A High-Efficiency Approach for Landslide Detection, Prioritization, and Monitoring

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Abstract

Landslide threats continue to be a prevailing concern for pipeline operators and the public. Although several methods and technologies exist to detect and monitor these geohazards, determining what strategies are most effective and efficient for integrity management can be challenging. High-resolution inertial measurement (IMU) data can be utilized to detect anomalous strains resulting from pipeline displacement. The knowledge of experienced geotechnical experts can then be leveraged to review and characterize geohazards coincident with these anomalies in more detail. Although this strategy is extremely effective, timely and detailed geohazard reviews can be challenging due to a manual analysis process and expert availability. However, without expert review, pipeline company integrity managers can be left with concerns regarding how to determine what results constitute an actual concern for the pipeline. To streamline efforts to prioritize landslide-affected pipelines, this paper proposes an alternative, highly efficient approach to geohazard screening, which incorporates IMU-based bending strain assessments and automated geohazard detection/characterization using high fidelity LiDAR (Light Detection and Ranging) data. This paper will present a brief overview of the ROSEN method of pipeline movement detection using IMU data from multiple in-line inspections, followed by an outline of the Teren method for streamlined geohazard screening, change detection, and severity assignment. To conclude, a review of three historical landslides areas will provide examples where pipeline movement, detected with IMU, was found to be coincident with ground movement detected with Teren's change detection analytics.

Introduction

Geohazards take many forms. For pipeline operators, landslides are a particular concern because the forces they generate can be significant, resulting in pipeline displacement, girth weld rupture, severe plastic deformation, and/or buckling of the pipe body. The landslide risk to a particular pipeline varies by topography, geological characteristics, weather patterns, construction practices, and other considerations. Determination of susceptibility can justify resourcing efforts, but finding an efficient and scalable approach of identification and prioritization of ground movement will be a challenge.

Landslide categories are derived from the mechanics of the soil's movement. They may be classified as falls, topples, slides (rotational and translational), lateral spreads, flows, and complex (i.e., a combination) (Highland, 2008). Figure 1 presents an example of a translational slide, which was identified and remediated by Marathon Petroleum as part of their geohazards management program.

Although the highest densities of recorded landslides occur in areas that one might expect, such as throughout Appalachia and along the seismically active U.S. west coast, they have also been documented in states absent of many of the typical features known to produce landslides. According to the U.S. Landslide Inventory, maintained by the United States Geological Survey (USGS), landslides have been documented in every US state and territory (USGS, 2023). Because of this, the level of susceptibility to landslide-induced damage should be carried out for each pipeline system individually and, ideally, for individual segments within those systems.

To deal with the modern challenges of geohazard management, this paper proposes an efficient and scalable approach to landslide detection and prioritization. This highly proficient, partially automated approach blends the proven method of pipeline movement detection using IMU with geohazard detection and characterization using LiDAR digital terrain models (DTM) and computer

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vision artificial intelligence (AI). This paper will present a proposed methodology, along with case studies using real-world data from historical landslides.

Figure 1. Example landslide crossing pipeline ROW, identified and remediated by Marathon Petroleum

Methodology

The methods presented in this section provide a framework for detecting and prioritizing areas of geohazard concern using IMU, LiDAR and AI informed geohazard detection, and advanced engineering calculations.

Pipeline Movement Detection Using Inertial Measurement Units

Using IMU to detect regions of high bending strain and pipeline movement has been widely adopted by the pipeline industry. The popularity of this approach continues to grow, primarily due to its efficiency and effectiveness. Because almost any inline inspection can be equipped with IMU, it is easy to integrate and perform post-ILI functions.

The IMU does not measure bending strains directly. Rather, it measures differentials in the unit's orientation relative to a calibrated starting position. The orthogonally mounted accelerometers and

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gyroscopes measure linear and rotational accelerations across six degrees of freedom, allowing the position (pitch, roll, and yaw) of the tool to be determined in three-dimensional space.

By using this information, it is possible to derive vertical and horizontal bending strain (ε_v and ε_h, respectively) (Czyz, 1994) as

$$\varepsilon_v = -\left(\frac{\Delta\varphi_{pitch}}{\Delta S}\right)\frac{D}{2} \times 100\% \qquad \text{and} \qquad \varepsilon_h = -\left(\frac{\Delta\varphi_{azimuth}}{\Delta S}\cos\varphi_{pitch}\right)\frac{D}{2} \times 100\%$$

where φ_{pitch} and $\varphi_{azimuth}$ are the pitch and yaw of the unit at a given point, S, along the pipeline. D is the pipe outer diameter. Instead of calculating bending strain using two adjacent data points, note that the value of ΔS is typically computed over a range of data points called the gauge length, which acts to smooth the bending strains (CRES, 2017).

This method assumes that the pipe begins as a straight segment and that any change to pipeline trajectory is due to cold bending of the pipe. It does not account for non-homogeneous materials or ovalization that might be present in the pipe cross sections.

Once these calculations are performed, the entire pipeline can be screened for bending strain anomalies using a predetermined set of criteria. This typically includes a required length, maximum strain, and pattern characteristics indicative of unintended bending of the pipe.

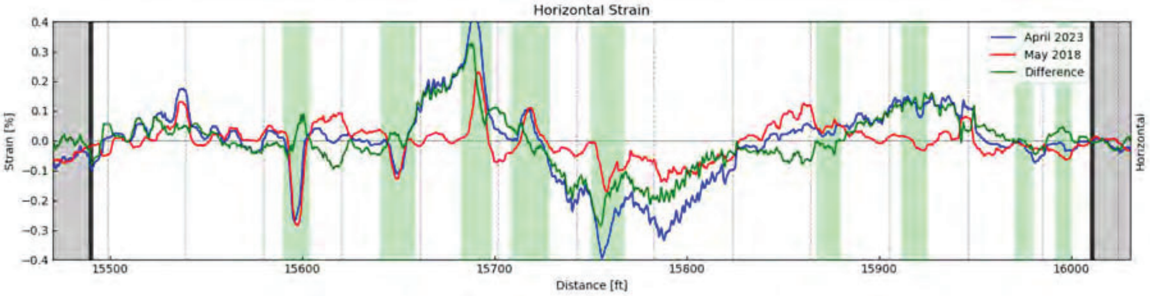

Figure 2. Example of strain change indicating pipeline movement

When two or more datasets are available, it is possible to compare strains across a defined length of time and determine if pipeline movement has occurred across that interval. When trajectory information is accessible, it is possible to tie two IMU datasets together at a localized interval to determine the magnitude of movement that has taken place in an area of concern. An example of a bending strain comparison is presented in Figure 2.

Landslide Detection Using LiDAR Digital Terrain Models and Artificial Intelligence

Utilizing LiDAR data to detect landslides and landslide potential is not a novel concept. LiDAR has been widely valued by pipeline operators and integrity consultants for geohazard identification. It is now a key tool for geotechnical experts assessing pipeline rights-of-way.

The growing prominence of artificial intelligence has allowed for development of a data-driven approach to significantly increase the efficiency of geohazard assessments in order to reduce timelines and scale the assessment process to a size that effectively meets operator's needs. Teren's computer vision algorithm detects geohazards within the pipeline right-of-way automatically based on the following variables:

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- Geohazard distance from the asset
- The degree of geohazard intersection with the asset
- Directionality of scarp and toe slopes movement in relation to the asset
- Slope steepness that the geohazard is on
- Geohazard shape (round or oblong)
- Geohazard distance from the asset
- Geohazard size

Additional algorithms are then implemented to characterize the structural components of the hazard and a manual review is performed by an expert analyst to finalize its extents and remove false calls.

Using multiple LiDAR datasets, additional algorithms are used to automatically identify changes to existing geohazards over a given time interval (e.g., land movement). Using a set of change detection analytics, identified ground movement is defined as:

- Remediated geohazards including landslides that were present at Time 1 and absent at Time 2
- New geohazards including landslides that were absent at Time 1 and present at Time 2
- Persistent geohazards that exist at both Time 1 and 2; these are evaluated for change to the body of the slide, scarp and toe slope migration and distance from an asset

An example of this change detection is presented in Figure 3. Material added is signified by the green shaded areas and material removed by the red shaded areas.

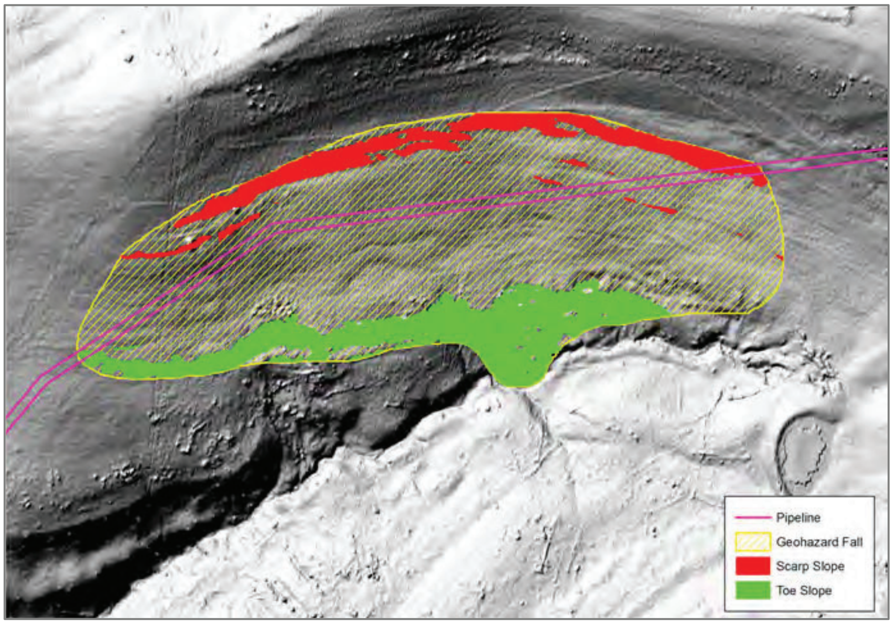

Figure 3. Example change detection for landslide

The proposed approach for identifying bending strain anomalies and coincident landslides boasts significant benefits, but also contains inherent limitations. For hazards identified as severely affecting the pipeline, additional assessments are required. These benefits, limitations, and requirements for follow-on assessments are provided in the following section.

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Prioritization

Beyond the inputs outlined in the previous two sections, other known variables can also be included to aid in the process of prioritizing areas of concern and assigning severity. This includes calculation of the tensile and compressive strain capacities for the pipe populations coinciding with areas of concern, and determination of the impacts of other anomalies interacting with the area (if additional ILI data is available). Although the details regarding these recommended additional inputs are not covered as part of the scope of this paper, a graphic representation of this process of prioritization is presented in Figure 4 and a brief outline is presented thereafter.

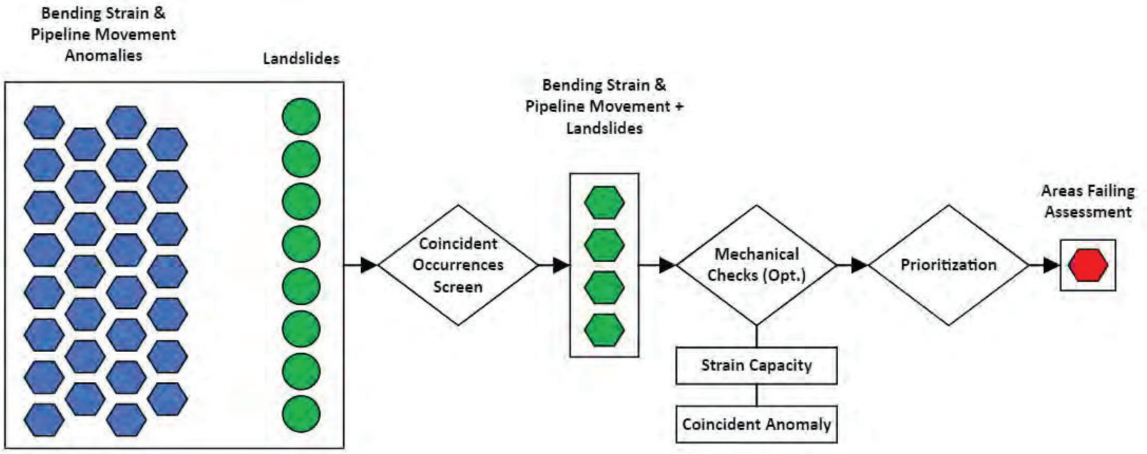

Figure 4. Example illustration demonstrating process of reducing areas of concern

Anomalies can then be prioritized based on the following considerations.

- Magnitude and orientation of identified bending strain anomalies and any associated movement
- Characteristics and severity of geohazards interacting with identified bending strain anomalies or pipeline movement
- Compressive and tensile strain capacities, using industry accepted criteria
- Presence of coincident anomalies and their influence on strain capacity and burst pressure (dents, buckles, wrinkles, ovalization, metal loss, girth weld anomalies, cracking, etc.)

The final product of the approach proposed here is a list of anomalies ranked by severity and likelihood of failure.

Note that not all variables are required, but additional detail will better inform the assigned severity levels of areas of concern. All variables are incorporated by Marathon Petroleum as part of their geohazard management process and are considered during prioritization efforts whenever possible.

By assessing anomalies based on this group of inputs, it is possible to reduce the results of either standalone assessment and provide operators with a concise and valuable list of areas of concern.

Advanced Assessment for High Severity Anomalies

With the prioritization complete, low severity bending strain and pipeline movement anomalies can be identified as those just needing to be monitored during future ILI and LiDAR campaigns. High severity anomalies (i.e., those failing the assessment process) should then be subject to additional

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investigation, reviewed in detail by a geotechnical expert who can provide informed recommendations based on additional sources of information. This may involve one or more of the following efforts:

- Assessment of active ground movement areas
- On-site geotechnical evaluation and support
- Finite element analysis to quantify all strains
- Modeling of further ground movement to establish KPI's and actionable limits
- Creation of site-specific action plan

Although these advanced assessment steps are not covered in detail as part of the scope of this paper, it is recommended that they be implemented as a part of a complete geohazard management framework.

Benefits and Limitations

This approach to geohazard and bending strain detection has several advantages. By combining the results of these independent assessment methods, pipeline operators are able to determine if a landslide exists within the right-of-way and if it has affected the pipeline with an increased level of efficiency. However, there are also inherent limitations.

An important distinction between the proposed method of geohazard detection and the conventional right-of-way geohazard review is the time, level of detail, and final product provided to the operator.

Conventional Geohazard Approach

Typically, a pipeline geohazard assessment involves manually screening the entire right-of-way by a geotechnical engineer or geologist. The utilization of LiDAR data (either public or pipeline-specific) has greatly enhanced this process, which involves identification, characterization, prioritization, and recommendations for all geohazards identified, regardless of whether they have been shown to influence the pipeline. Although this method has proven effective in its own right, it possesses several inherent drawbacks:

- Expert availability is limited, i.e. someone who possesses proficiency in both geotechnical and mechanical engineering fields and can provide valid insights
- Required timeline to complete a thorough manual review of the entire right-of-way is typically lengthy
- Level of detail provided can be in excess of what is required at the stage of prioritization
- Presence of human error within a fully-manual process
- Inability to efficiently scale as the threat of geohazards and increased regulation continues to demand

Proposed Geohazard Approach

By utilizing the partially automated, data-driven approach presented in this paper, this process becomes notably more efficient. By leveraging modern data processing speeds and computer vision artificial intelligence, timelines and expert availability requirements are both reduced. LiDAR can be acquired, geohazards identified and characterized automatically, and quality checks performed within as little as 14 days. This means the geohazard assessment does not constrict the proposed assessment process.

Because errors within an AI program are systematic, they can be identified and corrected as this service approach matures. A single geotechnical expert can review the results of multiple lines in a fraction of the time required for a standard manual geohazard assessment, reducing both time required and likelihood of human error.

The application of IMU bending strain analysis allows for hazards which are not currently impacting the pipeline to be specified as lower priority and not needing immediate intervention while identifying high priority areas requiring follow-on review. Lastly, the efficiency and ability to scale this approach for entire pipeline systems is unmatched by its manual counterpart. Nevertheless, automation of geohazard detection as has limitations:

- Because geohazard identification is automated, it is possible that some hazards may be overlooked by the program
- Assessment process is limited to characterization, severity, and prioritization
- Recommendations for high priority areas still require expert insight to determine is remediation or further assessment is required
- Additional, advanced assessments will still need to be carried out for high priority areas by a geotechnical expert

Despite these limitations, the benefits of this approach are apparent as long as it is applied appropriately. It is of paramount importance that the details outlined above are examined during the planning stage and implemented during execution and review. It should be noted that IMU bending strain analysis can be also applied to the Conventional Approach with similar results.

Case Studies

Using the proposed approach, several historical landslide locations coincident with regions of high bending strain and/or pipeline movement were analysed.

In each case study, the IMU and LiDAR results are split into two panels. The top panel contains a set of plots corresponding to the calculated bending strains in the study area. The bottom panel shows the pipe centerline, landslide extents, and change detection identified by the AI program, confirmed manually by a geotechnical expert.

Case Study #1 presents recorded pipeline movement in the form of a bending strain comparison in the top panel; Case Studies #2 and #3 present bending strains calculated from a single run in the top panel. For all cases, landslide change detection is presented in the bottom panel. All strains have been derived based on the measurements taken by an IMU. The layout of the strain plots is described in Figure 5 and Figure 6.

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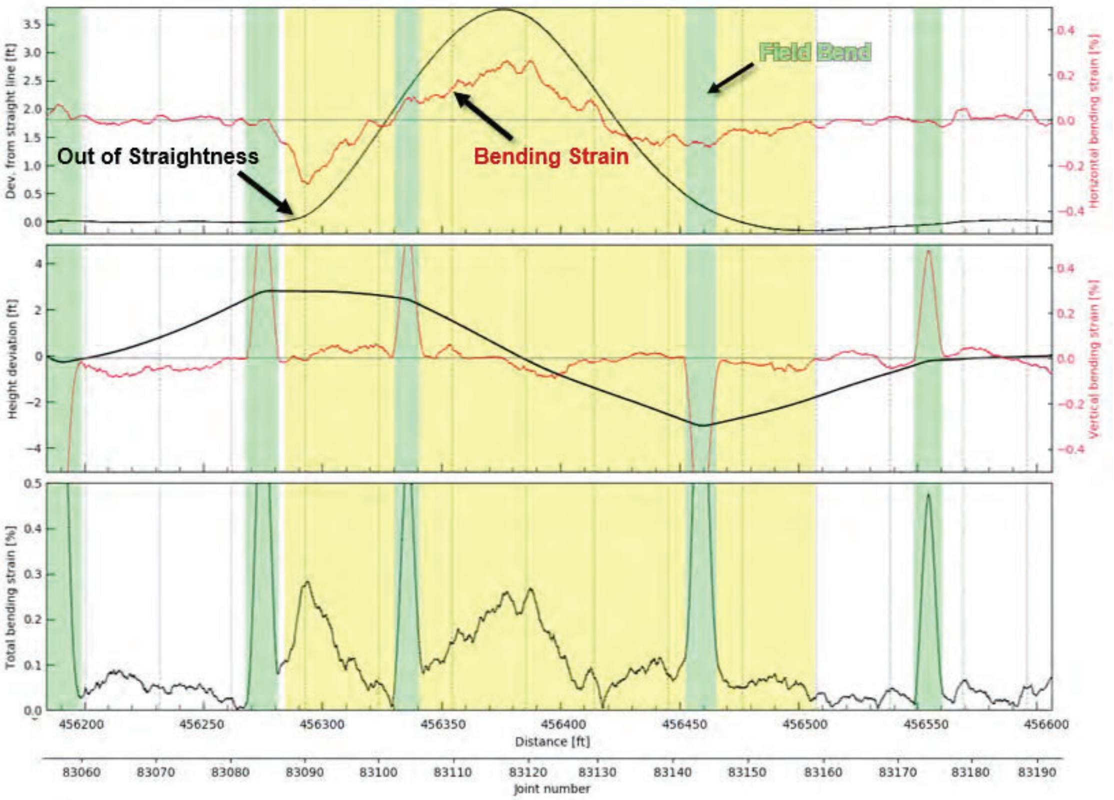

Figure 5. Bending strain plot description

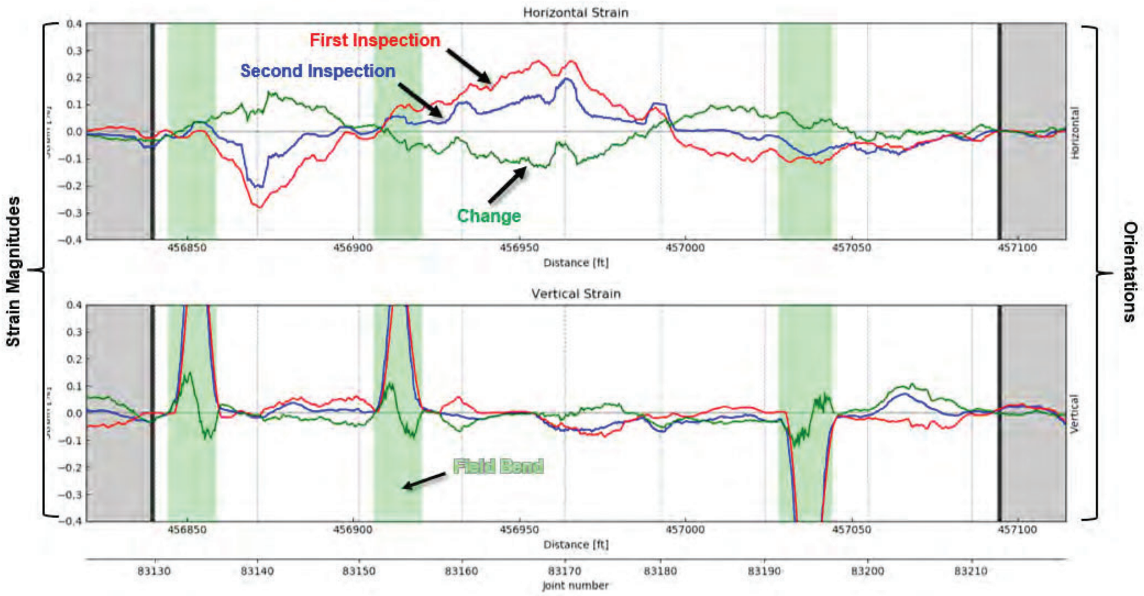

Figure 6. Strain comparison plot description

Case Study #1

The first case study is presented for a 16-inch refined products pipeline located in Eastern Ohio within the Kanawha section of the Appalachian Plateau. The pipeline in this case was installed within the banks of a historic mining impoundment dam.

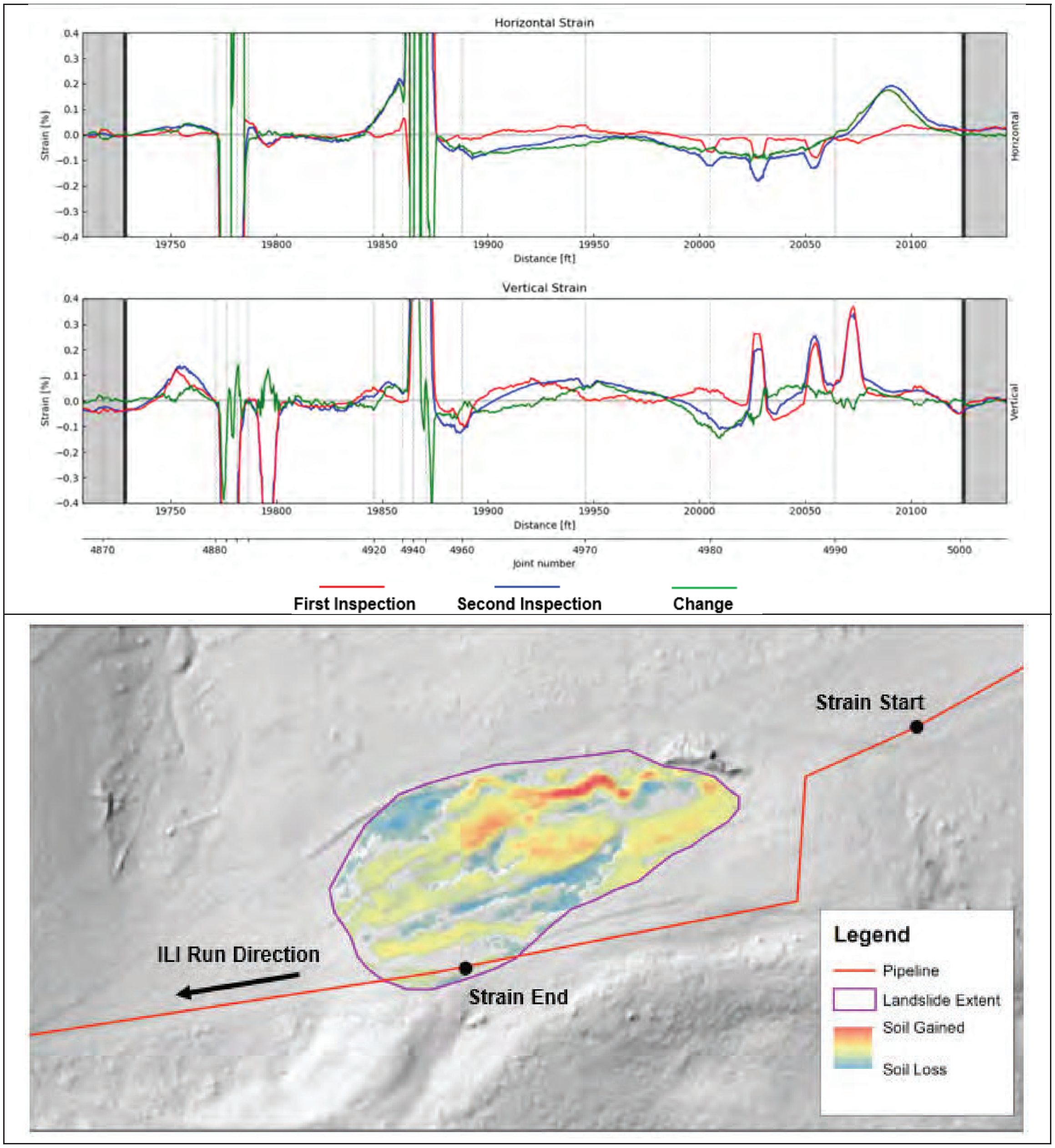

Figure 7. Case Study #1, 16-inch refined products pipeline segment with pipeline movement and landslide

The top panel of Figure 7 presents a comparison of the bending strains calculated for two inline inspections equipped with IMU. Strains are displayed as percentages. The first inspection, indicated by the red line, took place in 2016 and the second, indicated by the blue line, took place in 2022. The green line is the calculated difference in strain between the two inspections. The results in both

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vertical and horizontal planes show that strain change, e.g. pipeline movement, has occurred. The horizontal plane reflects a somewhat characteristic movement response pattern. The vertical plane reflects significant strain change as well, although with a less consistent quality. This is likely due to orientation of the landslide relative to this span and the 90-degree change in centerline trajectory occurring within the landslide area. Based on the observed changes in strain and specified sign convention, movement has occurred to the right and downward when observing the pipeline from upstream to downstream according to the direction of the ILI.

The bottom panel of Figure 7 shows the vertical change in terrain (soil movement) for the landslide between spring 2020 and fall 2021. The landslide is outlined in purple, the warm tones are areas of soil gain and the cool tones are areas of soil loss. Investigation of this site indicates that the landslide is active with a significant amount of change at the toe slope, and that it is moving downhill and to the right of the pipeline (red line). The change detection of the toe slope (lower right of the landslide) shows the largest amount of vertical soil gain. Based on Teren's ranking algorithm, this feature was classified as 6 on a scale between 1 and 10, 10 being the highest ranking. This ranking was assigned because the scarp slope intersects the pipeline (end point), it is moving away from the pipeline (downslope), it is relatively large (.5 acres), and on a gradual slope (17 degrees). As a note, this landslide is highlighted in Figure 1 and shows the features detected in the LiDAR DTM.

The results of the IMU-based pipeline movement and LiDAR-based geohazard assessments are in strong agreement. Based on the time intervals over which the two datasets were collected, it is possible to attribute causation. In addition, it is possible to quantify the amount of pipeline movement that has taken place as well as determine the characteristics of the landslide itself using this methodology.

Although additional material limit calculations and a coincident anomaly review would be recommended during the prioritization stage for cases such as this, the presence of active movement of both the ground and the pipeline are key indicators that remedial interventions are likely required for this site. For this case in particular, Marathon took prompt action to remediate this landslide.

Case Study #2

The second case study is presented for a 24-inch crude oil pipeline. This segment of the pipeline system is located in a mountainous region of Northern Kentucky underlain by bedrock with high potential for karst development.

The top panel of this case study provides a representation of the plan (horizontal plane) and elevation (vertical plane) profiles of the pipe centerline, along with the calculated bending strains in the study area. The IMU data was collected in 2018. Absent any bending strain, the red line should remain near the x-axis in both plots and remain below a detection threshold of 0.125%. However, notable horizontal strains are observed within the yellow highlighted region with a maximum total calculated bending strain of 0.260%. The characteristics of the observed strain and out of straightness patterns indicate leftward displacement when observing the pipeline from upstream to downstream according to the run direction of the ILI. These particular patterns and the horizontal orientation of the bending strain are highly indicative of ground movement [ref.].

The bottom panel of Figure 8 shows the vertical change in terrain (soil movement) for the landslide between spring 2019 and fall 2020, which occurred after the inline inspection. The landslide is outlined in purple, the warm tones are areas of soil gain and the cool tones are areas of soil loss. This figure shows that the landslide is most active along a ridgeline with the scarp slope (cool tones) and

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the toe slope (warm tones) intersecting the pipeline (red line). This activity also highlights the direction of movement, which is generating both tensile and compressive loadings. Based on Teren's ranking algorithm this feature was classified as 8 on a scale between 1 and 10, 10 being the highest ranking. This ranking was assigned because the scarp slope and toe slopes are intersecting the pipeline, it is moving along the pipeline (down ridgeline), it is relatively large (.55 acres), and on a moderate slope (25 degrees).

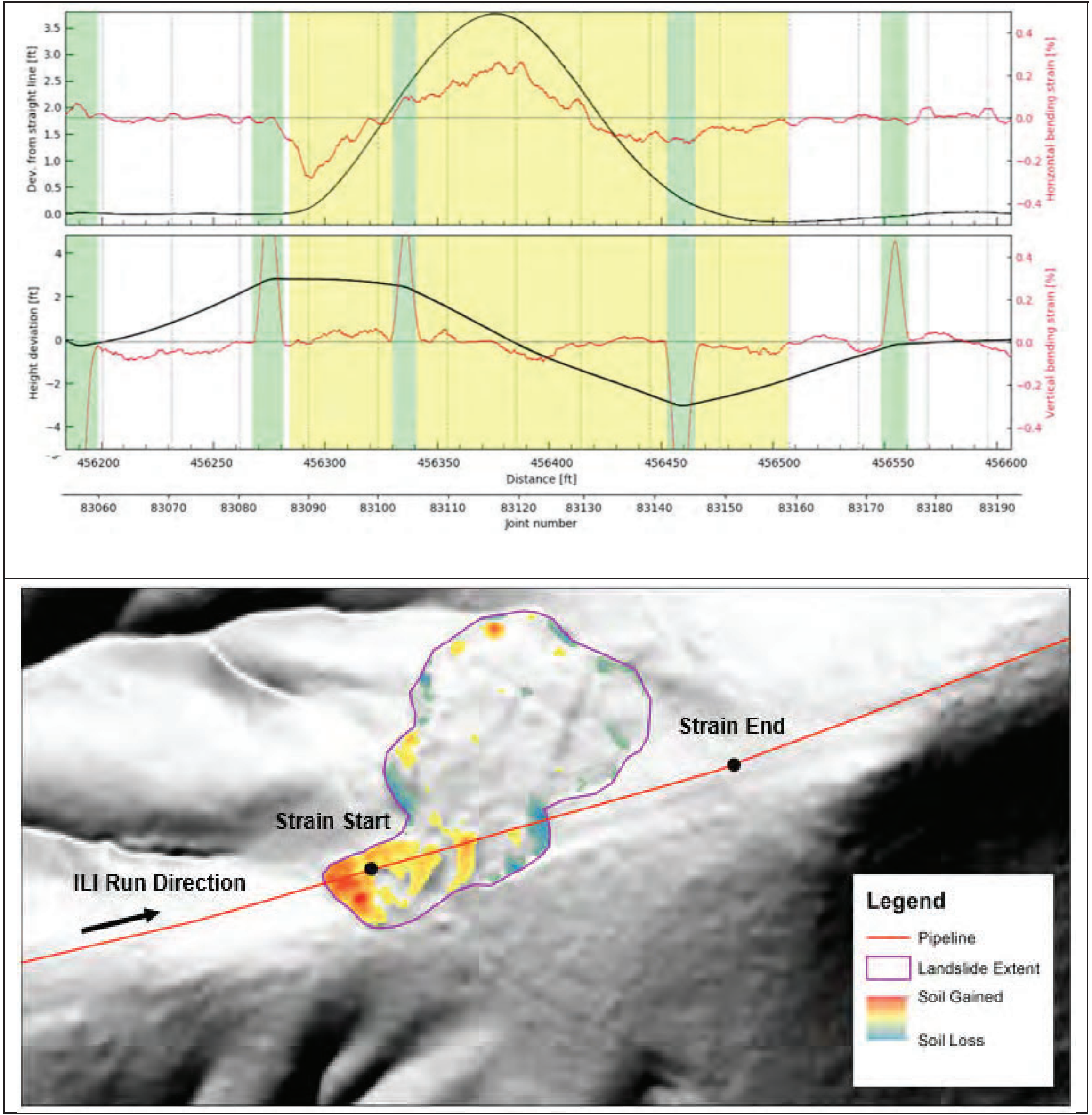

Figure 8. Case Study #2, 24-inch crude oil pipeline segment with landslide and pipeline movement

The results of the IMU-based bending strain and LiDAR-based geohazard assessments are in agreement. The bending strain anomaly indicates leftward displacement of the pipeline, oriented in the downslope direction. The region of identified ground movement intersects the upstream half of the bending strain anomaly, where the highest strains are observed. The 2018 IMU ILI has revealed that movement began prior to the 2018 inspection. The change detection identified using the 2019 and 2020 LiDAR datasets shows that this hazard has continued to be active during subsequent years. Although it is beneficial when IMU and LiDAR data has been collected at approximately similar

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intervals, this study illustrates how valuable this approach is when data has also been collected at distinctly different times – a landslide has been detected and it is actively affecting the pipeline.

Once again, material limit calculations and a coincident anomaly review would be recommended during the prioritization stage for this area. The presence of high strain and patterns consistent with active movement are key indicators that remedial interventions are likely required for this site. For this site, Marathon performed strain relief and remediated the hazard.

Case Study #3

The third case study is located within the same pipeline system as Case Study #2, situated approximately 2.6 miles to the Southwest, with similar geographical characteristics and high potential for karst development.

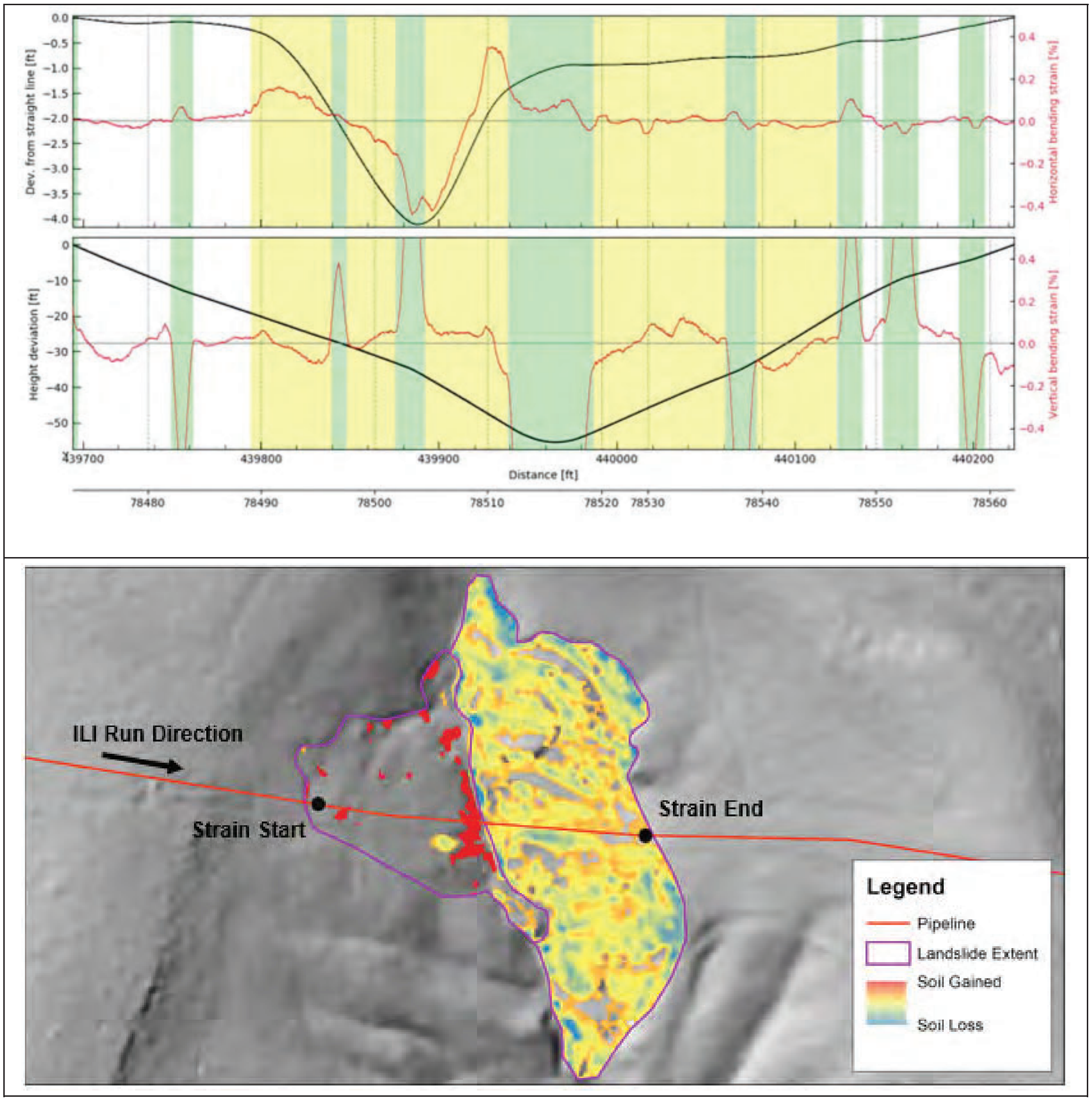

Figure 9. Case Study #3, 24-inch crude oil pipeline segment with landslide and pipeline movement

As with Case Study #2, the top panel of Case Study #3 depicts the plan and elevation profiles of the pipe centerline, with the calculated out of straightness and bending strain for each plane. The IMU data was collected in 2018 and the maximum observed bending strain falling within these extents is 0.425%, well above the detection threshold of 0.125%. The top plot of Figure 9 indicates high strains and characteristics of rightward movement (observing the pipeline from upstream to downstream) in the first half of the anomaly. In the vertical plane, minor strains are present and vary throughout. Once again, these particular patterns and the horizontal orientation of the bending strain are highly indicative of ground movement. The middle of this bending strain anomaly is coincident with a naturally formed drainage path. The rightward orientation of the pipeline's displacement is consistent with the downslope storm water runoff direction.

The bottom panel of Figure 9 shows the vertical change in terrain (soil movement) for the landslide outlined in purple between spring 2019 and fall 2020 with warm tones being areas of soil gain and cool tones being areas of soil loss. This figure illustrates that the landslide is highly active through the western side with a sub-scarp slope (cool tones) intersecting the pipeline (red line). This activity also highlights the direction of movement which is perpendicular to the pipeline which cuts the landslide in half. Based on Teren's ranking algorithm, this feature was classified as a 9 on a scale between 1 and 10, 10 being the highest ranking. This ranking was assigned because the scarp slope and toe slopes are above and below the pipeline, it is moving perpendicular to the pipeline with 40 percent of the landslide above it, it is relatively very large (2.2 acres), and on a steep slope (36 degrees).

Once again, the results of the IMU-based bending strain and LiDAR-based geohazard assessments are in agreement. The bending strain anomaly is fully encompassed within the independently delineated landslide extents. The orientations of the observed pipeline movement and the landslide match that of the storm water runoff path. By combining the results of these two standalone assessments, using data collected over a three-year timespan, it was possible to detect the existence and characteristics of this geohazard, as well as its influence on the pipeline.

The presence of high strain and patterns consistent with active movement are key indicators that remedial interventions are likely required for this site. To determine the severity of loading on the pipe, determination of the compressive and tensile strain capacities would be recommended, along with a review of other interacting anomalies. For this site, Marathon performed strain relief and remediated the hazard.

Discussion

The aforementioned case studies illustrate the proposed method's ability to detect and characterize high-risk geohazards and their related impacts to pipelines. This boasts not only a high level of efficacy, but also of efficiency. This approach can be implemented into any geohazard management program to not only identify hazards, but also to monitor hazards which have not yet triggered remedial actions. This may be the case for active ground movement which has not adversely impacted the pipeline. Even more valuable to resourcing efforts, this assessment method provides the ability for integrity engineers to identify areas in which ground movement has taken place, but the slip is above and not influencing the pipeline itself. Finally, it can also be used to track the effectiveness of remediation that has taken place to ensure such interventions are performing as expected.

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Conclusion

The presence and influence of geohazards pose many challenges for pipeline integrity. This is due to the increased frequency of soil-mobilizing extreme weather events, public awareness, and regulatory requirements. As concerns regarding ground movement and pipelines continues to grow, finding efficient and scalable solutions will be demanding.

To adapt to the present operational environment, Marathon Petroleum has adopted modern methods of identifying and tracking geohazards that leverage highly efficient processes and emerging technology. This includes geohazard identification and landslide detection using LiDAR digital terrain models and AI analysis, corroborated with identification of bending strain and pipeline movement using IMU. In tandem with these measures, additional checks against material limits and interactions with other pipeline anomalies allows for efficient and informed prioritization of areas of detected movement.

The case studies reviewed in this paper highlight the efficacy of the proposed approach. Each study utilized real world data from historical landslide locations to reveal pipeline movement coincident with soil displacement. As the pipeline industry continues to adapt and grow to meet modern challenges, strategies such as this will be required to ensure the safety of operational assets.

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