SIMPLIFIED METHOD FOR IDENTIFICATION OF FREE SPANS ON SUBMARINE PIPELINES

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Abstract. *It is well known that, after a submarine pipeline is laid over the seabed, free spans may appear due to the unevenness of the seafloor, associated to the relatively high bending stiffness of the pipe, and to the residual tension from the pipe laying process.*

In order to numerically determine the final equilibrium configuration of a pipeline laying on the seabed after its installation procedure, a numerical tool has been developed (Jacovazzo et al., 2013). The tool is based on global Finite Elements models, and simulates the evolution of *the pipe laying process along a predetermined route, using the actual seabottom bathymetry data. However, the use of numerical tools may be computationally expensive in some cases.*

In this context, this work describes the development of a simplified method (called Spinning Circle Method) to determine the final equilibrium configuration of a pipeline laying on the seabed after its installation procedure. A parametric study has been performed to compare results obtained by the Spinning Circle Method and the Finite Elements numerical tool for several pipe sections.

Keywords: *Spinning Circle Method, Submarine pipelines, Free spans.*

1 INTRODUCTION

The definition of submarine pipeline routes is a complex task that involves many variables and requires sensibility and experience from the designer. To minimize costs, it would be ideal to establish a straight route between the two connection points; however in general this is not feasible due to several factors, including the following ones:

- Irregular bathymetry of the seabed, associated with different types of soil, especially in very large routes, including unstable soils that should be avoided.
- Natural and artificial obstacles to be avoided, such as environmental preservation areas, pipelines already installed, platform mooring lines etc. Many fields now contain dozens of platforms with hundreds of pipelines crossing them, creating a complex and dense mesh of obstacles.
- Lateral instability of the pipe due to wave and current action (DNV-RP-F101, 2007; Lima Jr., 2010).
- Free spans that may occur in some regions of the pipeline, possibly leading to fatigue caused by vortex induced vibration (VIV).
- Mandatory waypoints defined in project.

Therefore, the design of pipeline routes must seek a balance between the cost of increasing the length of a pipeline route (in order to avoid the problems previously described) and the cost of engineering interventions that may be required for routes with shorter length.

To help engineers solving this problem, a computational tool for the synthesis and optimization of pipeline routes using evolutionary algorithms has been developed by researchers from LAMCSO-COPPE-UFRJ in partnership with Petrobras (Baioco, 2011; Vieira et al., 2010; Lima Jr. et al., 2011). This tool employs nature-inspired optimization algorithms (Vieira, 2011; Lucena, 2011; Monteiro, 2008; Silva, 2010), and is able to automatically generate and analyze innumerous candidate routes for a given scenario, taking into consideration the various aspects involved in the definition and evaluation of the routes.

In summary, the route optimization tool seeks to minimize the length of the route verifying a set of constraints associated with pipeline design criteria, such as:

- Avoid interference of the pipeline with obstacles present in the region of launching.
- Avoid areas with steep slopes.
- Verify the stability criteria of the pipeline laying on the seabed under the action of hydrodynamic and hydrostatic loads.
- Verify the maximum length of free spans (excessive lengths may lead to vortex induced vibrations, which require engineering interventions).
- Verify the minimum horizontal radius of curvature of the pipeline, which is function of the residual tension of the launching process.
- Verify other aspects of the structural behavior of the pipe in terms of stresses and displacements.

2 PROBLEM DESCRIPTION

As previously mentioned, there are many variables that have to be taken into account when defining a submarine pipeline route. Among all the variables presented before, this paper is focused on the identification of free spans (sections of the pipeline that loses contact with the seabed, mainly because of the unevenness of the seafloor associated to the relatively high bending stiffness of the pipe). Figure 1 schematically presents an example of free span.

The current flow acting on the suspended portion of the pipe may generate vortex shedding (as represented in Figure 2) which induces vibrations on the pipeline. This phenomenon is known as "Vortex Induced Vibration" (VIV) and may generate fatigue problems at the pipeline.

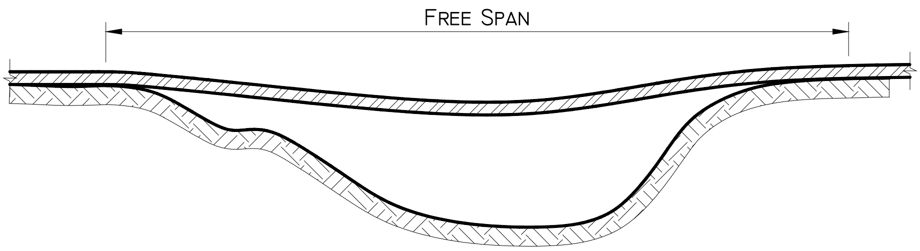


Figure 1. Schematic representation of a pipeline free span

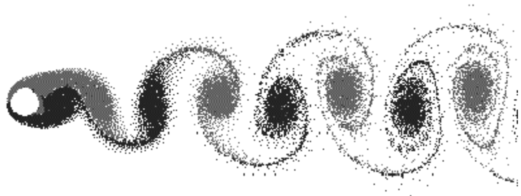


Figure 2. Vortex shedding in a pipeline due to the flow action

Engineers should be able to identify where free spans may occur when designing a pipeline route in order to verify if there would be fatigue problems at the pipe. However this is not a simple task as the formation of free spans depends on several factors inherent to the installation procedure and to the pipeline and soil characteristics.

In this context, a numerical tool has been developed by Jacovazzo et al. (2013) to obtain the final equilibrium configuration of submarine pipelines on the seabed after the laying operation, by generating Finite Element models and performing nonlinear analyses while automatically activating/deactivating finite elements along the evolution of the pipe laying operation. Thus, this numerical tool is able to provide several details of the final configuration of the pipeline after the installation process, such as its stresses and free spans characteristics. Then, the engineer would be able to apply criteria based on the recommendations of DNV-RP-F105 (2006) code in order to investigate possible fatigue problems due to VIV at any proposed route.

The numerical tool has been implemented in the SITUA-Prosim system (2006), that has been developed by LAMCSO-COPPE-UFRJ in collaboration with CENPES-Petrobras.

3 OBJECTIVE

Although the use of numerical tools for identifying free spans leads to fairly accurate results, in some cases it can be necessary to perform simplified parametric analyses, providing faster results so that it can be taken as a basis for more detailed analyses. This becomes more evident considering the utilization of optimization tools for determining the best pipeline route for a given scenario. A lot of candidate routes are constantly proposed by the program and, for each one of them, the free spans must be identified so they can be evaluated considering the normative criteria.

Performing a Finite Elements simulation for each one of the candidate routes may significantly increase the computational cost of the optimization process. Thus a simplified method for the identification of free spans could be used as a preliminary filter that would select the best routes to be analyzed with the numerical algorithm during the optimization process.

In this context, the objective of this paper is to present the development of a simplified analytical method, the Spinning Circle Method, which is able to detect free spans on pipeline routes with irregular bathymetry. The method is based on a simple premise that the final equilibrium configuration of the pipeline laying on the seabed after the installation process can be compared to the trajectory of a spinning circle over the seabed. The radius of this circle is approximately adopted as equal to the curvature radius of the pipeline's Touch Down Point during the installation phase.

4 SPINNING CIRCLE METHOD

4.1 Basic Premise

Figure 3 schematically presents a typical S-Lay configuration for the installation of a submarine pipeline. As it has been mentioned before, the formation of free spans depends on several factors inherent to the installation procedure and to the pipeline and soil characteristics. Some of them can be listed below:

- Launching tension applied to the pipeline by the vessel.
- Bathymetry data, providing the seabed profile.
- Soil physical properties.
- Pipe section data providing information like weight and bending stiffness of the pipeline.
- Environmental loads acting on the pipeline and on the vessel.

Defining an analytical expression that consider all of these aspects and provides the final configuration of the pipeline on the seabed may be a hard task that should be adapted to all of the endless possibilities that may be encountered. Instead, this article aims to bring a simplified method that can be easily used by engineers in order to provide fast preliminary results.

The basis of the method lies on the premise that the radius of curvature of the pipeline at the TDP during the installation phase (which is directly related to the horizontal launching tension applied by the vessel) is maintained relatively constant during the launching procedure. It could be modified at certain points of the route once the horizontal tension was adjusted. Anyway, it could be considered constant along sections of the route. This is a simplified premise, but quite reasonable since the launching tension applied by the vessel is controlled by a tension machine that maintain this parameter within a small operating range defined by the engineers.

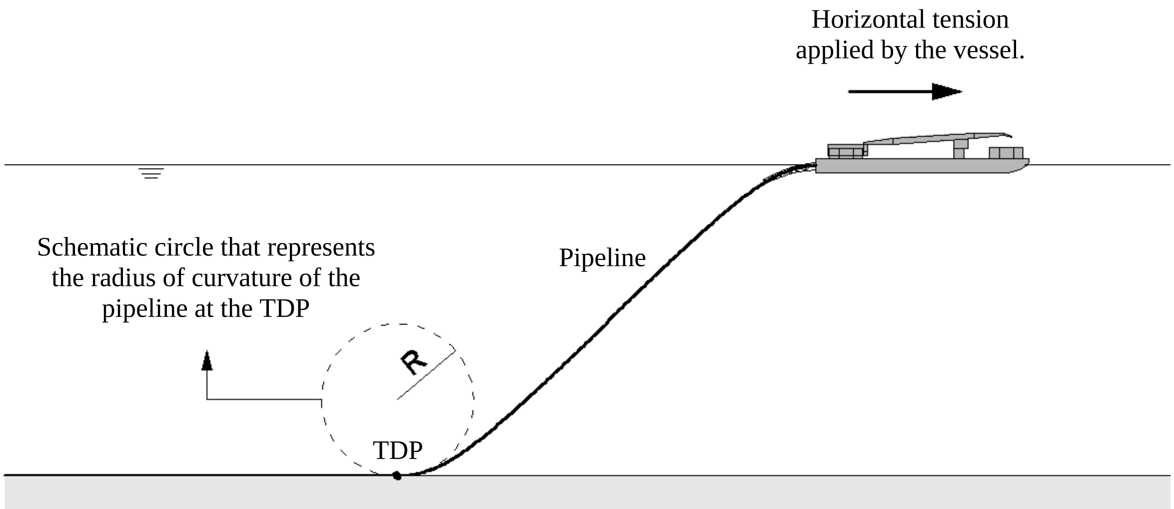


Figure 3. Schematic S-Lay configuration for pipeline installation

4.2 Pipeline Behavior Hypothesis

Considering the case presented in Figure 3, during the installation phase the vessel slowly moves forward, slightly increasing the horizontal tension applied to the pipeline and thus slightly increasing the value of the radius of curvature at the TDP. To compensate that, the tension machine releases more pipe into the water, maintaining these parameters within the original specified values. By continually repeating this process, the pipeline is slowly accommodated on the seafloor.

When the seabed has an irregular bathymetry (like the depression presented in Figure 4), the pipeline radius of curvature at the lowest point is assumed to be very similar to the initial one at the TDP presented in Figure 3. Following this logic, the point where the pipeline would touch the seabed again on the other side of the depression would be geometrically equivalent to fit a fictitious circle with the same radius of curvature at the seabed depression, as illustrated in Figure 5.

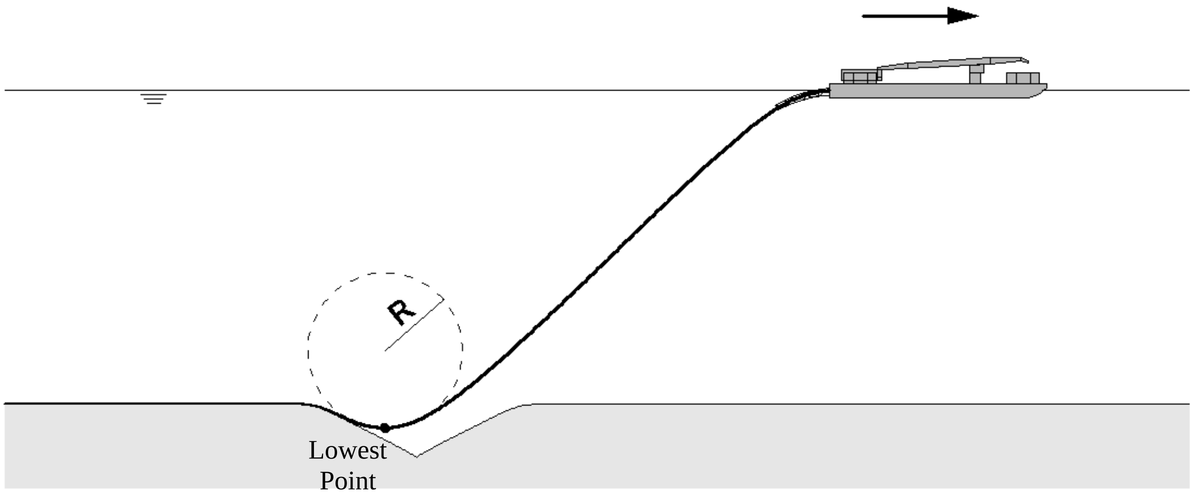


Figure 4. Pipeline being launched on a seabed with irregular bathymetry

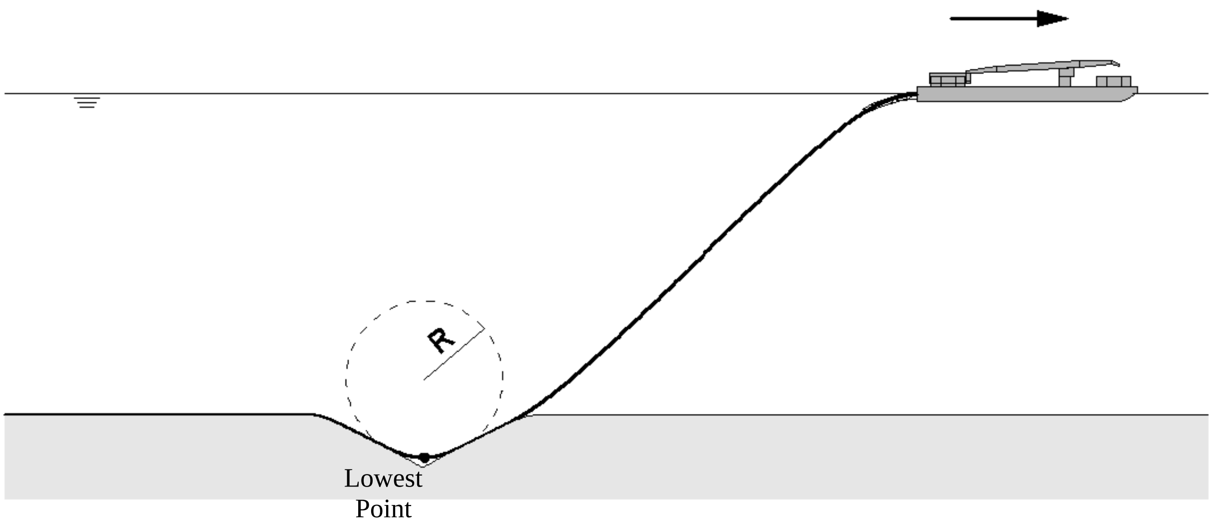


Figure 5. Free span formation during the installation of the pipeline

As the pipeline continues to be installed, after crossing the region with irregular bathymetry, the friction forces between the pipeline and the seabed prevent the free span configuration of the pipeline to be modified, as illustrated in Figure 6.

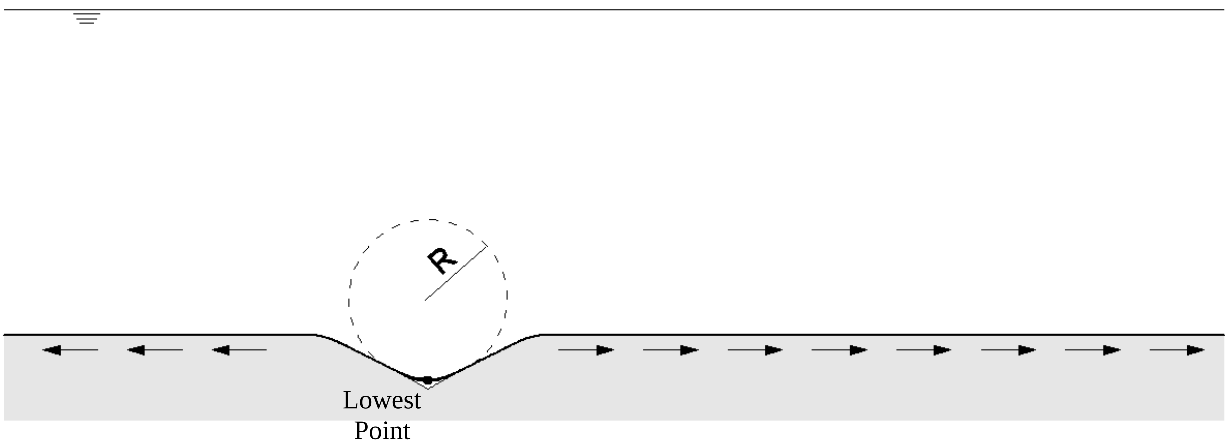


Figure 6. Friction forces that prevent the pipeline from modifying the free span configuration

4.3 Description of the Method

According to the pipeline behavior hypothesis presented above, this article proposes a simplified method to identify free spans on submarine pipelines called "Spinning Circle Method".

The method proposes that the final configuration of the pipeline, after the installation process, can be compared to the trajectory described by a spinning circle over the seabed. The radius of this circle is considered to be equal to the radius of curvature of the pipeline at the TDP as presented in Figure 3. Thus, free spans can be identified when the circle loses contact with the seafloor, as shown in Figure 7.

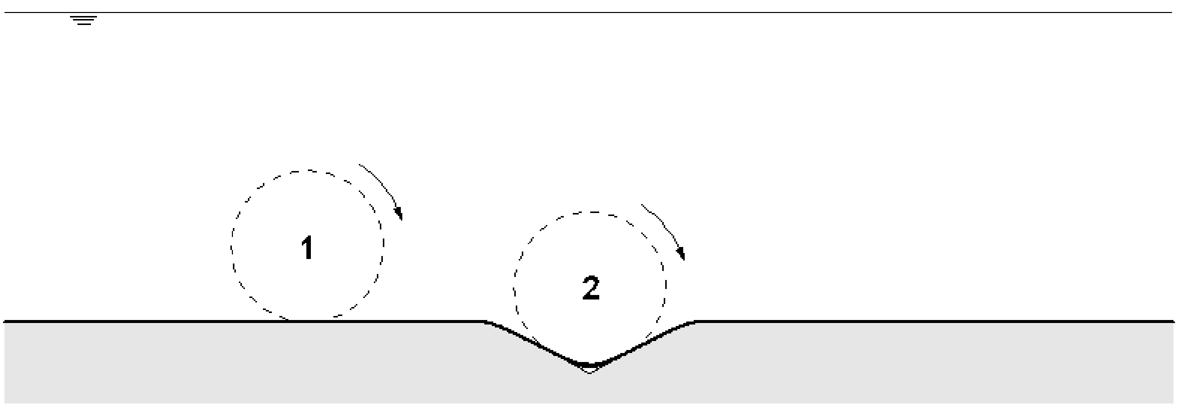


Figure 7. Spinning Circle Method idealization

4.4 Determining the Radius of Curvature at the TDP

In order to determine the value of the pipeline radius of curvature at the TDP, it is necessary to know what is the horizontal tension applied to the pipeline by the vessel during the installation phase. Then, it is possible to correspond this parameter with the radius of curvature itself. This can be made either by using an analytical method or by performing a simple equilibrium static analysis in appropriated software that considers the pipeline stiffness and all of the other characteristics listed before.

As the intention of the Spinning Circle Method is to be simple and fast without losing precision, the first solution seems to be more desirable, especially in the cases that the method is going to be used within route optimization programs. However, it is perfectly acceptable to follow the second path by performing a parametric study varying the horizontal tension for different commercial pipe sections associated to different types of vessel and installation methods. The results of this study can be used as an abacus which is also simple and fast.

Below, a simplified analytical method is proposed to determine the radius of curvature of the TDP. Figure 8 presents a truncated version of the model presented in Figure 3. The truncation point has been chosen as the inflection point that divides the overbend and the sagbend regions. The forces acting at the truncation point represent the influence of the removed section of the model.

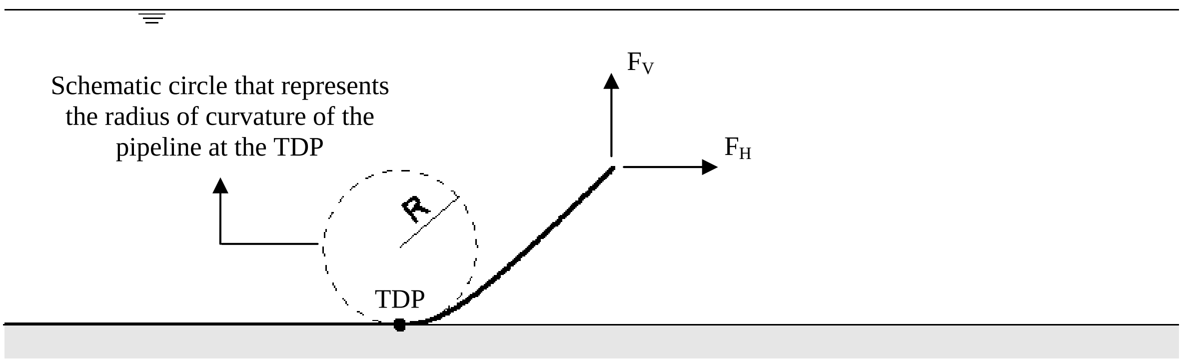


Figure 8. Truncated version of the schematic S-Lay configuration for pipeline installation

This simplified method for determining the radius of curvature at the TDP assumes that the pipeline configuration of the truncated model can be obtained through the inextensible catenary equation tangent to the soil, represented by Eq. (1).

$$y = a\left[\cosh\left(\frac{x}{a}\right) - 1\right] \tag{1}$$

where:

$a = \frac{F_H}{q}$, known as the catenary parameter.

F_H = horizontal force, represented in Figure 8.

q = linear submerged weight of the pipeline.

This equation does not consider the influence of the pipe bending stiffness at the equilibrium configuration of the pipeline. However, as the length of the suspended segment of the pipeline increases, this parameter becomes less important. The radius of curvature, considering that the pipeline can be represented by Eq. (1) can be expressed by Eq. (2).

$$r = a\,cosh^2\left(\frac{x}{a}\right) \quad (2)$$

The minimum radius of curvature can be obtained deriving Eq. (2) and equating it to zero. The minimum value occurs at the TDP and the result can be expressed by Eq. (3).

$$r_{min} = a \quad (3)$$

Then, once the horizontal force represented in Figure 8 is known, the radius of curvature of the pipeline at the TDP can be estimated simply dividing this horizontal force by the linear submerged weight of the pipeline. It is important to observe that the horizontal force indicated in Figure 8 is not necessarily equal to the horizontal tension applied by the vessel (represented in Figure 3) as the stinger acts as a complex system of sheaves. The relationship between these two parameters is still being studied.

This formulation is in accordance with the hypothesis presented in Section 4.2, where the pipeline radius of curvature at the lowest point of a seabed depression (Figure 4) is assumed to be very similar to the initial one at the TDP presented in Figure 3. In this situation, the pipeline configuration could be represented by two catenary curves with horizontal tangents at the lowest point, as shown in Figure 9. The radius of curvature at this point can also be calculated by Eq. (3), respecting the basic premise presented in Section 4.1.

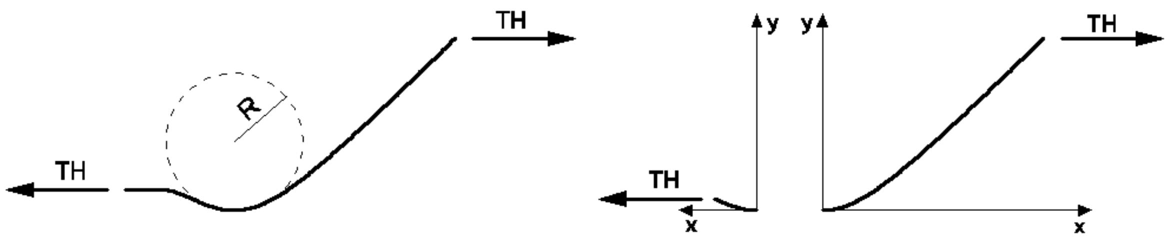


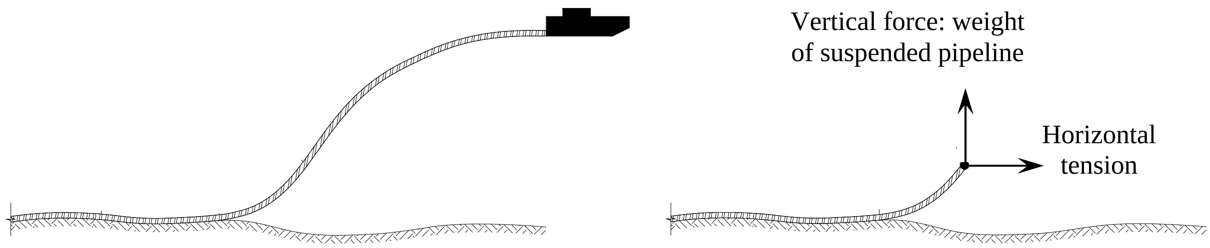
Figure 9. Pipeline represented by two catenary curves

5 FINITE ELEMENTS TOOL

The numerical tool for automatic identification of free spans on submarine pipelines is used at the parametric study presented in Chapter 6 . The development of the numerical tool has been described with details by Jacovazzo et al. (2013). Below, a very simple summary of this tool is presented.

Figure 10a schematically presents a pipeline being launched by a vessel. As the objective of the numerical tool is to obtain the final equilibrium configuration of submarine pipelines on the seabed after the laying operation and assuming that the design of the pipe laying procedure itself will include solutions in order to maintain the pipeline being launched along the predetermined route, considering an acceptable environmental window of operation, the action of environmental loads is not considered in the model.

For the same reason that has been described above, as the behavior of the suspended portion of the pipeline during the laying operation will not be investigated, the example that has been presented in Figure 10a can be truncated as shown in Figure 10b. For this configuration, the vertical component acting on the truncation point is equal to the submerged weight of the remaining suspended pipeline segment. The horizontal component is defined in project; so that the pipe is able to maintain a minimum tolerable radius of curvature at the TDP region. This force must be controlled by the algorithm implemented in the program.



(a) (b)

Figure 10. Truncation of the model

The simulation of the progressive pipe laying process is performed by prescribing incremental displacements at the truncation point of the model following the predetermined route, at every step of successive static analyses (quasi-static simulation), as can be seen in Figure 11. As the launching point progresses along the route, the horizontal component of the force acting at the truncation point would increase. Therefore, a procedure to control the value of this force during the simulation (maintaining it close to the design value defined by the user) has been implemented on the numerical tool.

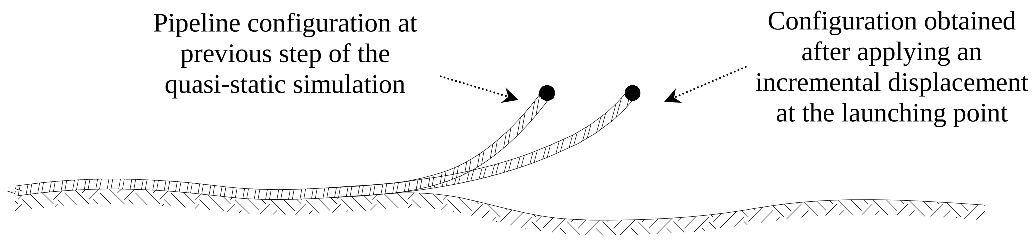


Figure 11. Pipeline configuration after applying a prescribed displacement at the launching point

On each step of the quasi-static simulation, the program verifies the value of the horizontal force component, and compares it with the specified design value. Whenever the horizontal force obtained in a given simulation step is higher than the design value, the program automatically increases the undeformed length of the top element of the mesh so that the force returns to the specified value. Thus, the total length of the pipeline is progressively increased, leading it to accommodate on the seabed as the pipeline is launched.

However, if the top element length were increased indefinitely, the mesh discretization would be impaired, leading to instability and convergence problems in the solution method of the nonlinear problem, reducing the quality of the results. To solve this problem, the simulation procedure automatically subdivides the top element whenever its length exceeds twice the original length. This leads to the introduction of new finite elements in the mesh.

6 PARAMETRIC STUDY

In order to qualitatively demonstrate the use of the procedure developed in this work, a parametric study has been performed comparing the results of free span obtained between the Spinning Circle Method and the numerical tool based on the Finite Elements Method described in Chapter 5 . Several pipe sections have been analyzed for a simplified seabed profile.

6.1 Pipelines Characteristics

The characteristics of the pipelines sections used in the study are specified in Table 1. As it can be observed, it was necessary to increase the submerged weight of the 24" and 32" pipelines with ballast as they tend to fluctuate.

Table 1. Pipe sections characteristics

Pipeline			Ballast
Nominal Diameter (in.)	**Outside Diameter (in.)**	**Wall Thickness (in.)**	**Submerged Weight (kN/m)**
$10^{3/4}$	10.75	0.50	-
16	16.00	0.75	-
24	24.00	0.75	0.695
32	32.00	0.75	2.091

The physical characteristics of the steel are described below:

- Grade – X60
- Yield Stress – 414 MPa
- Specific Weight – 77 kN/m³
- Elasticity Modulus – 210 000 000 kN/m³

6.2 Seabed Characteristics

For this parametric study, the seabed profile has been defined by a "V" shaped layout that forms a 30 degree angle with the horizontal, as illustrated in Figure 12. This layout is ideal to compare the results of this study as it allows the free span to assume a configuration that is basically dependent on the problem characteristics. In order to illustrate that, Figure 12 presents three different configurations of free span obtained with the numerical tool presented in Chapter 5 for the same pipeline but applying different horizontal tensions at the simulations.

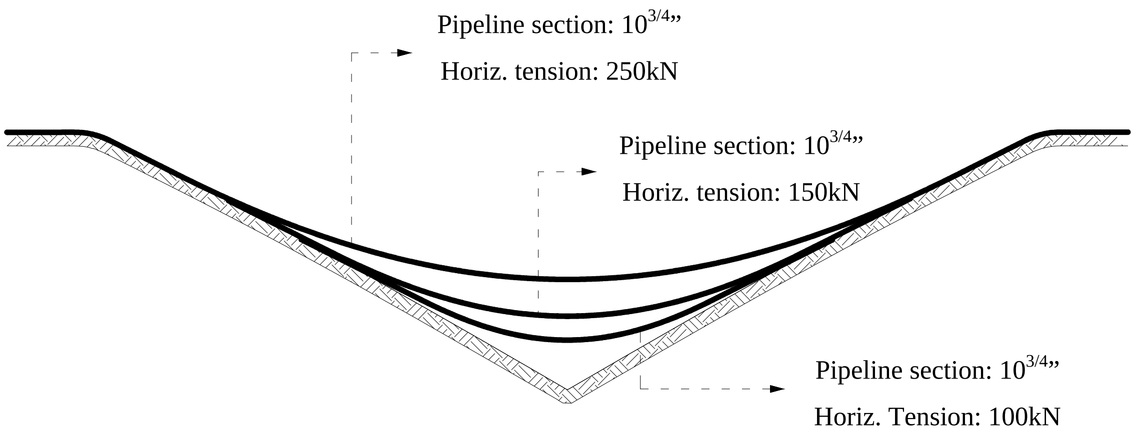


Figure 12. "V" shaped seabed profile

6.3 Analyses Characteristics

Each pipeline defined in Section 6.1 has been analyzed considering the application of several horizontal forces. The range of values of these forces are not the same for each pipe section once the sections with higher diameters need higher values of horizontal forces to avoid plastification and local buckling problems on the pipeline.

The numerical tool has been performed using frame finite elements with two meters length. The free spans for the Spinning Circle Method have been obtained using radii of curvature estimated by the simplified formulation presented in Section 4.4.

6.4 Results

Table 2 presents the results of free span configuration comparison between the Spinning Circle Method and the numerical tool based on the Finite Elements Method.

Table 2. Comparison of free span results

Pipeline	Horizontal Tension (kN)	Free Span Length (m)		Difference
		Numerical Tool	Spinning Circle Method	
10"	**50**	202	218	7.92%
	100	407	439	7.86%
	150	670	669	-0.15%
	200	829	877	5.79%
	250	1117	1111	-0.54%
	300	1371	1334	-2.70%
16"	**100**	182	192	5.49%
	150	262	288	9.92%
	200	363	387	6.61%
	250	464	487	4.96%
	300	567	585	3.17%
	350	672	684	1.79%
24"	**150**	312	295	-5.45%
	200	431	401	-6.96%
	250	461	433	-6.07%
	300	531	502	-5.46%
	350	604	574	-4.97%
	400	675	649	-3.85%
32"	**200**	445	362	-18.65%
	250	466	415	-10.94%
	300	543	486	-10.50%
	350	609	559	-8.21%
	400	676	633	-6.36%
	450	693	649	-6.35%

7 FINAL REMARKS

This work has presented the development of a simplified method (called Spinning Circle Method) to determine the final equilibrium configuration of a pipeline laying on the seabed after its installation procedure. Therefore, the method is able to detect free spans for a seabed with irregular bathymetry.

In order to qualitatively demonstrate the potentiality of the method, a parametric study has been performed comparing the free spans obtained by the Spinning Circle Method and by the numerical tool based on the Finite Elements Method that has been referenced in Chapter 5 . This parametric study considered different pipe sections over a simplified seabed profile.

The results presented in Section 6.4 have shown that the difference of free spans values between the numerical tool and the simplified method was small. It is important to observe that the radii of curvature of the fictitious circles that have been used by the Spinning Circle Method for this parametric study have been estimated through the simplified process proposed in Section 4.4. As mentioned before, this simplified process does not consider the bending stiffness of the pipeline. Therefore, if the radii of curvature for the Spinning Circle Method have been taken directly from the numerical tool or calculated by an improved process, the results would be even more precise.

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