Complementary ILI data-driven Analysis to Identify the Interaction of Pipe Geohazards in Colombia's specific Geomorphological Conditions

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Abstract

Nowadays the use of inertial measurement unit (IMU) derived bending strain data to identify and assess pipeline movement events due to geohazards has become a standard process. Service providers and operators should also be aware of the limitations of this process and the complementary analysis that is required or necessary to provide a complete picture of the threat. Understanding the results of the IMU bending strain analysis (pipeline movement included) and going further to obtain a deep knowledge between what is shown in the graphical information and what is occurring in the pipe-soil interaction makes a real difference. For this reason, the interaction between pipeline operator and In Line Inspection (ILI) service provider is a crucial part of effective geohazards management.

In this paper, two case studies will be presented where the complexity of geomorphological conditions interacting with the pipeline dictates that more comprehensive investigation and assessment methods are necessary to ensure effective understanding of the pipeline condition and the impact of geohazards. Oil transportation through a mountainous region is a challenge, even more so if there are areas with known active landslides, extreme weather conditions and earthquakes. The use of special construction and mitigation techniques, like casings, supports or even concrete structures could lead to a more complicated scenario compared with a pipe-soil interaction only.

The first case study describes a section of a pipeline under a special type of casing built to mitigate pipe-soil interaction in an area with known landslide occurrences and monitored by the operator to identify and measure ground movement. Thanks to an expert assessment and additional interpretation of the strain plots combined with the use of high-resolution reporting thresholds, the extension of the displaced area was accurately correlated and measured. This specific case led to an improvement in the analysis process.

The second case study involves a pipeline running through the toe of a hill with no report of geotechnical activity (taking other inspection techniques into consideration) or need for any mechanical remediation. However, two wrinkle-type anomalies were reported by the ILI geometry analysis. After a detailed review of the tool angle variation from previous inspections, the nature of these anomalies was compared to the kinematics of ground movement, and the wrinkle-type anomalies were verified, with an axial load component, in subsequent on-site inspections.

Introduction

Bending strain analysis based on IMU data has proved to be an effective tool to identify and monitor geohazards affecting a pipeline. Data from IMUs provide the x, y, and z position of the pipeline over time and can be used to calculate pipe curvature and from that, bending strain [1]. The integration of this data with geotechnical information results in a solid framework for the assessment of these threats. On one side, geotechnical input, such as high-resolution topographic data or known landslides

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activity, would trigger the evaluation of an area of interest. On the other side, signals from bending strain data are used to identify and determine extension and magnitude of the acting forces in the pipeline. This geotechnical IMU bending strain review process involves the inertial data signatures evaluation with an understanding of geohazard mechanisms [2].

This paper seeks to share situations where due to the complexity of the topography and the loading mechanisms involved, an accurate analysis of what the real pipeline condition is could be a challenge. In Colombia, hydrocarbon transport systems run on paths that have high susceptibility to ground movements [3]. This unique scenario leads to a wide variety of pipeline deformation events that require a more comprehensive analysis approach. Typical contents of bending strain reports include multi panel plots with the pipe position, orientation, and strain values of a reported area. The evaluation of this data is not always a straightforward process and relies on the experience of the person in charge of this task. To make the most of IMU bending strain assessments the use of multiple data in a strain change or pipe movement analysis are recommended and will enable the understanding of an active ground movement area or to monitor the results of a mitigation done in field. The change in curvature in a pipeline represents a change of shape that could be attributed to a geohazard threat.

As described in this paper there are instances where strain change presence is not enough information to identify an affected area. Additional review of the position difference plots, like Plan or Profile change will complement the study of some pipeline special conditions. This will also be complemented with field validation by geotechnical specialists. In other cases, reported strain change events will become an actionable item in terms of the strain response criteria of an operator if the information is evaluated with the latest geometry ILI data as wrinkle-type anomalies were identified. The generation of load hypotheses and comparison of the deformation profiles allowed the determination of different areas of the pipeline being affected by the loading.

Methodology

This section includes the methods used for the evaluation of the case studies presented later in this paper.

IMU Bending Strain, Strain Change and Pipeline Movement Assessments.

Inertial measurement units (IMU) are most frequently coupled to an in-line inspection (ILI) tool. This enables the calculation of the pipeline trajectory and location. Additionally, this data can be used to calculate curvature along the pipeline and estimate bending strain, strain change and pipe movement (deformation and position differences identified between 2 or more ILI inspections).

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While single run bending strain analysis is a useful tool to indicate if the pipeline has been affected by an external loading, strain change (or strain comparison) assessments facilitate the understanding of the activity of a ground movement between the timing of the ILI runs by measuring the difference in curvature of the pipeline. Within the strain comparison study, it is also possible to determine the pipeline movement. This is the displacement between the inspection trajectory within a specific area, usually triggered by a change in the curvature.

It is important to consider the strain reporting thresholds that are used as a criterion to report bending strain and strain change features. Most typical and recommended values are 0.125% for single bending strain extending more than one circumferential weld of a pipe segment and 0.04% for bending strain change threshold.

During the strain data analysis, bending strain plots are screened to spot signals above the already mentioned thresholds and classify events accordingly (i.e. field bend, deformation, data spike, etc.). In addition to these strain plots, that include the horizontal, vertical and total bending strain, other panels are used. Vertical and horizontal out-of-straightness (OOS) profiles depict the distance between the pipeline centerline and a straight line connecting the start and end of the area of interest. Pitch and heading (or azimuth) represent the tool angle change in the vertical and horizontal plane respectively. Another useful plot includes signals of the IMU gyroscopes, these profiles have a defined signature and are helpful for field bend identification. While bending strain signals can be used to recognize changes in the curvature of the pipeline, when performing a comparison of two or more runs, strain change plots are used to have a direct visualization of those values. Change plots could also include heading, pitch, plan and profile differences. Examples of these plots are shown in Figure 1 and 2 below.

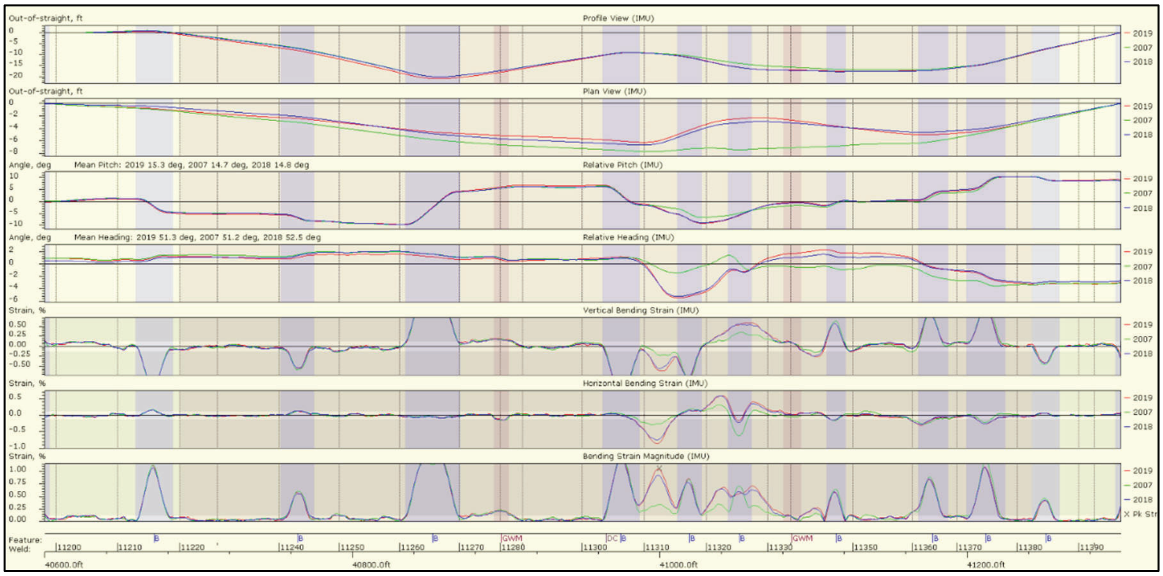

Figure 1. Bending strain plots multiple panels. (Source: Baker Hughes)

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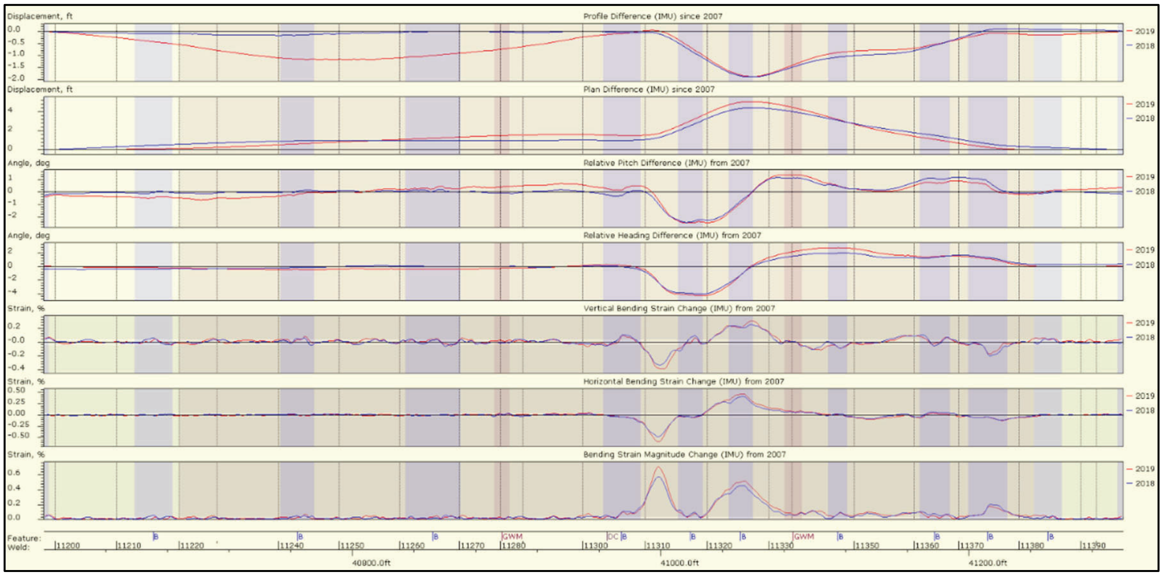

Figure 2. Bending strain difference plots multiple panels. (Source: Baker Hughes)

This analysis is typically performed at 100m (~300ft) screen window, but it is also recommended to extend this window for potential large landslides that exceed this length. As shown in the following case studies, understanding of the extension of a deformation would be critical to determine a mitigation plan.

Axial Strain Assessment

ILI tools are also used to measure axial strain acting in a pipeline based on the magnetostriction effect in ferromagnetic materials. This principle allows us to identify the axial strain component within a geohazard event, not detected during bending strain analysis [4].

Understanding the axial mechanism affecting a pipeline (compression/tension) enables the prediction of stress concentrations that could tend to pipe diameter distortion restrictions or in the worst-case scenario to buckling.

It should be noted that there are three main components of strain that combined provide the total state of strain in the wall of the pipe section under external loading. These are bending strain, axial strain, and hoop strain.

ILI Geometry Analysis

ILI tools normally combine the IMU information with the highest resolution mechanical caliper system available (CAL). Those mechanical calipers (arms) are mounted in the middle of the carrier, and they scan the pipe wall inner surface generating a full picture of the internal shape of the pipeline,

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of which a comprehensive set of geometrical data for assessment of the pipeline integrity in a variety of applications is recorded.

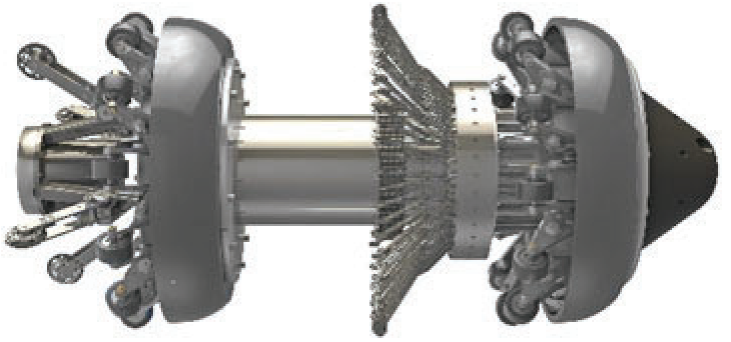

Figure 3. Large-diameter single-body caliper ILI tool. (Source: Baker Hughes)

The geometrical data can provide not only a detailed 3-D image (Figure 4) and multiple sectional views but also can be used for fitness for purpose and detailed finite element analysis. Data collected from multiple geometry tool runs can also be used to perform deformation (e.g., wrinkles and dents) growth monitoring due to ground or pipeline movement.

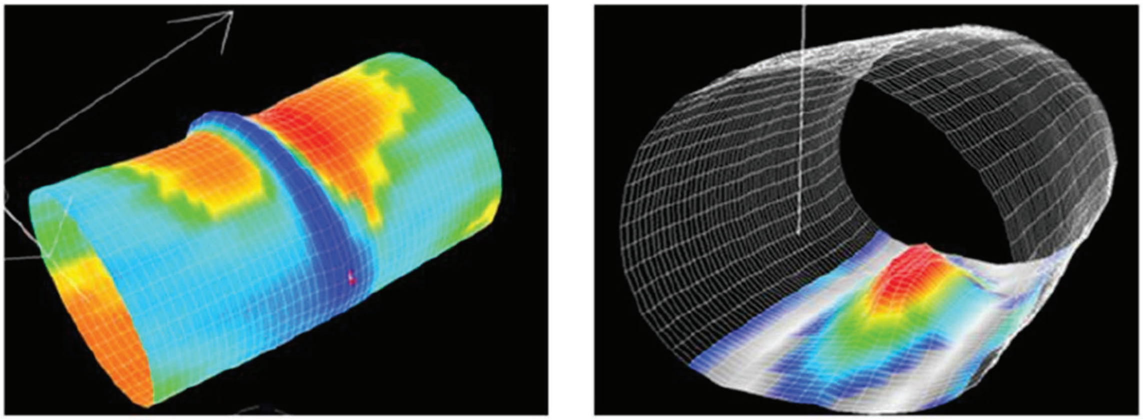

Figure 4. 3-D view representation. (Source: Baker Hughes)

By a direct measurement of the pipe internal diameter and shape of the pipe cross-section, the analysis procedure includes, not limited, both detection and sizing of pipe wall anomalies defined as dents, ovalities and wrinkles. This data is also used to identify any pipe bore restrictions that could impede a subsequent inspection of other tools, e.g., metal loss inspection tools.

The anomaly identification process involves a joint-by-joint assessment by capturing the start/end of the caliper arm deflections, and classifying the feature according to the anomaly morphology described as follows:

Dent: a very localized deformation that occurs because of some outward force being applied in a concentrated location on that pipeline. The outward force may be due to third party intervention (like an excavator) or due to the pipe settling on rocks or due to the rocks pressing up against the pipeline

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in an area of earth upheaval. Also, it might be a depression caused by mechanical damage that produces a visible disturbance in the pipe wall's curvature without reducing pipe wall thickness.

Ovality: condition where the pipeline is 'out of roundness'. Ovality designates how close to a perfect circle a pipeline tube is at the point being measured. It could also be said that an ovality is the degree of no circularity or deviation from perfect circularity of the cross section of the pipeline tube. This smooth deformation produces a compressed and expanded area on either edge of the pipe diameter (3:00 and 9:00 o'clock or 6:00 and 12:00 o'clock) and often occurs on bends. These anomalies look like dents but have signals that seem to slowly start and end with no discernible peaks as dents exhibit.

Wrinkles: which can be classified as inward or outward. The outward wrinkles are characterized by sudden increase of pipe diameter, typically over 5cm (about 1.97 in) –15cm (about 5.91 in) and develop when the pipe is under internal pressure. The inward wrinkles have a more convoluted shape (diamond shape deformations) and are created under low internal pressure, sometimes during construction.

The condition triggering the development of a wrinkle is the axial compression force (due to internal pressure or elevated product temperature) combined with the increased compression on one's side of the pipe caused by pipe bending. The bending can be caused be many reasons including landslides, riverbed erosion, settlement of the pipe due to permafrost thaw or oil/gas field subsidence, or during the construction, e.g., tying in two misaligned sections of the pipeline, or uneven trenching for offshore pipelines which can result in upheaval buckling.

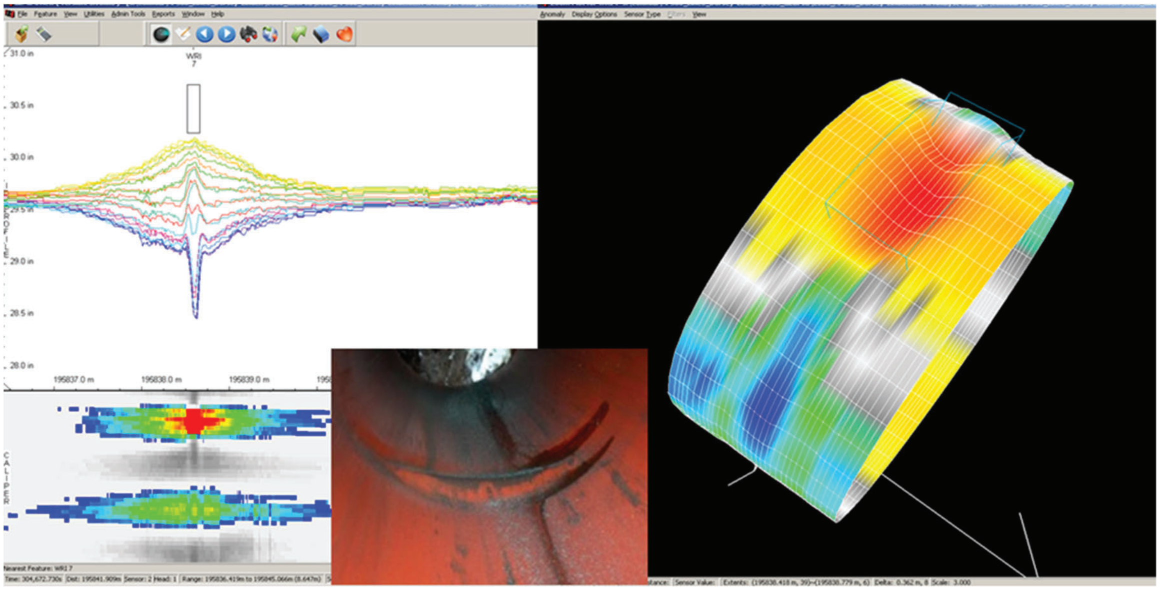

Figure 5. Inward wrinkle profile (Source: Baker Hughes).

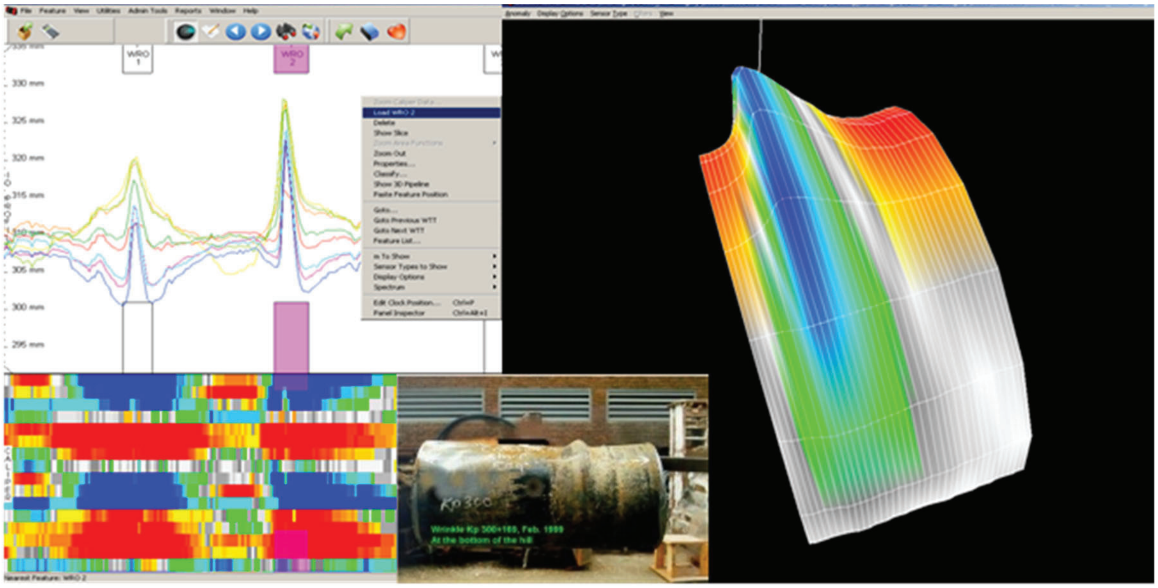

Figure 6. Outward wrinkle profile. (Source: Baker Hughes)

Evolution monitoring through geographical analysis

This capture and analysis of information considering pipeline alignment from several surveys is a process that is built specific to each exercise. There are also different variables, behaviours and nuances that must be reviewed in detail including environmental conditions and inherent errors of the tools (ILI, surveying, remote sensing, etc.)

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

From the above, different methods are developed that allow to visualize displacements according to their direction and magnitude. This is done with the aim of being able to identify the tendency of the movement and its relationship with the vector of an eventual instability process, regarding kinematic possibility by considering its direction and influence to develop additional movements.

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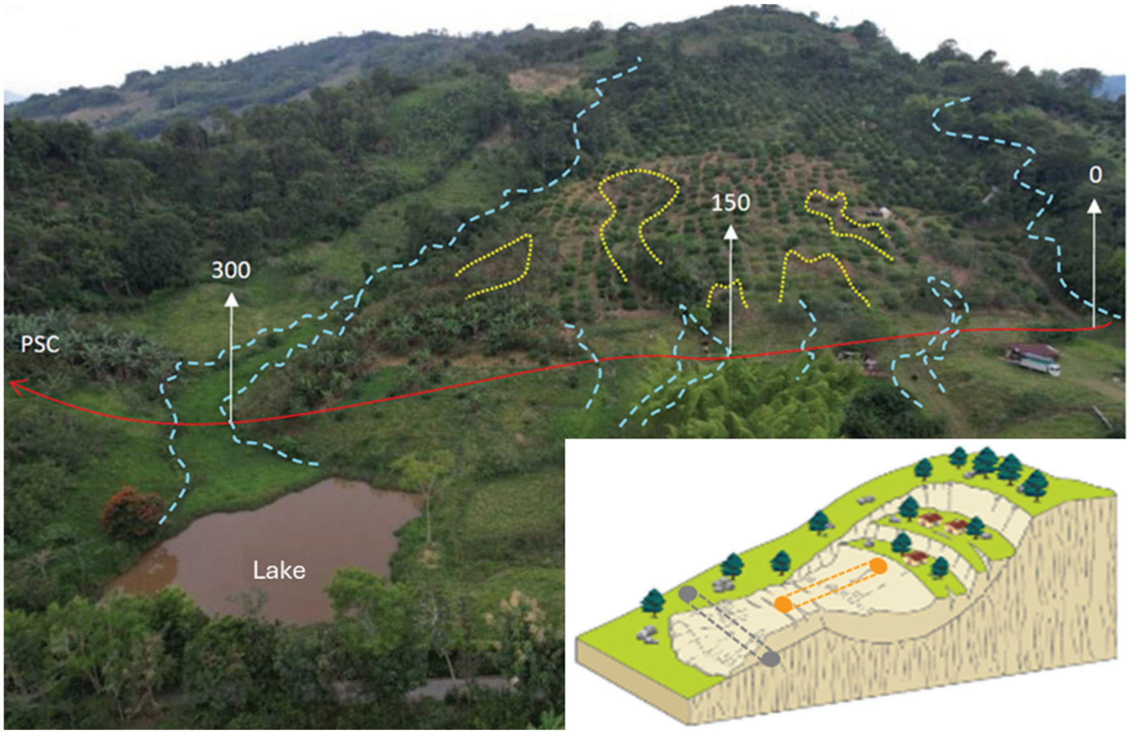

Figure 7. Geographical analysis using pipeline location, topography, orthophotography and visual inspection. (Source: CENIT)

Case Study 1

Pipeline displacement

This 18-inch diameter pipeline runs through the Colombian mountain chain transporting crude oil for around 60 miles. It was inspected with an ILI geometry and IMU tool in 2019, 2022 and 2023. The area of study corresponds to a monitored active ground movement. The pipeline runs within a corrugated steel pipe (acting as a casing) through a section of ~500m (1640ft) to reduce the impact of any external loading. This casing was installed in 2016 and is bolted at 1.2m sections with an outside diameter of 42 inches. This mitigation measure needed to be verified so the results of the ILI were critical for this purpose.

Bending strain comparison assessment between runs from December 2019 and May 2022 showed no variation in the signals for this area. Additionally, strain values were below the reporting threshold considered for this study (0.125%), apart from field bends.

Once 2023 IMU strain data was processed and aligned with previous information, the area was further reviewed. At first glance, bending strain change signals of this section did not show evidence of movement. After reviewing in more detail, with a focus on the difference plots, it was noticed that a displacement was occurring.

In this case, during the analysis stage a minimum strain change was visible coincidentally with a field bend. This bend has an under (sag) direction while the strain change can be seen mostly in the horizontal plane. The change is only visible between 2023 and previous data and is above the reporting threshold at ~0.05%. This type of scenario requires extra expertise from the analyst as the change could be masked by the presence of the bend (Figure 8). It is also common to get a response from the opposite direction of field bends in the strain signals that could lead to different assumptions during signal interpretation.

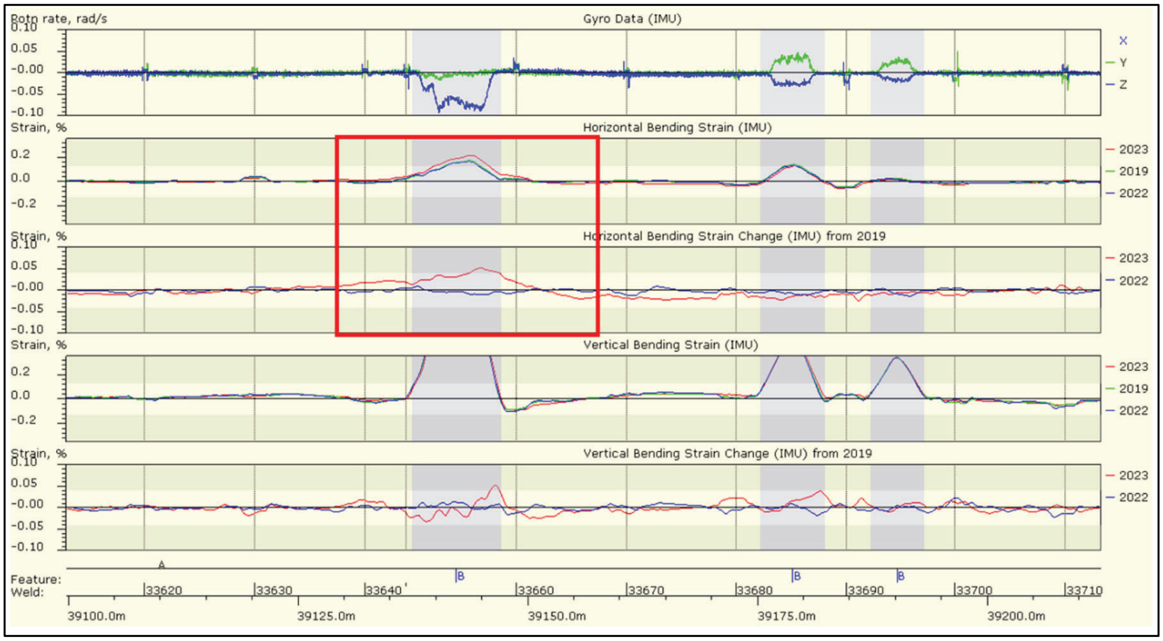

Figure 8. Bending strain plots showing small horizontal strain change. (Source: Baker Hughes)

From this point and with the information of a possible displacement in the area, more plots were brought up for investigation. Considering the extension of the region of concern, all plots were adjusted to show 300m (~1000ft) of the pipeline (Figure 9). Special attention was centred on the plan view difference and heading variation between runs since strain change was predominant in the horizontal plane. This observation led to identification of the displacement in the data.

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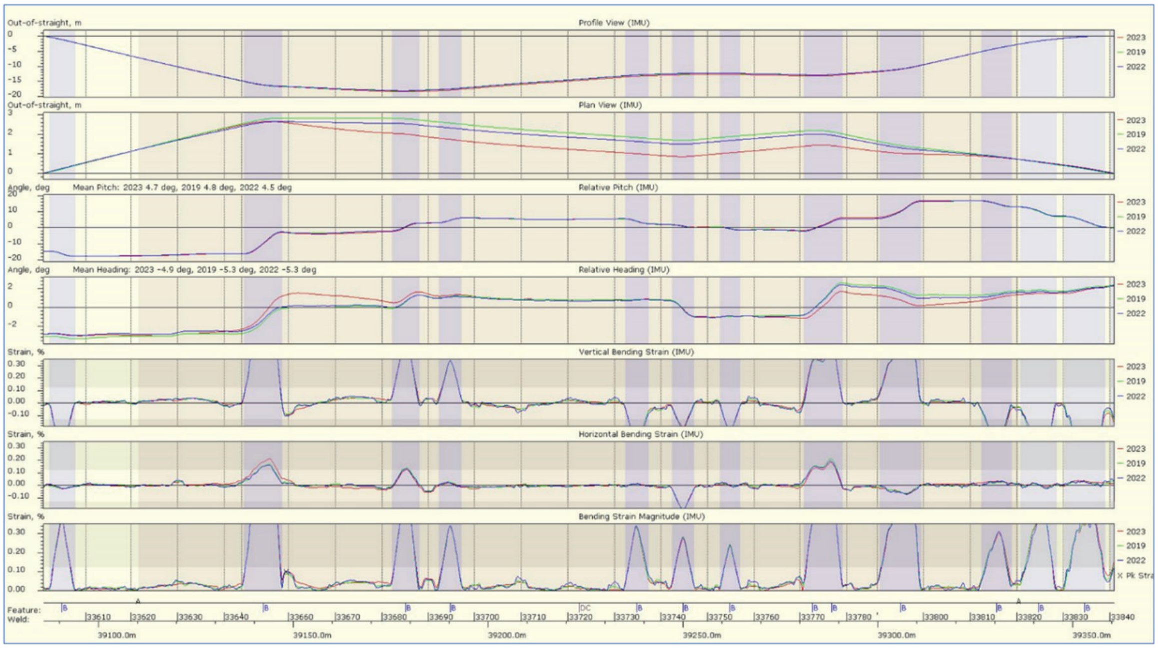

Figure 9. Strain plots showing an extension of ~300m. (Source: Baker Hughes)

Based on the horizontal origin of the movement, it is noted that the plan view, which represents the out-of-straightness, shows a variation in the trajectory between the 3 runs. This variation is observed in the plan difference showing a displacement of 0.8m (2.6ft) at its maximum point (Figure 10). It should be also mentioned that the corresponding change in the heading angle helped to determine the limits of the movement. Within the strain change plots there is only evidence of this event at its start, associated with the horizontal strain change observed previously, and close to the end of the displacement with a minimum strain change below the reporting threshold.

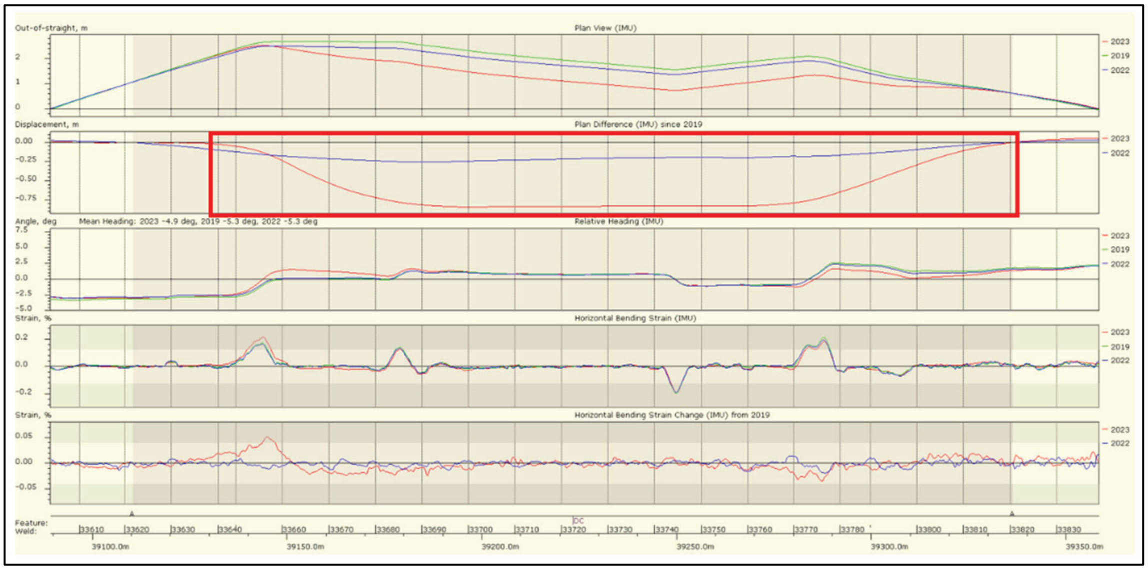

Figure 10. Displacement visible in Plan Difference panel plot. (Source: Baker Hughes)

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This special construction arrangement reduced the actual loading to the pipeline with a visible effect of minimizing the change in the curvature making the identification process not as straightforward. Fortunately, the mitigation system performed as expected supporting the landslide and allowed the remediation action to be planned in a timely manner. Stress relief was first implemented during area excavation. It was noticed that at the upstream flank of the displacement coincident with the horizontal strain change, the external casing was broken. Findings from the in-field verification and remediation of the site can be seen in Figures 11 and 12.

Figure 11. Upstream flank of the movement showing displacement and fracture of the external casing. (Source: CENIT)

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Figure 12. Downstream flank of the movement showing pipeline displacement and eccentric casing section view. (Source: CENIT)

Case Study 2

Wrinkle-type anomalies

An ILI (CAL+IMU) run was performed on a 16-inch fuel pipeline in May 2023 with an available previous inspection from September 2019. The latter also included an axial strain tool run, which was completed a month later. The latest inspection reported two wrinkle-type anomalies located at the lower side of a hill, not present in previous data. The first wrinkle according to the run direction was reported with a maximum depth of 12%OD at the bottom of the pipe (Figure 13), with the next wrinkle located 9.5m downstream. According to ASME B31.4 crest-to-trough height criteria [5], this anomaly was not acceptable and required further action.

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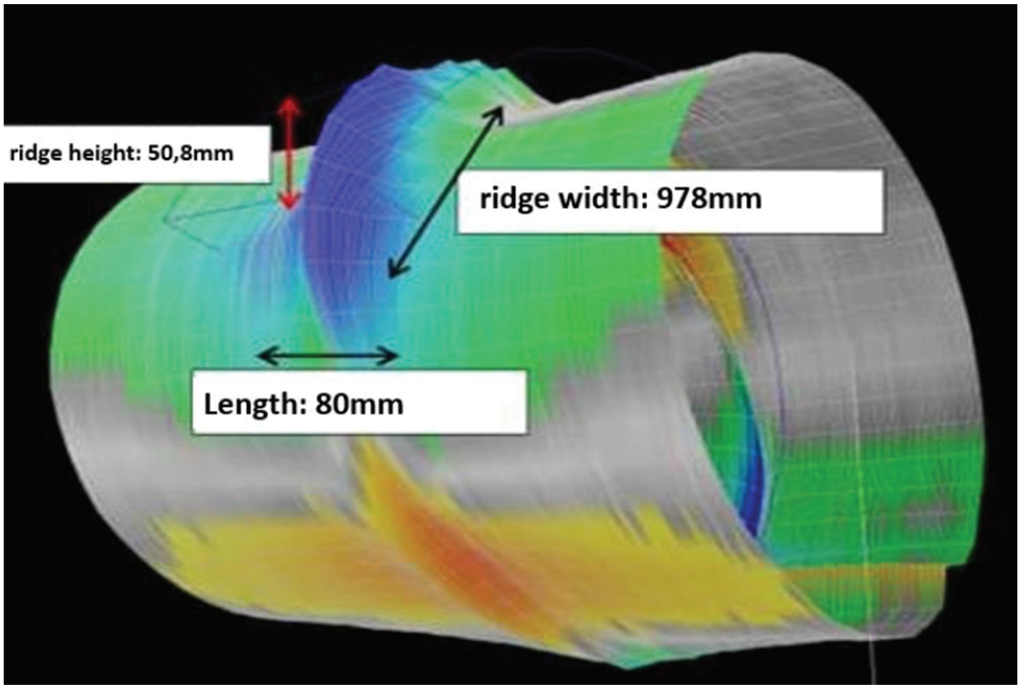

Figure 13. Geometry of the wrinkle-like anomaly. (Source: Baker Hughes / CENIT)

This location was under a follow-up plan according to 2019 ILI (CAL+IMU) results where the reported bending strain magnitude for this deformation was 0.350%. The 2023 report also showed high bending strain and strain change values within an area of ~100m (328ft). The maximum overall bending strain magnitude was 0.535%, coincident with a maximum strain change of 0.356% adjacent to a field bend. The deformation was mainly visible in the vertical plane around the reported wrinkles. Bending strain values are not considered at the wrinkle location as it was originally associated with a field bend, but these results were in the order of 2% vertical strain with an associated 1.4% strain change.

Regarding geotechnical conditions, in the surrounding area there were no symptoms of instability processes related to these strain changes, but with other ones related with bending strain report. However, considering these features, it was necessary to reassess the area with a field campaign to identify relationships between strain changes and kinematics of an instability process. These instability symptoms were mainly a “creep” (a very slow slope movement type with annual rates lower than 0.10 m approximately) with a load vector transverse to alignment of the pipeline [6].

The wrinkle formation was an abrupt process that took place post 2019 inspection where loading concentration occurred at a field bend. Gyros signals have been distorted at wrinkle area (Figure 14).

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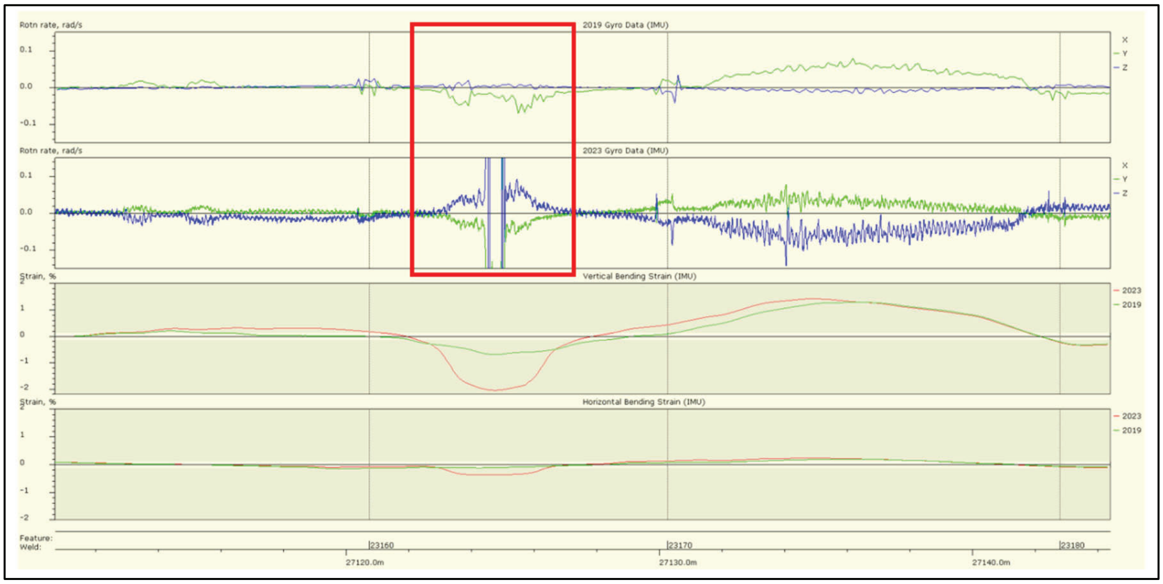

Figure 14. Gyro signals distortion at wrinkle area. (Source: Baker Hughes)

Strain profile and vertical angle (pitch) showed variation around the area of interest. Profile difference shows a 0.5m (1.64ft) displacement at the wrinkle that corresponds to a 10 degrees angle change visible in the pitch difference plot (Figure 15). On the other hand, horizontal difference was less noticeable with an angle change of 2 degrees represented at the heading difference plot (Figure 16). This is to be expected since the wrinkle was identified at the bottom of the pipe.

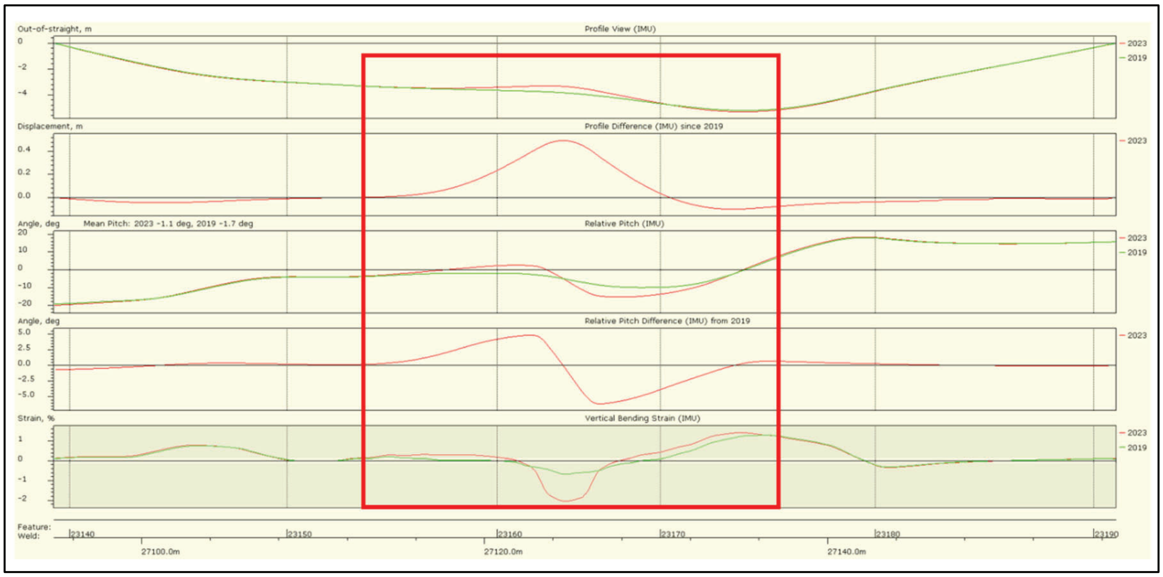

Figure 15. Vertical strain profile and angle variation. (Source: Baker Hughes)

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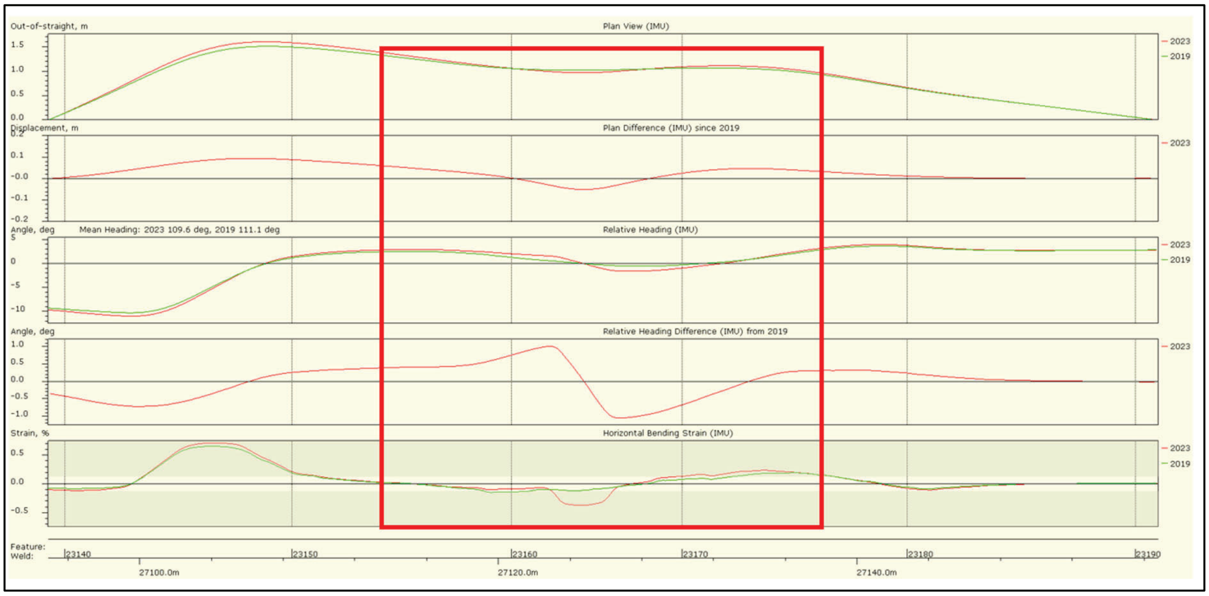

Figure 16. Horizontal strain profile and angle variation. (Source: Baker Hughes)

Loading mechanisms associated with bend deformation (open/close) allowed the interpretation within the strain profiles of the areas of stress concentration by tension and compression. A review of the 2019 axial strain report also revealed that the location of the wrinkle was under compression during the time of this inspection (Figure 17).

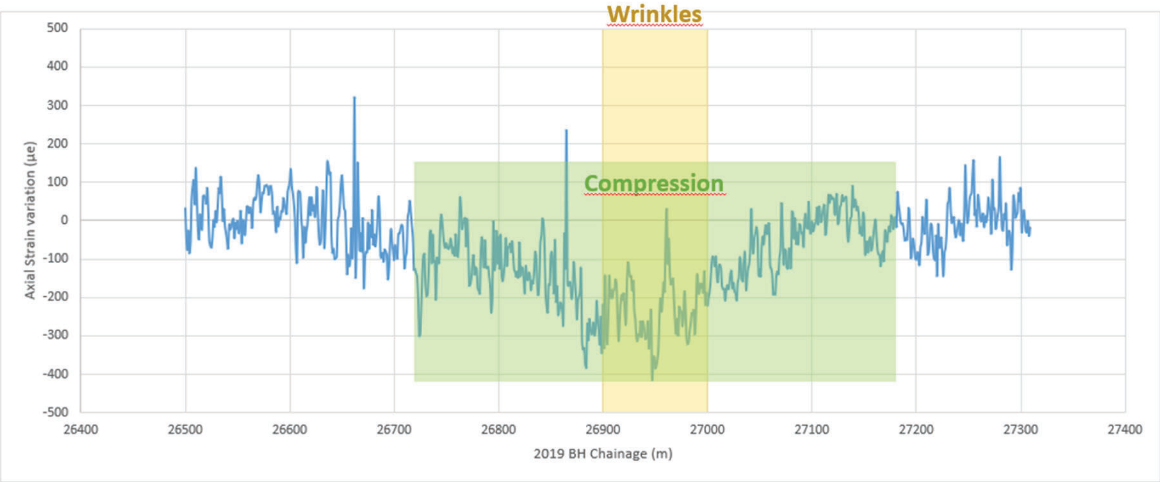

Figure 17. 2019 Axial strain signals. (Source: Baker Hughes)

The identification of the loading sectors allowed to establish the digging sequence, promoting a correct release of accumulated stresses, and thus reducing the risk of failure until the final repair was completed by replacing the section (Figure 18).

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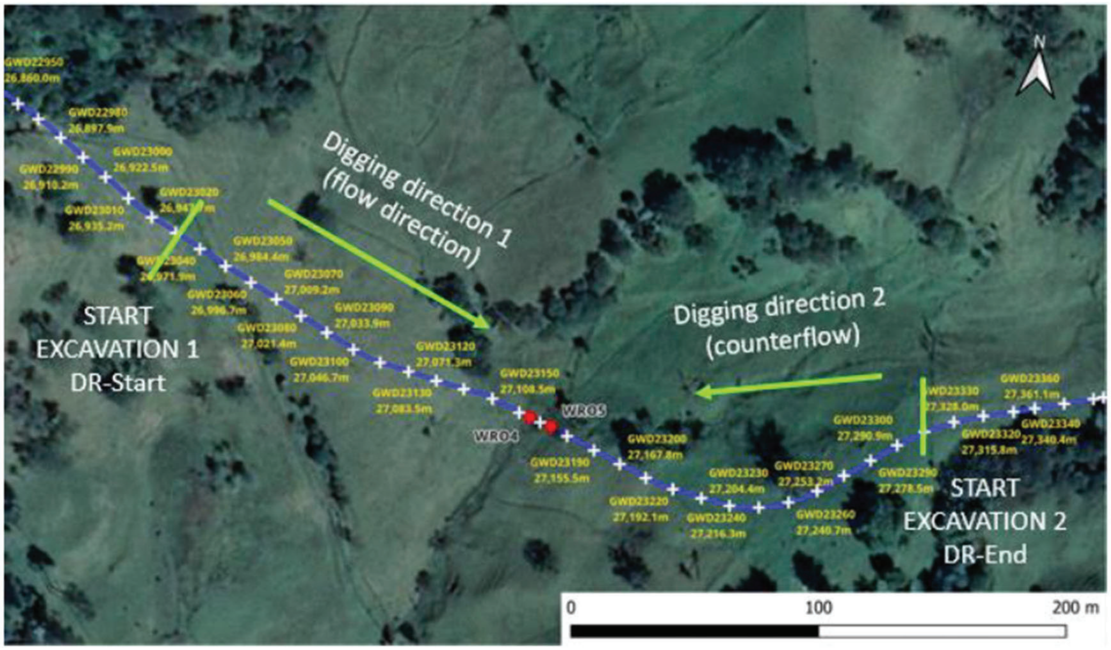

Figure 18. Digging procedure. (Source: CENIT)

In field inspections validated the axial load hypothesis. Wrinkle dimensions were rejected by the crest-to-trough height criteria (ASME B31.4) (Figure 19). This level of deformation generated grooves that coalesce into fissures and obvious cracks. These fissures were oriented axially with respect to the axis of the wrinkle and some circumferential crack colonies.

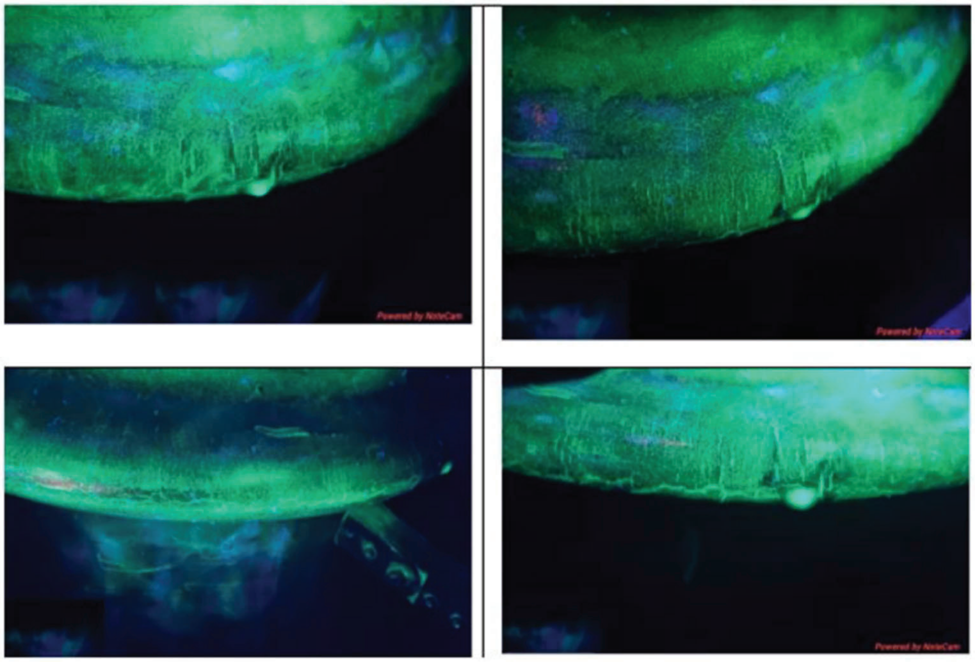

Figure 19. Ridge height of wrinkle anomaly. (Source: CENIT)

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Lessons Learned

The complex nature of each case study encompasses different challenges, from a detailed review of the processed IMU signals to an integrated approach in the pursuit of the root cause identification.

For example, there could be instances where still under a pipeline displacement of approximately 1 meter (3.28ft), there is no significant evidence of change in the pipeline curvature. This was demonstrated in our first case study where a pipeline laying inside a casing acting as a mechanical protection from geohazards could mask the strain change despite the actual movement. For this reason, the comparison of the plan/profile or heading/pitch angle signals between runs can provide useful insights of the pipeline behavior. The use of different plot scales allows the identification of the limits of the area of concern, especially when we deal with large areas of ground movement.

Sharing information about previous inspections, excavated areas or special construction methods, like the external casing in this case could help with the identification of potential threats. Operators should also consult about in-house software availability to perform internal checks and the review of areas of interest.

Case study number 2 is a clear example where repetitive study through redundancy provides an objective conclusion and confirmed congruency. This kind of inverse engineering allowed the understanding of the interaction of the soil-pipe system promoted by an integral analysis of the mechanical behavior of the pipeline. At the same time, it contributes to the comprehension of these types of events within stakeholders without technical background.

The study of bend deformation (in-bend strain variation) around the geohazard location could contribute to the interpretation of the kinematics involved in the pipeline movement, facilitating correct identification of the soil-pipe interaction as well as the effective mitigation of the threat. This level of interpretation allows to coexist with the condition and response in a maintenance window that would not affect the operational continuity of the asset.

Conclusions

IMU data is proven to be a powerful tool for the identification of ground movement impacting a pipeline. Most of its benefits are leveraged with the use of multiannual inertial mapping inspections to monitor the evolution of areas under external loading or mitigation measures efficiency in favor of a successful geohazards integrity management plan.

Adding other sources of information such as geotechnical inspections to bending strain and pipeline movement analysis helps to increase the success rate of strain relief.

The interaction between vendor and operator is crucial to enable continuous improvement and knowledge between parties, even more in complex scenarios like the ones described in this paper. Collecting all available information and its integration during the bending strain and strain change assessment simplifies and facilitates a better understanding and resolution of the study.

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