INFLUENCE OF SOIL STIFFNESS CALCULATIONS ON UMBILICALS ANALYSES RESULTS

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Abstract. *Umbilicals play a fundamental role in offshore systems for oil production. Their structural integrity must be assured, and for this, several analysis tools can be used, most of them based in the finite element method. A point that all these tools have in common is the concern with the point that the cable touches the soil, usually named TDP or touchdown point (TDP). This point usually presents the critical results regarding radii of curvature and fatigue, making it necessary to have a good understanding of the umbilical-soil interaction. One of the parameters that governs this interaction is the soil stiffness. Therefore, the objective of this paper is to evaluate the impact of soil stiffness calculations in the results of umbilicals' dynamic analyses. For this, some alternative approaches for the calculation of soil stiffness are going to be applied. The results from these approaches will then be used as input in sensitivity analyses for extreme and fatigue conditions. The outputs of these series of simulations such as minimum bending radius and tension at TDP, will be evaluated and discussed.*

Keywords*: umbilicals, sensitivity analyses, soil stiffness*

1. INTRODUCTION

Umbilicals are composite cables used in offshore oil exploitation. They are responsible for providing power and control to subsea equipments, such as manifolds, christmas trees and pumps, connecting them to the platform's topside. Their main components are hoses, tubes, signal and power cables and fiber optics; a typical umbilical can be seen in Fig. 1.

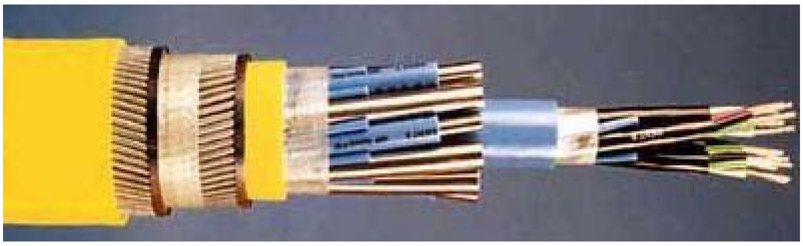

Figure 1. Typical umbilical component layout

Each umbilical component has a specialized function. Hoses (usually made of thermoplastic polymers) and tubes (manufactured with special steel) are responsible for conducting hydraulic fluid to the subsea equipments, and used to execute actions such as valve opening and closing. Power cables are used to transmit electric power and the signal ones transmit control and monitoring signals, which is the same role for fiber optics.

In terms of structural behavior, there are two main regions of concern for umbilicals. The first is the top region, near its connection to the platform. This region presents the highest values of tension due to umbilical weight and the movements caused by the environmental loads, mainly waves and vessel offset. The second, and usually more critical, is the region where the umbilical touches the seabed, named the touchdown point (TDP). This point is susceptible to issues regarding fatigue, compression and minimum bending radius (MBR). This criticality comes from the fact that this region has the simultaneous influence of the platform behavior and the soil characteristics, characterizing a typical pipe-soil interaction problem.

This is a complex non-linear phenomena. Usually it is modeled using discrete uncoupled springs to represent the effect of the soil in the pipe. These springs can be non-linear or linear; the linear ones are described by a parameter called seabed stiffness.

The objective of this paper is investigate the influence of the seabed stiffness in umbilical´s analyses results, discussing the current methodologies and presenting some sensitivity analyses performed in OrcaFlex as case studies.

As usually the compression levels of umbilicals are under their design limits, this work is focused in studying the seabed stiffness' influence in MBR and fatigue damage.

2. LINEAR SEABED MODELING

The seabed modeling using linear springs is based in Eq. (1), where k is the seabed stiffness, R_v, is the soil reaction force and v is the pipe penetration into the soil:

$$R_v = kv \tag{1}$$

Usually, this reaction force R_v is applied to the pipe in two directions, normal and parallel to the seabed. There are some aspects in this formulation that should be considered:

- It does not take into account changes in soil characteristics due to the pipe's movements; possible changes in the seabed stiffness or trenches' generation are not considered, for example.
- It does not consider any damping effects, which could mitigate possible numerical problems resulting from the interaction between the springs and the pipe. Sometimes this is corrected including a damping force, as done by (Takafuji, 2010). In this case, the damping force is represented by Eq. (2), where $z(t)$ is the vertical coordinate, ζ is the damping ratio and m is the mass laid on the seabed:

$$F_d(t) = 2\zeta\sqrt{km}\,\frac{\partial z(t)}{\partial t} \tag{2}$$

2.1. Linear seabed stiffness

As explained by (Chakrabarthi, 2005), the unit and definition of seabed stiffness is a common source of misunderstandings, because there is more than one way of defining this parameter. The traditional method is using the module of sub grade reaction K_{su}, defined by Eq. (3):

$$K_{su} = \frac{q}{\delta} \tag{3}$$

δ is the deflection at the center of a uniformly loaded beam or strip on a quasi-elastic seabed, while q is the average stress applied over the loaded area. The units of K_{su} are force/area/length, or force/length cubed; using SI units we have, for example, kN/m^2/m or kN/m^3. An alternative definition for seabed stiffness is given by K_u in Eq. (4), where B is the width and L is the length of the loaded area:

$$K_u = \frac{BLq}{\delta} \tag{4}$$

K_u has units of force/length, for example kN/m. As other parameters used in risers' engineering, K_u also can be considered per unit of length, so its units become force/length/length, which leads to stress units for this quantity.

Seabed stiffness also can be characterized using a nondimensional parameter, as the soil rigidity parameter defined by Pesce *et al*. (2006):

$$K = \frac{kEI}{T_0^2} \tag{5}$$

k is the soil stiffness per unit of length and penetration, EI is the flexional stiffness of the pipe and T_0 is the static tension at TDP.

Another important aspect of seabed stiffness is that it is classified regarding the behavior of the considered pipe. As a result, we have static (related to the initial penetration in the soil) and dynamic (related to pipe's cyclic motions) stiffness. The basic concept behind them is the same; both represent the proportionality between the pipe's penetration and the soil's reaction. However, the dynamic stiffness is usually higher than the static one and they are calculated using different methods. These factors and, sometimes, the limited information available about the soil, make the use of sensitivity analysis regarding seabed stiffness a recommended approach, as well as the use of conservative (higher) values for this parameter.

A first action for calculating the seabed stiffness may be consulting the adequate standards regarding this subject. (DNV, 2006) is the most common guide used for this. It presents some different ways for evaluating the seabed stiffness, and defines the static stiffness using Eq. (6), which is a rearrangement of Eq. (1):

$$K_{v,s} = \frac{R_v}{v} \tag{6}$$

where R_v is the static vertical soil reaction per unit length of pipe and v is the vertical penetration of the pipe required to mobilize this reaction. This equation is a rearrangement of Eq. (1), and it is useful only if both values of R_v and v are given. R_v, due to its nature of a static reaction, can be considered equal to the pipe's weight per length. Due to difficulties obtaining the ideal *in situ* measurements, v is best estimated. (DNV, 2006) also has expressions for evaluating R_v; for example, Eq. (7) represents R_v for clay assuming a constant shear strength.

$$R_v = N_c s_u B + A_p \gamma_{soil} \tag{7}$$

where N_c is the bearing capacity factor, considered equal to 5.14, s_u is the undrained shear strength, B is the contact width between the pipe and the soil (evaluated using Eq. (8), where D is umbilical's diameter), A_p is the cross-sectional of the penetrated part of the pipe and $_{soil}$ is the submerged unit weight of the soil.

$$B = \begin{cases} 2\sqrt{(D-v)} \text{ for v} \le 0.5\text{D} \\ D \text{ for v} > 0.5\text{D} \end{cases} \tag{8}$$

An easier way for estimating the static soil stiffness is also provided (DNV, 2006). The standard provides two tables with recommended values for the static stiffness for clay and sand soils. These data are summarized in Tab. (1) and Tab. (2), in terms of K_u per unit of length,.

Table 1. Static seabed stiffness for sand (DNV, 2006)

Sand Type	$K_{v,s}$ (kN/m/m)
Loose	250
Medium	530
Dense	1350

Table 2. Static seabed stiffness for clay (DNV, 2006)

Clay Type	$K_{v,s}$ (kN/m/m)
Very soft	50-100
Soft	160-260
Firm	500-800
Stiff	1000-1600
Very stiff	2000-3000
Hard	2600-4200

The dynamic stiffness also is defined (DNV, 2006) in Eq. (9). ΔF_v is dynamic vertical force between pipe and soil per unit length of pipe, and $\Delta\delta_v$ is the associated vertical displacement of the pipe relative to its static position:

$$K_v = \frac{\Delta F_v}{\Delta \delta_v} \tag{9}$$

The same reference suggests Eq. (10) for determining the dynamic seabed stiffness. In this expression, G is the soil shear modulus and v is the Poisson's ratio:

$$K_v = \frac{0.88G}{1-\nu} \tag{10}$$

Another suggestion from the same reference can be applied just in non-complex topographical conditions and homogeneous soils (Eq. (11)):

$$K_V = \frac{C_v}{1-\nu}\left(\frac{2}{3}\frac{\rho_s}{\rho}+\frac{1}{3}\right)\sqrt{D} \tag{11}$$

In this expression, C_v is a coefficient that depends on the soil type and the value of undrained shear strength, and ρ_s/ρ is the specific mass ratio between the pipe mass (not including added mass) and the displaced water. This relationship can be applied only if $1.2<\rho_s/\rho<2.0$.

As in several others technical issues, standards are not the only source of information available. (Bridge and Laver, 2004) developed a model for calculating the dynamic seabed stiffness when the pipe breaks away from the soil. They were based on SCR (steel catenary riser) data collected during the CARISIMA and STRIDE JIP's, and concluded that the seabed stiffness could be calculated using the expression presented in Eq. (12):

$$K = 20 N_c s_u \tag{12}$$

In this expression, N_c is called a non-dimensional shape and depth factor, calculated as follows:

$$N_c = \min\left(5.14\left(1+0.23\sqrt{\frac{z}{B}}\right), 7.5\right) \tag{13}$$

3. ANALYSES

Several sets of sensitivity analyses were performed using the software OrcaFlex 9.4b, from Orcina Ltd. In this software, there are two options for soil modeling: linear and non-linear. The linear modeling was chosen, and it is based in Eq. (1). In addition to the vertical soil stiffness, the user also can choose a value for the soil stiffness parallel to the seabed; the value of this parameter is, by default, equal to the one chosen for the normal stiffness, but this can be modified. If the integration scheme used in the analysis is the explicit one, the user also can input a value for the seabed damping, which is a percentage of the critical damping. If the implicit integration scheme is used, this data cannot be input.

All the analyses used real information regarding the umbilicals, platforms and environmental conditions, but for legal reasons not all the data is revealed.

3.1. Direct comparison between different methods

The first set of analyses was performed with the intention of comparing two different methods of evaluating the seabed stiffness. As the soil shear modulus G and the Poisson's ratio ν were not available, Eq. (10) was not used for seabed stiffness calculation. Additionally, the relationship $1.2<\rho_s/\rho<2.0$ was not true for the umbilical considered in the analyses; consequently, (DNV, 2006) was not able to furnish any method for calculating the dynamic seabed stiffness, therefore it was decided that from this reference, only the static values would have been used. This can be seen as a less conservative but still valid approach.

Based on this, three different values of stiffness were evaluated, considering a clay soil: 100.0 kN/m/m^2 (the OrcaFlex 9.4b default value for this parameter), 281.7 kN/m/m^2 (calculated from Eq. (6) using a R_v value based on the estimated penetration of 30% of umbilical's diameter) and 2122.3 kN/m/m^2, derived using Eq. (12). The same parameters were used for all the load cases, except for the stiffness values; they represented a FPSO in a water depth of 2250 m subjected to regular waves of 20.58 m of height and period of 13.74 s. The FPSO was subjected to an offset of 188.5 m in the opposite direction (182° measured counterclockwise from the East) of the umbilical azimuth (2°); current and wave loads were applied ±22.5º from this azimuth. The umbilical configuration used in all the analyses performed in this study was the free hanging catenary; the umbilical modeled in this direct comparison has a diameter of 0.136 m, a bending stiffness of 8.00 kN.m^2 and an axial stiffness of 172 MN.

Table (3) summarizes the critical results of these analyses for top tension and minimum bending radius (MBR) at TDP, and Fig. (2) shows a comparison between the curvature results at the umbilical touchdown point for the three load cases. The nondimensional soil rigidity defined by Eq. (5) could be used for these plots, but the real stiffness used in OrcaFlex was chosen for this.

Table 3. Critical results (Analyses set #1)

Stiffness Used (kN/m/m^2)	Maximum Top Tension (kN)	MBR (m)
100.0	992.8	1.59
281.7	993.9	1.55
2122.3	994.8	1.49

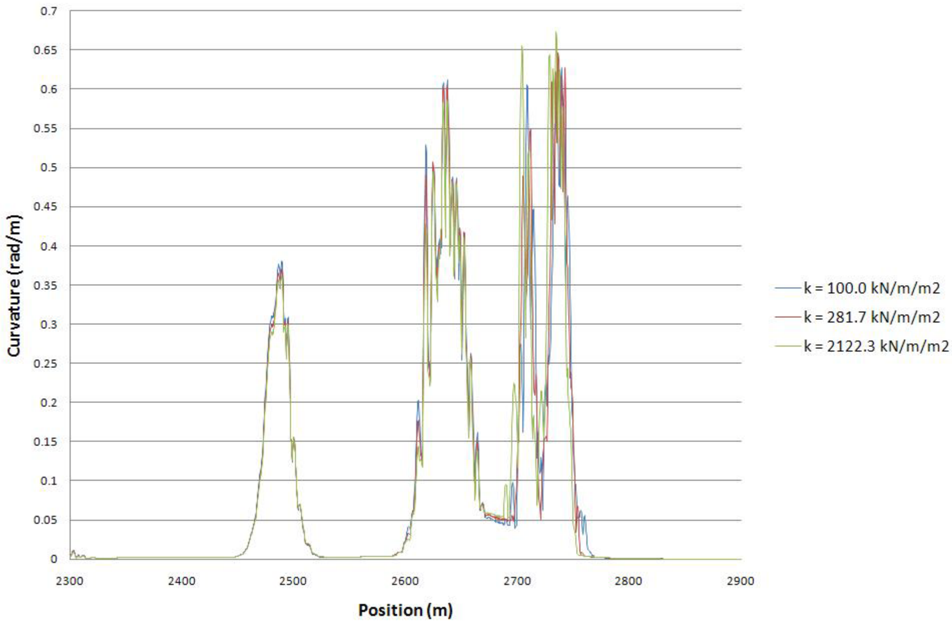

Figure 2. Curvature results comparison (Analyses set #1)

3.2. Sequential stiffness values comparison

The second set of analyses was a comparison between several identical load cases with different stiffness values. The vessel considered was a semi-submersible subjected to regular waves of 12.00 m height and 11.40 s period and no vessel offset. The line azimuth was 64.3°, whilst the currents propagated towards 45°, and the waves propagated towards 90° (angles measured counterclockwise from the East). The umbilical modeled in this sequential comparison has a diameter of 0.098 m, a bending stiffness of 1.59 kN.m^2 and an axial stiffness of 150 MN.

Figure 3 presents a comparison of the curvature values obtained. Table 4 presents the seabed stiffness value used in each case, with the respective worst results in terms of top tension and MBR at TDP. The dashes mean that the case did not converge in the static analysis.

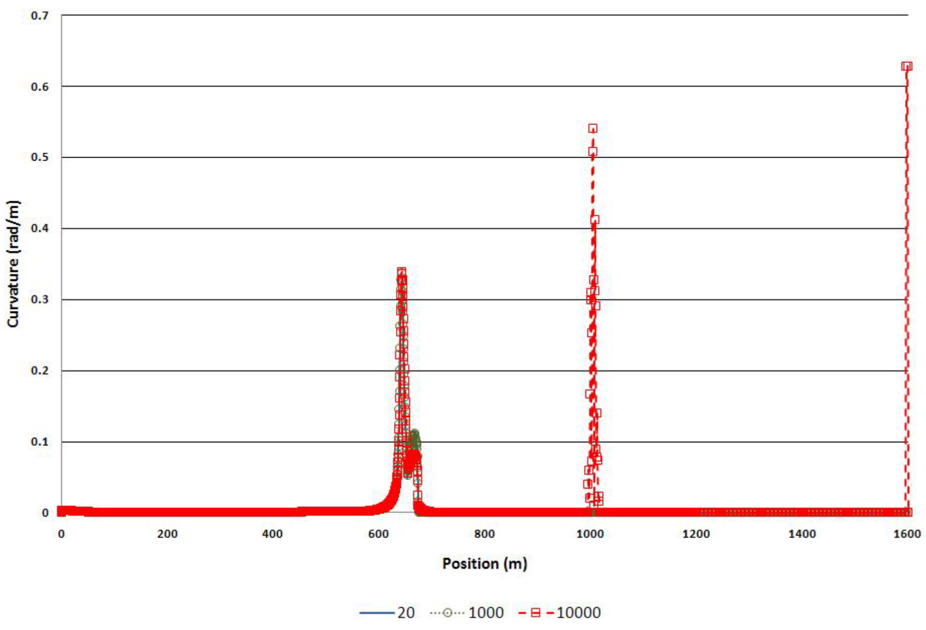

Figure 3. Curvature results comparison – selected cases (Analyses set #2)

Table 4. Critical results (Analyses set #2)

Stiffness (kN/m/m^2)	Top Tension (kN)	MBR (m)
20	91.47	3.09
40	91.46	3.02
60	91.47	3.00
80	91.47	2.99
100	91.47	2.98
120	91.48	2.98
140	91.47	2.98
160	91.47	2.98
200	91.47	2.98
250	91.48	2.97
300	91.48	2.97
350	91.48	2.97
400	91.48	2.97
450	91.48	2.97
500	91.48	2.97
550	91.48	2.97
600	91.48	2.97
650	91.48	2.97
700	91.48	2.97
750	91.48	2.97
800	91.48	2.97
850	91.48	2.97
900	91.48	2.97
950	91.48	2.97
1000	91.48	2.97
1050	91.48	2.97
1100	-	-
1150	91.48	2.97
1200	91.48	2.97
2000	-	-
3000	-	-
4000	-	-

Table 4. Critical results (Analyses set #2) (continued)

5000	91.50	1.59
6000	-	-
7000	-	-
8000	-	-
9000	-	-
10000	91.50	1.59

3.2. Fatigue damage comparison

The influence of seabed stiffness in fatigue analyses was also evaluated. A fatigue analysis evaluating a turret moored FPSO in a water depth of 1000 m was performed, considering both seabed stiffness values of 250 kN/m/m^2 and 3750 kN/m/m^2. The umbilical modeled in this fatigue comparison has a diameter of 0.160 m, a bending stiffness of 9.70 kN.m^2 and an axial stiffness of 392 MN. Figure (4) compares the values of damage in signal cable, and Fig. (5) compares the values of damage for the armor wires.

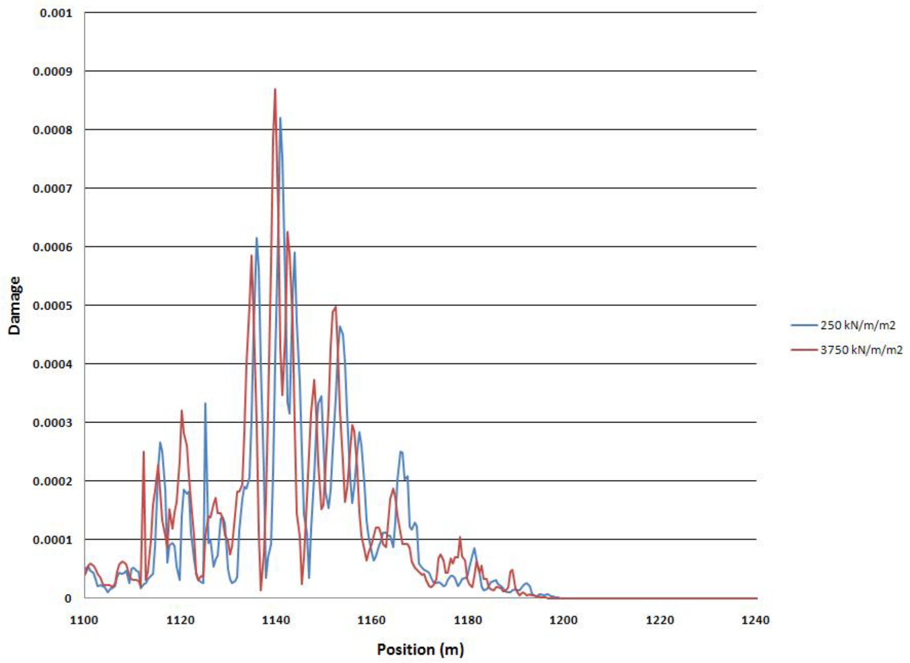

Figure 4. Fatigue damage in the signal cable

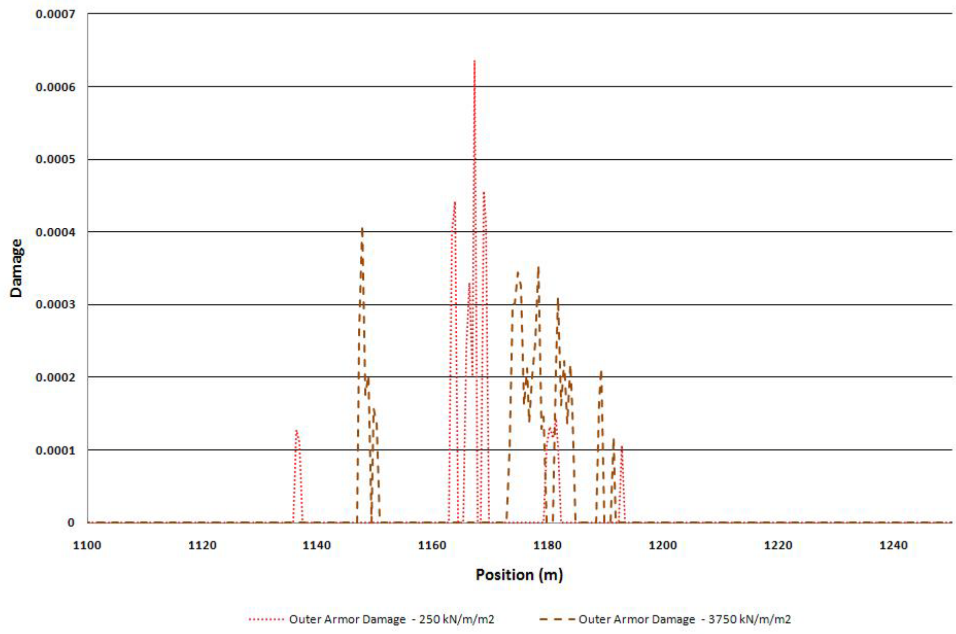

Figure 5. Fatigue damage in the armor wires (worst layer)

4. RESULTS DISCUSSION AND FINAL REMARKS

The main conclusion from the sensitivity analyses performed is that the influence of soil stiffness using linear seabed modeling in the results of umbilicals' dynamic analyses is very small within the TDP region. Also, this parameter has very low effect on the fatigue damage at the TDP region. This small influence of seabed stiffness also was shown by Pesce *et al*. (2006).

The literature predicts that the seabed stiffness will have a significant influence in the fatigue life of SCRs (steel catenary risers), as affirmed by (Bridge and Laver, 2004), but no similar indication for umbilicals was found. Due to its composition and internal arrangement, umbilicals have a lower axial and bending stiffness than SCRs. Therefore, umbilicals are subjected to smaller stress ranges, minimizing the influence of parameters such as seabed stiffness.

As expected, the variation in seabed stiffness did not influence the top tension results, as can be seen in Tab. (3) and Tab. (4). The changes in curvature and, consequently, in MBR, were more noticeable, but still small. Table (3) shows that, for the largest seabed stiffness which correspond to a 2100% increase compared to the lowest one, the corresponding worsening in MBR was just about 6%. This behavior also is shown in Tab. (4), where the difference between the MBRs of cases with stiffness of 20 kN/m/m^2 and 1000 kN/m/m^2 is less than 3%.

Table (4) also shows an interesting aspect of seabed stiffness influence. As the stiffness value increases, the load cases static convergence becomes more difficult, which generated several non-convergence failures. Two cases with high values of seabed stiffness (5000 kN/m/m^2 and 10000 kN/m/m^2) converged, and presented very low values of MBR (1.59 m; the others were in the range 2.97 to 3.09 m). It was noticed that this values come from the static stage of the analysis, where an equilibrium configuration of the system must be found; Fig (6) presents the curvature along the umbilical in the case with higher seabed stiffness, and Fig. (7) shows the equilibrium configuration reached by the line around its 1000 m of length.

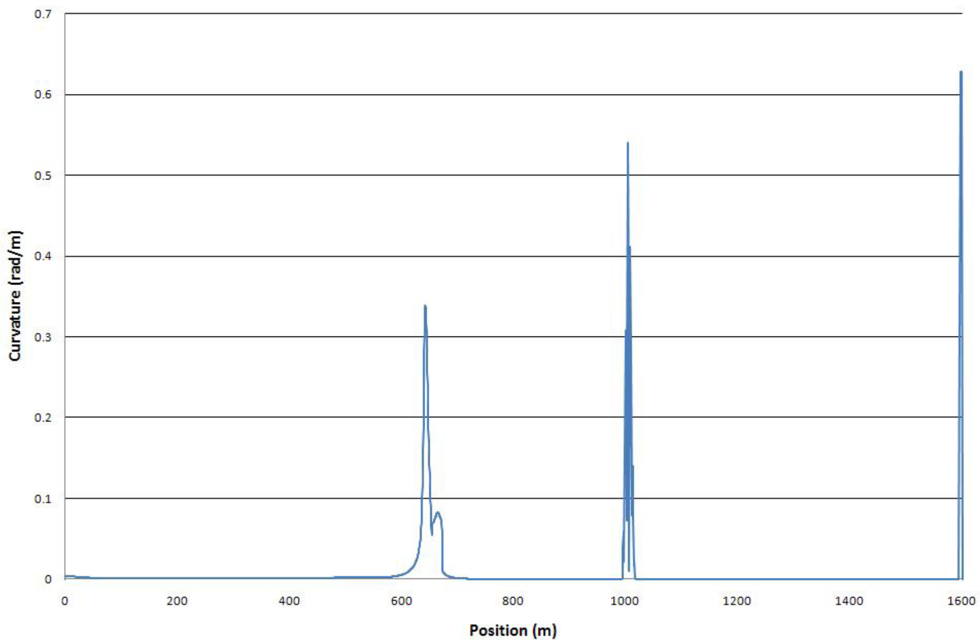

Figure 6. Curvature results (high seabed stiffness)

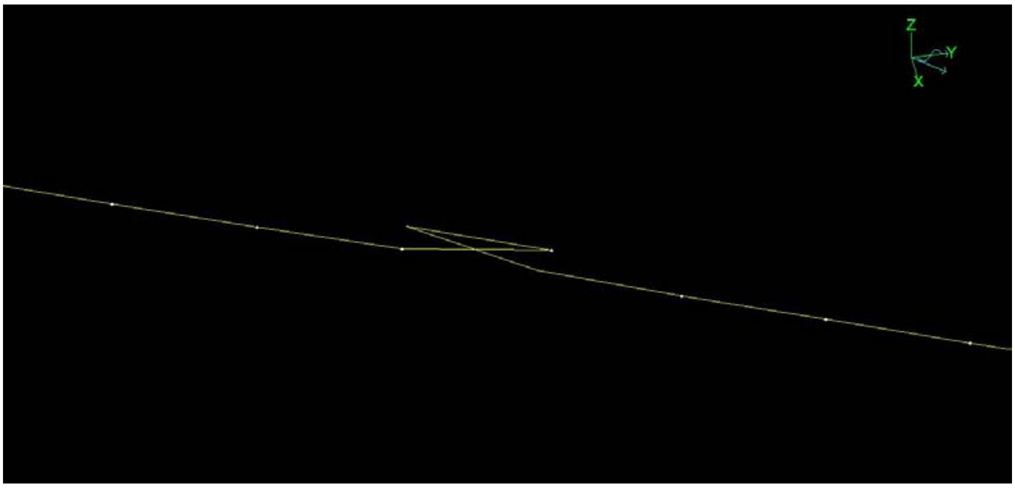

Figure 7. Line configuration at the end of static stage (high seabed stiffness)

The line configuration showed in Fig. (7) is not natural; it shows a non-feasible unstable equilibrium configuration. It can be avoided reducing the step taken in each iteration of the convergence process, which shows that this is a numerical issue inherent to the solution method and probably triggered by the high soil reaction forces. (Orcina, 2011) states that the results from analyses that present unstable equilibrium are invalid. As stated above, the seabed stiffness does not have a significant impact to the dynamic performance of the umbilical, however it can influence the model convergence in association with other factors.

This conclusion is important because it enables us to save time and resources avoiding to perform unnecessary analyses only for checking the effect of the seabed stiffness on the model. Since this effect is not significant under the conditions explored, only a few sensitivity analyses can be simulated to adequately characterize the impact of the seabed stiffness on the system.

Finally, we emphasize that all the analyses were performed using water depths and environmental conditions typically found in Brazilian offshore oil exploitation. It reinforces the significance of the conclusions achieved, and also sets a comparison point for further studies based on investigation of seabed stiffness influence on shallow water applications. Other aspect that has to be accounted for is the umbilical type: all the umbilicals evaluated on this study are thermoplastic, composed of hoses and signal cables, and then future work can be done considering steel tube and power cable umbilicals.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bai, Q., Bai, Y., 2005. "Subsea Pipelines and Risers", Ed. Elsevier, 812 p.
Bridge, C., Laver, K., 2004, "Steel Catenary Riser Touchdown Point Vertical Interaction Models", Proceedings of the Offshore Technology Conference, Houston, United States.
Carvalho, M.F.M.S. "Formulação corrotacional para análise de vigas com elementos finitos". Master thesis in Engineering presented to Universidade Nova de Lisboa.
Chakrabarthi, S.K., 2005. "Handbook of Offshore Engineering", Ed. Elsevier, Vol.2, 1268 p.
DNV, 2006. "Recommended Practice DNV-RP-F105 Free Spanning Pipelines", Norway.
Orcina Ltd., 2011, OrcaFlex Manual Version 9.4b. United Kingdom.
Pesce, C., Martins, C., Silveira, L. 2006, "Riser-Soil Interaction: Local Dynamics at TDP and a Discussion on the Eigenvalue and the VIV Problems", ASME Journal of Offshore Mechanics and Arctic Engineering, 125, pp. 39-55
Takafuji, F.C.M., 2010. "Dinâmica tridimensional de risers". PhD thesis in Engineering presented to Universidade de São Paulo.

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