IPG 2023
INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE
23 y 24 de Noviembre
Bogotá Plaza Hotel. Bogotá D.C. - Colombia

Con el auspicio de: arpel
ASOCIACIÓN DE EMPRESAS DE PETRÓLEO, GAS Y ENERGÍA RENOVABLE DE AMÉRICA LATINA Y EL CARIBE

Organiza: C-IPG ACIEM Asociación Colombiana de Ingenieros

6ª CONFERENCIA INTERNACIONAL GEOTECNIA DE DUCTOS

IPG2023-####

UNDERSTANDING AND DEFINITION OF LOAD VECTORS IN HIDDEN GEOTECHNICAL HAZARD ZONES BASED ON MULTI-YEAR INERTIAL MAPPING AND SURFACE MONITORING.

Oscar Jair Gualdron
CENIT Transporte y Logística de Hidrocarburos
Bogotá, Colombia

Daniel Mauricio Moncada
CENIT Transporte y Logística de Hidrocarburos
Bogotá, Colombia

Camilo Eliecer Torres
PENSPEN
Bogotá, Colombia

Paula Andrea Rodriguez
PENSPEN
Bogotá, Colombia

SUMMARY

The analysis applied to determine the existence, directionality and geometric effect of displacements and strains of pipes (Bending Strain) based on sectors with relatively low displacement rates and ground movement kinematics, that even from the surface are not evident, challenge the structural condition evaluations of sections that interact with specific and regional geotechnical events that require the determination of load vectors. It corresponds to the dynamics of displacement of the ground and what is more important, they help to understand the mechanical effect of these strains and displacements allowing to reveal the stresses to which the pipes are exposed and, in this way, define alternatives that allow correct mitigation decisions. The spatial alignment of information from base topographies, geotechnical monitoring, inertial mapping runs, orthophotography and slope evaluation, are the basis that allow describing the kinematics of the load model generated in the pipes. The identified load vectors are the main input for mechanical strength and plastic collapse analysis that are simulated using numerical methods such as FEA analysis. Once the models are correlated with the evidence found in the inspections and monitoring, the frequencies of specialized monitoring are established and depending on the magnitude and changes identified, the mitigation measure and/or stress release will be recommended. The case-studies where the load vectors were identified and translated into success stories. Thus, allowing CENIT Transport and Logistics of Hydrocarbons, to appropriately manage the condition. Attend in a maintenance window stablished to not have a negative impact on the operational continuity. ensuring the safety and integrity of the pipelines.

NOMENCLATURE

ArcGIS: Is software that provides tools for mapping and spatial reasoning. ArcGIS is a complete system that allows to collect, organize, manage, analyze, share and distribute geographic information.

AZIMUTH: An angle that characterizes a direction or vector with respect to a reference direction (usually True North) in a horizontal plane. Azimuth is usually indicated in degrees, from 0 to 360 and is always measured clockwise.

BENDING STRAIN: Strain in the outer fibre of the pipe induced by a bending process. It is determined or calculated based on information from inertial mapping units, from intelligent inspections to search for deformations along the pipeline under study.

DEM: Digital elevation model is a visual and mathematical representation of the height values with respect to the mean sea level. which allows to characterize the shapes of the terrain and the elements or objects present in it.

DSM: The Digital Surface Model, shows the elevations above sea level of the surfaces including elements such as trees, buildings, constructions etc. It shows the surface of the land along with the characteristics placed on them.

DTM: Digital Terrain Model, in this one there are no elevated elements only the terrain.

ILI: In-line inspection of pipe using an instrumented tool that use technologies to determine the structural condition of pipelines.

IMU: It is an electronic device, which measures and reports about the speed, orientation, and gravitational forces of a device, using a combination of accelerometers and gyroscopes.

PIPE MOVEMENT: It is the displacement of the pipe measured from two or more ILI inspections, under parameters of change in deformation, elongation and change in the position of the pipe according to the inertial mapping.

PITCH: An angle indicating a deviation in the vertical direction from the plane that is orthogonal to the tangent vector of the pipe centerline

BENT RADII: It describe the angles of the curve in a pipe. The smaller the radius of curvature, the greater the bending strain.

SUSCEPTIBILITY: That which is potentially willing to be modified or evolve in the face of possible natural or anthropic circumstances.

UTCD: Ultrasonic Crack detection (UTCD) tool is designed to measure pipe wall thickness and detect longitudinal and circumferential cracks for pipelines.

1. INTRODUCTION

In Colombia, hydrocarbon transport systems run on paths that have high susceptibility to ground movements, generating strain in the pipeline in any direction depending on the alignment and characteristics of the movement that result in misalignment and deformations of the pipeline.

Because the behaviour and mechanical response of the pipeline is conditioned to the alignment of the pipe before the movement of the ground, it is important to define this factor for the purposes of understanding the projected stresses and deformations that in general can be: 1) alignment of the pipe perpendicular to the movement of the ground presents stresses and deformations to bending, 2) Alignment of the pipe parallel to the direction of soil movement presents stresses and axial deformation where tension occurs behind the beginning of the strain (usually in the part of the pipe that sits at a higher altitude) and compression in the lower part where sometimes they materialize in diameter deformation anomalies.

Therefore, the identification and determination of the load vectors that occur in the pipeline are a key component for understanding the behaviour of the soil-pipe system.

The understanding of the effect soil/pipe system is based on the integral analysis of the mechanical behaviour of the line, with the objective of determining the structural integrity and suitability for service from the pipeline inspections using an instrumented tool (ILI) based on inertial mapping.

Based on the information reported in the ILI, the evolution and behaviour of diameter distortion anomalies, curve deformation zones and pipe movements are evaluated and determined. To the objective of locating areas of interest associated with anomalies that are related to deformations in pipes. To which a load hypothesis is established that allows in the understanding of the effect of the associated load vectors that creates strains on the pipe.

Examples of this are wrinkle-type anomalies whose relationship corresponds to axial stress zones. Areas identified with buckling whose configuration corresponds to compression and/or tension zones. Such tension zones show "Cracks" oriented circumferentially and recorded by an ILI-UTCD.

From the load hypotheses that are constructed from the sites of interest, these hypotheses are validated in the field by geo-hazards specialists, which allows us to understand the ground movement kinematics and how it relates to a geometric response of the pipe to the transverse or axial movement that will generate a bending strain or axial strain and associated with scenarios of increasing displacement there is the probability of stress concentration from compression and / or tension with a tendency to fail due to diameter distortion or what is more critical due to localized buckling.

These hypotheses allow to understand the way the pipeline responds to the defined load vectors. Thus, allowing strategies to limit affected area. The areas are prioritized to carry out follow-ups such as topographic monitoring with orthophoto-mosaic geo-references. If considered necessary are complemented by means of numerical methods such as finite elements analysis in order to estimate the structural condition of the evaluated segment, based on the hypotheses of pipe movement.

Finally, when the analysis determines a corrective strategy, recommendations are made according to the process and response of the pipeline, defining the type of actions to be taken, length of pipe to be stress released and intervention procedure, optimizing operating strategies.

2. MATERIALS AND METHODS

2.1. Inertial Mapping

Based on pipeline inspection using an ILI instrumented tool with IMU and Caliper, the pipeline is examined by detecting deformation anomalies and changes in pipe geometry, as well as evaluating areas affected by bending strain induced stresses and pipe movements (deformation and position differences identified between 2 or more ILI inspections).

From the above, it will be important to consider the reporting criteria of the different ILI suppliers. For total anomalies the criteria is between 0.125% and 0.2% and for areas of strain with total stress difference exceeding 0.04% and for the two cases covering more than 1 circumferential weld of a pipe segment.

Now, there are three (3) main components of strain that combined give the total state of strain in the wall of the pipe section under conditions of ground movement (external loads), see FIGURE 1~~FIGURE 1~~: i) bending strain, ii) axial strain and iii) hoop strain.

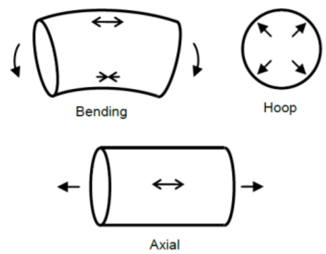


FIGURE 1. Significant components of deformation.

Inertial mapping inspection is the primary source of information in the calculation of bending strains in pipe segments where additionally the indications of the terrain are evident and consistent with the ILI reports.
Bending strain is obtained from the radii of curvature that are calculated by considering pitch and azimuth inclination angles.

However, and although the axial stresses/strains cannot be determined (quantified) directly based on the data of the inertial mapping inspection (due to the limitations of IMU-ILI technique), it is possible to identify the existence of these, including within the soil-tube interaction analysis, the diameter distortions registered by geometric tools, cracking registered by ILI UTCD. Effects of displacements in supports or aerial crossings upstream or downstream of the site under analysis. These must be evaluated individually and associated in layers of analysis applying analytical methods that help to understand the vectors that are determining the ground movement kinematics in a sector and the stresses they are transferring to the evaluated pipe segment.

2.2. Analysis of the deformation profile and monitoring the evolution of the zones.

The analysis of the zones of strains by bending and pipe movement will depend on the information available for each of the case studies, especially the number of ILI's (history of ILI's done in the past).

The procedure to identify the changes in the alignment of the pipe and the deformations reported by the ILI allows in the determination of the beginning of possible movements of the ground to catalogue the areas in active or stable zones.
The variations in deformation and alignment are obtained from the comparison of the results of inertial inspections of the same section of the pipe. The bending strain (horizontal, vertical and total) obtained from the inertial inspections are calculated from

radii of curvature obtained from the angles of inclination and azimuth of the pipe with nominal diameter (OD).

The changes in the pitch and azimuth angles, on a distance between two points or recording distances, allow to calculate the radius of curvature and its vertical and horizontal components for which a process of analysis of deformations in pipes. The analysis procedure is summarized as follows.

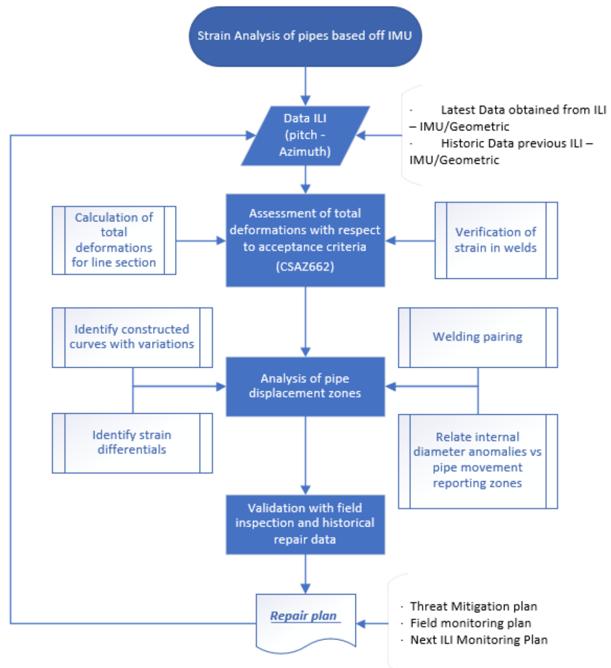


FIGURE 2. Strain analysis procedure based on IMU data (Source: Own)

2.3. Pipe Movement Analysis

Pipe movements are identified by comparing the change of trajectory between two inertial inspections, finding the displacement of the pipeline based on the change of the bending strain from one inspection to another, identifying the beginning of possible ground movements in areas with possible ground movement activity.
Likewise, the monitoring of the evolution of the pipe sections as a result of possible ground movements is carried out based on the previous and current information of the inertial mappings and the alignment of the information.

The inertial ILI matching exercise additionally allows tracking of changes in construction curves based on changes in reported azimuth and pitch.
The evaluation allows to define areas vulnerable to damage or mechanical failure, define adequate response times for the intervention of the anomalous condition and recommend actions that allow to reduce the risk of a rupture in the pipe, and keep the reliability of the pipeline in optimal levels.

2.4. ILI Alignment Analysis of different Vendors and/or topographic tracking

The geographic analysis of information for alignment is a process that is built specific to each exercise due to the different variables, behaviours and nuances that must be reviewed in detail including environmental conditions, which adds to the inherent errors of the tools (ILI, surveying, remote sensing, etc.)

The geographical analysis of information allows to visualize the alignment of the ILI's of different years, topographies, and topographic monitoring. The trend of changes in the behaviour of the movements found between inspections or between inspections and topography is done through a process of cleaning and filtering data, obtaining the refined data to be analysed.

From the above, different methods are developed that allow to visualize the movements according to the direction and magnitude, with the aim of being able to identify the tendency of the movement and the direction and with which contributes to the development of possible movements.

2.5. Determination of Load Vectors

According to the analysis of the data of the ILI where the deformation profile (bending strain) is included, the pipe movements (strain variation) between runs and the existence (location, clock position) of internal diameter anomalies or circumferential cracks allows to determine a hypothesis about the load conditions of the soil to the pipe, which can be in axial direction, see FIGURE 3~~FIGURE 3~~, or transverse direction, see FIGURE 4~~FIGURE 4~~.

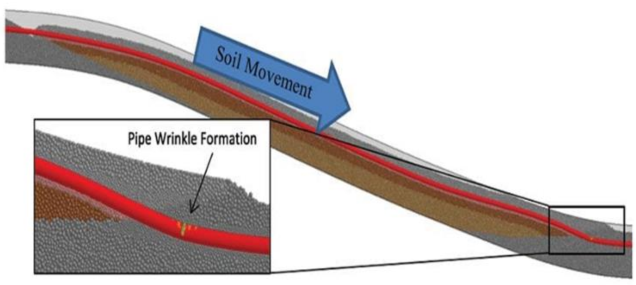


FIGURE 3. Axial Load (hypothesis) Movement of the ground in an axial direction to the alignment of the pipe and generation of anomaly by compression.

FIGURE 4. Cross-loading (hypothesis). Movement of the ground in a transverse direction to the alignment of the pipe, condition to bending. (Source: Own)

2.6. Numerical Methods Modelling

Through numerical methods modelling it is possible to understand the soil-pipe interaction under a motion scenario (pipeline load hypothesis), using constitutive models suitable for soil and pipe including the combined action of loads such as soil thrust and internal operating pressure (Pereira 2009).

The FEA analysis (Finite Element Analysis) seeks to determine the condition of current residual stresses and strains along the pipeline under study where the mechanical resistance can be validated. Through the displacement profile it allows to carry out an analysis of the evolution of stresses and strains and the effect of the displacements that the pipe section has experienced, with which critical displacement limits, monitoring and mitigation actions can be defined.

On the other hand, displacement analysis allows studying the behaviour of the pipeline under scenarios of increasing movements over time, in order to determine its suitability for service.

2.7. Integration of Analysis Results

Integrating the previous numerals as layers of the analysis and cross referencing of the events or findings reported in the different inspections, it allows to determine areas of prioritization, as well as to have an overview of the state of the pipeline according to the load hypotheses.

Additionally, it is included in the cross referencing of events through geographic matching performed in ArcGIS, with refinement of weld matching of ILI's made by the different Vendor and geo-hazard sectors.

3. RESULTS AND DISCUSSION

The integration of the information layers, spatial visualization of correlated events and the determination of load vectors that explain the pipe-soil interaction and its maximum resistance to stress and external load, allows defining actions that, depending on the context of each sector, lead to the following possible actions:

1. Coexistence of low-risk events for the safe operation of the pipeline through the implementation of local monitoring and ILI's during the life cycle of the asset.
2. Mitigation of loads through reinforced ground actions and mechanical protection of the pipeline.
3. Definition of stress release strategies in order not to trigger plastic collapse of the pipes and reduce residual stress; pre and post digging process.
4. Decision making to establish operational restriction or shut down of operations in the pipeline, changes of sections and / or staking out of new right of way.

Giving a better understanding of the process of defining load vectors, two (2) case studies involving the scenario of transverse and parallel load vectors to the pipeline in imperceptible geotechnical threat zones based on multi-year inertial mapping and surface monitoring are presented.

3.1. Case 1

3.1.1 Bending deformation

According to the report of the last ILI, there is an area with pipe movement with mainly horizontal displacement. When reviewing the information, it is found that: 1) there are no reports of additional anomalies within the last run, 2) there is no report of any type of mechanical attention pending, 3) there is no report of geotechnical findings, which is related to a slow movement of soil imperceptible in inspections to the right of way and only identifiable through the analysis of ILI's where bending strain is observed.

FIGURE 5~~FIGURE 5~~ profile where mainly horizontal alignment changes are evident and related to horizontal deformation changes involving 2 pipes in the maximum movement. The strain change of the weld is highlighted, going from 0.170% in previous run to 0.359% in last ILI run (close to the maximum strain value).

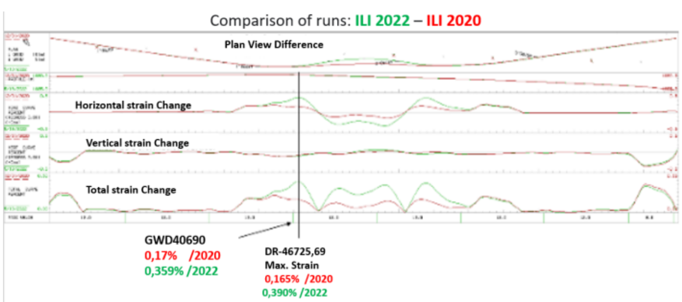
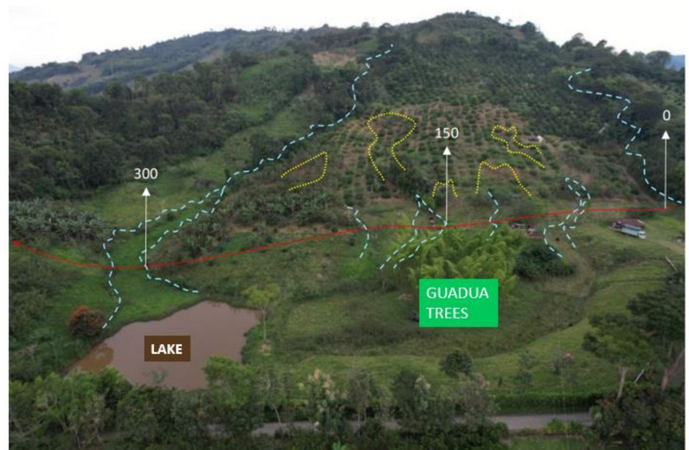


FIGURE 5. Strain profile case 1. (Source: Own)

Based on the analysis, the hypothesis of transverse load vectors to the alignment of the pipeline is established and allows to define the area affected by the movement of the ground. To validate this hypothesis, the following activities are carried out:

1. Location of pipe, topography and orthophotography of the site covering the area located to the top of the slope adjacent to the road.
2. Visual inspection by a geo-hazard specialist of the identified area and its surroundings.
   An approximate length of 300m of the pipeline alignment was inspected (see FIGURE 6~~FIGURE 6~~) finding elements that corroborate the load hypothesis and confirm the condition of geotechnical instability interacting with the pipeline



Distance	0	30	60	90	120	150	180	210	240	270	300
Depth	1,6	2,2	2,4	2,3	2,2	2,5	3,1	2,9	2,5	1,9	2,1

FIGURE 6. Panoramic front view of the find. (Source: Own)

As response plan to the area according to the analyzes carried out, a threat mitigation plan was recommended, which includes activities of stress release in the pipeline, drainage improvement of the ground and geotechnical monitoring and follow-up plan.

3.2 Case 2

3.2.1 Axial strain analysis

In the last ILI run, two wrinkle-type anomalies were reported, located in the lower side of a hill. The evaluation of the wrinkle is performed according to the crest-to-trough height criteria of ASME B31.4, resulting in rejection of the wrinkle dimensions.

Previously the location was in a follow-up plan according to previous run report where there was a Bending strain zone with a length of 95 m, where the maximum deformation is 0.35% with vertical orientation; this maximum deformation is located downstream of the wrinkle reported in a distance record where the last ILI showed no strain variation (no pipe movement) and diameter distortions.

The FIGURE 7~~FIGURE 7~~ corresponds to the report of the Geometry ILI tool.

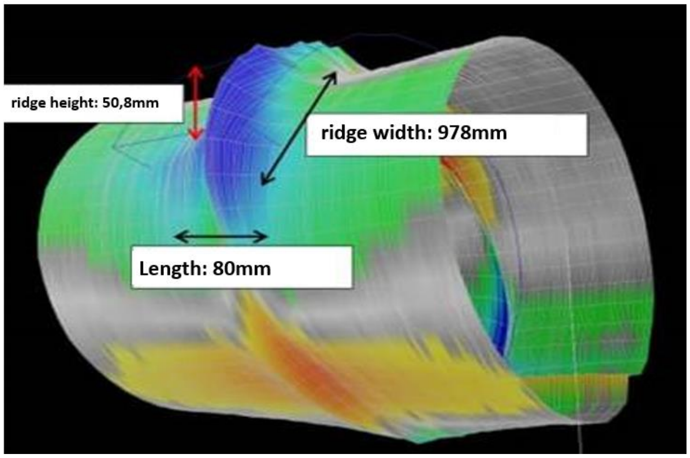


FIGURE 7. Geometry of the wrinkle-like anomaly. (Source: Own)

In accordance with the above, it is identified that the maximum deformation point of the historical BS zone has no direct relationship with the process of wrinkle formation.

According to the ILI data, was performed some analysis of comparisons of the deformation profiles in order to visualize the deformation differentials and possible movements of the pipe, to determine the areas of stress concentration by tension and compression.

FIGURE 8~~FIGURE 8~~ Shows the variations in the strain profile and the vertical angle (pitch) of the area of interest. It shows how the pipe with the wrinkle and the immediately previous one has had a rather variation between the last two ILI's.

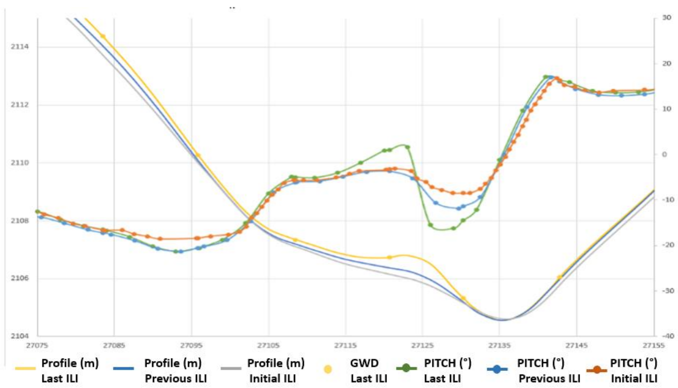


FIGURE 8. Alignment variations. (Source: Own)

TABLE 1~~TABLE 1~~ horizontal deviation for the section of interest, likewise, highlights in red letter the rather variation that generates the wrinkle and shows the presence immediately before and after the wrinkle # 2 that have had mainly vertical variations between previous and last run of up to 3 degrees. Values Registered in initial ILI present behavior like the previous ILI.

	Last ILI					Previous ILI					Initial ILI				
	Distance [m] Last ILI	Clchain (m)	N° GWD	Vertical Change	Horizontal Change	Distance [m] Previous ILI	Distance [m] Last ILI	N° GWD	Vertical Change	Horizontal Change	Distance [m] Initial ILI	Distance [m] Last ILI	N° GWD	Vertical Change	Horizontal Change
	1A		GW-1			1B	1A	GW-2			1C	1A	GW-2		
				5.96	0.18				2.37	0.20				2.28	0.41
wrinkle #1	2A		GW-2			1B	2A	GW-2			1C	2A	GW-2		
				-17.82	3.06				-6.61	0.85				-5.39	-0.76
	3A		GW-3			1B	3A	GW-2			1C	3A	GW-2		
wrinkle #2				29.12	-4.25				26.28	-3.37				25.34	3.02
	4A		GW-4			1B	4A	GW-2			1C	4A	GW-2		
				-2.16	0.70				-1.18	0.37				-1.14	0.84
	5A		GW-5			1B	5A	GW-2			1C	5A	GW-2		
				-0.33	-0.06				-0.81	-0.05				-0.49	0.01

TABLE 1. Horizontal vertical variation. (Source: Own)

Analysis of the alignment between the previous run and the last run was performed, see FIGURE 9~~FIGURE 9~~, finding XY displacements of 15 cm and Z displacements of 76 cm.

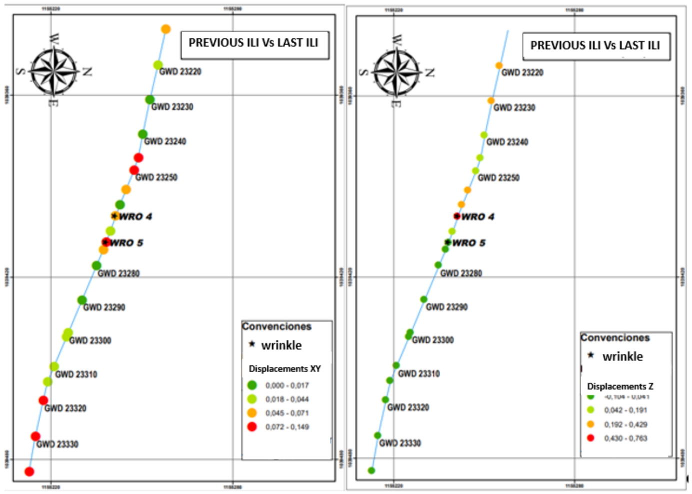


FIGURE 9. Alignment between runs. (Source: Own)

FIGURE 10
~~FIGURE 10~~ the changes in the profile of strains with mainly vertical orientation, in the reported wrinkle anomalies, as well as

at least 3 welds that are found with deformations of 0.4%, 1.21% and 2.59%.

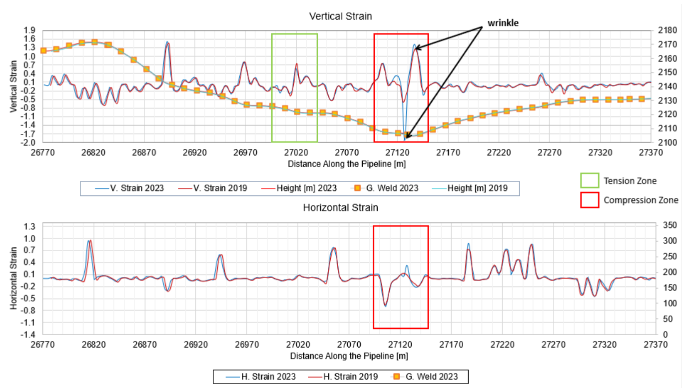


FIGURE 10. Strain profile. (Source: Own)

The identification of load vectors allowed to establish the digging sequence as shown in FIGURE 11~~FIGURE 11~~, guaranteeing the correct release of the accumulated stresses and thus reducing the risk of failure of the wrinkle until the final repair done by replacing the section.

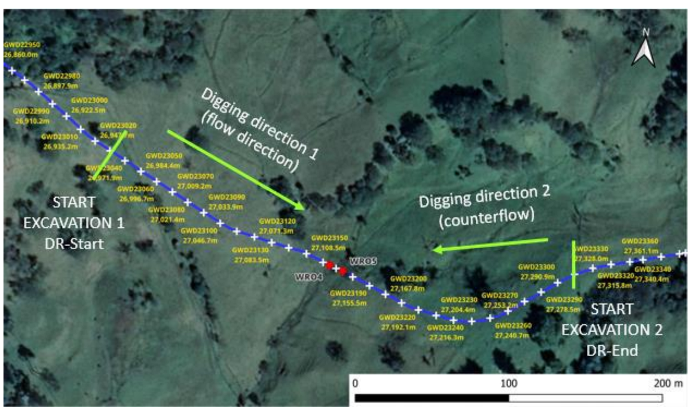


FIGURE 11. Digging procedure. (Source: Own)

From the direct assessment it was found that the crest-to-trough height, is rejected (ASME B31.4). This level of deformation generates grooves that coalesce into fissures and obvious cracks. The orientation of the fissures is axial with respect to the axis of the wrinkle and some circumferential colonies.

In field inspections the load hypotheses were validated. The determined vector corresponds to the axial load evaluated on the pipe. The integration and multilayer assessment found additional conditions to those reported by the ILI Vendor.

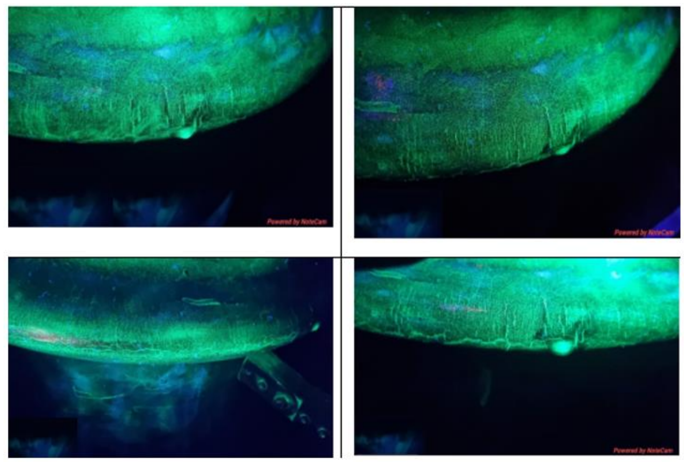


FIGURE 12. Ridge height of wrinkle anomaly found in the field. (Source: Own)

4. CONCLUSIONS

The multidisciplinary and comprehensive analysis results in the definition of load vectors that are part of the assessment that is carried out based on multiannual inertial mapping and surface monitoring.

The identification and generation of load hypotheses (load vectors) allows the identification of new sectors that are being affected by external loads not identified in the inspection of the right of way (difficult to identify due to geomorphological conditions and / or low displacement rates- hidden ground movements).

The identification and determination of the load vectors are a key component for the understanding of the behavior of the soil-pipe system and this understanding is based on the integral analysis of the mechanical behavior of the pipeline, with the aim of determining the structural integrity and suitability for service from the pipeline inspections through an instrumented tool based on inertial mapping.

The load vectors associated with a previous analysis with layers of aligned information, will determine the displacement effects that may be occurring in the pipelines and that are input for fitness for service analysis under FEA simulations.

Once the models are concatenated with the evidence found in the inspections and monitoring, the frequencies of specialized monitoring are established and depending on the magnitude and changes identified, the mitigation measure and / or relevant attention will be recommended.
Finally, the determination of load vectors that explain the pipe-soil interaction and its maximum resistance to stress and external load, allow defining actions that, depending on the context of each sector, lead to the following type actions:

1. Coexistence of low-risk events for the safe operation of the pipeline through the implementation of local monitoring and ILI's during the life cycle of the asset.
2. Mitigation of loads through reinforced soil barriers and mechanical protection of the pipeline.
3. Definition of stress release strategies in order not to trigger plastic collapse of the pipes and reduce residual efforts pre and post digging process.
4. Decision making to establish operational restriction or stop pumping fluid through pipeline, changes of sections and / or staking out new right of way.

The case studies where the load vectors were identified and explained the kinematics of the tube/soil condition, were success stories that allowed CENIT Transport and Logistics of Hydrocarbons, to coexist with the condition, response in a maintenance window that did not affect the operational continuity and ensure the integrity of the pipeline.

THANKS TO

To the head of Department of Performance of pipelines of CENIT transport and Logistics, for allowing to share the case studies and to be able to use the specialists and technical authority of the current Assessment services.

REFERENCES

- [1] ASME B31.4. "Pipeline transportation systems for liquids and slurries".
- Canadian Standard CSA Z662:19- Oil and gas pipeline systems
- API 1160 - Managing System Integrity for Hazardous Liquid Pipelines
- DOT CFR 195
- API 579- Fitness for service
- Pereira, Mauricio. 2009. "Numerical Modeling of Soil-Pipe Interaction in Landslides."