FINITE ELEMENT METHOD MODEL FOR PREDICTION OF WRINKLE GENERATION IN PIPELINES UNDER GEOTECHNICAL SLOW MOTIONS

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OSCAR GUALDRON

6 de Noviembre de 2025

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Finite Element Method Model for Prediction of Wrinkle Generation in Pipelines Under Geotechnical Slow Motions

Por: Jairo F. Useche - Integrity Assessment - ADVAN R&D

Oscar Gualdron - CENIT

The objective of this work is to develop a numerical formulation based on the Finite Element Method for the study of pipelines under soil movement, which allows predicting the development of wrinkles due to axial loads by ground movement.

Defining the problem

1. The integrity of pipelines subjected to bending stress/strain generated by ground motion represents a recurring problem in Colombia due to the complex geomorphological characteristics that characterize much of the country.

2. Furthermore, the possible appearance of wrinkles in a pipeline must be considered due to the high plastic deformations developed within it, which increase the risk of breakage.

3. ILI runs does not brings all strains-stress components.

taken from: https://www.tdwilliamson.com/

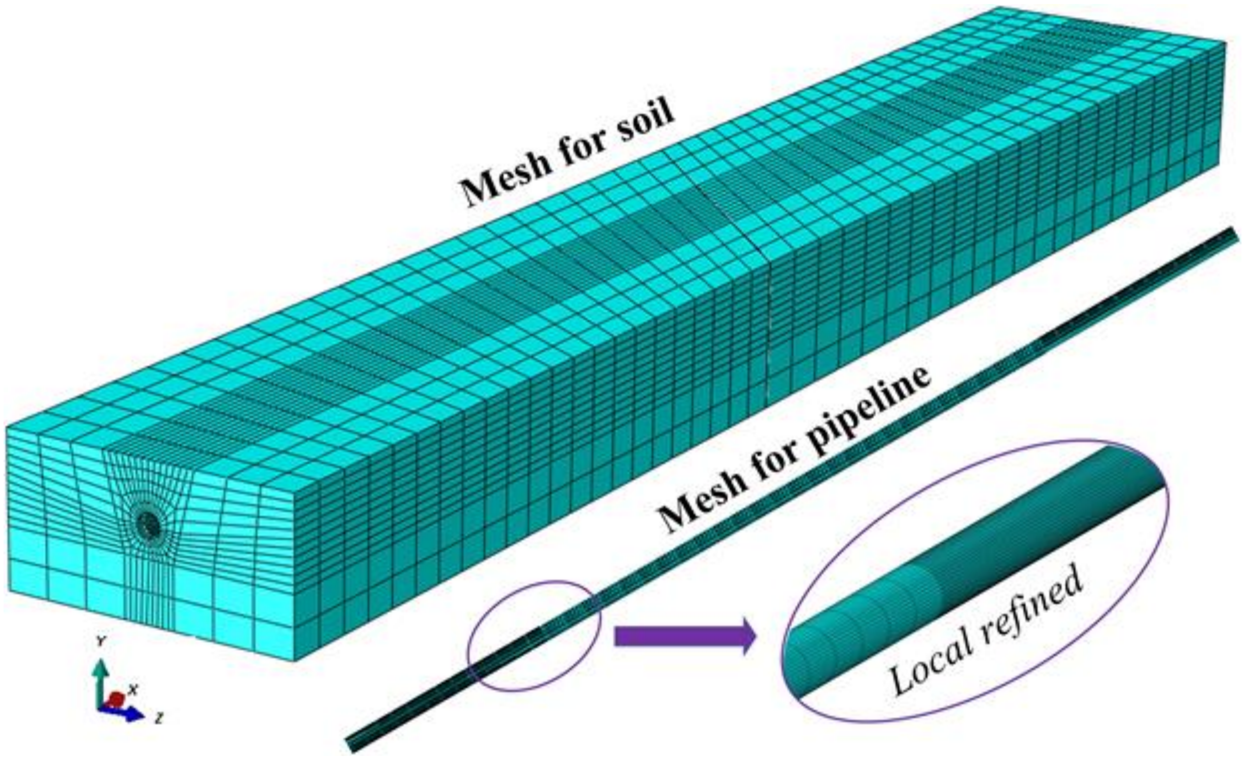
Defining the Problem

- Geotechnical spatial and time continuous slow movements (along the time).
- Full coupled soil-pipe movements.
- Large displacements, large strains/small strains.
- Axial bearing.
- Full strains/stress fields.
- Getting the geotechnical forces acting along the pipe is cumbersome.

taken from: https://www.tdwilliamson.com/

Assessment Methodology

It is based on pipe-soil interaction advanced FEA models using ILI information.



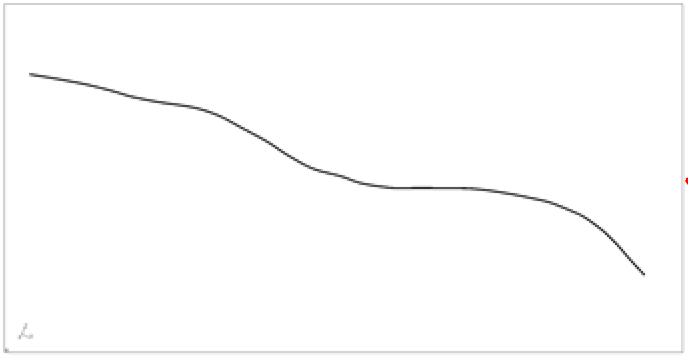
https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ese3.524

The Assessment Methodology

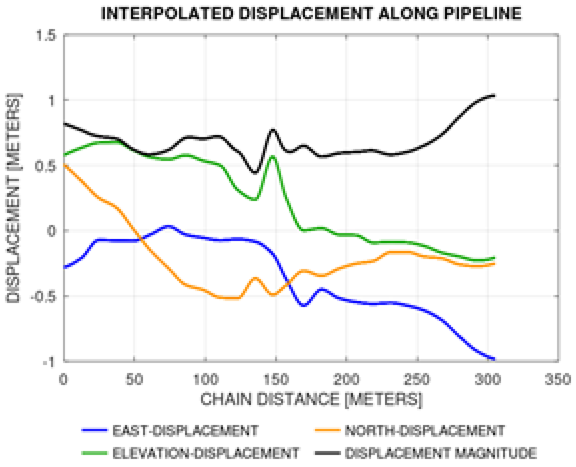
Displacement based coupled interaction Finite Element models of pipeline/Soil:

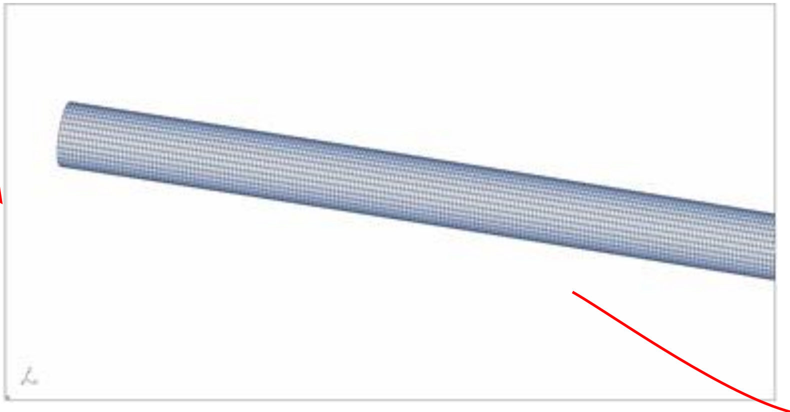
- Fully 3D model (all stress/strains components)
- SHELLS elements (considering thickness change).
- Non-Linear geometrically formulations (large displacements/rotations).
- Finite Elasto-plastic constitutive models + Damage mechanics models.
- Coupled Pipe-Soil interaction through contact model.
- The pipeline, in its current state, is free of initial stresses and deformations.
- The displacement profile is constructed from the profile obtained through the ILI runs of the section's displacement history.
- The analysis considers operating pressure acting on the pipeline.

The Assessment Methodology



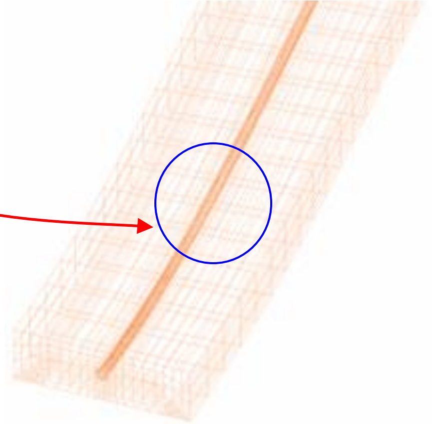
DISPLACEMENT FIELD





ILI RUN INFORMATION

FINITE ELEMENT MODEL



The Assessment Methodology

finite plasticity

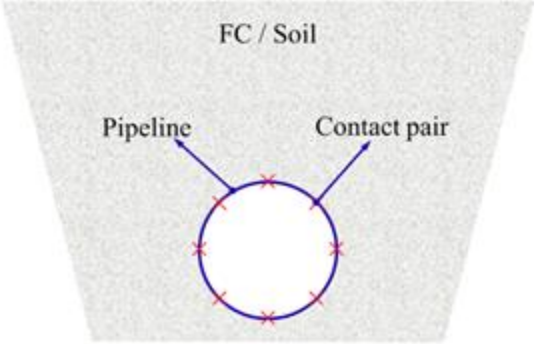
large displacements

HIGHLY NON-LINEAR PROBLEM

$$\int_\Omega \delta \boldsymbol{d} : \mathbf{c} : \boldsymbol{\varepsilon} d\Omega + \int_\Omega \boldsymbol{\sigma} : \left[(\nabla \mathbf{u})^T \nabla \delta \mathbf{v} \right] d\Omega + \kappa v \left[\overline{div} \left(\delta \mathbf{v} \right) \overline{div} \left(\delta \mathbf{u} \right) \right] -$$

$$\int_\Omega f \delta \mathbf{v} \; d\xi d\eta + \int_\Gamma q \left[\frac{\partial \mathbf{x}}{\partial \xi} \left(\frac{\partial \mathbf{u}}{\partial \eta} \times \delta \mathbf{v} \right) - \frac{\partial \mathbf{x}}{\partial \eta} \left(\frac{\partial \mathbf{u}}{\partial \xi} \times \delta \mathbf{v} \right) \right] d\xi d\eta = 0$$

follower loads

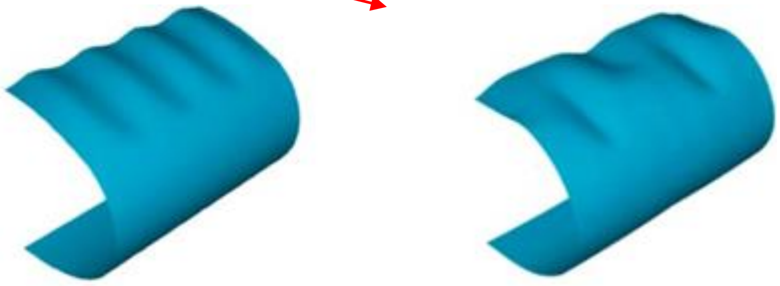


contact boundary conditions

Pipeline wrinkles

Local buckling

https://link.springer.com/article/10.1007/s11668-015-0020-y



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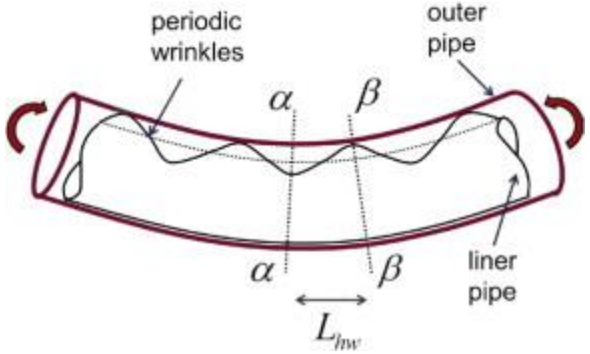

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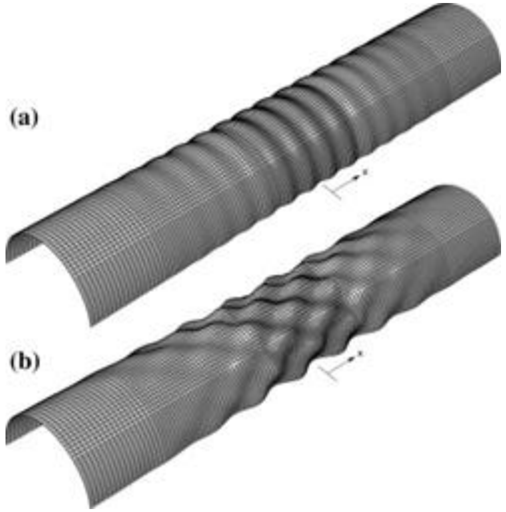
geometrical
-structural
instabilities

Wrinkles:
Highly non-linear
structural problems



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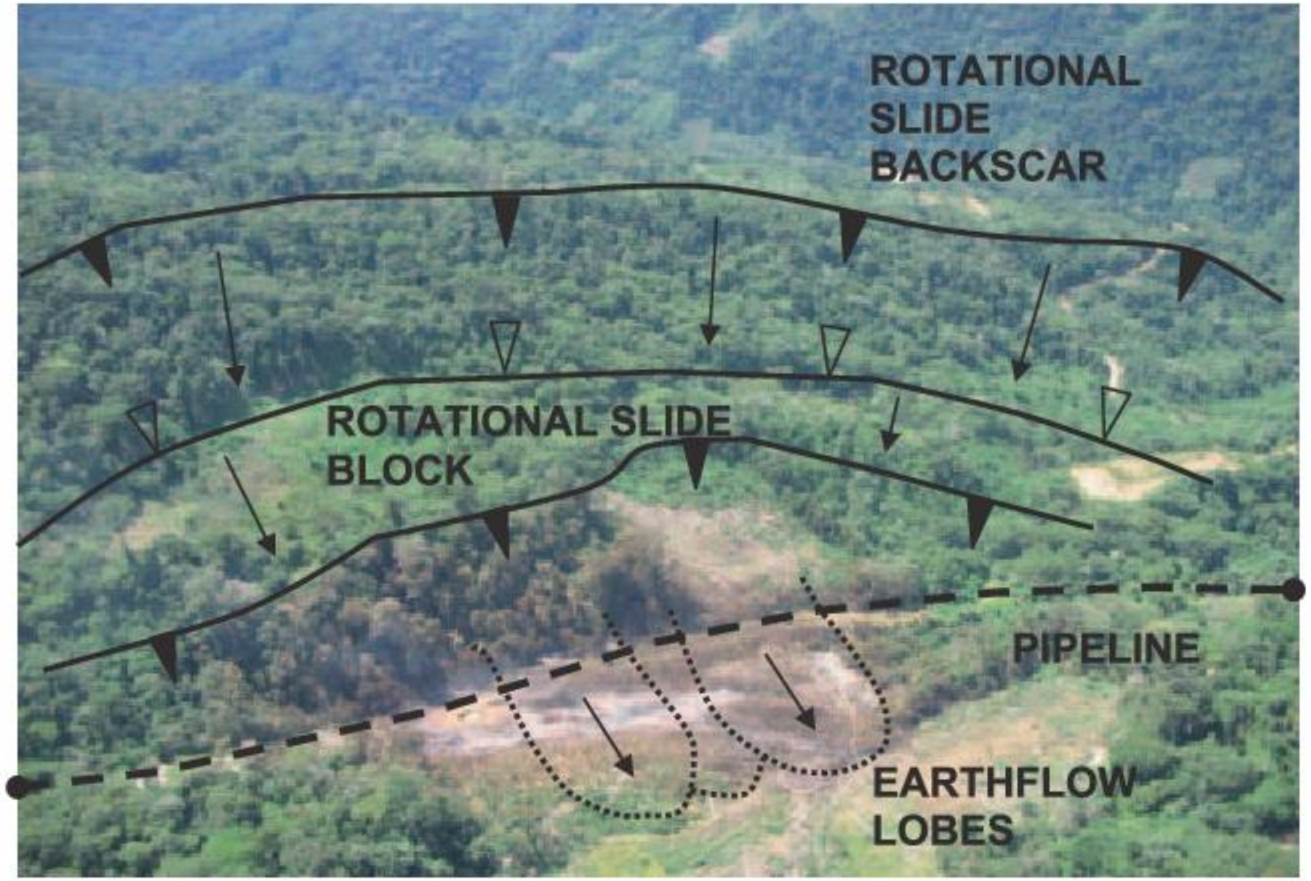
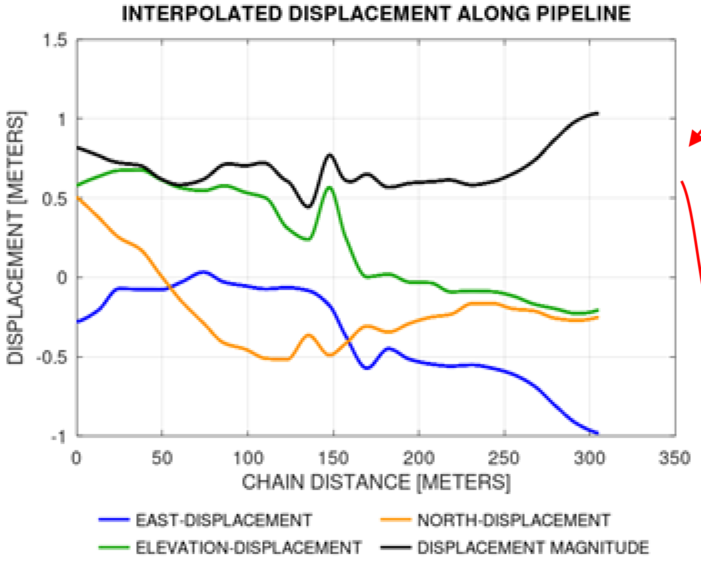
Case Analysis

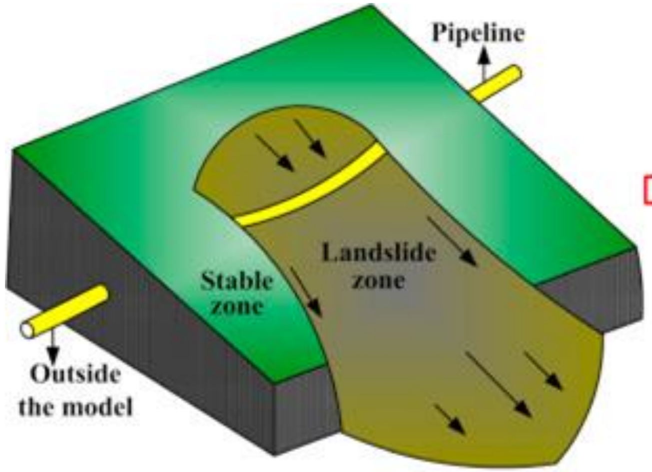


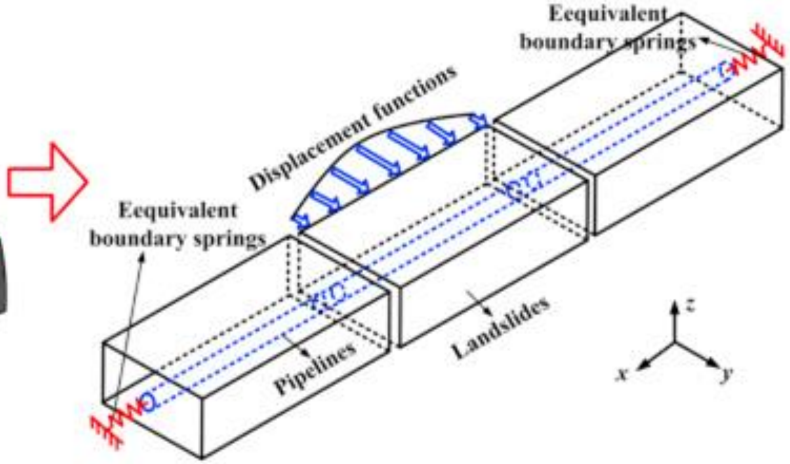
https://www.semanticscholar.org/paper/Landslide-related-ruptures-of-the-Camisea-pipeline-Lee-Audibert/bcbf7e0a81cf4c5c5577e611b14089e7f1716a46

+30 FEM bending analysis in Colombia

Case Analysis: Stress and Strains







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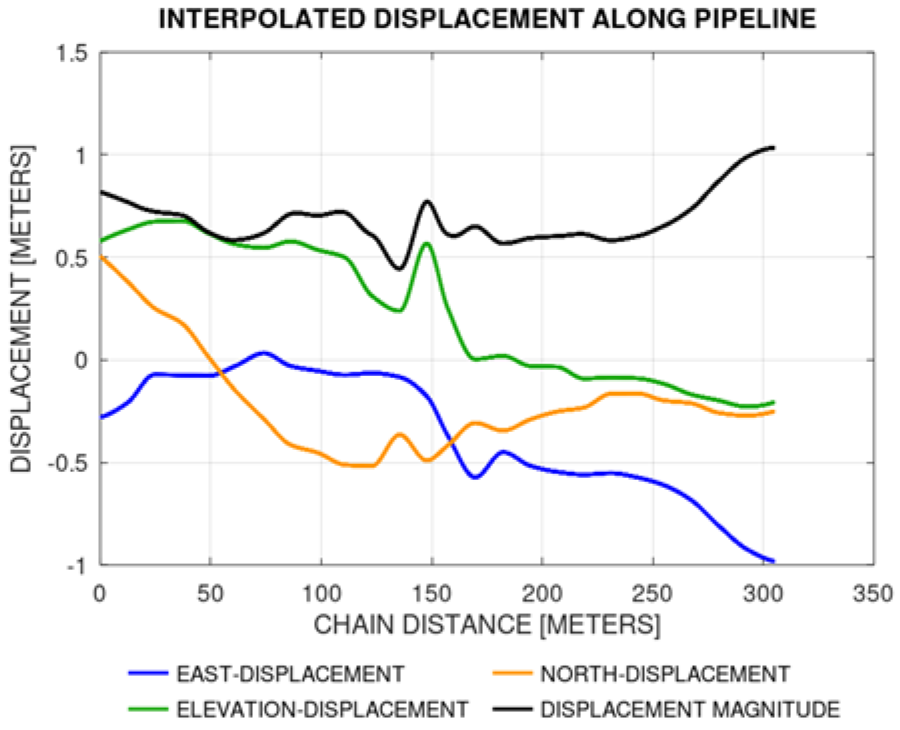
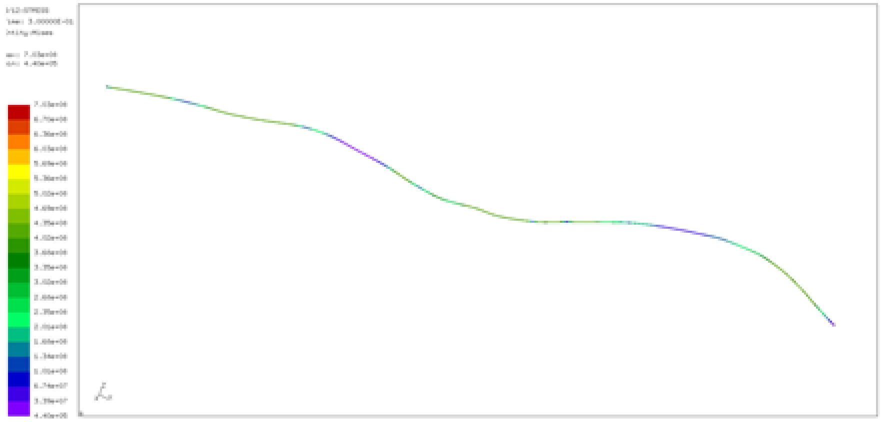
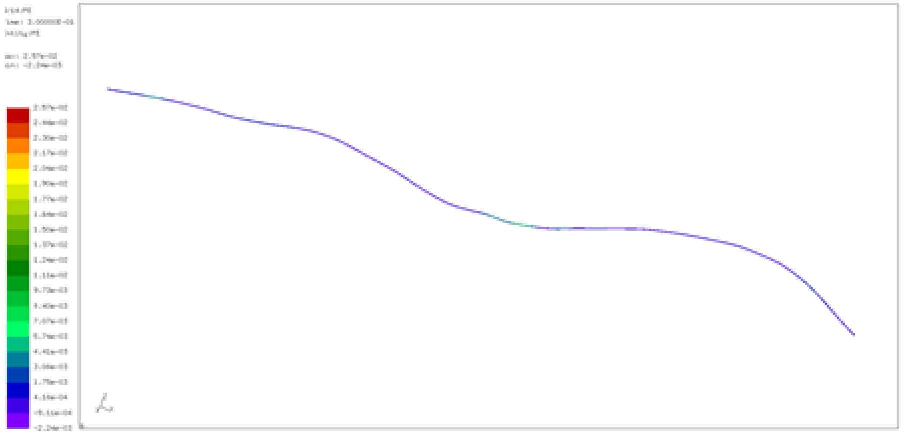
cenit ADVAN R&D

Case Analysis: Stress and Strains





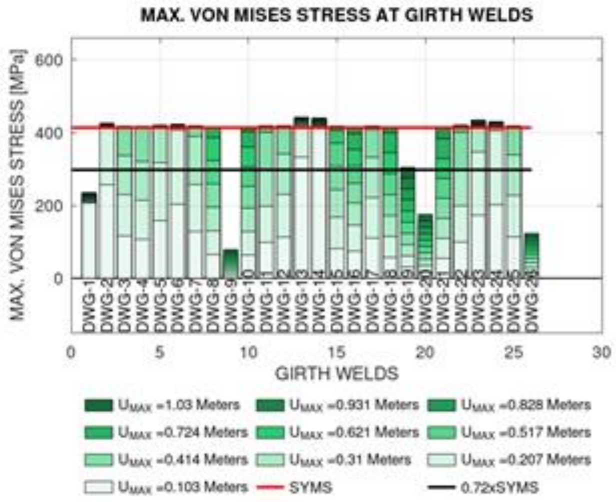
Stress along pipeline

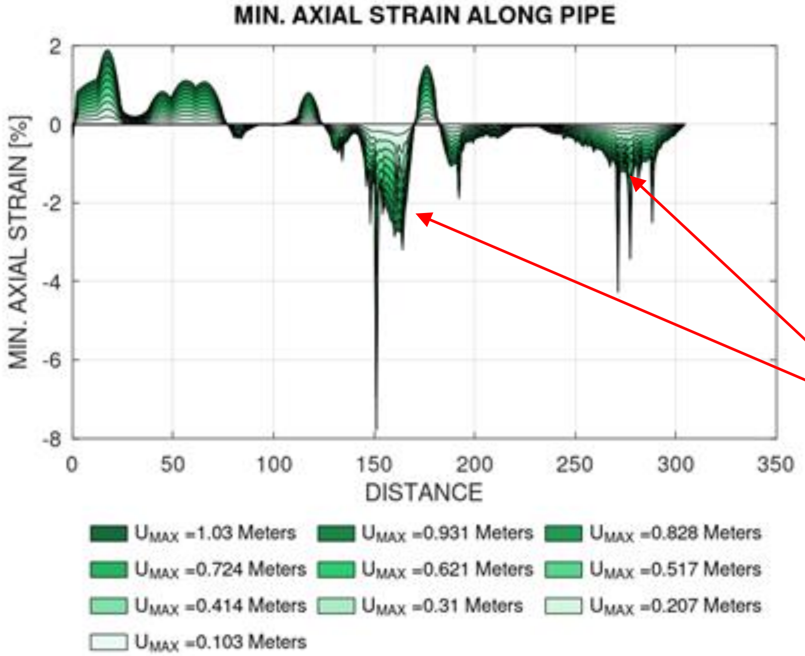


Strain along pipeline

Displacement from ILI

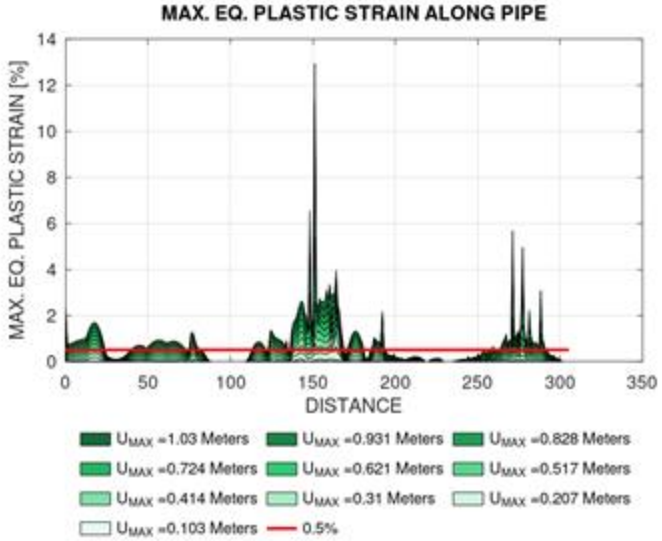
Case Analysis: Stress/Strains



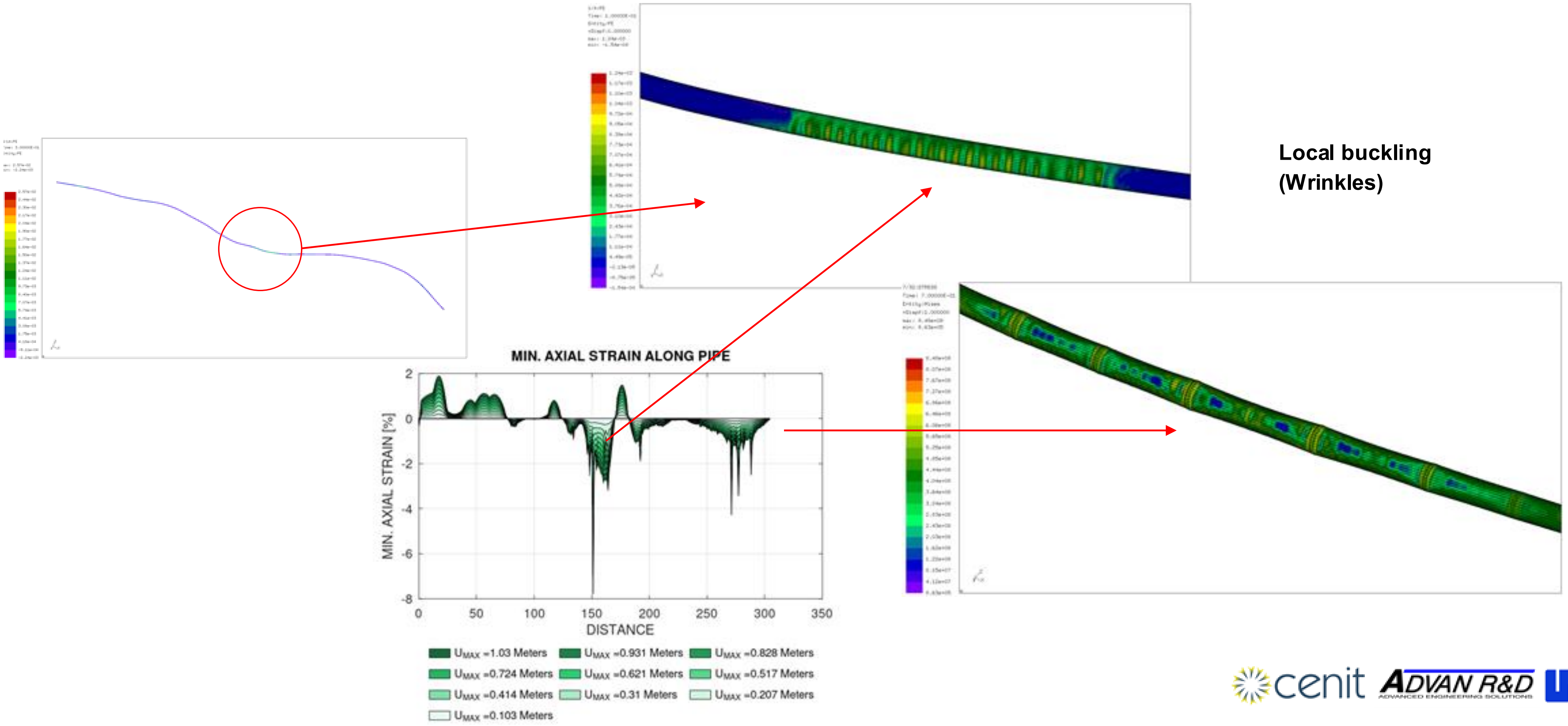


Local buckling
(Wrinkles)

(Residual
ductility)



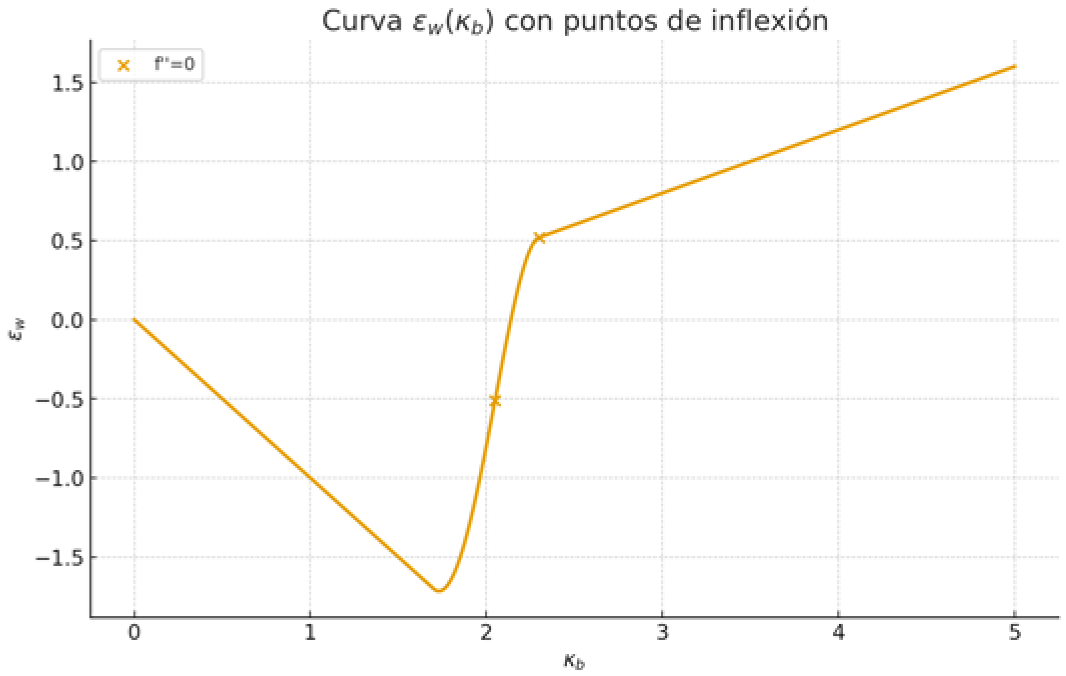
Case Analysis: Local Buckling



Case Analysis: Prognosis of Wrinkles

The following hypotheses are used to predict the formation of a wrinkle:

- The axial strain developed in a pipe cross-section is described by a harmonic function with a negative minimum value at the circumferential position where the wrinkle develops.
- The axial strain evolves monotonically and linearly with the curvature measured in the bending plane.
- The evolution of the axial strain reaches a point of instability where it undergoes a change of sign (compression to tension), passing through an inflection point for a given curvature. This curvature is the critical buckling curvature.



$$\varepsilon_w(\kappa_b) = [1 - H(u)](\frac{\varepsilon_{inf}}{\kappa_{inf}}) + H(u)[\varepsilon_{sup} - s_2\kappa_{sup} + s_2\kappa_b\ ]$$

$$\boxed{\frac{d\varepsilon_w}{d\kappa_b} = 2[s_2 - (\frac{\varepsilon_{inf}}{\kappa_{inf}})]S'(\kappa_b) + [\varepsilon_{sup} - s_2\kappa_{sup} + [s_2 - (\frac{\varepsilon_{inf}}{\kappa_{inf}})]\kappa_b]S''(\kappa_b) = 0}$$

The solution to this equation allows us to obtain the critical buckling curvature (condition for a wrinkle).

Conclusions

- The finite element numerical modeling methodology, based on elastoplastic shell models coupled with three-dimensional soil models, allows for the study of the evolution of stresses, deformations, and the appearance of plastic instability zones, such as wrinkles, along pipeline lengths based on information obtained from ILI runs.
- Wrinkles can be predicted from FEM shells models using ILI information.
- Analytical model can be established from axial strain evolution curves for the prediction of wrinkles appearing at given level of displacements in a pipeline under slow geotechnical models.

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ABSTRACT

The integrity of pipelines subjected to bending stresses and strains is a recurring challenge in Colombia due to the country's complex geomorphological conditions. The potential development of wrinkles in the pipe must be taken into account, as the large plastic deformations involved increase the likelihood of failure. This study proposes a methodology for assessing residual stresses and strains along an oil pipeline, using ILI data combined with numerical models based on the Finite Element Method. The displacement profile for the analysis is derived from ILI runs. The pipeline is modeled with shell elements, while the soil is represented using a Mohr-type constitutive model. The damage model incorporates the formation of microdefects as material deformation progresses, and the soil–pipeline interaction is simulated through contact elements. Results from the integrity assessment of a Colombian pipeline are presented, demonstrating the effectiveness of the proposed methodology by successfully predicting wrinkles that were actually observed in the pipe.

Keywords: Oil pipelines, buckling, wrinkles, stresses, soil sliding, geotechnics.

1. INTRODUCTION

The integrity of pipelines subjected to bending stress/strain generated by ground motion represents a recurring problem in Colombia due to the complex geomorphological characteristics that characterize much of the country. This type of analysis is among the most complex. The use of computational models for fitness-for-service studies is the most appropriate approach in terms of cost-benefit ratio. The theoretical prediction of a pipeline's deformation behavior using numerical models allows for the study of its behavior and structural integrity under ground motion scenarios.

Furthermore, the possible appearance of wrinkles in a pipeline must be considered due to the high plastic deformations developed within it, which increase the risk of breakage. Therefore, predicting the appearance of wrinkles is a critical task in the structural analysis of a pipeline subjected to ground motion. The numerical modeling methodologies used in these tasks must be considered in their formulation.

This paper presents a methodology for studying residual stresses and strains along an oil pipeline, using ILI data and numerical models based on the Finite Element Method. The displacement profile used in the analysis is constructed from ILI runs in the pipeline and the displacement history of the section measured between consecutive runs. The pipeline model was constructed using four-node shell elements with six degrees of freedom (DOF) per node, whose formulation takes into account large displacements and rotations and is capable of modeling finite plasticity and thickness reduction. This element allows the control of "hourglassing" and "shear locking", which refer to fictitious (or "zero energy") deformation modes and flexural stiffness of the element, respectively.

The mechanical response of the pipeline material was modeled using an elasto-plastic model based on damage mechanics that considers isotropic hardening. This constitutive model is based on the multiplicative decomposition of the strain tensor, allowing for modeling problems involving large displacements and unit strains. The soil is modeled using an elasto-plastic model based on the Mohr constitutive model. The damage model allows for the generation of microdefects as the deformation in the material evolves. The soil-pipe interaction is modeled using contact elements, taking into account the friction between them.

The results of the integrity analysis of a pipeline in Mexico are presented, demonstrating the effectiveness of the proposed methodology through the prediction of wrinkles actually found in the pipeline in subsequent ILI runs.

2. MATERIALS AND METHODS

2.1 Modelo numérico

The pipeline finite element model was constructed using four-node shell elements with 6-DOFs per node, whose formulation takes into account large displacements and rotations and the ability to model finite plasticity and thickness reduction [1][2][9]. This element allows the control of "hourglassing" and "shear locking", which refer to fictitious (or "zero-energy") deformation modes and flexural stiffness of the element, respectively. The FEA software used is FEASY® (Finite Element Analysis System) developed by ADVAN R&D (www.advanrd.com).

The numerical model used in the analysis is based on the following assumptions:

- The pipeline, in its current state, is free of initial stresses and deformations.
- The displacement profile is constructed from the profile obtained through the ILI runs of the section's displacement history.
- The analysis considers the maximum operating pressure acting on the pipeline.

The soil behavior was modeled using a large-displacement, finite-plasticity model and the Mohr-Coulomb yield criterion using brick-type solid elements with reduced integration and a structured mesh generated along the pipe's extrusion axis. Contact elements were used to model the soil-pipe interaction using a penalty model.

2.2 Constitutive modeling

The mechanical response of the material was modeled using an elastoplastic model with isotropic hardening based on the multiplicative decomposition of the strain tensor, considering the damage evolution model proposed by Gurtin and Francis [8]. This model has no limitations in terms of its applicability for the range of unit deformations found in the analysis. The stress-strain curve used was constructed using the MPC model presented in API-RP-579.

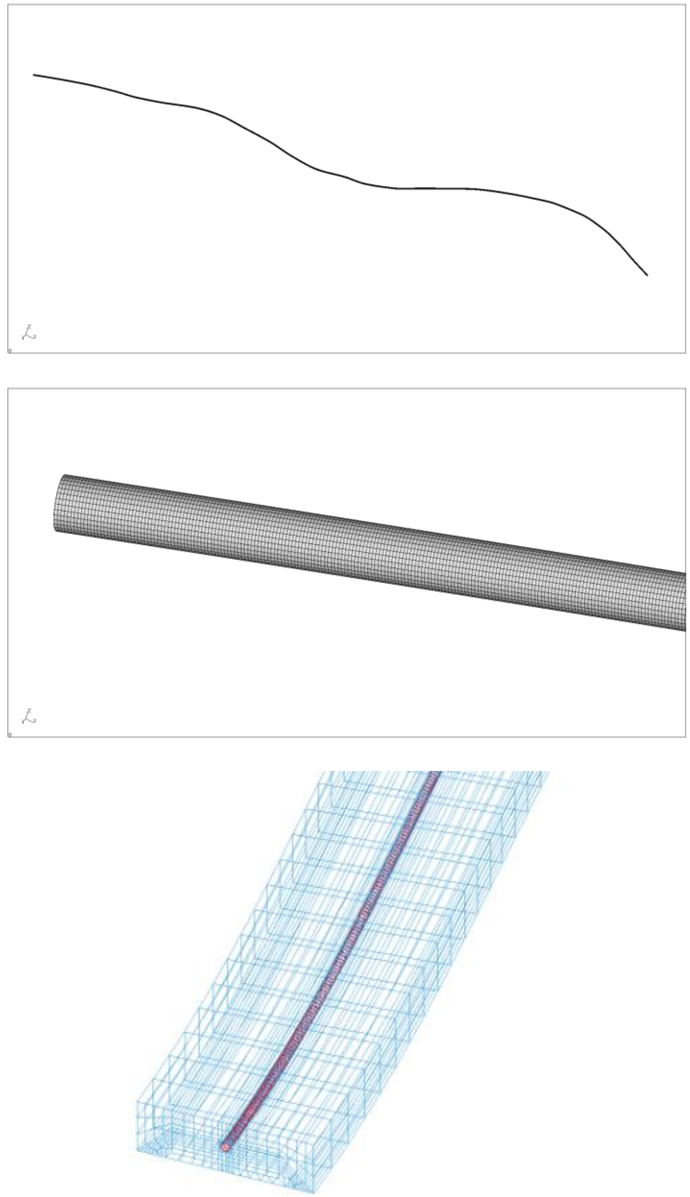

FIGURE 1. FINITE ELEMENT MESH FOR THE PIPE (SOIL MODEL BELOW).

2.1 Load modeling

The model considers the maximum operating pressure of the analyzed section as working loads, as well as the weight of the pipe, the soil and the transported product[4][5]. Other loads and/or conditions such as stresses, deformations or initial displacements are not considered in the analysis. At the ends of the pipe, nodal displacements and rotations are restricted in the plane normal to the pipe section.

2.2 Soil-displacement modeling

The displacement profile is constructed by field measurements using two ILI runs spaced two years each one. In this way a displacement field can be obtained and the evolution of pipe deformation can be extrapolated to the future. Figure 2 shows the displacement profiles for a Colombian pipeline located in a complex geomorphological zone. In the present study, displacements up to 1.5 times the displacement curve thus constructed are implemented in order to study the effect of larger displacements on the development of stresses and strains in the pipe[6][7][8].

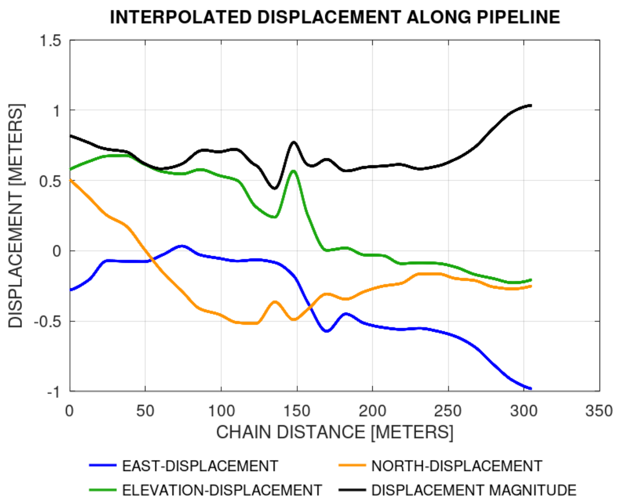

FIGURE 2. DISPLACEMENT PROFILE FROM ILI TOOL.

3. RESULTS AND DISCUSSION

3.1 Strain and stress distributions

Although the objective of this work does not focus on the failure (breakage) of the pipe, it is worth noting that the remaining ductility in the material is used as a failure criterion in this work, which is defined as:

$$D_r = 1 - \frac{\varepsilon_p}{\varepsilon_{UT}} \quad (1)$$

Where ε_{UT} is the ultimate strain for the material (taken as 0.18 m/m in this work) and ε_p is the equivalent plastic deformation defined as:

$$\varepsilon_p = \sqrt{\frac{2}{3} D_p{}^{dev} : D_p{}^{dev}} \quad (2)$$

where $D_p{}^{dev}$ The plastic flow deviatoric tensor. The damage model through the expression:

$$\psi(C_e, \kappa, D, \nabla D) = (1 - D)\psi_e(C_e) + \psi_h(\kappa) + \psi_d(D, \nabla D) \quad (3)$$

In this equation, κ is an internal variable related to hardening, C_e is the left Cauchy tensor; ψ_h y ψ_d, are functions that define the damage model, which describes the breakage process in the material. $D \in [0,1)$ is the damage parameter that indicates the evolution of the damage during the deformation process.

Figures 3 and 4 show the evolution of the Von Mises stresses and equivalent plastic strains obtained along the pipeline for a API-5L-X65 with diameter 0.4064 m and 8.3 mm of thickness. These graphs show the maximum Von Mises stress value for the final displacement condition. Thus, maximum stresses of the order of 530 MPa are developed, with accumulated plastic strains exceeding 0.019 mm/mm at a distance of 150 meters from the left edge.

Figure 4 shows the variation in stress and maximum strains along the pipeline. The distances shown on the horizontal axis are measured from the GWD-1 weld, located at the PR reference point. This figure shows the highest stress values between distances of 130 and 170 meters, with values above the yield strength of the material and highly concentrated at 150 meters with a value close to 580 MPa, observing that the majority of the material in the pipe generates plastic deformations for maximum displacements of 0.103 meters.

The distribution and evolution of the equivalent plastic deformation in the welded joints and along the pipe are also presented, where plastic deformations are observed with values in the range of 0.025 mm/mm (2.0%) to 0.025 mm/mm (2.5%). In this same figure, areas located between 130 and 170 meters show plastic deformations with maximum values of 0.02 mm/mm (2%) with maximum values above 0.12 mm/mm at 150 meters.

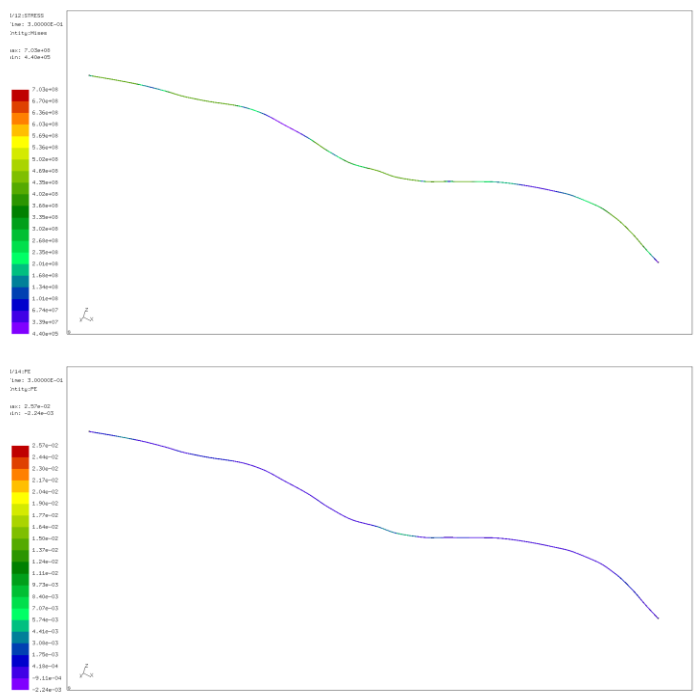

FIGURE 3. PROFILE OF EQUIVALENT PLASTIC STRESS AND DEFORMATION ALONG THE PIPE.

3.2 Wrinkle generation

Figure 5 shows the evolution of plastic deformations between recording distances 130 and 170 meters. It is observed how plastic deformations of the order of 0.00124 mm/mm are generated in this area from 0.103 meters of maximum displacement, presenting a wave-like distribution that favors the evolution of localized buckling (wrinkles). Figure 6 shows that this plastic zone evolves towards concentrated zones of deformation and geometric instability in the pipe wall, presenting localized buckling (wrinkle) for maximum displacement between 0.31 and 0.414 meters, presenting plastic deformation values in the range of 0.093 mm/mm. Finally, in this same figure, a wrinkle is observed with plastic deformation values of 0.225 mm/mm, indicating that between a displacement of 0.414 meters and 0.621 meters, the pipe breaks at the wrinkle.

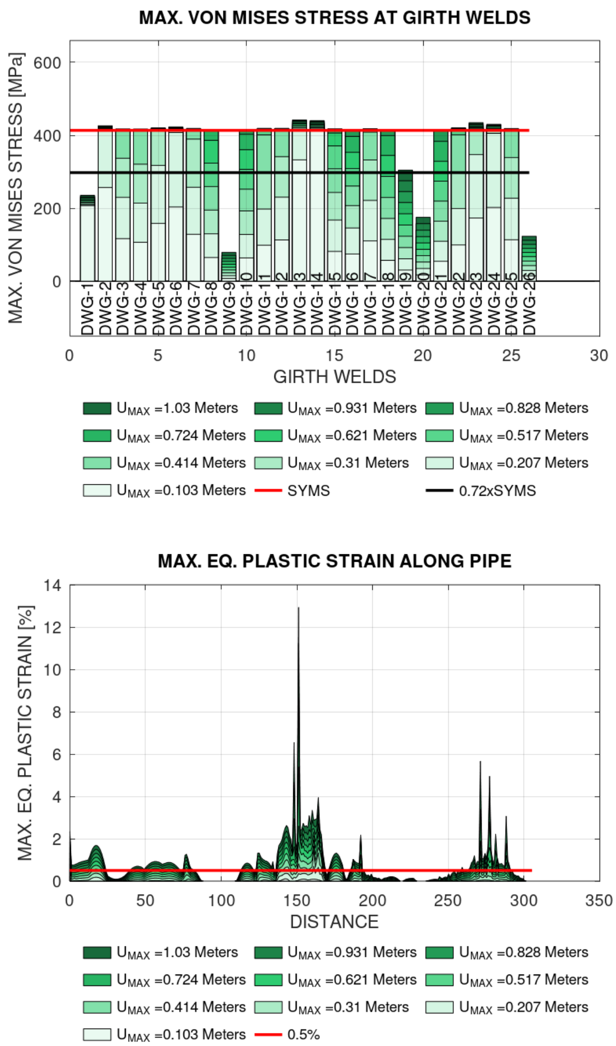

FIGURE 4. ABOVE: VON MISES STRESSES IN WELDS. BELOW: EQUIVALENT PLASTIC DEFORMATION.

The presence of other wrinkles in this area indicates the pipe's high susceptibility to plastic deformation failure in this section, which occurs for small maximum displacements (on the order of 0.10 m) and buckling. This can be explained by the pipe's geometry and the way in which displacement is distributed and evolves along the pipe's length, which indicates a pipe layout that is highly susceptible to these types of failures in the area considered.

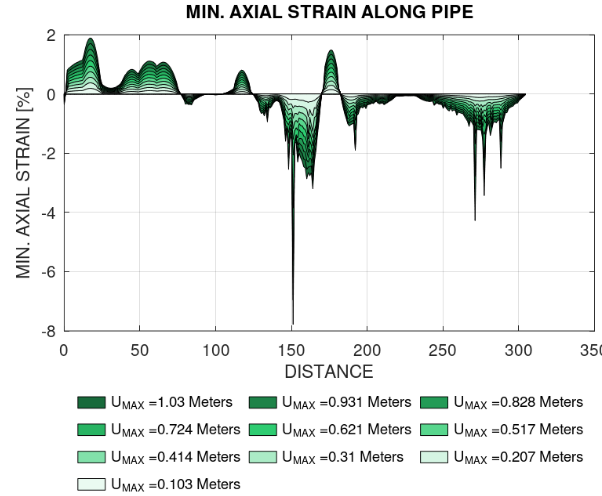

FIGURE 5. AXIAL DEFORMATION ALONG THE PIPE, FOR THE MAXIMUM DISPLACEMENT CONDITIONS SHOWN.

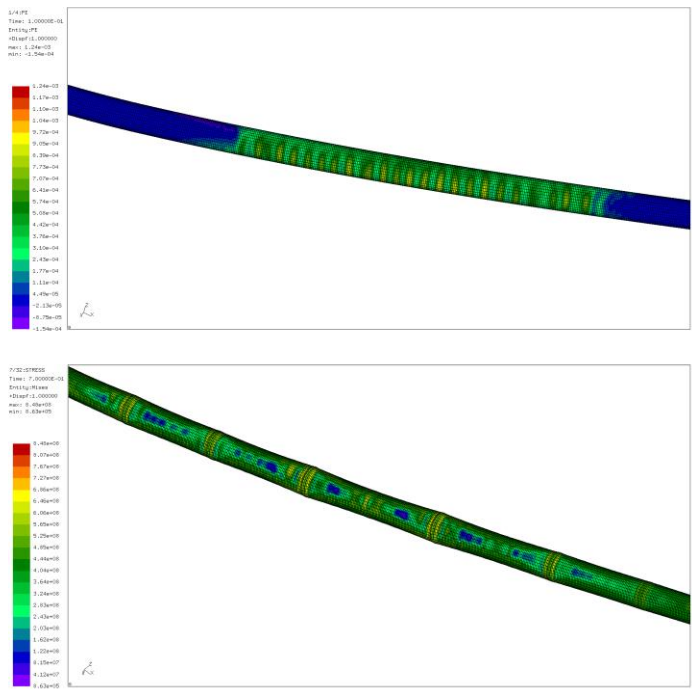

FIGURE 6. DISTRIBUTION OF PLASTIC DEFORMATION TOWARDS THE CENTER OF THE PIPE GENERATION OF WRINKLES (ABOVE INITIAL STAGES BELOW: FINAL GEOMETRY).

3.2 Wrinkle generation criteria

Based on the results, the following hypotheses are used to predict the formation of a wrinkle:

- The axial strain developed in a pipe cross-section is described by a harmonic function with a negative minimum value at the circumferential position where the wrinkle develops.

- The axial strain evolves monotonically and linearly with the curvature measured in the bending plane.
- The evolution of the axial strain reaches a point of instability where it undergoes a change of sign (compression to tension), passing through an inflection point for a given curvature. This curvature is the critical buckling curvature.

These considerations allow us to propose the following evolution equation for the axial strain as a function of the curvature as:

$$\varepsilon_w(\kappa_b) = [1 - H(u)](\frac{\varepsilon_{inf}}{\kappa_{inf}}) + H(u)[\varepsilon_{sup} - s_2\kappa_{sup} + s_2\kappa_b] \qquad (4)$$

where κ_b is the main curvature of the pipe in the cross section; $\kappa_t \in [\kappa_{inf}, \kappa_{sup}]$ is the transition curvature; ε_{inf} and ε_{sup} are the minimum and maximum axial unit strains, respectively; s_2 es un setting parameter and $H = 0\ if\ u \leq 0$, $H = 3u^2 - 2u^3\ \ if\ 0 < u \leq 1$ y $H = 1, u \geq 1$, with:

$$u = \frac{\kappa_b - (\kappa_t - \frac{w}{2})}{w}$$

The critical curvature for wrinkling, κ_w, occurs at the inflection point of the curve $\varepsilon_w(\kappa_b)$, i.e. $d\varepsilon_w/\kappa_b = 0$. Thus:

$$\frac{d\varepsilon_w}{d\kappa_b} = 2[s_2 - (\frac{\varepsilon_{inf}}{\kappa_{inf}})]S'(\kappa_b) + [\varepsilon_{sup} - s_2\kappa_{sup} + [s_2 - (\frac{\varepsilon_{inf}}{\kappa_{inf}})]\kappa_b]S''(\kappa_b) = 0 \qquad (5)$$

The solution to this equation allows us to obtain the critical buckling curvature (condition for the appearance of a wrinkle). Figure 5 presents the evolution of $\varepsilon_w(\kappa_b)$ for the pipe analyzed in this work.

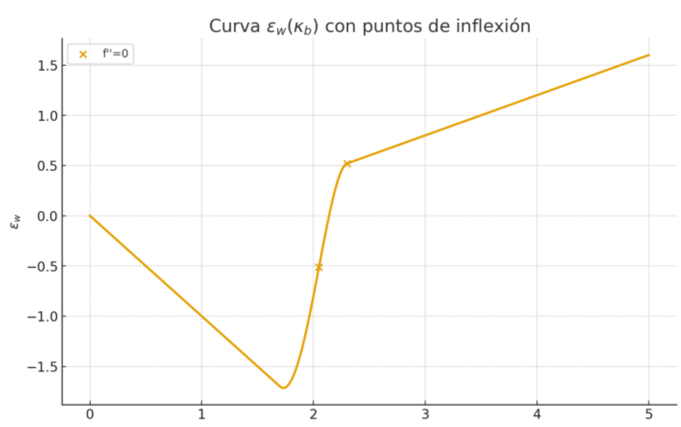

FIGURE 7. AXIAL STRAIN CURVE AS FUNCTION OF CURVATURE.

4. CONCLUSION

The finite element numerical modeling methodology, based on elastoplastic shell models coupled with three-dimensional soil models, allows for the study of the evolution of stresses, deformations, and the appearance of plastic instability zones, such as wrinkles, along pipeline lengths based on information obtained from ILI runs. This provides a predictive tool for pipeline integrity analysis.

ACKNOWLEDGEMENTS

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