Axial Strain Evaluation and Integration into Geohazard Management Program

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Abstract

Pipeline geohazard identification, assessment, and mitigation remain critical areas of focus in the industry, with continuous advancements across multiple technologies. Effective geohazard management exemplifies the necessity for integrating new technologies to mitigate risks more effectively. Traditional approaches to geohazard management rely on a combination of ILI IMU (bending strain), LiDAR, InSAR, Strain gauges and deformation platforms. Recently inline inspection (ILI) vendor(s) have developed novel strain measurement technologies designed to detect and measure the external loading caused by geohazards.

This paper examines the successful technology validation to address the threat of geohazards to pipelines. A case study of a pipeline currently monitored for geohazard activity at multiple locations is included. The pipeline was inspected using a newly developed ILI strain tool (ETEC-Geo), with a specific focus on assessing how the inclusion of axial strain data can enhance the overall geohazard management program. This review will show how the ILI strain tool data correlates to existing ILI IMU bending strain, with links to known geohazard sites currently being monitored using strain gauges.

The second part of the review will show how the axial strain measurement identified additional geohazard locations where the bending strain was not present. The axial strain was predominantly detected over longer pipeline spans affected by landslides acting longitudinally, while bending strains were more common in shorter lengths where landslides moved transversely or oblique to the pipeline orientation. Correlation between technologies allowed us to further refine the risk assessment across the potential geohazard sites and better estimate the strain demand on the pipeline.

The Geohazard ecosystem and the missing link

Geotechnical and hydrotechnical hazards, or so-called geohazards [1], have gained prominent interest in the industry over the last decade following significant incidents. Geohazard management is a complex process requiring multiple datasets integrated to provide details about the geohazard and its impact on the pipeline. Although various technologies are available in the industry for identifying geohazards, no single tool can serve as the sole source of information. Geohazard assessments require cross-referencing a range of data, including ground movement measurements, simulations, and inline inspections. This comprehensive suite of technologies and measurements is known as the Geohazard Ecosystem, developed by pipeline operators and the industry to manage these threats effectively.

To understand the geohazard potential treat, the operator must understand the external force element and its interaction with the pipeline. In the case of a landslide, the slip plane and its interaction with the pipeline is key. An external survey like a ground survey or slope monitoring is often the starting point to understand the landslide itself and its interaction to the right of way (ROW). Other technologies that are used to commonly identify and manage geohazards from above ground are LiDAR, InSAR or aerial patrol using advanced imaging technique [2]. LiDAR and InSAR

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have proven to be suitable for identifying and monitor landslips, however, they are unable to determine if a geohazard is impacting a pipeline directly. They are both surface measurement technologies with no indication of related depth of the slides versus pipeline depth of cover.

When a geohazard site is identified, operators have tools available to measure the geohazard's effects on the pipeline, with strain gauges and fiber optic cables being the most common. While effective, these solutions are deployed at specific locations, requiring operators to have already identified the geohazard accurately. Additionally, their installation involves invasive methods and cannot capture the strain imparted to the pipeline prior to deployment. Figure 1 illustrates the interacting elements of what is referred to here as the Geohazard Ecosystem, using a landslide parallel to the pipeline right-of-way (ROW) as an example.

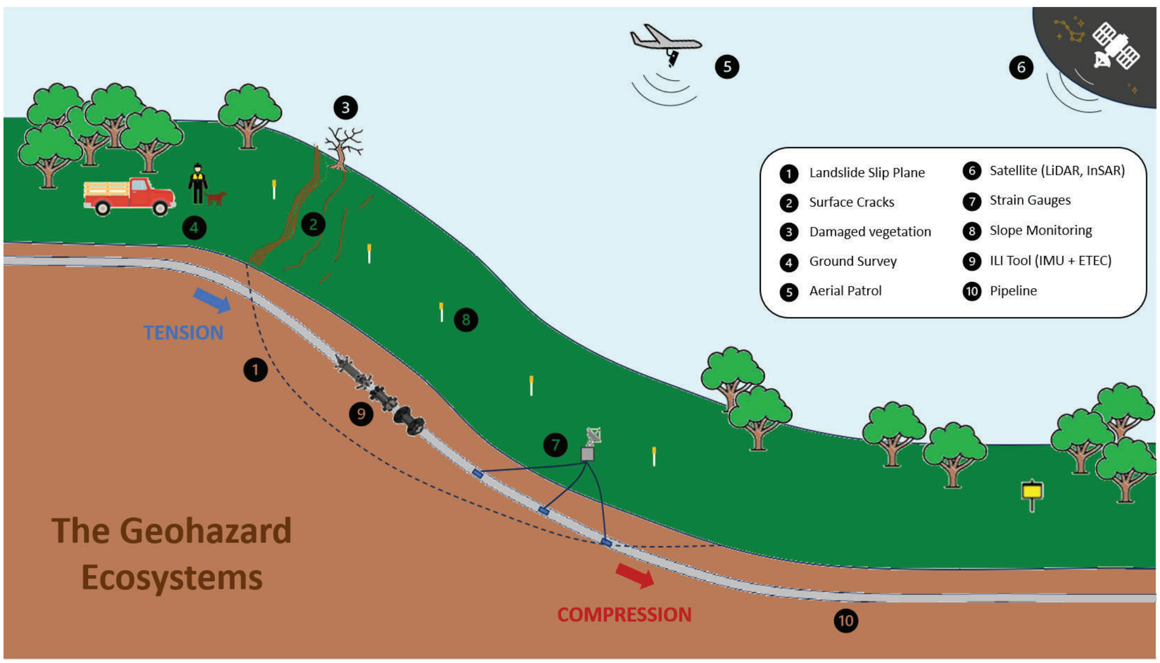

Figure 1. Illustration of the interacting elements forming the Geohazard Ecosystem

Direct assessment of the impact from geohazard on a pipeline is most commonly performed using an ILI tool equipped with IMU [3]. While an ILI IMU tool can be used to derive bending strain measurement over the length of the pipeline, it is not capable of determining the full strain demand exerted on the pipeline by a geohazard. In the case of a landslide, the displaced soil will exert a force on the pipe. This force will cause two primary strains on the pipeline, bending and axial. Figure 2 illustrates the longitudinal strain across a pipe cross-section. It can be separated into the axial component and the bending component [4]. The bending strains are most simply the horizontal and vertical movement or bending of the pipeline. These strains are the reason for the traditional 'S' shape a pipeline will have due to a landslide. Axial strain is the elongation or contraction of the pipe, where the pipe is being stretched or shortened due to the impacts of the landslide.

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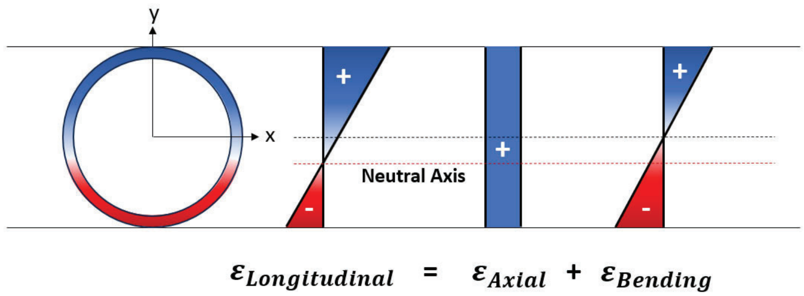

Figure 2. Illustration of axial and bending strain components distribution in a pipe cross section

Early implementation of ILI technology showed the potential to report axial strain [5]. However, improvements in the reporting range, absolute strain values combined with higher data resolution were needed to draw meaningful conclusions regarding the impacts of a geohazard on the pipeline.

Evaluating Strain Measurement Technology (ETEC)

As part of any geohazard program, evaluating axial strain is a key priority to determine the total strain demand on a pipeline. Marathon and NDT Global (NDTG) share a long-standing partnership focused on developing innovative inspection technologies. The Axial Strain Challenge represents the next chapter in this collaborative journey [6].

NDTG has developed the latest generation of ILI strain measurement technology, in part nourish on the experience and learning from early development in the parent organisation [5,7] While the fundamental physical principle, magneto-elastic coupling, remains unchanged, an extensive research and development program has introduced additional physics, advanced sensor designs, upgraded hardware, and innovative analysis methodologies. This effort has culminated in the next-generation strain measurement technology, branded as ETEC [8], which is deployed via the ETEC-Geo ILI tool. Initial validation of this technology was conducted on an operator's pipeline, comparing results against strain gauge data [9]. The current inspection forms part of a broader validation program with selected pipeline operators to further enhance the technology and refine the insights gained.

Load measurement, commonly referred to as stress or strain measurement, is a specialized application of electromagnetic measurement known for decades under the term Magnetoelastic effect (or Villari Effect [10] or Inverse Magnetostrictive Effect). Summarized in Figure 3 below, the magneto-elastic coupling principle relies on the application of a known magnetic field H over a ferromagnetic material (pipeline steel) where the local magnetization level M will reflect the stress level σ the material is experiencing. Within the elastic domain, stress and strain are interchangeable parameters through the Elastic Modulus (E), which relies on the material's elastic properties. Outside the elastic domain, changes in magnetization are predominantly influenced by strain effects.

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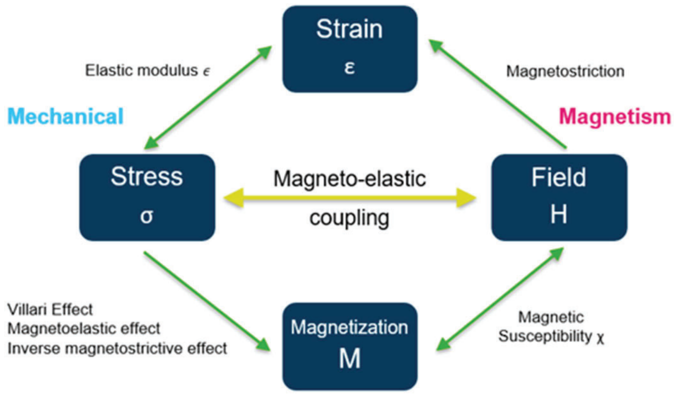

Figure 3. ETEC principle - Magneto-Elastic Coupling

The inspection results presented in this paper were collected using the 24" tool implementation. In this range of diameters, the ETEC-Geo tool uses 16 probes equally spaced around the pipe circumference. This configuration allows the detection of full-scale geohazard events (1 m to several 100 m) which produce axially oriented load in the pipeline. The detection capabilities rely on the high-resolution data with a sub 1" resolution axially up to 5m/s. To fully assess geohazard events, the tool is integrated with ultrasonic caliper sensors and an IMU for this inspection as in Figure 4. The eddy current sensors, not requiring an MFL magnetizer, can be deployed in any tool combination (Ultrasonic, Acoustic resonance) or even as a standalone tool.

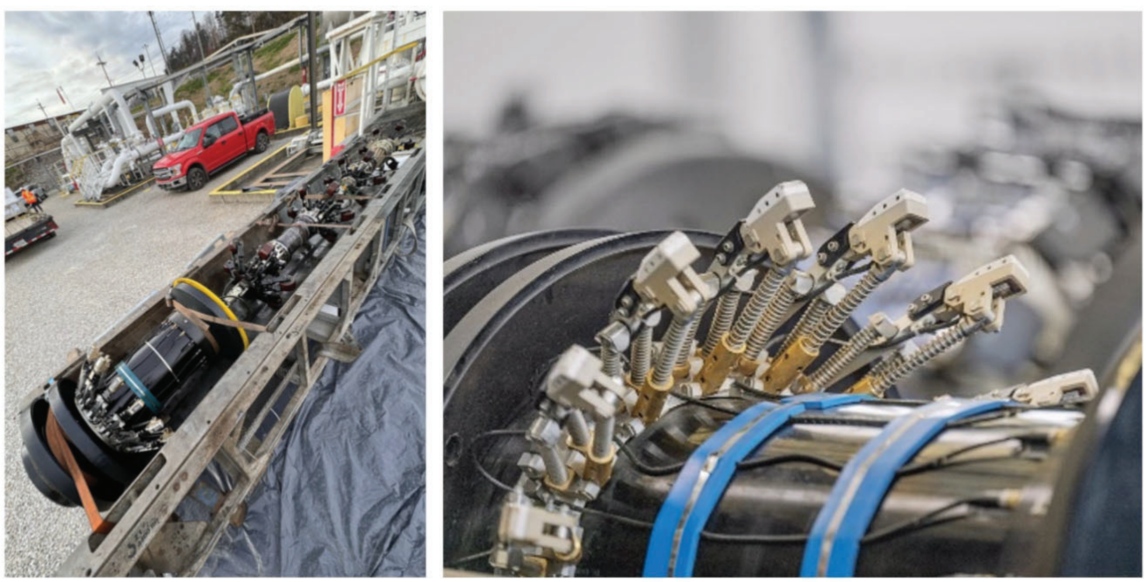

Figure 4. ETEC-Geo tool post inspection (left) & ETEC sensing module clos-up (Right)

Case Study: A 264 Mile Inspection in the Appalachian Region

The inspection discussed in this paper is part of Marathon's evaluation of axial strain measurement and its integration in integrity management. The 24" pipeline inspected in Kentucky; USA covered a distance of 264 miles over rugged terrain in the Appalachian. The inspection length and terrain

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maximized the chance of detecting strain-related features to provide sufficient data to conduct the technology evaluation. Marathon has an extensive geohazard management program in place for this pipeline with notably sites already equipped with strain gauges. The pipeline follows a regular program of inspection notably using ILI IMU tool for bending strain and LiDAR for slope movement. At the time of inspection, the LiDAR survey identified close to 150 sites in the proximity of the ROW or interacting with the ROW indicating of possible landslide.

Site visits by the ILI vendor team during the interim of the inspection provided an opportunity to visually document selected sites equipped with strain gauges and relay critical observations to the analysis team. This step is particularly valuable in a geohazard context, as desktop studies alone cannot always accurately capture the real-life scale and impact of geohazards. These on-site insights helped bridge the gap between theoretical analysis and practical realities, enhancing the overall evaluation process.

Strain Measurement using Strain Gauge

Distributed strain gauge around a pipe circumference allowed captures both the axial and bending strain components acting on a pipeline. They represent the most used option to measure pipeline strain at discrete location. Strain gauge measurement at the monitored sites were reviewed to assess if the data could be used to validate the ILI strain measurement. However, it was clear early in the review that the likelihood will be low. Strain gauge measures the difference between the installation time and the measurement time. Therefore, they cannot report prior loading. Moreover, the strain gauges were installed post stress-relief mitigations. Assuming the stress-relief was complete, the strain at installation of the gauges would be close to zero. And therefore, the strain gauge would monitor any reloading on the pipeline over time. This is an effective way to monitor the sites for further movement. At the time of the ILI ETEC-Geo inspection, the strain gauges were in place for just a few years with no significant reloading detected on the pipeline demonstrating the effectiveness of the mitigation efforts. Figure 5 illustrates one of the locations monitored with strain gauges where no significant pipe reloading occurred post stress-relief. The primary effect measured was related to seasonal temperatures changes.

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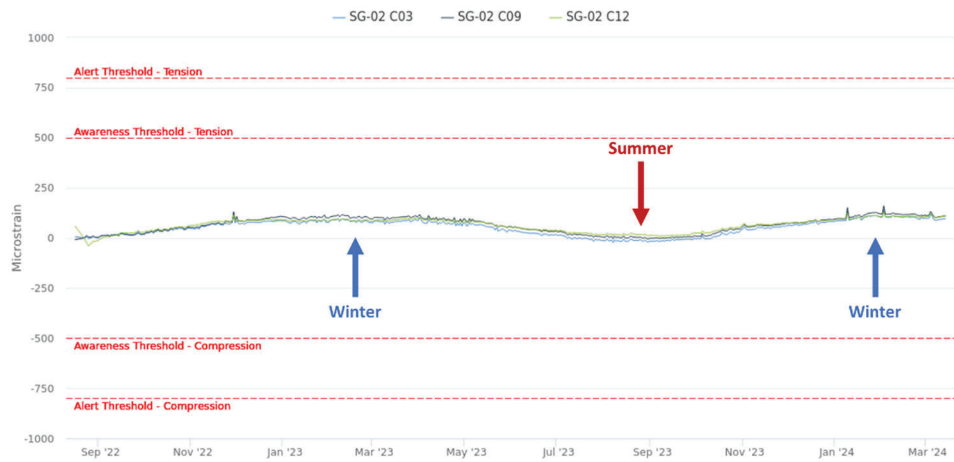

Figure 5. Example of Strain gauge monitoring post stress-relief with no significant movement

The ILI ETEC-Geo tool measures the strain at the time of inspection hence in order to correlate to strain gauge, either the strain gauge must have been installed at assumed zero strain level (e.g. prior to the geohazard event) [9] or as part of a run-to-run comparison where the ETEC strain difference can be compared to the strain gauge difference between the two points in time. With no indication of strain level prior installation and a strain amplitude reported by strain gauge in the order of 0.02% in average, correlation to the ETEC measurement was of limited value.

Bending Strain using ILI IMU

Bending strain captured by IMU (Inertial Measurement Unit) is the most established technology available to pipeline operator to detect along the full length of inspection any related pipe movement. IMU are capable of detecting change in direction either from construction or from external force. IMU are not capable of detecting axial strain as no change in direction is produced by pure axial tension or compression. The distinction between fabrication vs geohazard is often driven by analyst expertise and industry practice. In general, bending strain from construction of a fabricated field bend is limited to a single pipe joint. Geohazard related bending strain often crosses multiple pipe joints. Strains can also be introduced by overburden forcing the pipeline to conform to the trench bottom or those caused by forcing the pipe into a horizontal bend without proper field bending are also common forms of strain from original construction that can be easily confused for those caused by a geohazard.

Bending strain is referred to pipeline movement analysis when one or more subsequent inspections are compared to identified difference in the pipeline position. Pipeline movement analysis also helps to distinguish between strain from construction vs strain from geohazard. Pipeline movement analysis was conducted on the inspection presented using IMU data collected during three previous inspections. The main movement highlighted the location of the prior stress-relief and associated with the already know strain gauge sites. On slow moving landslide, a significant time gap is required between IMU inspections to distinguish active loads on the pipeline.

IMU processing to produce bending strain analysis is relatively well established with some variation in filtering technique or calculation parameters and has gained prominent exposure in the last decade across the industry. One source of error in bending strain is related to the tool's attitude in the pipeline. The IMU measures the tool position and not the pipeline position. So, one must assume the tool maintains a perfect centreline position during the inspection (by mechanical mean, e.g. sefl-centering wheels) or implement adequate compensation factor for example based on caliper mounted on the tool. The primary goal of the ETEC measurement is to capture the missing axial strain but as secondary deliverable, the bending strain component can be extracted as well. This offers a direct comparison to bending strain measured by IMU. Figure 6 illustrates the fundamental difference in measurement technique between IMU and ETEC used to derive the horizontal and vertical bending strain.

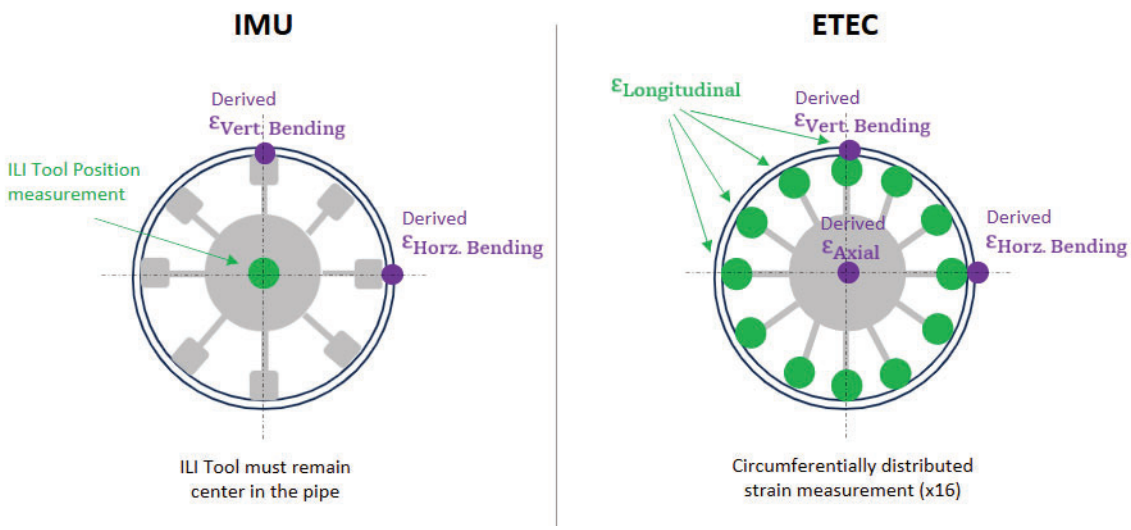

Figure 6. IMU measurement on wheel mounted tool (Left) vs ETEC measurement (Right) based on individual sensor equally distributed around the pipe circumference. Both methods can be used to derived horizontal and vertical bending strain.

ETEC strain is related to external loading, so, one could superimpose the datasets to evaluate if a bending strain feature is due to construction (no load) or geohazard (active load). Additionally, the ETEC strain sensors are measuring the strain on the pipe wall and therefore are not affected by tool attitude producing artifact in the data. Finally, ETEC strain can be calibrated to IMU bending strain to guarantee an accurate axial strain reporting.

An overlay of both ETEC and IMU measurement is presented in Figure 7. The location represents a 1,000ft extract of the inspection at a location of geohazard. The data displays, especially in the vertical direction, an underlying undulating trend typical of bending strain from overburden conforming a pipe to the excavated trench profile (item 1), both ETEC and IMU are displaying the same trend due to the force exerted on the pipeline. A field bend can be seen (item 2), again with strain mostly in vertical direction to conform with ditch profile. However, only the IMU data identified the horizontal component curvature as bending strain as no force is applied in that direction, the ETEC data shows approximately zero strain. At the location under external geohazard

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force (item 3), both ETEC and IMU display the same profile and amplitude of bending strain due to the external force inducing change in curvature. When external forces are adjacent or combined at field bend (item 4), again, the ETEC results do not increase at the change in curvature from fabrication and only responds to the presence of external force.

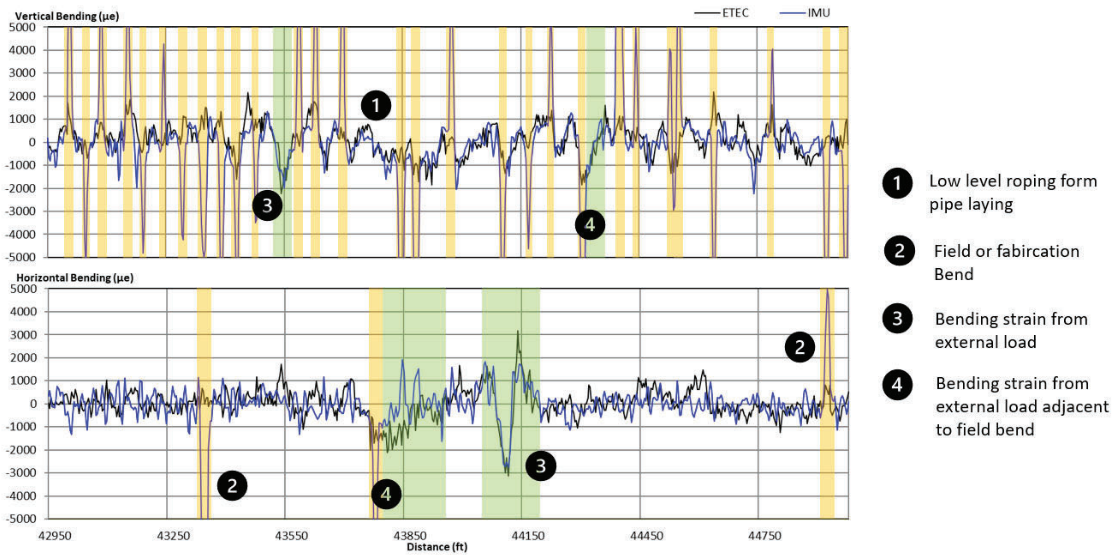

Figure 7. Vertical and horizontal bending strain calculated from IMU (Blue) and ETEC (Black) with features identified guideline. IMU reports all curvature changes including field/fabricated bend. ETEC reports strain from external loading only.

As described previously, small variations between both technologies are expected, for example due to local out of roundness where the idealized profile of the IMU curvature tends to smooth local effects around the pipe circumference. The use of the combined technologies offers the best approaches to differentiate features and increase confidence level.

Axial Strain using ETEC and Correlation to LiDAR

Axial strain captured by ETEC-Geo tool was the main goal of the evaluation. Axial strain complements the bending strain assessment by allowing a total strain assessment in the longitudinal direction. The importance of the axial strain assessment would depend greatly on the terrain encounter and the type of geohazard. In the case of short landslides (few hundred feet) acting perpendicular to the pipeline, the dominant component is expected to be bending strain. Landslides parallel/longitudinal to the ROW are more likely to not only introduce bending strain at the toe but also an amount of tensile to compressive strain along the length of the slide. Without strain gauge data or an ILI tool capable of directly measuring axial strain the axial strain can only be modelled using established landslide limits, displacement data, and soil properties.

The primary assumption is based on the previously reported Bending strain. The ETEC sensors measure the total longitudinal strain therefore the axial and bending strain are decoupled during the

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analysis and not as two different measurements. If one has proven the bending strain is measured accurately, the sensor fundamental measurement is proven. Decoupling axial strain relying on analytical methods (e.g. averaging around the circumference minus local effect as seam weld) should then also produce accurate axial strain measurements.

One of the technologies used to detected larger scale landslide is LiDAR imagery. Marathon has conducted LiDAR surveys along the ROW and identified close to 150 sites. An example of such site is displayed in Figure 8. LiDAR can map the ground morphology though the vegetation, allowing the user to identify morphology indicative of ground movement.

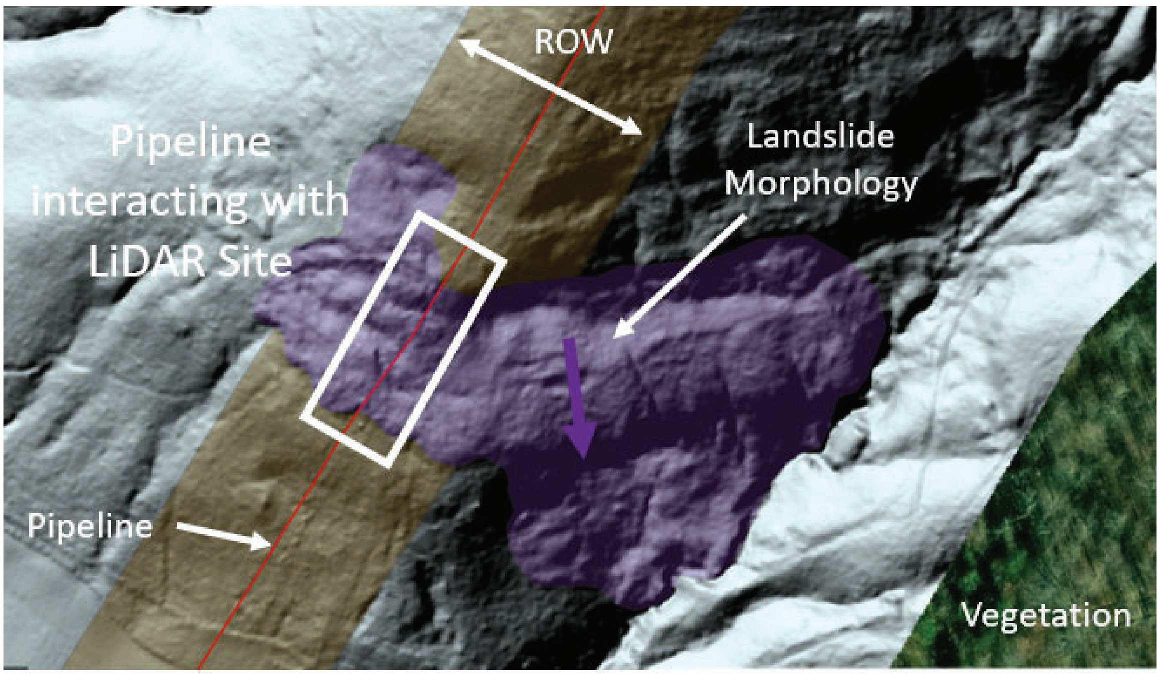

Figure 8. LiDAR site correlation interacting with the ROW and the pipeline. The grey imagery represents the LiDAR image of the ground profile minus vegetation vs the satellite imagery in the bottom right corner. Distinct ground movement morphology can be identified in the purple zone overlapping the ROW and pipeline location.

Any sites interacting with the ROW and of significant length can be assessed qualitatively against elevated strain location detected by the ETEC-Geo tool. Location where soil movement is detected from LiDAR data, axial strain from ETEC and bending strain from IMU/ETEC would form a clear indication of landslide interacting with the pipeline pattern.

A first example of two LiDAR sites with different level of interaction with the pipeline is shown in Figure 9. The site 2 shows a clear correlation with elevated strain detected by the ETEC-Geo tool, whereas site 1 shows limited interaction with the pipeline. Site 2, based on the ETEC, IMU and LiDAR correlation was identified as priority for mitigation and scheduled to be stress-relief in 2025. Figure 9 present the most significant strain component distribution at the location, here the horizontal bending strain induced by the oblique movement to the pipeline from the landslide in site 2. Axial strain and vertical bending strain are also present at the site 2 but at lower magnitude.

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The short length of the affected site 2, around 300ft, combined with the oblique slide direction explained the limited amount of axial strain at the site.

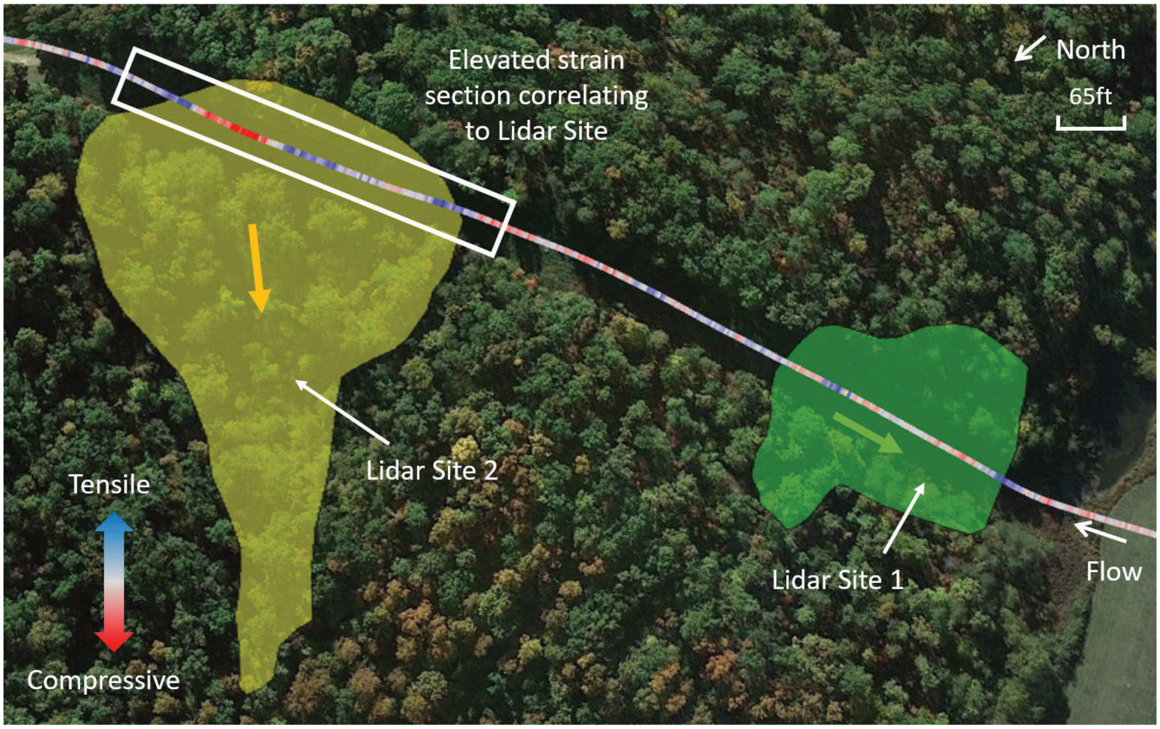

Figure 9. Example of LiDAR site correlation with strain measurements. Site 1 at the bottom of the slope show no corresponding strain above the general trend. Site 2 show a clear correlation with tensile to compressive strain variation overlapping the delimited slide boundary. Site 1 is classified as not interacting, site 2 is classified with interacting with the pipeline.

A second example of LiDAR site correlation to strain measurement is presented in Figure 10. The movement as in the previous example, is mainly perpendicular to the pipeline inducing a dominant strain as vertical bending strain. Limited axial and horizontal bending strain are present at this site. Based on the ETEC, IMU and LiDAR correlation the location was identified as priority for mitigation and scheduled for stress-relief in 2025. Again, with an interacting length of around 300ft, the pipeline is predominantly affected in term of bending strain.

The presence of axial strain in lateral or oblique landslide is linked to both the magnitude of the displacement and the length of the interacting site. It is expected that adequate ROW surveillance would limit the number of cases where large lateral landslide has developed unnoticed and therefore triggering significant axial strain. However, lateral displacement of significant length, sometimes over several miles, from mining subsidence [9] or even slow-moving landslide along river valleys, are common occurrences in certain part of the world. In such scenarios, significant axial strain tends to develop over time with bending strain is limited to the slide boundary. In the case study presented, the pipeline did not cross any significant lateral landslide producing axial strain.

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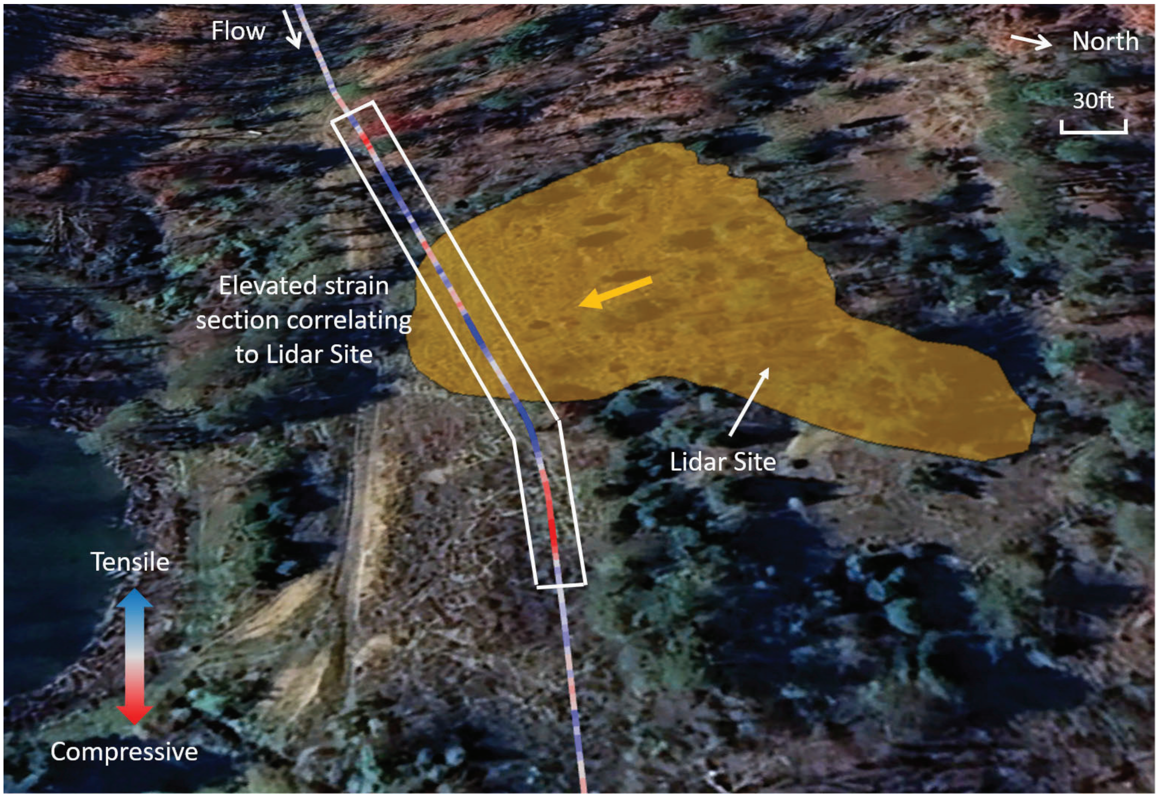

Figure 10. LiDAR site correlation with vertical bending strain measurements from ETEC-Geo tool. Lateral movement to the pipeline for a length of around 300ft inducing pipeline displacement and resulting bending strain.

The most common scenario of axial strain, especially in the Appalachian region as of this pipeline, is landslide parallel to the ROW. Figure 11 presents the axial strain measurement from the ETEC-Geo tool over a 1.6miles section in total including an area instrumented with strain gauges. Additionally, to the pre-identified section with strain gauges, the tool detected a feature downstream of the known location. The axial strain feature shows a clear trend matching theoretical trend with tensile on top of the slope and compressive strain at the tow. The principal strain component acting was axial strain with additional low level horizontal bending strain at the slide bottom boundary. Based on bending strain only, the site would be unlikely be reported by other ILI tools. The site location was not known by the ILI vendor and detected purely based on the ETEC measurements. As previous sites, based on the ETEC, IMU and LiDAR correlation the location was identified for mitigation and scheduled for stress-relief in 2026.

Figure 12 focus on the main slope of Figure 11 with additional LiDAR imagery showing the ground morphology associated with the landslide. The slope in Figure 12 is close to 1,600ft (5 times longer than Figure 9 & 10), over such length, the axial strain tends to develop from tensile at the top of the slope to compression at the bottom of the slope. In some cases, additional bending strain also develops at the toe of the slope, marking the boundary of the slide.

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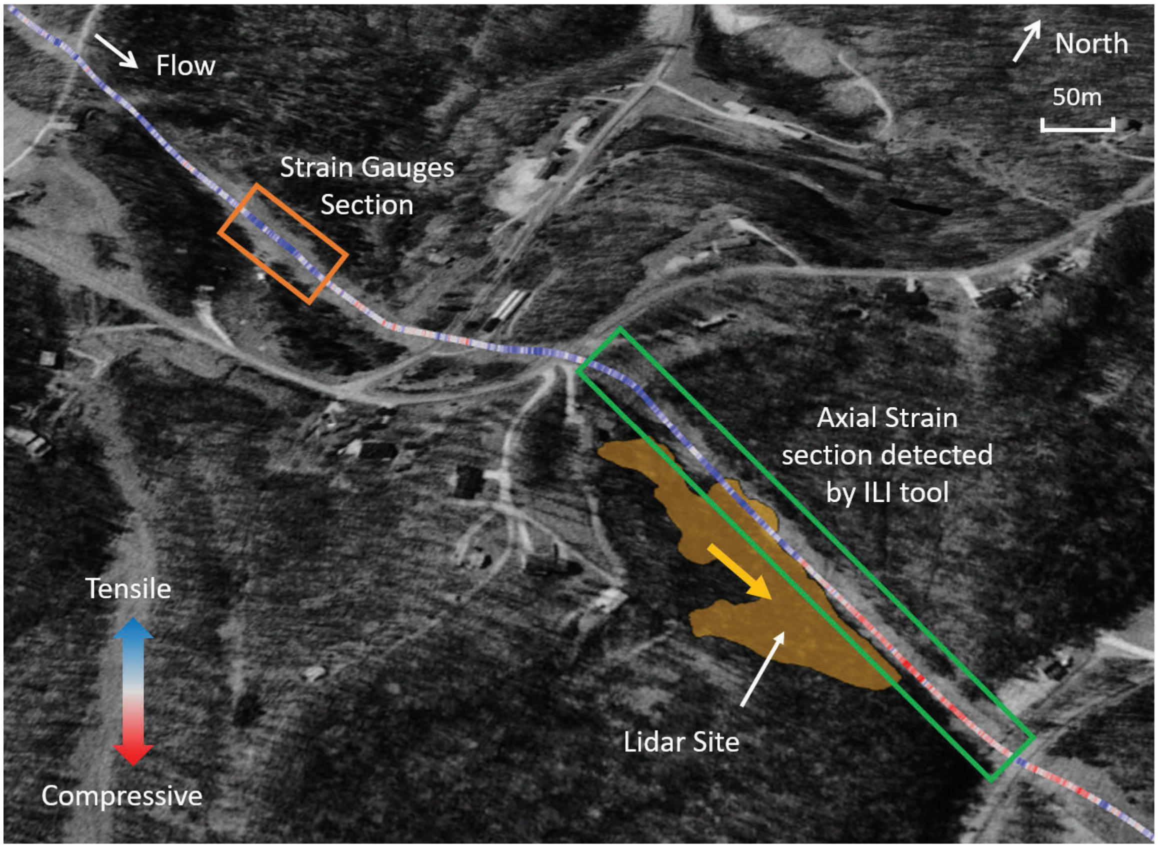

Figure 11. Axial strain section downstream of a strain gauges section. Tensile strain at top, compressive strain at the bottom of the slope. Landslide identified from LiDAR runs parallel to ROW.

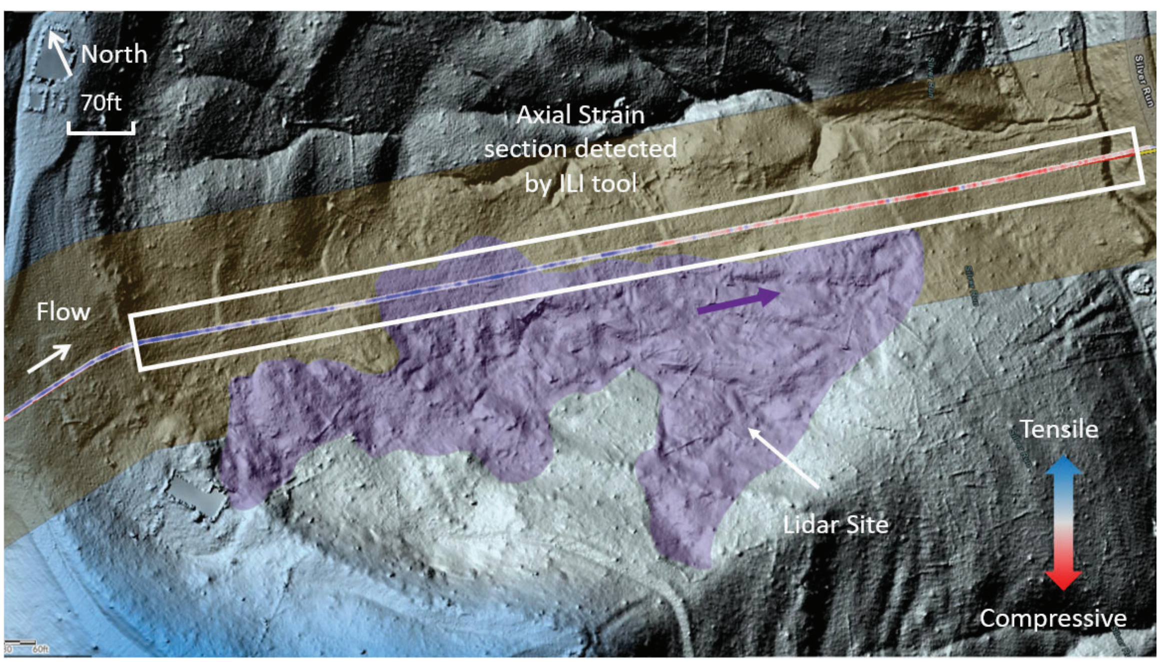

Figure 10. Axial strain section identified in Figure 11 zoom in and overlay with LiDAR data to correlate ground morphology associated with landslide interacting with the ROW.

The LiDAR data used was based on a single survey, so the sites are identified based on the ground surface morphology and not actual movement from multiple surveys. This is one of the challenges with single LiDAR survey. A site might show clear morphology in line with landslide, but the landslide might be dormant or active. Ground survey might help to differentiate but become time intensive when the sites inventories is over 100s of locations, spread 100miles apart. If ROW disturbance is present crossing the pipeline centerline, it can be concluded that the pipeline has been acted upon by the landslide, if the slip plane is determined to be deeper than the pipeline burial depth. A second LiDAR survey, after the initial review versus ETEC measurement, was conducted 3 years after the first one to identify differences between surveys and to better differentiate dormant vs active sites. No significant movement or only limited differences were detected, confirming that most site were dormant or slow-moving landslides.

One of the core values of adding both bending and axial strain assessments to pipeline geohazard management programs is the ability to differentiate between sites where the pipeline has or has not been impacted. In the example presented, about 5% of the LiDAR sites showed direct correlation to elevated strain demand (axial or bending or combined). So, in practice using the axial and bending strain aids the desktop assessment process and allows operators to better prioritize landslide hazards for field assessment and remediation.

What's Next?

Axial strain data interpretation

High-resolution axial strain is a new dataset in the pipeline operator portfolio. The primary goal is to identify and quantify Geohazards interacting with a pipeline. To do this the tool measures stress/strain from external forces, the resulting effect of a geohazard, but also from any source of external loading like construction interference or surface loading. In a similar approach to the IMU bending strain, learnings and practices must be developed to better decouple strain related to geohazard to strain related to construction. Part of this learnings will come from repeat inspection, like IMU bending strain, where movement in the pipeline will be reflected as increase in tensile or compressive axial strain from one run to another.

Strain Demand Definition

For integrity assessment, the analysis of strain demand versus strain capacity governs the prioritization for mitigation. Strain demand is often simply defined as stress from pressure (mostly internal). Integration of bending strain in the longitudinal direction is now being done routinely based in IMU bending strain. Axial strain is sometimes inferred from simulation [11] at localised sites. Having an estimate of strain capacity allows operators to determine a margin of safety for a given location. The strain demand, even if mentioned in assessment code, is rarely clearly defined. The best approach often relies on the stress demand defined in the design related chapter of pipeline standard and must be converted into strain based on best estimation of material properties. Moreover, strain demand

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down to a specific feature should be related to a strain field at a certain distance to the feature. For example, should a crack assessment be based on the crack tips, the strain across the full crack length or even across the full pipe joint? Strain demand definition in integrity assessment remain an ongoing research topic in the industry.

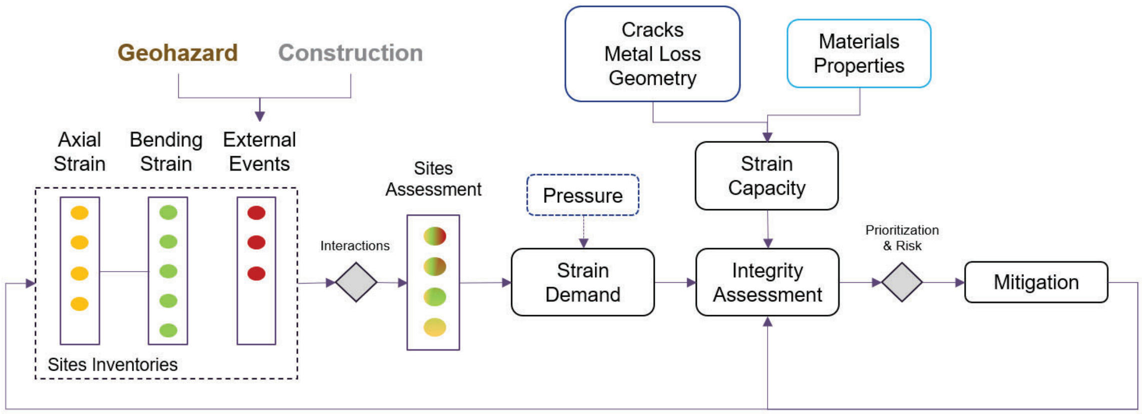

Figure 11. Axial Strain integration in Integrity Management Program

Features assessment

With a defined strain demand, the comparison to strain capacity remains the main challenge to solve for the industry. Limited amounts of industry standard or recommended practice clearly codifying the strain capacity vs strain demand analysis in term of longitudinal loads. The best definition available is for circumferential crack features assessment using Failure Assessment Diagram as per API 579-1/ ASME FFP-1. However, looking at metal loss assessment, only one recommended practice for offshore pipeline gives some guidance, DNV-RP-F101(Part B). Correlation to geometric features like dents for example would rely on simulation (FEA). This also remains an industry topic to research further as the strain demand measurement becomes more widely available.

Conclusion

The case study presented the first step in measuring axial strain for integration in geohazard management program at a pipeline operator level. The main outcomes being an initial validation of the technology capabilities based on qualitative site correlation using LiDAR and quantitative correlation using IMU bending strain. Full axial strain validation was conducted by the ILI vendor and published previously [9]. The technology was not only able to confirm existing site monitored based on IMU bending strain but also to identify additional sites where the axial strain component is dominant and therefore unreported using IMU. Furthermore, the added information provided by the axial strain component provides a better understanding of the landslide sites impacting the pipeline. The ILI strain tool measured all external forces interacting with the pipeline, as geohazard or construction interference. The next step in the validation is to conduct a repeat inspection post stress-relief [12] on selected sites. The repeat inspection, like IMU movement analysis, will enhance understanding of the stable feature from construction vs the moving feature from geohazard interaction. The following inspection is scheduled for 2025 and resulted to be presented the following year.

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