Analysis of Submarine Pipelines Installation through Progressive Immersion Method

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Abstract

Submarine pipelines installation is a complex and delicate maritime operation, which becomes more important due to the increasing energy needs and environmental concerns of modern societies.

The most common installation methods, S-Lay, J-Lay and Progressive Immersion, introduce bending efforts that may cause the collapse of the conduit whose limit state is known as buckling. In order to reduce the bending efforts and consequently avoid buckling, maritime contractors apply a pulling force to the pipeline.

The present thesis focuses on the theoretical study of submarine pipelines installation and on the calculation of the required pulling force according to three calculation methods, two analytical methods which do not consider dynamic forcing (wave, current and wind) and one numerical method which does.

This thesis was developed within the framework of the Raoued – Tunis Sea Outfall installation, currently carried out by the maritime contractor Etermar – Engenahria e Construção, S.A, which is the case study for the thesis.

The comparison between the results from the analytical methods and the ones from the numerical method leads to the conclusion that the analytical methods provide a conservative estimate for the pulling force. On the other hand, the results from the numerical method (finite element model) shows the importance of considering the dynamic forcing when calculating the pulling force, since changes in environmental conditions generates considerable variations of said pulling force.

The present dissertation deepens the knowledge about the subject, through a comparison study between calculation methods, thus making the process of pipe installation safer.

Keywords: Buckling, Progressive Immersion, Sea Outfall, Submarine Pipelines Installation, Orcaflex.

1. Introduction

The growth of the world’s population, the depletion of freshwater reserves, and the increasing energy needs have led, in the last decades, to an increase in submarine pipelines installation projects focused on both the disposal of wastewater and the obtainment of seawater for desalinization stations and thermoelectric plants.

Submarine pipelines have been installed according to S-Lay, J-Lay and Progressive Immersion methods. The installations methods induce bending efforts, along submarine pipeline, that may cause the collapse of the conduit whose limit state is known as buckling.

In order to avoid buckling, marine contractors usually apply a pulling force that reduces bending efforts.

The present study was developed with the support of the maritime contractor Etermar – Engenharia e Construção, S.A, currently carrying out the project of the Raoued – Tunis Sea Outfall. The study carries out a theoretical analysis of the subject (submarine pipelines installation) and calculates the pulling force by utilizing three calculation methods (two analitical methods and one numerical method), using as a case study the installation of the Raoued – Tunis Sea Outfall.

The case study aims to evaluate the importance of considering the dynamic forcing (wave, current and wind) during the operation and on the pulling force calculation, as the analytical methods, unlike the numerical method, do not take the dynamic forcing into account.

2. Installation Methods

The installation of submarine pipelines is a delicate maritime operation due to bending efforts induced. Installation methods bend the submerse conduit so, in order to maintain structural stability the induced curvature must be smaller than its critical value (associated with buckling).

The most common installation methods are: S-Lay, J-Lay and Progressive Immersion. Etermar – Engenharia e Construção, S.A has used, throughout several projects, the Progressive Immersion Method.

The S-Lay Method derives its name from the “S” configuration adopted by the submerse conduit during installation, Figure 1. The pipeline leaves the S-Lay barge through a curved structure (stinger) while the tensioners, mounted on the top of the stinger, apply the pulling force.

The pipeline is composed by a set of short length tubes, welded together on the horizontal welding ramp.

The “S” configuration has two main regions: overbend and sagbend. In the overbend region, the induced curvature (bending efforts) is controlled trough stinger’s curvature and composition. In the sagbend region, induced bending efforts are only regulated trough the applied pulling force.

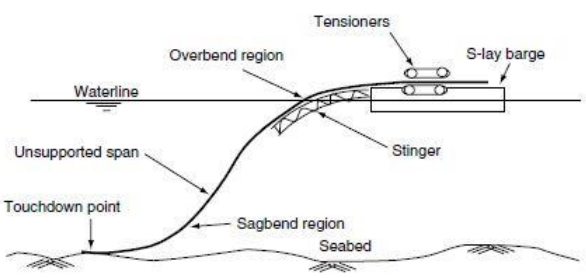


Figure 1 – S-Lay configuration

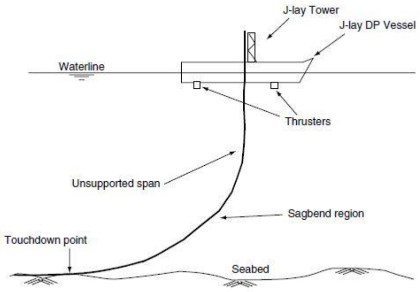


Figure 2 - J-Lay configuration

The J-Lay Method is much like the aforementioned method, named as such due to the “J” configuration adopted by the submerse conduit during installation, Figure 2. According to this method, the pipeline leaves the J-Lay barge through a J-Lay Tower (vertical orientation) and the tensioners, mounted in the bottom of the J-Lay Tower, apply the pulling force.

The short length tubes are welded together in the welded stations along the J-Lay Tower.

The “J” configuration has one main region: sagbend. In which, the induced curvature is controlled trough the applied pulling force.

The Progressive Immersion Method is the method used by Etermar. In this method, the submerse conduit adopts the same “S” configuration mentioned above. However, in this case the pulling force is assured by a tugboat and not by tensioners, Figure 3.

The Progressive Immersion Method is mainly used in the installation of HDPE (High Density Polyethylene) pipes. Due to HDPE’s density (smaller than one), the conduit’s immersion is only possible with the assembly of a set of concrete ballasts (weights).

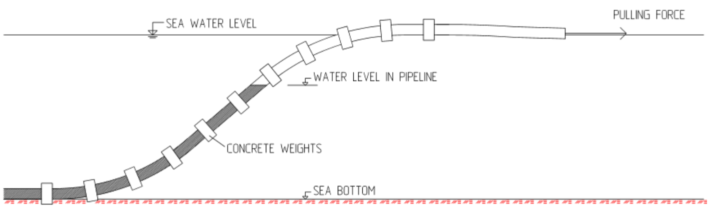


Figure 3 – Progressive Immersion configuration

The pulling force, applied to an extremity of the pipeline, is balanced by an anchorage system (two steel cables and two concrete blocks with 12tons) connected to the opposite extremity.

The “S” configuration has two main regions: overbend and sagbend. In both regions, the applied pulling force regulates the induced bending efforts.

3. Buckling

The limit state associated with the induced curvatures during submarine pipelines installation is known as buckling. The buckling is controlled by the combined effect of bending efforts (due to "S" and "J" configurations), traction efforts (due to the pulling force) and hydrostatic pressure (pressure exerted by the surrounding fluid).

The buckling expresses itself through the cross-section ovalization, Figures 4 and 5.

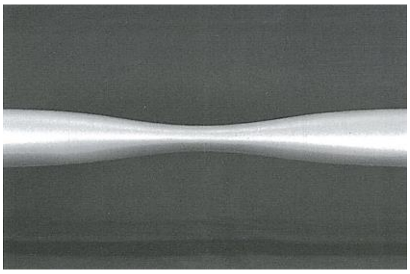


Figure 4 – Local buckle

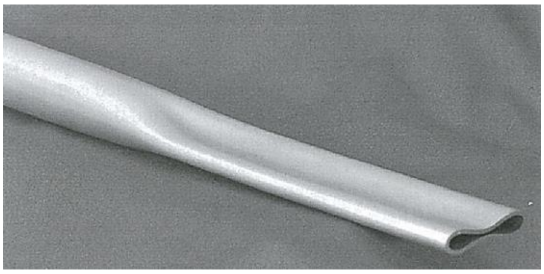


Figure 5 – Propagating buckle

(Kyriakides, S & Corona, E. 2007.)

In the overbend region, the limit state is regulated mainly by the combined effect of bending efforts and traction efforts, since the hydrostatic pressure is negligible. In the sagbend region, the combined effect of bending efforts and hydrostatic pressure controls buckling, since the pulling force is reduced.

The collapse hydrostatic pressure (associated with the beginning of buckling) is given by 1). It depends on the yield hydrostatic pressure, $P_0 = \frac{2t\sigma_0}{ø_{ext}}$, the yield stress, σ_0, the wall thickness, t, the outer diameter, $ø_{ext}$, the initial ovality, $\Delta_0 = \frac{\Delta ø_0}{ø_{ext}}$, the registered difference between maximum and minimum diameters, $\Delta ø_0$, and the critical buckling hydrostatic pressure, $P_C = \frac{2{,}2t\sqrt{E}}{l}\sqrt{\frac{E}{4(1-\upsilon^2)}\left(\frac{t}{R}\right)^3}$. The critical buckling hydrostatic pressure represents the beginning of buckling for perfect conduits (Δ_0=0).

$$P_{CO} = 0{,}5\left\{\left[P_0 + P_c\left(1 + 3\Delta_0\frac{ø_{ext}}{t}\right)\right] - \left[\left(P_0 + P_c\left(1 + 3\Delta_0\frac{ø_{ext}}{t}\right)\right)^2 - 4P_0P_c\right]^{\frac{1}{2}}\right\} \qquad 1)$$

The consideration of traction efforts reduces the collapse hydrostatic pressure, 2). The reassessed collapse hydrostatic pressure depends on the pulling force, T, the yield traction effort, $T_0 = \pi t ø_{ext}\sigma_0 - \pi t^2\sigma_0$, and the yield hydrostatic pressure taking into account the traction efforts, $P_{0T} = P_0\left(-\frac{\frac{T}{T_0}}{2} + \sqrt{1 - \frac{3}{4}\frac{T}{T_0}^2}\right)$.

$$P_{COT} = 0{,}5\left\{\left[P_{0T} + P_c\left(1 + 3\Delta_0\frac{\emptyset_{ext}}{t}\right)\right] - \left[\left(P_{0T} + P_c\left(1 + 3\Delta_0\frac{\emptyset_{ext}}{t}\right)\right)^2 - 4P_{0T}P_c\right]^{\frac{1}{2}}\right\} \qquad 2)$$

Bending efforts promote cross-section ovalization and reduces pipeline's bend stiffness.

In the sagbend region, the hydrostatic pressure ovalizes conduit's cross-section reducing its bend stiffness and consequently its maximum bending moment. Therefore, the used installation method cannot induce high curvatures because bend stiffness is already reduced. The induced curvatures are regulated through the applied pulling force.

On the other hand, the applied pulling force induces traction efforts that interact directly with bending efforts in the overbend region. Thus, the pulling force has a double effect: it reduces the induced curvature (reducing the bending efforts) while inducing traction efforts that may reach high values in deep-water installations.

4. Calculation Methods

The present study uses two analytical methods and one numerical method to calculate the pulling force relative to the practical case study, Raoued – Tunis Sea Outfall.

The analytical methods are The Theory of Pure Bending and Chain Link Theory. The numerical method is Orcaflex.

a. Orcaflex

Orcaflex is a widely known software that reproduces a given maritime operation according to six available elements. The software also considers the dynamic forcing (wave, current and wind).

In this study, the "Line" element models the submarine pipeline and the anchorage system (steel cables) whereas the pulling force is modeled by the "Winch" element.

The "Line" allows the user to introduce all the geometric and physic properties of a given entity, such as the submarine pipeline as well as the steel cables of the anchorage system. The concrete blocks of the anchorage system are modeled by a stiff connection between the steel cables and the seabed.

The "Line" is modeled by a set of line segments (stiff and massless segments) with a node at its extremities (Orcina.), Figure 6. At each time step, tension forces, bending moments, shear forces and torsion moments are calculated, in each line segment, in accordance with the instantaneous position of the extreme nodes and the considered properties (geometric and physic).

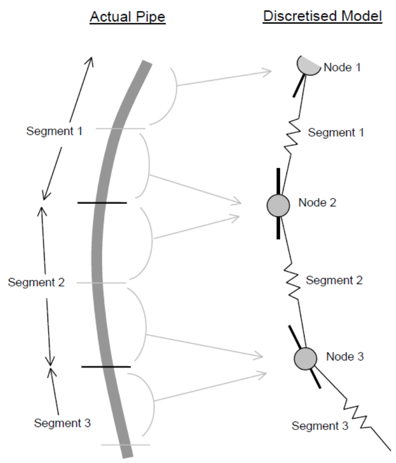


Figure 6 – Line model, Orcaflex (Orcina.)

The "Winch" simulates a given force and applies it to a given element (pipeline, vessel…). The calculation of the pulling force with Orcaflex is a trial and error process in which the user inputs a given value to the pulling force ("Winch") and registers the minimum bending radius calculated during the simulation. If the minimum bending radius is smaller than its critical value, $R_{lim}^{F.S=1,5}$, the user needs to increase the provided value. Otherwise, the value is enough to carry out the installation.

Dynamic forcing (wave, current and wind) induce extra forces that increase the bending efforts (curvatures) during pipelines installation. The Wave (Non Linear Dean Stream Theory) is modeled by its direction, peak period, T_p, and significant wave height, H_s. The Current is modeled by its direction and intensity at sea surface (the present study does not consider any change in depth). The Wind is modeled by its direction and intensity.

b. The Theory of Pure Bending and Chain Link Theory

The Theory of Pure Bending and Chain Link Theory are used together and solve the static system shown in Figure 7 to calculate the pulling force.

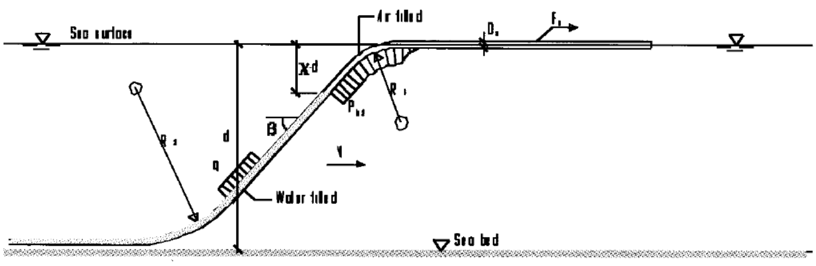


Figure 7 – Static system use by the analytical methods (Grann-Meyer, E. 2005)

The Theory of Pure Bending assumes the pulling force equal to zero and compares the bending radius at sea surface and seabed, $R_1 = 2{,}75\varnothing_{ext}\sqrt{\frac{E}{d}}\sqrt{\left(1-\left(1-\frac{2}{SDR}\right)^4\right)}\sqrt{\frac{1}{\chi^d(1-\beta_0^1)}}$ and $R_2 = R_1\frac{(1-\beta_0^1)}{\beta_0^1}$, to its critical value, 3). If $R_1 < R_{lim}^{F.S=1,5} \vee R_2 < R_{lim}^{F.S=1,5}$, The Theory of Pure Bending is not applicable and Chain Link Theory must be used, since the installation may not be carried out without pulling force.

The bending radius at sea surface and seabed depends on the outer diameter, $ø_{ext}$, the Young's Modulus, E, water depth, d, the Standard Dimension Ratio, $SDR = \frac{ø_{ext}}{t}$, the air pressure factor, $\chi^d = \frac{p_i}{d}$, the internal pressure of the conduit, p_i, and the net submerged loading percentage given as a percentage of the pipe's displacement, β_0^1.

$$R_{lim}^{F.S=1,5} = 1{,}5ø_{ext}\left(\frac{\upsilon(SDR-1)}{0{,}56}\right) \quad 3)$$

In order to ensure $R_1 > R_{lim}^{F.S=1,5} \wedge R_2 > R_{lim}^{F.S=1,5}$, Chain Link Theory calculates two pulling forces, each one relative to the bending radius at sea surface and seabed, and the greater value represents the required pulling force to avoid buckling along the entire submarine pipeline.

The pulling forces, $F_{s\,1} = R_{lim}^{F.S=1,5}|P_{b2}|$ and $F_{s\,2} = R_{lim}^{F.S=1,5}|q|$, depends on the critical bendig radius, $R_{lim}^{F.S=1,5}$, the net buoyance in air filled section, P_{b2}, and the net weight of water filled section, q. The greater value of $F_{s\,1}$ and $F_{s\,2}$ depends on the relation between P_{b2} and q. It is important to note that P_{b2} and q are linear weights and take into account the weight of the concrete ballasts.

5. Case Study – Calculations

The Raoued – Tunis Sea Outfall is 6300m long. According to Etermar's planning, the sea outfall is composed by seven conduits (seven installations) whose lengths are comprised between 232m and 1093m. This document studies the installation of the first 1091m.

The geometric and physic properties of the sea outfall are as follows: $ø_{ext}$=1600mm; SDR=26; υ=0,42, E=1080Mpa; HDPE's Density=960kg/m^3 and Direction=64ºN.

The geometric and physic properties of the concrete ballasts are as follows: Volume=2,49m^3; Reinforced Concrete's Density=2500kg/m^3; Mass=6230kg; Spacing=5m and Total Number of concrete ballasts =216.

The geometric and physic properties of the steel cables are as follows: Material=Steel; Length=70,8m and ø=30mm.

The seabed properties are as follows: Average Slope=0,3%; Tide Level (N.G.T)=0,8m; Maximum Natural Terrain Level (N.G.T)=-18,4 and Maximum Installation Depth=19,2m. N.G.T – Nivellement Général de la Tunisie is the local altimetric referential.

The following Installation Scenarios (dynamic forcing), Table 1, have been set up according to (Serah Arteliah. 2014.).

The present study considers three Installation Scenarios. It is important to remind that the Installation Scenarios are the basis of the comparison between the static analysis (analytical methods) and the dynamic analysis (numerical method).

Entity	Parameter	Unit	Scenario 1 - Static	Scenario 2 - Dynamic	Scenario 3 - Dynamic
Seawater	Density	kg/m³	1025		
Wave	Significant Wave Height, H_s	m	0	0,5	1
	Peak Period, T_p	s	0	4	
	Direction	ºN	-	30	
Current	Intensity	m/s	0	0,5	
	Direction	ºN	-	337,5	
Wind	Intensity	m/s	0	5,56	
	Direction	ºN	-	0	

Table 1 – Installation Scenarios (dynamic forcing)

a. Analytical Methods

i. The Theory of Pure Bending

According to 3), the critical bending radius is equal to 53,57m.

The bending radius at sea surface and seabed depend on p_i and β_0^1. Etermar usually adopts p_i=0,6bar, since this value generates a controlled installation without the appearance of considerable dynamic forces. The net submerged loading percentage given as a percentage of the pipe's displacement is the submerged height of a conduit whose linear mass equals q divided by the total height of the real conduit ($ø_{ext}$=1600mm). According to all the geometric and physic properties presented above (conduit, concrete balasts and seawater), q=712,83kg/m and χ^d=0,39. Hence, the bending radius at sea surface and seabed are R_1=39,63m and R_2=61,20m, respectively. Being $R_1 < R_{lim}^{F.S=1,5}$, the installation may not be carried out without pulling force and Chain Link Theory must be used.

ii. Chain Link Theory

According to all the geometric and physic properties presented above, q=712,83kg/m and P_{b2}=-1043,19kg/m. Hence, $F_{s\,1}$=55,89ton and $F_{s\,2}$=38,35ton.

The required pulling force to avoid buckling is equal to 55,89ton.

iii. Orcaflex

The following figures illustrate the installation when using Orcaflex.

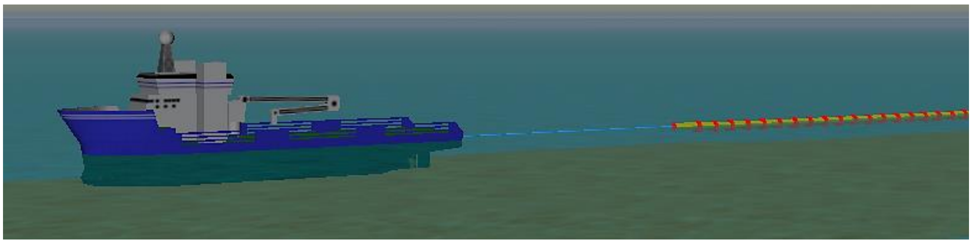


Figure 8 – Tugboat exerting the pulling force

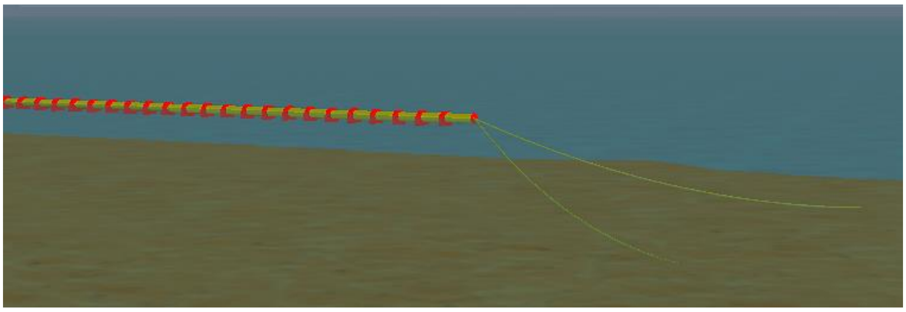


Figure 9 – Steel cables of the anchorage system

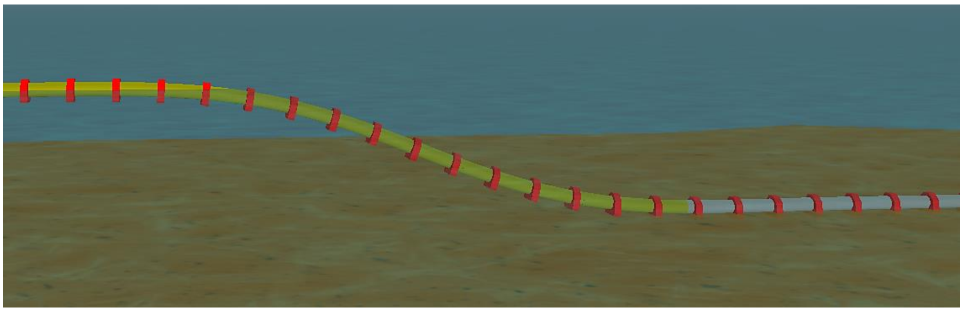


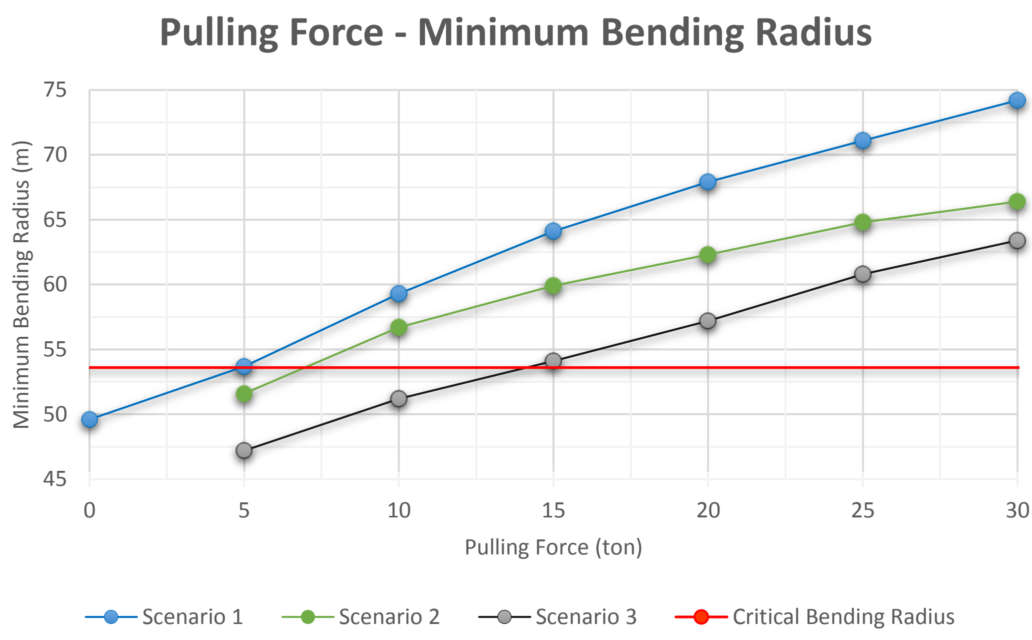
Figure 10 – "S" configuration during immersion

Table 2 presents the required pulling force for each Installation Scenario and its respective minimum calculated bending radius.

Installation Scenario	Required Pulling Force (ton)	Minimum Calculated Bending Radius (m)	Critical Bending Radius (m)
Scenario 1	5	53,7	53,6
Scenario 2	10	56,7	53,6
Scenario 3	15	54,1	53,6

Table 2 – Required Pulling force – Installation Scenario

Graphic 1 represents the relationship between the pulling force and the minimum calculated bending radius for the three Installations Scenarios.



Graphic 1 – Relationship Pulling Force – Minimum Bending Radius

The results obtained with Orcaflex are significantly different from the one calculated by the analytical methods. The required pulling force obtained by Chain Link Theory is eleven times greater than the one determined by Orcaflex for Scenario 1 and four times greater than the one calculated for Scenario 3.

6. Conclusion

This study allowed several conclusions to be drawn, namely:

- Results from the analytical methods are very conservative, as expected by Etermar since the adopted values in several projects have always been smaller.
- Results from Orcaflex are in accordance with Etermar's expectations (based on their experience).
- Dynamic analysis carried out using Orcaflex leads to the conclusion that dynamic forcing play an important role in the calculation of the pulling force, since it varies between from 5ton (Scenario 1) and 15ton (Scenario 3).

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