ALERTAS TEMPRANAS PARA LA INTEGRIDAD DE DUCTOS EXPUESTOS A MOVIMIENTOS GEOTÉCNICOS LENTOS: UN ENFOQUE BASADO EN ANÁLISIS DE DESPLAZAMIENTO Y CRITERIOS DE STRAIN CAPACITY

Paula Rodríguez
Bending Strain Expert
PENSPEN
Bogotá, Colombia

Camilo Torres
Technical Manager
PENSPEN
Bogotá, Colombia

Oscar Gualdrón
Cenit Transporte y Logística de Hidrocarburos
Bogotá, Colombia

00 de Noviembre de 2025

Tabla de Contenido

Contexto y Problema

Sector con movimiento de tubería, cumple criterios de strain capacity.

Que hacer? Cuando atender?

01

Movimientos lentos del terreno

02

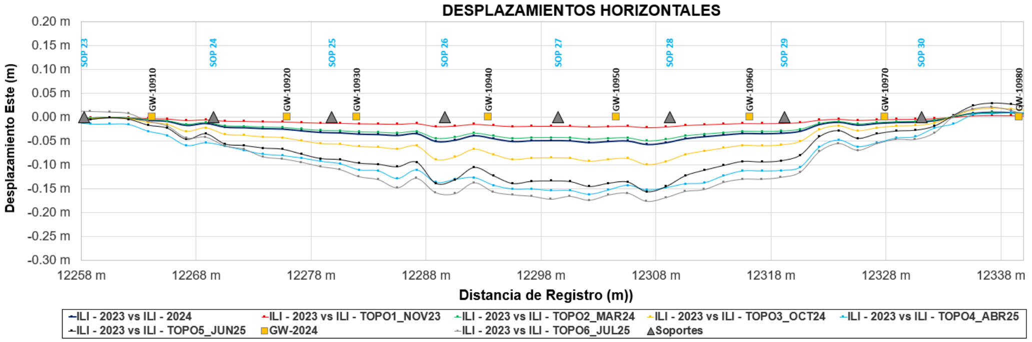
Movimiento y Deformación del Ducto

03

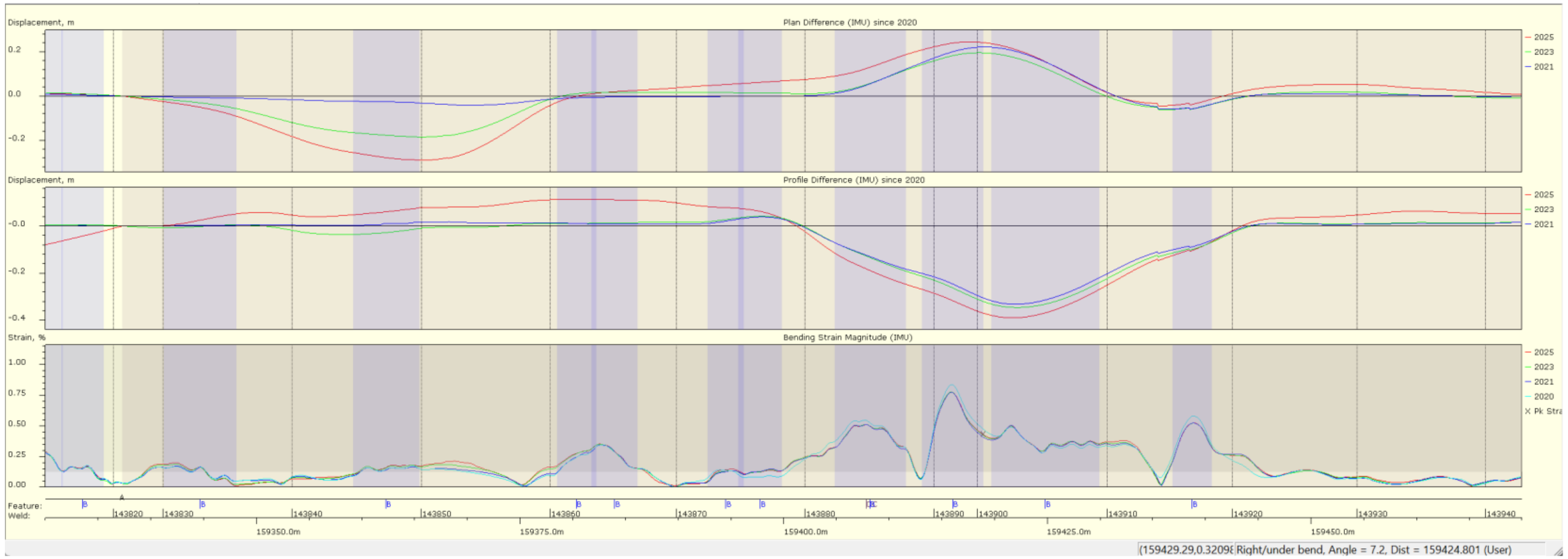
Definir cuando se atenderá?

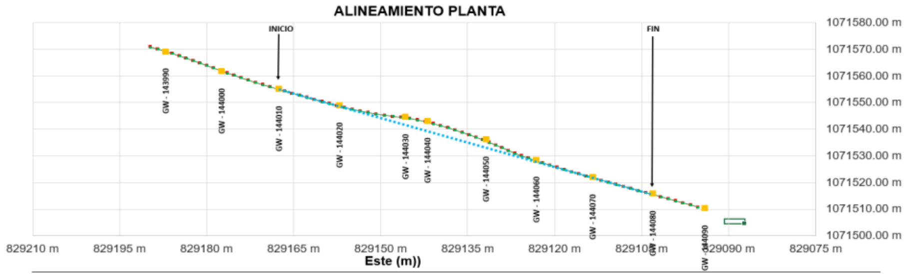
Movimientos lentos del terreno

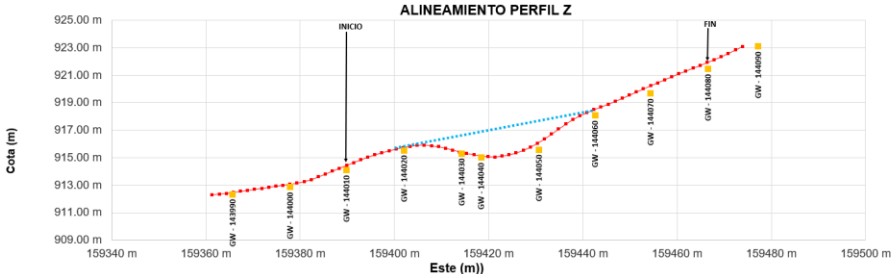
Clase	Descripción	Desplazamiento	Poder Destructor
7	Extremadamente rápida	5 m/seg.	Catástrofe de violencia mayor; edificios destruidos por el impacto o el material desplazado, muchas muertes, escape improbable.
6	Muy rápida	3 m/ min.	Alguna pérdida de vidas; velocidad demasiado alta para permitir a todas las personas escapar.
5	Rápida	1.8 m/hora	Escape posible; estructuras, propiedades y equipos destruidos.
4	Moderada	1.3 m/mes	Algunas estructuras temporales y poco sensitivas pueden mantenerse temporalmente.
3	Lenta	1.6 m/año	Construcciones remediales se pueden realizar durante el movimiento. Algunas estructuras insensitivas pueden mantenerse con mantenimiento frecuente.
2	Muy lenta	16 mm/año	Algunas estructuras permanentes no son dañadas por el movimiento.
1	Extremadamente lenta		Movimientos imperceptibles sin instrumentos; posible construcción, pero teniendo ciertas precauciones.



Movimiento y Deformación del Ducto





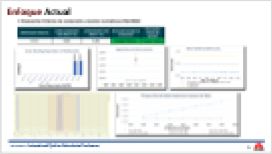


Definir cuando se atenderá?

Enfoques Metodológicos

Enfoque Actual

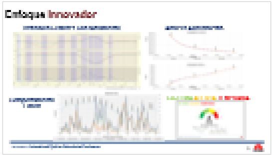
1. Sitios de interés BS/PLMM
   Proveedor ILI
2. Evaluación Vs Strain Capacity
3. Proyección Deformación Lineal



4. Definición plan de acción

Enfoque Innovador

1. Identificación sectores con Mov.
   Proveedor ILI

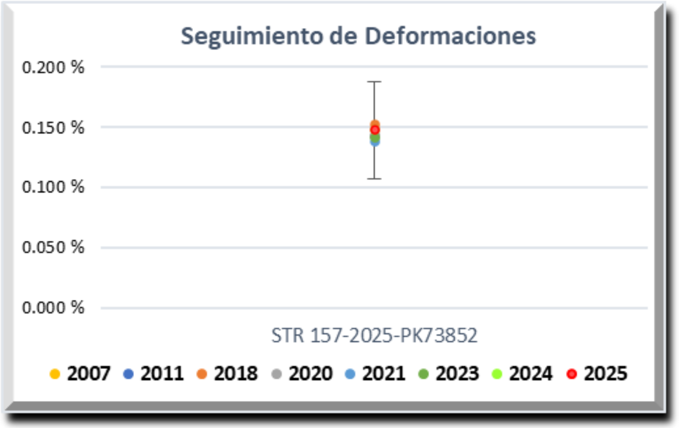


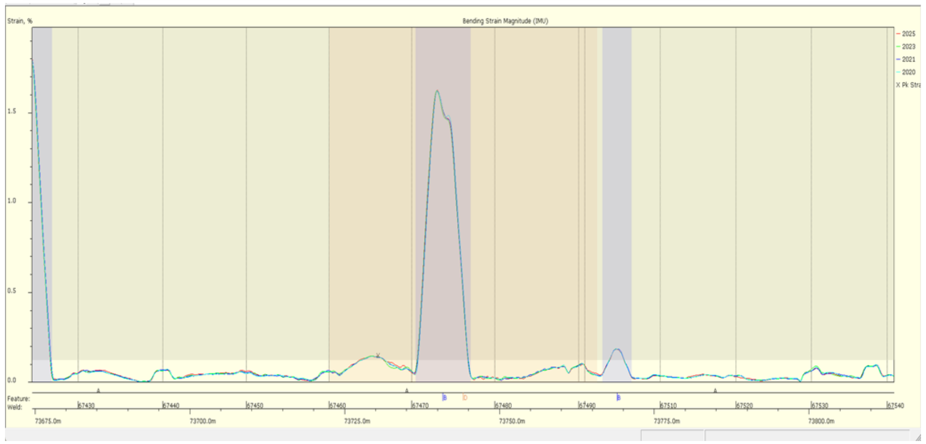
2. Análisis alineamiento: Tasas Desplazamiento Proyección Futura: Alineamiento y Deformaciones
3. Evaluación Deformación actual Vs Proyectada Con Strain Capacity
4. Planes de Atención Optimizado

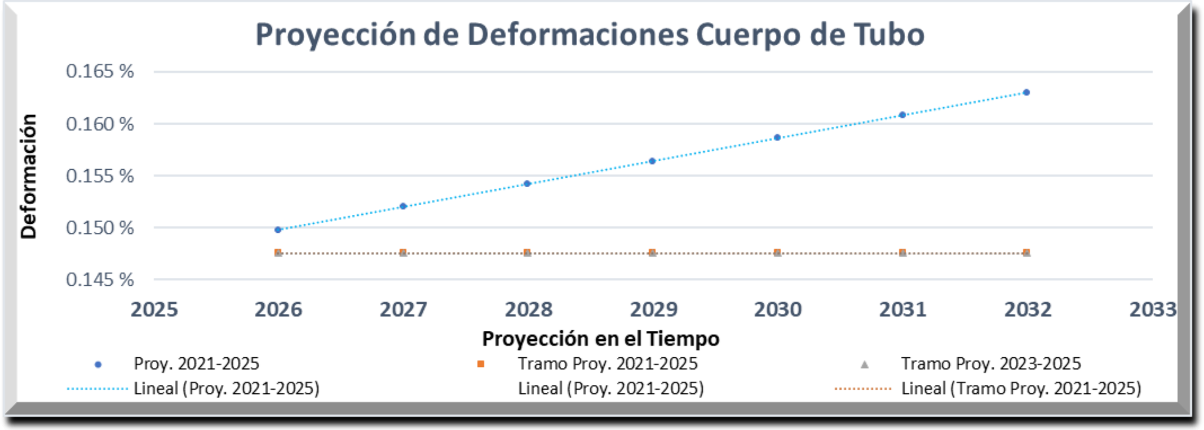
Enfoque Actual

2. Evaluación Criterios de compresión y tensión normativos (CSA Z662):

Deformación total (%)	Límite compresión CSA Z662-15 (%)	Límite tensión CSA Z662-11 (%)	Evaluación estado de compresión	Evaluación estado de tensión
0.15 %	0.84%	0.45%	Cumple Criterios	Cumple Criterios

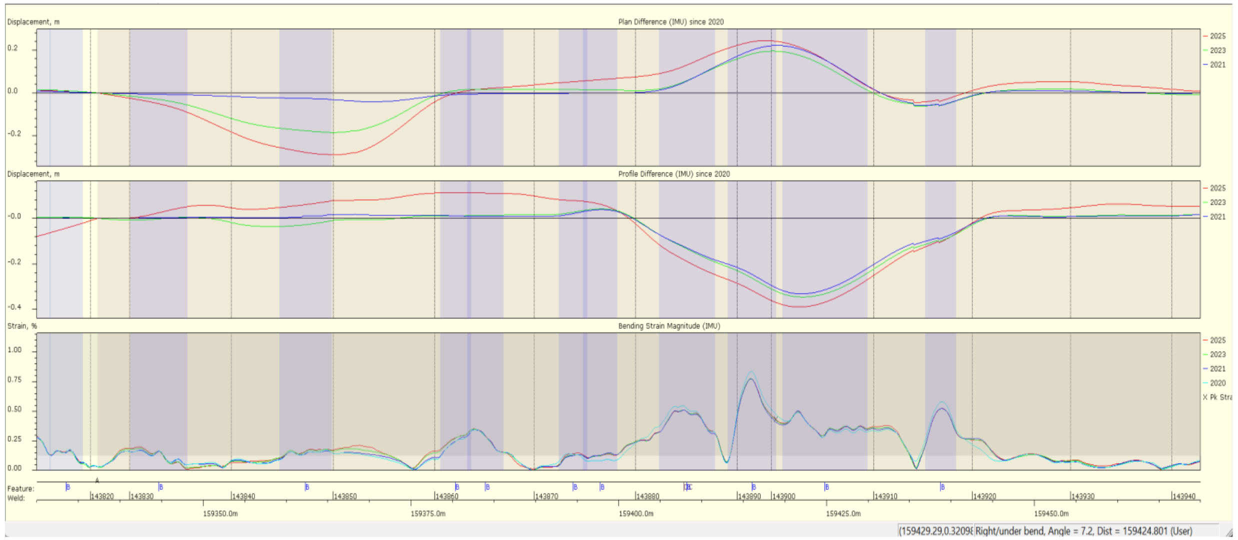




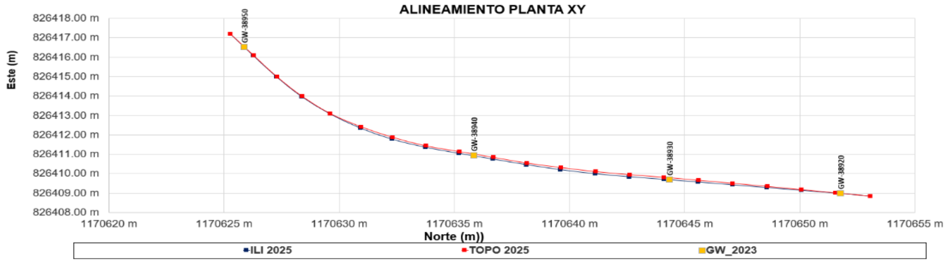


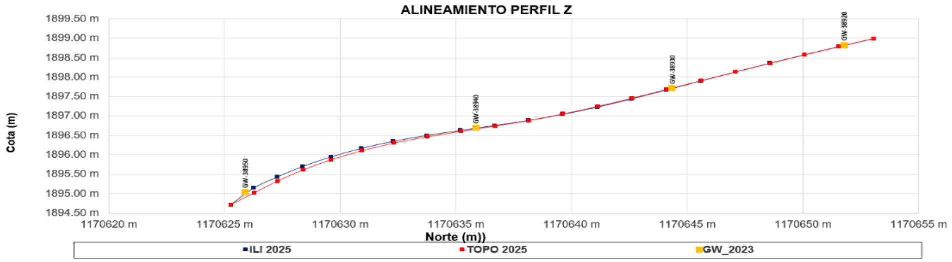
Enfoque Innovador

Definición Sectores Con Movimiento

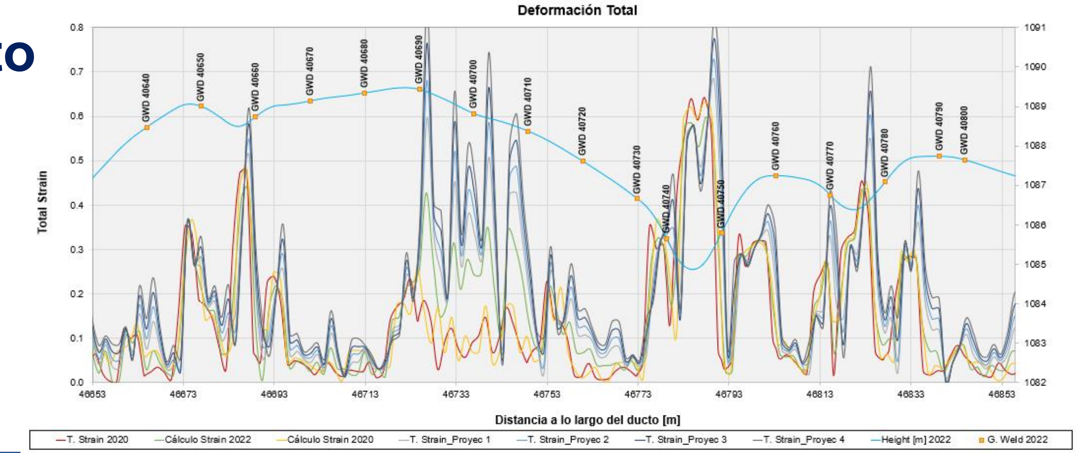


Análisis Alineamiento



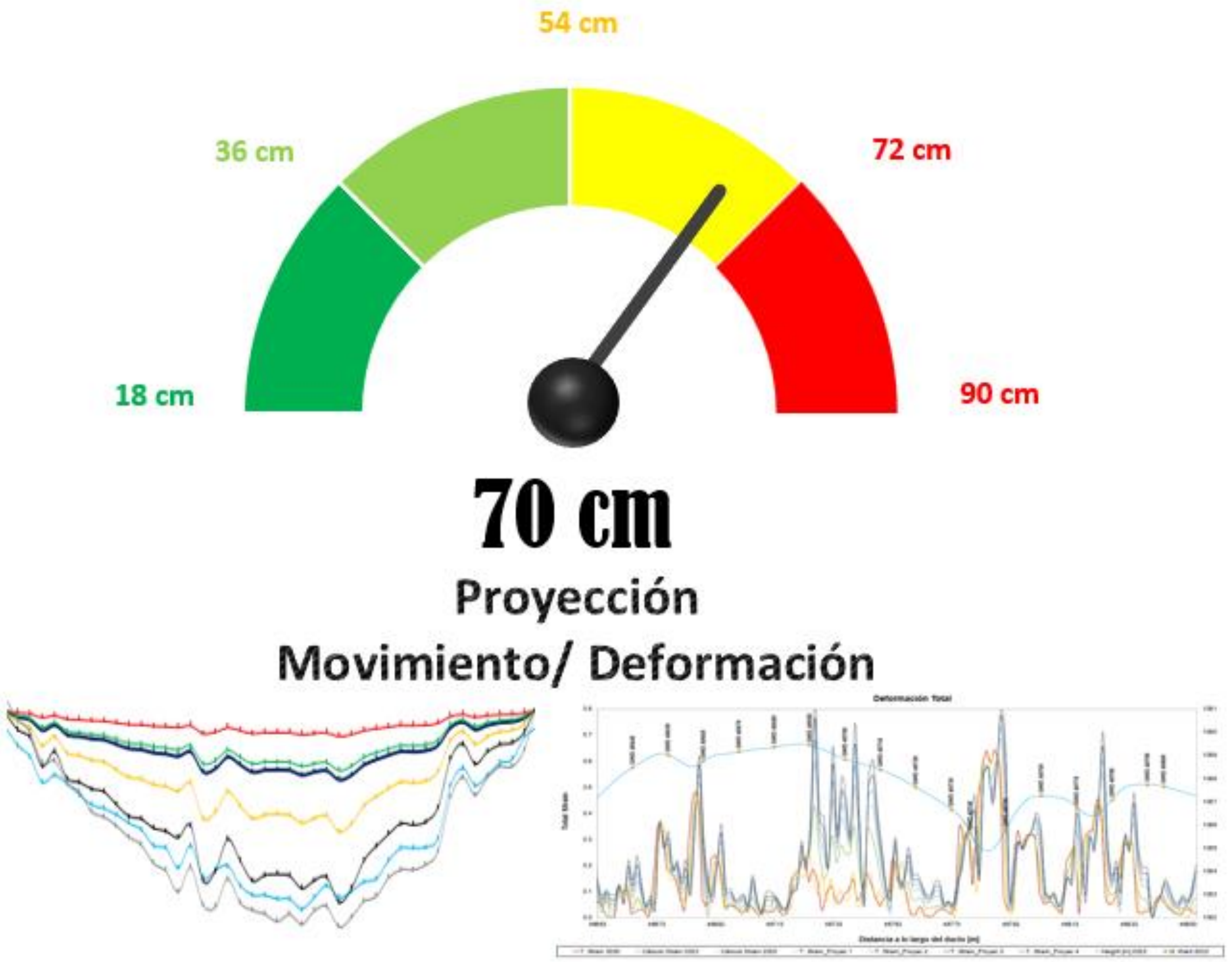


Comportamiento Futuro



SISTEMA ALERTA TEMPRANA

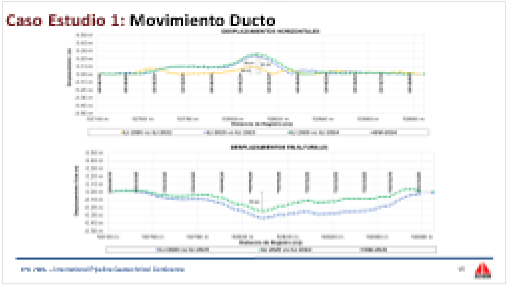
SISTEMA ALERTA TEMPRANA



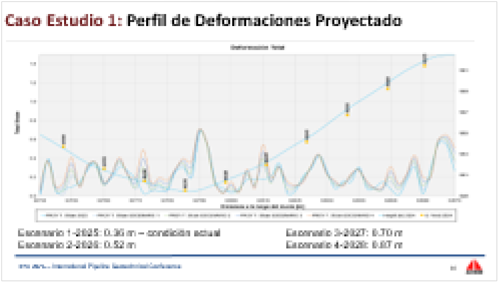
CASOS DE ESTUDIO

Caso de Estudio 1

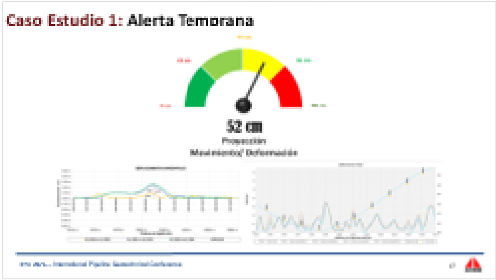
Identificación Sectores con movimiento



Análisis alineamiento: Tasas Desplazamiento



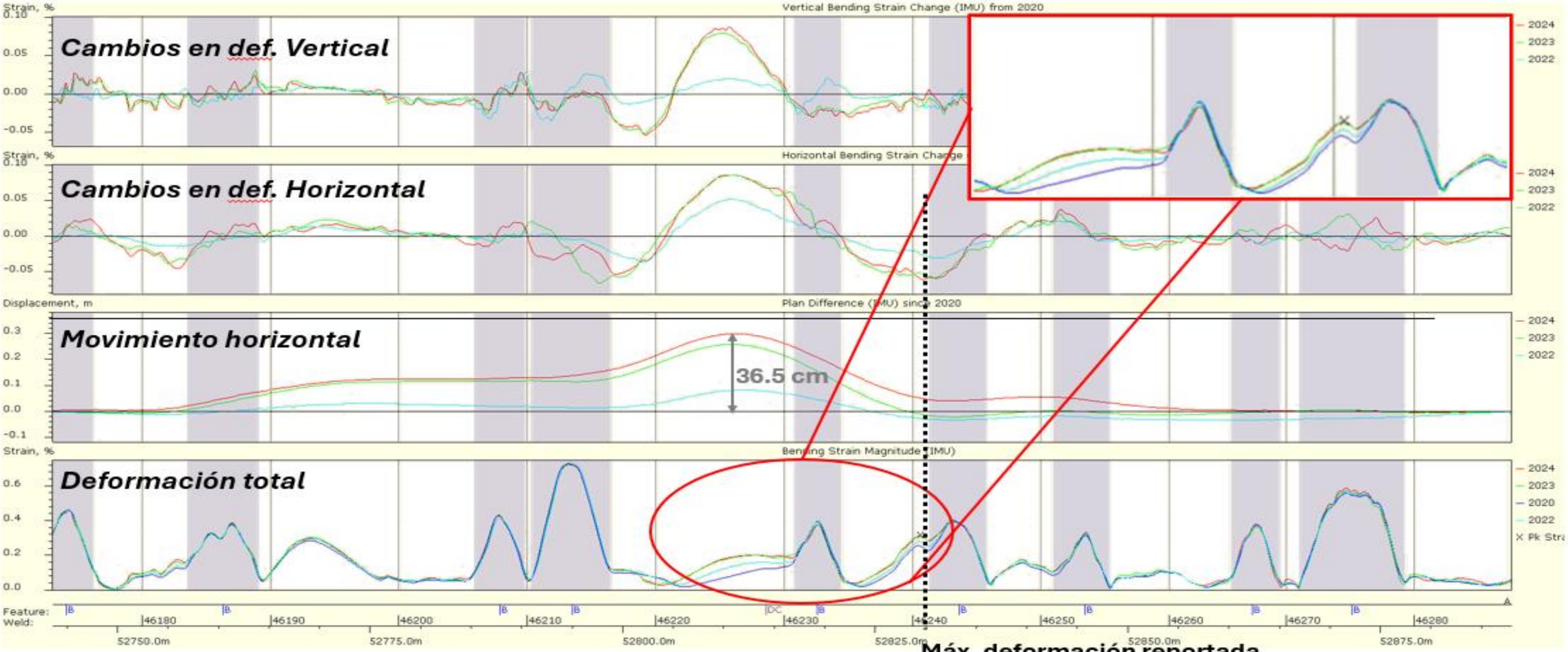
Proyección Comportamiento Futuro Ducto



Alerta Temprana

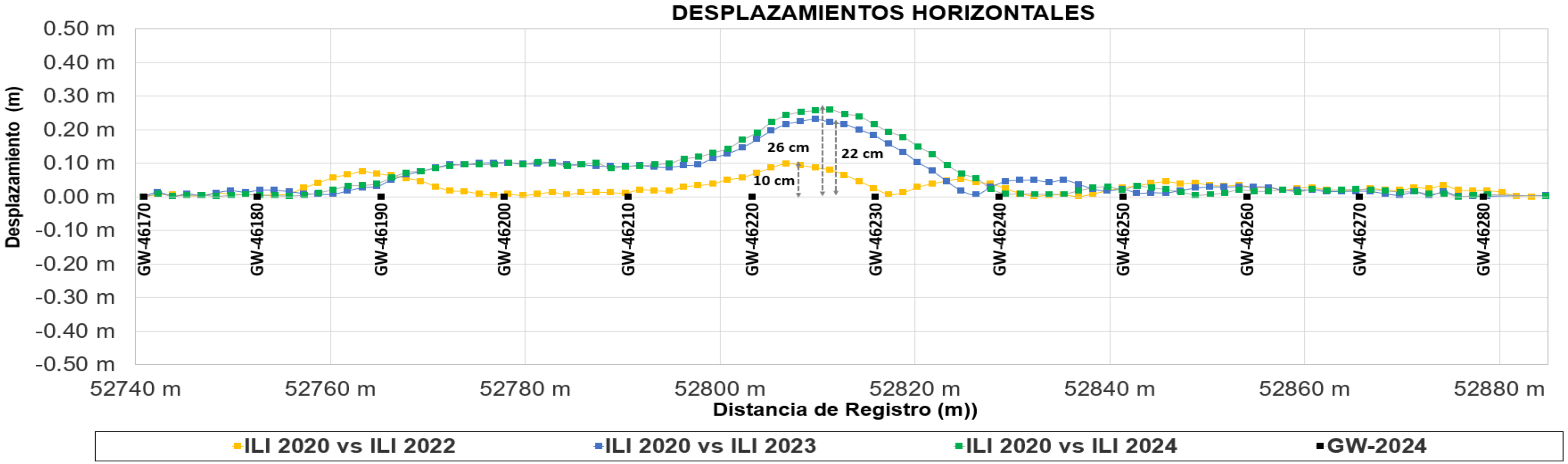
Caso Estudio 1

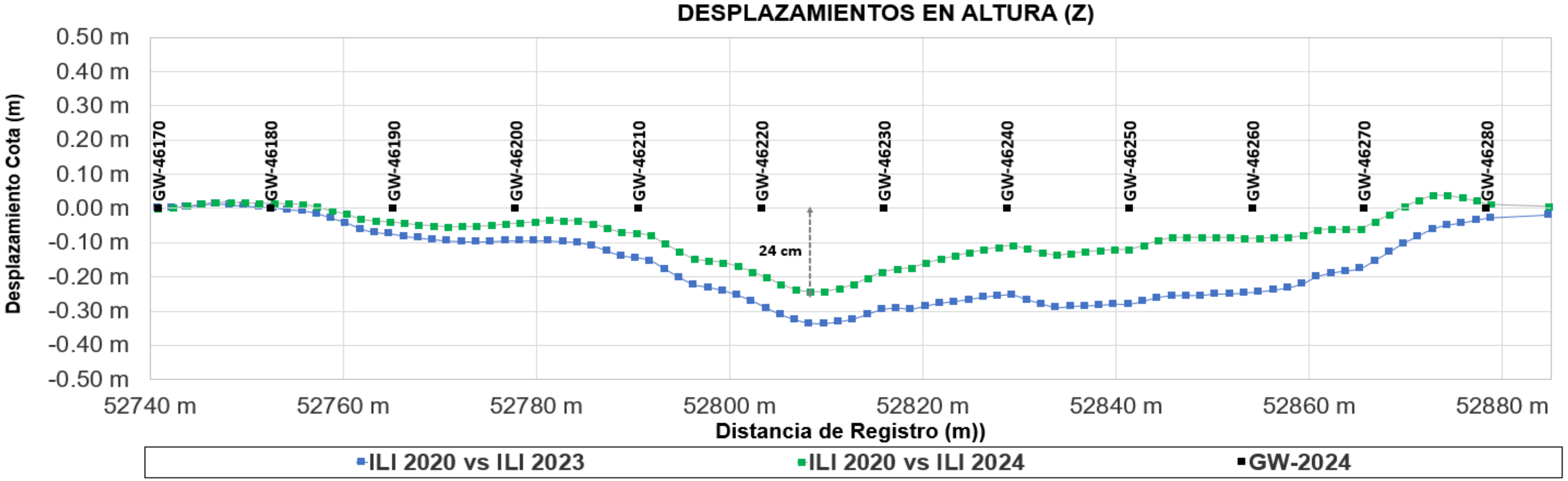
Caso Estudio 1: Movimiento y Deformación Ducto



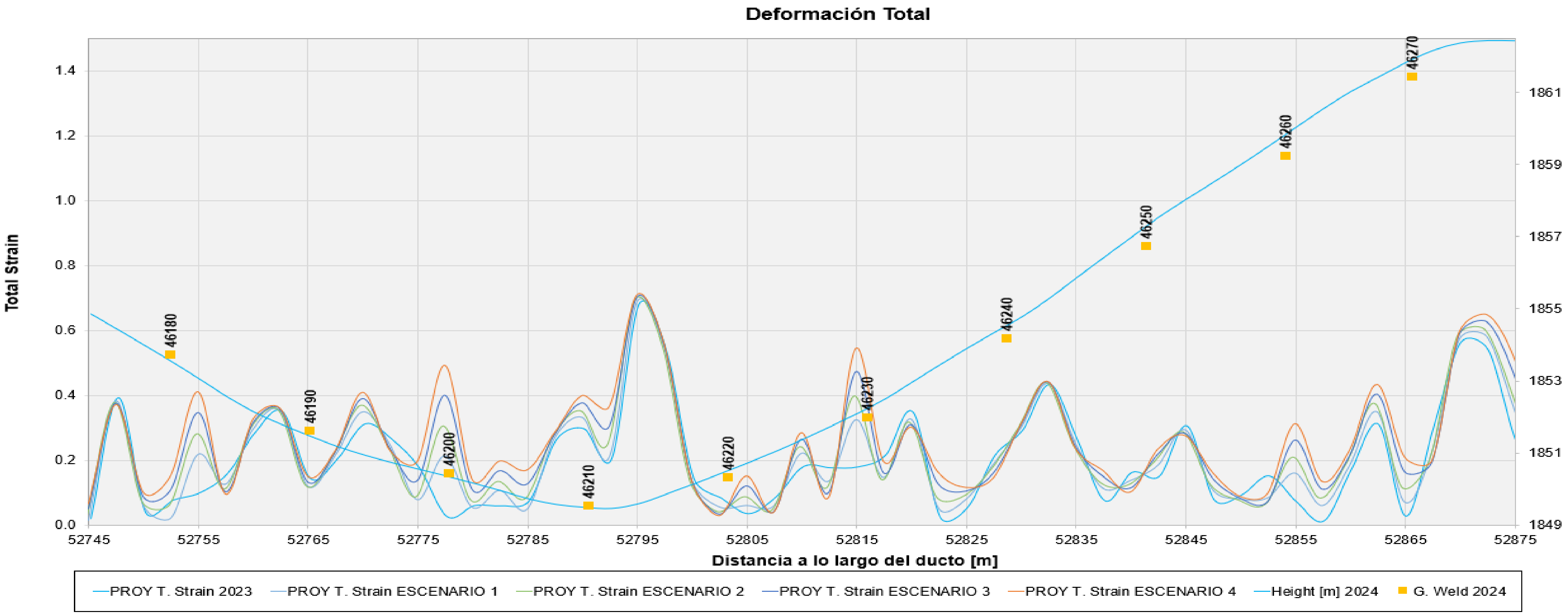
Máx. deformación reportada
0.312% (corrida ultima)
0.189% (corrida previa)

Caso Estudio 1: Movimiento Ducto





Caso Estudio 1: Perfil de Deformaciones Proyectado



Escenario 1-2025: 0.36 m – condición actual
Escenario 2-2026: 0.52 m

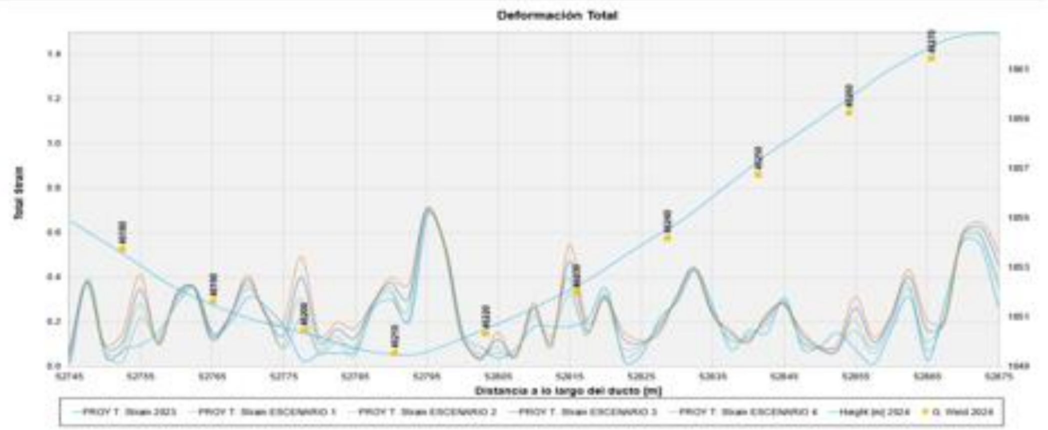
Escenario 3-2027: 0.70 m
Escenario 4-2028: 0.87 m

Caso Estudio 1: Alerta Temprana

52 cm

Proyección

Movimiento/ Deformación



ACIEM

Caso Estudio 1: Conclusiones

01

Entendimiento Problema
Evolución y cambio de alineamiento

02

Establecer límites de desplazamiento seguros, Vs (Strain Capacity)

03

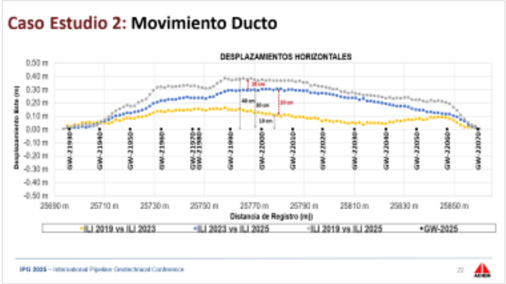
Definición umbrales de alerta temprana - Atención
Umbral de atención
Escenario 2-2026: 0.52 m

04

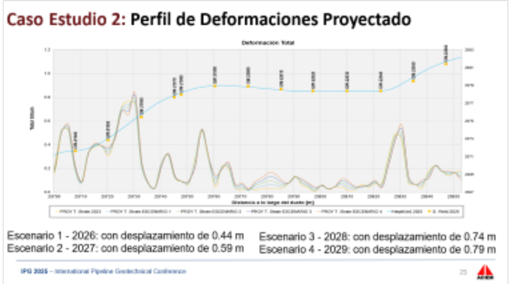
Definición umbrales de alerta temprana – monitoreables técnicas directas / indirectas

Caso de Estudio 2

Identificación Sectores con movimiento



Análisis alineamiento: Tasas Desplazamiento

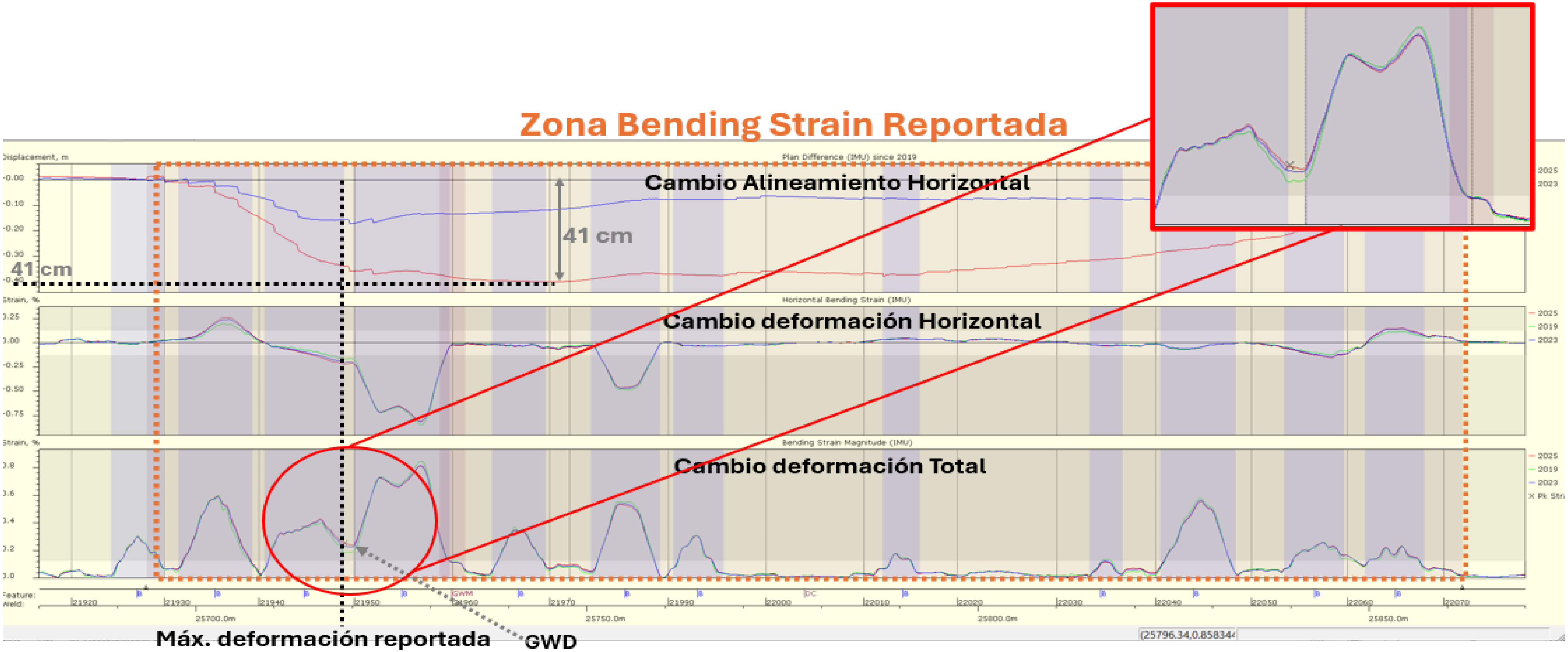


Proyección Comportamiento Futuro Ducto

Alerta Temprana

Caso Estudio 2

Caso Estudio 2: Movimiento y Deformación Ducto

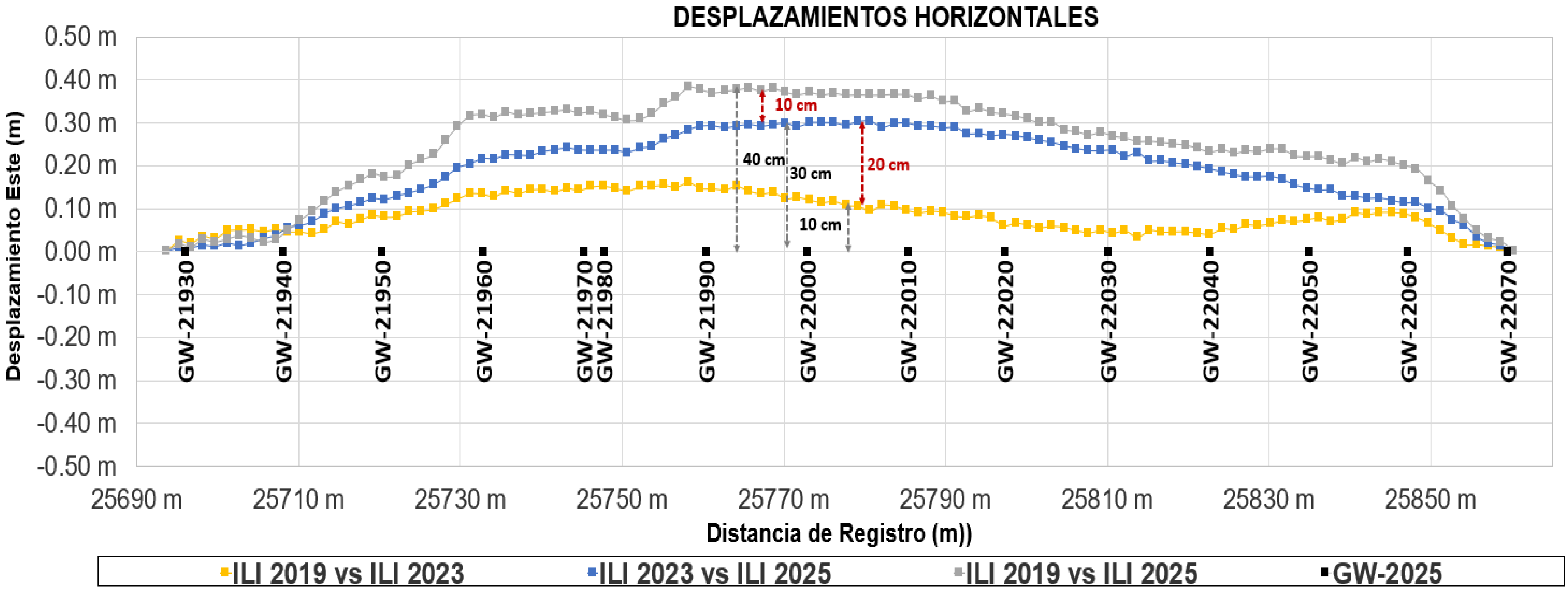


Máx. deformación reportada
0.25% (corrida ultima)
0.18% (corrida previa)

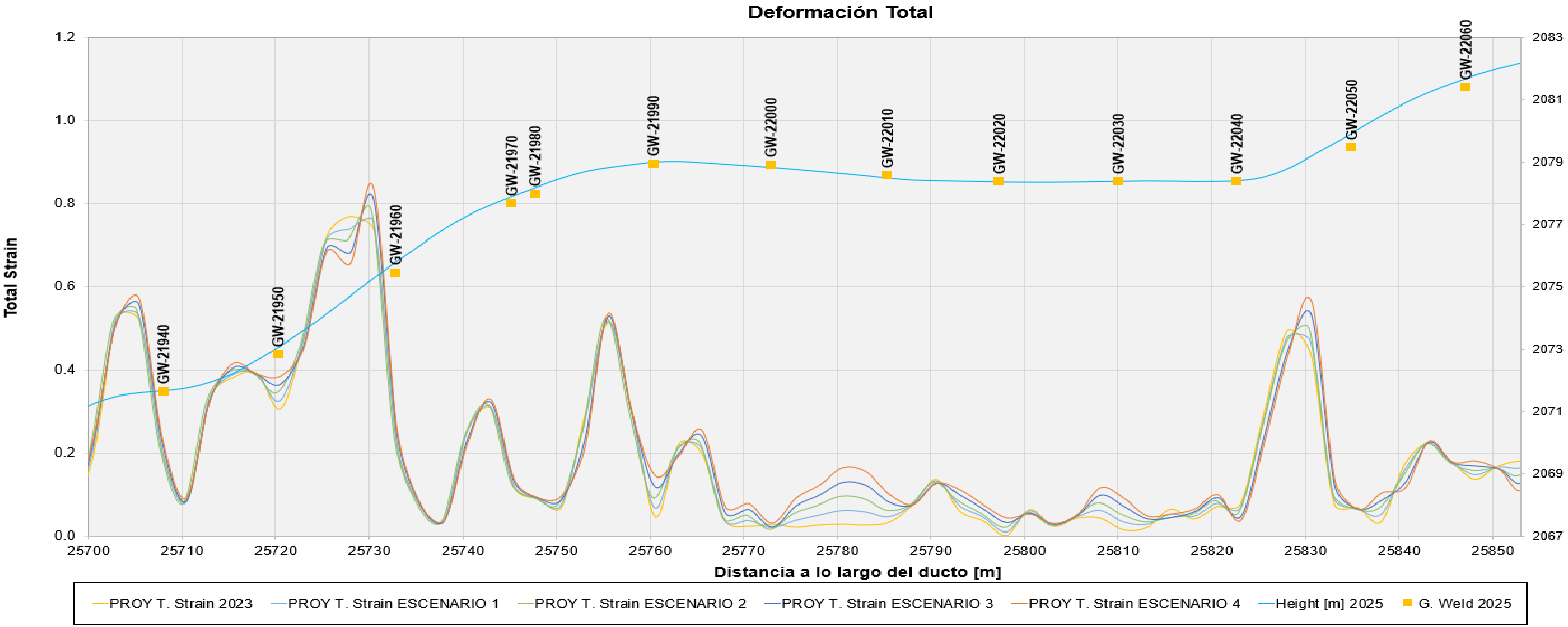
GWD
0.25% (corrida ultima)
0.20% (corrida previa)

ACIEM

Caso Estudio 2: Movimiento Ducto

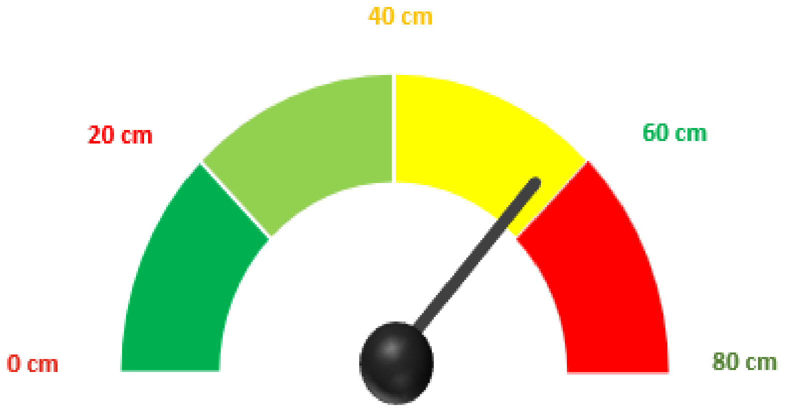


Caso Estudio 2: Perfil de Deformaciones Proyectado



Escenario 1 - 2026: con desplazamiento de 0.44 m
Escenario 2 - 2027: con desplazamiento de 0.59 m
Escenario 3 - 2028: con desplazamiento de 0.74 m
Escenario 4 - 2029: con desplazamiento de 0.79 m

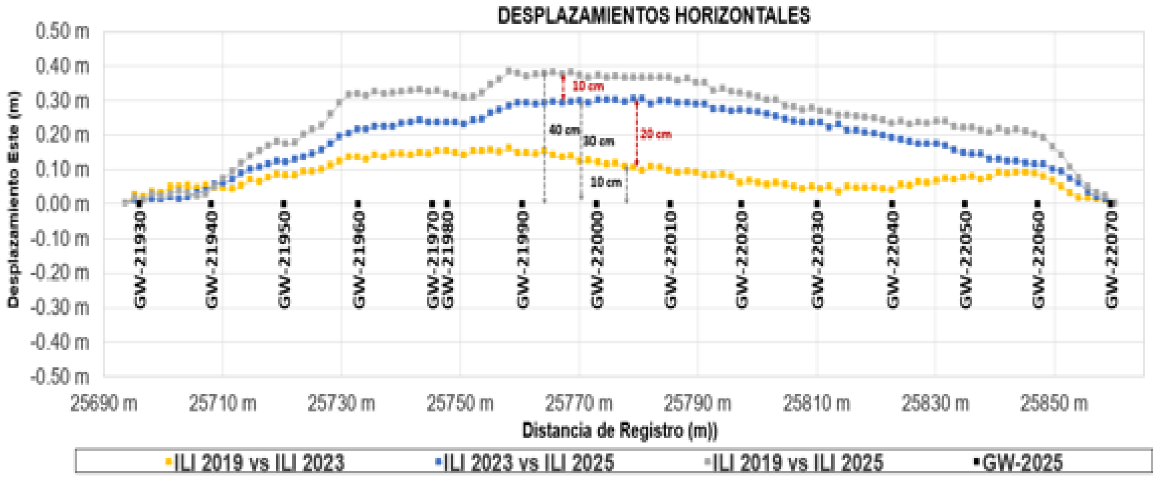
Caso Estudio 2: Alerta Temprana

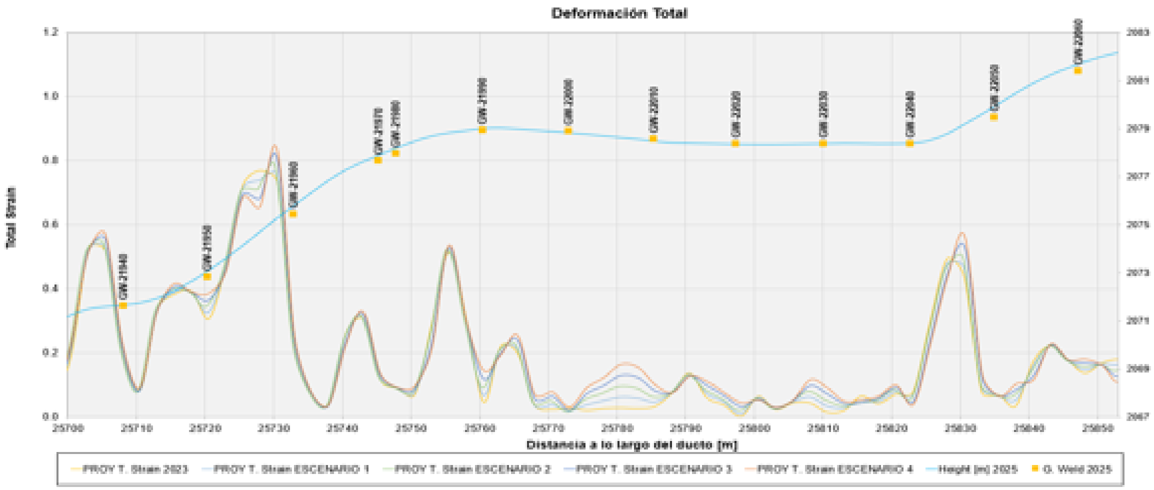


59 cm

Proyección

Movimiento/ Deformación





Caso Estudio 2: Conclusiones

01

Entendimiento Problema Evolución y cambio de alineamiento

02

Establecer límites de desplazamiento seguros, Vs (Strain Capacity)

03

Definición umbrales de alerta temprana - Atención Umbral de atención Escenario 2-2027: 0.59 m

04

Definición umbrales de alerta temprana – monitoreables técnicas directas / indirectas

Conclusiones

METODOLOGÍA PROPUESTA

Integra datos ILI-Topografía para identificar desplazamientos y deformaciones imperceptibles en el terreno.

CRITERIOS DE DEFORMACIÓN LÍMITE

Basados en Strain Capacity, permiten anticipar movimientos y orientar el mantenimiento predictivo.

UMBRALES DE ALERTA TEMPRANA

Definen límites seguros correlacionados con la capacidad de flexión, medibles por monitoreo topográfico y sensores geotécnicos.

GESTIÓN PROACTIVA DEL RIESGO

Optimiza la toma de decisiones y la planeación de mantenimiento según el comportamiento real del ducto.

ACTIVIDADES A IMPLEMENTAR

Monitoreo topográfico, instrumentación geotécnica y seguimiento continuo de desplazamientos.

ENFOQUE INNOVADOR

Enfoque preventivo que anticipa riesgos y valida resultados en campo para fortalecer la gestión predictiva.

¡Gracias!

IPG 2025 7th International Pipeline Geotechnical Conference
IPG2025
6-7 November 2025, Bogotá, Colombia

IPG2025-033

EARLY WARNINGS FOR THE INTEGRITY OF PIPELINES EXPOSED TO SLOW GEOTHECNICAL MOVEMENTES: AN APPROACH BASED ON DISPLACEMENT ANALYSIS AND STRAIN CAPACITY CRITERIA

Paula Rodríguez
Bending Strain Expert
PENSPEN
Bogotá, Colombia

Camilo Torres
Technical Manager
PENSPEN
Bogotá, Colombia

Oscar Gualdrón
Cenit Transporte y Logística de Hidrocarburos
Bogotá, Colombia

ABSTRACT

In Colombia, hydrocarbon transportation systems frequently cross terrains with a high susceptibility to unstable geotechnical movements. These conditions cause changes in the alignment and deformation of pipelines, continuously compromising their structural integrity. Movements with low or very low displacement rates are particularly critical because they are imperceptible to the naked eye and even with monitoring using inertial tools. This condition significantly complicates the proactive management and planning of maintenance. This scenario demands innovative approaches to ensure pipeline integrity and facilitate effective preventive maintenance. A key strategy is to define safe displacement limits, correlated with the allowable bending strain capacity of the pipeline (Strain Capacity).

The methodology proposed here uses data from at least two successive intelligent inspections (ILI with an inertial module) to build a detailed displacement field of the pipeline. This comparative analysis makes it possible to identify critical points with a high concentration of strains and to locate precise changes in the horizontal and vertical alignments of the sections evaluated. From this displacement field between inspections, it is possible to project the future change in the pipeline's alignment (geometric response). Crucially, a correlation is established between accumulated displacements and the allowable strain capacity. This allows for the definition of displacement thresholds that serve as early warnings, which can be monitored through direct and indirect measurements in the field. This work presents a methodology, based on positional analysis derived from ILI inspections, to define early warning thresholds for slow ground movements that affect pipelines in areas with low or very low displacement velocities..

NOMENCLATURE

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

DEFORMATION (STRAIN): Changes in a characteristic dimension of a structure generated by internal or external stresses. When the strain is axial, it is denoted by the Greek letter ε. For the case of linear strain, $\varepsilon=\Delta L/L$, where L is the original length of the structure and ΔL is the change generated. The strain ε is a dimensionless value; units are generally in microstrain or as a percentage.

BENDING STRAIN: Strain in the outer fiber of the pipeline induced by a bending process. It is determined or calculated based on information from the inertial mapping of smart inspections and topographic monitoring, in the search for deformations along the pipeline under study.

DEM: Digital elevation model is a visual and mathematical representation of height values with respect to mean sea level, which allows for the characterization of landforms and the elements or objects present in them.

DSM: The Digital Surface Model represents the elevations above sea level of surfaces, including elements such as trees, buildings, and constructions. It shows the terrain surface along with elevated features on top of it.

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

Right of Way (DDV): It is the strip of land, with a determined width, along the corridor, over which a right of way is held and which serves as a path for all maintenance purposes.

ILI: In-line inspection of a pipeline using an instrumented tool from inside the pipe.

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

IVDDV: Visual inspection of the right of way.

PIPELINE MOVEMENT: It is the displacement of the pipeline measured from two or more ILI inspections, based on parameters of change in strain, elongation, and change in the position of the pipeline according to inertial mapping.

PIPETALLY: It is a tool or software used in the pipeline inspection industry to record, organize, and analyze data related to the physical characteristics of inspected pipelines. Its main function is to keep a detailed record of each pipeline section, including length of each segment, diameter and wall thickness, material and coating type, location of welds, valves, fittings, and other features, and installation conditions and relevant observations. This record is essential for correlating data obtained from in-line inspections (ILI) with the physical location of detected defects or anomalies, facilitating decision-making in maintenance and integrity programs.

PITCH: Angle that indicates a deviation in the vertical direction with respect to the plane that is orthogonal to the tangent vector of the pipeline's center line.

RADIUS OF CURVATURE: They describe the angles of the curve in a pipeline. The smaller the radius of curvature, the greater the bending strain.

STRAIN CAPACITY: Refers to the "strain capacity" of the pipeline and is the maximum strain that a pipeline can withstand without structural failure, that is, without cracking or breaking, when subjected to stresses such as bending, compression, or tension. It is normally measured as a unit strain, expressed as a percentage (%), and indicates how much the material can be stretched or compressed before losing its structural integrity.

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

1. INTRODUCTION

The Colombian geomorphology, dominated by the presence of three Andean Mountain ranges (Western, Central, and Eastern), presents topographic and geological conditions that favor the occurrence of mass movements. Many of these movements are slow or very slow, which makes their early detection difficult and generates an apparent superficial stability. The combination of geotechnical, climatic, and anthropogenic conditions that generates high vulnerability in hydrocarbon transportation infrastructure constitutes a challenge that opens the door to structuring strategies to anticipate these effects. This document seeks to share the experience related to one of the strategies proposed and implemented for this purpose.

Likewise, this strategy makes it possible to anticipate scenarios of threat to the pipeline's integrity through the analysis of projected displacements, identifying attention thresholds from which the induced strain could exceed the normative limits of strain capacity. With this, it facilitates proactive decision-making, based on the continuous monitoring of critical zones using high-precision tools different from ILI such as topographic surveys, georeferenced orthomosaics, and Lidar technology. Based on this evaluation, corrective or preventive maintenance actions are defined, depending on the level of affectation identified, which allows for planning, prioritizing, and optimizing interventions.

2. CURRENT METHODOLOGICAL APPROACH

The current methodology proposes that for each site identified as of interest, reported as a bending strain zone or pipeline movement, it is evaluated by comparing its maximum observed strain with the calculated strain capacity. This evaluation allows for determining the level of criticality of each section and, based on this, defining the most appropriate action plan to mitigate the identified condition (FIGURE 1**¡Error! No se encuentra el origen de la referencia.¡Error! No se encuentra el origen de la referencia.**).

Additionally, as part of the methodology, a linear projection of the maximum strain reported by the provider is carried out, to estimate its future evolution. This projection is defined according to the multi-year monitoring of the maximum strain value reported and is compared with the pipeline's strain capacity, which allows for, in a conservative manner, anticipating scenarios in which the strain could exceed the allowable structural limits. (FIGURE 2 AND FIGURE 3**¡Error! No se encuentra el origen de la referencia.**).

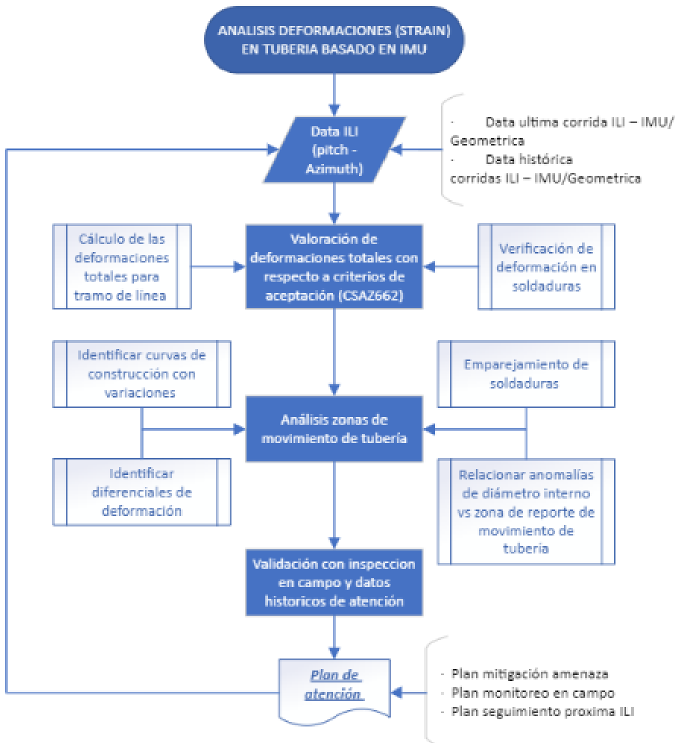


FIGURE 1. STRAIN ANALYSIS PROCESS BASED ON DATA IMU

The projected strain value is obtained from historical monitoring, calculating the differential between successive inspections to determine the rate of increase or strain velocity of the pipeline. This analysis is key to evaluating the progression of the phenomenon and defining timely preventive actions to guarantee the integrity of the transportation system.

$$\dot{\varepsilon}_T = \frac{\Delta\varepsilon_T}{\Delta t} \qquad (1)$$

Donde:

$\Delta\varepsilon_T$ = Difference between total strains between runs in
ΔT = Time between runs in years

$$\varepsilon_T{}^* = \varepsilon_T + \Delta t * \dot{\varepsilon}_T \qquad (2)$$

This projection, which assumes that the current conditions will remain constant, allows for estimating the times in which the allowable structural strain limits (strain capacity) could be exceeded.

However, experience has shown that this practice is not always applicable, since the behavior of the pipeline in response to external loads is not necessarily linear along the entire section evaluated. The structural response of the pipeline depends on multiple factors, such as the relative alignment between the pipeline and the terrain displacement vector, as well as the presence of construction curves, which limits the possibility of generalizing the results obtained.

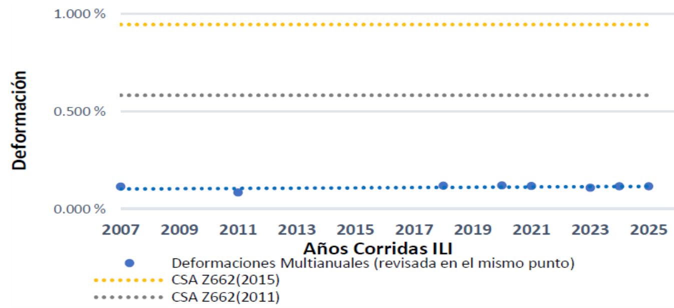


FIGURE 2. SEGUIMIENTO EN DEFORMACIONES

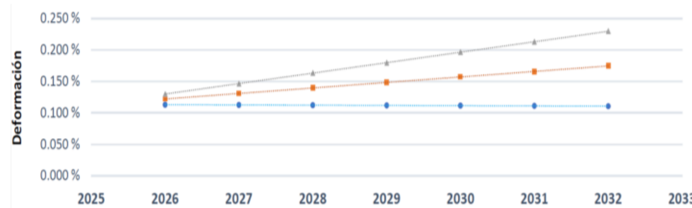


FIGURE 3. PROYECCIÓN DE DEFORMACIONES

In scenarios of loading due to slow or very slow movements, the pipeline may show a linear behavior in terms of displacements; however, this does not guarantee that the strain profile follows the same trend. For this reason, this document proposes a complementary methodology that allows for estimating a projected strain profile, based on the pipeline's displacement rate.

3. FUNDAMENTALS OF THE STRATEGY

The proposed strategy combines multi-year displacement analysis with Strain Capacity evaluation, incorporating the following key elements aimed at the early identification of critical conditions:

- Identification of sectors with slow displacements through ILI inspections, topographic surveys, and visual observations.
- Comparative analysis between inspections to determine accumulated displacements and movement rates.
- Projection of the future behavior of the pipeline.
- Evaluation of current and projected structural strain against the normative strain capacity.

The general methodology for applying this strategy is outlined in the following figure and explained in detail below.

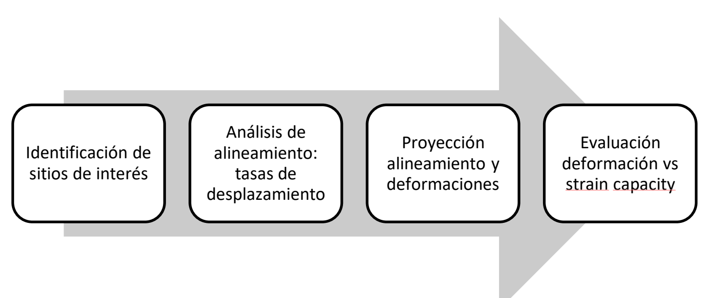


FIGURE 4. GENERAL PROCESS FOR STRAIN ANALYSIS AND ALIGNMENT CHANGES

3.1 Sites of interest identification

The identification and delimitation of sectors that present pipeline movements detected by ILI runs or visual inspections of the right of way constitute a key component to understanding the behavior of the soil-pipeline system. This analysis is applied exclusively to sectors that have presented ground movements classified as slow or very slow. In areas with higher velocity rates, this strategy is not suitable due to the uncertainty associated with the geometric response of the pipeline to accelerated loads. These types of movements are particularly critical due to their imperceptible nature, which makes preventive maintenance planning difficult. Additionally, the approach should not be applied in sectors that present visible cracks, scarps, or significant ground displacements, as these require immediate interventions and the application of different evaluation methodologies.

Clase	Descripción	Desplazamiento	Poder Destructor
7	Extremadamente rápida	5 m/seg.	Catástrofe de violencia mayor; edificios destruidos por el impacto o el material desplazado, muchas muertes, escape improbable.
6	Muy rápida	3 m/ min.	Alguna pérdida de vidas; velocidad demasiado alta para permitir a todas las personas escapar.
5	Rápida	1.8 m/hora	Escape posible; estructuras, propiedades y equipos destruidos.
4	Moderada	1.3 m/mes	Algunas estructuras temporales y poco sensitivas pueden mantenerse temporalmente.
3	Lenta	1.6 m/año	Construcciones remediales se pueden realizar durante el movimiento. Algunas estructuras insensitivas pueden mantenerse con mantenimiento frecuente.
2	Muy lenta	16 mm/año	Algunas estructuras permanentes no son dañadas por el movimiento.
1	Extremadamente lenta		Movimientos imperceptibles sin instrumentos; posible construcción, pero teniendo ciertas precauciones.

TABLE 1. Velocity of Movements (Adapted from Cruden, Varnes-1996).
Source: Montero Olarte, J. (2017). Clasificación de movimientos en masa y su distribución en terrenos geológicos de Colombia. Servicio Geológico Colombiano. https://doi.org/10.32685/9789585978218[1](https://libros.sgc.gov.co/index.php/editorial/catalog/book/36).

The analysis starts from the validation of historical information from at least two ILI runs or, failing that, from high-precision topographic surveys. This data allows us to compare the pipeline trajectories at different times and calculating accumulated displacement rates. From this comparison, the critical movement rate is determined, that is, the one that represents the greatest displacement or that reflects the most representative behavior of the terrain. This systematic stage of selecting sites of interest is based on the following premises:

- The sector must be within the normative bending limits established for the pipeline, according to the normative limit criteria for compression and tension (CSA-Z662).
- There must be evidence of pipeline movement, reported by ILI inspections or topographic monitoring.
- The terrain must present slow or very slow movements, without superficial manifestations of instability.

The list is built from:

- ILI provider reports (Bending Strain and Pipeline Movement).
- Observations from visual inspection of the right of way (IVDDV).
- History of areas with documented displacements due to instability processes.

3.2 Alignment Analysis

The geospatial analysis of the pipeline's alignment is developed specifically for each case, given the diversity of variables, behaviors, and environmental conditions that must be evaluated in detail. This process requires considering the possible sources of error inherent in the tools used (such as ILI inspections, topographic surveys, and remote sensors) whose precisions can significantly influence the quality of the results.

It also facilitates comparison with topographic surveys and periodic monitoring, which is decisive for identifying movement patterns.

For this, it is essential to implement a rigorous process of data management and matching, which establishes a common basis between the different techniques used. The identification of movements between two trajectories is carried out by aligning the base run with the current run, matching weld by weld, and defining start and end points as references without displacement (anchors).

This correction allows for detecting deviations from the general displacement trend. This procedure facilitates the identification of accumulated displacements and the calculation of pipeline movement rates over time, allowing for an understanding of the multi-year behavior of the soil-pipeline system.

From this evaluation, the movement rates recorded in different periods are determined and the most representative one is selected, generally the highest, as it is considered the most critical for the structural and integrity analysis. With this information, analytical exercises are developed that allow for visualizing displacements based on their direction and magnitude, with the objective of identifying the trend and orientation of the pipeline's movement in the areas evaluated.

3.3 Alignment Projection According to Displacemente Rates

Based on the previously defined displacement rate, a displacement field is constructed, understood as the unitary differential of the movement that the pipeline has experienced over time. This field forms the basis for a prospective analysis of the pipeline's behavior, which consists of projecting its future alignment under different scenarios (time).

From this model, the expected displacements are estimated in annual intervals, which is fundamental for planning monitoring, maintenance, and mitigation activities aimed at preserving the integrity of the system.

The process consists of applying the estimated displacement rates to the original route, generating projected trajectories that reflect the expected evolution in response to external loads on the soil-pipeline system. Each annual scenario incorporates variations in the magnitude of displacements, which allows for evaluating the potential impact of different load levels or geotechnical conditions.

This projection facilitates the anticipation of critical zones, the optimization of monitoring strategies, and the definition of preventive actions. Finally, the comparative analysis between the projected alignments and the current route allows for identifying sections where accumulated displacement could compromise the structural integrity of the pipeline or generate interference with the environment, thus strengthening decision-making based on technical evidence.

3.4 Prospective Strain Analysis

Traditional analyses that estimate the trend of pipeline movement provide a view of the pipeline's displacement over time ; however, by itself, it does not allow for precisely dimensioning the criticality of said displacements.

For this reason, it is necessary to correlate the cumulative displacements with the allowable strain capacity of the pipeline (Strain Capacity). This correlation allows for evaluating the severity of the movements based on the structural strain, which makes it possible to establish displacement thresholds that act as early warnings, which can be monitored through direct and indirect measurements in the field.

From the new projected alignments of the pipeline under different annual scenarios, it is possible to determine the bending strain, which is derived directly from the previously determined displacements. Based on these displacements, the spatial coordinates corresponding to each projection scenario are calculated, which provides the inclination (pitch, P) and azimuth (A) angles through the integration of Euler, a reliable method that estimates the relative position of a point “k+1” of the pipeline profile, from the angles recorded at the adjacent point “k” and the measured distance. This technique is fundamental for accurately modeling the three-dimensional geometry of the pipeline and evaluating its structural behavior in response to accumulated displacement scenarios.

The formulas used are:

$$\Delta N = \Delta S * \cos\theta * \cos\gamma \quad (3)$$

$$\Delta H = \Delta S * \sin\theta \quad (4)$$

$$\Delta E = \Delta S * \cos\theta * \sin\gamma \quad (5)$$

Donde:

- ΔN, ΔH, ΔE: increments in the North, Elevation, and East coordinates, respectively.
- ΔS: distance increment along the pipeline.
- θ: inclination angle (pitch).
- γ: azimuth angle.

3.4.1 Curvature and Strain Calculation

The bending strain is determined from the radii of curvature, which are calculated considering the inclination (pitch, P) and azimuth (azimuth, A) angles, as illustrated in FIGURE 5.

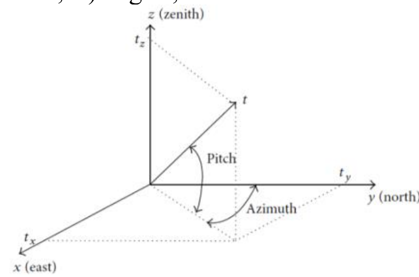


FIGURE 5. Pitch and azimuth

The total curvature k is calculated using the following expression:

$$k = \sqrt{{k_v}^2 + {k_h}^2} \quad (6)$$

This curvature value allows for estimating the bending strain, assuming that the neutral axis is in the center of the pipeline. This methodology is fundamental for evaluating the structural response of the pipeline to external loads and cumulative displacements.

Under this assumption, the bending strain ε is calculated as:

$$\varepsilon = \frac{D}{2} \cdot k \quad (7)$$

Where D is the outside diameter of the pipeline and k is the total curvature obtained. This relationship allows for quantifying the structural strain induced by bending, facilitating the evaluation of pipeline integrity against cumulative stresses.

3.4.2 Multi-year Analysis and Critically Evaluation

Once the horizontal, vertical, and total strains have been calculated, the current and projected profiles are graphed (according to the established displacement scenarios). This analysis allows for evaluating the evolution of the projected multi-year strain profile and identifying stress concentrators (in compression or tension), and detecting vulnerable critical zones such as construction curves or welds, and identifying zones where failures due to diameter distortion or localized buckling could occur.

Based on this analysis, critical displacement thresholds can be established that correspond to the allowable strain capacity of the pipeline. These thresholds allow for the implementation of early warning systems and the definition of monitoring and mitigation strategies.

3.5 Integration of Analysis

From the analyses carried out, it can be established that the two projection approaches (linear and displacement field) allow for estimating and projecting future strains in hydrocarbon transportation systems according to specific conditions for each case, with the displacement field projection being recommended for sectors where movements with very low to low movement rates occur.

The integral analysis of projected strains with displacement fields provides an objective, substantiated, and technically supported view to proactively address latent threats, especially those associated with ground movements with low or very low displacement rates. These movements, being imperceptible to the naked eye, represent a significant challenge for proactive maintenance planning.

This scenario demands innovative approaches that ensure the structural integrity of the pipelines and allow for the implementation of effective preventive maintenance. A key strategy is to define safe displacement thresholds, correlated with the allowable bending strain capacity of the pipeline (Strain Capacity), which allows for activating early warning mechanisms and prioritizing interventions in the field.

4. RESULTS AND DISCUSSION

In order to delve into the process of defining early warnings for the integrity of pipelines exposed to slow geotechnical movements, an approach based on displacement analysis and Strain Capacity criteria is presented. This approach allows for an anticipatory evaluation of the severity of ground movements and their impact on the infrastructure, facilitating proactive decision-making.

In this context, two (2) case studies are presented that illustrate real-world scenarios of pipeline movement in areas without evidence or findings of ground movements according to the visual inspection of the right of way. These cases are based on the analysis of data obtained through multi-year inertial mapping and surface monitoring, which allows for identifying cumulative displacements, movement rates, and their correlation with the allowable strain capacity of the pipeline.

4.1 Case 1

An area of interest has been identified according to the ILI monitoring. This area meets the premises set out in the methodology by being within the normative (defined) bending limits for the pipeline, with the presence of movement (according to the ILI report) and the terrain is determined to have the possible existence of a slow to very slow movement.

According to the report from the last ILI run, a pipeline displacement is recorded with a predominantly horizontal movement of approximately 41 cm between.

FIGURE 6 presents the strain profile corresponding to the case analyzed. This shows the alignment changes, mainly horizontal, that affect a section of 11 pipes (132 m), with a maximum displacement of 41 cm between the initial and final inspection. An increase in strain of 0.065% in the pipe body and 0.05% in the weld is highlighted, going from 0.20% in the previous run to 0.25%

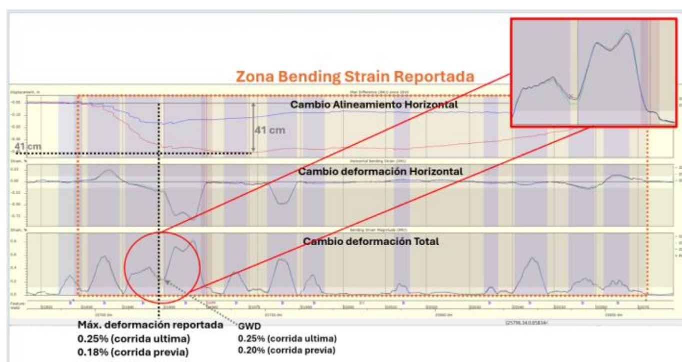


FIGURE 6. Perfil de deformaciones caso 1

4.1.1 Alignment Analysis and Displacement Projection – Case 1

Following the proposed methodology, a comparative alignment analysis of the different ILI runs is carried out, in order to determine the displacement rate (displacement fields).

FIGURE 7 shows the variation in horizontal alignment according to the 2019, 2023, and 2025 runs, where a greater displacement is evident between the 2023 and 2025 runs, reaching a maximum value of 30 cm. This period presents the greatest activity, so it is established as the basis for the generation of the displacement field.

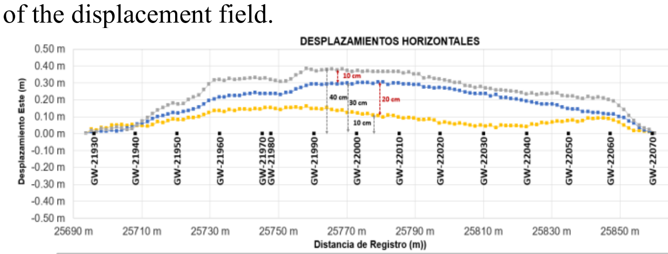


FIGURE 7. Cambio alineamiento horizontal en el tiempo caso

The generated displacement field allows for projecting the possible future displacements of the pipeline, annually over the next 4 years (2026 to 2029). The four scenarios are detailed below:

- Scenario 1 - 2026: with a displacement of 0.44 m
- Scenario 2 - 2027: with a displacement of 0.59 m
- Scenario 3 - 2028: with a displacement of 0.74 m
- Scenario 4 - 2029: with a displacement of 0.79 m

Subsequently, the strain is calculated for each of the projected scenarios. The results are represented in the strain profile shown in FIGURE 8, where the different strain profiles are observed according to the four proposed scenarios.

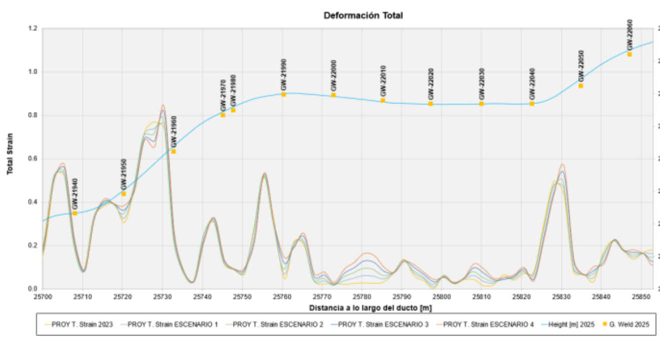


FIGURE 8. Variación de Deformación Total caso 1

This analysis allowed for establishing safe displacement limits, correlated with the allowable bending strain capacity of the pipeline (Strain Capacity). From this correlation, early warning thresholds were defined, which can be monitored using direct (topography, geodesy) and indirect (ILI runs, geotechnical sensors) techniques, allowing for the implementation of a continuous surveillance system.

Based on these results, the following actions are recommended:

- Periodic semi-annual topographic monitoring of the pipeline, accompanied by alignment analysis, with the objective of verifying the evolution of displacements.
- In the event that these exceed 59 cm, the sector should be intervened with corrective actions.
- Instrumented geotechnical monitoring of the terrain on a quarterly basis, through the installation of inclinometers, piezometers, or other sensors that allow for the detection of underground movements and changes in soil conditions.
- Continuous monitoring for at least 2 years, in order to validate the validity of the projected displacement field and confirm that the movements remain within the controlled ranges.

These measures will allow for proactive risk management, ensuring the integrity of the infrastructure and facilitating the planning of maintenance strategies based on the actual behavior of the system.

The proposed methodology has proven to be successful, as it is based on a preventive approach that allows for anticipating possible risks or problems. As part of the process, a second publication is planned in which the results obtained in the field work will be presented, with the objective of complementing and validating the initial findings.

4.2 Case 2

As a result of the analysis of ILI runs and the visual inspection of the right of way, an area of interest has been identified, which meets the premises set out in the methodology by being within the normative (defined) bending limits for the pipeline, with the presence of movement (according to the ILI report) and, due to the evolution of the strain and pipeline movement, the existence of a slow to very slow movement is inferred. Proactive drainage improvement works have been carried out in the sector, with the objective of mitigating possible effects associated with water accumulation and soil saturation.

According to the last ILI run report, although a decrease in the displacement rate was evidenced, the strain continues to increase. In the base run, a strain of 0.189% was recorded, which increased by 0.123%, reaching a value of 0.312% in the most recent run. The cumulative pipeline displacement between the base run and the last one was 36.5 cm, while between the previous run and the last one, a displacement of 19.6 cm was recorded.

FIGURE 9 presents the strain profile. Alignment changes with combined horizontal and vertical orientation are observed, affecting a section of 7 pipes (84 m), with a maximum displacement of 36.5 cm. A strain increase of 0.125% is highlighted.

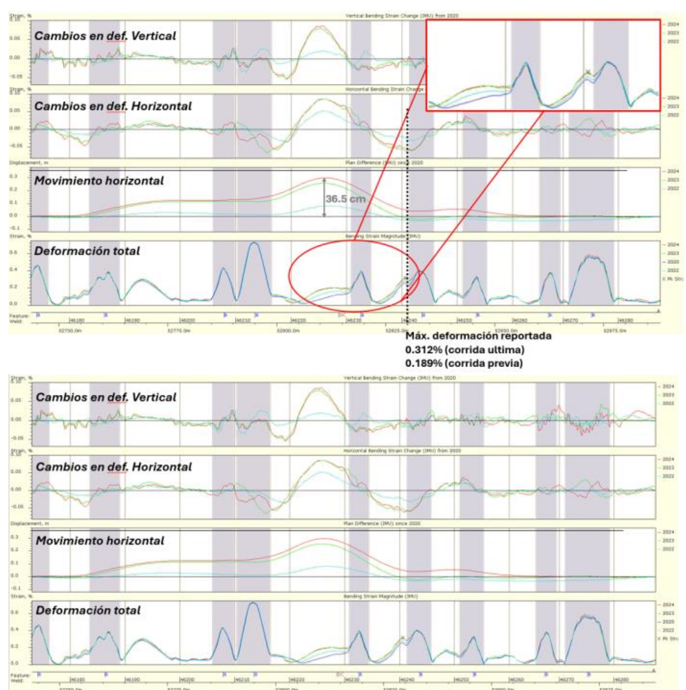


FIGURE 9. Case 2 – Strain Profile

4.2.1 Alignment Analysis and Displacement Projection – Case 2

A comparative alignment analysis was performed between historical ILI runs to confirm pipeline movement and evaluate its temporal evolution. FIGURE 10 and FIGURE 11**,** show the variation in horizontal and vertical alignment, where a gradual increase in displacements is evidenced, reaching maximum values of 26 cm (horizontal) and 24.0 cm (vertical)

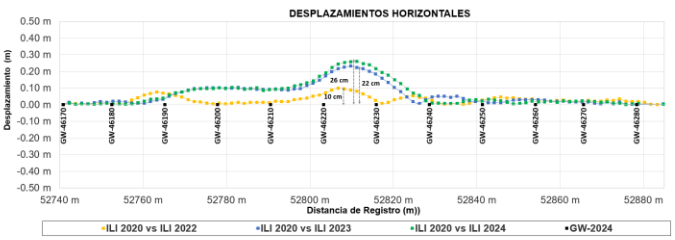


FIGURE 10. Horizontal alignment change – Case 2

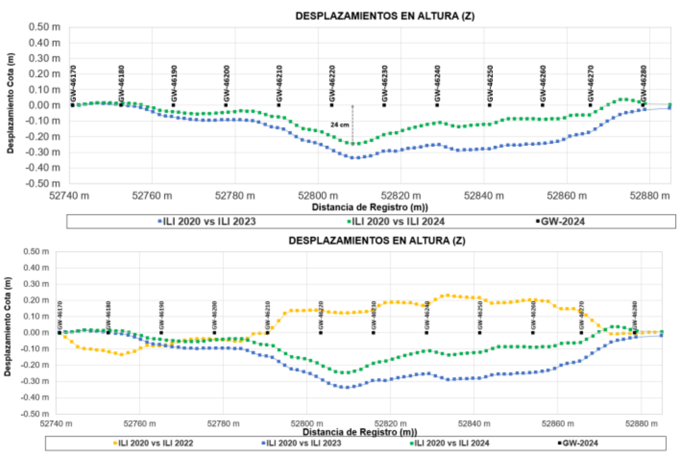


FIGURE 11. Vertical alignment change – Case 2

This behavior indicates a greater recent activity, so these runs were used as the basis for the generation of the displacement field, which allows for projecting future displacements under an annual progression. Four projection scenarios were defined based on the 2023-2024 run, detailed as follows:

- Scenario 1-2025: 0.36 m – current condition, last run
- Scenario 2-2026: 0.52 m
- Scenario 3-2027: 0.70 m
- Scenario 4-2028: 0.87

FIGURE 12 presents the projected strain profile, where the evolution of the total strain induced by annual displacements is observed.

The analysis of the strain profile corroborates a progressive increase in strain as displacements increase.

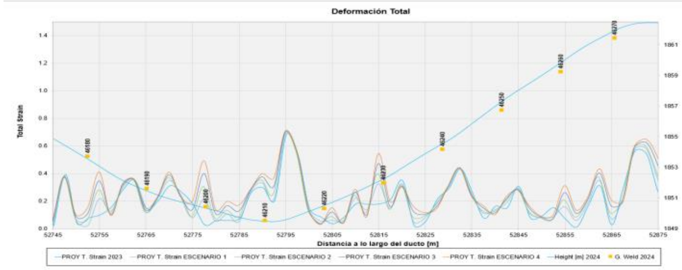


FIGURE 12. Variación de Deformación Total caso 2

Scenario 1-2024 represents the current condition, while Scenario 2-2025 with a movement of 52 cm is identified as an attention threshold, where it is guaranteed that the pipeline is still mainly within the elastic range and that, at the time of executing mitigation activities by releasing stresses, the pipeline can "return" or "rebound" to its original design position or as close to it as possible. For the case of Scenario 3-2026 with a pipeline movement of 70 cm, strain values are already present that could require short-term or immediate actions because the calculated strain values are close to the defined threshold (strain capacity).
This analysis allowed for establishing safe displacement limits, correlated with the allowable bending strain capacity (Strain Capacity). From this correlation, early warning thresholds were defined, which can be monitored using direct (topography, geodesy) and indirect (ILI runs, geotechnical sensors) techniques.
The following actions are recommended:

- Periodic semi-annual topographic monitoring of the pipeline and alignment analysis.
- If displacements exceed 52 cm, it is recommended to intervene in the sector.
- Instrumented geotechnical monitoring of the terrain on a quarterly basis using inclinometers, piezometers, or other sensors.
- Continuous monitoring for at least 1 year, to validate the validity of the projected displacement field and confirm that the movements remain controlled.

These measures will allow for proactive risk management, ensuring the integrity of the infrastructure and facilitating the planning of maintenance strategies based on the actual behavior of the system. The proposed methodology has proven to be successful, as it is based on a preventive approach that allows for anticipating possible risks or problems. As part of the process, a second publication is planned in which the results obtained in the field work will be presented, with the objective of complementing and validating the initial findings.

5. CONCLUSION

The proposed methodology is based on the understanding of the evolution and change in alignment of previous and current ILI/IMU information, allowing for determining a state of displacement and/or an increase in strains in pipeline sections where the predominant external load is of an imperceptible nature on the terrain. The normative limit strain criteria are complemented by taking the state of stresses and the strain based on Strain Capacity as a basis, with which the prospective analysis method becomes a tool that facilitates the understanding of low-rate displacement movement processes and serves as a decision-making parameter for the planning of predictive monitoring and maintenance activities.

ACKNOWLEDGMENTS

To the integrity assurance leadership (Jefatura de aseguramiento de integridad) of Cenit Transporte y Logística de Hidrocarburos, for allowing the case studies and the base information of the analysis in the case studies to be shared.

To the Technical management of Penspen for the support in the structuring of the analysis methodology and its constant systematization.

REFERENCES

- **ASME B31.4.** American Society of Mechanical Engineers. (2022). *ASME B31.4: Pipeline transportation systems for liquids and slurries* (2022 ed., ISBN: 9780791875377). ASME. https://www.asme.org/codes-standards/find-codes-standards/b31-4-pipeline-transportation-systems-liquids-slurries[1](https://www.asme.org/codes-standards/find-codes-standards/b31-4-pipeline-transportation-systems-liquids-slurries)
- **CSA Z662/2015**. CSA Group. (2015). CAN/CSA-Z662-15: Oil and gas pipeline systems (868 pp.). CSA Group. https://www.csagroup.org/store/product/2021420/[2](https://www.csagroup.org/store/product/2021420/)
- **CSA Z662/2011.** Canadian Standards Association. (2011). CAN/CSA-Z662-11: Oil and gas pipeline systems. Standards Council of Canada. https://scc-ccn.ca/standardsdb/standards/4026057[3](https://scc-ccn.ca/standardsdb/standards/4026057)
- **CSA Z662/2011.** Canadian Standards Association. (2011). CAN/CSA-Z662-11: Oil and gas pipeline systems. Standards Council of Canada. https://scc-ccn.ca/standardsdb/standards/4026057[3](https://scc-ccn.ca/standardsdb/standards/4026057)
- Norma DOT (Reglamento Técnico para el Transporte de Hidrocarburos por Cañerías). Secretaría de Energía de la Nación Argentina. (s.f.). Reglamento Técnico para el Transporte de Hidrocarburos Líquidos por Cañerías (RTHL). Subsecretaría de Combustibles. https://oilproduction.net/files/ResumenReglamentoTecnicoTransporteHidrocarburos.pdf[3](https://oilproduction.net/files/ResumenReglamentoTecnicoTransporteHidrocarburos.pdf)
- **API 579-1 / ASME FFS-1: Fitness-For-Service.** American Petroleum Institute & American Society of Mechanical Engineers. (2016). *API 579-1 / ASME FFS-1: Fitness-For-Service* (3rd ed.). API & ASME. https://standards.globalspec.com/std/10039859/api-579-1[1](https://standards.globalspec.com/std/10039859/api-579-1)