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ANALYSIS OF THE BEHAVIOR OF STEEL PIPELINES WITH LOW FRICTION COEFFICIENT COATING SUBJECTED TO GROUND MOVEMENT.

Jaime Segura
TGI - ECI
Bogotá, Colombia

ABSTRACT

The development of new types of anticorrosive coating paints for steel, with optimization of properties such as the reduction of its friction coefficient, has led different industries such as icebreaker ships, to successfully use this type of products in the hulls of their vessels, reducing contact abrasion wear. It has also encouraged industrial sectors such as Oil&Gas to test this type of coatings on their hydrocarbon transportation assets in order to control the negative influence of friction in the soil-pipeline interaction. This research seeks to estimate the reduction of resistance request by the use of low friction coefficient coatings in pipelines subjected to transverse and axial ground movement, through the comparative evaluation of the stress-strain behavior of pipelines of different steel grades, diameters and coating types, simulated by numerical modeling in the Abaqus CAE software. For this purpose, physical modeling corresponding to inclined plane tests and direct shear tests between soil samples and steel samples with different types of coatings were carried out in order to contribute to the validation of the hypothesis of the work. Among the results, it was concluded that the use of low friction coefficient coatings in ducts subjected to axial ground movement to alignment leads to a significant reduction in the levels of stresses and unit deformations in most of the sectors of interest, while for ducts subjected to transverse ground motion the efficiency of the use of this type of coatings is concentrated in certain sectors of the alignment and in other sectors results in increased deformations, allowing to infer that for ground motions with direction perpendicular to the alignment of the duct the use of the coating should be sectorized.

Keywords: Friction coefficient, coatings, soil-pipe interaction, permanent ground movements, mechanical behavior.

1. INTRODUCTION

Although in Colombia the frequency of pipeline failures associated with mass removal processes is low, in the order of 0.00075 failures/km/year (Amórtegui, 2015), it is one of the countries with the highest probability of presenting this type of natural phenomena, taking into account its geological, hydrological and topographical characteristics, which can be summarized in data such as the following: 61% of the hydrocarbon transportation infrastructure is located in areas with rainfall greater than 2000 mm/year, only 9% of this infrastructure is located in areas of low seismic threat, that is, 91% is located between areas of intermediate and high seismic threat, 35% of this type of infrastructure is located in areas of mountainous and inter-Andean relief and 33% of its layouts are located in areas of high and very high threat due to mass movements.

The high probability of occurrence of mass movements makes the linear hydrocarbon transportation infrastructure susceptible to ground movements that may generate stresses and/or deformations that may affect its integrity or operation. In the industry there are currently several ways to control stresses and deformations in pipelines induced by ground displacements, such as stress relief, relief chambers, replacement of trench materials, monitoring, etc., being all these actions external to the pipeline and reactive in nature, but proactive and intrinsic actions of the pipelines are not common, such as the use of low friction coefficient coatings in pipelines subjected to ground movements.

The efficient use of low friction coefficient coatings on icebreaker hulls in order to reduce abrasion wear and fuel consumption has encouraged other industrial sectors such as Oil&Gas to test this type of products on one of their assets such as transportation pipelines. In high pressure and temperature subsea pipelines, axial stresses depend on the friction coefficient between the seabed soils and the pipeline coatings, which has led to study the use of the roughness of the coatings to control the friction of the soil-pipeline interaction and influence its stress-strain behavior (De Leeuw et al., 2020).

This research work is aimed at estimating the reduction of resistance request by the use of low friction coefficient coatings in pipelines subjected to ground movement with transverse and axial direction to their alignment, having as a starting point information resulting from physical models of inclined plane and direct shear tests and through the comparison and analysis of 54 numerical models that contemplate two ground motion geometries, three steel grades, three pipe diameters and three types of coating, with the finite element analysis software Abaqus CAE in terms of unit stresses and deformations.

2. DEVELOPMENT

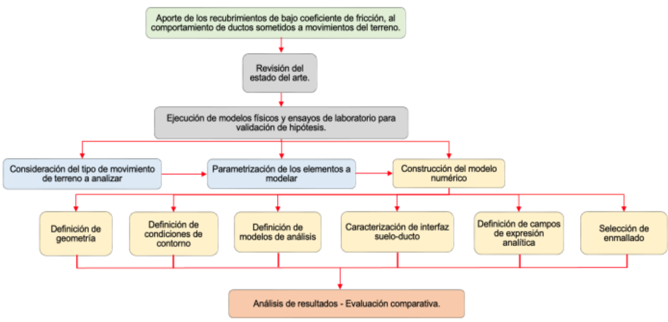

FIGURE 1: METHODOLOGICAL CHART OF THE RESEARCH

2.1 Physical modeling and testing.

A physical model was built, which consisted of an acrylic box with an internal system of pulleys connected by cables to a pair of carbon steel plates, one of them without coating paint and the other with a low friction coefficient coating RBCF (Sigma Novashield), supplied by Cambridge International Service, as shown in Figure 2. Soil samples (cohesive and granular) were placed on each of these plates in order to determine the angle of inclination at which these samples slide on the plates (see Figure 3) and to estimate the coefficient of friction on the interface.

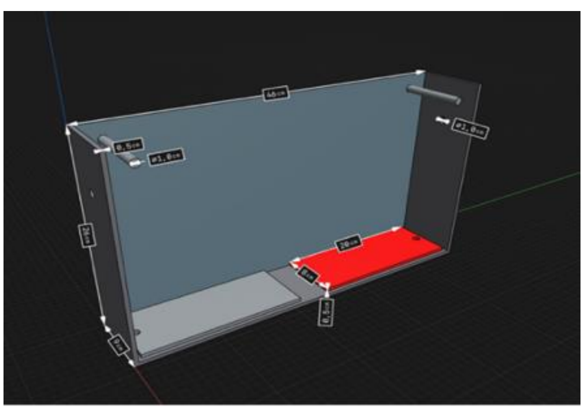

FIGURE 2: PROTOTYPE OF THE PHYSICAL MODEL OF INCLINED PLANE

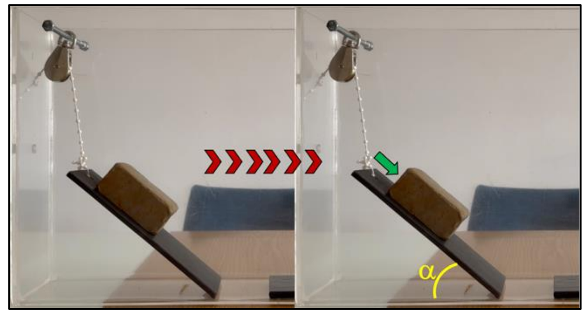

FIGURE 3: INCLINED PLANED TEST

Additionally, and with the objective of evaluating the behavior of the friction coefficient at different confining stresses, direct shear tests were carried out between steel plates with each of the coatings under analysis (coal tar, FBE and Sigma Novashield) and cohesive soil samples. The confining forces established for the test represented regular line burial conditions with depths of 1.2m and 2.0m. The test execution is illustrated below.

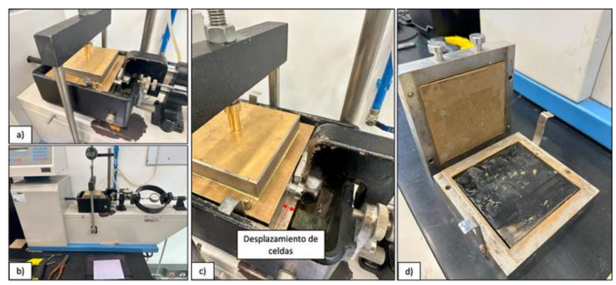

FIGURE 4: DIRECT SHEAR TEST BETWEEN STEEL PLATE AND SOIL SAMPLE

2.2 Ground movement conditions

For the purposes of the modeling of this research, it was considered that the pipe would be subjected to the deformation of a single soil stratum in which it would be completely embedded and which could easily be produced by a translational landslide, a low velocity earth flow or a permanent deformation of the soil. Two movement direction conditions were evaluated, one perpendicular to the pipe and one parallel to the pipe, as shown in the following figure:

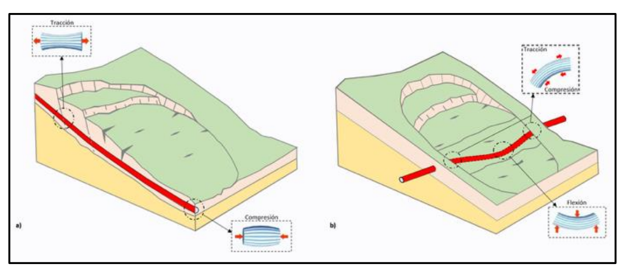

FIGURE 5: a) CONDITION IN PIPELINE SUBJECTED TO GROUND MOTION AXIAL TO THE ALIGNMENT. b) CONDITION IN PIPELINE SUBJECTED TO GROUND MOTION PERPENDICULAR TO THE ALIGNMENT

2.3 Modeling element parameters

The following is the set of mechanical, geometric and operational parameters for the type of soil and type of pipelines used in the numerical modeling.

- Soil

Parameters of a cohesive silty-clay soil are used, with typical values of a soil of residual origin, as presented in Table 1.

Description	Symbol	Value	Unit
Unit weight	γ	18	$\frac{kN}{m^3}$
Angle of friction	ϕ	20	°
Cohesion	C	15	kPa
Poisson's ratio	μ	0.25	
Modulus of elasticity	E	10000	kPa

TABLE 1: SOIL PHYSICAL AND MECHANICAL PARAMETERS

- Pipe

Three references of carbon steel pipelines (smooth and continuous) are considered for the numerical modeling, corresponding to API SL X42, API SL X56 and API SL X65.

Table 2 shows the mechanical parameters defined for the modeling of the pipelines, while Table 3 shows their geometric characteristics.

Description	Unit	Materials		
		API 5L X42	API 5L X56	API 5L X65
Unit weight (γ)	$\frac{kN}{m^3}$	78.5	78.5	78.5
Yield stress (σ1)	kPa	290000	390000	450000
Breaking stress (σ2)	kPa	415000	490000	535000
Poisson's ratio (μ)		0.33	0.33	0.33
Modulus of elasticity (E)	kPa	210 x 10^6	210 x 10^6	210 x 10^6

TABLE 2: MECHANICAL PARAMETERS OF THE PIPELINES

Reference Pipe	Diameter (")	Operating Thickness (m)
X42	6	0.0050
	8	0.0095
	20	0.0130
X56	6	0.0050
	8	0.0095
	20	0.0130
X65	6	0.0050
	8	0.0095
	20	0.0130

TABLE 3: GEOMETRIC CHARACTERISTICS OF PIPELINES

As operating and installation conditions of the pipeline, a state of internal pressure of 900 PSI is considered in the modeling, corresponding to a normal operating pressure value of hydrocarbon transport pipelines and a pipe confinement depth of 1.5 m, typical value of a regular line condition.

2.4 Numerical modeling

To numerically determine the effect that the variation of the type of coating has on the stresses and deformations of the pipelines when subjected to ground displacement, the general purpose finite element software Abaqus CAE was used. The Mohr-Coulomb elastoplastic constitutive model was used to represent the soil and an elastoplastic model based on the formulation of Ramberg & Osgood (1943) was used for the pipeline.

- Geometry

For the two movement conditions (transverse and axial) the surrounding soil is modeled as a 90 m long, 10 m wide and 5 m high prism, sectored in three 30 m blocks along the alignment, where the blocks at the ends correspond to stable zones and the central block corresponds to the unstable zone where ground displacement is induced. The depth of the pipeline placement corresponds to 1.5 m to the keystone. Continuous solid type elements (Continuum) were used for the soil blocks and shell type elements for the pipeline. The following figures illustrate the basic geometry of the models to be evaluated.

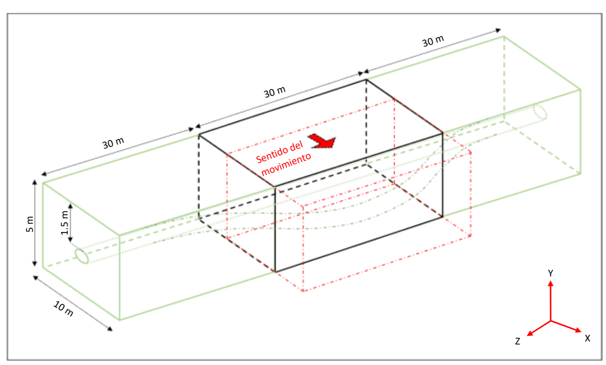

FIGURE 6: GEOMETRY OF THE MODEL WITH TRANSVERSAL MOVEMENT TO THE PIPELINE ALIGNMENT

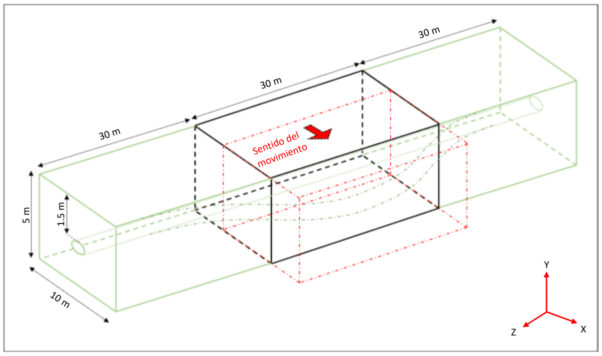

FIGURE 7: GEOMETRY OF THE MODEL WITH AXIAL MOVEMENT TO THE PIPELINE ALIGNMENT

- Boundary conditions

Both for the edges of the soil prisms and for the ends of the pipeline it is necessary to establish boundary conditions that represent them. In the case of the pipeline for the transverse ground motion condition, the ends of the pipeline are left free without any displacement or rotation restriction, while for the axial motion condition the pipeline is assigned an embedment type restriction (without degrees of freedom) at the upstream end of the ground motion and at the other end no type of restriction is considered. For the transverse ground movement condition, restrictions are set for the stable blocks on the X axis for their front, rear, back and front faces and degrees of freedom are left on Y and Z for the deformations due to the action of gravity (geostatic forces), the base of the three blocks considers restriction only on the Y axis and for the central block where the displacement is induced, the movement is not restricted. In the axial ground motion condition, restrictions are set for all the blocks on their front and rear faces, on the X axis and the Y displacements are left free for the deformations due to the action of gravity and on the Z axis for the deformations generated by the induced displacement of the central block. As for the front and rear faces, they are fixed with constraints in the X and Z axes.

- Analysis models

Based on the resulting combination of different factors such as duct alignment condition versus ground movement direction, steel grade, diameter and type of coating considered for the investigation, 54 models to be analyzed were established. These analysis models were grouped into six packages in order to facilitate the analysis of the results. The first three packages are associated with models with the transverse ground motion condition and the remaining three packages are associated with the axial duct motion condition. Each package groups for the same material grade (X42, X56 or X65) the variations of stresses and unit deformations, between the different pipeline diameters (6", 8" and 20") and types of coating considered (Tar, FBE and RBCF).

- Soil-Pipe interface

The modeling contemplates for the two movement conditions the contact between the external surface of the pipeline and the soil, as well as the contact between the internal faces of the soil blocks. For its modeling, the "Surface to Surface" type of contact formulation was used, parameterized with a tangential behavior with a "Penalty" type friction formulation in which the main variable corresponds to the friction coefficient of the soil-duct contact and with a "Hard contact" type normal behavior.

In the evaluated analysis models, three types of interfaces are contemplated, derived from the contact between the defined soil type and coal tar, FBE and Sigma Novashield (RBCF) coated ducts, interfaces to which the following friction coefficient values were assigned: 0.32, 0.21 and 0.16 respectively.

- Fields of analytical expression

Particularly for the condition of transverse movement to the pipeline alignment, a velocity distribution is parameterized for the central soil block, which responds to a polynomial (equation 1) adapted from the function with which Susuki et al. (1988) and Kobayashi et al. (1989) consulted within the article "Fragility analysis of continuous pipelines subjected to transverse permanent ground deformation" (Ni et al., 2018), describe a transverse permanent ground deformation (PGD) characterization. The magnitude of the velocity defined for the modeling is calculated as a function of the maximum displacement to be evaluated in the pipeline which for this case is 2 m and the total time of the simulation steps.

$$y(x) = \delta * \left(\frac{\pi x}{W * \lambda}\right)^{n} \tag{1}$$

Where x represents the distance measured from the center of the ground motion (where the largest deformation occurs) to one of the limits of the motion (flanks), δ represents the maximum displacement of the soil, W indicates the width of the unstable process, n is a random parameter that should always be positive (higher n values represent more concentrated displacement distributions while lower n values show wider displacement distributions) (Tipán et al., 2023) and 2 corresponds to a variable defined by the author based on the interpretation of the results obtained by Murcia et al. (2023) in the experimental work presented for the IPG 2023, in order to improve the representation of the ground motion, so that at the limits of the unstable process (flanks) the deformation values are different from zero. The following figure illustrates the predefined analytical expression field for the above condition.

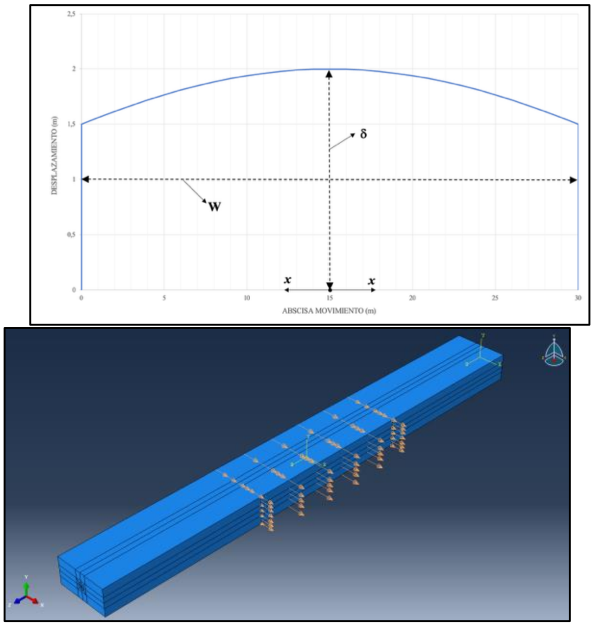

FIGURE 8: ANALYTICAL EXPRESSION FIELD FOR VELOCITY

For the condition of ground motion axial to the alignment, a "uniform" velocity distribution is used, where all nodes and elements of the unstable block move uniformly according to the velocity defined for the modeling, calculated from the maximum displacement to be evaluated, which for this condition is 4 m and the total time of the simulation steps.

- Meshing

Shell-type elements with four reduced integration nodes (S4R) are used to model the duct, while for the soil regions, brick-type elements with eight reduced integration nodes (C3D8R) were used.

To reduce the complexity of the meshing and improve its definition, actions such as the generation of partitions to the soil blocks and duct, which improve the structuring of the mesh, and the biased seeding of markers along the edges of the regions of the elements in such a way that the areas of greater interest (such as interaction areas) are left with refined meshes and their transition to areas of less interest is incremental without abrupt jumps. The following figure shows the density and distribution of the meshing in the modeling elements.

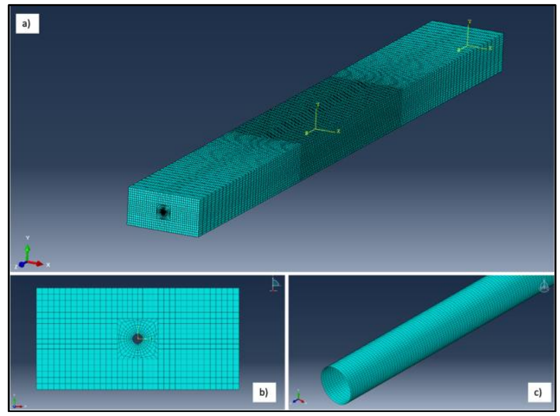

FIGURE 9: MESHING OF MODELING ELEMENTS

3. RESULTS

The inclined plane tests yielded for the cohesive soil sample, a friction coefficient value m =1.0 for the contact with uncoated steel and m = 0.6 for the contact with steel with RBCF, showing a 35% reduction in the value of m, when the type of coating is varied. On the other hand, for the granular soil sample, a friction coefficient value m =0.53 was obtained for the contact with uncoated steel and m = 0.4 for the contact with steel with RBCF, showing a reduction of 16% in the value of m, when the type of coating is varied.

With the data obtained from the tests, shear and normal forces and horizontal unit deformations were calculated to evaluate the effect of confinement on the frictional behavior of the soil-steel interface. Figure 10 shows the variation obtained between shear forces vs. horizontal unit deformations, for each of the samples and for their two loading conditions (load 1 corresponds to a confinement of 1.2 m and load 2 corresponds to a confinement of 2.0 m). Where it is highlighted that the reduction of shear stress when the type of coating is varied (from higher to lower roughness, is higher when the confinement level is lower.

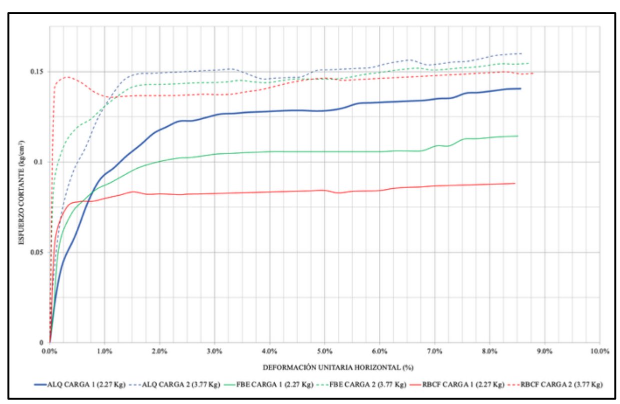

FIGURE 10: SHEAR STRESS VS HORIZONTAL UNIT DEFORMATION

Regarding the numerical modeling, in order to standardize the interpretation of the results between the different analysis models, particular and representative sections were considered for the two ground motion conditions. For the ground motion condition perpendicular to the pipeline alignment, two analysis axes were contemplated (Figure 11), one along point A located in the internal rib of the pipeline, zone where direct soil thrust occurs (time position 9:00) and another along point B in the external rib of the pipeline, zone that is not directly subjected to soil thrust (time position 3:00).

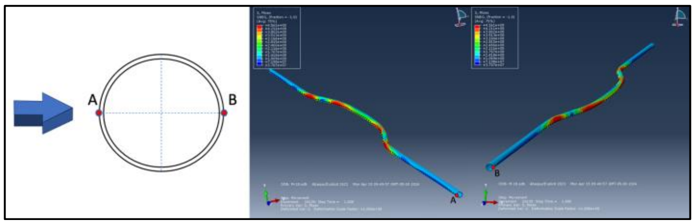

FIGURE 11: LOCATION OF GROUND MOTION ANALYSIS SECTIONS PERPENDICULAR TO THE PIPELINE

For the condition of movement axial to the pipeline alignment, two analysis axes were also defined, one of them along point A at the keystone of the pipeline (time position 12:00) and another along point B located at the pipeline trough (time position 6:00), as illustrated in the following figure:

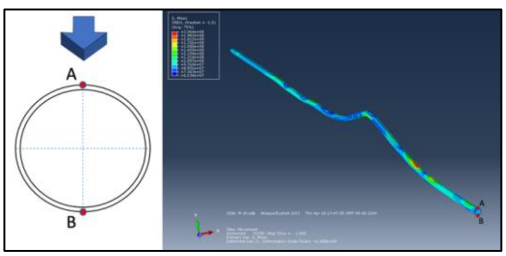

FIGURE 12: LOCATION OF ANALYSIS SECTIONS GROUND MOTION AXIAL TO THE PIPELINE

3.1 Stress behavior

Below are a couple of representative graphs of the behavior of axial forces along one of the defined axes of analysis when varying the type of coating and diameter for the same steel grade, for the condition of ground movement perpendicular and axial to the pipeline, respectively.

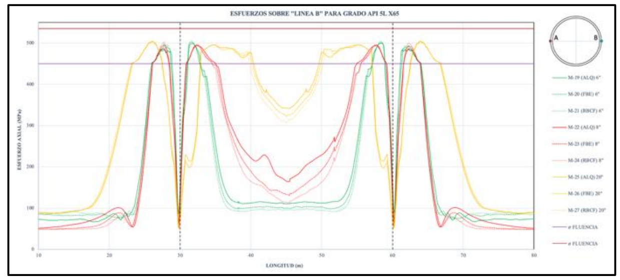

FIGURE 13: AXIAL STRESS DISTRIBUTION ALONG LINE B FOR API 5L X65 GRADE DUCTS WITH GROUND MOTION TRANSVERSE TO THE PIPE

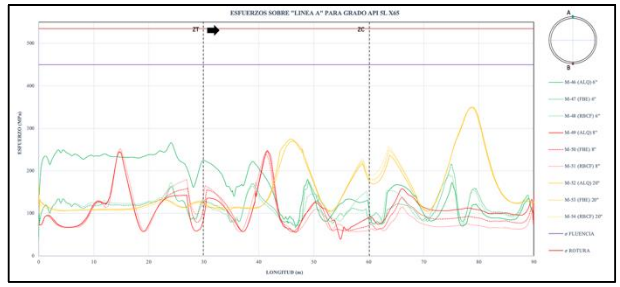

FIGURE 14: AXIAL STRESS DISTRIBUTION ALONG LINE A FOR API GRADE 5L X65 DUCTS WITH GROUND MOVEMENT AXIAL TO THE PIPE

3.2 Strain behavior

A couple of representative graphs of the behavior of unit deformations along some of the defined analysis axes are presented when the type of coating and diameter are varied for the same steel grade, for the condition of perpendicular and axial ground movement to the pipeline, respectively.

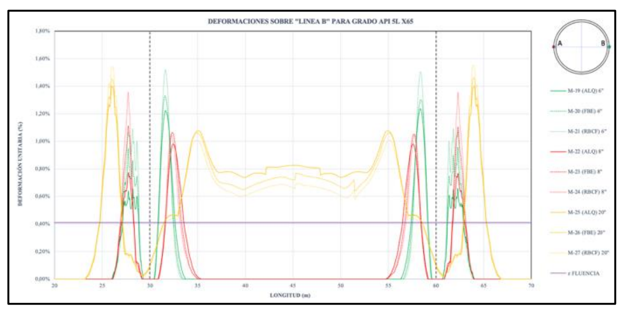

FIGURE 15: DISTRIBUTION OF UNIT STRAINS ALONG LINE B FOR API 5L X65 GRADE PIPELINES WITH TRANSVERSE GROUND MOTION OF THE PIPELINE.

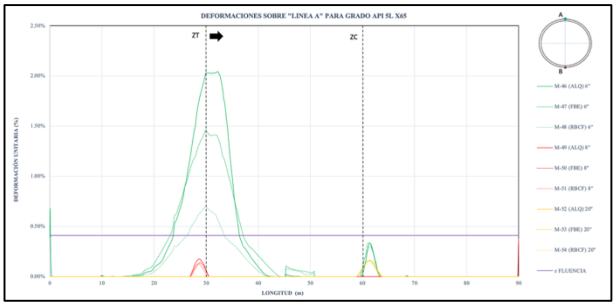

FIGURE 16: DISTRIBUTION OF UNIT STRAINS ALONG LINE A FOR API GRADE 5L X65 PIPELINES WITH AXIAL GROUND MOVEMENT TO THE PIPELINE.

3.3 Interpretation of results

Once the information of the axial stresses and unit deformations behavior of each of the 54 models was consolidated, three (3) relevant zones were established for the analysis of the modeling packages of the transverse ground motion condition (Figure 17) and two (2) important zones for the analysis of the axial ground motion condition (Figure 18).

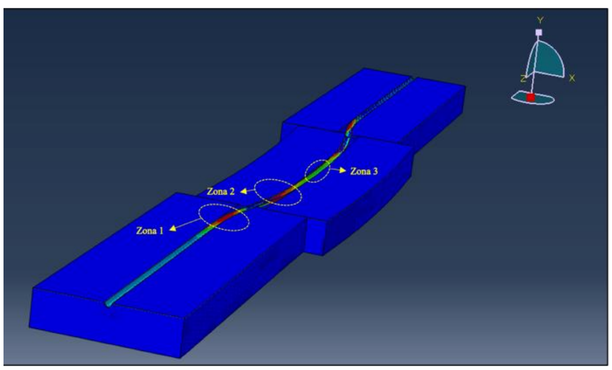

FIGURE 17: LOCATION OF RELEVANT ZONES ALONG THE PIPELINE ALIGNMENT FOR TRANSVERSE MOVEMENT.

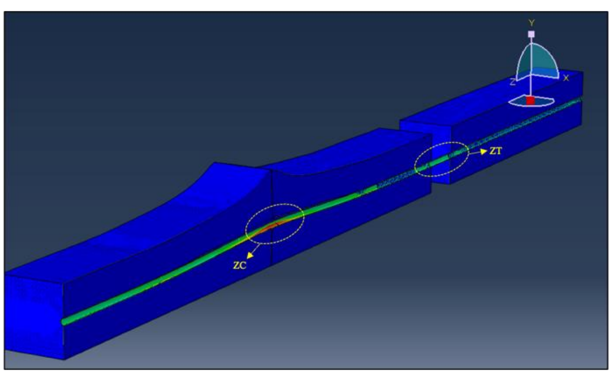

FIGURE 18: LOCATION OF RELEVANT ZONES ALONG THE PIPELINE ALIGNMENT FOR TRANSVERSE MOVEMENT.

The following three graphs show the comparative evaluation in terms of percentage (%) of change in equivalent stresses and unit deformations, between ducts with conventional coating (FBE) and ducts with low friction coefficient coating (RBCF), for the three critical sectors identified in the analysis of the results and for each of the analyzed packages. Values (+) represent increases and values (-) represent decreases in the magnitudes of the evaluated characteristics.

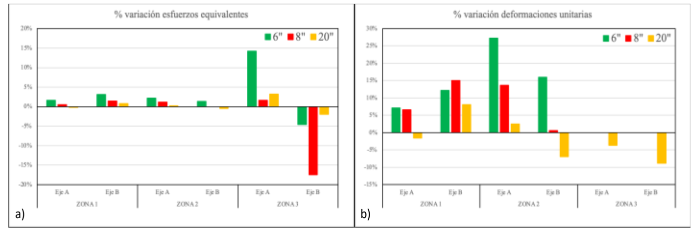

FIGURE 19: EVALUATION OF % CHANGE PACKAGE 1 a) STRESS VARIATION. b) STRAIN VARIATION.

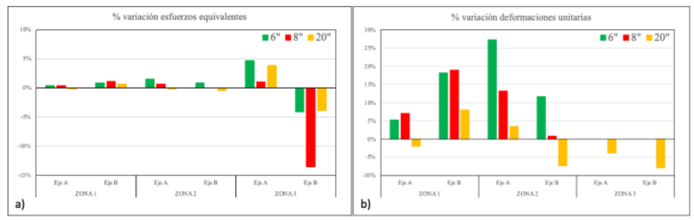

FIGURE 20: EVALUATION OF % CHANGE PACKAGE 2 a) STRESS VARIATION. b) STRAIN VARIATION.

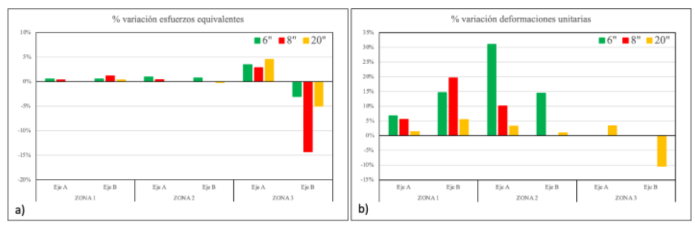

FIGURE 21: EVALUATION OF % CHANGE PACKAGE 3 a) STRESS VARIATION. b) STRAIN VARIATION.

The following three graphs show the comparative evaluation in terms of percentage (%) of change in equivalent stresses and unit deformations, between ducts with conventional coating (FBE) and ducts with low friction coefficient coating (RBCF), for the three critical sectors identified in the analysis of the results and for each of the analyzed packages, for the condition of ground movement axial to the duct. Values (+) represent increases and values (-) represent decreases in the magnitudes of the evaluated characteristics.

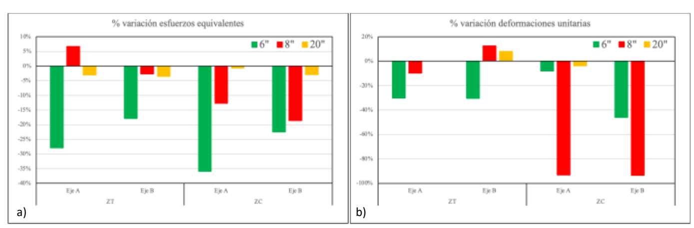

FIGURE 22: EVALUATION OF % CHANGE PACKAGE 1 a) STRESS VARIATION. b) STRAIN VARIATION.

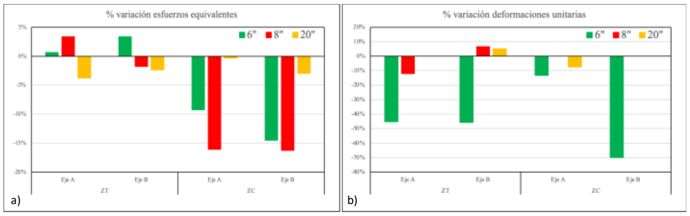

FIGURE 23: EVALUATION OF % CHANGE PACKAGE 2 a) STRESS VARIATION. b) STRAIN VARIATION.

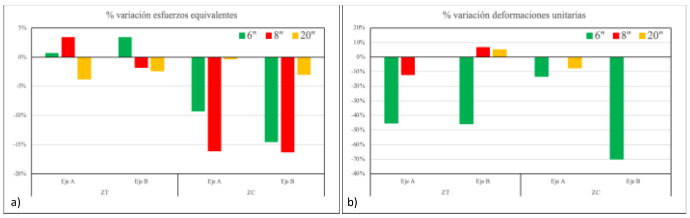

FIGURE 24: EVALUATION OF % CHANGE PACKAGE 3 a) STRESS VARIATION. b) STRAIN VARIATION.

4. CONCLUSIONS

The physical models and laboratory tests allowed determining that the friction coefficient for the interface between a cohesive soil sample and a pipeline with a low friction coefficient coating can be of the order of 0.16 and corresponds to 24% less than the friction coefficient of an interface with a pipeline with a conventional FBE type coating.

The use of low friction coefficient coatings is more efficient for conditions of ground movement axial to the duct, where reductions of up to 36% in stress levels and up to 95% in unit strain levels are achieved, a reduction that is frequent in most sectors of the alignment, while for the transverse movement condition only reductions of up to 14% in stress concentrations and up to 11% in unit strain levels are achieved for specific sectors of the alignment.

The increase observed in the unit deformations towards the flanks of the transverse movement of the pipeline alignment, when the conventional coating is replaced by one of lower roughness, is due to the decrease in the contact (friction) between the pipeline and the stable soil blocks, where the duct is displaced axially by the deflection generated in the center of the ground movement, allowing the duct to deform much more and generate curvatures with smaller radii that are more critical in terms of stresses and unit deformations, especially in ducts of lower stiffness such as 6" and 8".

For the condition of ground movement transversal to the pipeline and at the site of greatest ground displacement (center of the process), only pipelines with a diameter equal to 20" incur in plastic deformations, while pipelines with diameters of 6" and 8" do not, since they are more ductile pipes that generate wider bending radii, thus reducing the concentration of stresses and deformations. This condition makes attractive the use of low friction coefficient coatings towards this sector of the alignment in larger diameter pipelines, where the greatest reduction in the % variation of unit deformations was evidenced.

For the axial ground motion condition, the ducts of smaller diameter and stiffness (6" and 8") are more susceptible to deformation towards the traction zone of the motion (ZT), while in the compression zone of the motion (ZC), the ducts of larger diameter are more prone to deformation due to their stiffness.

In order for the use of low friction coefficient coatings to be more efficient in the conditions of transverse ground movement to the alignment, their application should be sectorized, so that their use is concentrated towards the place where maximum deformations are expected and their use is reduced towards the stable zones close to the limits of the movement.

REFERENCES

[1] Amórtegui, J. V. (2015, julio 15). Pipeline Vulnerability to Natural Hazards. ASME 2015 International Pipeline Geotechnical Conference.

[2] De Leeuw, L. W., Diambra, A., Dietz, M., Milewski, H., Mylonakis, G., Kwon, O. S., & Sextos, A. (2020). Using coating roughness to control pipe-soil friction and influence pipeline global buckling behaviour.

[3] Murcia, P., Amórtegui, J. V., & Garzón, J. C. (2023). Approximate numerical method to evaluate pipelines in sites with geotechnical instability problems.

[4] Ni, P., Mangalathu, S., & Yi, Y. (2018). Fragility analysis of continuous pipelines subjected to transverse permanent ground deformation. Soils and Foundations, 58(6), 1400-1413.

[5] Petroleum Institute, A. (2004). By Authority of the United States of America Legally Binding Document API 5L: Specification for Line Pipe.

[6] Ramberg, W., & Osgood, W. R. (1943). Description of stress-strain curves by three parameters.

[7] Tipán, R., Mendoza, C., Caiza, P., De, O., & Pesados, C. (2023). IPG2023-Numerical model, soil vs. buried pipeline interaction in Ecuador.

[8] Wang, Y.-Y. (2017). Management of Ground Movement Hazards for Pipelines Final.