Ground Movement or Construction? How to Identify Clear Ground Movement Signatures in Inertial Measurement

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Abstract

Inertial measurement unit (IMU) bending strain data has been recognized as a crucial tool for detecting ground movement impact along operating pipelines. In Line Inspection (ILI) vendors produce bending strain and movement reports which often include impact from landslides and sinkholes, but also include a host of other causes. While these bending strain reports serve as a useful initial screening tool, previous studies have found that often over 90% of these reported features are related to pipeline construction or operation, not ground movement impact. It is not uncommon for hundreds of bending strain features to be reported on a single 100-mile pipeline segment, and it is important for pipeline operators to be able to identify ground movement caused bending strains. Unlike construction-related bending strains, ground movement tends to increase strain demand over time and often have a larger longitudinal strain component because of axial loading or pipe elongation. Often, landslides and sinkholes produce signatures in IMU data that are evident during a cursory review by subject matter experts (SMEs) with experience in geohazard mechanisms. Drawing upon 10 years of experience using IMU data to characterize and monitor geohazard impact along pipelines and geotechnical assessment of more than 6,500 bending strain features, this paper provides examples of common IMU signatures indicative of landslide and sinkhole impact with the intent that operators can learn to understand ground movement mechanisms that produce IMU bending strain and how SMEs prioritize these for further assessment or action. Examples of signatures from single run and run-to-run IMU data are presented along with a discussion of the basic mechanisms that produce the signatures. Key ground-movement signatures within other IMU outputs such as pitch, heading, and out-of-straightness (OOS) are also discussed. Construction-related IMU signatures are provided to help operators understand how these differ from ground movement signatures.

Introduction

Inertial Measurement Units (IMU) have become standard tools included in In Line Inspection (ILI) runs performed by pipeline operators. Data from IMUs provide the x, y, and z position of the pipeline over time and can be used to calculate pipe curvature and from that, bending strain (Hart et al, 2019). These tools are used to provide accurate pipeline positional data, as well as identify areas of anomalous bending strain induced by either ground movement or from pipeline construction. In conjunction with traditional geotechnical assessment techniques, IMU bending strain data can be a useful tool for geohazard identification and characterization as it can indicate pipeline impact from ground movement as well as provide information on the ground movement pattern and extents of the impacted pipe. Essentially, the IMU data enables the pipeline to become a horizontal slope inclinometer, a typical in-ground installation that is utilized by geotechnical engineers to measure slope movement and rates. ILI vendors have been able to distinguish intentional bends (bends formed either in the field with a pipe bending machine or in the mill through induction) from unformed bends (bends unintentionally induced on the pipeline either during construction or from

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ground movement) by assessing the location and length of the bending strain and the strain magnitude. However, the majority of these reported bending strain features have been found to be construction related, rather than related to soil loading associated with a geohazard.

This paper seeks to demonstrate the value in assessing IMU bending strain signatures as part of a geohazard management program and introduce pipeline operators to the basic ground movement mechanisms that induce bending strain. The paper provides an overview of common bending strain signatures induced by geohazard loading scenarios and provides an explanation of the ground movement mechanisms and loading that create the patterns. The paper reviews not only what the signatures look like in vertical and horizontal bending strain profiles, but also how they appear in position, pitch and heading plots. Common construction-related bending strain signature examples are also provided. The examples provided are simplistic to demonstrate the key signatures and loading mechanism; however, in most cases, the loading induced by landslides is complex and the bending strain signatures are often much more complicated. Additionally, bending strain is only one component of the total longitudinal strain demand induced by landslide loading, and IMU bending strain assessments need to consider the proportion of axial loading anticipated based on the length and orientation of ground movement in relation to the pipeline. In practice, assessing IMU bending strain data for evidence of ground movement impact requires a deep understanding of landslide processes and mechanics and should be completed by qualified subject matter experts (SMEs). This paper seeks to enable pipeline operators to understand how they can best leverage the value of IMU bending strain reports in geohazard assessment and prepare them to understand how loading induced by ground movement produces identifiable patterns within bending strain data.

Background and Previous Work

Inertial measurement units have been used for pipeline geometric survey since the late 1980's to detect pipeline deformation related to ground movement. As described in Chyz and Adams (1994), the pitch and heading is measured and combined with the odometer distance to provide the northing, easting and elevation, based on surveyed tie-in locations along the pipeline route. This orientation information can be differentiated with the odometer distance to calculate pipeline curvature, which is proportional to bending strain. Bending strain reports are now a common add-on to ILI tool runs. Within these reports, vendors provide a list and plots of bending strain "features" that were either induced during pipeline construction or from post-construction ground movement or third-party impacts.

In a typical bending strain report, ILI vendors distinguish between intentional bends (i.e., cold field bends or manufactured elbows) and unformed bends by considering a combination of amplitude and length of a bending strain feature. Intentional bend signatures have a single, relatively high strain bending lobe (i.e. a curved/rounded shape similar to half of a sine wave) contained within a single joint of pipe (typically 40 feet in length) in between two girth welds and are typically provided in

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operator pipe books, while unformed bending signatures typically extend over much longer pipeline lengths and multiple pipe joints and have relatively lower bending strain amplitudes. Unformed bending strain features are typically those identified in a vendor bending strain report.

A typical vendor bending strain report may have anywhere from tens to hundreds of identified bending strain features over a given pipeline segment. However, as found by others, (Scheevel et al., 2022; Theriault et al., 2019; and Hart et al., 2019), the majority of vendor-reported bending strain features (typically over 90%) are not related to ground movement but are likely the result of construction. When IMU bending strain features are assessed in conjunction with geohazard inventories and high-resolution topographic data (i.e., lidar data), bending strain features can be further screened to reduce the number of IMU features that may be related to ground movement. Theriault et al. (2019) assessed whether bending strain magnitude and orientation (horizontal vs vertical) correlated with geohazard presence, finding that higher magnitude bending strains greater than 0.35% and horizontal bending strain greater than 0.15% did tend to correlate with geohazards. However, just because a bending strain feature may coincide with a documented geohazard, it does not mean the feature is related to ground movement. Also, relatively small magnitude bending strain features that correlate with a geohazard may be indicative of ground movement impact. Scheevel et al. (2022) advocates not only assessing whether bending strain features correlate with mapped geohazards but also reviewing the bending strain signatures with the anticipated ground movement mechanism and site history to evaluate whether the bending strain does indeed indicate ground movement impact. In their assessment, Scheevel et al. (2022) found that by reviewing IMU bending strain signatures with this additional insight, a prioritized subset of previously identified geohazard sites was able to be refined to a prioritized list approximately 10% the size of the original inventory. This method of combining an understanding of the slope movement mechanism, site history, and bending strain signatures can be used to effectively identify which sites are impacted by ground movement, providing the clearest picture of whether geohazards are impacting the pipeline. Being able to distinguish IMU features consistent with ground movement from construction-related ones is valuable as using magnitude or bending strain orientation alone can lead to unnecessary integrity digs or missing key geohazard sites.

Typical data required for Geotechnical IMU Bending Strain Review

To describe how IMU signatures are evaluated in conjunction with an understanding of geohazard mechanisms, a high-level overview of the necessary data is provided. The IMU data requirements are based largely on the work outlined in Hart et al. (2019).

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Inertial Measurement Unit Data and Plots

To assess bending strain cause, bending strain reports should provide a series of plots for each flagged bending strain feature. Hart et al. (2019), provides a useful outline of plots and pertinent details to include. The recommended "seven panel" plots include:

- Vertical out of straightness or elevation profile
- Horizontal out of straightness profile
- Pitch
- Heading
- Vertical bending strain
- Horizontal bending Strain
- Total Bending strain

In some cases, vendors may provide individual plots for each field listed above or may combine relevant data, such as pitch and vertical bending strain, in single plots. The plots should include the location of girth welds, as well as the location of formed bends (derived either from as-built records or based on the shape and length of the bending strain profile from the IMU data). Plots should be scaled to observe detail along the bending strain features. This is often done automatically by the vendor based on the bending strain feature length and magnitude. Due to the relatively lower magnitude of unformed bending strains compared to formed bends, bending strain along formed bends tends to be cut-off on bending strain plots appropriately scaled to assess unformed bending strain. However, loading from slope movement, particularly axial-oriented movement, can deform formed bends. Because of this, it is often beneficial to include additional vertical, horizontal, and total bending strain plots scaled to show the bending strain magnitude of the formed bends.

As described in Hart et al. (2019), there are unique cases where vendor-provided plots may not suffice to assess potential geohazards. These cases can include large landslides, where bending strain features may only cover a portion of the pipeline length likely impacted by ground movement and the pure axial component of strain (the uniform strain along the cross section of the pipe) may be much larger than bending strain. In these situations, it can be useful to have the vendor provide processed digital data in tabular format so that SMEs can create their own plots at the appropriate length and scale.

Single Run versus Comparison Run IMU Data

Single Run IMU data can provide an indication if the pipeline has been impacted by slope movement in the past; however, there is typically a greater amount of uncertainty of in the assessment. As noted by Hart et al. (2019), it can be difficult to distinguish positive ground movement impact from

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construction, using single-run IMU data alone. Deformation of formed bends (indicative of axial loading) is particularly difficult to assess using single run IMU.

Multiple run (also referred to as run-to-run) IMU data can show whether continued ground movement is occurring by showing changes in bending strain between the timing if the IMU runs. SMEs can evaluate whether the change in bending strain is consistent with the ground movement mechanism or due to repairs/construction activities. Additionally, multiple run IMU can indicate if formed bends are changing over time, which is useful to identify axial loading. For multiple run IMU, additional plots showing the difference between IMU runs are recommended to assess whether the pattern of change is consistent with the anticipated ground movement mechanism.

In order to produce multiple run IMU plots, the IMU data from multiple runs must be carefully aligned through the process of "odometer matching", typically done using a subset of pipeline girth welds or known bends (Clouston et al., 1999; Hart et al., 2020). Vendors can often do this with tabular data from past IMU runs completed either by themselves or other vendors. However, due to differences in tools and processes, there is typically some amount of noise inherent in multiple run IMU data. Hence, many vendors have a bending strain change threshold of 0.04% to define bending strain change features and typically do not call out bending strain change that may appear along identified formed bends.

Multiple run IMU enables IMU data to be used as one method of monitoring geohazard sites, if combined with other instrumentation (slope inclinometers or strain gauges), regular field inspections, and/or remote sensing techniques (lidar change detection and/or InSAR).

The frequency at which operators should acquire IMU data for ground movement assessment is dependent on that rate of ground movement typical within the region. From the authors' experience, a frequency less than 1 year is often too short to positively identify strain change in multiple run IMU data, even in areas with relatively active ground movement, such as the Appalachian Plateau. However, the maximum reassessment frequency required for interstate transmission pipeline (5 years for liquid and 7 years for natural gas transmission pipelines) (49 CFR 195 and 49 CFR 192) is often too long to effectively utilize IMU to monitor ground movement impact along a pipeline. Operators are encouraged to engage with a geohazard SME to evaluate the optimum frequency to complete IMU runs to detect bending strain change and enable operators to act should an integrity threat become known.

Geohazard Information

In addition to IMU bending strain plots, it is important to understand whether they intersect documented geohazards or potential geohazard morphology as well as understand what the likely mechanism and movement direction of the hazard would be. To do this, the extents of the bending strain features should be plotted within a Geographical Information System (GIS) workspace that includes aerial or satellite photographic imagery, lidar data, and the outline and extents of known

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geohazards. With this data, a geohazard SME can evaluate whether the IMU strain feature intersects a known geohazard and can also consider the anticipated ground movement direction and loading patterns. Remote sensing data such as lidar change detection and InSAR can provide helpful insight in evaluating the landslide movement direction and differing rates of movement within larger landslide complexes. Understanding the mechanics of the geohazard and then comparing these to the signature within the bending strain plots is what enables a geohazard SME to assess whether an IMU feature is the result of ground movement.

Site History

Any construction history or past repair records at a site should be compiled into the previously mentioned geospatial database. Information on past integrity digs, past slope repairs and mitigations, pipeline cutouts and replacements, and adjacent pipeline construction is useful in evaluating IMU signatures and in evaluating whether a bending strain feature may be related to a one-time event (such as lateral deflection due to a downslope pipeline installation) or an ongoing hazard that will continue deforming and inducing additional strain on the pipeline. Records of integrity digs are useful to confirm whether vertical bending strain signatures are related to settlement signatures from past digs.

Bending Strain Classification

As outlined in Scheevel et al. (2022), assessed bending strain features should be categorized as either ground movement related, construction related, or unknown. The classified sites should be reviewed with a pipeline operator's integrity team to rate and prioritize for future action. A system outlined in Scheevel et al. (2022) has been utilized as an effective means for classifying bending strain features (Table 1). This classification scheme not only differentiates strain based on cause, but also indicates the level of possible severity of a bending strain feature, both for ground movement and construction-related strains.

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Table 1. Bending Strain Features tier definitions and typical follow-up actions (modified from Scheevel et al., 2022).

	Strain Due to Geohazard-Related Ground Movement?				
	Likely		**Unclear**	**Unlikely**	
Tier	**1**	**2**	**3**	**4**	**5**
Site Description	Critical site (Combination of slide activity, site condition and strain level) with ground movement related strains.	Site with ground movement related strains.	Site with possible ground movement related strains.	Strains not consistent with expected ground movement; max girth weld bending strain ≥0.2%.	Strains not consistent with expected ground movement; max girth weld bending strain <0.2%.
Typical Recommended Baseline SME Field Assessment	Detailed inspection as soon as practical (< 6 months).	Detailed inspection within 6 to 12 months.	Baseline inspection as part of normal managed field program. (>12 months).	Determined by geomorphic factors, no influence from strain presence.	
Typical On-going Management Actions	As per SME/Operator review: • Mitigation • Site-specific monitoring • Routine monitoring			Routine monitoring. Re-evaluate for strain change when new IMU data available.	

Common Characteristics of Ground Movement Induced Bending Strain Features

A bending strain signature consistent with ground movement impact (Tier 1 or Tier 2 as provided in Table 1) tends to have all or most of the following attributes:

- The bending strain feature is located at the crossing of a known landslide or subsidence prone area.
- The direction of the bending is consistent with what would be expected, considering the direction of ground movement.
- The bending feature may be located at a point of differential ground movement such as the margins of a landslide or boundaries between landslide blocks or movement zones. Differential ground movement transverse to the pipeline axis is typically accommodated by pipeline bending.
- The bending feature may be located at an area of suspected longitudinal tension or compression.
- There is a “sinusoid” bend pattern with adjacent bends and reactionary “side lobe” bends which are distinct from typical formed and roped bends.
- The bends do not follow the typical construction signature of formed or roped bends in terms of bend length, location, uniformity, and curvature (see the later section on construction-related bending strain features).

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The last two bullets are discussed in more detail in Hart et al. (2019), which provides a thorough description of bending strain signatures from ground movement but does not discuss evaluating the pattern in the context of potential landslide loading.

The following attributes are also common and strengthen the assessment that the bending strain signature is consistent with ground movement impact:

- Multiple runs of IMU are available and reveal a pattern of bending strain change which indicates ongoing pipeline deformation (e.g., bending strain growth)
- The landslide is known to be active and spatially intersecting the pipeline (e.g., through geotechnical instruments, lidar change detection, axial strain ILI tools or other independent measurements)
- The magnitude of bending strains interpreted to be caused by ground movement impact are different from typical construction bending strain magnitudes (particularly roped bends).

Typical Ground Movement Signatures

Landslides deform pipelines due to lateral, vertical and axial deformation. Lateral deformation and bending strain have been recognized as key indicators of landslide impact in IMU data (Theriault et al., 2019; Hart et al., 2019); however, ground movement also can be apparent in vertical bending strain signatures, particularly at the margins of active ground movement. The following subsections describe typical signatures in IMU data that may indicate ground movement impact and explain the loading scenarios responsible for the signatures.

General Bending Strain Patterns from Ground Movement

The pattern/signature of a bending strain feature refers to the magnitude, direction, uniformity, length and shape of the bend or series of bends, and how the bending strain corresponds to other formed bends and girth welds.

The most common signature of landslide impact is a pattern of sinusoidal bends; adjacent bends with opposing bend direction created by differential ground movement (e.g., at a scarp or toe location). These bend signatures are sometimes referred to as “S-shapes”, “W-shapes”, or “sinusoid patterns”. Typically, the adjacent bends will have opposite bend directions formed by bend/reactionary-bend sequences, but this may be masked-by or overprinted by formed bends and construction related bends. These signatures are characterized by a directional pattern which is consistent with the landslide loading direction and differential movements at the landslide boundaries or at points of differential movement within a landslide, discussed in the following subsections.

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Bend signatures generated by landslide loading tend to have a longer total bend length (tens of meters) relative to formed bends (a few meters), and more variable bend curvature geometry compared to formed bends which tend to have nominally uniform curvature through the bend. The longer bend signature length also means the bends tend to span girth welds, causing elevated girth weld strains compared to other sections of the pipeline outside of the landslide extents. Pitch and heading plots are also useful for identifying landslide-induced bends. Formed bends typically have a consistent ramp in pitch and heading plots that levels off at girth welds, as the curvature is uniform over the bend and is within one pipe joint. The long and variable bending caused by landslide loading produces curved pitch and heading ramps that often cross girth welds (Figure 1).

The magnitude of bending strain induced by slope movement is reflective of the stiffness of the trench material at the interface between stable and moving ground or transitions between zones of differential movement in a slide mass. An abrupt transition between relatively stiff substrates (i.e., bedrock or stiff clay) can cause strain concentration leading to high reactionary bending strain over a fairly short pipe length due to the differential stiffness of the bedrock walls along the in-place trench and the softer trench material within the slide mass. High confining pressures due to depth often induce acute bending strains where directionally drilled pipelines intersect landslide slip surfaces, making it fairly easy to identify ground movement induced bending strain within a horizontal direction drill bore.

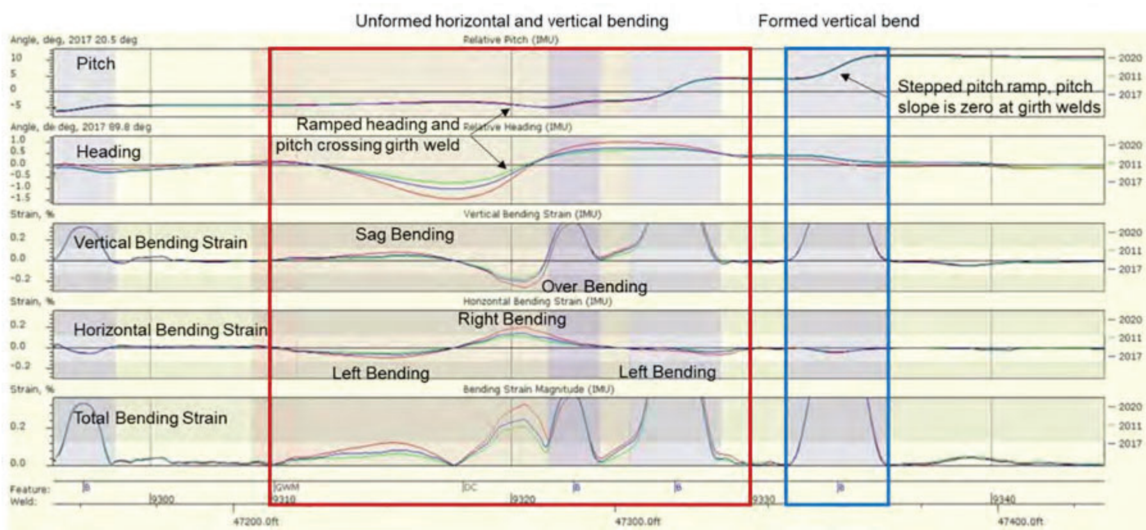

Figure 1. IMU plots (pitch, heading, vertical bending strain, horizontal bending strain and total bending strain) showing typical signatures of unformed and formed bends. The unformed bending in this plot is induced by landslide movement. Slope movement has produced both vertical and horizontal bending strain that track – the over bend aligns with the dominant right bend. Plot produced by Baker Hughes.

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Lateral Ground Movement Bending Strain Signatures

Often the clearest bending strain signature indicative of slope movement is that induced due to lateral deflection of the pipeline in the direction of slope movement. Lateral deformation is typical on side slope construction, as well as in cases where landslide movement is encroaching on a pipeline at a slope toe or along a ridgeline. The lateral deflection produces a horizontal bending strain signature with a broad horizontal bend across the maximum zone of deflection and opposite-direction reactionary bends at the margin of slope movement (Figure 2). In an IMU bending strain plot, the strain pattern commonly forms a W-shape. This W-shape is indicative of slope movement impact if the horizontal bending strain pattern is consistent with the direction of slope movement (as assessed from geomorphic data or in-place instrumentation). If related to ground movement, the horizontal "W" shape will often occur across the full width of moving ground, hence it can be particularly useful for characterizing the extent of active ground movement.

Consider a landslide moving across the pipe from the 9 o'clock to 3 o'clock position (Figure 2). In this case, slope movement pushes the pipeline to the right (3 o'clock position) within the slide mass. This results in a broad left bend along the section of maximum deflection. Reactionary right bends are apparent where the pipeline enters and exits the slide mass. In the IMU plots, the horizontal bending strain shows a W-shape going from zero to positive (right) to negative (left) to positive (right) and returning to zero. The bending strain typically extends over multiple pipeline joints, causing elevated strain on girth welds. As bends extend across girth welds, the heading will be "ramped" rather than level, indicating the pipeline orientation is changing across the weld (see Figure 2). In the horizontal out of straightness (OOS) plot, there is typically a clear deflection in the direction of the lateral slope movement. The OOS estimate from this plot can be compared to OOS measurements made in the field (e.g., based on pipe locator data). The width of the landslide will influence the horizontal bending strain signature. A smaller landslide may produce a single clear right-left-right W-shaped bending strain signature. However, if the landslide is wide, a long length of pipe may be relatively evenly deflected through the middle portion of the slide mass. In this case, the pattern may be right-left-left-right (corresponding to an S-shape at both "shoulder" locations of the landslide rather than a W-shape).

Landslide movement oblique to the orientation of the pipeline can produce an asymmetric horizontal bending strain signature. This orientation of loading typically induces compressive strain at the downslope side of the lateral deflection and tensile strain at the headward end of the deflections. This results in more acute bending strain in the downslope section of pipe and broader strains in the upslope section of the slide mass. Oblique loading often leads to elevated total longitudinal strain, particularly at the location of maximum deflection and at the downslope reactionary bend.

Horizontal bending strain signatures related to slope movement can often be detected in single-run IMU bending strain data if the strain signature overlaps landslide morphology and is consistent with the direction of slope movement. In areas where landslide morphology is not as clear, such as colluvial aprons at slope toes, multiple IMU runs may be needed to confirm whether the horizontal bending

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strain is from ground movement or from construction roping. In cases of side slope pipeline construction on shared corridors, lateral deformation and strain may be induced by downslope construction. Multiple run IMU data is important in these cases to confirm whether ground movement ceased following construction or has continued deforming the pipeline.

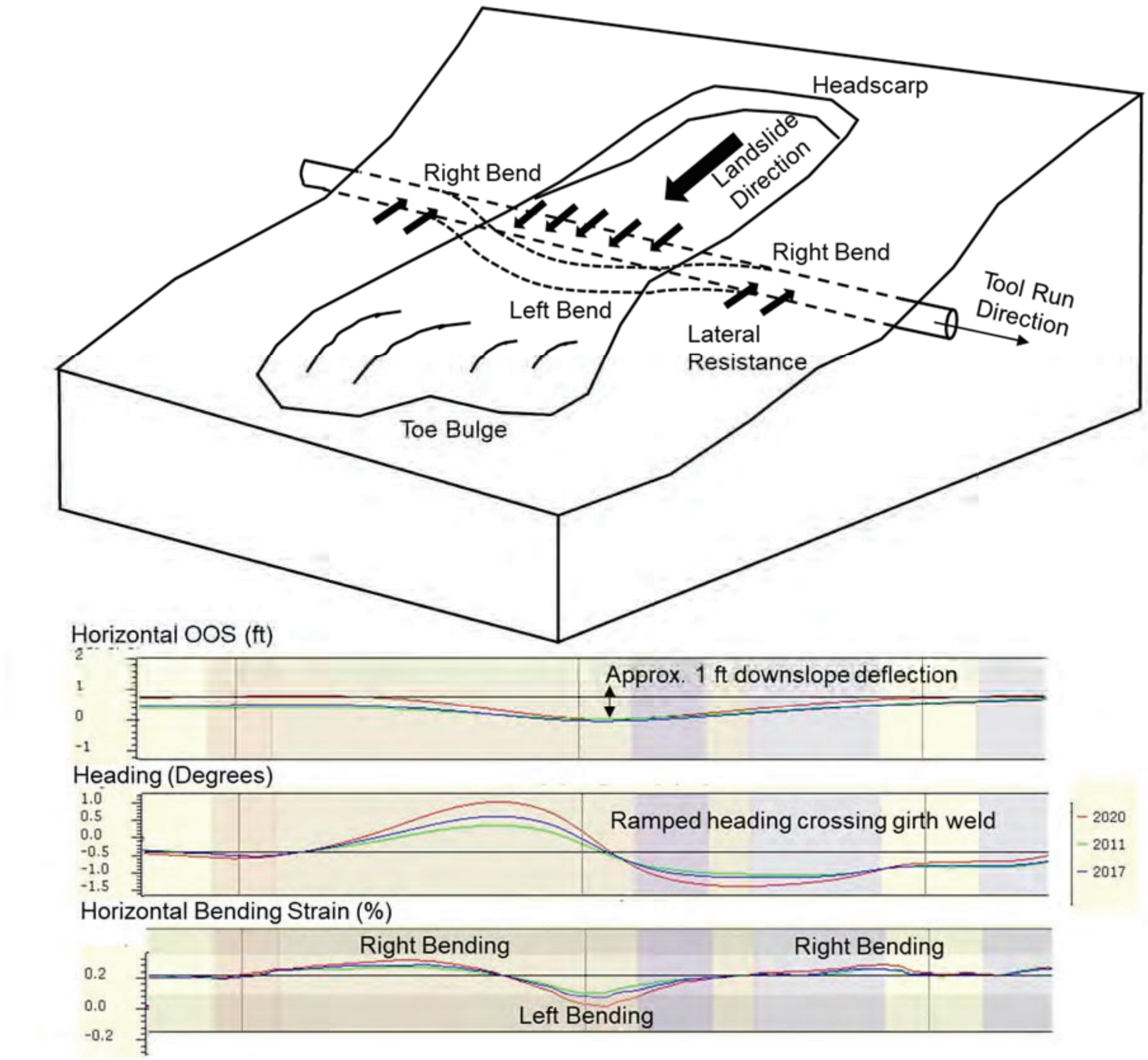

Figure 2. Diagram of a lateral landslide loading scenario and the IMU signature produced by the loading. Note the downslope deflection in the out-of-straightness plot (top) and the right-left-right horizontal bending strain signature (bottom). Plot produced by Baker Hughes.

Vertical Ground Movement Bending Strain Signatures

Vertical ground movement signatures can be observed in IMU bending strain plots where vertical loading occurs on a pipeline. In a landslide, this typically occurs where a pipeline crosses a zone of

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downward vertical movement at a headscarp (the upper boundary of a landslide where ground movement has offset the slide mass downward from the adjacent stable ground) or an internal scarp (a vertical ground displacement feature within the slide mass) (Figure 3). Upward vertical displacement typically occurs at the toe of a landslide, where the slide plane reaches the ground surface (Figure 3). Vertical bending strain is also induced where the pipeline is pulled downward over an area of subsidence such as a sinkhole related to karst processes or underground mine collapse.

At a landslide headscarp, the typical bending strain pattern, from upslope to downslope, is an over–sag pattern (see Figure 2). This occurs because the predominant vertical movement at a headscarp is downward. In oblique and axial landslide movement, this pattern is not always very high in magnitude and may not appear at all due to tensile axial strain, typical in this upper portion of the slide mass. This tensile strain can limit the magnitude of bending strain induced on the pipeline.

The most pronounced vertical bending signatures within a landslide can be at the toe, where the slide plane(s) thrust up to the ground surface, creating a “toe bulge” (see Figure 3). The portion of the pipeline that crosses this toe bulge is upthrust as well, producing a characteristic over bend strain bounded by reactionary sag bends. If oriented oblique or axial to the direction of slope movement, this pattern may be more pronounced due to compressive axial strain at the toe of the landslide.

In many cases, there is a high degree of uncertainty for vertical bending strain features, even if they do intersect a known landslide feature. Vertical bending strain induced by ground movement is not as apparent as horizontal slope movement. Vertical loading can be complex within a landslide mass, which can produce multiple vertical strain patterns. Unlike lateral deflection, the pipeline lengths that are impacted by vertical deformation in a landslide tend to be relatively short and may often only be one to two pipeline joints in length. If vertical bending strain does extend multiple pipe lengths, ramping will be observed across girth welds in pitch plots. Vertical bending strain patterns may appear to mimic topography, which is a typical of construction-induced bending strain signatures. If slope movement is oblique, the unformed vertical bending strain signature often will follow or “track” with the horizontal bending strain signature (see Figure 1). This can be helpful in identifying ground movement induced vertical bending strain. If ground movement is actively occurring, the best way to verify the source of the strain is through multiple IMU runs to detect changes in the vertical bending strain.

Vertical bending strain induced by ground settlement is often quite apparent and produces an over-sag-over bending strain pattern, similar to what could be expected at a landslide headscarp. However, the downward deflected area may be more extensive and thus, it can be easier to see, particularly if there is evidence of subsidence in geospatial data (sinkholes and or documented historic mining activity). To evaluate whether the strain is related to subsidence, additional information on karst activity and active/historic mine activity are usually necessary, gathered either through desktop literature reviews or field investigation programs.

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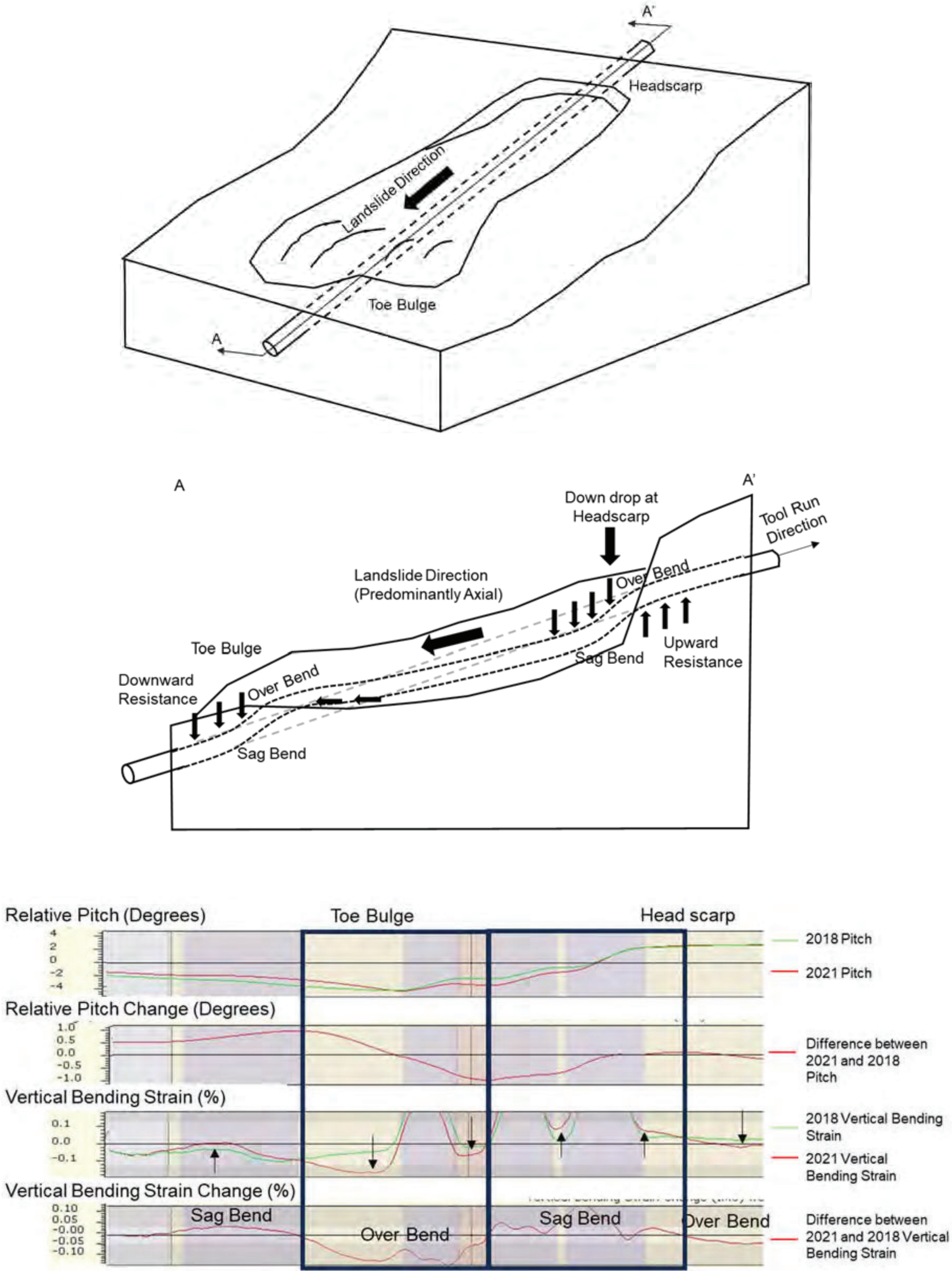

Figure 3. Diagram of an axial-oriented landslide (top), the vertical loading and deformation produced in cross section (middle), and the IMU pitch and bending strain signature produced in multiple run IMU data. Plot produced by Baker Hughes.

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Axial Slope Movement Signatures

IMU data cannot measure axial strain. However, axial loading can sometimes induce changes in bending strain, particularly at formed vertical and horizontal bends (e.g., due to cable action P-Δ effects). In zones of tensile loading, formed bends will usually straighten/open, meaning the magnitude of the bend curvature will decrease over time. Alternatively, in areas of compressive loading, formed bends will close, or increase in bend curvature magnitude over time. For bends that are closing, the bending strain can sometimes be observed extending into neighbouring pipe joints, leading to strain on the girth welds bounding a formed bend.

While this deformation may be apparent in single-run IMU, typically multiple run IMU data can greatly decrease uncertainty on whether the formed bends are deforming over time. To fully assess formed bends, additional IMU plots may be required that show the full magnitude of formed bends. The bending strain vertical axis should be scaled differentially than plots used to assess unformed bending strains due to the higher magnitude bending strains found on formed bends. Often, large axial loading occurs within larger landslide complexes, where individual vendor-provided bending strain plots do not provide full coverage. In these cases, it is helpful to create plots using tabular IMU data to allow for plot customization and to enable the bending strain profiles throughout the entire landslide mass to be viewed.

While bending strain data does not provide axial strain, it can be used to estimate the axial strain demand on a pipeline. If there is measurable OOS, a simplified axial strain calculation can be completed based on the magnitude of OOS and the length of deflected pipeline. In some cases, it is beneficial to evaluate the current strain demand on a pipeline by completing a finite element analysis (FEA) that models the impacted pipeline including axial force effects. Bending strain data from IMU can be used to develop the input ground displacement profile used in the FEA model so that the model is calibrated to the soil loading being experienced by the pipeline. This enables the estimation of a more accurate axial strain component and total longitudinal strain demand being imposed on the pipeline. If the strain capacity of the pipeline and girth welds are known, an operator can evaluate whether the strain demand estimated by the FEA is nearing any critical thresholds that may warrant further action.

Typical Construction Induced Signatures

The majority of bending strain features identified in bending strain reports tend to be induced during initial pipeline construction or from regular maintenance activities such as integrity digs. These bending strain signatures are not expected to continue changing over time and once identified, do not necessarily require additional monitoring unless they correlate with a known geohazard.

Tie-In Locations

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Construction related bending strain features are often observed at suspected tie-in locations associated with road, rail, and watercourse crossings, which is supported by Theriault et al. (2019) and Scheevel at al. (2022). These bending strain features may be oriented horizontally or vertically and are induced when the line pipe is tied in with an adjacent pipeline segment. Typically, small offsets between the two ends of the pipe to be joined require some amount of deflection to bring the joint together, inducing unformed bending strain on both side of the joint. The bending strain features tend to be short, typically limited to one or two pipe joints (see Figure 4). In vendor IMU plots, these strain features can often be observed on pipeline joints adjacent to wall thickness changes (often indicative of a crossing). These locations can typically be identified by assessing geospatial data to see where road, rail and watercourse crossings are in relation to the pipeline. In some cases, particularly at watercourse crossings at the base of slope, these construction strain features can appear similar to vertical ground movement strains. Because of this, multiple run IMU data may be necessary to confirm whether the bending strain is related to construction.

Construction Roping

An additional source of construction-related bending strain features is roping. Roping is common where minor variations of topography do not require formed bends and where trench backfill creates irregular loads on the pipeline. Roping often occurs after the pipeline is welded into a string, and therefore bending strains may cross girth welds and be superimposed on formed bends.
In IMU data, roping results in irregular increases or decreases in the heading or pitch data and irregular horizonal or vertical strains (see Figure 4). Common construction practices tend to produce roping strains less than 0.2%, however this is dependent on the installation stresses and stiffness of the pipeline. When a pipeline is routed through a landslide it is common to observe roping that follows the benched and stepped topography typical of landslides, therefore it can be challenging to differentiate landslide movement from roped bends that follow topography.

Roping patterns may occur in pipelines of any diameter but are more distinctive in small diameter pipelines that are more flexible. Roping strain magnitudes in smaller diameter pipelines tend to be higher as the pipeline is more flexible and can overlap into ranges typical of formed bends. Understanding typical construction practices for a pipeline is important for identifying roped bends and differentiating from ground movement bends and other causes. In these cases, multiple run IMU data is often helpful to assess for changes in bending strain signatures over time to correctly categorize the bending strain feature.

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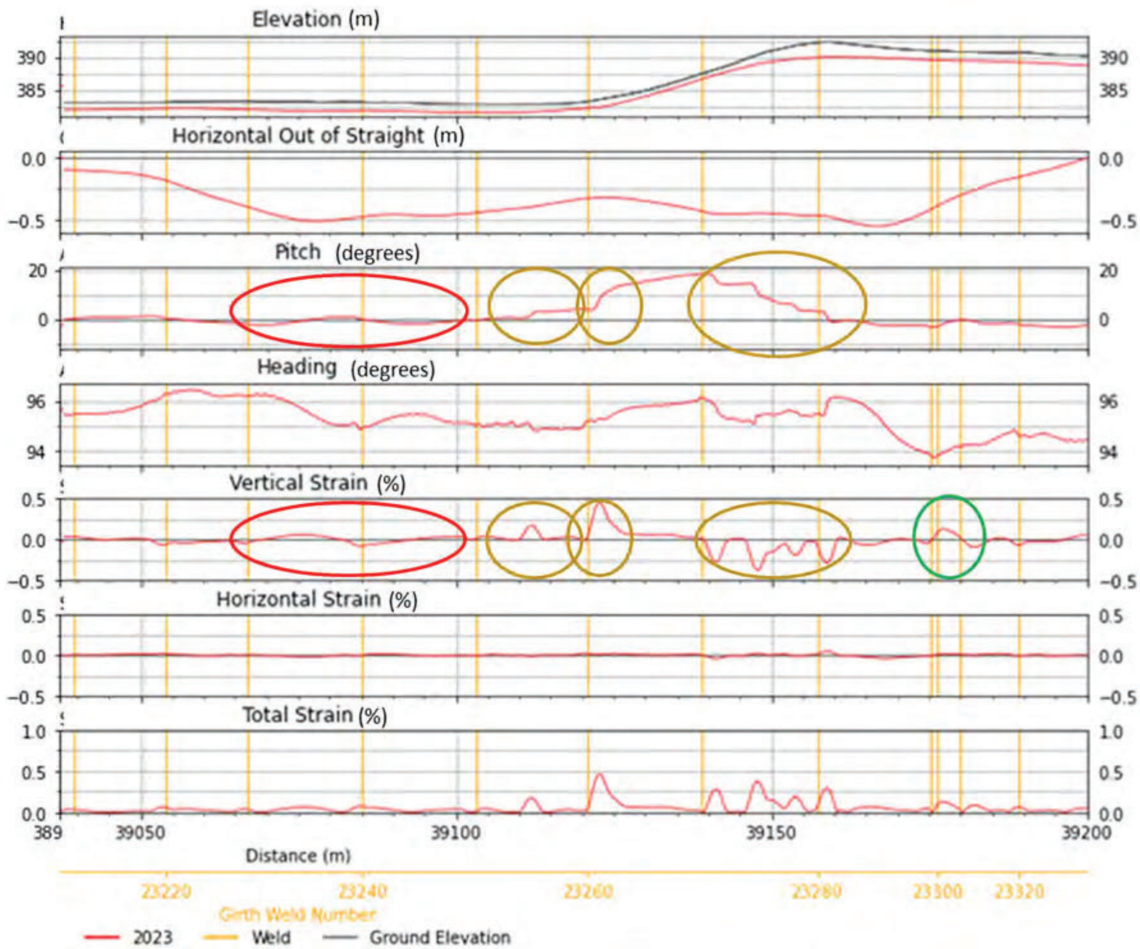

Figure 4. A seven-panel plot showing examples of roped vertical bends associated with straight sections of pipeline (circled in red), formed bends (circled in yellow) and pup pipeline segments associated with a road crossing (circled in green). Note the unform ramp in the pitch plots associated with formed vertical bends and the irregular pitch signature associated with the roped vertical bends.

Integrity Dig Signatures

Integrity digs produce readily apparent bending strain signatures that can easily be observed in multiple run IMU data. These occur when a full 360-degree exposure of a pipeline is completed either for an inspection or repair. Due to limitations with compacting backfill beneath and adjacent to the pipeline, the underlying soil at the dig location tends to consolidate and settle during and after backfilling. This creates a clear (over-sag-over) settlement signature along the pipeline in IMU vertical bending strain plots (Figure 5). Often the length of this signature is limited to the pipe segment exposed during the dig and the segments immediately adjacent. If a record of integrity dig locations is available, these sites can be easily identified in both single and multiple run IMU data. In multiple run bending strain reports, these locations are often identified as pipeline movement zones.

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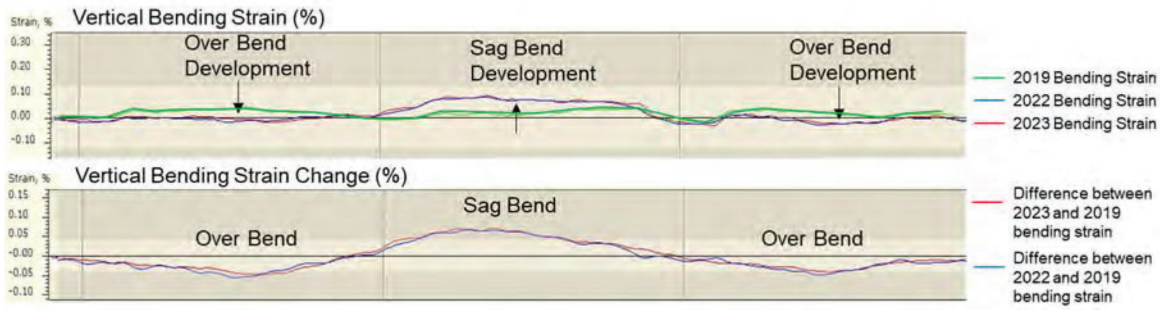

Figure 5. Vertical bending strain and multiple run change plots for an integrity dig site. Note the bending strain change occurs between 2019 and 2022, with no change reported between 2022 and 2023. This is consistent with the date of the integrity dig (2021). Plot produced by Baker Hughes.

Horizontal Directional Drill Installations

Horizontal directional drill (HDD) installations are made without formed bends; however, the pipeline typically forms a broad roped bend as a result of being dragged into a curved drill path. Typically, these bends are oriented vertically – with pipelines often having a broad sag bend (positive or negative vertical bending strain, depending on the vendor) signature. Usually, the bending strain is lower than 0.05% for the extent of the drilled portion but may be higher. Particularly with smaller diameter pipelines which are more flexible, bending strains may be higher where a shallow bore abruptly changed direction during installation. At the entry and exit of the drill a formed overbend is often required to tie in the conventionally trenched section and because of the restricted position of the HDD, roped bends are often also present as the less constrained conventionally trenched pipeline is maneuvered to align with the HDD portion. If depth of cover or as-built information is available, HDD installations can often be confirmed by installation depth.

Additional Considerations Regarding Bending Strain Assessment

Bending Strain is One Component of Total Longitudinal Strain

The bending strain derived from IMU data is only one component of the total longitudinal strain state of the pipeline which also includes axial strain. IMU does not measure the axial strain component resulting from elongation or compression of the pipeline, which in some cases can be larger than bending strain. Axial strain is often assessed through a pipeline stress analysis (e.g., FEA) if sufficient data on ground movement and pipeline impact are available or a simplified axial strain calculation based on the OOS and length of OOS. Correctly positioned stain gauges can also be used to provide information on axial strain at a specific location.

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A Bending Strain Assessment Cannot Rule Out Ground Movement Impact

A bending strain analysis cannot rule out ground movement impact because small amounts of ground movement may result in pipeline bending that is indistinguishable from construction related bends (particularly roped bends). Landslide loading may also be axial to the pipeline and can generate strains which are dominantly longitudinal and do not result in significant (i.e., distinguishable) bending. Even with multiple IMU runs, there is uncertainty due to the accuracy of the tool and data noise, which may be indistinguishable from low magnitude changes in bending due to landslide loading. Additionally, on vintage pipelines, bending strain induced by ground movement may have occurred prior to the baseline IMU run, so a lack of change in bending strain from multiple IMU runs does not rule out past landslide impact.

A Bending Strain Assessment Provides Insight into the Condition of the Pipeline

Despite not being able to rule out ground movement impact, a bending strain analysis which does not identify evidence of impact still provides insight into the condition state of the pipeline by limiting the severity or rate of bending strain change over an observation period. A bending strain analysis which does not identify evidence of landslide impact implies that either the pipeline has not been impacted by a landslide or it has been impacted but has only generated bending strains or bending strain change at a low enough magnitude that the impact is not distinguishable from bending strain from other causes. The insight this observation provides into the condition of the pipeline needs to be considered on a site-by-site basis as scenarios with potential for axial pipeline loading and longitudinal strain may not manifest in unusual bending.

Bending Strain Analysis Does Not Confirm a Pipeline's Fitness for Service

Bending strain analysis may identify potential integrity threats, such as landslide impact, or provide supporting information as part of a comprehensive integrity assessment but is not able to directly confirm pipeline integrity or fitness for service.

Conclusions

Profiles of bending strain, pitch, heading and out-of-straightness from IMU data can be used for geohazard impact identification and characterization, when the data is assessed with an understanding of the geohazard mechanism. Loading scenarios induced by ground movement can produce signatures that are readily apparent and different than those induced by construction. To maximize the value of bending strain reports for geohazard management programs, pipeline operators should not only assess the magnitude and location of bending strain features but should assess the bending strain, pitch, heading and out-of-straightness plots in conjunction with an understanding of ground movement and loading.

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Ground movement induced by geohazards, particularly landslides, is complex with different loading patterns across the landslide that vary based on the orientation of the pipeline. Especially in large, complex landslides, varying zones of ground movement can induce complex bending strain on a pipeline. While the IMU signatures presented in this paper are from real sites, these cases are considered exemplary in simplicity and clarity regarding the loading and bending strain signatures produced. In most cases, bending strain induced by ground movement, particularly landslides, should be assessed by SMEs with a thorough understanding of the mechanics of the geohazard and the anticipated loading scenario.

IMU data is a powerful tool in that it can indicate whether the pipeline has been impacted by ground movement, provide insight into the condition of the pipeline, and provides closely spaced (essentially continuous) data along the entire length of the pipeline. This differentiates IMU data from discrete point in-ground instrumentation such as slope inclinometers and location-specific instrumentation such as strain gauges. However, IMU data is only one tool for assessing geohazard impact along pipelines. It is important to assess IMU data in conjunction with other information such as lidar, lidar change detection, satellite imagery, slope inclinometers and strain gauges. When this data is fully integrated and assessed by knowledgeable SMEs, pipeline operators can leverage the maximum value of the data within an effective geohazard management program.

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