IPG 2023
INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE
November 23rd - 24th. Bogotá D.C. - Colombia
Under the auspices of: arpel
Organize: C-IPG ACIEM
6TH INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE IPG 2023

IPG2023-0008

ASSESSING ARC-SHAPED DEFORMATION IN A BURIED GAS PIPELINE WITHIN SOFT COASTAL SOILS: A CASE STUDY IN SÃO PAULO, BRAZIL

Thiago da Costa Santos, Vinicius Carvalho Peixoto, Wanderley Camargo Russo Junior, Anderson Pacheco, William Soares Tomaz, João Duarte Guimarães Neto, João Mauricio Homsi Goulart and Pedro Victor Serra Mascarenhas

TRANSPETRO, PETROBRAS Transporte S.A., Guararema, São Paulo, Brazil

ABSTRACT

This paper presents a geotechnical case study of a 16-inch gas pipeline located in São Vicente, SP, Brazil, which experienced deformation due to the displacement of soft soil. The pipeline exhibited deformations and incurred lateral bending stresses, leading to the formation of a 4-meter arch-shaped deformation over a 100-meter stretch. The identification of this deformation was achieved through angular mapping and further corroborated by rigorous geotechnical analyses and on-site inspections. The excessive soil movement, attributed to the Tschebotarioff effects, was primarily triggered by an adjacent railway subgrade reinforcement project. Notably, despite the substantial soil displacement, integrity assessments demonstrated that the pipeline remained well within established safety parameters. This study underscores the critical significance of vigilant monitoring when conducting third-party construction activities in proximity to pipelines. It highlights the necessity of adhering to established standards, implementing Geographic Information Systems (GIS) for spatial data management, and employing geotechnical instrumentation to effectively manage and mitigate associated risks.

Keywords: soil movement, lateral bending stresses, third-party construction, inertial pigs, Tschebotarioff effects

1. INTRODUCTION

In Brazil, the coastal region assumes a pivotal role in the logistics of oil and gas operations, owing to the substantial presence of offshore oil platforms.

Within this coastal expanse, gas pipelines traverse a diverse array of terrains characterized by various geological morphologies. While it is commonplace for these pipelines to navigate sandy regions along the coastline, a noteworthy proportion of the coastal lowlands, particularly in the vicinity of the southern coast of the state of São Paulo, comprises marshy areas replete with sedimentary deposits of organically saturated clays exhibiting low consistency. These soft soils are characterized by their diminished resistance, low permeability, and heightened deformability, all hallmarks of unstable geological substrates that inherently harbor the potential for natural movements capable of affecting buried gas pipelines.

1.1 Case of Excessive Deformation

This study delves into a comprehensive case analysis of a 16-inch gas pipeline situated in the São Vicente region of São Paulo, Brazil. The pipeline encountered lateral forces triggered by the shifting of soft soil within the coastal plain, characterized by low slopes. This geological interaction induced deformations and lateral bending stresses on the pipeline, ultimately culminating in the formation of an arc-shaped deformation with a peak deflection of approximately 4 meters. This deformation extended over an extensive span of nearly 100 meters, with the pipeline buried within the aforementioned soft soil. The emergence of this arc-shaped deformation raised pressing concerns related to the potential for steel ductile fracture and the associated risk of pipeline rupture.

As depicted in Figure 1, this pipeline extends across a land segment of approximately 29 kilometers. It features a nominal diameter of 16 inches and a nominal wall thickness of 0.375 inches (9.5mm). The pipeline is constructed from API 5L X65 steel, characterized by a minimum yield strength of 448 MPa (65,000 psi). It is engineered to operate under a maximum allowable operating pressure of 101 kgf/cm2. This pipeline serves as the critical link connecting the offshore extraction platform in the sea to a major refinery located in the state of São Paulo.

FIGURE 1: PATH OF THE 16" GAS PIPELINE, EXTENDING FROM THE SEAFLOOR (SUBMERGED ALONG THE COASTLINE) TO THE REFINERY, NAVIGATING THROUGH DIVERSE TERRAINS, INCLUDING MULTIPLE MARINE SOIL DEPOSITS.

In Figure 2, a ground-level photograph of the area is observed, and the pipeline is buried on the right side of the image, where individuals are locating the pipeline using geophysical methods.

FIGURE 2: AT-GRADE PHOTOGRAPH DEPICTING THE SITE WHERE THE ARC-SHAPED DEFORMATION IMPACTED THE GAS PIPELINE.

2. MATERIALS AND METHODS

This section provides a concise overview of the methodologies and procedures applied in the execution of this case study, encompassing the following key actions and methods:

• Confirmation of pipeline positions:

- Initial identification employing the MAPI method (2015) [1], which utilizes Instrumented PIG runs equipped with Inertial and Geometric modules to detect movements in soft soil.
- On-site physical confirmation through pipeline probing utilizing PCM equipment and rod with a rubber-tipped probe.

• Conducting Field Technical Inspections by subject matter experts.

• Utilization of Geographic Information Systems (GIS) for soil mapping and Geotechnical Susceptibility Mapping.

• Implementation of a Geo-referenced Planialtimetric Topographic Survey of the region.

• Execution of Geotechnical Investigations, incorporating the following methodologies:

- CPTU (ASTM - D5778-[7]) with measurements of soil pore pressure dissipation in specific layers.
- A comprehensive combined SPT [3] and Rotary Drilling Geotechnical Investigation.
- Performance of Stress and Deflection Analysis of the pipeline in accordance with API 1117 [2].

• Undertaking Deformation Analysis of the pipeline as per the CSA Z662 standard [8].

• Installation of instrumentation, including inclinometers and Casagrande piezometers.

• Inspection of pipeline integrity through excavations, ultrasonic thickness measurements, and non-destructive testing for defect detection using magnetic particles [10]. Additionally, ovalization measurements of pipeline sections using millimeter gauges ([9] and [10]).

2.1 Methods for Identifying Arc-Shaped Deformations and Conducting Field Inspections

The identification of this arc-shaped deformation was achieved by applying an angular mapping technique that relies on the comparison of at least two runs of pipeline inspection gauge (PIG) position estimation using inertial measurement unit (IMU), as detailed in the publication presented at the Rio Pipeline 2015 (Russo et al., 2015).

This method entails comparing the angles between pipeline magnets and welds, capturing their respective coordinates, establishing vectors connecting them, and scrutinizing the angular variations within these vectors.

The results, systematically logged within a spreadsheet, are subsequently translated into a graphical representation, greatly facilitating the expeditious identification of any angular anomalies. This process yields the coordinates of areas where ground and pipeline movements are suspected, warranting further on-site examination through more granular and intricate methodologies, as depicted in Figures 3 and 4.

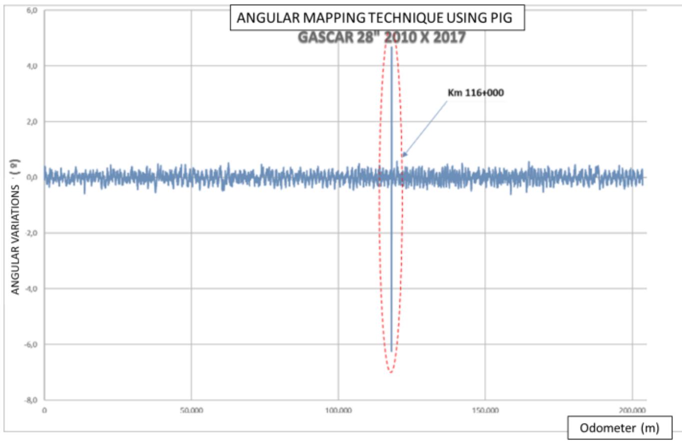

FIGURE 3: VISUALIZING ANGULAR VARIATIONS USING RUSSO'S METHOD (2015) [1].

Following the observation of the graphical disparities, georeferenced coordinates are extracted, necessitating a comprehensive field survey. To accomplish this, a confirmation campaign is initiated to ascertain the precise location and depth of the pipeline, employing the indirect PCM method (Pipeline Current Mapper). This technique involves the injection of current into the pipeline and the subsequent measurement of the magnetic field generated by the current using a handheld device (refer to Figure 5) at five-meter intervals along the entirety of the suspected displacement section, spanning approximately 150 meters.

Subsequently, the pipeline's precise position underwent meticulous validation using a direct physical method: a metal rod was carefully inserted into the ground until it contacted the upper generatrix of the buried pipeline.

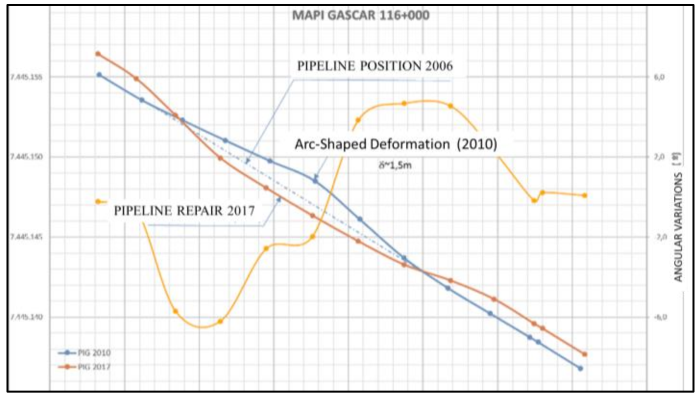

FIGURE 4: SITE PLAN DEPICTING ARC-SHAPED DEFORMATIONS AND ANGULAR DEVIATIONS FROM A 2017 GAS PIPELINE CASE STUDY

FIGURE 5: PIPELINE POSITION MAPPING USING PCM EQUIPMENT AND METHODOLOGY

To enhance comprehension and analysis, a specialist team, consisting of experienced field technicians, geotechnical engineers, and engineering geologists, conducted a comprehensive field inspection (Figure 6).

Additionally, georeferenced planialtimetric surveys were conducted to better understand the phenomenon by mapping the pipeline's position and the surrounding area.

FIGURE 6: GEOREFERENCED PLANIMETRIC, ALTIMETRIC, AND TOPOGRAPHIC SURVEY OF THE PIPELINE AND SURROUNDING TERRAIN, INCLUDING SIMULTANEOUS SPECIALIZED TECHNICAL INSPECTION.

2.2 Types of Geological and Geotechnical Investigation and Mapping

For an initial regional overview, we examined the geological map (see Figure 7), incorporating upper-layer estimations from prior surveys. Additionally, we consulted a composite susceptibility map, which encompassed five studied hazards: landslides, debris flows, erosion, rockfall, and creep. These hazards were categorized into three levels of susceptibility: low (green), moderate (yellow), and high (red), as illustrated in Figure 8.

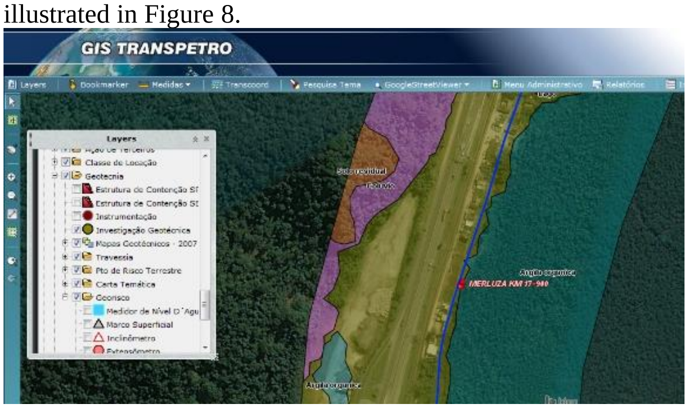

FIGURE 7: GEOLOGICAL CARTOGRAPHY OF THE PIPELINE'S VICINITY.

FIGURE 8: AERIAL PHOTOGRAPHY REVEALING COMPOSITE SUSCEPTIBILITY ZONES (HIGH, MODERATE, AND LOW) FOR MULTIPLE RISK TYPES.

Given the identified soil type as organic clay, a geotechnical investigation was undertaken, primarily consisting of Cone Penetration Testing with pore pressure measurements (CPTU) at five designated borehole locations. These tests encompassed the assessment of soil pore pressure dissipation within specific strata employing the same CPTU apparatus. This choice was informed by the historical occurrence of artesian phenomena in proximate regions exhibiting similar geological characteristics. Borehole selection prioritized locations in close proximity to the pipeline's maximum deflection point and at its terminal ends.

Furthermore, a supplemental combined drilling operation was executed in the vicinity of the central area of the Arc-Shaped deformation (refer to Figure 9) to obtain soil and foundation rock samples for analysis. The drilling procedures adhered to the protocols outlined in the Drilling Manual [14].

The characterization of soil samples adhered to the specifications outlined in accordance with the Brazilian standard [04]. In the case of rock core descriptions, they were conducted in accordance with the criteria delineated by ABGE in their 1998 publication on Engineering Geology.

FIGURE 9: INTEGRATED GEOTECHNICAL INVESTIGATION EMPLOYING SPT (STANDARD PENETRATION TEST) AND ROTARY DRILLING TECHNIQUES.

2.3 Methods of Failure Analysis and Criteria for Deformation Acceptance

In the context of pipeline analysis, two theoretical approaches were employed to comprehend the phenomenon in terms of stress and deformation. These analyses were analytical in nature, relying on equations prescribed in industry standards, and did not involve numerical simulations.

For stress analysis in the pipeline, equations from reference [2] were utilized, employing 2D analyses alongside the F-TOOL application developed by the University of São Paulo (USP) in Brazil.

Regarding deformation analysis, the guidelines specified in reference [8] were adopted, with a particular focus on the "buckle" failure mode, which entails excessive compressive deformations due to bending moment. Specifically, section C.6.3.3.3 was followed, guided by the subsequent equation.

$$\varepsilon_c^{crit} = 0{,}5\frac{\mathrm{t}}{\mathrm{D}} - 0{,}0025 + 3000\left(\frac{(\mathrm{p}_i-\mathrm{p}_e)D}{2\mathrm{tE}_s}\right)^2 \quad .(1)$$

$$for\ \frac{(\mathrm{p}_i-\mathrm{p}_e)D}{2\mathrm{tF}_y} < 0{,}4$$

$$\varepsilon_c^{crit} = 0{,}5\frac{\mathrm{t}}{\mathrm{D}} - 0{,}0025 + 3000\left(\frac{0{,}4\mathrm{F}_y}{\mathrm{E}_s}\right)^2 \quad \ldots..(2)$$

$$for\ \frac{(\mathrm{p}_i-\mathrm{p}_e)D}{2\mathrm{tF}_y} \geq 0{,}4$$

Where:

ε_c^{crit} = ultimate compressive strain capacity of the pipe wall

t = pipe wall thickness, mm

D = pipe outside diameter, mm

pi = maximum internal design pressure, MPa

pe = minimum external hydrostatic pressure, MPa

Es = 207 000 MPa

Fy = effective specified minimum yield strength, MPa (see also Clause C.5.7 in [8])

3. RESULTS AND DISCUSSION

The application of the methodology detailed in the previous chapter yielded pivotal insights into assessing the structural integrity risk of the pipeline, particularly in the context of conspicuous lateral deformations.

This section comprehensively presents all actions and analyses undertaken, with the primary objective of sharing the findings derived from this case study.

3.1 Alça de Deformação, Identificação e Confirmações Identification of Arc-Shaped Deformation

As part of the company's pipeline integrity program, various activities are conducted, including regular pigging for cleaning purposes, internal and external corrosion inspections utilizing the MFL (Magnetic Flux Leakage) module, detection of geometric irregularities such as dents and deformations using the geometric module, and the assessment of pipeline coating quality using PCM (Pipeline Current Mapper). The latter process results in valuable data regarding the pipeline's position in both plan and georeferenced depth.

Over the past decade, inertial module-based pigs have been incorporated into select pipelines, guided by geotechnical risk susceptibility thematic maps. This module offers precise three-dimensional pipeline positioning (x, y, and z coordinates). Since its development by [1], the pipeline operator has adopted this method to monitor potential pipeline movements caused by soil mass displacements.

During an inertial PIG run in 2018, a noticeable angular deviation in curvature was observed when compared to the previous run in 2012. This discrepancy is graphically represented in Figure 10 and is further detailed in Figure 11.

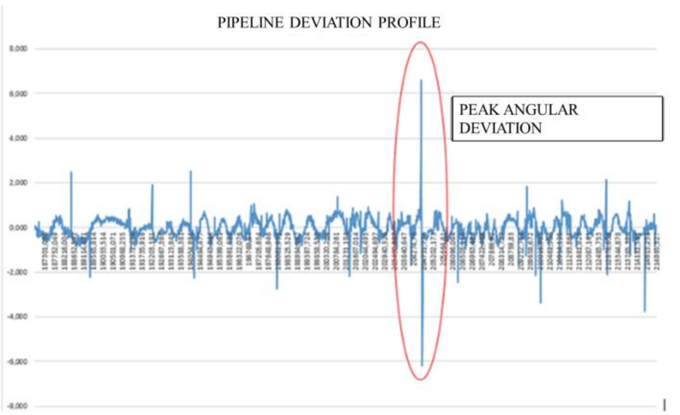

FIGURE 10: PEAK ANGULAR DEVIATION OBSERVED IN THE PIPELINE DEVIATION PROFILE, HIGHLIGHTING A DISTINCTIVE NON-NATURAL ARC-SHAPED DEFORMATION AT KILOMETER 17+900.

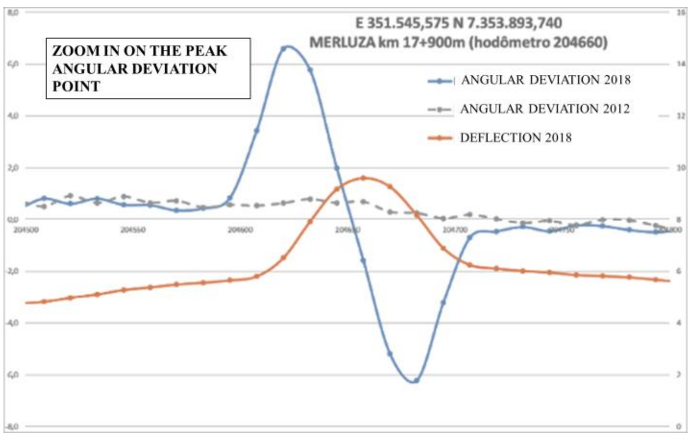

FIGURE 11: ZOOM IN TO EXAMINE THE PEAK ANGULAR DEVIATION POINT, AS ILLUSTRATED IN FIGURE 10.

Figure 12 offers a site plan of the pipeline's alignment, specifically focusing on the area of peak angular deviation, observed during both inertial PIG runs in 2012 and 2018 (a 6-year time span). It vividly portrays an arc-shaped deformation characterized by a maximum deflection of 3.96 meters over a distance of 98.95 meters. This deformation is precisely located at kilometer position 17+900 within the Municipality of São Vicente, São Paulo, situated along the southern coast of São Paulo state, Brazil.

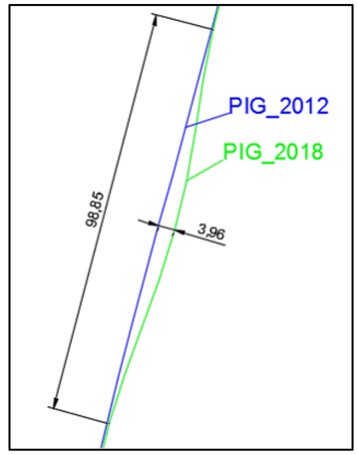

FIGURE 12: SITE PLAN OF THE PIPELINE'S ALIGNMENT OBSERVED DURING BOTH INERTIAL PIG RUNS IN 2012 AND 2018.

To validate the results in the field, a PCM survey was carried out, followed by physical verification at identical locations using a rod with a rubber tip. This comprehensive approach was implemented to mitigate any uncertainties pertaining to the precision of the inertial PIG's predicted location.

Furthermore, leveraging the PCM data acquired during a comprehensive coating investigation campaign conducted in 2009, we were able to superimpose and analyze the disparity in pipeline positioning between 2009 and 2018, as visually represented in Figure 13.

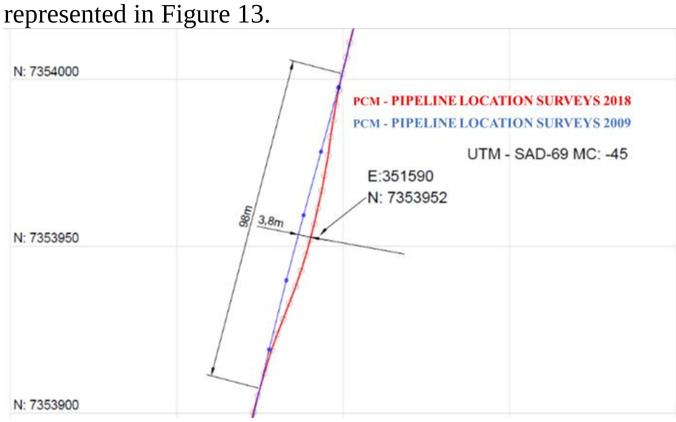

FIGURE 13: SITE PLAN COMPARING PIPELINE LOCATION SURVEYS USING PCM METHOD: 2009 (20 M SPACING) VS. 2018 (5 M SPACING).

The analysis of PCM (Pipeline Current Mapper) results revealed an arc-shaped deformation of 3.80 meters occurring along a 98-meter stretch. This finding closely aligns with observations made using inertial PIGs, showcasing a minimal disparity of only 4.7% from the maximum deflection value. This congruence underscores the robustness and efficacy of the inertial PIG method in detecting arc-shaped deformation. Moreover, this study highlights the viability of PCM as a valuable tool for monitoring the positional changes of pipelines over time, particularly in cases involving unppigable pipelines. This reinforces PCM as a compelling option for long-term pipeline position tracking.

3.2 Geotechnical Characterization Results

After confirming the presence of the arc-shaped deformation, a comprehensive assessment of its underlying causes was initiated. This assessment leveraged the capabilities of a Geographic Information System (GIS) tool, encompassing a comprehensive database of all pipeline installations. Additionally, the analysis incorporated the geological map corresponding to the pipeline's trajectory (as depicted in Figure 7) and a tabulated representation of the geotechnical susceptibility chart, as illustrated in Figure 14.

Initial Km	Km Final	Distance	Degree of Susceptibility
0,0	1,0	1,0	LOW
1,0	2,0	1,0	LOW
2,0	3,0	1,0	LOW
3,0	4,0	1,0	LOW
4,0	5,0	1,0	LOW
5,0	6,0	1,0	[illegible]
6,0	7,0	1,0	[illegible]
7,0	8,0	1,0	[illegible]
8,0	9,0	1,0	[illegible]
9,0	10,0	1,0	[illegible]
10,0	11,0	1,0	[illegible]
11,0	12,0	1,0	[illegible]
12,0	13,0	1,0	[illegible]
13,0	14,0	1,0	[illegible]
14,0	15,0	1,0	[illegible]
15,0	16,0	1,0	[illegible]
16,0	17,0	1,0	HIGH
17,0	18,0	1,0	HIGH
18,0	19,0	1,0	HIGH
19,0	19,5	0,5	MODERATE
19,5	20,0	0,5	HIGH
20,0	21,0	1,0	HIGH
21,0	22,0	1,0	HIGH
22,0	23,0	1,0	LOW
23,0	23,5	0,5	MODERATE
23,5	24,0	0,5	HIGH
24,0	25,0	1,0	LOW
25,0	26,0	1,0	LOW
26,0	27,0	1,0	LOW
27,0	28,0	1,0	LOW
28,0	29,0	1,0	LOW

Summary	
HIGH	20%
MODERATE	3%
LOW	77%
TOTAL	100%

FIGURE 14: GEOTECHNICAL RISK SUSCEPTIBILITY SUMMARY TABLE FOR THE PIPELINE ROW, EMPHASIZING A CRITICAL CONDITION AT KM 17+900

It was observed that a pipeline segment spanning from kilometers 15 to 22, constituting 20% of its total length, exhibits a pronounced susceptibility to geotechnical risks. This observation prompted the implementation of a comprehensive suite of PIGs, including the inertial module, for continuous monitoring. This proactive approach was ultimately proven to be the most effective course of action.

Additionally, the type of soil mapped in the region (Figure 7), where the pipeline is situated in Marine Organic Clay (a sedimentary material with low compaction, typically saturated), is noteworthy. This is a typical soil prone to significant displacements, high deformations, plastic behavior, and subsidence. Hence, the geological classification aligns with a form of lateral movement experienced by the pipeline.

The technical field inspection (Figure 15) reveals a flat region, confirming a swampy area and soft soil near a coastal plain. Upstream in the region (with maximum elevation differences of only 2.5 meters over a span of more than 35 meters), there is a low embankment with sparse vegetation, an unpaved road, and a railway. Further upstream, there is a major highway, followed by a mountain range.

Following the identification of the arc-shaped deformation during the field inspection, no indications of surface soil movement were apparent. There were no observable signs, such as cracks, sinkholes, displaced markers, or fallen trees, that could initially account for the lateral movement of the pipeline. This absence of surface soil movement was further corroborated by the aerial image depicted in Figure 16.

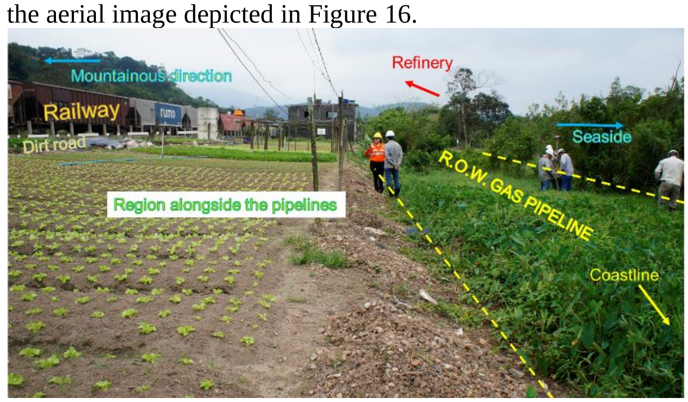

FIGURE 15: AT-GRADE PHOTOGRAPH CAPTURED DURING FIELD INSPECTION OF THE CASE STUDY AREA AT KM 17+900 OF THE PIPELINE.

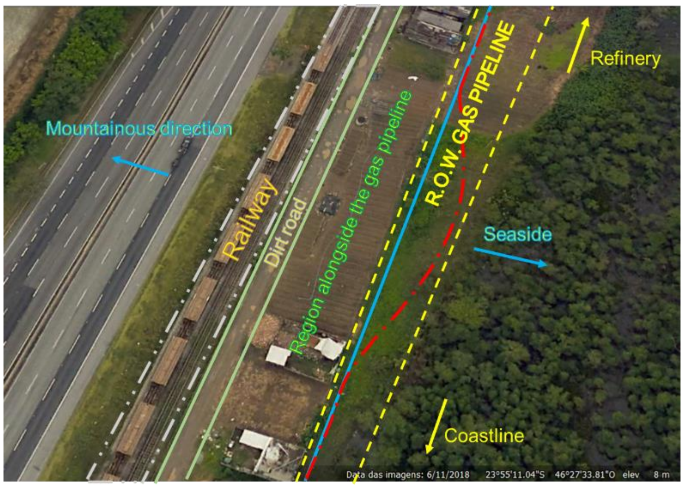

FIGURE 16 AERIAL IMAGE OF THE CASE STUDY AREA AT KM 17+900 OF THE PIPELINE (PIPELINE IN RED).

A subsurface investigation was then initiated to gain a deeper understanding of the region. The campaign primarily comprised Cone Penetration Testing with Pore Pressure Measurement (CPTU), owing to the soft and saturated soil characteristics of the site. Additionally, considering past reports of artesian conditions along the same pipeline route, located just 3 kilometers away, pore pressure dissipation tests were also conducted at various depths within the CPTU. Table 1 provides details on the 5 CPTU boreholes and the 14 pore pressure dissipation tests carried out at different depths.

SUMMARY TABLE OF CPTU BOREHOLES		
Test	Deep of Water pore pressure dissipation tests (m)	Deep (m)
CPTU-01	2,17 / 4,16 / 9,01	10,96
CPTU-02	3,21 / 3,82 / 8,08 / 9,94	10,04
CPTU-03	3,20 / 4,93	11,58
CPTU-04	3,05 / 6,02	15,96
CPTU-05	3,86 / 8,01 / 14,78	15,05

TABLE 1: CPTU BOREHOLE SUMMARY TABLE.

In complement to the CPTU testing program, an adjunctive Mixed Test borehole was executed within the central region of the pipe's deformation, proximate to the point of maximum deflection. This Mixed Test encompassed Standard Penetration Test (SPT) and rotary drilling in the rock strata.

The outcomes derived from this investigative endeavor, comprising the analysis of the retrieved rock samples (Figure 17), the profile ascertained through the Mixed Test procedure (Figure 18), and the inference of the subsoil composition amalgamating insights from the CPTU tests (Figure 19), offer the following geotechnical stratification:

Superficial Layer: A thin fill layer, not exceeding a depth of 1 meter.

Organic Clay Layer: Predominantly characterized by dark gray plastic organic clay, spanning a thickness ranging from 6 meters to 10 meters.

Fine Silty Sand Layer: A compact and confined stratum of fine silty sand, with an estimated thickness ranging from 5 meters to 7 meters.

Metamorphic Rock Layer (Gneiss): Situated immediately below the aforementioned layers, featuring an excellent Rock Quality Designation (RQD) within the initial 5 meters of depth.

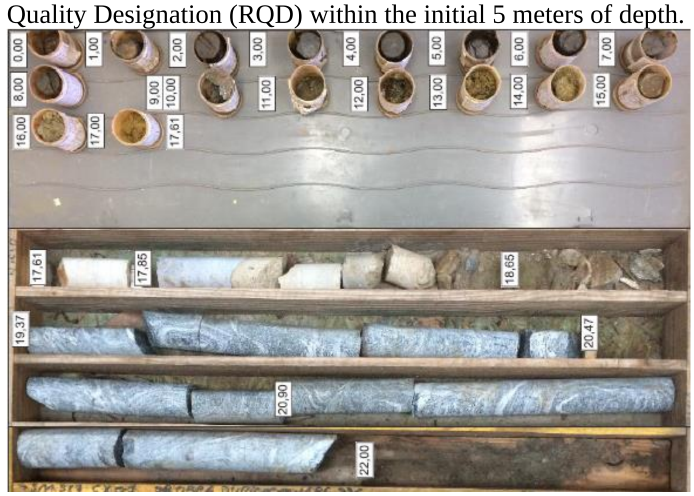

FIGURE 17: ROCK SAMPLES IN THE RQD TEST.

The pore pressure dissipation tests conducted, as depicted in Figure 20, have unveiled artesian conditions, prominently noted at a depth of 9 meters within borehole 1. These observations were particularly pronounced near the interfaces between the soft clay and the compact sand layers. This finding provides compelling evidence of confined groundwater presence, thus underscoring the heightened vulnerability to soil deformations and associated geotechnical challenges in the studied area.

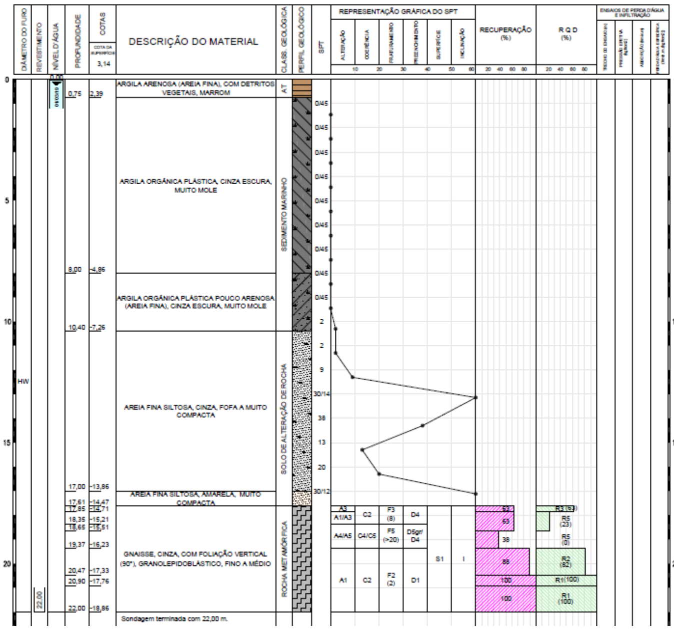

FIGURE 18: GEOTECHNICAL PROFILE OBTAINED FROM MIXED TEST BOREHOLE (SPT + ROTARY DRILLING IN ROCK).

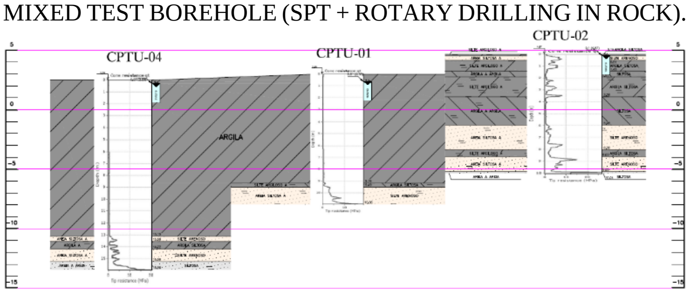

FIGURE 19: INTEGRATED GEOLOGICAL PROFILE DERIVED FROM MULTIPLE CPTU BOREHOLES.

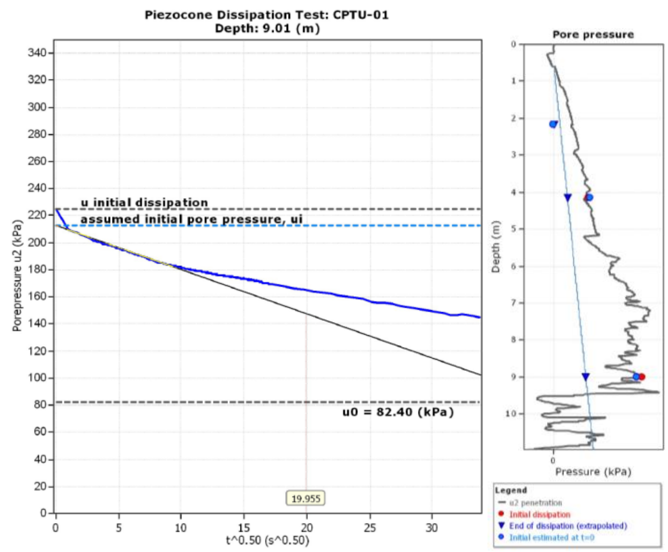

FIGURE 20: PORE PRESSURE DISSIPATION TEST AT 9M DEPTH, PROXIMATE TO THE SOFT ORGANIC CLAY TO COMPACT SANDY SOIL TRANSITION.

3.3 Analysis of Soil Movements

In light of the comprehensive geological assessment of the region, the delineated soft soil profile susceptible to deformation, and the artesian flow-induced pore pressure within the clayey layer, there are compelling indications that lateral soil displacements have influenced the pipeline movements.

The local topography exhibits a gentle slope, aligning with the direction of pipeline displacement, progressing from the railway/unpaved road towards the sea. Moreover, the area remains persistently waterlogged, forming a marshland characterized by gray-hued soil possessing a high clay content and exceptionally low bearing capacity, rendering it a markedly compressible soil type.

Within this context, one of the phenomena that could elucidate the lateral soil displacements is the 'Tschebotarioff effect.' This phenomenon encompasses lateral movements of compressible and soft soils induced by unilateral (or asymmetric) surcharges that trigger compaction within the compressible soil, accompanied by lateral displacements and stress redistribution.

The 'Tschebotarioff effect,' originally elucidated by the Russian civil engineer Gregory P. Tschebotarioff in 1962, was initially conceptualized within the realm of foundation piles proximate to bridge abutments, particularly in scenarios characterized by multiple embankments and cuts, leading to the imposition of asymmetric loads. The applicability of this stress phenomenon has also found resonance in the domain of pipeline engineering, as underscored in certain geotechnical investigations concerning pipelines, notably exemplified in references [6] and [5], and illustrated in Figure 21.

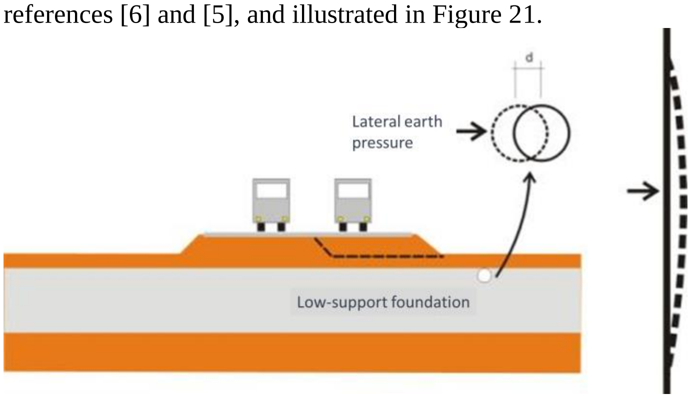

FIGURE 21: LATERAL SOIL PRESSURES INFLUENCING STRESS AND STRAIN BEHAVIOR IN THE PIPELINE (REFERENCE [5]).

One challenge we faced was understanding the factors responsible for vertical compression forces exerted on the soft soil. This challenge arose because there were no significant differences in elevation between the pipeline area and the upstream embankments, as illustrated in Figure 15. To investigate this matter further, we conducted a historical analysis of available Google Earth images from the region spanning the period from 2012 to 2018, prompted by initial suspicions.

Upon scrutinizing the images captured between January 2014 and June 2018, as depicted in Figures 22, 23, and 24, it was observed a railway line duplication project running parallel to the pipeline alignment. It's worth noting that this project maintained a lateral separation of more than 30 meters from the pipeline itself.

FIGURE 22: GOOGLE EARTH IMAGE FROM JANUARY 2014, DEPICTING A SINGLE RAILWAY LINE UPSTREAM OF THE PIPELINE.

FIGURE 23: GOOGLE EARTH IMAGE FROM JUNE 2015, FEATURING THE CONSTRUCTION OF A LINEAR STRUCTURE ADJACENT TO THE EXISTING RAILWAY, STILL UPSTREAM OF THE PIPELINE.

FIGURE 24: GOOGLE EARTH IMAGE FROM JUNE 2018, DISPLAYING THE PRESENCE OF TWO ADJACENT RAILWAY LINES.

The pipeline operator was previously unaware of this construction work and had not monitored it from such a distance. This lack of awareness was due to Brazilian national legislation, as indicated in [11], which mandated only a 15-meter clearance on either side of the pipeline right-of-way.

During the analysis period of the incident, upon reaching out to the railway authorities, confirmation of the railway line construction during that period was obtained, along with additional construction details. To support the railway construction, they enhanced the road foundation by introducing and compacting rocky materials (rock blocks) across the entire railway implementation area. This area featured soft gray, low-consistency soil, similar to the soft soil identified in proximity to the road and within the pipeline area during the geotechnical investigations.

Subsequently, we gained insights into the underlying phenomenon. Indeed, a 'Tschebotarioff effect' had occurred, although not through the typical means of excavations and cuts. In this case, the vertical compression of the soft soil and the resulting lateral displacement were a consequence of rock block compaction for soil foundation improvement. There was no visible surface embankment or excavation, but a significant volume of material was compressed and internally displaced within the soft soil to enhance the road's foundation. This phenomenon, therefore, clarified the significant lateral movement of the pipeline. Figure 25 illustrates the events that occurred in this case study.

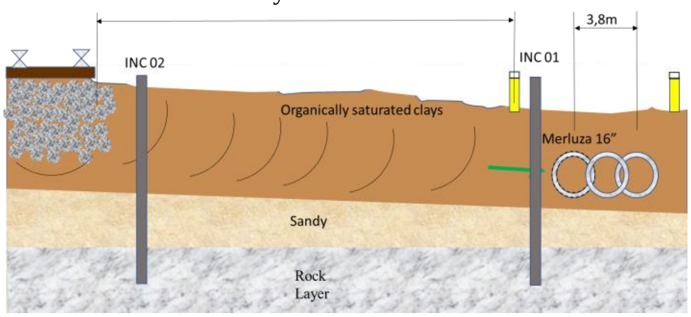

FIGURE 25: LATERAL DEFORMATION OF SOFT SOIL INDUCING PIPELINE DISPLACEMENTS DUE TO ASYMMETRICAL EMBANKMENT RESULTING FROM RAILWAY DUPLICATION IN THE SAME UNCONSOLIDATED SUBSTRATE, OVER 30 METERS AWAY.

Given the existence of previous pipeline position measurements dating back to 2007, with no observed movements until 2018, it becomes evident that natural soil creep phenomena were not at play in the region. Instead, the lateral movements can be attributed to the construction of the railway, which is a human-induced event.

Hence, the geotechnical hypothesis posits a scenario akin to the behavior seen in standard consolidation curves derived from oedometer tests following a singular load application over time. In this context, the soil undergoes compression and dissipates the initially incorporated energy. Notably, substantial soil displacements manifest primarily during the early stages of loading, and these displacements exhibit an exponential decline over time. This phenomenon is elucidated further by [12], as illustrated in Figure 26.

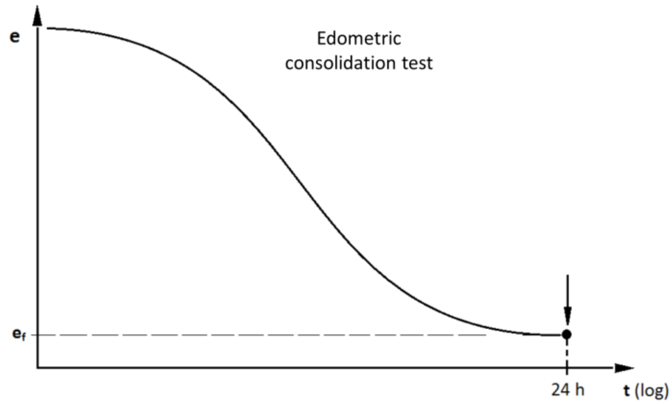

FIGURE 26: FIGURE MODIFIED FROM [12] OF A UNIDIMENSIONAL COMPRESSION CURVE.

Considering the principles of consolidation theory and recognizing that the observed movement in 2018, initiated around mid-2015, did not align with natural creep behavior, we postulated the hypothesis that this movement had already reached a state of stability. In other words, it had entered the phase characterized by residual and inconsequential displacements, as depicted on the displacement curve.

To substantiate this hypothesis, a comprehensive geotechnical soil instrumentation array was deployed. This array featured two inclinometers aligned orthogonally to the observed maximum deflection in the pipeline, with one positioned closer to the railway (INC-02) and the other in proximity to the pipeline itself (INC-01), Figure 27.

The graphical representation in Figure 28 provides empirical confirmation of the stabilization hypothesis. In this context, only residual displacements of minimal magnitude are discernible. Displacements along axis A (orthogonal to the pipeline) are negligible, measuring in the order of 4 millimeters per year. These values correspond to velocities less than 16 millimeters per year, classifying them as extremely slow on the scale proposed by Cruden and Varnes (1996), as cited in Lacerda (2003).

While continuous monitoring of these movements persists, they are technically stable. It becomes imperative to conduct an assessment of the current state of the pipeline's integrity within its deformed geometry and determine whether it is at risk or remains structurally sound for ongoing operations. These analytical evaluations are expounded upon in the subsequent subsection.

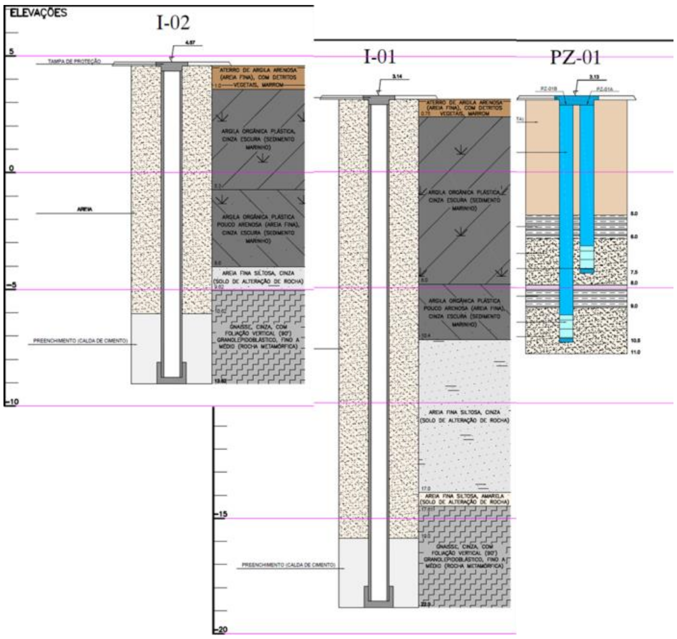

FIGURE 27: ILLUSTRATION OF INSTALLED INCLINOMETERS AND THEIR CORRESPONDING SUBSTRATES (DEPTHS IN METERS).

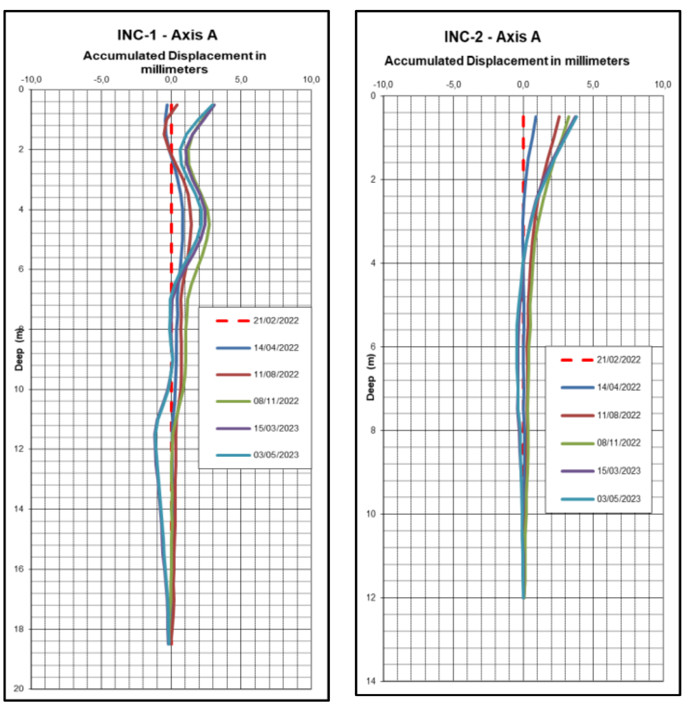

FIGURE 28: GRAPHS OF INC-01 AND INC-02 ON AXIS A (ORTHOGONAL TO THE PIPELINE), DISPLAYING DISPLACEMENTS LESS THAN 4 MILLIMETERS PER YEAR.

3.4 Pipeline Structural Integrity Analysis

The initial approach to analyzing the integrity of the pipeline focused on stress assessment to evaluate the risk of rupture stemming from plasticization or tension in the pipeline. These tensions arise due to the bending moments imposed during the maximum deflection caused by the Arc-Shaped deformation.

To conduct this analysis, we employed the equations outlined in [2] and utilized 2D modeling within the F-TOOL application [15], developed by the University of São Paulo (USP) in Brazil. The analysis treats the pipeline as a beam, allowing us to estimate the current bending moments.

Figure 29 illustrates the pipeline modeled as a structural beam, along with the applied loads under scrutiny. We adopted a distributed load model, representing the constant soil load, wherein the pipeline functions as a spring-supported continuous beam with fixed ends. These supports accurately mimic the soil's reaction on the opposing side of the soil load, emulating the concept of passive thrust. Furthermore, Figure 29 provides a visual representation of the bending moment diagram resulting from the comprehensive two-dimensional analysis.

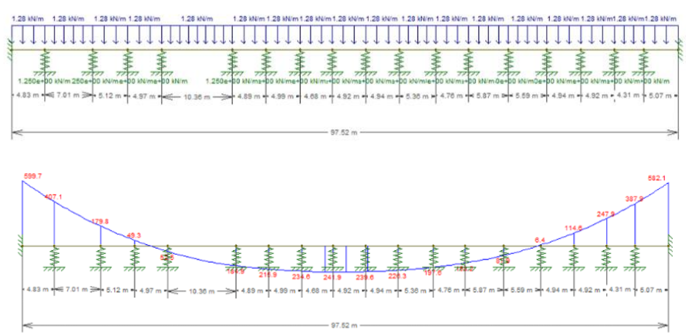

FIGURE 29: PIPELINE MODEL AS A SPRING-SUPPORTED CONTINUOUS BEAM WITH FIXED ENDS AND ITS BENDING MOMENT DIAGRAM.

In Figure 30, we present the user interface of specialized software designed for a comprehensive integrity analysis of the pipeline, adhering to the principles outlined in [2]. This software accommodates input parameters such as the deformed geometry of the pipeline under load, operational data of the pipeline, technical specifications of the steel pipe, and the maximum loads derived from the theoretical stress model obtained through the simulation within the F-TOOL application. The software yields essential insights, including the theoretical elongation of the pipeline under the tensile stresses it experiences in that particular state.

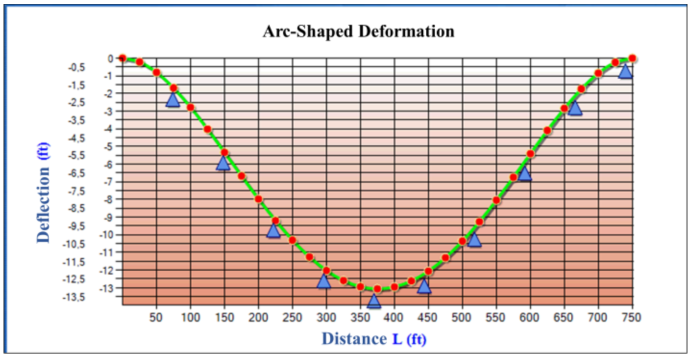

FIGURE 30: TRANSPETRO'S SPECIALIZED SOFTWARE FOR IN-SERVICE PIPELINE MOVEMENT ANALYSIS, IN ACCORDANCE WITH [2].

The initial stress analysis results revealed tensile stresses induced by bending moments on the magnitude of 520 MPa, accompanied by pipe elongation totaling around 0.21 meters over the span of the identified arc-shaped deformation, which extends for 98 meters. While the elongation values fall within acceptable parameters, the estimated tensile stress levels, as per this methodology, suggest the onset of plastic deformation in proximity to the maximum deflection. This concern arises due to the fact that the pipeline (API X65) possesses a tensile strength of approximately 535 MPa when safety factors are not taken into account.

In response to the potential plasticization of the pipe, a comprehensive field inspection campaign was initiated, involving excavation at three critical points along the Arc-Shaped deformation. This course of action became necessary as the 2018 PIG inspection, employing geometric and MFL modules, failed to indicate the presence of typical geometric anomalies or cracks such as ovalizations, wrinkles, or dents, which are typically associated with plasticization.

Figure 31 illustrates the precise locations of the three inspection points situated around the maximum extent of the arc-shaped deformation. Figure 32 provides a visual representation of the trench excavated at one of these points, offering insight into the integrity assessment of the pipelines. It's noteworthy that the pipeline is equipped with a concrete weight coating; however, it was observed that the welded joints of the pipeline lacked a concrete coating.

An array of tests and direct measurements was conducted on the pipeline steel at these selected points, encompassing visual inspections, assessments for geometric non-conformities, cross-sectional geometric measurements to verify ovalization, and crack detection tests using [10].

Upon the completion of these thorough inspections, no elements compromising the structural integrity of the pipeline or suggesting plasticization were identified. This outcome appears to contradict the stress analysis results. Consequently, alternative failure modes and analytical models for this specific situation were explored and evaluated.

FIGURE 31: AERIAL IMAGE SHOWING THE LOCATIONS OF PIPELINE INSPECTIONS CONDUCTED IN THE FIELD THROUGH EXCAVATIONS.

FIGURE 32: PHOTOGRAPH OF THE EXCAVATED PIPELINE JOINT FOR SUPPLEMENTARY STRESS ANALYSIS INSPECTIONS.

In this context, the devised approach revolves around assessing the susceptibility of pipe rupture due to excessive compressive deformation within the section experiencing the maximum deflection, potentially resulting in localized buckling. As such, we've adopted the compressive deformation limit delineated in section C.6.3.3.3 of reference [8] as our guiding criterion. This criterion prescribes a limit of 0.74% for compressive deformation in the pipeline section.

To ascertain the distribution of bending deformations along the pipeline, we utilized the position data (easting, northing, height) of the welds obtained from the most recent inspection conducted by an inertial PIG. To estimate the bending deformations between these weld positions, we employed a spline model to depict the elastic behavior of the pipeline in the region.

While horizontal plane displacements predominate in the pipeline, the calculated deformations account for flexure in space, encompassing not only a specific plane.

Figure 33 shows the positions (easting, northing) of the welds and the elastic line represented by the spline for the arc-shaped region. It also presents the calculated bending deformations for these elements and the compressive deformation limit.

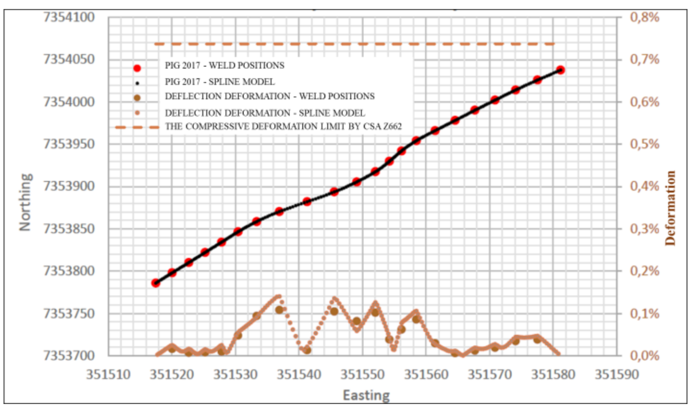

FIGURE 33: SPATIAL REPRESENTATION OF WELD POSITIONS, EMPHASIZING COMPRESSIVE DEFORMATIONS AND THEIR MAXIMUM STANDARD LIMITS.

Based on the analysis of Figure 33, it is evident that the compressive deformations induced by bending moments within the arc-shaped region exhibit values below 0.15%. This measurement is notably lower than the prescribed standard limit of 0.74%.

This deformation analysis, characterized by greater coherence compared to the initial stress analysis, has led to the conclusion that the existing Arc-Shaped deformation of the pipeline falls within acceptable parameters. No discernible factors have been detected that pose a threat to the structural integrity of the pipeline as a result of this Arc-Shaped deformation. Consequently, it can be inferred that there are no imminent risks to the pipeline's structural stability in this context. The recommended course of action is to install soil instrumentation to monitor potential additional displacements and deformations of the pipeline for subsequent evaluation, contingent upon necessity.

4. CONCLUSION

This study establishes that the observed event entailed lateral pipeline displacement, predominantly ascribed to lateral shifts in the soft soil substrate induced by embankment operations conducted at a distance greater than 30 meters from the pipeline axis. This occurrence conforms to the Tschebotarioff Effect (1960) and was additionally influenced by external actions beyond the purview of the pipeline operator, rather than manifesting as a consequence of natural and uninterrupted soil creep. The implications of this scenario have imparted noteworthy insights, succinctly summarized herein.

The findings underscore the significance of vigilance regarding third-party construction activities, even when they occur at distances greater than the 15-meter, threshold stipulated by the Brazilian National Petroleum Agency (ANP). One recommended approach for monitoring such scenarios involves the application of monitoring technologies that leverage satellite imagery and artificial intelligence to detect and recognize surface alterations in the vicinity of the pipeline.

Additionally, this study underscores the usefulness of a Geographical Information System (GIS) platform that includes geological mapping and thematic maps indicating the risk of geotechnical hazards along the entire pipeline route. This comprehensive mapping helps identify areas that require extra attention from pipeline operators. This mapping also played a role in determining the need for frequent launches of inertial Pipeline Inspection Gauges (PIGs) in this pipeline. The assessment of susceptibility at the incident location matched the observed phenomenon, showing the practical value of this mapping approach in strengthening pipeline integrity and safety practices.

The significance of periodically running PIGs equipped with Inertial and Geometric modules in pipelines situated within regions prone to geotechnical movements is evident. This practice should be continuous and standardized among pipeline operators as a fundamental means of monitoring and preserving facility integrity. Alternatively, periodic pipeline location surveys using Pipeline Current Mapper (PCM) technology could also be employed to achieve these objectives effectively.

Moreover, this study has substantiated the efficacy of the methodology presented by Russo et. al. (2015) [1] for detecting pipeline arc-shaped deformations resulting from soil movements. The applicability of this methodology extends to datasets obtained from Pipeline Inspection Gauges (PIGs) as well as georeferenced pipeline locations acquired through Pipeline Current Mapper (PCM) technology.

Lastly, the experiential learning derived from applying rupture criteria predicated on deformations, rather than stress considerations, in scenarios involving distributed lateral displacements imposed on the pipeline within soft and uniform soil substrates has yielded valuable insights. The practicality of employing equations delineated in industry standards for evaluating pipeline movements induced by soil conditions has proven to be adequate for the assessment of pipeline integrity, thereby contributing to the attainment of safety and operational objectives.

ACKNOWLEDGEMENTS

We deeply appreciate the support from PETROBRAS TRANSPORTES (TRANSPETRO) and the invaluable contributions of their professionals, without whom this article would not have been possible.

REFERENCES

[1] RUSSO, W. C., NEVES, R. A., and TOMAZ, W. S. Finding areas with slow soil movement (creeping) using XYZ mapping pigs [MAPI]. Rio Pipeline Conference and Exhibition, Rio de Janeiro, Brazil, October 2015.

[2] API RP 1117 - Recommended Practice for Movement in In-service Pipelines (Recommended practices of American Petroleum Institute).

[3] ASTM D1586 - Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils - American Society for Testing and Materials.

[4] ABNT NBR 6484. Soil - Simple recognition soundings with SPT - Test method - The Brazilian Association of Technical Standards.

[5] OLIVEIRA, H. R.; VASCONCELLOS, C. R. A. Geotechnical Risks Affecting Pipelines: The Bolivia-Brazil Natural Gas Pipeline Experience. In: GEOLOGY AND LINEAR DEVELOPMENTS, 2005, Lyon. Proceedings... FRANCE: CD, 2005a.

[6] VASCONCELLOS, C. R. A. et al. Integrity Management of Brazil Bolivia Gas Pipeline to Reduce Risks Due to Third Party Damage. In: RIO PIPELINE CONFERENCE & EXPOSITION, 2005, Rio de Janeiro. Proceedings... Brazil: CD, 2005.

[7] ASTM D5778-12 - Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils - American Society for Testing and Materials.

[8] CSA Z662 - Oil and gas pipeline systems (Canadian Standards Association).

[9] Petrobras Standard N-2098 rev. F: Inspection of land pipelines in operation.

[10] Petrobras Standard N-1598 rev. G: Non-destructive testing - Magnetic particle.

[11] RTDT (2011) - Technical Regulation for Land Pipelines (RTDT), Established in 2011 through ANP Resolution No. 6/2011, by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP).

[12] MARTINS, I. S. M., SANTA MARIA, P. E. L., & SANTA MARIA, F. C. M., 2009, Discussion: "Laboratory Behavior of Rio de Janeiro Soft Clays. Part 1: Index and Compression Properties", Soils and Rocks, v. 32, n. 2, pp. 100-103.

[13] LACERDA, W. A. Lecture notes for the Slope Stability course – COC-741. Rio de Janeiro: COPPE-UFRJ, 2003. 13 p.

[14] 4th edition of Bulletin No. 3 - Drilling Manual, as promulgated by the Brazilian Association of Engineering Geology (ABGE) in 1999.

[15] MARTHA, L.F. FTOOL - Um programa gráfico-interativo para ensino de comportamento de estruturas. Versão educacional 2.11, Rio de Janeiro, agosto de 2002, 33p.

