A Novel Method for Geospatially Organizing and Integrating IMU Bending Strain Feature Data to Optimize Geohazard Threat Detection

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Abstract

In line inspection (ILI) inertial measurement unit (IMU) bending strain features can provide key insights for early detection of geohazard risks to pipelines. A program of regular IMU data collection yields significant quantities of data. Appropriate organization, analysis, and integration with other key datasets enables integrity managers to maximize their returns on investing in this data collection. Earlier publications have shown that, with the incorporation of IMU into a geohazard program, the number of identified critical geohazard sites doubled, implying that IMU allows earlier identification of critical sites (Van Hove et al., 2024). This paper explores a novel approach of applying a data model to IMU data that both geospatially organizes the data and integrates the data with lidar, lidar change detection, InSAR, geohazard inspections, landslide hazard mapping, and instrumentation data. The data model establishes the relationship between ILI runs, bending strain reporting, IMU bending strain features, and IMU bending strain inspections. A software platform is used to visualize these data and enable workflows to enhance geohazard threat detection, assessment, and monitoring. Data associations are established with the geohazards threats such that analysts can easily investigate the geohazard and IMU bending strain feature histories, recommend and track next actions, and monitor changing conditions that could accelerate geohazard activity and impact the pipelines. This approach is currently in use by 12 pipeline operators in the United States and Canada.

Introduction

Threat detection for pipelines impacted by geotechnical loading, particularly from ground movement hazards such as landslides, bank failures, and subsidence, can be challenging given the vast geographies traversed by pipeline networks. Typical hazard inventories include hundreds to thousands of geotechnical hazards, necessitating classification of sites according to probability of failure or risk (Newton et al., 2019). Site-specific instrumentation is expensive to install and monitor and is therefore typically reserved for sites with the highest perceived risk; this means that sites with subtle signs of hazard activity may not be instrumented, and changing conditions are harder to detect.

Inertial measurement unit (IMU) data is collected over broad swaths of pipeline and can be used to monitor for ground movement impact to a pipeline anywhere within the collection length. The IMU curvature data can be transformed into bending strain and used to evaluate the actual shape of the pipeline (Hart et al. 2019). Considered with the pipeline's orientation to a given slope, the bending strains showing a pipeline bent "out of straight" and/or strains changing between runs can be indicative of a geohazard deforming the pipeline. The significance of a particular bending strain area is assessed by considering whether the strain pattern is consistent with the way a coincident ground movement hazard would deform the pipeline (Dowling et al., 2024). The bending strain magnitude also gives partial insight into the strain demand that the pipeline is experiencing (axial strain, which cannot be measured by IMU, would be needed to characterize longitudinal strain demand). Considering that IMU data is often collected as part of a standard inline inspection (ILI) run (adding minimal cost to existing integrity plans where ILI data acquisition was already budgeted) and is able

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to collect monitoring data for multiple geohazard sites in a single ILI run (including hazards that may not have been escalated or identified by other means), IMU bending strains are proving to be a valuable geohazard management tool.

The benefits of IMU, combined with regulator guidance, have led to its incorporation into geohazard management programs (Dowling, et. al., 2024; Van Hove, et. al. 2024; Scheevel et al., 2022; PHMSA, 2019). However, the same attributes that make it so valuable—broad coverage, ability to be parsed for distinct “strain features” at multiple sites, strain change due to changed conditions (often integrity digs) — result in data management challenges. Many IMU bending strain features are not indicative of geohazard impact and assessing and documenting interpretation is imperative. Figure 1 conceptualizes BGC Engineering (BGC)’s experience of incorporating more than 13,000 IMU interpretations into geohazard management programs, showing that geohazard sites where critical interventions have taken place also have pertinent IMU findings (Van Hove et al. 2024). Yet, the vast majority of IMU bending strain features identified by ILI vendors are unrelated to geohazard impact (McKenzie-Johnson et al., 2024; Scheevel et al., 2022; Theriault et al., 2019).

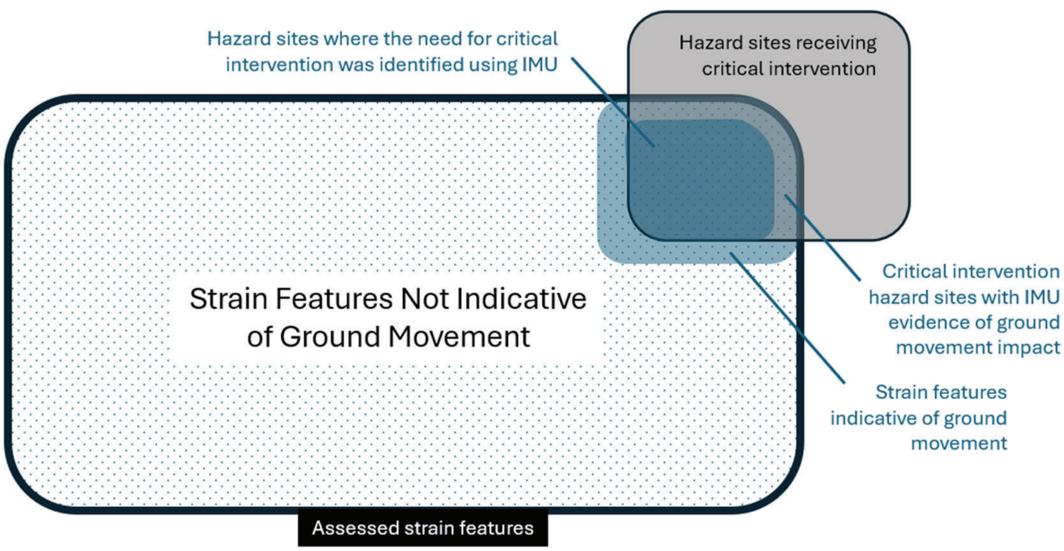

Figure 1. Conceptual visualization of scale challenges with IMU data. Critical geohazard sites usually have evidence of pipeline impact in IMU, but most IMU features are not geohazard-related.

Despite the challenges, the use of IMU data, in combination with traditional geotechnical hazard delineation, yields the most robust hazard inventory. This is because the bending strains can be used to identify locations where the pipeline has been deformed by geotechnical loading (Dowling, et al. 2024, Van Hove et al. 2024) and the strain magnitudes can help operators evaluate their probability of failure at a given site.

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Problem Definition

Several challenges exist with the management of IMU data, primarily related to the geospatial nature of the data and the large volumes of data that need to be effectively classified before they can support actionable decision-making in geohazard management programs.

Geospatial Considerations

IMU bending strain features must be georeferenced before they can be systemically incorporated into a geohazard management program. This is because operators need to be able to link features to their existing geohazard inventory. Once features are georeferenced, hazard management rankings can be adjusted to consider the ILI vendor-reported magnitudes of spatially coincident strains. However, co-location does not inherently mean that a strain feature was produced by ground movement (Dowling et al., 2024; Scheevel et al., 2022). Strain interpretation assesses causality. A trained analyst evaluates the coincident hazard morphology and asks: "if this particular ground movement hazard is active, how would the pipeline be laterally and vertically deformed here, and do I see evidence of that pattern in the data?" Reasonable assessment of the strain feature is dependent on accurate rendering of the feature location.

Managing Repeat Datasets

IMU data is often re-collected over the same area at multiyear intervals. In a scenario where the same strain feature is flagged in Year A and in Year B, there is no intrinsic link to identify that Strain A is the same as Strain B. The exact extents of the strain features often differ between runs (potentially due to changed ILI vendors, methodology updates even within the same vendor, vendor judgement, influences of tool effects, or other causes (Dotson et al., 2024)). The most robust way to identify re-reported features is to compare their geospatial extents, further emphasizing the importance of storing the data geospatially.

The more IMU data collected, the more complex the data management becomes. If 100 strain features were identified in Year A, and the same 100 features were re-reported in Year B, 200 strain features now need management even though they are duplicates of each other. In addition, strain feature metrics are typically summarized in a single spreadsheet per ILI run, leaving operators without a database management strategy in possession of hundreds of independent spreadsheets. The sheer quantity of IMU data that is accumulated over a pipeline network necessitates the use of relational databases for effective data management.

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Storing and Surfacing Interpretations

The interpretation of bending strain features as ground movement related or unrelated informs management actions. However, interpretation is challenging because, although ground movement produces bending signatures, pipelines are bent for many other reasons that are unconnected to ground movement hazards, and these bends also get flagged as "strain features." Analysts must therefore assess strain curves with consideration of the position of the bends relative to the terrain, consistency of the bend geometry over time, position of the bends relative to girth welds, history of integrity digs, and other construction on the pipeline. As well, backfill and roping signatures can sometimes be misinterpreted as associated with ground movement. BGC's analysis of more than 13,000 vendor-reported strain features has found that 70-90% of bending strain features identified by ILI vendors are unrelated to ground movement (typically construction or integrity dig related) and 2%-13% of features are related to ground movement. Documenting the evidence of the analyst's interpretation provides defensibility and saves time going forward when the same feature is re-reported.

Once the assessments have been carried out, sound data management practices are required to track the results of the analysis. This ensures that a subsequent strain call that results in identification of a bending strain features in the same geospatial positions can be assessed as related or unrelated to ground movement going forward.

What to Do?

Relational databases are critical in the ongoing management of the features and automation of their association with previously identified ground movement features and previously identified IMU features significantly reduce data management time and the potential for errors. Automated ingestions of the IMU data into the database are imperative. Too often pipeline operators maintain vast collections of spreadsheets representing tremendous amounts of IMU data, but the critical insights contained within the spreadsheets are not exposed until a geotechnical threat accumulates critical strains. Early detection of strain accumulation is possible when the data is parsed geospatially, anomalies are characterized as bending strain features, and interpretation of the bending strain features is well documented by analysts. Finally, applying a layer of review to the interpretation improves quality.

To address the problems defined in this section, a novel approach to geospatially organizing and integrating IMU bending strain feature data into a geohazard management system was developed with the objective of optimizing geohazard threat detection. An IMU data model was developed and integrated with data management, visualization, and workflows that support ongoing geohazard integrity management.

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IMU Data Model

A data model was developed to represent IMU data in a repeatable and consistent way with the purpose of improving the state of IMU data management for geotechnical threat assessment. Data models take real-world elements and abstract them by defining them as a standard set of properties that relate to one another. The data model normalizes data produced by variable ILI vendors and IMU analysts. The model defines the critical, required fields (i.e., peak resultant strain) and provides space for additional characteristics to be documented that may not be available in all cases (i.e., tensile strain capacity).

The data model consists of four main structures: ILI runs, Bending Strain Reports, Bending Strain Features, and Strain Feature Inspections (Figs. 2 and 3). These are defined as follows:

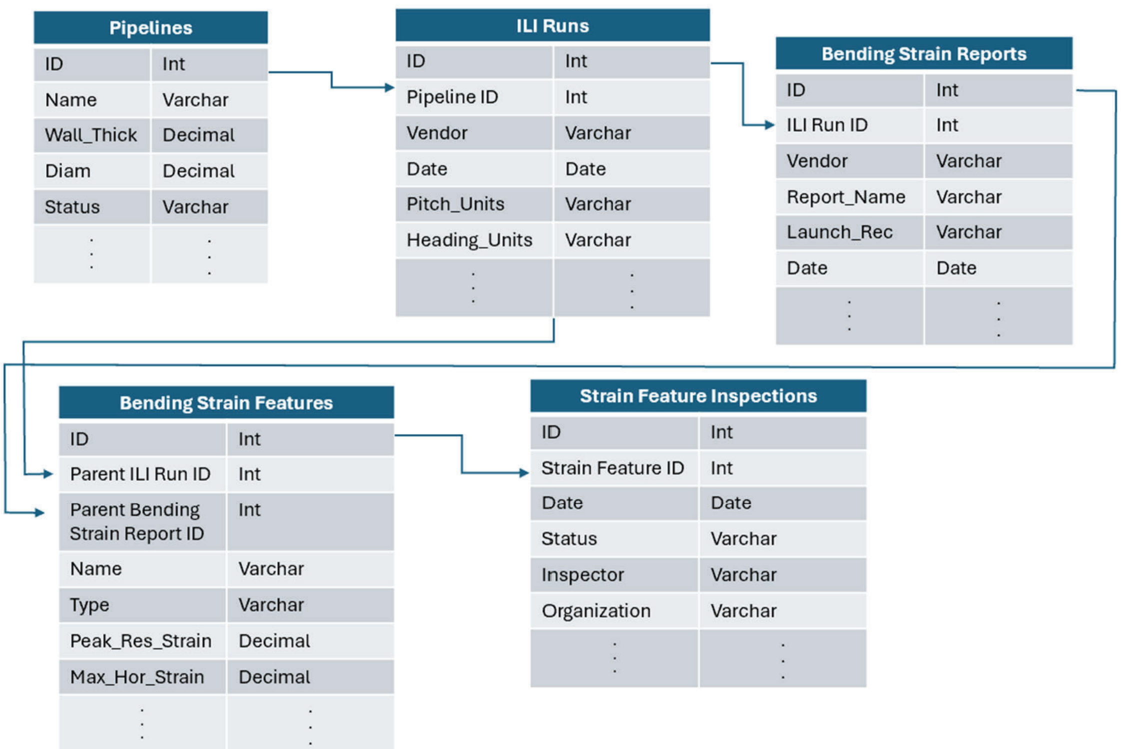

Figure 2. Partial relational schema of the IMU data model.

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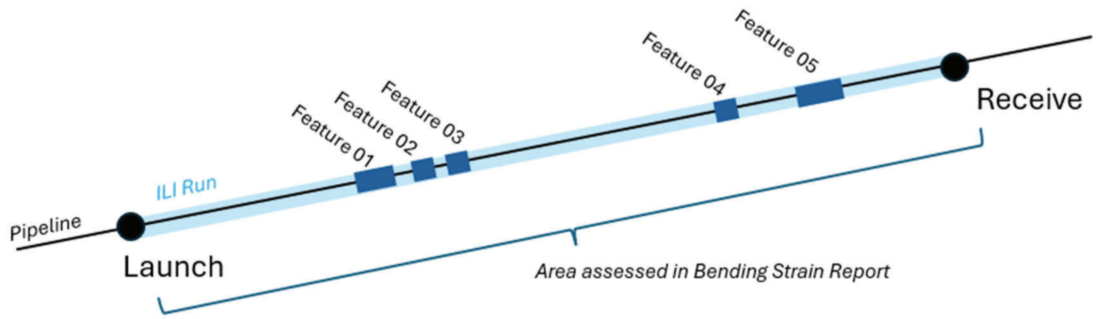

Figure 3. Graphic representation of the IMU data model elements.

ILI runs – Conceptually, the ILI run record represents a unique run, characterized by run date, pipeline inspected, geospatial length of the run (between tool launch and receive), and ILI vendor. The ILI run data record is relationally associated with the pipeline, has a unique ID for each run, stores metadata about the run, and defines the geospatial length of the run. The relationship of pipelines to ILI runs is one-to-many.

Bending strain report ("Reports") – Conceptually, the bending strain report represents the ILI vendor's analysis of the IMU data for anomalous strains. Operators do not commission bending strain reports for every ILI run, so this record is optional within the data model. The report record is relationally associated with the applicable ILI run, has a unique ID for each report (including report revisions), stores metadata about the report (i.e., vendor, report name, date issued, dates and tool types of compared ILI runs) and summarizes the vendor's analysis parameters (such as threshold bending strain magnitude, threshold bending strain change, and gauge length). The vendor's report file (typically a spreadsheet or PDF) is attached to the report record. The relationship of ILI run to bending strain report is one-to-many.

Bending strain feature ("Features") – Conceptually, the feature represents a specific area where anomalous strains have been identified by a vendor or an analyst. Features are defined in the data model based on their measured or calculated characteristics like peak resultant strain, maximum strain change, etc. but do not contain data related to interpretation. Plotted bending strain data becomes accessible at this level of granularity in the data model. The feature record is relationally associated with the pipeline, ILI run, and strain report (optional, if the feature was manually selected), documents the strain feature information (ID, name, date, previous run date), origination data (i.e., who identified the feature, when, gauge length used, processing method), spatial data (center location, geospatial position of the feature on the pipeline), strain metrics (such as maximum horizontal and vertical strains), girth weld strain data, and changes in strain metrics since last run. Strain plots and other files may be attached to the feature record. The relationships of ILI run to strain feature and of strain report to strain feature are both one-to-many.

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Bending strain feature inspection ("Inspection") – Conceptually, the inspection represents the interpretation of the strain feature at a particular point in time. Multiple inspections can be added to the strain feature if different information is known at different points in time. The inspection record is relationally associated with a bending strain feature and documents inspection metadata (analyst who completed in the interpretation, date of inspection, organization), geomorphic analysis (coincident with hazard morphology, ID of related ground movement features, pipeline orientation to movement vector), history (coincident integrity digs, nearby construction, or extraction), interpreted magnitudes if different than vendor statistics (interpreted maximum girth weld strain, interpreted strain change), pattern (horizontal and vertical sinusoidal pattern and change, continuing change through time, deforming formed bends), and overall conclusion (slope movement signature, settlement signature, Tier classification [Scheevel et. al., 2022, Dowling et. al. 2024], hazard activity changes), and summary comments. Attachments (any files, photos, and plots) are linked and typically include annotated strain plots. The relationship between strain features and strain inspections is one-to-many.

Data Integration and Management

The IMU data model forms the basis of the IMU module of the Cambio geohazard risk management platform (Fig. 4), which integrates the IMU data with other data models for geohazard sites, ground movement hazards, geotechnical inspections, and geotechnical instrumentation.

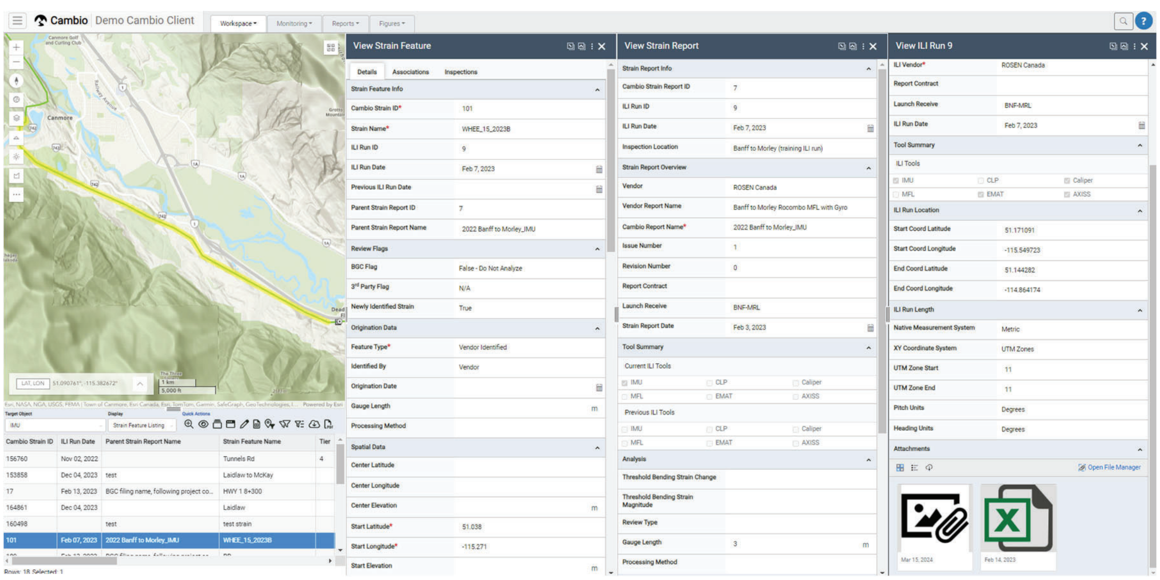

Figure 4. IMU data management platform.

It is the combined understanding of the ground movement hazards and the IMU bending strain features that yield the actionable interpretation of the data, and the challenge is to integrate the data efficiently so that insights can be surfaced quickly as new information becomes available from either the geohazard risk management program or the IMU tool runs.

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Automated Geospatial Data Ingestions

A data pipeline to ingest IMU data from vendors was developed to streamline the process of parsing data from vendor strain reports and upload the raw and processed data to the cloud-hosted Cambio software platform. The most complex element of the ingestion process is attributing geospatial data. The ILI run length must be snapped to the pipeline, and the length of the pipeline encompassed within individual bending strain features must be spatially represented as well. This is critical to being able to compare subsequent runs, and automatically associate bending strain features with mapped ground movement hazards.

Ingest and Generate Geometries for IMU Strain Features and ILI Runs

The direct implementation data ingestion for IMU data is vendor specific, as all vendors have a different format for representing data collected during an ILI run; however, the process revolves around three key steps:

1) Generating the linear feature that represents the extent of the ILI run and associating the run to segments of the pipeline dataset.
2) Extracting the tabular data/metadata for all components of the run: ILI Run, Bending Strain Reports, and Bending Strain Features. These are stored in the relational database in the format described above.
3) Generating the linear features for each of the identified bending strain features. This is done via a reference to pipeline datasets, the geometry of the parent ILI run, and the strain feature's own spatial metadata.

Spatial Algorithms Used to Generate Strain Features

Because the data format varies substantially between vendors, the spatial algorithms for generating strain feature geometries rely on linear referencing to pipeline infrastructure based on the spatial information the provided by the vendor about the identified strain features. When an ILI run is created, it is associated with a list of pipeline segments from the pipeline database. These pipeline segments serve as the base from which the features are generated. Different vendors provide different reference points – for example, some provide the location of the feature's center point and a total feature length, others include the location of the peak strain point and length, and some directly provide the start and end coordinates.

The combination of a spatial query and other metadata is used to filter the list of pipeline segments associated with the ILI run down to the closest pipeline segments to the strain feature. The reference point of the feature is then interpolated onto the pipeline segment. Once linearly referenced, the rest of the strain geometry is generated based on the data provided by the vendor. For example, if the

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vendor provided a center point of the feature, the center point is interpolated onto the associated pipeline segment and then the length of the strain feature is used to determine the start and end points of the feature along the pipeline segment. The pipeline segment is then split according to these interpolated start and end points, which results in a strain feature geometry that maps directly onto the pipeline digital centerline.

Integrating IMU data with Ground Movement Hazards

Once the geospatial data has been populated, intersecting IMU bending strains and mapped ground movement hazards are associated. Due to the robust data model employed by the platform for defining geotechnical hazard sites, documenting inspection histories, and associating geotechnical instrumentation, significant insights can be derived from these intersections. The likelihood of an IMU bending strain feature being ground movement significantly increases when the feature is identified to be spatially coincident with a ground movement hazard that was observed to be active based on prior ground inspection or geotechnical instrumentation data.

Data Visualization and Workflows

Once the IMU data has been ingested into the IMU data model and the bending strain features have been associated with ground movement features that have been previously mapped (where available), analysists must complete their interpretation of the features. This is most easily done on a platform that has previously integrated the relevant data sources for ground movement hazard interpretation, such as Cambio.

In the absence of significant prior geohazard identification and assessment work, intersection of the IMU data with publicly available landslide susceptibility maps can be used as a starting point for interpretation. The platform used for this work has pre-integrated with relevant United States Geological Survey (USGS) data sources such as the (3D Elevation Program) 3DEP lidar topography, landslide susceptibility mapping, and the National Aeronautics and Space Administration (NASA) global landslide hazard assessment (LHASA) model that provides a nowcast of landslide conditions. Intersection of the IMU bending strain features with these datasets can provide tremendous value at the outset of ground movement hazard identification, mapping, and assessment.

Visualization of additional data sources such as InSAR and lidar change detection (LCD), which visualize ground displacements, support the assessment of hazard activity, movement rates, as well as indicate the relative position of displacements relative to the IMU bending strain features identified (Fig. 5).

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Figure 5. Co-visualization of IMU data, LCD, and ground movement hazard mapping.

The combined visualization of these data sources with the IMU bending strain plots provide the IMU analysist with the information needed to correctly interpret the IMU data. The bending strain plots show the bending strain magnitudes as a function of distance along the pipeline. Correlation of the bending strain signatures with the ground movement hazard signatures obtained from lidar topography and LCD can indicate causality of the feature from ground movement sources. This interpretation can then be documented in the IMU bending strain feature inspection.

The workflow for bending strain data management is shown in Fig. 6. This workflow has been used by 12 pipeline operators in North America to optimize detection and assessment of IMU bending strain features.

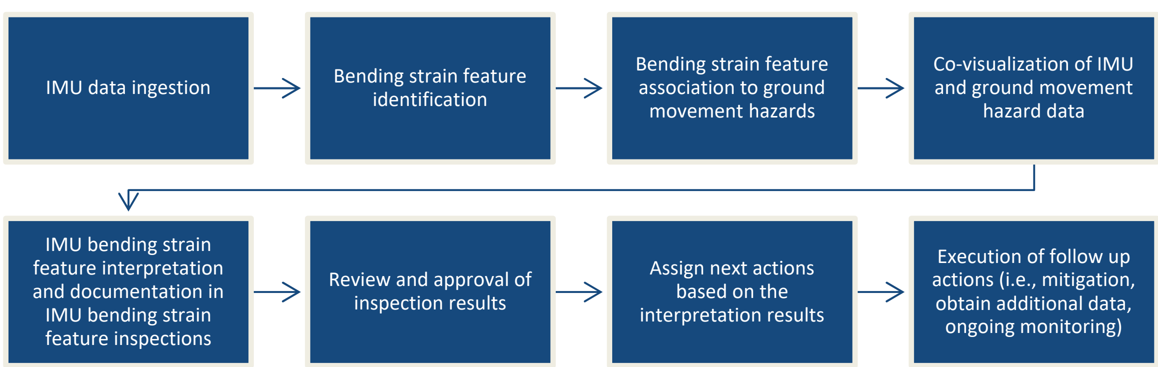

Figure 6. IMU data management workflow.

Of critical importance is the integrity management actions that are the outcome of the combined IMU and ground movement hazard assessment work. As documented in Newton, et. al. 2019, assessment of the hazard alone does not yield risk reduction for the pipeline system. Management actions reduce risk (i.e., monitoring with effective thresholds and action points, stress relief, or mitigation). Systematically documenting, tracking and completing actions at the hazard sites is ultimately what leads to better pipeline integrity performance over time.

Maximizing Returns on IMU Data Collection Investment

Organization, analysis, and integration of IMU data with other key datasets enables integrity managers to maximize their returns on investing in this data collection. Early detection of subcritical strains accumulating on pipelines from geotechnical loading enables proactive intervention, reducing the need for emergency stress reliefs, unplanned mitigations, and ultimately geohazard-related pipeline ruptures.

Case Study: Data Integration in Re-Reported Area

The following Case Study demonstrates how effective management of IMU data can aid effective decision making and monitoring. Considering the slope in Figures 7 and 8, the operator has collected IMU data on both pipelines in the right of way (RoW) but only one has a reported strain feature. Assessment of the strain data between 2011 and 2020 identified that strain growth was occurring within the landslide toe and that the strained pipeline was impacted by the ground movement hazard. The lack of strain on the adjacent pipeline indicated that the other pipeline had not yet been impacted by the landslide at the time that the IMU data was collected. This was potentially because the second pipeline was constructed outside of the landslide or because the pipe properties made it more resilient to deformation. The strain interpretation on both pipelines was critical to deciding that a proactive intervention was warranted.

IMU bending strains coincident with the red strain feature are plotted from 2011, 2017, 2020, 2021, 2023, and 2024. The operator installed drainage and monitoring instruments at the site in 2021, including a shape accel array (SAA) which measures the real-time rate of ground deformation at depth in a vertical borehole. The drainage mitigation consisted of installation of two curtain drains on a portion of the slope as well as an outlet drain to direct water off slope. Since mitigation, repeated IMU data in 2021, 2022, 2023, and 2024 have not shown additional strain change.

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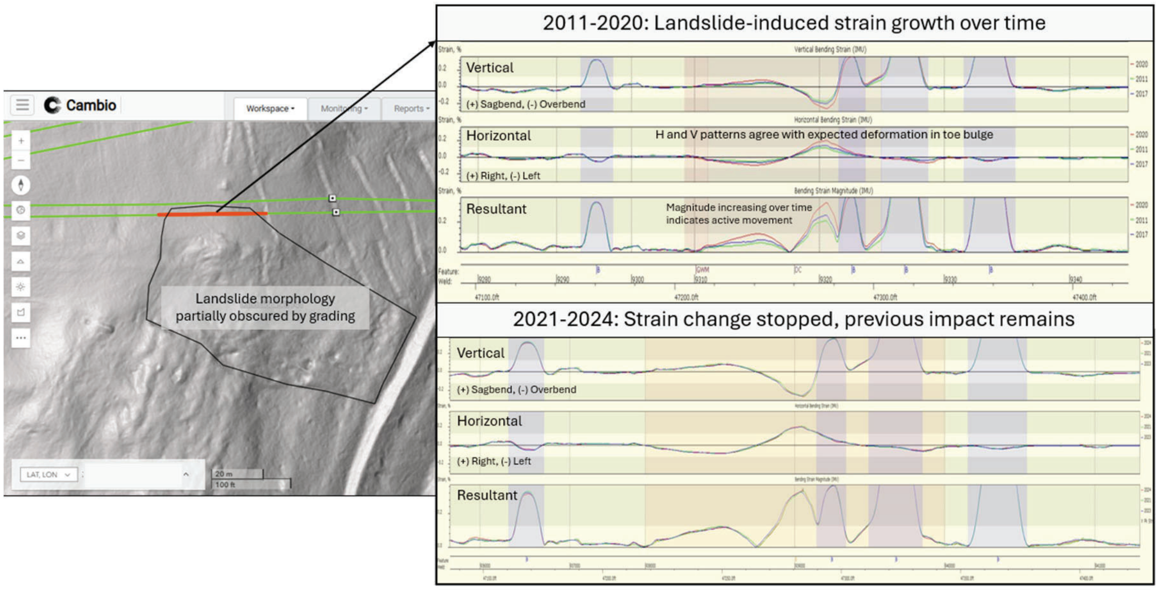

Figure 7. Lidar of the case study site is shown with centerlines (green), strain feature (red), and the interpreted landslide extent (black).

The SAA has detected <1 ft/yr of continued movement in the slide mass, but the lack of strain change on the pipeline suggests that the drainage mitigation has so far successfully stabilized a localized area around the pipeline. Should the pipeline become re-engaged by the landslide and strain change be reported in the next IMU dataset, the IMU data management strategy is expected to indicate the changed conditions for re-review.

Figure 8. View of SAA casing at case study site that was installed during drainage mitigation.

Conclusions

This paper presented the methods used to geospatially organize and integrate IMU bending strain data with geohazard risk management practices as part of an overall pipeline integrity management program. The combined interpretation of IMU data with ground movement data using a robust data model, visualization platform and hazard management workflows is an essential part of best practices in reducing the probability of geohazard related pipeline failures and emergency interventions.

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