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STRUCTURAL INTEGRITY MANAGEMENT IN HYDROCARBON TRANSPORTATION PIPELINES BASED ON SOIL-PIPELINE INTERACTION, APPLICATION CASE: OCENSA, COLOMBIA

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ABSTRACT

The integrity management of hydrocarbon transportation pipelines requires risk awareness and risk reduction activities, both vital for decision making in order to maintain the operational continuity of the system and avoid product containment losses. The risk awareness activities that manage the threat of weather and external forces are mainly focused on the results of the inertial tool (ILI in its IMU module), being this the main leverage in the identification of pipe movements associated with slow ground flows or slope creep, both difficult to identify visually and with high potential for damage to the pipeline; associated with the inertial inspection, topographic and geotechnical monitoring has been implemented for the ground and mechanical deformation for the pipeline. This article presents the methodology for the formulation of a coupled numerical model that allows to relate the soil behavior with the structural response capacity of the pipeline and, by means of an abacus that relates the two variables, allowing to project states of deformation in the pipeline from periodic monitoring of the ground.

Keywords: Finite Elements, Pile, Young's Modulus

1. INTRODUCTION

One of the main threats to pipelines are sites where slow ground displacements, known as reptations, occur due to their difficulty to be detected. The pipeline moves along with the ground, and this displacement over time can lead to rupture due to deformation. Inertial tools have become the key to determine the sites where the pipe has been displaced and to know precisely its magnitude. However, the cost and periodicity of inertial tool runs makes it necessary to have monitoring, modeling and indicative abacuses to be able to program timely mitigation actions.

In the literature there are some equations to try to determine the pipeline displacement from the knowledge of the ground displacement. However, a poor correlation has been detected between topographically measured ground displacement criteria and the displacement and deformation data of a hydrocarbon transport pipeline.

The correct correlation between the soil displacement criteria and the unit deformation of the pipeline are multivariable, depending on the stiffness characteristics of both the soil and the pipeline, as well as the operational characteristics of the latter. Therefore, for an accurate correlation obtained from soil-pipeline interaction models, the physical, elastic and strength parameters of both the pipeline steel and the soil must be sufficiently characterized.

Based on the correlation of the characteristics of the continuous medium where the pipeline is located (i.e. soil) and the properties and operational, geometrical and installation parameters of the pipeline, Finite Element Modeling (FEM) is performed to find the correspondence between ground displacements and the consequent deformation of the pipeline.

Based on the above, the pipeline transportation system operator will have a series of charts or abacuses where the displacement measured on the surface in meters or centimeters (on the X axis) is correlated with topography or geotechnical monitoring instrumentation, with the unit deformation of the pipeline in percentage (on the Y axis), in order to have a decision tool.

Based on the above, it is possible to define preventive maintenance activities such as excavations for stress relief, cutting and replacement of pipe segments and realignment of the original layout, based on the actual state of stresses and deformations, in order to avoid breaks and losses of pipeline containment in a predictive manner or, avoiding unnecessary maintenance activities.

2. SOIL-PIPE INTERACTION

2.1 Mechanical and Geotechnical World Meeting

Taking into account that the main task of the integrity engineers of a hydrocarbon transportation system is to guarantee the suitability of the pipeline for service, it is essential to recognize the importance of correlating, in an efficient and

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accurate manner, the influence of the terrain that houses the pipeline in terms of its stability and dynamic characteristics, with the available stresses and deformations in terms of the pipeline's admissible resistance.

The above reflects the need to physically, elastically and mechanically characterize the soils that make up the right-of-way over which the pipeline runs, as well as to carry out periodic measurements and monitoring to establish the displacement rates at which the ground moves, in order to establish thresholds and attention plans, once instability levels that exceed the admissible ones are reached.

However, it is at this point where the importance of parameterizing the behavior of the ground according to the pipeline Integrity gains strength, establishing the level of affectation that can generate its potential instability associated to its geotechnical characteristics, that is to say, differentiating when the movement of the ground, in spite of having a critical appearance, does not have the power to damage the pipeline or, on the contrary, when the ground, in spite of not showing large displacements, may be exerting large efforts or pressures on the pipeline, which could lead it to rupture.

This last statement gives way to the meeting of the branches of integrity management comprised by geotechnical and structural integrity, which when properly correlated allow optimizing the resources and intervention plans of the pipelines, associated to external forces derived from ground instability, by prioritizing those sites on the right-of-way that represent the greatest risk to the structural integrity of the pipeline, not only in terms of ground displacement measured by topographic and geotechnical monitoring, but also in terms of the consequent structural response of the pipeline, in terms of unit deformation.

Figure 1 shows the relevant parameters involved in the mechanical behavior of the pipeline and the geotechnical behavior of the soil, highlighting the relevance, in both cases, of the elastic or Young's modulus that governs the stiffness of each one; additionally, the importance of the geometric parameters in the pipeline that determine its inertia is evident, as well as its internal pressure that directly influences the state of equivalent stresses, while for the soil the shear strength parameters are also determinant.

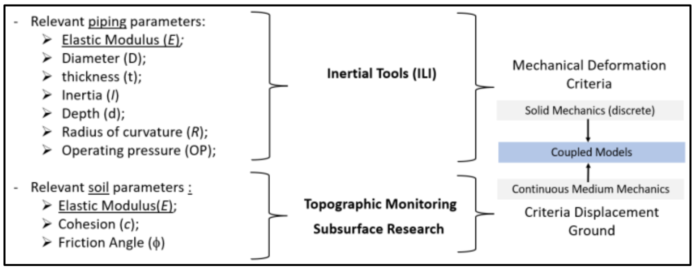

FIGURE 1: COMPARISON OF MECHANICAL, ELASTIC AND PHYSICAL PARAMETERS INTERACTING IN THE ENCOUNTER OF GEOTECHNICAL AND MECHANICAL BRANCHES IN SOIL-PIPELINE INTERACTION.

As will be discussed later in the case studies on the application of the above concepts, an example that describes in broad strokes the essence of soil-pipeline interaction can be seen in the hypothetical case of a pipeline subjected to the thrust of a section of the Right-of-Way that is unstable:

- In the case where the mobilized soil is a soft soil, with high water content and low elastic modulus, which in the geotechnical monitoring reports a displacement of 80 centimeters in the last 2 months, the level of interaction with the pipeline is reduced due to the low power of influence of the reduced stiffness of the soil and its mobilized cohesion and friction resistance parameters (i.e. contact pressures). As a result, despite the high measured ground displacement, the structural response of the pipeline in terms of unit deformation does not represent an alert of attention in the short term.

- On the contrary, in the same unstable right-of-way section where the mobilized soil is a stiff soil, with low water content and high elastic modulus, which in the geotechnical monitoring reports a displacement of 40 centimeters in the last 2 months, the level of interaction with the pipeline is increased due to the considerable power of influence of the high stiffness of the soil and its mobilized cohesion and friction resistance parameters.

As a result, although the measured ground displacement is lower than in the first case, the structural response of the pipeline in terms of unit deformation may represent a warning signal due to its high levels compared to the admissible thresholds, associated to the contact pressures in terms of soil-pipe interaction.

2.2 Methods and Models of Analysis

The origin of the soil-pipe interaction problem lies in the analysis methods based on soil-structure interaction, adapted by Civil Engineering in its branch of analysis and design of deep foundations (Figure 2 and Figure 3). In these models, corresponding predominantly to uncoupled load-deformation methods, there are limitations to analytical models, where the soil is assumed to be a continuous medium and the short structure (i.e. low slenderness ratio) is rigid and solid, among which the following methods and authors stand out: Brandl (1933,1977), Poulos curvas p-y (1971), Ito y Matsui (1975), Viggiani (1981), Broms (1981), Hassiotis et al. (1984), NAVFAC (1986), Pearlman et al. (1992), Ashour (1998), Kumar y Hall (2006), and others.

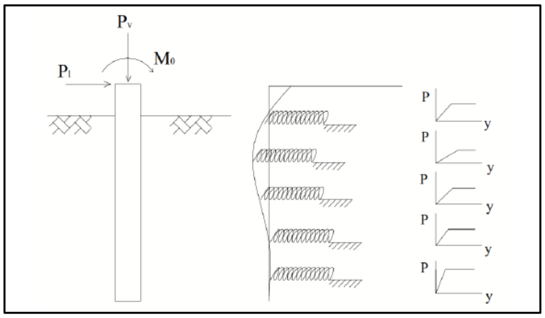

FIGURE 2: LOAD-DEFORMATION DIAGRAM OF PILE EMBEDDED IN SOIL, USING P-Y CURVES (POULOS 1971).

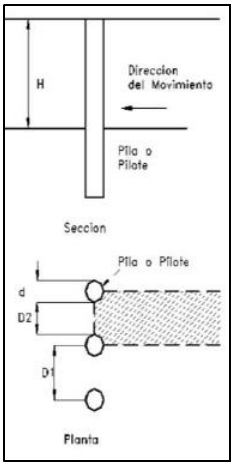

FIGURE 3: LOAD-DEFORMATION DIAGRAM OF PILE EMBEDDED IN SOIL, USING P-Y CURVES (POULOS 1971).

The natural evolution of physical and mathematical problems of this type took place through the appearance and application of the Finite Element Method, where the mathematical models are based on numerical methods and discrete elements, allowing to evaluate the interaction with long structures (i.e. high slenderness ratios) and cylindrical elements subjected to internal pressure, as is the case of a pipeline in operation (Figure 4).

Among the analysis models of this type are those developed by Liang y Zeng (2000), Cai y Ugai (2000), Yamin (2007), Al Bodour (2010), Lui et al. (2010), Kourkolis et al. (2011) y Kahyaoglu et al. (2012).

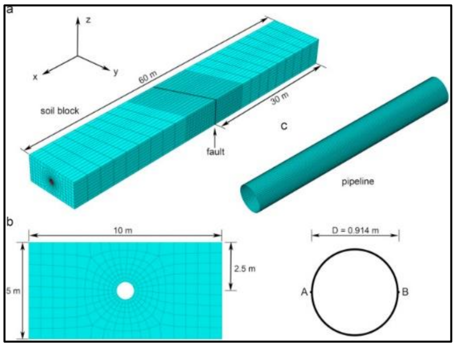

FIGURE 4: SOIL-PIPELINE INTERACTION MODEL USING FINITE ELEMENT METHOD (OCENSA, 2017).

2.3 Adaptation of the Finite Element Method (FEM) to soil-pipe interaction

The physical models studied by the finite element method (FEM) are ideal for the determination of responses or scenarios to complex engineering problems. This is because it allows the fragmentation of such complex system in an interaction of its parts, which can be solved and analyzed as small structures that interact with each other, through their nodes or under their boundary condition or defined type of contact.

In the same way, the construction of a soil-pipeline interaction system model can be described by the integration of several submodels such as:

- Pipeline Submodel;
- Soil Submodel;
- Hydraulic Submodel;

Once the submodels to be coupled for the development of the soil-pipeline interaction model have been defined, it is necessary to correlate the ground displacements reported by topographic and geotechnical monitoring with the displacements and deformations (i.e. elongations) reported by the on-line inspection with intelligent tool (ILI). This step is fundamental for the accuracy and approximation of the soil-pipeline interaction models with the reality of the stress and deformation states of the pipeline, because based on its accurate correlation evident in the calibration of the curves between FEM models and results of field monitoring and through ILI, the greater the reliability of the results of extrapolations that conform the interaction abacuses, in the fields of ground displacements that have not yet occurred.

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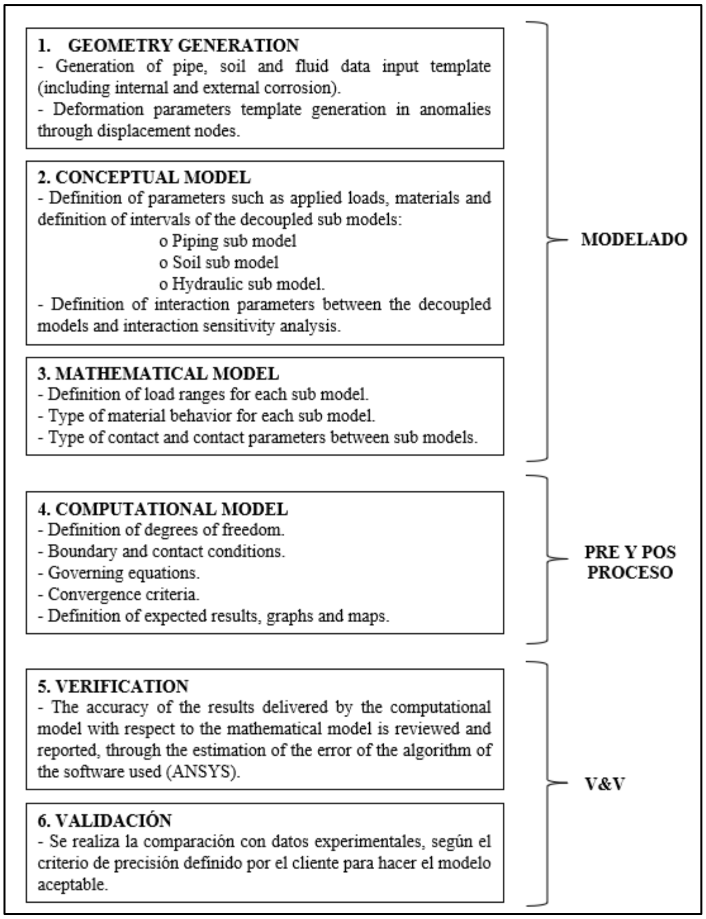
For the development of the soil-pipeline interaction models, a sequence of definition of variables and parameters is adopted, as shown in the following flow diagram:



1. GEOMETRY GENERATION
- Generation of pipe, soil and fluid data input template (including internal and external corrosion).
- Deformation parameters template generation in anomalies through displacement nodes.

2. CONCEPTUAL MODEL
- Definition of parameters such as applied loads, materials and definition of intervals of the decoupled sub models:
  - o Piping sub model
  - o Soil sub model
  - o Hydraulic sub model.
- Definition of interaction parameters between the decoupled models and interaction sensitivity analysis.

3. MATHEMATICAL MODEL
- Definition of load ranges for each sub model.
- Type of material behavior for each sub model.
- Type of contact and contact parameters between sub models.

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4. COMPUTATIONAL MODEL
- Definition of degrees of freedom.
- Boundary and contact conditions.
- Governing equations.
- Convergence criteria.
- Definition of expected results, graphs and maps.

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5. VERIFICATION
- The accuracy of the results delivered by the computational model with respect to the mathematical model is reviewed and reported, through the estimation of the error of the algorithm of the software used (ANSYS).

6. VALIDACIÓN
- Se realiza la comparación con datos experimentales, según el criterio de precisión definido por el cliente para hacer el modelo aceptable.

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FIGURE 5: PROCESS DIAGRAM FOR THE GENERATION OF SOIL-PIPELINE INTERACTION BAGS.

The correlation of absolute displacements and ground displacement rates, measured by topographic and geotechnical monitoring, with the results of the ILI runs in its inertial module IMU (Inertial Mapping Unit), are generated from polynomial functions to determine their behavior pattern and trend, which will govern the displacement rate applied in the soil model, which will influence the displacement and deformation of the pipeline.

Figure 6 shows the sequence of application of the ground displacements on the solid generated in the FEM model, which represents the soil where the pipeline is embedded. These displacements are coupled with the displacements and deformations reported by the ILI inspection carried out in each time window, thus obtaining the soil-pipeline interaction correlation.

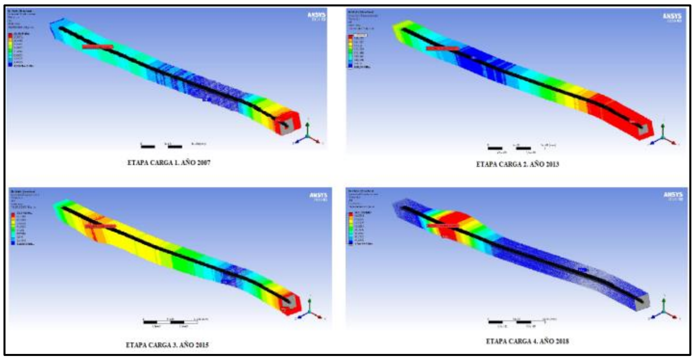

FIGURE 6: SEQUENCE OF SOLID GROUND DISPLACEMENT SURROUNDING THE PIPELINE, BASED ON TOPOGRAPHIC MEASUREMENTS TAKEN BETWEEN 2007 AND 2018.

Figure 7 shows the result of the unit deformation exhibited by the pipeline, associated to the ground displacement fields induced in the model. This value of the unit strain must coincide with the location and value reported by the ILI, in addition to coinciding with the component also reported as predominant by the ILI (i.e. compression or tension). Once this coincidence is given, the model is understood as calibrated.

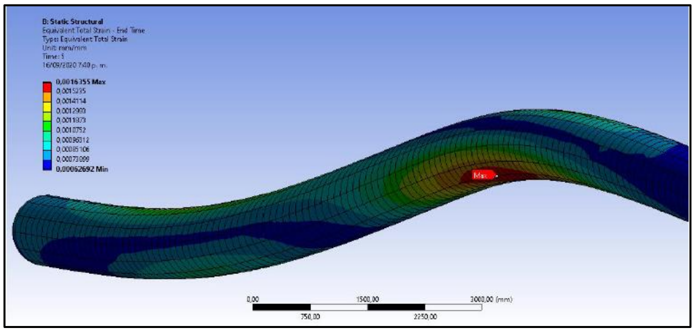

FIGURE 7: MAXIMUM UNIT STRAIN CONCENTRATION (COMPRESSIVE) ON THE PIPELINE. THIS LEVEL COINCIDES WITH THE ILI REPORT AND WAS ACHIEVED BY IMPOSING THE SOIL LOAD ON THE FEM MODEL.

Based on the above and having calibrated the soil-pipeline interaction model, we proceed to plot the entire spectrum of ground displacements, measured over time, versus the unit deformations of the pipeline associated with such displacements and corroborated by the ILI readings for each time period. Once this is done, the series of modeling is continued for ground displacements that have not yet occurred, with the purpose of estimating the unit deformation resulting from the interaction between the mobilized ground and the pipeline.

Consequently, a broad spectrum of ground displacements is plotted versus resulting deformations that the pipeline has experienced and would experience beyond the operator's own thresholds for allowable deformation levels for safe operation;

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thus, the soil-pipeline interaction abacus is created based on past displacements and deformations, calibrated between geotechnical and ILI monitoring, and projections of probable interaction associated with future ground movements.

A typical interaction abacus is shown in Figure 8, with the abscissa axis composed of the ground displacements in meters and, on the ordinate axis, the unit deformation of the pipeline in percent. The red line in the positive quadrant represents the envelope of tensile deformations, while the blue line in the negative quadrant represents the envelope of compressive deformations; the green line represents the envelope of axial deformations resulting from the bending pair (i.e. tension and compression).

The trajectory of each envelope in the graph includes the geometrical and bending characteristics of the duct, and may not exhibit symmetry in the bending pair in the case that the layout contains sharp bends.

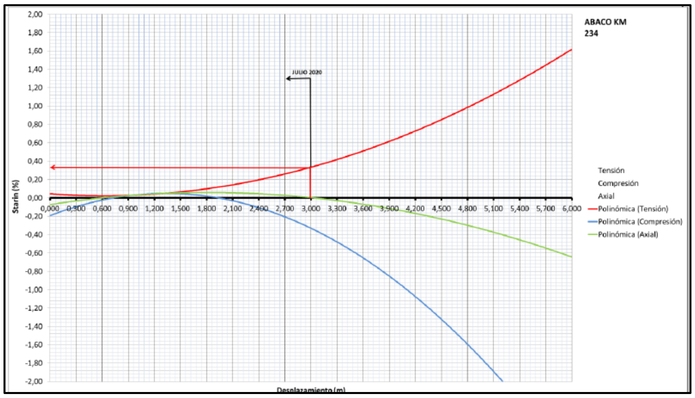

FIGURE 8: SOIL-PIPE INTERACTION TABLE WITH X-AXIS GROUND DISPLACEMENT IN UNITS OF METERS, AND Y-AXIS PIPE UNIT DEFORMATIONS IN PERCENT.

3. RESULTS Y DISCUSSION

The review of results is focused on two case studies applied in the Oleoducto Central S.A., in which integrity management had as main input the generation of soil-pipeline interaction abacuses that allowed to give greater reliability to the decisions taken in relation to the management of the condition found in each case.

3.1 Case Study One

The first case study corresponds to the use of a soil-pipeline interaction abacus for decision making associated with not performing risk mitigation activities (stress relief) on the pipeline, in a site with shared right-of-way where another operator performed a stress relief due to a vertical displacement in the pipeline that exposed the latter on the surface.

According to the initial structural integrity analysis performed based on the results of the inertial tool with the latest 2018 run record, a total accumulated deformation to date of 0.25% (value below the allowable 0.47%) was evidenced with a main component of vertical deformation and average deformation rates of 0.01% per year (Figure 9).

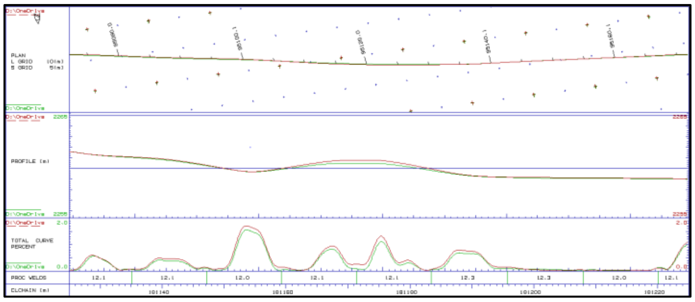

FIGURE 9: INERTIAL RUN DIAGRAM (PLANT-PROFILE-TOTAL STRAIN) FOR CASE STUDY 1.

This movement occurs on a low slope both transversally and longitudinally to the right-of-way, which has been modeled by large and/or extensive matrix-supported colluvial deposits in which very soft and saturated clays predominate, so that earthflows do not seem to be evident in this half slope; however, instrumentation evidences extremely slow displacement of colluvial masses.

The colluviums are the result of different deposition events and, likewise, ground displacements are differential, being more evident in places where there is greater humidity.

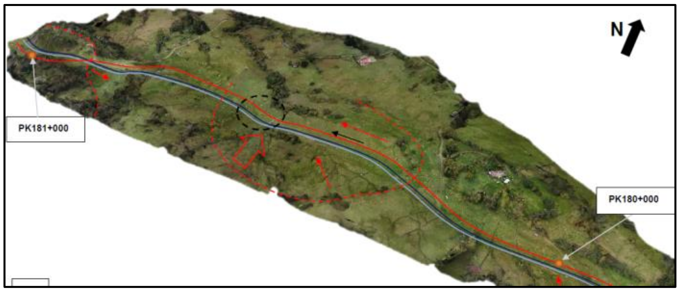

FIGURE 10: AERIAL PHOTOGRAPH OF THE ANALYSIS SITE CASE STUDY 1 (BLACK CIRCLE).

The site had geotechnical instrumentation by means of a 15 m deep inclinometer, as well as concrete cairns, the latter installed in the section of the right-of-way where the pipe movement was identified (Figure 11).

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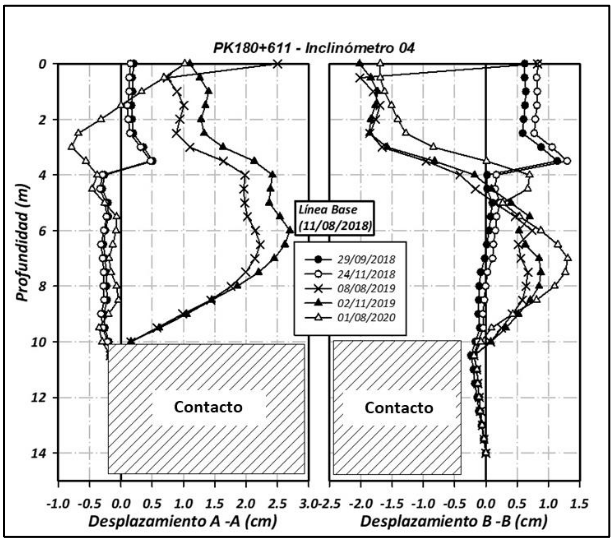

FIGURE 11: RECORDING OF INCLINOMETER INSTALLED IN THE SECTOR OF CASE STUDY 1.

According to the results shown in the geotechnical instrumentation, a very soft and saturated soil thickness of up to 10 m is identified in which progressive deformations are present and a defined contact with competent material overlying the colluvial deposit; the ground displacement rate according to the inclinometer was 0.003 cm/year. On the other hand, the topographic monitoring cairns showed an average accumulated displacement of 1.63 m by July 2020.

Given the uncertainty associated with the deformational state of the pipeline due to the alert in the pipeline adjacent to the pipeline, a soil-pipeline interaction abacus was implemented in order to integrate the information up to 2018 obtained with the inertial tool and the information of surface and depth displacements from the instrumentation installed at the site so as to estimate the percentage of deformation based on the maximum soil displacement recorded by the instrumentation, the latter being the only source of updated information at the date of evaluation. A soil-pipeline interaction abacus was generated for a soft soil (E=10 MPa) with a displacement field of 100 m and a cumulative ground displacement of 1.6 m for the deformation state of 0.25% at 2018 and assessing the deformation state for a cumulative displacement of 1.63 m at July 2020 (Figure 12).

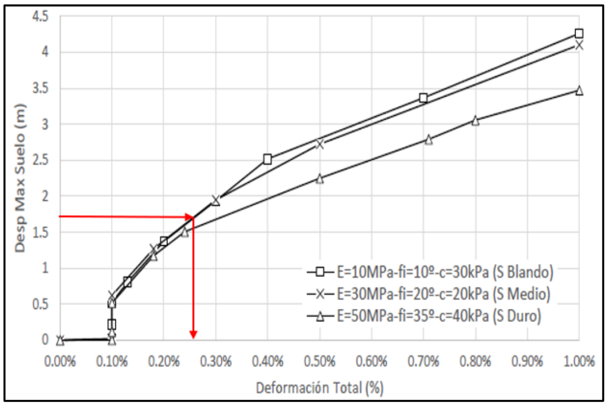

FIGURE 12: SOIL-PIPELINE INTERACTION DIAGRAM GENERATED FOR THE CASE STUDY SECTOR 1.

According to the results extracted from the abacus, it was evidenced that the unit deformation (%) estimated with the abacus of soil-pipeline interaction as of July 2020 was 0.28%, so from this result it is determined not to perform any risk mitigation action, understanding that the pipeline pipe still continues in the admissible deformation range.

When performing the ILI run after the use of the abacus, the level of deformation determined from the mathematical model was corroborated with the result of the inertial tool, which allowed calibrating the abacus and verifying the reliability of such tool, once it is well correlated.

3.2 Case Study Two

The second case study corresponds to the use of a soil-pipeline interaction abacus for decision making associated with declaring a state of emergency for intervention given the risk condition found after analyzing topographic and geotechnical instrumentation versus deformation estimates.

Based on the topographic and geotechnical monitoring carried out on the pipeline right-of-way, the ground displacement rates are monitored. During the monitoring carried out in August 2020, the accelerated displacement of the control points installed in the area of influence of the pipeline was evidenced, with movements that doubled in a period of ten (10) months, the accumulated ground movement measured in six (6) years of continuous monitoring. The above, associated with sudden ground movements in an area of high topographic and geotechnical complexity (Figure 13).

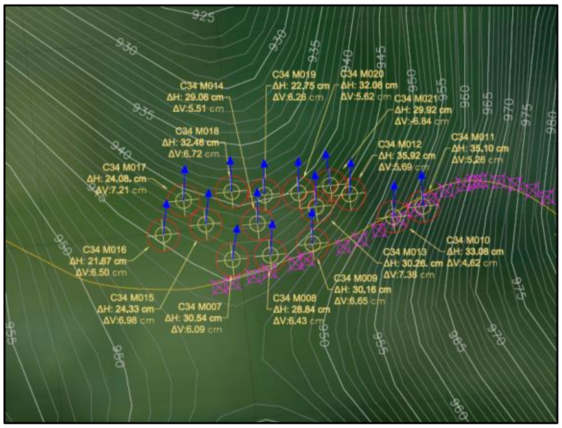

FIGURE 13: TERRAIN DISPLACEMENT VECTORS ACCORDING TO TOPOGRAPHIC CAIRN MONITORING.

Based on the above, a numerical modeling was performed using the Finite Element Method (FEM), in order to determine the stress and deformation levels of the pipeline as a function of the ground displacements measured in the field. Figure 14 and Figure 15 show the graphical output of the coupled model.

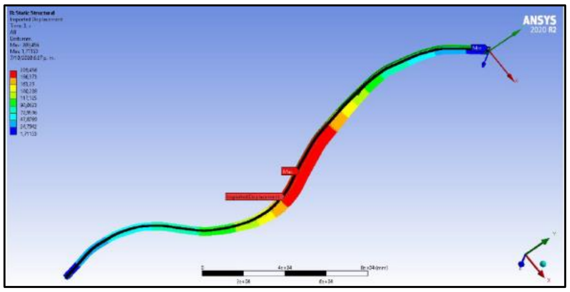

FIGURE 14: PANORAMIC VIEW OF THE FINITE ELEMENT MODEL REPRESENTING THE PIPELINE SECTION IN MOTION

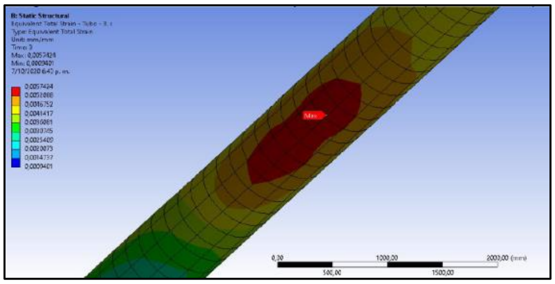

FIGURE 15: POINTS OF GREATEST DEFORMATION RESULTING FROM THE NUMERICAL MODEL.

Taking into account the results obtained in the modeling, where a level of unitary deformation equal to 0.57% was determined, with evidence of combined efforts that provide a torsion condition on the pipeline, in November 2020 the need for excavation for stress relief was defined within the intervention plan for the 2021 period.

Similarly, the soil-pipeline interaction abacus (Figure 16) was reviewed to follow up on the level of accumulated deformation of the pipeline, based on ground displacements measured by topographic monitoring, in the meantime the excavation for stress relief was carried out, the start of which was a function of property and environmental management.

Between the months of July and November 2021, topographic readings were taken at the control points, finding the constancy of displacement of these, which, translated into pipeline deformation level, from the soil-pipeline interaction abacus, accumulated a value of 0.68% as of August 2021 (Figure 16). This unit deformation value, in conjunction with the potential consequence resulted in a risk value that is located on the border between tolerable levels with controls (e.g. excavation for stress relief) and unacceptable risk levels, according to the corporate risk matrix, shown in Figure 17.

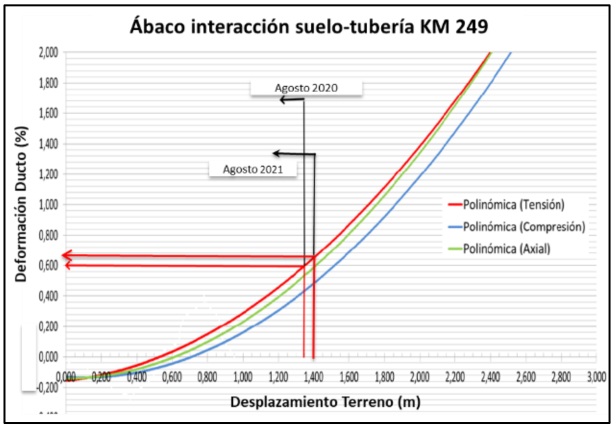

FIGURE 16: SOIL-PIPE INTERACTION ANALYSIS FOR CASE STUDY SITE 2 WITH DEFORMATION ASSESSMENTS BETWEEN AUGUST 2020 AND JULY 2021.

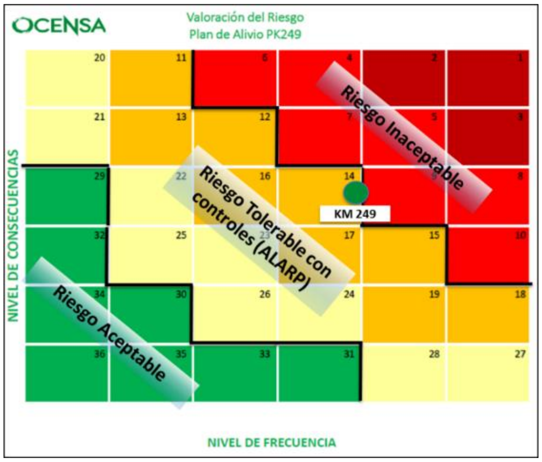

FIGURE 17: CORPORATE MATRIX RISK ASSESSMENT FOR CASE STUDY SITE 2.

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Based on this, and taking into account the evidence of continuity of ground displacements, the proximity of the second winter season of 2021 and, therefore, the increased probability of a new ground acceleration pulse, contrasted with the reduced deformation capacity of the pipeline due to its deformation levels, instrumentation monitoring was continued in order to review the evolution of deformation based on the progressive increase in the displacements of the instruments. By November 2021, movement pulses were recorded that are associated with deformation levels of 0.77% (Figure 18).

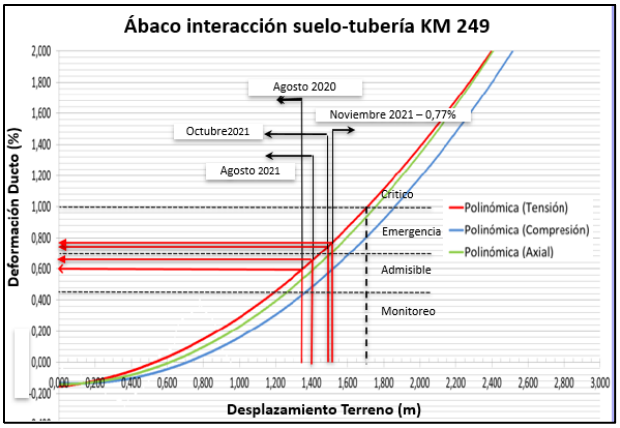

FIGURE 18: SOIL-PIPE INTERACTION ANALYSIS FOR CASE STUDY SITE 2 WITH DEFORMATION ASSESSMENTS BETWEEN AUGUST 2020 AND NOVEMBER 2021.

Given the sudden acceleration of the terrain in the last 10 months (topographic monitoring of cairns) and the eventual consolidation of the La Niña phenomenon, the increase in rainfall of up to 40% and therefore new pulses of ground displacements, the emergency declaration was activated to initiate the release work in the PK249+500 sector, in a 115 m section of the pipeline (Figure 19).

FIGURE 19: AERIAL PHOTOGRAPH OF THE PIPE EXCAVATION PROCESS CARRIED OUT AT CASE STUDY SITE 2.

During the excavation and as a result of the slope deconfinement generated by the excavation (the pipeline was buried an average of 3.5 m), an instability process was activated towards the middle third of the projected section to be released, which manifested itself with a deep crack and the marking of the right and left flanks of the process (Figure 20); this forced to stop the excavation works and implement a temporary stabilization pile, as well as the installation of preventive monitoring points to monitor the progress of this process. Once the instability process was controlled, excavation continued until its completion.

FIGURE 20: IN THE CENTRAL PART OF THE IMAGE, ESCARPMENT GENERATED DURING GROUND MOVEMENT WHEN THE SLOPE IS DECONFINED BY EXCAVATION.

When contrasting the instability manifestations with the results of the numerical modeling in terms of location of zones of increased deformation, consistency was found between these and the slip flank zones (transition between competent and non-competent materials).

4. CONCLUSIONS

Numerical modeling turns out to be a valuable and reliable tool to determine the influence of the soil that houses the pipeline in terms of its stability and dynamic characteristics, with the stresses and deformations available in terms of the allowable resistance of the pipeline.

The results of the numerical modeling allowed the generation of simplified tools for the estimation of pipe deformation states associated to ground displacement processes, being able to characterize by means of an abacus the interaction of the pipe with the soil in slow geotechnical processes (reptation and flows), with almost imperceptible evidence of instability on the surface.

The numerical models of correlation between ground displacement and unit deformation of the pipeline stand out at the time of decision making because the latter is the criterion to define the need for intervention or not, in terms of pipeline stresses. This is a remarkable difference on assuming high levels of deformation in a pipeline with high levels of displacement, since the levels of deformation will depend both on the length of interaction between the mobilized soil and the pipeline section, the slenderness ratio of the pipeline and the operational characteristics in terms of internal pressure.

The soil-pipe interaction abacuses allow estimating the pipeline deformation levels between inertial runs (3 to 5 years) from routine geotechnical and topographical monitoring, performed between these intervals, allowing to know the approximate levels of pipeline deformation without waiting for the results of inertial runs, including the implementation of risk reduction measures.

Although the soil-pipeline interaction abacuses should not constitute an absolute element of decision making, they are complementary elements that result in greater reliability to the same decisions, whether these are focused on implementing risk mitigation measures or on avoiding them.

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To Oleoducto Central S.A., in leadership of the operations management for leveraging the development of new integrity management elements for an asset of national importance.

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