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INTERNATIONAL PERSPECTIVE OF PIPELINE GEOTECHNICAL ADVANCES AND CURRENT CHALLENGES
(WE ARE MORE FALLIBLE THAN WE THINK WE ARE)

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ABSTRACT

The geotechnical engineering community continuously strives to enhance and improve their capability to identify, assess, monitor, and mitigate landslides. This has been achieved by significant advances in technology, implementation of best practices and applications of standards aimed at improving the detection, characterization, and mitigation of geohazards. Many national and international organizations are developing best practice management plans and industry standards (e.g., PRCI, ISO, CSA, API). This paper presents some recent advances in the detection and monitoring of landslides affecting buried pipelines and discusses current best practices along with the recent development of landslide geohazard standards related to buried onshore pipelines. Despite these advances, however, the authors express concern that the geohazard practice, relative to pipelines, may be falling short in two key aspects. These are the "failure to learn" from other events and thus improve our practices, and the delusion that monitoring is a mitigation in and of itself against landslide movements. While some pipeline companies and practitioners recognize these fallibilities, there are likely too many that would benefit from reflection on how to make buried pipelines less prone to so-called unexpected or "black swan" landslide events. The reduction in negative pipeline-soil interaction occurrences can be achieved by operators implementing the concepts of a "high reliability organization". The authors provide key aspects of these organizations.

Keywords: Pipeline geohazards, landslides, risk, consequence, monitoring, mitigation, high reliability organizations

NOMENCLATURE

DoC – depth of cover
GEO – geometry tool
GIS – geographical information system
GNSS – global navigation satellite system
GMP – geohazard management program
GPS – global positioning system
HDD – horizontal directional drill
ILI – in-line inspection
IMU – inertial measurement unit
InSAR - interferometric synthetic aperture radar
LiDAR – light detection and ranging
MT - magnetic tomography
PHMSA - Pipeline and hazardous materials safety administration
RoW - rights-of-way

Landslide nomenclature is per Cruden and Varnes [1] and soil-to-pipeline interactions are described using Dewar [2].

1. INTRODUCTION

Since the turn of the century there have been significant advances in the ability to identify, monitor and mitigate landslides. The geotechnical and pipeline industry should be justifiably proud of these advances and incidents that have been averted or avoided. This is not to say that our work is done, and a utopia of landslide threat control has been achieved.

The purpose of this paper is to highlight some of these advances and identify current gaps in our state-of-practice. One persistent troubling issue is to how to identify extremely slow-moving landslides that have no perceivable physical manifestation of movement until identified by a loss-of-containment. Thankfully, there are new ground and pipeline monitoring technologies to address this issue. But there are cautionary notes to consider regarding our reliance on these technologies and perhaps a recommendation to approach landslide-pipeline interaction in a slightly different way. In this regard, the following themes are raised:

- Monitoring landslides is not a mitigation and an end in and of itself.
- Risk-based decision making may be inappropriate for managing landslide-pipeline interaction.
- How can an operator increase reliability of their assets relative to geohazards?

While the discussion is applicable to most geohazards that may impact pipelines, the focus will be on landslides threats as these tend to represent most negative interactions with buried pipelines. Hydrotechnical threats, although also important, tend to represent a smaller number of pipeline failures. Further, this discussion is primarily focused on existing or operating assets but may be also relevant to new pipeline under design.

2. PIPELINE GEOHAZARD MANAGEMENT: INTERNATIONAL PRACTICES

2.1 International Standards and Best Practices

The international standard *ISO20074 Petroleum and natural gas industry: Pipeline transportation systems - Geological hazard risk management for onshore pipeline*, published in 2019 provides the current international practice for geohazard management of buried onshore pipelines. While this standard addresses geohazard management, it is relatively silent on monitoring. The new international standard *ISO 10903 Petroleum and natural gas industry: Pipeline transportation systems – Pipeline geohazard monitoring technologies, processes and systems* is presently under development and likely to be published in 2024. As with the geohazard management standard, this latter standard is not a how-to manual but provides general guidance for use of monitoring tools. The users still need to have a good understanding of the geohazard threat interacting with the pipeline.

An additional resource to the geohazard specialist is the 2020 INGAA report Guidelines for Management of Landslide Hazards for Pipelines (https://ingaa.org/guidelines-for-management-of-landslide-hazards-for-pipelines/). This joint industry project was led by geohazard and pipeline integrity experts and provides a reference for consultants and integrity professionals.

Finally, a new resource to be available to geohazard-pipeline specialists is under development. The development of API 1187 *RP Pipeline Integrity Management of Landslide Hazards* will capitalize on the INGAA work, including inclusion of lessons learned.

The pipeline industry recognizes the great value of case histories, examination, and discussion of geohazard -pipeline interactions and sharing these learnings. These activities will advance the approach to pipeline geohazard assessment, assessing both tensile and compressive strain capacity standard, assessing uncertainty and limitations, improving limit states in problem definition and others that can provide value for hydrogeotechnical practitioners in the management of landslide hazards.

2.2 Advances and Limitations in Characterization and Identification, Assessment and Monitoring

2.2.1 Remote Sensing

The use of remote sensing methods to identify many geohazards in proximity to pipeline corridors has reached a high level of maturity. These technologies include InSAR and LiDAR. Figure 1 shows an oblique aerial photograph and LiDAR image of two legacy (shallow-buried) pipelines traversing a landslide adjacent to a large river. The pipeline integrity managers for these assets would be well-advised to consider mitigation to reduce the threat posed by the active landslide that is seen to be advancing into the watercourse, potentially leading to a rapid and catastrophic ground movement. Figure 2 presents

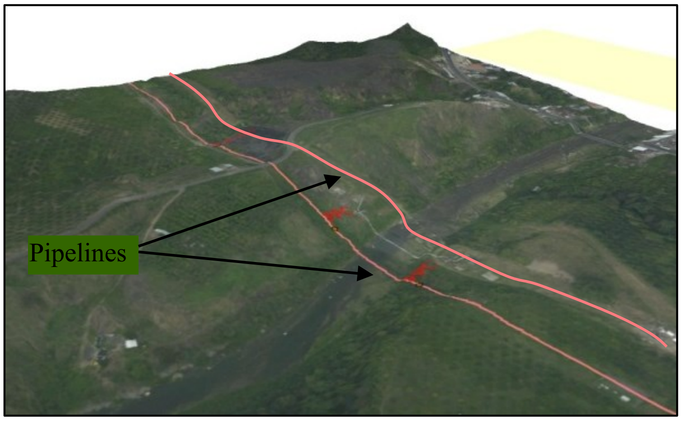

FIGURE 1a: OBLIQUE AERIAL PHOTOGRAPH SHOWING TWO PIPELINE RIGHT-OF-WAYS CROSSING A RIVER.

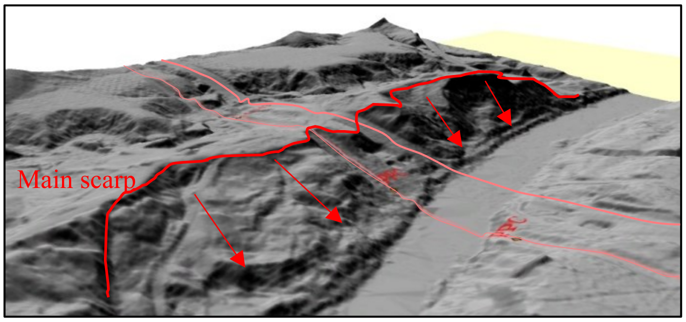

FIGURE 1b: LiDAR (BARE-EARTH DIGITAL ELEVATION MODEL) IMAGE SHOWING TWO PIPELINE RIGHT-OF-WAYS CROSSING A RIVER. INTERACTING PARALLEL AS PER DEWAR (2019).

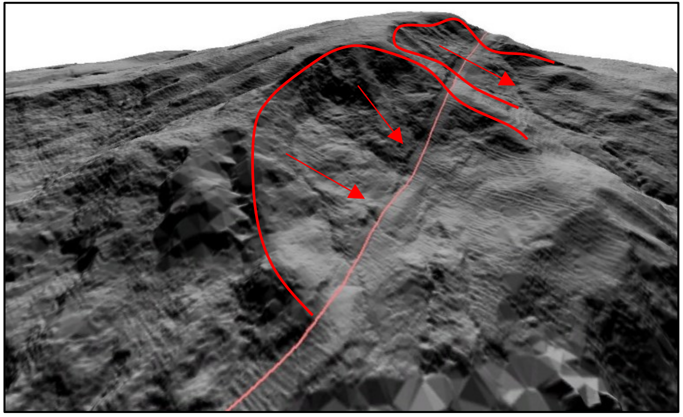

FIGURE 2: LiDAR (BARE-EARTH DIGITAL ELEVATION MODEL) IMAGE SHOWING PIPELINE TRAVERSING INTERACTING OBLIQUE LANDSLIDES.

a second example where two landslides are oblique to the pipeline and will induce significant tensile/bending stresses on the asset.

Recent advances in LiDAR processing and algorithms now allow "change detection" mapping to be completed even over large areas [3]. This process essentially takes a recent LiDAR image and subtracts the point coordinates from a previous image, with the result that ground movements may be measured. This is a useful tool, but one major proviso is that the two images should be of similar resolution. The authors are aware where a recent high-resolution image was compared to a lower-resolution image with the result that upslope areas showed deposition (soil accumulation) and apparent upslope ground movement, and the toe of the landslide showed ground loss and soil depletion. The lesson here is to exercise a fair amount of caution and perhaps skepticism in the interpretation of these results.

The authors recommend initial LiDAR assessments be subject to rigorous expert review or preferably have the assessments conducted by two independent specialists or at least an independent review. Although this represents an extra cost, it avoids the risk that one specialist may impose a bias towards identifying or missing certain types of features. The authors are aware of cases where the same LiDAR images were assessed by two consultants resulting in two polar-opposite interpretations requiring a reconciliation of the opposing interpretations.

Remote sensing imagery may be used at all stages of the pipeline lifecycle, including initial route planning. This gives the designers the opportunity to avoid identified geohazards. During operations remote imagery should be examined and assessed to determine if off right-of-way changes have occurred indicating the presence of a new landslide threat, or other events (such as road construction, clear-cut logging/deforestation, wildfire events) that could negatively impact previously stable terrain or inactive landslides.

2.2.2 ILI IMU Geometry Assessments

In-line inspection (ILI) tools provide direct evidence of soil to pipeline interactions resulting from landslides. Inertial measurement units (IMU) provide precise geometry, three-dimensional position data and measure changes in pipeline shape. Dewar [4] discussed the application of IMU in a geohazard program including a feature classification system. All IMU tools should be run with a caliper module (GEO tool) to detect wrinkles, dents and ovality that may be caused by landslide interactions especially in pipe segments experiencing compression [4]. The three-dimensional position of the pipeline may be compared to previous IMU data to assess the amount of pipeline movement or deformation. Typical accuracies for internal measurement are [5]:

- 0.8 mm to 2.5 mm for internal diameter changes (dents or wrinkles),
- 2.5 mm of ovality,
- 12.5 mm for weld-to-weld distance and
- 0.02% to 0.125% for bending strain determination.

While comparison of multiple sets of geometry data yields the best results in terms of potential pipeline movement, even analysis of single IMU/GEO run data is valuable. Theriault et al. [6] provide a protocol for using single-run IMU data to identify potential geohazard locations (generally limited to landslides and river hazards) along a pipeline. Key points of the study, based on the assessment of over 4000 ILI bending strain features on pipelines in the Appalachian foothills of the eastern United States, include:

- The vast majority (more than 90%) of the bending strain features were not associated with ground movement interaction with the pipeline.
- Only bends that encompass two or more pipe joints were analyzed. Bends confined to a single pipe joint are likely a deliberate (construction) field bend.
- For interpreted bending strain features with an estimated total strain over 0.35%, the most likely cause (more than 50% of the time) is of landslide origin. For estimated total strains greater than 0.42%, the likelihood of a landslide cause is over 90%.
- For interpreted horizontal bending strain features, the likelihood of geohazard causation is over 50% for strains greater than 0.14% and 100% for strains greater than 0.36%.

Note that the bending strain features attributed to landslides in the Theriault study were primarily interaction perpendicular or oblique landslides. Dewar [7] show the majority of landslides for a large operator within the Western Canadian Sedimentary Basin are interacting parallel movements with characteristic zones of compression at the toe of the slope. Murray and Guthrie [8] describe a typical landslide induced bending strain failure via a wrinkle at the toe of a slope in an interacting parallel landslide.

ILI-vendor bending strain assessments provide a good screening tool for IMU runs and very rarely miss critical interactions. However, the vendor is typically looking for pipe shape and geometry changes. For more detailed fitness-for-service assessments, raw data should be analyzed along with geotechnical and pipeline data. These detailed assessments incorporate results from ground monitoring techniques (slope inclinometers, GNSS surveys, LiDAR, visual inspections etc.), pipe monitoring data (ILI, strain gauges, DoC surveys/locates etc.) along with company records to feed into engineering stress analysis.

An emerging ILI technology is also allowing operators to assess axial strain in the pipeline. Current inline technologies do not detect pure tensile strains in pipelines or quantify the state of stress within a steel pipe. Technology details are provided in Westwood et al. [9] and Wang et al. [5] and recommended use of data is detailed in Dewar et al. [10]. The full development and commercialization of this axial pipeline strain technology is likely be a few years away but will be a welcome addition to the integrity toolbox.

In landslide-prone regions, running the IMU/GEO module should be a routine practice either as part of MFL runs or as scheduled stand-alone runs. Dewar [4] provides guidance on when IMU technology should be employed based on the presence of landslide threats (known or potential) in a given pipeline segment. Where there is a potential for pipelines to cross interacting landslides, IMU/GEO data should be collected during the post-construction baseline ILI surveys, which have been traditionally limited to a GEO tool. The use of a combined tool helps eliminate the largest uncertainty around determining whether bending strains are construction related or landslide induced. Often, construction related bending strains are more common on slopes due to the increased difficulty associated with installation and can be misinterpreted as landslide interactions during the first post-construction MFL run, typically performed 5 to 10 years after construction.

One potential issue of IMU surveys for landslide monitoring is the expense and logistical constraints of conducing either ad-hoc runs or long (>100 km) expensive runs where the zone of interest is a relatively short section of several hundred meters of pipeline subject to a landslide threats.

2.2.3 Low Altitude and Terrestrial Surveys

The use of terrestrial LiDAR scanning systems has reached a good level of maturity to monitor known ground movement features. Ground-based stations may be set up on stable ground, for example on a valley slope opposite the area of concern and the laser system automated to survey the area of concern on a fixed frequency. Machine learning algorithms may be used to automatically assess if ground movement has occurred and to automatically transmit an alert to operators. The advantage of these systems is that they can be employed to monitor a specific area, rather than using airborne LiDAR to sweep a much larger swath of terrain.

But what to do about undetected ground movements or unstable terrain with no visual manifestation of movement? IMU/GEO tools are very good at identifying pipeline displacements related to perpendicular and oblique ground movements, and pipeline segments in compression in movements parallel to the pipeline [4]. However, the devices only identify bending/curvature changes. Axial strain tools can be used to determine the tensile state of stress in the pipe but are still a maturing technology as far as interpretation and analysis of data.

The use of terrestrial and unmanned aerial vehicles (i.e., drones) carrying magnetic tomography (MT) units can now map the position of a buried pipeline to reasonable precision, in the order of 100 mm. The technology also assesses the magnetic response of the pipeline to indicate if there are anomalies associated with stress corrosion cracking, weld defects, strains induced by external forces, dents/wrinkles/buckles and corrosion. One current drawback of MT technology in these cases is that collected data does not differentiate between the various anomalies causes, nor can it determine the clock position of said anomalies. The technology is well beyond research and development and is in the field application phase. There is a lack of landslide specific case studies for its application for landslide management. Babcock et al. [11] show MT is useful when combined with IMU/GEO, LiDAR, GNSS surveys and slope inclinometers in managing a 4 km long pipeline segment within a deep-seated landslide complex with multiple landslide types and movements and interactions. The MT pipeline locating technology is most applicable to pipelines crossing side slopes where landslide movement is perpendicular or oblique to the pipeline. The advantage of this tool is that short sections of pipeline may be mapped in a few hours and at a fraction of the cost (likely orders of magnitude lower) of a typical IMU run. The positional data from MT units can be compared to as-build pipeline surveys or existing IMU surveys of the pipeline to determine if the pipeline has moved (typically laterally).

The development and refinement of real time kinematic GPS/GNSS surveying is very important and provides a new and important tool for ground movement monitoring. However, the geotechnical industry does not do use this technology to its full potential. Dewar et al. [7] reports on a study of GNSS-enabled surface monitoring stations that found more than 93% of the monitoring points correctly showed either static or moving points. The technology can be rapidly applied to large areas as compared to conventional surveying or static GNSS surveys. Bracic and McMahon [12] demonstrate the use of real time GNSS surveys to manage active landslides interacting with pipelines at or near fitness for service limits. Figure 4 shows the potential placement of monitoring stations.

One simple monitoring device is the so-called marker ball (Figure 5). These are radio frequency devices that have no battery and can be buried up to 1.5 m below ground surface. Once installed, they would move along with any near-surface ground movement and repeated positional surveys using hand-held locators will track their location and hence any ground movement.

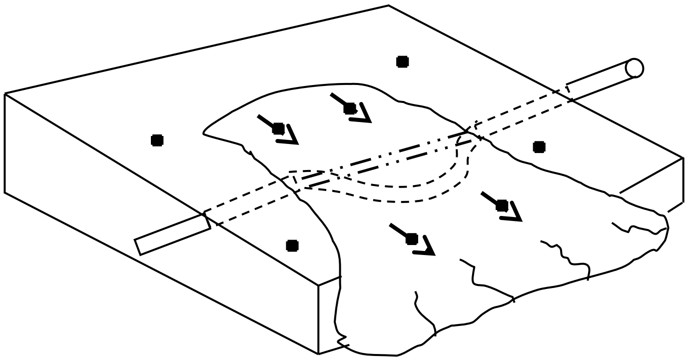

FIGURE 4: LAYOUT OF GNSS ENABLED MONITORING UNITS USED FOR LANDSLIDE MONITORING.

3. IDENTIFICATION OF GROUND MOVEMENT IN THE ABSENCE OF VISUAL CLUES

Perhaps the greatest challenge of geohazard specialists is to identify terrain that is outwardly stable but is experiencing very slow movements. Barlow [13] noted up to 75 mm of measured ground movement at Alberta pipeline slope crossing sites with no indications of ground movement from visual inspection. Dewar et al. [7] noted that only 40% of sites with confirmed ground movement show visual evidence of recent ground movements including tension cracks and/or displacement on scarps. There are a multitude of pipeline failures where there appeared to be no visual indication of preceding ground movement. With

FIGURE 5: MARKER BALLS FOR MONITORING NEAR SURFACE GROUND MOVEMENTS.

post-incident analyses, there are usually some indications of ground movement, although they are likely subtle and easily missed. This is, by no means, an exact science.

The use of good quality ILI tools and diligent assessment and review are important means to identify ground movement. Out-of-straightness measurements will provide a direct measure of pipeline displacements caused by ground movement. The emerging MT technology by surface or aerial surveys may be used to map the position of the pipeline subject to lateral or perpendicular ground displacement.

Repeated LiDAR surveys and change detection algorithms may be used to identify centimeter scale ground movement. In this regard, the operator should be careful to ensure that the quality of the LiDAR sets is of similar resolution to avoid false positives. In addition, the identification of translational landslides may be difficult to identify with LiDAR unless there is a clear main scarp and bulge at the toe. It is desirable to use multiple information sources (for example, LiDAR supplemented with GNSS surveys).

Careful observations and interviews with local landowners and residents may provide clues. As discussed in a later section of the paper, high reliability organizations will proactively spend the money and effort to ensure no undetected threats are present.

4. LANDSLIDE MONITORING FOR PIPELINE INTEGRITY

Our ability to monitor earth movements and other geohazards has reached a high level of precision and reliability. However, that does not mean that our predictive skills have kept pace. The authors raise a concern that perhaps too many geotechnical engineers accept the misconception that monitoring is a mitigation against catastrophic failure. To be clear, it is not. And indeed, in our present world with apparently greater variability in weather and climatic events, sudden activation or acceleration of some "well-behaved" earth features should be expected that will collapse any notion of medium to long-term predictability. Two examples highlight our concern.

4.1 Kentucky Gas Pipeline

In May 2020 a NPS30 (762 mm) gas pipeline ruptured at a site with a known and monitored landslide. Table 1 lists some of the important monitoring and observational events at this site [14] [15].

In the post-incident investigation, the operator (and/or their consultants) concluded that the slope movements had accelerated in the six months prior to the landslide due to higher precipitation. It is not known if geotechnical monitoring instrumentation was installed, but it seems unlikely. Nevertheless, the ILI data showed significant lateral ground movement over time. Figure 6 presents a summary of the out-of-straightness data in the years prior to the landslide [15]. The operator's stress analyses suggested that the strain capacity of 1.0% exceeded the calculated strain demand of 0.6%, presumably under status quo conditions. Documents indicate that the strain capacity of the pipeline would have been significantly lower than the operator's strain limit because of an undermatched vintage girth adjacent to the ILI peak strains. Unfortunately, the status quo was not maintained during early 2020. One additional risk of not initiating mitigation and continuing to monitor an "at-risk" feature is that the operator and consultant may come to accept a new normal. Hopkins [16] notes that the longer you operate an asset at a degraded state of safety (i.e., lower factor of safety), the greater the tendency to normalize the situation and tolerate the degraded state.

Of even greater concern for this specific case history is that an excavation to expose pipeline for either a strain gauge installation or strain relief was scheduled for only a few months after the rupture. If the ground movement had been slightly slower, it was very possible that the excavation to expose the pipeline could have been the trigger for the rupture resulting in many worker casualties.

TABLE 1: Summary of monitoring and observational results.

Date	Oblique Movement	Activity/observation
April 2018	1.2 m	ILI
Oct 2018		Site confirmed as geohazard
April 2019		Aerial inspection - erosion noted
June 2019	1.5 m	ILI
July 2019		Ground inspection of scarps
Late 2019 – early 2020		Tensile strain capacity versus strain demand assessment
May 2020	2.65 m	Slope failure and loss-of-containment
June 2020		Planned strain relief or strain gage install

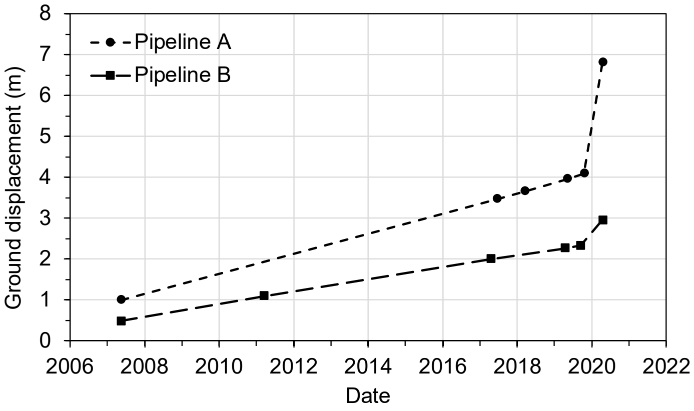

FIGURE 6: INFERRED TOTAL GROUND MOVEMENT INTERPRETED FROM ILI DATA. (Adapted from [15]).

4.2 Northwest Alberta Pipeline

In November 2018 a pipeline operator received information from an adjacent operator indicating that tension cracking was evident on a right-of-way and up to 1 m of recent movements, based on a GNSS survey, had occurred. The pipeline on this slope was a 305 mm (NPS12) high vapour pressure asset. The past three years had significantly more precipitation than normal. Subsequently, an urgent IMU/GEO run was conducted and identified high bending strains on both sides of a deep stream valley with a wrinkle formed on the west side of the valley. The operator had to install a surface pipeline segment supported on timber skids and a temporary bridge until an HDD could be installed. Bracic and McMahon [12] present the real-time GNSS monitoring of the slope during the operation of the surface pipeline segment. The following background and activities were conducted at this valley:

- Crude oil pipeline was constructed in 1996.
- MFL run was conducted in 2011. The run had an IMU/GEO module but a vendor bending strain assessment was not conducted.
- A geotechnical desktop review of the site was conducted in 2015 using LiDAR. Landslide-prone terrain was identified.
- A geotechnical site inspection was conducted in 2016 that focused on the pipeline RoW. Landslide features were identified, but a clerical error categorized the slope as a low rather than a high hazard.
- A geotechnical site inspection by the operator's staff in June 2018 identified fresh ground cracking but it did not appear to be acted upon.

A detailed incident investigation indicated that the urgent mitigation works may have been avoided with a proactive HDD if any of the following items were conducted or acted on:

- Route geotechnical was conducted prior to construction of the pipeline.
- The 2011 ILI run had a vendor bending strain analysis (which was done as part of the investigation in 2019). Evidence of landslide induced strains were obvious on either side of the valley.
- The 2016 field inspection conducted a detailed off RoW inspection after reviewing available othro-images.
- The findings of the 2018 staff inspection of new landslide features were properly assessed and acted on.

This incident occurred despite a mature geohazard management program being in-place and run by a large and capable pipeline operator. The main conclusion is that conducted activities are not useful if data or findings from those activities are not thoroughly analyzed or acted on. These findings are incorporated into the discussion in Section 6.

5. MITIGATIONS

Addressing landslide interaction with pipelines requires care, good planning, and a coherent strategy. First and foremost, any intervention should avoid exacerbating the existing threat or creating a new threat. Figure 7 presents data showing the ground movement before and after a mitigative dig. The ground movement accelerated after the excavation to expose the pipeline and the instability zone enlarged, encompassing a slope indicator off the cleared right-of-way. The lesson here is to reduce the size of any pipeline exposure to the absolute minimum and ensure sufficient instrumentation is in-place to monitor any ground movement or instability.

There are a wide variety of mitigations that may be applied to reduce the impact of landslides on pipeline integrity. Some of these strategies include, in descending preference:

- Hazard avoidance via an HDD or reroute.
- Hazard stabilization.
- Increasing strain capacity of pipeline or reducing strain demand by soil mass.
- Above ground installation or shallow burial.
- Strain relief.

Several pipeline design codes around the world allow for limit states design rather than the traditional stress-based design. For example, the Canadian pipeline code [17], Annex C allows for explicit limit state design for secondary loadings such as soil movement. Using this approach, the at-risk pipeline segment, designed under stress-based conditions could be replaced with a high strain capacity pipe that would tolerate higher deformations than the original pipe.

Figure 8 shows the results of numerical analyses by Lockey and Young [18] to illustrate the value of strain relief. Strain relief is a relatively common practice, but caution is advised when undertaking this activity. First, it is important to recognize that strain relief is a symptom treatment, not a direct-cause treatment. Thus, if one strain relief program is proposed, subsequent strain reliefs events will be needed in the future. Second, great care needs to be taken when sequencing how a pipeline is exposed. For parallel landslide movements the excavation must proceed

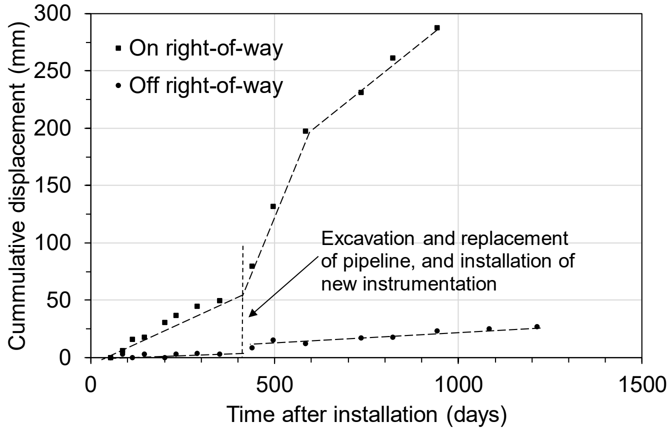

FIGURE 7: SLOPE INDICATOR DATA SHOWING EFFECT OF EXCAVATION ON SLOPE MOVEMENT AND AREA OF INSTABILITY.

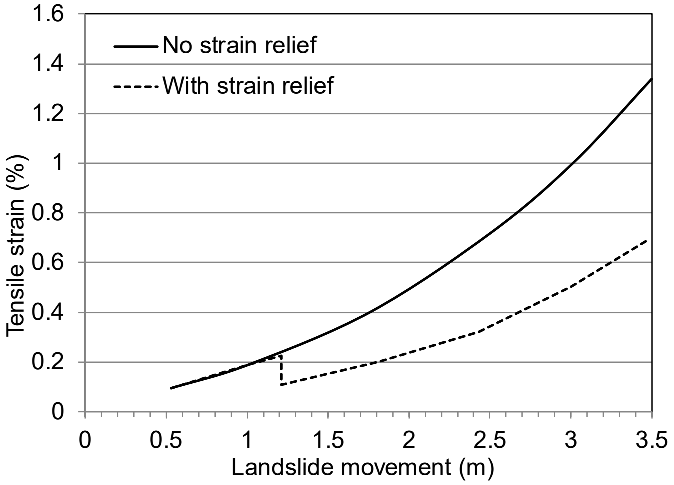

FIGURE 8: EXAMPLE OF STRAIN RELIEF ON PIPELINE SUBJECT TO LANDSLIDE MOVEMENT. PIPELINE DIAMETER IS 914.4 MM, WALL THICKNESS IS 12.7 MM, GRADE API 5L, X60, DEPTH OF COVER IS 1.2 [18].

from zones of tension to zones of compression. For perpendicular or oblique movements, temporary shoring may be required to avoid excavation convergence. Third, with each strain relief excavation and pipeline exposure, it is possible pipeline anomalies may develop and grow. Thus, strain relief mitigation should only be conducted a few (three or less) times. Fourth, strain relief excavations are inherently dangerous, particularly to the field crew conducting the work. Although there have been few reported serious human injuries associated with these activities, the potential for pipeline failure and/or human injury is considered high. As noted above for the Kentucky pipeline, it is possible that a strain relief excavation could have initiated the pipeline rupture.

Numerous pipelines are placed above-ground on skids (supports) to lessen the soil loads on the pipeline from ground movement. When placed above ground, the landslide mass may continue to move but the pipeline remains in its original position, sliding on the skids. Figure 9 shows a photograph of the OCP pipeline in Ecuador supported across a lateral landslide. In the design of the above ground supports, a conservative estimate of the long-term movement of the slope is critical to specify the width of the horizontal pipeline support. If the ground movement is underestimated or accelerates, the operator should ensure the pipeline does not fall off any elevated supports, causing additional pipeline damage. For this reason, on-grade supports (skids) are preferred over elevated supports. Where the pipeline is supported on skids directly on the ground, loose granular fill may be placed over the pipeline to provide protection. This strategy is referred to as "above-ground burial" or "surface pipeline segments" [19]. This strategy has the advantages of generally being less expensive than structural supports, does not severely impair the movement of wildlife and livestock and protects the pipeline from potential damage that an exposed pipeline might be subject to (i.e., firearm damage) and being easier to adjust and reposition as the slope movement progresses. The use of deformable or compliant backfill on the upslope side of a lateral landslide may allow the pipeline to be buried below ground. In this strategy, a wide trench is excavated on the upslope side of the pipeline to slightly below the base of the pipe and then backfilled with a highly compressible material ("geofoam"). The intent is that the ground movement will continue to push against the upslope side of the pipeline, but because the backfill is highly compressible, it will compress against the pipeline wall without exerting high horizontal stress. Figure 10 presents a comparison of uplift resistance for clay and expanded polystyrene foam (EPS). We expect the lateral resistance of the EPS foam to be very low compared to lateral soil resistance.

FIGURE 9: PIPELINE PLACED ABOVE GROUND ON VERTICAL SUPPORT MEMBERS TO ACCOMMODATE LATERAL SLOPE CREEP. (PHOTOGRAPH CREDIT: GUALBERTO CHIRIBOGA.)

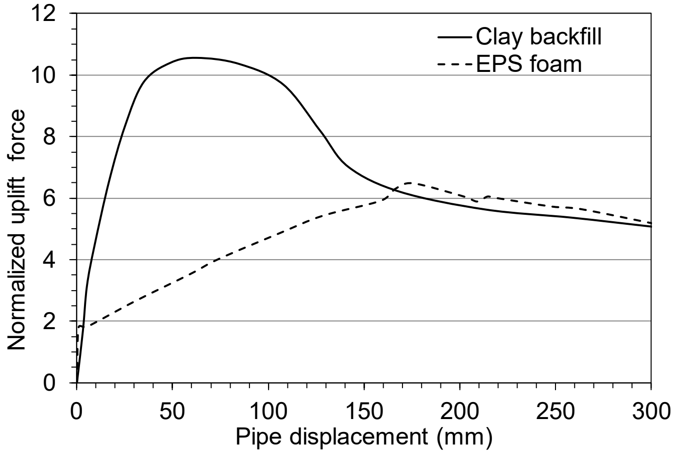

FIGURE 10: NORMALIZED UPLIFT FORCE VERSUS PIPELINE DISPLACEMENT FOR CLAY BACKFILL AND EXPANDED POLYSTYRENE FOAM BACKFILL. DATA FROM [20].

Slope grading, installation of surface and subsurface drainage to control groundwater and seeps, retaining structures are all intended to stabilize the slope and arrest ground movement. This approach is certainly preferred where instability is identified during the design stage and prior to construction and re-routing is unavailable. Reducing the overall slope gradient during construction is the most cost-effective means to stabilize the slope. During operations, slope grading may require taking the pipeline out of service while the grading activities take place and potentially involve lowering the pipeline. The Authors' experience is that where the native soils are re-used with drainage, these types of stabilizations fail approximately 50 percent of the time within 10 years. More robust stabilizations using imported material and civil type berm/pile wall/soil anchors are preferable to ensure long-term performance.

6. DISCUSSION

In 2019 the United States pipeline regulator responsible for safety (PHMSA) issued an advisory bulletin [21] outlining the agency's concern regarding recent loss-of-containment events due to ground movement and other hazards, such as hydrotechnical events. The bulletin explicitly mentioned seven events between 2016 and 2019. The intent of the bulletin was to remind operators of the need for hazard identification and applying appropriate mitigation measures to protect the assets. Between 2019 and mid-2022 when PHMSA issued a follow-up advisory, an additional nine geohazard-induced pipeline incidents occurred. Did anyone read the initial PHMSA bulletin?

The phase "black swan events" originated in England where the population of indigenous swans are all white [16]. Only very rarely did the necessary recessive gene arise giving a black swan. Thus, this phrase became associated with very rare events. As Hopkins [16] notes in his review of the Enbridge Mitchell County event and the PG&E San Bruno gas explosion, both in 2010, these events were entirely predictable, in hindsight. Likewise, landslide failures are rarely black swan events.

Failure rates for pipelines are often quoted in failures per thousands of kilometers of pipeline per year. Typical values related to geohazards are as follows [22]:

Region	Failure rate (per 1,000 km/year
Canada/U.S.	0.02
Western Europe	0.02
Australia	0.003
Brazil	0.07
Bolivia	0.5
Other South America systems	0.2

In contrast, one pipeline in southeast Asia that is only a decade old has a failure rate of approximately 1.5 per 1000 km/year. For this particular asset, the failure rate indicates that those geotechnical-related incidents are not black swan events but rather represents a systemic issue with geohazard management.

The intent of the case histories presented above is not to criticize the intent or capabilities of the operators or their consultants. The authors acknowledge that hindsight is 20/20; and hindsight is nearly always better than foresight. However, there are lessons to be learned that could be applied to similar conditions around the world to reduce the negative impacts of geohazard-pipeline interaction.

The first lesson is that monitoring is not mitigation, and nor is it perfect. It is important to use monitoring to identify the characteristics of the geohazard feature and to aid in the development of interventions, corrective action plans and the like.

Second, it may be very misguided and dangerous to conclusion from monitoring is that the feature is "well-behaved" and amenable to monitoring and an intervention can be scheduled many months (or years) in the future. In the case of the Kentucky event, the operator monitored the landslide to its failure. The monitoring program was unable to identify the inflection point in the displacement versus time plot necessary to schedule a timely intervention. Further, the operator may have underestimated the strain capacity of the pipeline, which may have led to a misinterpretation of the available time to intervene.

The changes being experienced in global weather such as the frequency, intensity and duration of rainfall events will exacerbate slope instability and our belief in "well-behaved" landslides. In addition, anthropogenic effects such as deforestation, hillside cultivation, construction of roadways or changes in river dynamics at toes of slopes and other changes to the terrain adjacent to pipeline rights-of-way may all negatively impact terrain stability. Thus, geohazard specialists should consider continuous review and updating their monitoring strategy and schedule because of ever-changing conditions and consider whether monitoring to a scheduled intervention is still a responsible option.

Third, geohazard specialists have generally advocated a risk-based decision-making process. This approach generally says that risk, being the product of likelihood times consequence, can be accurately measured and used to set intervention schedules, prioritize mitigation, and appease stakeholders and/or regulators. The problem with this approach is that it assumes our ability to characterize and predict the likelihood of a negative event, such as landslides, is sufficiently precise as to be applicable to this group of issues. There are many variables in the calculus of probability, many with high coefficients of variation. These include groundwater levels, undrained strength of the soil mass, rainfall intensity and duration, presence of non-uniform soil stratigraphy and more. Risk-based decision making may be suitable for other aspects of pipeline integrity such as wall loss where corrosion rates are better quantifiable or the structural integrity of the steel where the coefficient of variation of the yield strength is only about 2%, compared to a coefficient of variation of undrained strength of clay being typically 30%. If we are unable to accurately calculate the likelihood of slope instability with good precision (we use the word "calculate" rather than "estimate" risk deliberately) then perhaps a different approach should be considered and applied.

The precautionary principle generally states that over-caution is warranted when there is an absence of well-defined and predictable or known responses or behaviour to a particular event. Related to this is the consequence-based decision-making approach. The consequence-based decision-making process removes the likelihood of an event occurring and simply considers consequence. Thus, a pipeline loss-of-containment that interrupts natural gas service to downstream users, or a loss-of-containment on a hillside adjacent to a water course or near a roadway, or where the clean-up cost or environmental impacts are above a predetermined threshold would be considered high consequence compared to a pipeline where the impacts, costs, or other effects are low to moderate.

When consequence-based decision making is applied, the operator may be required to intervene to control the geohazard much sooner than if considered as a risk-based decision. Simply put, if there is a threat of moderate to high consequence, deal with it as soon as possible, particularly if there are many uncertainties in the estimate of time to failure. One potential outcome of a consequence-based decision approach is that it may result in higher operating costs. However, there are at least two rebuttal points to this concern:

1. Table 2 provides a short list of geohazard-induced pipeline ruptures in North America and South America. The list is far from complete, but the evidence is clear. Even a relatively small pipeline spill (particularly oil) will cost tens of millions of dollars to clean up and remediate. If this same monetary value was spent on proactive geohazard management, mitigation and control, there would be far fewer loss-of-containment events. Furthermore, the environment would be less impacted, and the reputation of the pipeline industry would be enhanced.
2. Many operators strive to be recognized as "high reliability organizations" (HROs). One key principle in HROs is the identification and mitigation of small issues before they become big issues. It requires the proactive use of inspection, reconnaissance, review, and mitigation to maintain the operational integrity of the asset. This concept is discussed below.

How does a pipeline company become a HRO relative to geohazards? The authors consider the following key steps and programs:

1. Ensure the operator has a geohazard specialist/team on staff, or as a minimum, has a dedicated consultant that spends adequate time and energy reviewing and assessing geohazard issues.
2. Consider geohazards wholistically on a system-wide basis and from a site-specific point of view. A risk of using multiple consultants within the same geographic area is that systematic issues and/or multiple threats may be missed. Avoid silos.
3. Ensure the company has a geohazard management plan (GMP). The GMP should include threat assessment, threat management, activities, mitigations and databasing/documentation. GMP activities would start with pipeline design, routing and construction. The GMP should ensure that

TABLE 2 SUMMARY OF SELECTED LOSS-OF-CONTAINMENT EVENTS AND IMPACTS/COSTS

Location	Date	Product	Impacts and approx. costs ($US)
Dosquebradas, Colombia (earth movement)	2011	Gasoline	33 fatalities; cleanup costs unknown
Near Peace River Alberta	2011	Crude oil	$11 million+ in cleanup costs
Yellowstone River, Montana (vortex shedding)	2011	Crude oil	$165 million in cleanup costs
Red Deer River, Alberta	2012	Crude oil	$53 million+ in cleanup costs
North Saskatchewan River, (earth movement)	2016	Crude oil	$107 million in cleanup costs
Noble County Ohio (earth movement)	2018	Natural gas	$5.2 million in cleanup costs
Nixon Ridge, West Virginia (earth movement)	2018	Natural gas	$13 million
Noble County Ohio (earth movement)	2019	Natural gas	Several injuries, two residences destroyed: cleanup costs unknown

available ground and pipeline monitoring technologies are used to their maximum potential. As an example, the program would define when IMU/GEO runs are required (including during the post-construction run).

4. Use multiple sources of data. This includes visual observations on and off the right-of-way, GNSS survey, in-situ monitoring, LiDAR, imagery, locates, IMU/GEO, axial strain, and other emerging pipe monitoring activities. Multiple sources of information will lead the geohazard specialist to a better understanding of mechanisms at-play. Ensure the data from multiple sources is consistent and resolve inconsistencies and conflicting data.
5. Examine all data. While this may seem obvious, consider the case of one oil pipeline rupture in western Canada. During the post-incident investigation, it was revealed that the operator ran IMU tools every few years, but they did not use the available data to assess changes in bending strain and pipeline geometry. If they had, they would have identified a growing wrinkle in a segment of compression at an HDD entry point in the toe of an active interacting landslide moving parallel to the pipeline one year before the loss-of-containment [23]. Many post-failure investigations have found ample evidence, particularly in the IMU/GEO data, was present well before the failure to dispel the "black swan" defense.
6. Ensure that funding and resources are available to have the GMP data fully assessed.
7. Train field staff in geohazard identification. This means field staff being able to recognize small, seemingly inconsequential changes and question their source, or as a minimum, alert the geohazard specialist. For example, why has the paved highway adjacent to the right-of-way now have subsidence features or cracks in the asphalt that have been patched? Are there leaning trees or split trunks on the side slopes; are there new groundwater seeps on the hillside. Why is wetland vegetation growing on the hillside? The field staff should also be surveying the terrain off the right-of-way for signs of instability.
8. Communicate with stakeholders. Field and technical staff should be speaking to local landowners and residents, stakeholders and other operators regarding terrain issues and changes that may be related to potential instability. Has a local landowner recently diverted drainage or clearcut trees on land upslope from the pipeline right-of-way?
9. Ensure staff are skeptical about rationalizing data and potential explanations. Confirmation bias is a significant problem in many industries and geohazard specialists are not immune. Be wary of installing monitoring and trying to schedule an intervention more than a few months in advance, particularly when a rainy season is forecast. Recognize that changes in precipitation behaviour may exacerbate landslide movements and "well-behaved" landslide may be a self-deception or represent "embedded ignorance" [24].
10. Ensure the company culture encourages reporting and threat identification, even if a hazard arises from field operations (for example, during a site dig, the backhoe operator damages the pipeline coating but does not report it). This includes the ability of field staff to freely contact supervisors at home after normal working hours and on weekends.
11. Ensure the company organization does not silo technical groups to the point that communications and interaction is hampered. The integrity team should be multidisciplinary, including geohazard, corrosion, metallurgical, weld, construction, GIS and data specialist/experts. A multidisciplinary approach will allow each discipline a seat at the table to present their expert perspective, which might not be appreciated by other experts. For example, what is the significance of a slow-moving landslide on a 50-year-old X52 pipeline with overmatched welds versus a new X80 pipeline with undermatched weld heat-affected zones? Ensure there is adequate discussion and interaction between the geohazard specialist and the ILI review team.
12. Ensure that the company is adhering to the intent of the regulations and/or company management plans. The authors are aware of operators who have carried out IMU runs but did not analyze the data because the regulations did not explicitly state that data analysis was required and there is no company plan to define how the data should be reviewed and/or acted on.
13. Ensure the integrity team does not miss the forest for the trees. That is, consider both individual, site-specific threats, but also the whole system. Some very large landslide complexes may impact a pipeline over five or more kilometers. A focus on discrete sites may lead to missing a larger regional threat. The focus may be on active ground movements with clear visual indicators where the actual threats may not be identified as there is no visual manifestation of recent landslide activity.
14. Ensure asset integrity budgets are such that all critical integrity issues can be addressed in a timely period. That is, repair and mitigation of identified threats should not be constrained by operating budget limitations.
15. Mid-level and senior management should consider long-term asset integrity implications and not focus on short-term goals such as personal bonuses and cost-cutting efforts.
16. Ensure those responsible for the integrity of the asset are completely independent of commercial considerations related to asset operations.

7. CONCLUSION

The subtitle of this paper is "We are more fallible than we think we are". The intent of this comment is to impress on all geotechnical and geohazard specialists that, despite the many advances in geotechnical instrumentation, numerical modelling, remote sensing, ILI inspection methods and technology, and other techniques, geohazard identification and control remains a very inexact science. In a world of changing climate, we should not be lulled into a belief that well-behaved landslides will continue to be well-behaved. We should question our confidence that we can monitor and predict changes in landslide behavior.

We have identified our current practice with respect to the tools available for geo-professionals to monitor some geohazards on pipelines. Despite these technical advances, there still are many avoidable loss-of-containment events due to our inability to predict the behaviour of slopes where ground movement is occurring.

The authors promote a consequence-based decision-making process over an exclusively risk-based approach. While this may cost the pipeline operator more in the short-term, there are clear long-term benefits.

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