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Stress Analysis Of Stress Relief On Onshore Pipeline Bent By Soil Movement Using The Finite Elements Method

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Abstract

This work proposes a numerical model to represent the process of lateral displacement of a buried pipeline, and its subsequent stress relief. In the model, it is considered the generation of a bent segment, which was field-measured, and due to the soil movement through the years, and which final position is a function of the pipe loading and the soil stiffness. The conformation of this bent segment creates stress in the pipeline that may compromise its integrity, and therefore must be monitored and at times released. The stress relief process is characterized by the lessening of the pipe stress through excavations across the bent segment, permitting the partial or full return of the pipeline to its original position. The numerical analysis in this study was performed through ANSYS softwares, and allows for better detailing of the pipe's stress and strain profiles, at the final displacement condition (bend), and during the stress relief process, and provides data for better evaluating the excavation process. The numerical model contemplated the full extension of the bent segment, considering both the initial and final outlines of the pipe, its diameter and thickness, and its material properties, as well as the soil stiffness. Once the pipe geometry was defined, a mesh sensitivity study was developed for the finite element simulation. The initial outline of the pipe was considered to be linear, and its final outline was obtained through field measurements. For the analysis, the pipe material was defined as elastoplastic, and modeled by the Multilinear Plasticity model, to better represent possible effects of residual strain. The buried pipe hypothesis was used, and therefore the pipe was restrained only at its extremities, and a length extension was added to the pipe at each side, to avoid boundary effects in the region of interest. The numerical simulations performed allows the observation of stress and strain through the pipeline at different stages of the bent segment generation and the stress relief process, and the evaluation of their potential effects to the pipeline integrity, as well as an estimate of its final position after the stress relief. It can also predict the most adequate field procedure for the pipe stress relief, and its effects.

1. Introduction

TRANSPETRO, in a constant monitoring process of their pipelines, has identified a lateral displacement in the position on a stretch of the pipeline. This was caused by the slow movement of the soil on a hillside of Serra do Mar, between the towns of Rio de Janeiro and Angra dos Reis. In this region, it is common to encounter areas of deposited soil, transported by gravity, as in colluvium and talus.

The bent segment was initially identified in 2003, through a field survey, and in a new evaluation in 2012, by inline inspection (ILI), an increment in the pipe deformation was detected, as can be observed in Figure 1. The stretch of pipe subject to the soil movement was found to have a length of approximately 130 m, with a displacement of over 2 m in the maximum deformation point between the surveys of 2003 and 2012.

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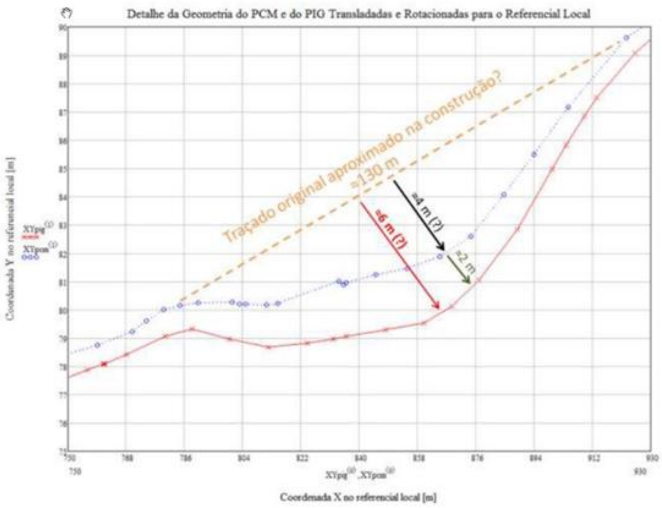


Figure 1: Pipeline Segment profile at three different stages: installation, identification of the bent segment (2003), and detection of a displacement increase (2012), as extracted from a TRANSPETRO's internal document.

Once the bent segment was identified, causing potentially high stresses, a blind-hole drilling test was proposed to verify the stress on the pipe cross section. This test is performed through the installation of at least three strain gage rosettes to the pipe wall, which allow the measure of residual stresses.

The residual stresses are composed by manufacture stress, stress caused by the construction and assembly procedures, stress due to the pipe internal pressure and operational loads and, finally, stress caused by the soil movement around the pipe.

After the verification of elevated stresses on the pipe, the uncertainties related to the blind-hole test results, and the evidence of further soil movements, verified thrpugh field instrumentation (inclinometer), TRANSPETRO team opted for the stress relief of the pipe, through a process of trench digging, allowing the decreasing of the stress on the pipeline section, and its return to the original, design position.

The excavation for stress relief requires a strict understanding of the process of pipe liberation, and must be made in a controlled manner, to avoid damage to the pipeline segment due to abrupt movements, and the soil-pipe interaction should be considered.

The conditions for the pipe return were studied numerically through the finite elements method, that is, the excavation sequence proposed by the TRANSPETRO team was simulated to analyze the pipe's behavior and residual stresses during and after the stress relief process.

The computational simulation provided important information for the safety requirements of the stress relief process, as well as data on the expected displacement of the pipe on the whole excavation procedure, therefore serving as a guiding tool for the field team. The numerical model and the subsequent simulations were developed in ANSYS 17.

2. Numerical Methodology

In this study, a stretch of pipe in the region where a bent layout was found is analyzed; the bent segment detected spans around 130 m of pipe. To avoid any influence of the defined supports on the numerical results (boundary effect), an analysis length of 200 m was considered. Table 1 summarizes the pipe dimensions used in the numerical modeling.

Table 1: Pipe Dimensions as used in the numerical model

Parameter	Dimension
External Diameter (D)	D = 40" (1016mm)
Thickness (t)	t = 7,92mm
Diameter/Thickness Ratio (D/t)	D/t = 128,2
Length (L)	L = 200m

Once the geometry was defined, a tridimensional numerical model was developed, under the hypotesis of a homogeneous, undamaged pipe. The mesh characteristics are presented in Table 2, while the mesh itself is ilustrated in Figure 2.

Table 2: Mesh characteristics as employed in the study.

Property	Value
Number of elements through thickness	3
Number of tangential elements	50
Number of axial elements	800
Total number of nodes	~ 578 thousands
Total number of elements	~ 116 thousands

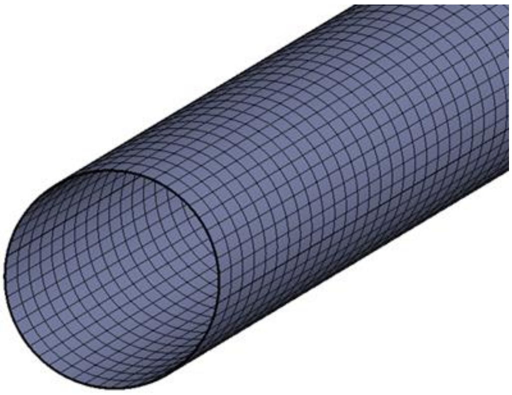


Figure 2: Numerical mesh used in the analysis.

The pipe material is API 5L X56, which properties are presented in Table 3. As a representation methodology, this study adopts the elastoplastic approach through a multilinear model, with a curve obtained by the Ramberg-Osgood equation. Figure 3 presents the material curve defined in the numerical model.

Table 3: Material properties of the pipe.

Property	Symbol	X56
Young Module [GPa]	E	200
Poisson Coefficient []	ν	0,3
Yield Strength [MPa]	S_y	429
Ultimate Tensile Strength [MPa]	S_u	572
Strain Hardening Exponent []	n’	0,098
Strength Coefficiente [MPa]	H’	793

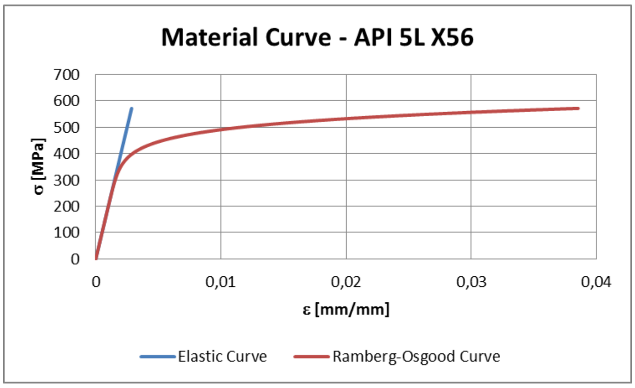
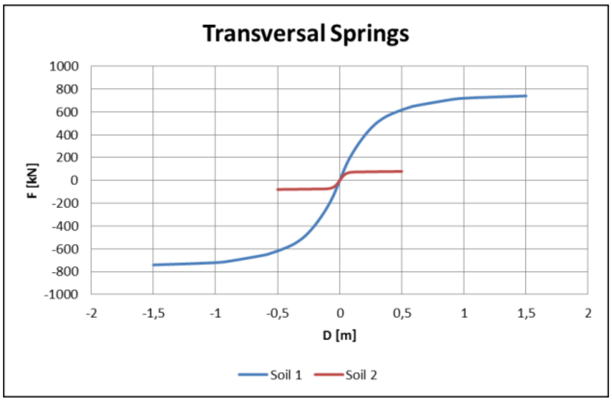
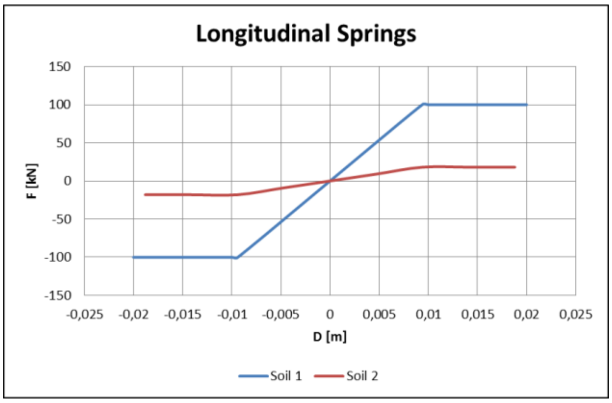


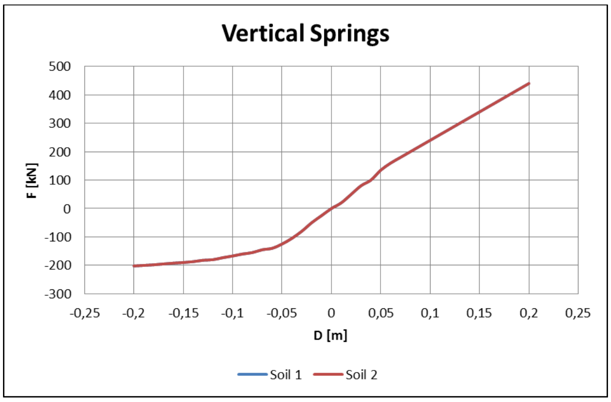
Figure 3: Material curve according to the Ramberg-Osgood equation.

The main boundary condition imposed to the model was the equivalent of an infinite buried pipe, that is, the longitudinal movements in the pipe were limited in both extremities, as well as the rotations around the pipe's axis; however, variations in the radial direction of the pipe are free. The interaction between pipe and soil was modeled through the Winkler method, which uses springs to represent the soil stiffness. In this study, two types of soil were considered, and modeled by vertical, longitudinal and transversal springs, all with nonlinear stiffness. Figure 4 shows the directional stiffness of the springs defined. An operational internal pressure of 30 kgf/cm² was also adopted as the model load.





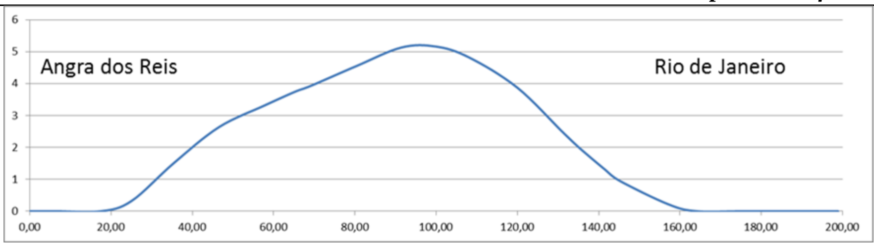
(a) (b)



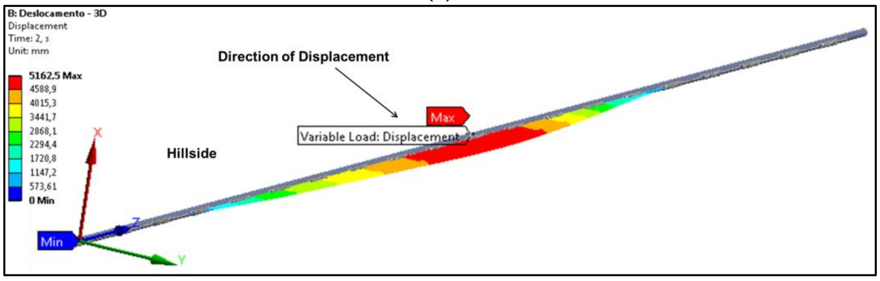
(c)

Figure 4: Soil stiffness data, considering a nonlinear spring approach, for the transversal (a), longitudinal (b) and vertical (c) directions.

The main goal for this study is to evaluate the capacity of the pipe to return to its design position, and so the simulation was defined in three stages. The first stage consists in the pressuring of the pipe up to its operational load.
The second stage represents the generation of the bent segment, as shown in Figure 5 (a), numerically implemented by defining nodal displacements through the pipe, which move the pipe's nodes from the original design position to the final deformed arc position. Figure 5 (b) shows the displacements prescribed in the second stage of the analysis.



(a)



(b)

Figure 5: Profile of the pipe's side bent deformation (a) and displacement applied to the numerical model (b).

The third stage of the simulation represents the excavation procedure, where 5 meters in length are released in the longitudinal direction, simultaneously, on each side of the maximum arc of deformation (totaling 10 m release), per excavation phase. Meanwhile, in the transversal direction, 2 meters are excavated, only in the direction contrary to the maximum arc of deformation, per excavation phase.

The excavation procedure is numerically implemented through the simultaneous termination of the springs representing the soil, and of the prescribed displacement, for each segment of the excavation. Therefore, the release of the springs and displacements affects 10 meters of pipe in each excavation phase, and simultaneously liberates 5 meters on each side of the maximum arc point (first phase), or on each side of the already freed pipe.

It should be noted that, though the stress relief physical process includes a transversal release of 2 meters in the direction contrary to the maximum arc of deformation, this is not numerically reflected. The methodology adopted considers free transversal displacement of the excavated pipe stretches, and does not limit movement at 2 meters. This is because, should this boundary be employed, the model would be imposing a final position, making it impossible to observe the real recovery of the pipe.

During the third simulation stage, the slip restriction caused by the soil over the pipe, in the excavation direction, is considered through linear springs with a stiffness of 10% the maximum soil stiffness. These springs are only activated on this third stage, which models the pipe recovery, and are initiated according to the excavation process described.

3. Results

Table 4 summarizes the results found for the higher stiffness soil, considering the three simulation stages: imposition of the pressure load, pipe displacement up to the maximum bent segment, and the recovery of the pipe through destressing after the whole excavation process. Table 5 shows similar results for the lower stiffness soil.

Table 4: Results at the maximum bent segment cross-section for the higher stiffness soil.

Property	Step 1 (Pressure)	Step 2 (Displacement)	Final Step (Recovery)
Maximum von Mises Stress [MPa]	169,63	477,97	242,07
Maximum Displacement [mm]	1,0	5164,2	3133,9
Pipe Recovery [mm]	-	-	2030,3
Maximum Total Strain [%]	0,08%	0,96%	0,81%
Maximum Plastic Strain [%]	0,00%	0,72%	0,72%

Table 5: Results at the maximum bent segment cross-section for the lower stiffness soil.

Property	Step 1 (Pressure)	Step 2 (Displacement)	Final Step (Recovery)
Maximum von Mises Stress [MPa]	169,65	469,53	239,79
Maximum Displacement [mm]	2,8	5167,1	3058,1
Pipe Recovery [mm]	-	-	2109,0
Maximum Total Strain [%]	0,08%	0,74%	0,61%
Maximum Plastic Strain [%]	0,00%	0,50%	0,50%

Figure 6 shows the pipe profile, for the higher stiffness soil, at the beginning of the stress relief procedure (maximum bent segment at the displacement stage), and at each phase of the procedure, considering the gradual excavation of the pipeline.

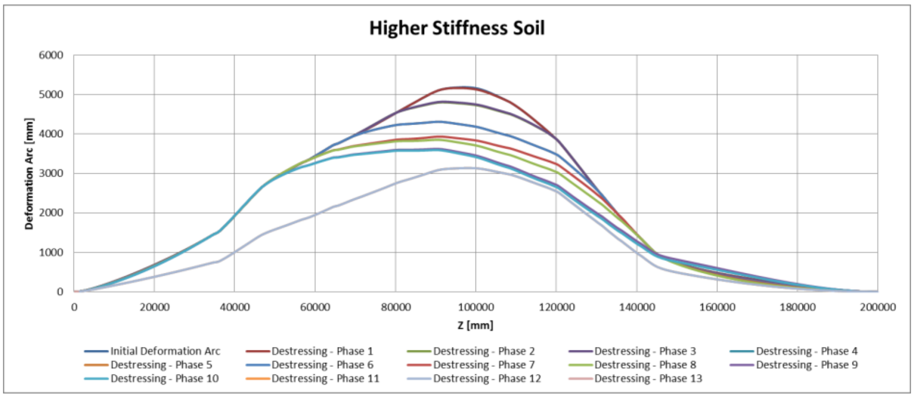


Figure 6: Pipeline profile on each stress relief phase, for the higher stiffness soil.

Figure 7 presents similar profile results for the lower stiffness soil.

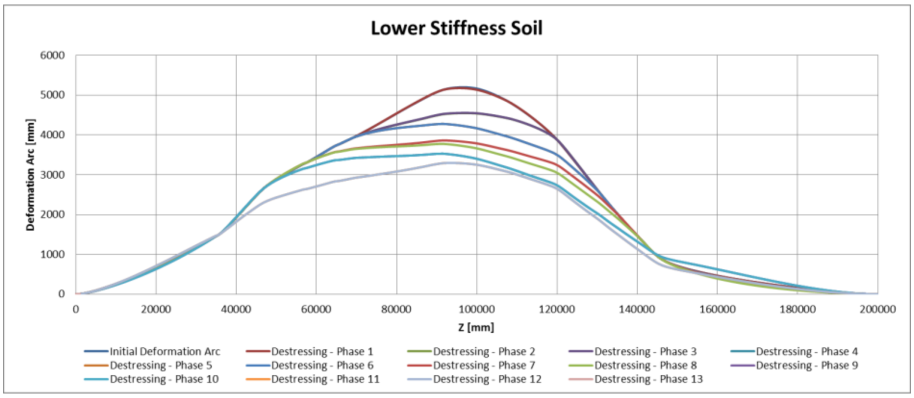


Figure 7: Pipeline profile on each stress relief phase, for the lower stiffness soil.

The blind hole technique was employed in field assessments of the pipe, as is discussed in this article’s introduction. Aiming to evaluate the numerical model’s consistency, numerical results found at the pipe displacement stage are compared with the blind-hole measurements. The higher stress among the blind-holes available was used for the comparison, considering the maximum bent segment cross-section. The results for the numerical stress overestimated the measured stress, as can be seen in Table 6.

Table 6: Comparison between the numerical results and the stress measured by the blind-hole technique.

Stress measured by the blind-hole technique [MPa]	436
Stress found through the numerical model [MPa]	452
Bent segmentin which the measured stress was found in the model. [mm]	4547 (88% of the maximum bent segment)

Due to this overestimation, the displacement in which the measured stress was numerically reproduced was also estimated. It was found that the stress found through the model equals the blind-hole assessment in a bent segmentof 88% the maximum segment modeled (4547 mm). Since there is some uncertainty about the original positioning of the pipe, it is possible the ~620 mm difference might be explained by a potential curvature in the pipeline's installation topology. Figure 7 shows the stress progression found through the model in relation to the maximum bent segment.

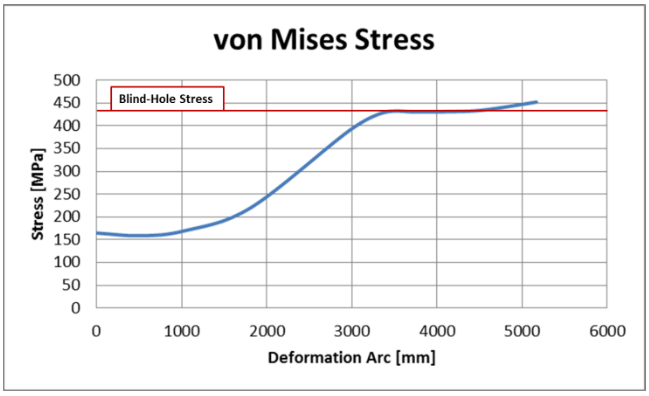
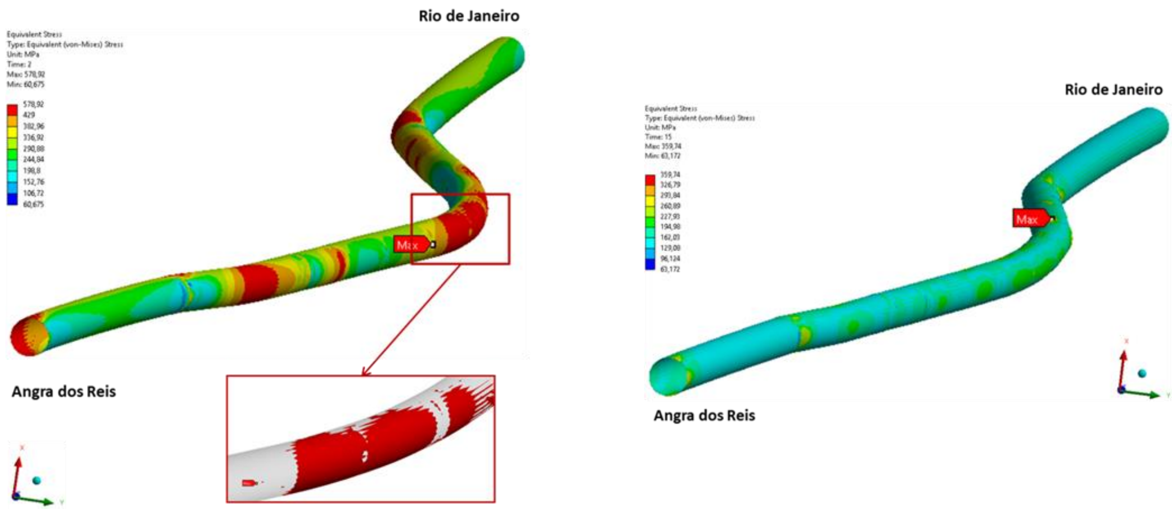


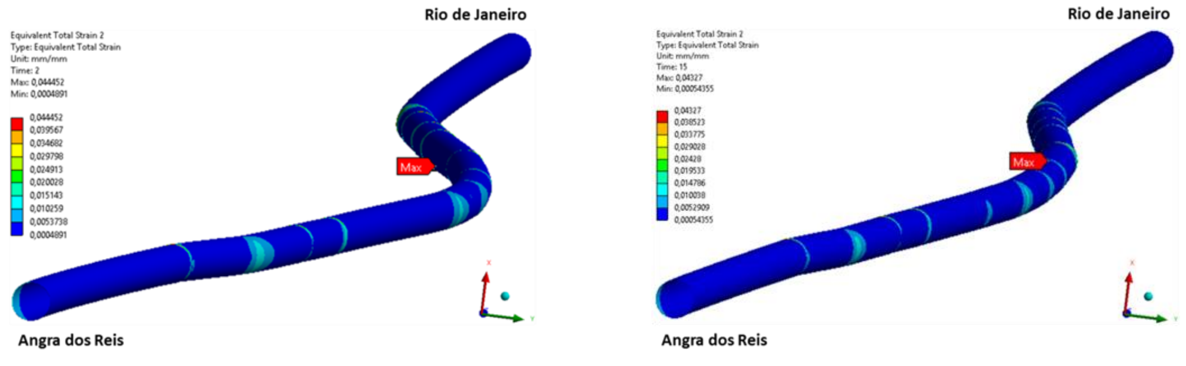
Figure 8: Stress found on the blind-hole assessment position as a function of the maximum bent segment.

Figure 8 and Figure 9 show the stress and strain profiles for the highest stiffness soil, for the displacement and recovery stages of the pipeline. Similarly, Figure 11 and Figure 12 show these results for the lower stiffness soil.



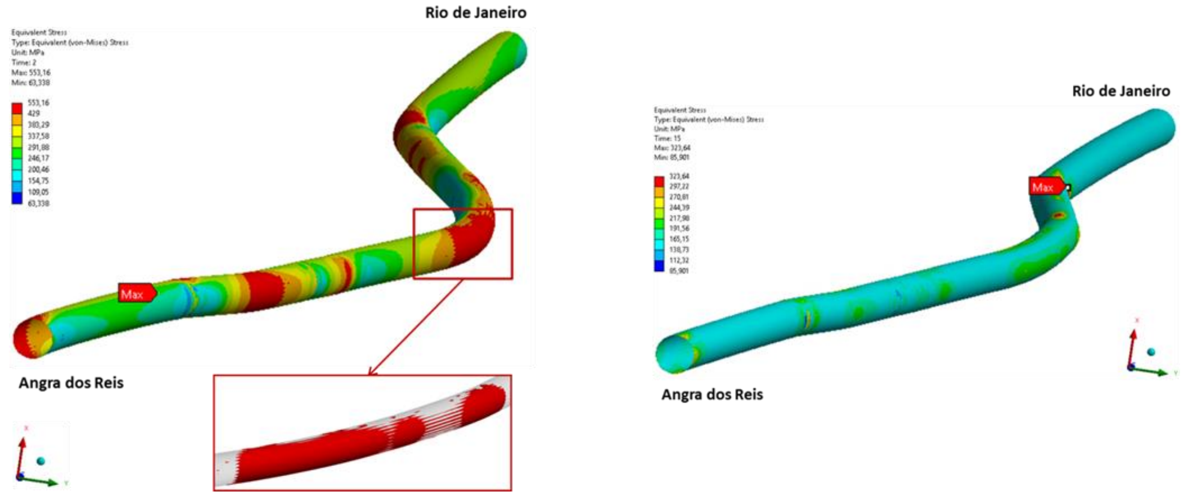
(a) (b)

Figure 9: Stress profiles for the pipe on the higher stiffness soil at the (a) displacement and (b) recovery stages.



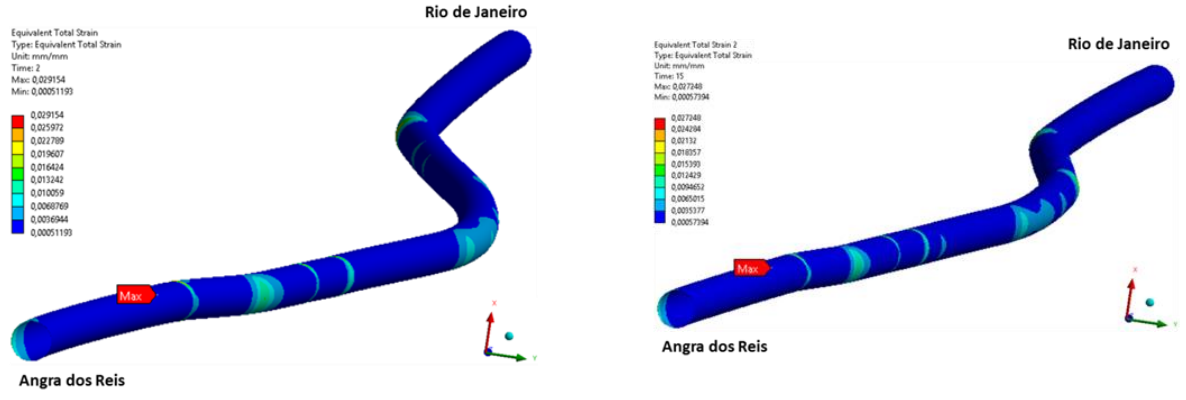
(a) (b)

Figure 10: Strain profiles for the pipe on the higher stiffness soil at the (a) displacement and (b) recovery stages.



(a) (b)

Figure 11: Stress profiles for the pipe on the lower stiffness soil at the (a) displacement and (b) recovery stages.



(a) (b)

Figure 12: Stain profiles for the pipe on the lower stiffness soil at the (a) displacement and (b) recovery stages.

4. Conclusions

The numerical simulation realized allows the observation of stresses and strains in different parts of the pipeline segment, its operational characteristics, the stresses generated during the formation of the bent segment, up to its maximum point, and finally the possible effects of the stress relief process on the pipe and the potential for its return to the initial construction position, considered to be rectilinear.

This study encompasses the entire length of the bent segment, and truthfully models the pipeline geometry and its material properties, as well as two soil's stiffness. Once these parameters are defined, a mesh sensitivity test was developed to insure good accuracy in the numerical results.

The pipe was considered as elastoplastic, and the simulation defined the multilinear model to allow for the possible effects of residual strains. The buried pipe hypothesis was adopted for the restrictionsat the pipe extremities, and the pipe length on each side was increased to avoid boundary effects on the main interest area. The soil was considered in the study according the Winkler methodology, through springs with directional stiffness.

The stress relief process was simulated by the removal of prescribed displacements forming the bent segment, as well as the springs which model the soil for the buried pipe hypothesis. Springs with a continued stiffness were activated to simulate the soil resistance after the excavation, with a stiffness of 10% the maximum soil stiffness for the completely buried pipe, for both types of soil.

The results found for the stress relief procedure indicate permanent strains, located in the maximum bent segment point. The blind-hole assessment and the numerical results were compared and a good agreement was found, verifying the consistency of the developed model.

The pipe stress after the stress relief process is, globally, below the admissible limit stress, for both soil stiffness considered in this study.

5. Acknowledgements

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