The Use of Inertial Measurement Unit Data for Managing Slow-Moving Landslides

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Abstract

Well-structured geohazard management programs (GMPs) for pipeline systems have become common over the last two decades in North America as pipeline companies have become more aware of the risks presented by natural hazards and the value in adopting proactive approaches to manage risk. The case study presented in this paper represents the GMPs of 30 major pipeline companies in North America comprising approximately 100,000 miles of operating and actively managed pipeline. The performance of these GMPs has been measured to reduce pipeline failure rates from geohazards 4 times. Over the past 10 years more than 95% of the observed geohazard pipeline failures have been from slow-moving landslides. The study scope includes approximately 10,000 landslide crossings. The average annual probability of failure given pipeline impact from a slow-moving landslide has previously been estimated at 1 in 50, meaning any landslide which is actively moving and intersecting a pipeline presents a potentially serious integrity concern. The primary challenge with managing slow-moving landslide hazards is that determining landslide activity without instrumentation is often not possible, and installing conventional instrumentation such as slope inclinometers at such a large number of landslides is prohibitively expensive. Slow moving landslides also cannot reliably be visually identified as movement rates are often low enough that visible surface disruption is subtle or undetectable, but those same movement rates will be enough to cause pipeline failure over the life of the pipeline. To address this challenge many forms of low-cost instrumentation have been pursued to measure ground movement and/or pipeline impact including Interferometric Synthetic Aperture Radar (InSAR), lidar change detection, and in-line inspection tools such as axial strain and inertial measurement unit (IMU). Over the last 10 years IMU has become a critical and frequently utilized tool for assessing landslide activity and has been integrated into the geohazard management programs of all the operators in the study scope. In 2022 IMU was credited for identifying 53% of the active landslides where operators completed critical interventions to manage risk (e.g., pipeline shut in, stress relief mitigation). Key lessons and observations for successfully integrating IMU into GMPs are presented from a case study spanning 10 years and 100,000 miles of pipeline.

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Introduction

As well-structured geohazard management programs (GMPs) have become industry standard for most pipeline companies in North America, thorough hazard inventories have been developed for the most common geohazard types, watercourse and landslide crossings. Of these two hazard types, watercourses have proven easier to identify, characterize and manage and the industry has been successful at mitigating risk by adopting measures such as reinstalling pipelines at greater depths by horizontal directional drilling (HDD) and establishing proactive flood monitoring and shut-in protocols. Landslides have proven more challenging to identify and characterize, but over the past 10 to 20 years the widespread availability of light detection and ranging (LiDAR) imagery and other technologies for landslide inventory development has greatly enhanced the quality of landslide inventories (Van Hove et al., 2019). The enduring challenge for managing landslide risk to pipelines is characterizing the activity and behavior (i.e., velocity and tendency to change velocity) of landslides. Landslides which are inactive within the design life of a pipeline do not pose a threat, but evaluating which landslides are inactive vs active has historically been largely based on visual inspection and professional judgement. Many landslides are subtle and move without visible surface expression (Barlow, 2002), therefore the industry has historically operated with high uncertainty around landslide risk.

Since the first inertial measurement unit (IMU) in-line inspection (ILI) tool run in the late 1980s, it was acknowledged that the data would be useful for characterizing pipe movements from outside forces such as landslide loading. Over the past ten years IMU data has become increasingly available and has become the single most useful tool for evaluating risk from slow-moving landslides crossed by pipelines.

This paper presents a case study of landslide risk and the positive impacts of integrating IMU assessment into the GMP of approximately 100,000 miles of North American pipeline over a 10-year period. The pipelines represent a range of operators, physiographies, pipeline diameters, products and operator risk tolerances from across Canada and the United States. The pipelines have not been managed to the same standard during the 10-year period of the study but are managed to a similar standard currently. Geohazard inventories have been completed for every pipeline, but the data availability and methodologies have varied. This database likely represents the most comprehensive database for North America over a 10-year period in terms of the number of miles of operating pipeline and the consistency with which landslides are documented and characterized. There are many reasons why the database could be inconsistent – for instance if LiDAR has been used for developing a hazard inventory for one pipeline, but not for another – but these artefacts of the database are not considered significant enough to impact the usefulness of the insights.

Slow-moving landslides are the greatest geohazard threat to pipelines

Pre-existing slow-moving landslides are the most common documented cause of geohazard related pipeline failures in North America within the last 10-years. Within the case study, 27 geohazard failures are documented over the 10-year study period, 26 from slow-moving landslides and one from river scour. Previous studies have estimated the rate of pipeline failure from geohazards in North America to be 0.02 per 1000 km (621 miles) per year (Porter et al., 2016). The failure rate represented in this case study is 0.016 failures per 1000 km per year, and slow-moving landslides account for more than 95% of all failures (Figure 1).

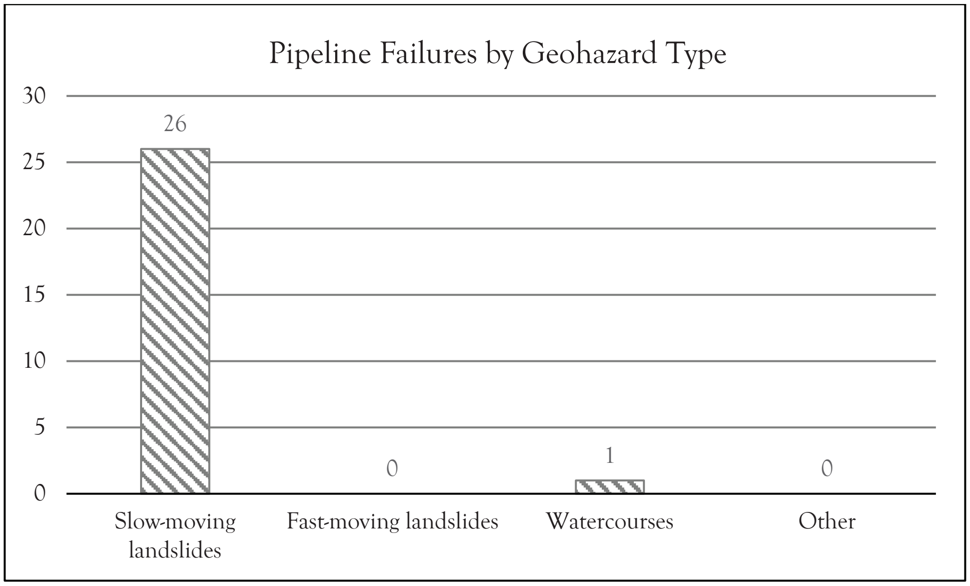

Figure 1. Pipeline geohazard failures from 100,000 miles of pipelines over 10 years, summarized by hazard type.

Slow-moving landslides are generally considered those in landslide velocity class 1 to 3 (Table 1), however slow-moving landslides affecting pipelines tend to fall within velocity class 1 and 2a (Porter et al. 2022) because pipelines can often tolerate class 1 and 2a movement for years to decades before exceeding the strain capacity of the pipeline. Landslides which have a velocity class of 2b or faster and are intersecting a pipeline are rare because they often present an immediate integrity concern and must be addressed once identified.

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Table 1. Modified landslide velocity classification after Cruden and Varnes (1996) (Porter et al., 2022).

Class	Description	Typical velocity	Proposed annual displacement criteria (m)	Proposed mean annual displacement (m)
7	Extremely rapid	>5 m/sec		
6	Very rapid	>3 m/min		
5	Rapid	>1.8 m/hr		
4+	Moderate	>13 m/mo	>16	64
3	Slow	>1.6 m/yr	>1.6	6.4
2b	Very slow	>160 mm/yr	>0.16	0.64
2a	Very slow	>16 mm/yr	>0.016	0.064
1	Extremely slow	<16 mm/yr	>0	0.005
0	Dormant	0 mm/yr	0	0

Note: Class 4+ refers to all velocity classes Moderate or greater

Table 2 summarizes six of the slow-moving landslide caused failures from the case study where cumulative movement and movement rates prior to failure are known or can be reasonably estimated. This is a small dataset and should not be relied on too heavily but demonstrates that pipelines can tolerate some movement prior to exceeding the strain capacity of the pipeline, and that faster landslide velocities will use up the “runway” quicker than slower velocities. The average pipeline age at the time of failure is 36 years, and the average velocity estimated over the life of the pipeline prior to failure is 65 mm/yr. All of the landslides were active throughout the life of the pipeline, and the pipeline failure was due to progressive increase in strain demand and deterioration of the remaining pipeline capacity over years to decades rather than being solely attributable to movement acceleration prior to failure.

The amount of ground movement that a pipeline can tolerate will vary based on many factors including the length of pipe engaged, pipeline diameter, wall thickness, girth weld and steel properties, pipeline depth of cover, and loading conditions (Barlow 2002; Ferris et al. 2016, Van Hove et al., 2022). In the authors’ experience the tolerance of pipelines to ground movement has varied from as low as 100 – 200 mm (e.g., Trigg and Rizkalla, 1994) to other instances where pipelines have laterally translated more than 5 m but are still safely operating. Despite this wide range, in most failure case histories and pipeline stress analyses completed by the authors, pipelines affected by landslides can tolerate between 100s of millimeters and a few meters of movement.

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Table 2. Landslide velocity and pipeline age for select pipeline failures.

Identifier	Location	Relative Movement	Pipeline age at failure (years)	Average Velocity (mm/year)	Estimated Displacement at failure (m)
1	Canada	Oblique	8	100	0.8
2	Canada	Oblique	34	91	3.1
3	USA	Oblique	68	100	6.8
4	USA	Transverse	67	38	2.6
5	Canada	Axial	18	27	0.5
6	Canada	Axial	19	35	0.7

The proposition that faster landslides are more damaging is intuitive and has been made by many others including Mansour et al. (2011) who demonstrates a relationship between landslide velocity or cumulative displacement and the expected degree of damage to infrastructure (e.g., pipelines, roads, bridges). Building on this work, Porter et al. (2023) present a model for pipeline deterioration which uses Markov Chains and Monte Carlo Simulation to produce a probabilistic model for landslide displacement and proposes the use of pipeline condition states which will be realized at varying landslide displacements.

Fast-moving landslides do cause pipeline failures but are easier to identify and avoid during construction due to visible surface expression of movement, i.e., the presence of an active fast-moving landslide is easily identified by signs of landslide disruption such as fresh scarps and cracks as well as tilted and deformed vegetation. Therefore, failures from fast-moving landslides tend to take the form of either event-based hazards such as debris flows that originate off right-of-way (Boultbee et al. 2006; Jakob et al., 2004), and landslides which are normally slow-moving but experience an acceleration event.

Porter et al. (2023) provides proposed behavior types and landslide velocity characteristics for pre-existing slow-moving landslides which enable an estimation of the probability of landslide acceleration. In the authors' experience, rapid acceleration events which result in displacement magnitudes that can cause pipeline failure (100s of millimeters to meters) are rare. From the case study failures where movement history was known (Table 2), all the landslides were consistently active within the life of the pipe and impact was evident or would have been evident from IMU analysis. Three of the landslides experienced an acceleration prior to failure, but accelerated movement rates were still very slow to slow and the amount of tolerable movement had already been reduced by years to decades of prior movement. In some regions of the world these events are more common and correctly characterizing the behavior type of landslides with potential for sudden accelerations is critical for applying this type of model as these accelerations have a high probability of causing pipeline failure.

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In recent years, management practices around watercourse crossings have improved and there have been very few hydrotechnical failures within the last ten years. Key improvements have been around developing probability of failure estimates to enable risk-based approaches, proactively mitigating higher risk crossings with deeper burial or HDD and developing and implementing automated flood monitoring and alerting systems with trigger action response plans.

Other geohazards, such as seismic hazards (e.g., fault rupture and liquefaction) and subsidence have caused pipeline failures in the past, but at a rate which is much lower than landslide or watercourse related failures.

Pipelines frequently cross pre-existing landslides

For pipelines in the case study, the average number of landslides per mile varied from one landslide every 0.6 miles in regions with many slopes and high landslide frequency (Scheevel et al., 2022) to one landslide every 25 miles or less, in flat prairie areas. On average, pipelines within the study cross or cross near a landslide once every 10 miles, meaning for the 100,000 miles of pipelines in the case study, there are an estimated 10,000 landslides which may intersect pipelines.

Crossing landslides may be unavoidable during pipeline routing because of the location of the resources and the location of refineries and markets. Some of the geographical regions crossed by pipelines in the database have such a high density of landslide features that it is common for valleys to have nearly continuous landslide features along both valley walls for much of their length. Another factor for many of the pipelines is that data which makes terrain assessment easier such as lidar imagery was not available, leading to unidentified landslide crossings. Landslide risk has also been under appreciated in the past and has resulted in a higher rate of landslide crossings than might be expected from modern practice.

Pipeline vulnerability (V) to landslides is defined as the annualized probability of pipeline failure given landslide impact. Ferris et al. (2016) estimates that average vulnerability is 1 in 50 (2%), meaning that for every 50 sites subject to landslide loading in a year, one will result in pipeline failure. Pipeline probability of failure (PoF) can be calculated according to Equation 1 by taking the product of pipeline vulnerability and the annual probability of pipeline impact (PoI) (spatial intersection from an active landslide). For managing probability of pipeline failure, this means that an average landslide that is active and intersecting a pipeline should be considered a serious integrity threat until otherwise determined because the probability of pipeline failure is on average 2%.

$$\mathbf{PoF = V \times PoI} \qquad \textbf{Equation 1.}$$

Given the observation of a high average vulnerability, the threat from each landslide is mainly differentiated by assessing the likelihood that the landslide intersects the pipeline, and the likelihood that the landslide moves. A pipeline that intersects an inactive slide is not at risk provided the

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landslide does not reactivate, regardless of other factors which may increase the vulnerability. Likelihood of spatial intersection is often known because landslides are frequently deeper than the depth of a pipeline installed in a conventional trench, therefore the key uncertainty for many landslides in the inventory is landslide activity. A landslide which is confirmed to be active and intersecting the pipeline will on average have a probability of failure of 1 in 50 and according to Newton et al. (2022) will be rated as one of the top 4% highest hazard sites in the inventory. In the context of the case study this would mean the 400 highest likelihood of failure landslide sites for the 100,000 miles of pipeline. Without knowing landslide activity many of the 10,000 landslides could be as important. Undertaking meaningful proactive risk reduction measures is impossible with so many potentially critical threats, therefore assessing landslide activity is essential for effective risk management.

Determining the activity of slow-moving landslides is a challenge

While technological advances such as lidar have made identification of pre-existing landslides much easier, tools to assess landslide activity have not yet had the same success. Traditionally, landslides have been assessed using a combination of visual inspection by a landslide expert and high-precision geotechnical instruments such as slope inclinometers (SI) or shape accel arrays (SAA) installed at select sites to measure subsurface deformation.

Visual assessment of a landslide by an expert provides critical information to characterize the landslide and, in some cases, evidence of recent movement can be observed. While a landslide inspection will always improve the site characterization by identifying features which have a bearing on the probability of landslide activity (e.g., the observation of seepage or recent fresh scarps), determining landslide activity or inactivity is not always possible. Barlow (2002) presents data from 17 slow-moving landslides with known velocities between 3 and 188 mm per year and compares movement rates to visible indications of movement at surface. Landslides with movement rates slower than 50 mm per year did not have visible indicators of movement at surface, while landslides moving faster than 100 mm per year did. In total 70% of the landslides in the study were active without visible indications of movement at surface.

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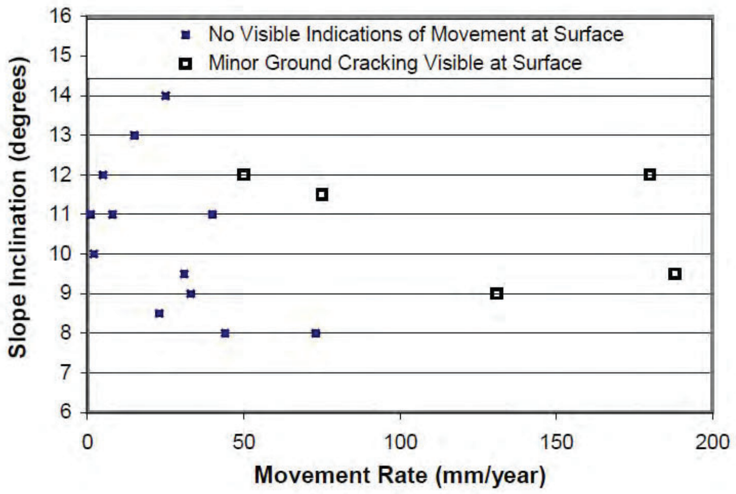

Figure 2. Landslide velocity vs visible indicators of movement at surface (Reproduced with permission from Barlow, 2002).

Dewar et al. (2023) report similar observations comparing the results of a Global Navigation Satellite System (GNSS) survey monitoring program to visible indicators of movement at surface. In that study 44% of the sites with movement confirmed by GNSS had visible indicators of movement at surface. Since GNSS has a higher limit of detection, closer to +/- 25 mm, it is possible that this data set would be missing some of the slowest moving landslides which did not move more than the detection limit during the period of observation. Based on the results of Barlow (2002) these uncaptured active landslides would very likely not have visible indication of movement at surface.

From the current case study, data are available from 884 landslides where landslide velocity class was recorded by an instrument. The data presented are from 2023, which is the first full year of consistently catalogued data. Instruments include SI, SAA, GNSS, lidar change detection (LCD), interferometric synthetic aperture radar (InSAR), and IMU.

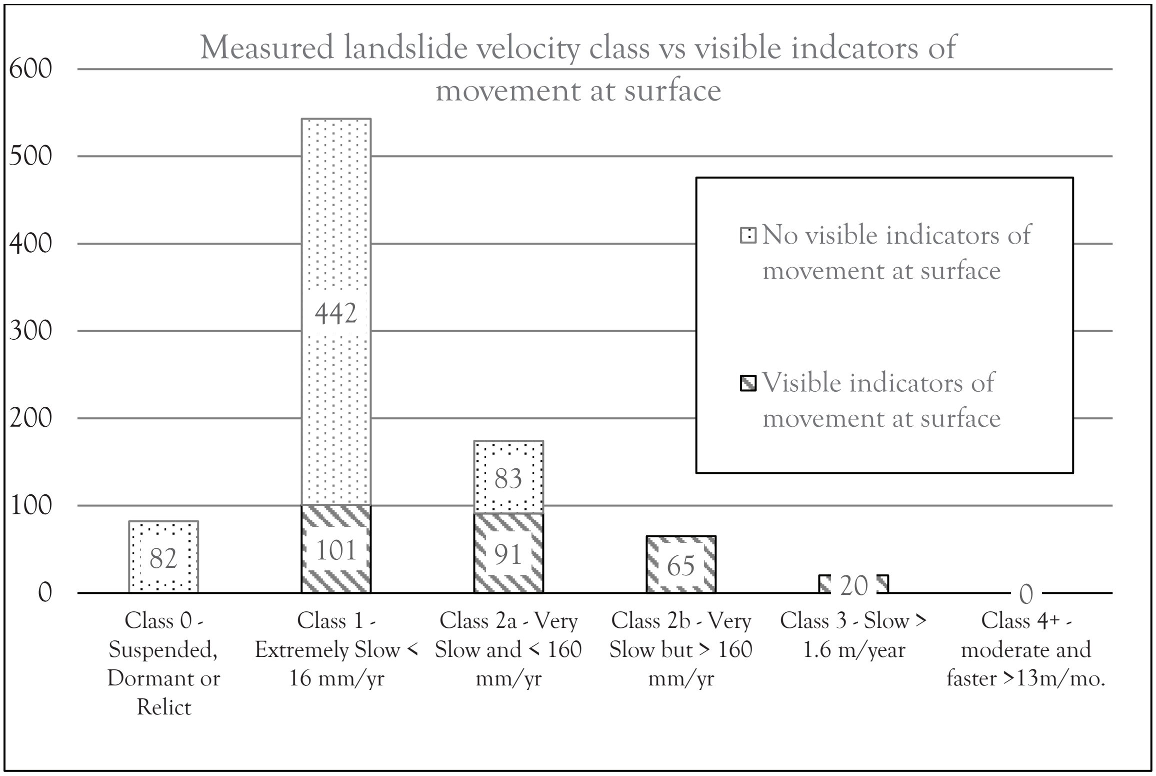

Figure 3. Landslide velocity class vs visible indicators of movement at surface for sites with landslide velocity measurements in 2023.

The data presented only represents a portion of the landslide inventory because not all landslides were inspected in 2023, and instrument data only exists for a portion of the landslides. These data do not represent an accurate distribution of landslide velocity for all landslides because many of the methods of measurement are not precise enough to measure movement in the slower classes. These data include all landslides documented as potential threats to pipelines, but not all of them spatially intersect a pipeline (e.g., a pipeline may be drilled deeply below an active landslide and protected by spatial separation).

What these data do affirm is that landslides moving at velocity class 2b or faster are consistently identified by visual inspection, while slower moving landslides frequently are active without visible indication of movement at surface. About 50% of velocity class 2a have visible indicators of movement at surface while for velocity class 1 only 18% of landslides had visible indication of movement at surface. In summary, this study and others have presented data which indicates that visible indicators of movement at surface are consistently recognized by a landslide expert at velocity class 2b and faster, may be recognized at velocity class 2a, and are unlikely to be recognized at velocity class 1.

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The limitations of other available tools for assessing landslide activity

Apart from visual inspection, many other tools exist which are capable of characterizing landslide activity. For the purpose of explaining why IMU has become so important to pipeline GMPs over the past decade, the limitations of select other tools are briefly presented.

SIs and SAAs are similar and have excellent precision and provide point measurements of landslide displacement at depth. The key limitations include a prohibitive installation and monitoring cost and limited service life often requiring multiple replacements during the life of a pipeline.

LCD is low cost for wide area acquisition and processing, but even with two epochs of high-resolution data and state of the art processing, the 95% confidence interval for change detection is around 100 mm of vertical change. High-resolution lidar data is often less than 5 years old which results in LCD not detecting movement of extremely slow and some very slow landslides. While this could change in the future with more mature datasets, currently the detectable range of landslide velocity for LCD is comparable to visual inspection.

InSAR is a promising tool which, given a deep enough stack of repeat measurements, offers the precision to measure extremely slow landslides, but currently readily available data is C-band, which struggles to penetrate vegetation. L-band data is more suitable for monitoring vegetated slopes, but acquisition is often cost prohibitive. In 2024 a joint earth observing mission between NASA and the Indian Space Research Organization (ISRO) named NISAR is being launched, which will provide free L-band data and could become another valuable tool for ground deformation monitoring.

GNSS and other survey techniques are also frequently utilized but can be cost prohibitive and, as previously discussed, may not be able to measure extremely slow movement rates (cumulative movement less than 25 mm).

In addition to the limitations outlined, all of these instruments only measure displacement after the first reading (i.e., no historical data is available). This can be critical because often landslides move for many years prior to failure. All these instruments also only measure ground movement which requires an additional assessment to determine whether the ground movement is spatially intersecting the pipeline, and the degree to which the pipeline is impacted by ground movement (pipeline condition).

The measurable impact of integrating IMU into GMPs

IMU has become the most frequently used instrument for the management of slow-moving landslides because it addresses many of the limitations of other available tools. The key advantages include:

- IMU is usually the most economical tool available. Often the data is already collected for other purposes and assessment is an inexpensive desktop exercise.

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- One tool run provides continuous data for an entire pipe segment, which may include many landslide crossings.
- Reviewing continuous data provides the opportunity to identify impact from landslides which are missing from the inventory and might otherwise have been undetected for years.
- Bending strain measurements are precise and it is often possible to identify impact from extremely slow-moving landslides where visual inspection and other instruments cannot detect change.
- IMU provides a direct form of measurement of pipeline impact since the pipeline deformation is what the IMU is measuring. This can provide insight on the length of pipe engaged by ground movement, the condition of the pipe and potentially critical strain areas.
- IMU can provide insight into the movement history of the landslide if movement prior to the initial IMU run has generated a bending strain feature.
- IMU can provide a relationship between ground movement and bending strain demand. Understanding how, where and at what rate bending strain is developing in response to ground movement provides valuable information for modelling the strain state of the pipeline and the future strain demand given ongoing movement.
- IMU can provide one form of ongoing monitoring, both for sites without prior evidence of impact, and sites with more detailed monitoring plans where pipe impact is observed.

Since the first IMU run in the late 1980s it was acknowledged that IMU could be a useful tool for understanding pipeline movement from outside forces including landslide impact. Although publications discussed these applications (Hart et al., 1992; Hart et al., 2002; Czyz and McClarty, 2004), it took several decades to become consistently integrated into the GMPs for many operators.

The authors' first experience with IMU for landslide characterization was during response to the Cheecham Landslide event, which is summarized in Barlow and Richmond (2016). That event involved a loss of containment due to pipeline impact by a 1.4 km (0.9 mile) long reactivated landslide. After the event, IMU was used to characterize landslide movement patterns and estimate cumulative displacement. An average displacement of 0.8 m was estimated in the peak movement zone at the time of the event, which occurred without significant visible indications of slope movement at surface, beyond some minor cracking at mid-slope.

Following the Cheecham event, the value of IMU was recognized and promoted by BGC as a useful tool for characterizing landslides which do not have instrumentation and, because of their slow velocity, may not have visible indications of slope movement at surface. In 2014 the authors estimate that 1,000 hours of IMU analysis was completed for landslide assessment, and over the past three years upwards of 30,000 hours per year of IMU analysis has been completed.

This shift represents a recognition from the industry of the value of IMU as an assessment tool, with many operators spending 10% or more of the total program effort on projects supported by IMU, with some as high as 50%. Over the past 10 years, BGC has tracked the impact these GMPs have on

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failure rates and in 2019 estimated that the historic North American average failure rate of 0.02 failures per 1000 km per year had been reduced by a factor of 4 (Newton et al., 2019). Over the past two years there have been zero failures, and over the past three years only one. Assuming the average historical rate applied to 100,000 miles of pipeline would result in ten expected failures, the past three years the failure rate achieved by these programs is 10 times lower than the historic average (Figure 4).

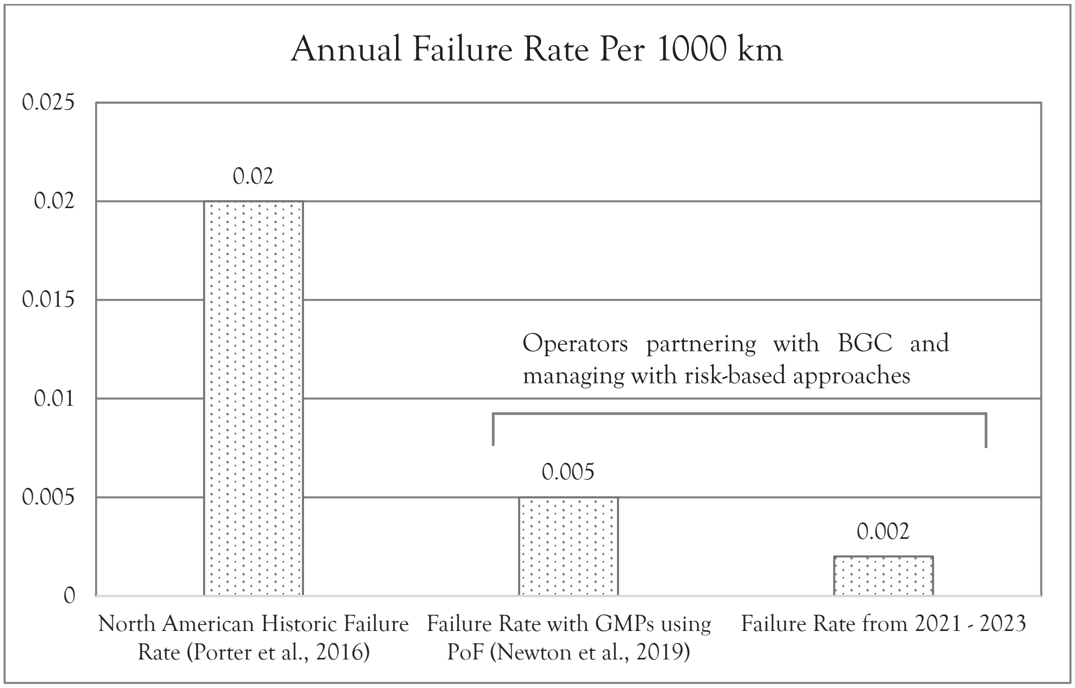

Figure 4. Annual failure rate per 1000 km from historical data and more recent program performance metrics.

Since the failure rate has decreased significantly in recent years, other metrics have been tracked to understand the performance of the program and what is responsible for the improvements. In 2022 BGC started tracking "critical interventions". These are defined as instances where new information resulted in an updated threat assessment which required urgent intervention to manage risk. Examples of immediate interventions would include shutting-in a pipeline, completing an unplanned stress relief, completing an unplanned mitigation, completing a pipeline cut out or reinforcement, and completing a reroute or crossing replacement.

In 2022, 19 critical interventions were documented for slow-moving landslides and for 10 (53%) of them the critical new information prompting the intervention was from IMU. The key information source for other critical interventions was visual inspection (e.g., identifying recent landslide movement) and geotechnical instrumentation (SIs and SAAs) at known active landslides (Figure 5).

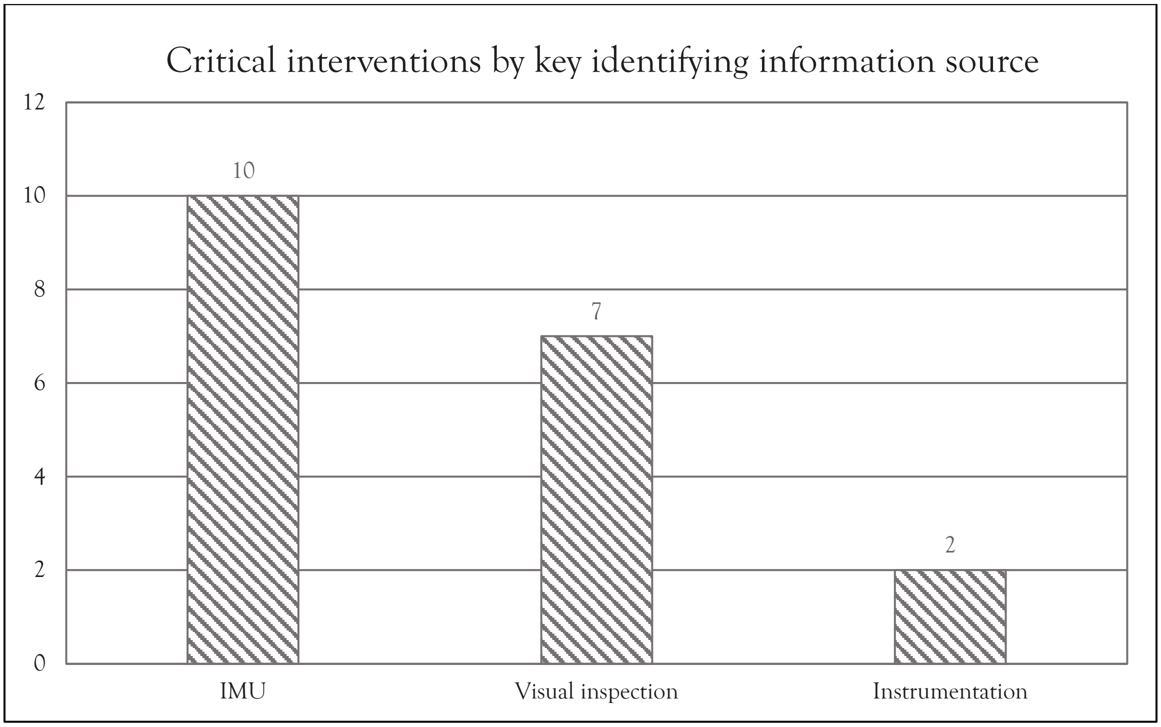

Figure 5. Number of critical interventions in 2022 summarized by key data source.

Critical intervention sites represent the highest risk sites identified in the hazard population and as such would most likely be amongst the sites to cause a pipeline failure in the next years to decades if left unaddressed. The performance of the GMPs over the last several years has likely been the result of many years of program improvements ranging from inventory improvements to proactive mitigations. It is impossible to entirely separate the impact of IMU from other program improvements, but the high proportion of critical intervention sites identified by IMU suggests the impact has been material.

One application which IMU is particularly well suited for is evaluating HDD installations which cross landslides for evidence of impact. IMU is well suited because it can often be used in conjunction with lidar to produce a pipe as-built cross section, and because landslide-impacted bend patterns in HDDs tend to be distinct and easy to distinguish due to the high confining pressures and the generally low-magnitude bending strain present along an HDD profile. Reviewing HDD effectiveness is important because HDD pipelines impacted by landslides have a failure rate 15 times higher than impacted conventionally trenched pipelines due to higher stresses at depth (Van Hove et al., 2022).

A Critical Intervention Case Study: Site 10084

A short case study is presented to demonstrate the multiple ways that IMU can be used to support landslide management. The site is located near Pincher Creek in Southern Alberta, Canada. The slope is 260 ft long, inclined at 7° and is used for grazing animals. The pipeline was built in 1990

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and the first IMU run was completed in 2014. The slope was identified during a hazard inventory in 2012 but was not added to the inventory as a potential hazard because the slope was less than 10° and a landslide was not observed during review of aerial imagery (Figure 6A).

In 2020 a second run of IMU identified a movement area near the toe of the slopes which coincided with a wrinkle (Figure 7B). A site visit was completed which identified fresh landslide scarps and the IMU was analyzed with context from the ground inspection and lidar data (Figure 6B), and it was concluded that the bending strain feature and wrinkle were likely a result of landslide loading.

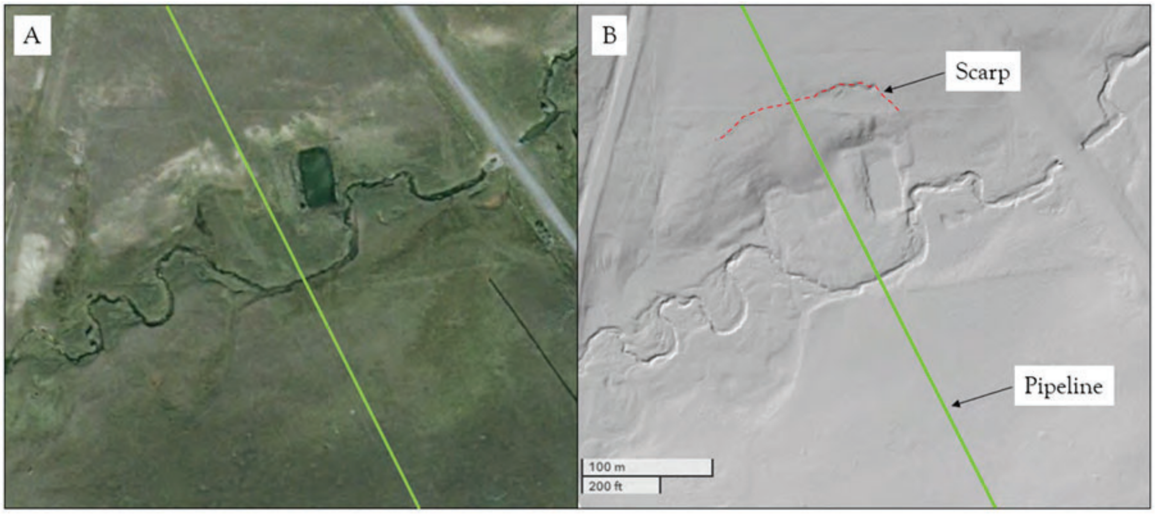

Figure 6. Aerial imagery of Site 10084 (A) and lidar imagery (B) with the main head scarp annotated.

SAAs were subsequently installed, and LCD analysis completed to characterize the extent and velocity of ground movement. The results of these assessments confirmed the interpretation of the IMU which characterized the extent of movement based on an unformed overbend-sagbend sequence at the landslide head scarp (Figure 7C) and the movement area at the slide toe (Figure 7D).

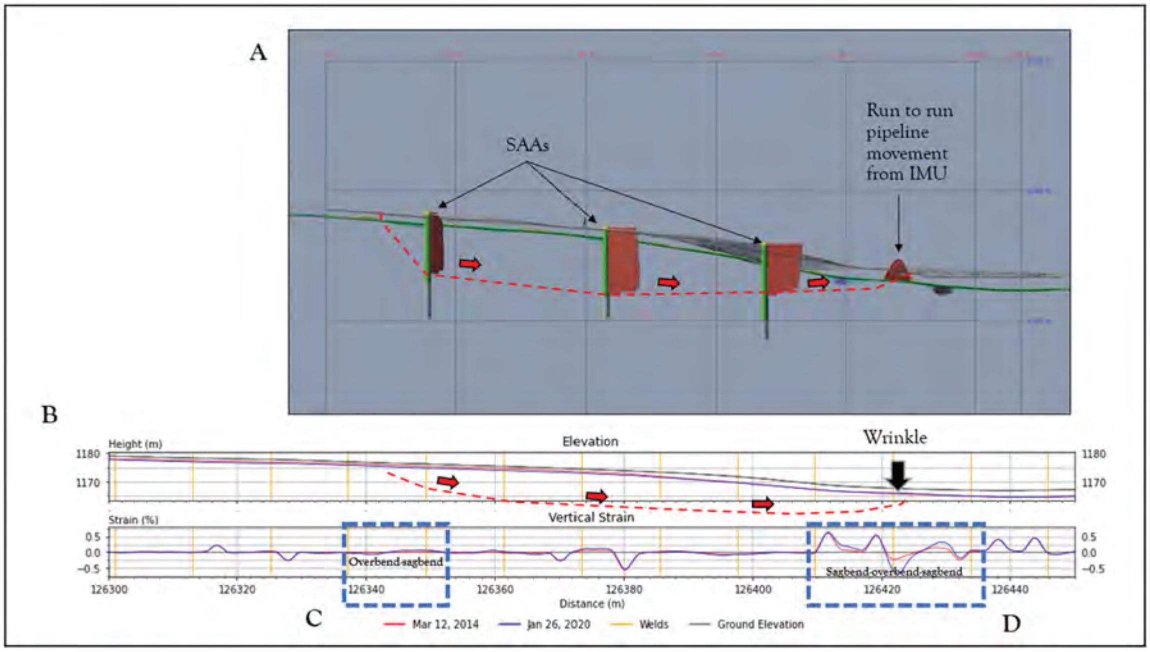

Figure 7. A visual model of topography, pipeline movement, and ground movement measured by slope inclinometer is presented in (A). (B) presents plots of elevation and vertical bending strain from two runs with key bending strains highlighted at (C) and (D).

Historical landslide displacement was estimated based on the deformation of the pipeline observed in the 2014 IMU run and the changes between the 2014 and 2020 run, as well as comparison with the movement rates measured by the SAAs. In total, the pipeline was estimated to have experienced 1.5 m of landslide displacement between construction in 1990 and 2020 (Velocity class 2a). Evidence of landslide impact is not always apparent with axial landslide loading and can be subtle (Figure 7C) or undetectable. IMU signatures for different loading scenarios and limitations are discussed in detail in Dowling et al. (In press).

A pipeline integrity assessment was completed, and a decision was made to cut out and replace the section of pipeline affected by ground movement. Given land use constraints, the pipeline could not be rerouted or drilled easily, and slope dewatering was not permitted, therefore the new pipeline was installed in the same configuration – trenched through a very slow-moving landslide.

The management plan for the site was determined to be real-time monitoring of ground deformation and pipeline strain with a trigger action response plan to intervene with stress relief to avoid pipeline damage. A strain based finite element analysis (FEA) was completed to model the effects of future ground movement and inform the slope displacements at which trigger thresholds should be set. Since the pipeline was installed in the same configuration, the IMU from the original pipeline was used to characterize the ground displacement pattern and calibrate the model outputs (Figure 8, Figure 9). Without IMU data, critical assumptions would have been required for the model (historical displacement, ground movement pattern and pattern/rate of strain development), likely introducing too much uncertainty to produce reliable results.

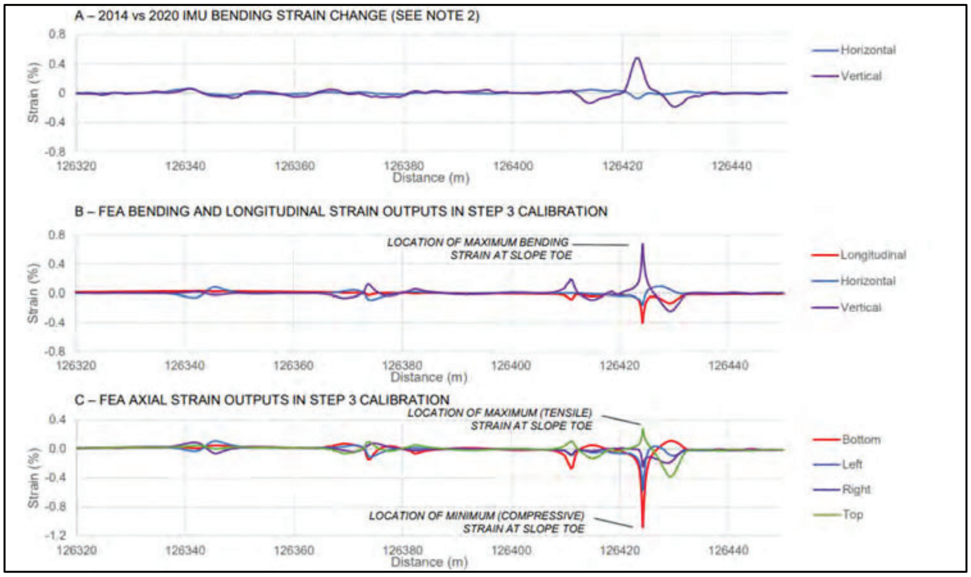

Figure 8. IMU bending strain and FEA model outputs at the calibration point.

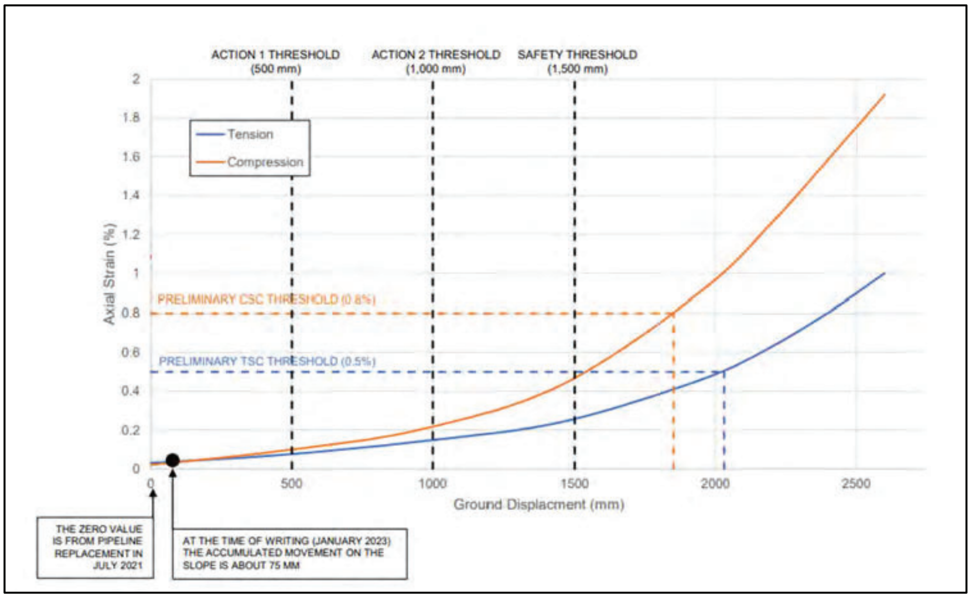

Figure 9. Peak tensile and compressive strain vs ground displacement with trigger action response plan thresholds indicated.

IMU is currently a critical part of the monitoring plan, which also includes visual inspections and real-time geotechnical instruments. Ongoing review of IMU will be used to confirm that the model is adequately reflecting the strain development observed in reality and is valid for ongoing use. IMU also provides an indication of the condition of the pipe continuously through the section impacted by the landslide.

The case study of Site 10084 illustrates how IMU was a critical tool for hazard identification, hazard characterization, providing key input to the pipeline stress analysis, and providing a critical form of ongoing monitoring as part of the site-specific hazard management plan.

Conclusion

In the authors' experience and in the data presented for the case study, slow-moving landslides are the greatest geohazard threat to pipeline integrity. Despite industry recognition of this for many years, slow-moving landslides have proven to be a challenge to manage. The key challenge is that landslide crossings are frequent, on average one every 10 miles, and pipelines are highly vulnerable to landslides (Average vulnerability of 1 in 50) so any landslide that is known to be moving is an important potential integrity concern. While technologies exist to determine landslides activity, most have critical limitations which prevent widespread application. IMU has limitations as well, but is particularly well suited to monitoring landslide movement and pipeline impact where a slow-moving landslide is interacting with a pipeline. IMU is cost-effective, continuous, precise, and provides insight into the condition of the pipeline as a result of past movements.

While IMU has existed for more than 30 years, over the last 10 years it has become commonplace in all GMPs supported by BGC. Over that same period those GMPs have achieved failure rates up to 10 times lower than historic rates, and IMU is the leading source of information for all critical intervention sites.

IMU is useful at all stages of landslide hazard management including identification of unrecognized hazards, characterization of landslide movements and impacts, pipeline stress analysis models which relate ground movement to pipeline strain, and as part of an ongoing monitoring program.

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