	9,64672E-42	9,64672E-42	1,81959E-40	3,2859E-25	6,35039E-12	1,81959E-40	0,00055169	0,03032988
Spectral moment of order n (M2)	6,76504E-34	1,24137E-41	2,56754E-40	4,54505E-25	8,42118E-12	0,000168752	0,00076145	0,03504434
Significant amplitude of flow velocity at pipe level (Us)	6,21183E-21	6,21183E-21	2,69785E-20	1,14646E-12	5,03999E-06	2,69785E-20	0,04697598	0,34830954
Mean zero-crossing period of the oscillating flow at pipe level (Tu)	0,000750299	5,538845784	5,28942774	5,342415953	5,456238791	6,52443E-18	5,34817496	5,8452936
Reference period (Tn)	13,54570923	13,16406315	12,36548417	10,09637555	7,139215615	4,51523641	3,49748708	3,11191194

Note: The image corresponds to the results of the variables considered by the dynamic method obtained using the tool.

Results reflected for the generalized lateral stability method: In this tab you can see the results of the criteria for the vertical and horizontal safety factor, where you can make an analysis of the thickness of the concrete and thus comply with the specifications of the method for different sheets of water.

Figure 22.

Results of safety factors meeting the criteria established by the generalized method.

Condición Gráficas	L[illegible]	L[illegible]	Sg	RECOMENDACIÓN		Factor de Seguridad (0,5D)	Factor de Seguridad (10D)
Tabla 4	11,32	4,26	1,12	CUMPLE		0,35	0,09
Tabla 4	11,26	4,22	1,12			0,23	0,06
Tabla 4	11,17	4,25	1,12	INTERPOLACIONES		0,12	0,03
Tabla 5	13,13	4,98	1,12			3,97	1,05
Tabla 5	11,19	3,97	1,12			0,88	0,25
Tabla 5	13,11	4,34	1,12	Gs	Gc	1,38	0,42
Tabla 5	12,93	4,16	1,12	2,6258	0,0021	1,21	0,38
Tabla 5	11,64	4,09	1,12		RECOMENDACIÓN	0,68	0,19
Tabla 4	11,28	4,26	1,12			2,73	0,07
Tabla 4	11,30	4,25	1,12		No hay recomendación	1,83	0,05
Tabla 5	12,65	4,65	1,12			29,31	0,80
Tabla 5	12,65	4,65	1,12		0,001	29,31	0,80
Tabla 5	11,89	4,11	1,12		10	11,24	0,33
Tabla 5	11,81	4,00	1,12		100	10,09	0,30
Tabla 5	11,72	3,98	1,12		1000	8,99	0,26
Tabla 4	11,47	4,21	1,12			3,72	0,10

Note: The image corresponds to the results of the safety factors that meet the criteria established by the generalized method obtained using the tool.

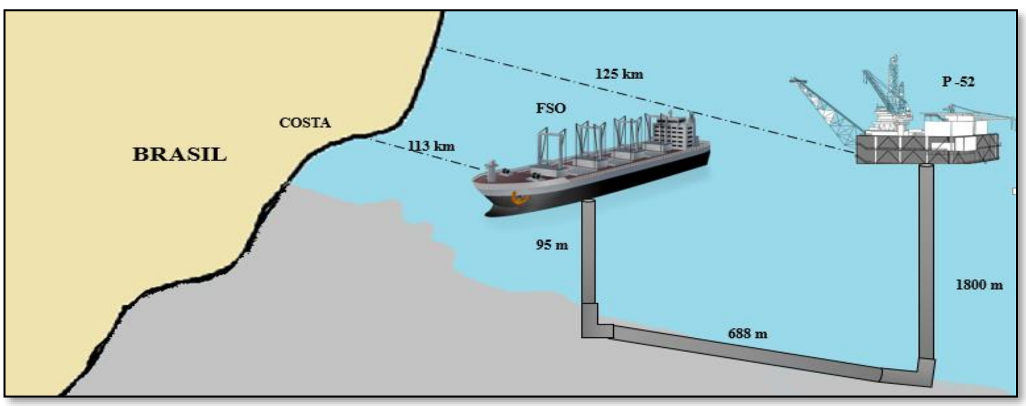
The tool allows an analysis to be made for each type of sheet, in addition to obtaining results that can be tabulated for the creation of comparative graphs as desired by the user.

5. CASE STUDY

To determine the stability analysis under the DNV RP F109 practical standard, a case taken from the literature was considered, which corresponds to the thesis entitled "Verificação de critérios de estabilidade de dutos apoiados no leito marinho", based on the operating conditions considered by the same, an additional document entitled "Chronology: Offshore Reservoir Discoveries and Activities 2007- 2008 by PETROBRAS", from which the pipeline route and initial operating conditions were determined for the definition of the pipeline sizing [9].

Figure 23.

Study route.



Note. The image corresponds to the schematic considered for the analysis using the tool.

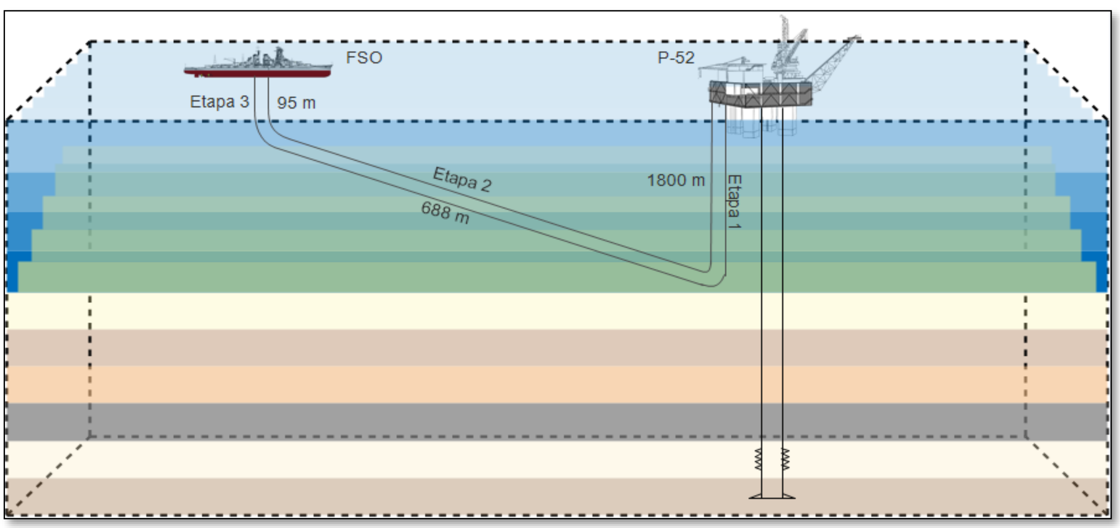
Table 1.
Reference for sensitivity analysis.

Reference point for performance verification	
WATER SHEET (m)	
TOOL	**LITERATURE**
95 m	91,44 m
Changes considered	1

Note: The table corresponds to the reference data considered for running the tool.

In order to obtain a complete analysis of the pipeline, three points of the pipeline trajectory are considered, one of which has similarity with the base data, that is to say that through this similar point a comparison of efficiency of the tool will be made and in this way the results of the other points of the pipeline are guaranteed. The similar point corresponds to a depth of 91.44 m as base data and 95 m as data considered by a field located in basins of field-Brazil.

Figure 24.
Schematic diagram of staged pipeline trajectory.



Note: The image corresponds to the step-by-step schematic considered for the analysis using the tool.

Table 2.

Pipe lengths per stage.

Elbow spacing	
Stage 1	**1800 m**
Stage 2	**688 m**
Stage 3	**95 m**
Total, pipeline	**2,583 m**

Note: The table corresponds to the lengths of the tubes per section considered for running the tool.

Figure 25.

Satellite map with the coordinates of the pipeline location.

Note: This image shows the location of the well taken as a reference or base for the development of the tool and the calculations. taken from: PETROBRAS. (S. f). [Location offshore welloffshoreBrazilcoast]. [Online]. Available:

https://www.google.com/maps/place/Maragogi,+Alagoas,+57955-000,+Brasil/@-9.6549798,-37.2551858,9z/data=!4m8!1m2!2m1!1spozo+ofshore+brazilero!3m4!1s0x700f54d6c7b13db:0x7a5d839403b9f392!8m2!3d-9.0127163!4d-35.2213954?hl=es

[15/09/2021].

Ambient temperature of the area of interest: The temperature and pressure in the area of interest is extremely important, because these can influence the transport of the hydrocarbon, i.e., if there is an increase in temperature the hydrocarbon can change state and also present pressure drops.

Figure 26.
Map of climates and ocean currents of Brazil.

Note. The image corresponds to the Map of climates and ocean currents of Brazil.Taken from: Geografia. laguia2000.

The figure shows a range of marine temperatures between 18 and 30 °C. These ocean currents in the Brazilian Sea come from the African coasts and are mostly made up of warm currents [11].

Table 3.
Ocean temperatures in the months of the year.

Temperature °C	Month
28	January
24	February
30	March
29	April
18	May
20	June
23	July
26	August
27	September
25	October
28	November
29	December

Note: The table corresponds to the ocean temperatures in the months of the year to run the tool.

6. RESULTS

To obtain the results for the design of the pipeline, properties and parameters of the pipeline, insulator and transported oil must be considered.

Table 4.
Input variables for pipeline design.

Fluid name	**Liquid hydrocarbon**
Temperature T (°C)	**30**
Flow Q (m3/h)	**1,145**
Length L (m)	**2583**
Fluid density ρf (kg/m3)	**890**
Viscosity (μ)	**7**
Absolute roughness of the pipe material (ε)	50
Pressure difference Δpf (Mpa)	0,01
Fluid height difference ΔHf (m)	1,188
ΔH (m)	1705
Specific Gravity	0,887
Density kg/m3	890
°API	28
Thermal conductivity K (w/m °C) of piping	4386,4
Thermal conductivity K (w/m °C) of the insulating material	0,5
Inside diameter D1 (in)	28,97
Outside diameter D2 (in)	30

Note: The table corresponds to the Input variables for the piping design to run the tool.

Table 5.

Minimum diameter and coefficient of friction.

Minimum diameter per plot (m)	0,0145
Coefficient of friction per graph (λ) by extrapolation	0,025
Minimum diameter per formula (m)	0,0138
Coefficient of friction by formula(λ)	0,0113

Note: The table corresponds to the results obtained by the tool.

For the calculation of the minimum pipe diameter, the Reynolds number and the relative roughness are considered, in order to obtain the friction coefficient by graph and formula.

Subsequently, the minimum diameter of the pipe is obtained, with a difference of 0.001 between the two procedures.

Table 6.
Cost comparison of larger and smaller diameter pipes.

Option	Pipe	Cost (USD)	Maintenance (USD)
A	20 in	1732	1692
B	10 in	259,8	253,8

Note: This table shows the comparison between the pipeline costs closest to the problem to be tartarized, where the closest to the problem to be tartarized is selected.

The most appropriate option for the case under study is option A, since it has a diameter close to the optimum operating diameter, but it should be noted that option B represents a lower cost and does not guarantee efficient operation.

Optimum duct diameter

For the determination of the optimum diameter, a table entitled "Optimum velocities for non-viscous liquids in pumping lines" should be considered.

Table 7.
Optimum duct diameter

Q m^3/h	Diameter at minimum speed (m)	Diameter at maximum speed (m)	Average value of optimum diameter (m)
1145	0,88	0,62	0,754

Note: The table shows the maximum, minimum and optimum diameter to be handled for the selected pipe.

Table 7 represents the optimum diameter, which is determined by considering technical and economic calculations to ensure adequate operating conditions for the system's conveyance capacity, where the result was an optimum diameter of 0.754 m with a flow rate of 1145 m^3/h.

Table 8.

Determination of the fluid regime inside the pipeline. Source: Own elaboration.

Diameter (m)	Flow rate (m^3/h)	Flow velocity (m/s)	Reynolds number	Regime
0,754	1145	0,686	65773,50	**TURBULENT**

Note: The table shows the calculation of the flow regime for the conditions worked along the path.

A turbulent regime is obtained for the conditions considered in the operation, due to the high flow produced by the reservoir, the diameter handled in the pipeline and additionally for the type of fluid transported.

Criteria for pipe thickness.

Table 9.

Criteria for pipe thickness.

Nominal thickness (tn) in	0,511
Tolerance (A) in	0,05
Design pressure thickness (t) in	0,310

Note: The table shows the nominal diameter and the tolerance to work with according to ocean and pipeline conditions.

In order to comply with the criterion, it is assumed that the nominal thickness must be greater than the sum of the tolerance and the design pressure thickness, where it can be seen in Table 9 that these variables comply with the above mentioned.

Maximum operating pressure (MAOP)

This maximum pressure that the pipe must withstand before suffering any deformation depends on the composition of the pipe, it should be noted that the pumping pressure cannot exceed the MAOP at any point of the pipe section.

Tabla 10.

MAOP

F	0,72
T	0,5118
E	1
T	1
SY	70000
MAOP (psi)	**1433,07**

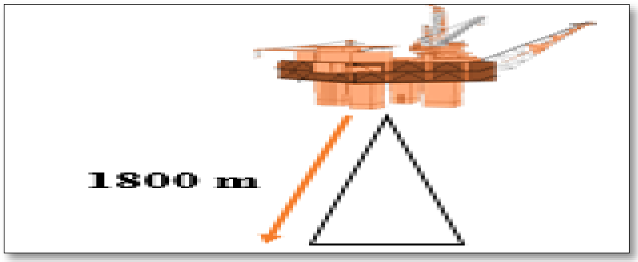
Note: The table shows the factors that must be taken into account to find the maximum allowable pressure for the pipe and what they would be for the case in question.

The maximum allowable operating pressure considers a minimum stress of the pipeline material by the creep obtained for the mechanical and operational conditions of the pipeline, the pipe wall thickness is considered by a criterion that ensures that the nominal thickness meets the design pressure requirements and additional tolerance for threading, The design factor is selected depending on the zone where the pipeline will be located, the joint factor is selected by the specifications and category of the pipe and finally there is the temperature factor which is given by the operating temperature of the system.

Pressure drops and pumping stations per stage

Figure 27.

Diagram of the first stage



Note: The table shows the pressure variation during the first stage.

Table 11.

Pressure losses and number of pumps for the first stage.

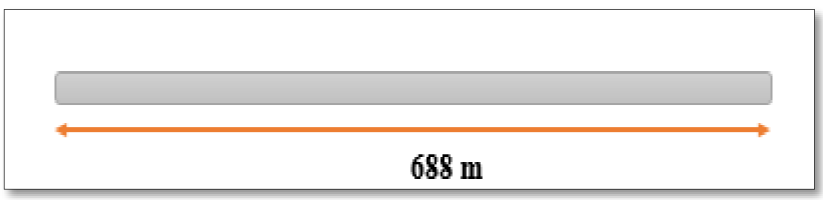
Friction loss (HL) ft (30 in)	3,278
Loss of pressure (ΔP) psi (30 in)	1,421
Outlet pressure (Pi) psi (30 in)	1003,149
POWER REQUIRED IN PUMPING EQUIPMENT	
Electrical Work (BPH) hp	3548,086
Mechanical work (WHP) hp	2838,468
1 pump is required to ensure less than maximum pressure per line in a 30" diameter.	

Note: The table shows an example of the force required through pumps to overcome a specific friction force (first stage).

Stage 2 (elbow1 - elbow2)

Figure 28.

Diagram of the second stage.



Note: This image shows the path length for the second stage.

Table 12.

Pressure losses and number of pumps for the second stage.

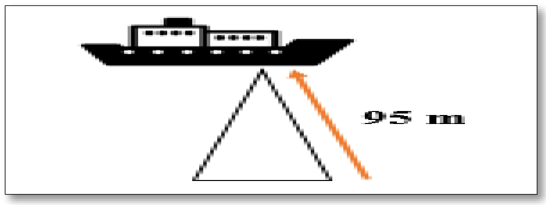
Pipe length ft (30 in)	2257,217
90 ° elbow (30 in)	150
Equivalent length (Le) ft (30 in)	2407,217
Friction loss (HL) ft (30 in)	1,336
Pressure loss (ΔP) psi (Stage 2) (30 in)	0,5794
Total pressure losses stage 1 and 2 (ΔP) psi	35,370
POWER REQUIRED IN PUMPING EQUIPMENT	
Electrical Work (BPH) hp	97318,932
Mechanical work (WHP) hp	46721,724
1 pump is required to ensure less than maximum pressure per line in a 30" diameter	

Note: The table shows an example of the force required through pumps to overcome a specific friction force (Second stage).

Stage 3 (elbow 2 - FSO)

Figure 29.

Diagram of the third stage.



Note: The table shows the pressure variation during the second stage.

Table 13.

Pressure losses and number of pumps for the third stage.

Outlet pressure (psi) (30 in)	1003,149
Arrival pressure (psi) (30 in)	80
Pressure losses (Δp) psi (30 in)	119,727
Friction loss (HL) ft (30 in)	0,173
Total pressure losses in all stages (psi) (30 in)	121,725
POWER REQUIRED IN PUMPING EQUIPMENT	
Electrical Work (BPH) hp	3548,086
Mechanical work (WHP) hp	2838,468
1 pump is required to ensure less than maximum pressure per line in a 30" diameter.	
Total loss of all stages (psi)	121,725

Note: The table shows an example of the force required through pumps to overcome a specific friction force (third stage).

To obtain the pressure losses and number of pumps used to guarantee an inlet pressure of 80 psi, the maximum allowable operating pressure (MAOP) was considered multiplied with a safety percentage of 70%, on the other hand, the total pressure losses in all stages was 121,726 psi, therefore it is required to use 3 pumps in total and one for each stage. It was observed that the stage that had the highest pressure loss was stage 3, due to the fact that it is on an upward trajectory towards the FSO.

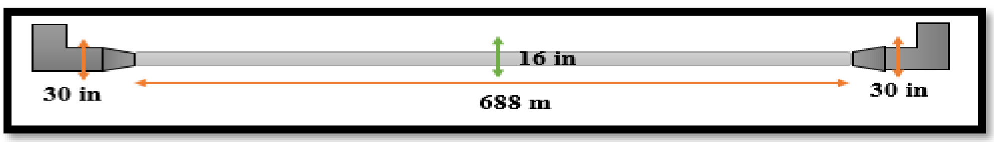
The first pump will be located on the platform, the second at the beginning of stage 2 and the third at the end of stage 2, so as not to affect the desired flow rate and operating conditions.

Change of hydraulic resistance

A change of hydraulic resistance of the entire pipeline was considered by varying a diameter in stage 3, obtaining the following results:

Figure 30.

Diagram of the second stage with diameter change.



Note: The graph shows the distance between elbows, with the diameter handled and the respective length.

Table 15.

Change in hydraulic resistance.

Stage 1	Friction loss (HL) ft (30 in)	3,2789
	Pressure losses (Δp) psi (30 in)	1,421
Stage 2 Diameter Change	Friction loss (HL) ft (16 in)	31,776
	Pressure losses (Δp) psi (16 in)	13,775
	MAOP (16 in)	3224
	Electrical Work (BPH) hp (16 in)	218962,882
	Mechanical work (WHP) hp (16 in)	105121,616
Stage 3	Friction loss (HL) ft (30 in)	0,173
	Pressure losses (Δp) psi (30 in)	119,727
Total loss of all stages (psi)	134,922	

Note: The table shows the pressure losses according to the stages contemplated.

Analyzing the diameter change for stage 2, it can be observed that the total pressure losses for all stages are greater than those that work with a diameter of 30 in, which means that a diameter change is unnecessary because there is no reduction in the number of pumps, in addition the power required in the pumping equipment is greater and therefore the costs would increase if this option is considered.

Table 16.

Thermal behavior without insulation.

Without insulation	
Fluid inlet temperature T (°C)	30
Heat transfer per meter q/L (w/m)	10513,006
Heat transfer all the way through q (w)	27155095,322
Fluid outlet temperature T (°C)	34,42

Note: The table shows the heat transfer values for the uninsulated pipe.

Table 17.

Thermal behavior with insulation.

with insulation	
Fluid inlet temperature T (°C)	30
Heat transfer per meter q/L (w/m)	111,553
Heat transfer all the way through q (w)	288141,899
Fluid outlet temperature T (°C)	30,04

Note: The table shows the heat transfer values for the insulated pipe.

For the thermal analysis, the heat transfer case is evaluated for multilayer cylindrical walls with convection boundary conditions, where the heat transfer by convection and also the small fraction of transfer by conduction is taken into account. For this specific case, the two types of convective heat transfer must be taken into account, i.e. forced convection (oil flow inside the pipe) and natural convection (underwater environment).

Calculations were made for pipes without insulation and with insulation, where a higher heat transfer was obtained in the pipe without insulation and a temperature loss of 4.42 ° C in the total path of the hydrocarbon. Taking into account the temperature changes in the Brazilian coast and marine currents, the implementation of an insulator along the entire pipe route was considered to reduce thermal energy losses, which resulted in a loss of 0.04 ° C, i.e., a reduction of 4.38 °C compared to the first scenario proposed.

The implementation of the pipeline with thermal insulation is recommended, due to the frequent temperature changes in the environment caused by the current climate change, thus decreasing changes in the properties and operational requirements considered, increasing the efficiency of the pipeline, to ensure the continuity of the operation.

Hydrodynamic stability

For this analysis the DVN- RP - F109 practical standard was considered, which is correlated with operational and environmental data from a field offshore Brazil, with hydrodynamic stability data similar to those presented in this country, therefore the following input data were considered.

Table 18.

Physical and geometrical properties of the pipeline.

Parámetro	Data
Hydrodynamic diameter (D) m	0,96
Duct length (L) m	2,583
Outer pipe diameter (OD) m	0,7620
Steel thickness (ts) m	0,013
Thickness of external corrosion inhibitor (tp) m	0,00397
Concrete thickness (tc) m	0,1
Specific gravity of steel (ρs) lbf/ft^3	490
Specific gravity of concrete (ρc) lbf/ft^3	190
Specific gravity of water (ρw) lbf/ft^3	63,99
Specific gravity of the anticorrosive (ρp) lbf/ft^3	115
Specific gravity of the internal fluid (ρf) lbf/ft^3	For the empty pipeline (0) and for the pipeline transporting hydrocarbons (890 kgf/m^3)
Clay shear strength (Su) N/m^2	4000

Note: *The table shows the Specific geometric and physical properties data for the selected pipe.*

Table 19.

Background data. Source.

Type of soil	SAND
Soil friction factor (µ)	0,7
Soil dry weight (ys) N/m^3	18000
Soil wet weight (y´s) N/m^3	13500
Trench Depth (Zt) m	0
Trench angle (Ɵt) °	0

Note: The table shows the specifications of the soil to be worked.

Table 20.

Current data. Source

Reference depth in stages (m)	1800	688	95
Fluid acceleration (A) m/s^2	0,54		
Speed (V) m/s	2,0 - 0,5		

Note: The table shows the characteristics of the fluid for each of the proposed stages.

Table 21.

Seabed roughness. Source.

Type of soil	Grain size (d_{50}) mm	Roughness (Zo) m
Arena media	0,5	0,00004

Note: The table shows the grain size and roughness according to soil type.

Table 22.

Wave properties.

Address	Maximum height (Hmax) m	Significant height (Hs) m	Peak period (Tp) s	Maximum period (Tmax) s	Depth (m)
Platform-elbow1	13,72	6,19	14,1	15,05	1800
Elbow 1-elbow 2 (point 1)	13,30	7,16	12,1	13,05	1700
Elbow 1-elbow 2 (point 2)	13,00	3,57	11,6	12,55	1500
Elbow 1-elbow 2 (point 3)	13,00	5,6	12,05	13	1000
Elbow 1-elbow 2 (point 4)	12,54	3,2	13,08	14,03	500
Elbow 1-elbow 2 (point 5)	13,05	7,6	13,7	14,65	200
Elbow 1-elbow 2 (point 6)	13,08	4,3	12,1	13,05	120
Elbow 2 to FSO	12,98	9	14,07	15,02	95

Note: The summary table shows the weights, maximum, significant and other specific characteristics for each section along the entire route.

Table 23.

Hydrodynamic properties.

Lift coefficient (CL)	0,9
Drag coefficient (Cd)	0,7
Coefficient of inertia (Cm)	3,29

Note: The table shows the hydrodynamic properties used.

Table 24.

Comparison of calculations by means of the tool and the base document.

Parameter	Tool values	Base values	% of Error
Ai (m^2)	0,425	0,426	0,2 %
Wi (N/m)	0,000	0,000	0 %
Ap (m^2)	0,010	0,009	2,8 %
Wp (N/m)	174,211	172,491	0,9%
Ac (m^2)	2,490	2,508	0,7 %
Wc (N/m)	286,346	288,420	0,7 %
As (m^2)	0,031	0,030	1,9 %
Wsd (N/m)	2377,110	2301,344	3,2 %
Sg	1,699	1665	2 %
D (m)	0,970	0,970	0 %
At (m^2)	0,738	0,733	1 %
We (lbf/m)	1670,136	1658,858	1 %
W (1/s)	0,446	0,450	1 %
K (m^{-1})	0,021	0,020	6 %
P (m)	95	91,44	4 %
VERTICAL STABILITY IN WATER			
$yw = \frac{b}{ws+b} = \frac{yw}{Sg} \leq 1$	0,950	0,957	0,7 %
	0,647	0,660	1,9 %

Note: The table summarizes some of the input data and some of the data used to find the vertical stability.

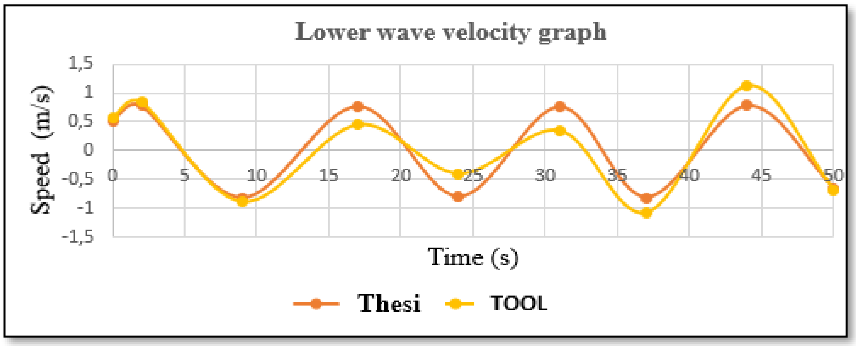
For the calculations of the weight of the pipeline, the base data were considered and a comparison of efficiency was made with the data provided by the tool, obtaining a maximum error of 3.2% and a result of vertical stability criteria in water of below 1, which indicates that the pipeline is declared safe because it meets the criteria according to DNV RP F109.

On the other hand, the horizontal velocity and acceleration were analyzed by using a similar depth with the modified case in the present article, it should be noted that there is an additional margin of error due to the assumed data not considered in the base thesis.

The following graphs represent the behavior of the velocity and acceleration in the different stages of the pipeline, it should be noted that the similar point corresponds to stage 3, where the base data has a depth of 91.44 m and the modified case has a depth of 95 m, which indicates that there is a margin of error of 4% in that reference depth.

Graph 1.

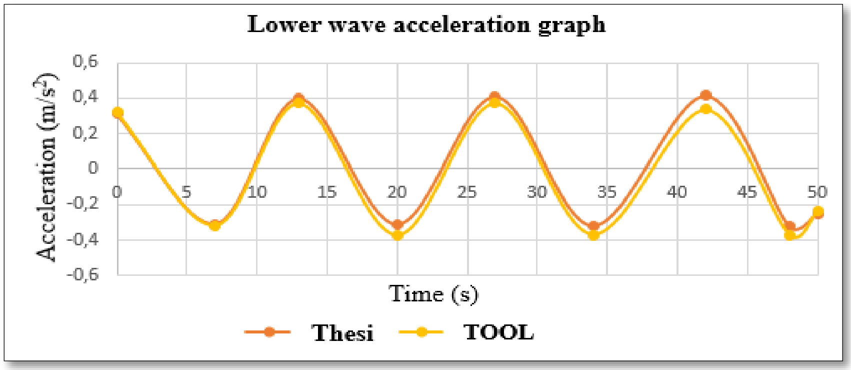
Horizontal velocity of lower wave stage 3.



Note: The graph shows the horizontal velocity of the wave in stage 3.

Graph 2.

Horizontal acceleration of lower wave stage 3.



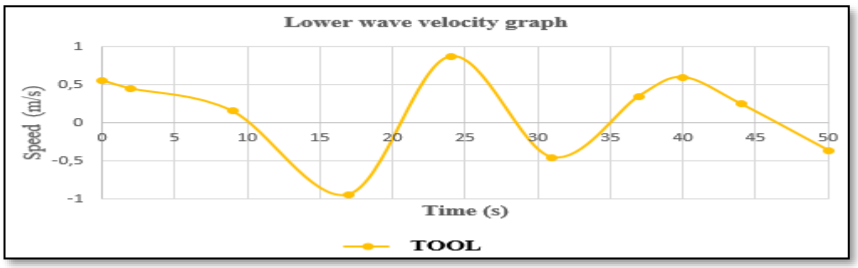
Note: The graph shows the horizontal acceleration of the wave in stage 3.

By means of the graphs it can be observed that the velocity and acceleration in stage 3 have a difference in their results < 0.1 in the different times, after obtaining these results, the process is repeated for the two remaining stages represented in the following two graphs.

For stage 2, an average depth of 1500 m was considered and thus the behavior of the velocity and acceleration at different times was obtained.

Graph 3.

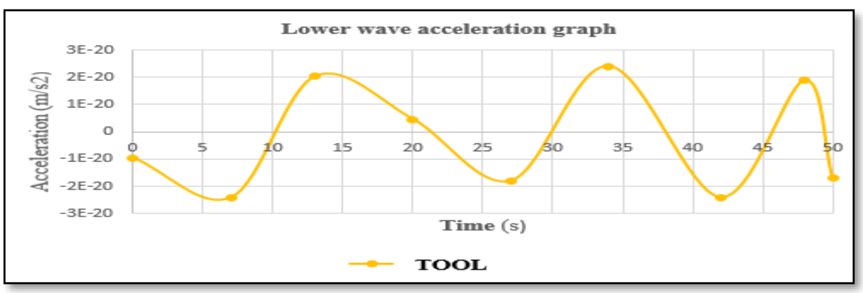
Horizontal velocity of lower wave stage 2.



Note: The graph shows the horizontal velocity of the wave in stage 2.

Graph 4.

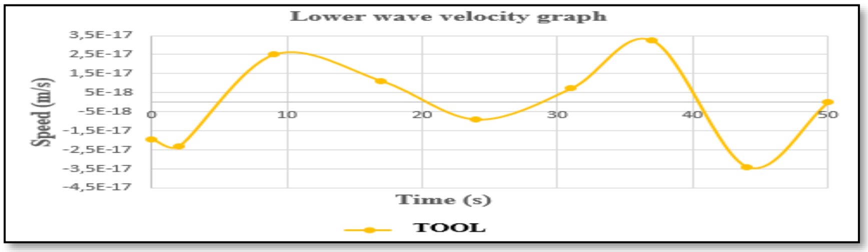
Horizontal acceleration of lower wave stage 2.



Note: The graph shows the horizontal acceleration of the wave in stage 2.

Graph 5.

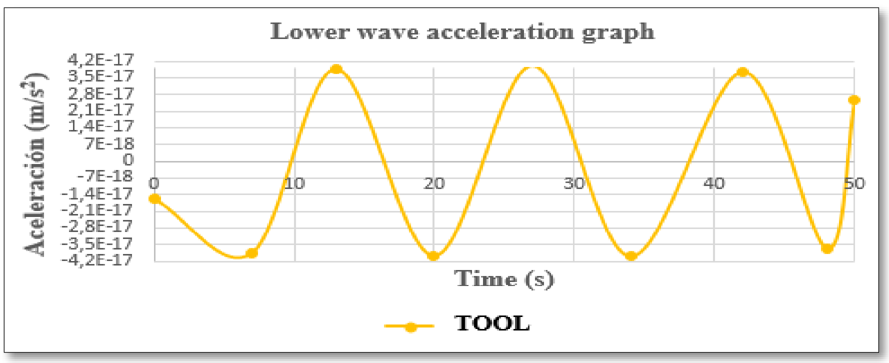
Horizontal velocity of lower wave stage 1.



Note: The graph shows the horizontal velocity of the wave in stage 1.

Graph 6.

Horizontal acceleration of lower wave stage 1.



Note: The graph shows the horizontal acceleration of the wave in stage 1.

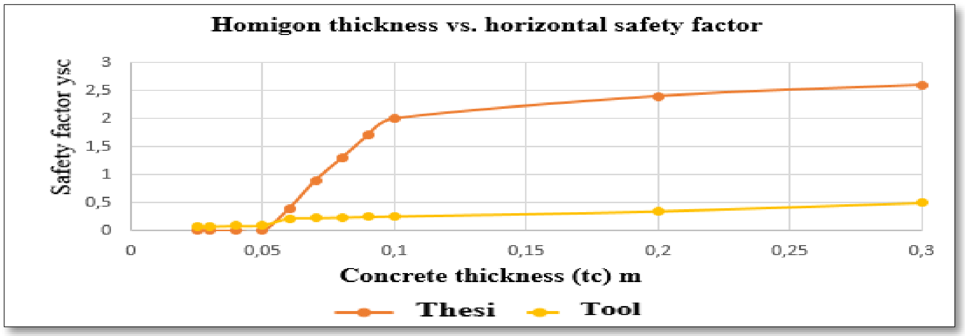
It can be observed that the graphs of stages 1 and 2 have discontinuous behavior compared to stage 3, which indicates the presence of marine currents that produce these changes.

Absolute Static Stability

For this method the DNV - RP -F109 standard considers some requirements of lateral static equilibrium for the pipe to be classified as stable and in this way the following results are obtained.

Graph 7.

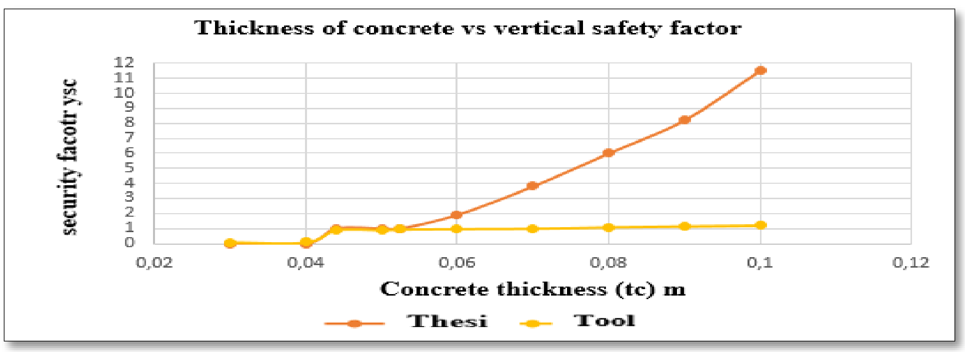
Horizontal safety factors with a variation of concrete thickness in stage 3.



Note: The table shows the value of the horizontal safety factors with a variation of the concrete thickness in stage 3.

Graph 8.

Vertical safety factors with a variation of concrete thickness in stage 3.



Note: The table shows the value of the vertical safety factors with a variation of the concrete thickness in stage 3.

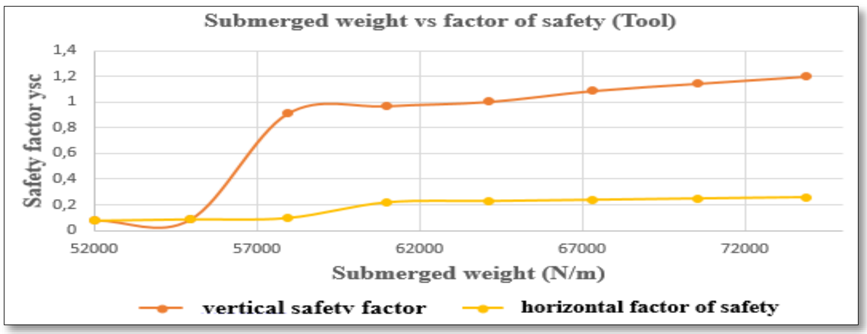
Figure 6 and 7 show the graphs corresponding to the horizontal and vertical safety factors obtained as a function of concrete thickness variation for stage three. These two graphs reflect a significant difference in the data, because the tool considers the calculation of the safety factor by formula, which works with the variables of horizontal and vertical hydrodynamic load, amplitude of the operating velocity for a simple design oscillation, current velocity and peak load coefficient for the two directions at the site conditions, contrary to the safety factor taken from the thesis that works with data according to the ocean where the pipeline is located.

On the other hand, there is a variation in the behavior of graph 7, due to a phenomenon that occurs when the submerged weight of the pipe reaches values close to the lift force.

Stability is reached first in the vertical when it has values higher than 1.1, i.e. it is reached in a thickness of 0.06 m for the base case and for the proposed case in a thickness of 0.07 m and horizontal stability is reached in a thickness of 0.6 m for the base case and for the proposed case in a thickness of 0.59 m.

Graph 9.

Vertical and horizontal safety factors with their respective submerged weight for stage 3.



Note: The graph represents the vertical and horizontal factors of safety with their respective submerged weight for stage 3.

Graph 8 shows that vertical stability is reached at 64104 N/m, while horizontal stability is only reached (≥ 1.1) at a submerged weight of 322138.92 N/m for a safety factor equal to 1.1. It should be noted that if horizontal stability meets the safety factor criteria, which dominates stability, then vertical stability will also meet the safety factor criteria.

Table 25.

Stability results and safety factors for each stage of the pipeline.

Parameter	STAGE 3	STAGE 2	STAGE 1
Concrete thickness for horizontal stability (tc) m	0,59	0,9	0,5
Concrete thickness for vertical stability (tc) m	0,065	0,45	0,19
Horizontal safety factor	1,168	1,129	1,193
Vertical safety factor	1,100	1,153	1,215
Horizontal stability	0,00043	0,00027	0,00054
Vertical stability	0,00011	0,000039	0,000075

Note: The table shows the stability results and factors of safety for each pipeline stage.

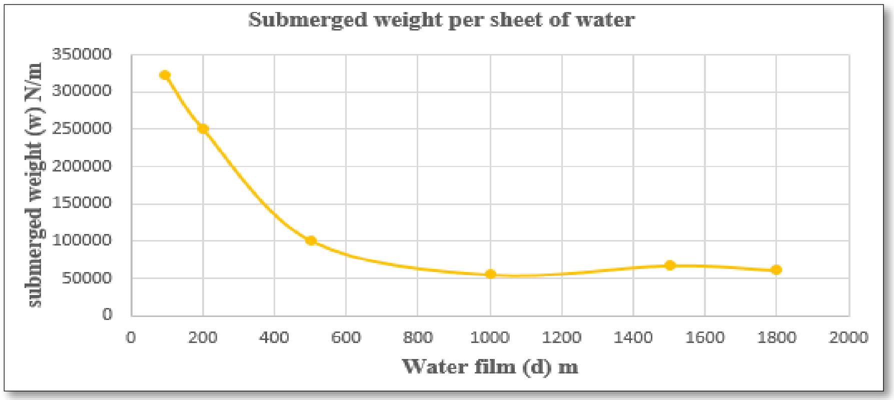
Table 25 shows the concrete thickness corresponding to the safety and stability factor for each stage studied in the proposed case, with a thickness range between 0.065 - 0.59 and a stability of less than 1, which means that the pipe meets all the criteria to declare it safe for all the stages that the hydrocarbon passes through.

Water sheet

The following graph represents the study obtained for the water sheets, which reach a required submerged weight by varying the underwater weight of the concrete thickness, until obtaining vertical and horizontal safety factor values (≥1.1), in this study the depths of each stage are analyzed for its graphical representation.

Graph 10.

Submerged weight depending on the sheet of water of each stage.



Note: The graph shows the submerged weight values as a function of water depth for each stage. Graph 10 shows that the submerged weight is inversely proportional to the depth of each stage, i.e., at shallow depths it is necessary to use pipes with large submerged weights to achieve pipe stability.

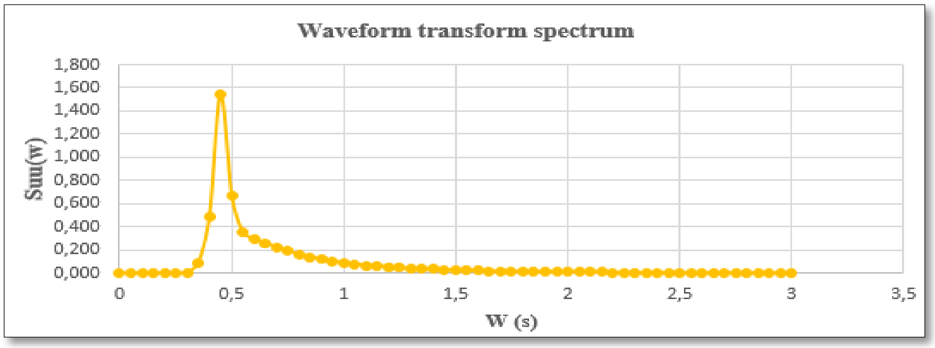
Lateral stability dynamic analysis

This analysis is focused on the study of the lateral displacement of the pipeline, due to hydrodynamic loads, i.e. presence of waves and current. On the other hand, the high temperatures in the pipeline play a very important role because they lead to increase the lateral displacement. It should be noted that the temperature is controlled throughout the pipeline by means of a thermal insulator that will ensure that this event is mitigated.

For stage three we analyze the surface wave spectra reflected in graph 10, which are transformed at a given time, where the velocity is varied with respect to the velocity induced by the location of the pipe on the seabed, adding a constant current velocity to the velocity induced by the pipeline.

Graph 11.

Waveform Transformation Spectrum for 3 stages.



Note: The graph shows the waveform transformation spectrum for 3 stages.

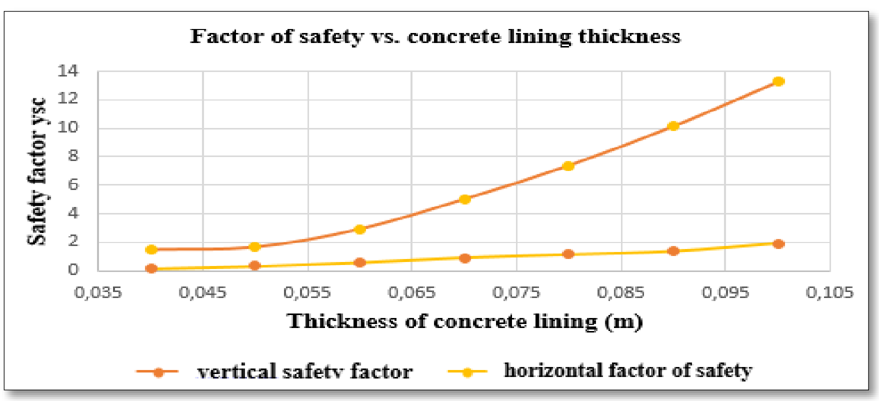
Instability due to hydrodynamic loads due to wave irregularity, which will be controlled by adjusting concrete thicknesses at each stage, will vary depending on compliance with the safety and stability factor criteria considered in the absolute static lateral stability method.

Generalized lateral stability

This analysis studies the displacements caused by the action of an oscillating wave spectrum provided by the data contemplated throughout the work.

Graph 12.

Safety factor versus coating thickness.



Note: Graph of safety factor vs. coating thickness.

The previous graph shows the comparison between the safety factors based on concrete thickness and coating. This graph shows that taking into account the concrete lining, the behavior of the previous graph is maintained, where the horizontal safety factor presents low values with respect to the vertical one. The safety factors for this method show higher values than those of the absolute static stability method.

Table 26.

Stability results and safety factors for each stage of the pipeline.

Parameter	STAGE 3	STAGE 2	STAGE 1
Concrete thickness for horizontal stability (tc) m	0,52	0,6	0,5
Concrete thickness for vertical stability (tc) m	0,035	0,45	0,15
Horizontal safety factor	1,127	1,134	1,221
Vertical factor of safety	1,100	1,163	1,210

Note: The table shows the stability results and safety factors for each pipeline stage.

Table 26 shows the concrete thickness corresponding to the safety factor, with a thickness range between 0.035 - 0.5, which meets the safety factor criterion, i.e. the pipe meets all the criteria to declare it safe for all the stages that the hydrocarbon passes through.

7. CONCLUSIONS AND RECOMMENDATIONS

- HPS is suitable for the determination of simplified pipeline design and hydrodynamic stability analysis at different water depths for a specific case.
- The HSP tool was developed by implementing the standards for the case discussed in the literature at a specific depth and subsequently at different water depths.
- Through the development of the equations and variables, an analysis for the hydraulic and thermal behavior adequate to the specific case discussed in the literature was obtained for a subsequent stability analysis.
- The performance of the tool was validated, taking into account a reference point according to the data provided by the literature.
- Taking into account the difference in results, recommendations were formulated to guarantee results with less uncertainty.

8. RECOMENDATIONS

- The use of complete data is recommended to ensure the reliability of the results.
- It is important to calculate the safety factor by formula in the proposed tool to mitigate errors and reduce uncertainty.
- In case of using general safety factors of a particular ocean, it is recommended to use only the pipeline design and stability methods variables independent of the safety factor of the HSP tool.
- In obtaining the result, a variation with respect to the base data was observed, due to the implementation of input data not provided by the literature, so the use of cases of pipeline designs linked to hydrodynamic stability under DNV -RP F109 is recommended.
- This analysis can only be used as a study tool for issues related to sizing and hydrodynamic stability under DNV RP F019.

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