# Integrating Terrain and Geohazard Knowledge into the Pipeline Lifecycle

Michael Porter, Mark Leir and Alex Baumgard
*BGC Engineering Inc., Vancouver, BC, Canada*
Gerry Ferris
*BGC Engineering Inc., Calgary, AB, Canada*

ABSTRACT
The lifecycle of a pipeline typically involves several phases, from conception, including route selection, environmental assessment and engineering design, through construction, and into integrity management during operation. Each phase benefits extensively from the characterization of the terrain and existing or potential geohazards along the pipeline corridor. This paper provides a vision for integrating terrain and geohazards knowledge into the pipeline lifecycle. It is divided into three main parts: geohazards significance and management framework; integrating geohazards into pipeline project development; and geohazard management for operating pipelines.

RÉSUMÉ
Le cycle de vie d'un pipeline implique généralement plusieurs phases allant de la conception comprenant choix du tracé, évaluation environnementale et conception technique, à la construction, en passant par la gestion de l'intégrité du pipeline lors de son exploitation. Chaque phase bénéficie de la caractérisation préalable du terrain et des géorisques potentiels ou réels le long du tracé. Cet article présente la prise en compte des connaissances du terrain et des géorisques dans le cycle de vie du pipeline. Il est divisé en trois parties: l'importance de l'évaluation des géorisques et leur intégration dans la gestion opérationnelle des pipelines, la prise en compte des géorisques dans les phases de développement de projets de pipeline et la gestion des géorisques lors de l'exploitation de pipelines.

## 1 INTRODUCTION

The lifecycle of a pipeline typically involves several phases, from conception, including route selection, environmental assessment and engineering design, through construction, and into integrity management during operation. Each phase benefits extensively from the characterization of the terrain and existing or potential geohazards along the pipeline corridor. The information requirements change considerably in scope and detail from one phase to the next, as does the level of effort for information gathering and analysis. In addition, safety, environmental, and regulatory requirements are increasingly stressing the geoscience and engineering industries' ability to characterize terrain and geohazards in a timely manner compatible with typical pipeline project development schedules.

This paper provides a vision for integrating terrain and geohazards knowledge into the pipeline lifecycle. It is divided into three main parts: geohazards significance and management framework; integrating geohazards into pipeline project development; and geohazard management for operating pipelines.

In the first part we focus on the types of ground movement geohazards that can influence pipeline routing, design, and operation; we describe the relative significance of geohazards-related pipeline failures; and we provide a general framework for geohazard risk management for pipelines. In the second part we describe the types of geohazard information that can be gathered quickly at the early stages of project development to aid in route selection; information with long-lead acquisition times that will be needed for environmental assessment and front end engineering design (FEED); and information that is best acquired later in the design phase or during construction. The third part focuses on pipeline integrity management for geohazards and new tools that are being developed to facilitate risk-based decision-making.

## 2 GEOHAZARD SIGNIFICANCE AND MANAGEMENT FRAMEWORK

### 2.1 Types of Geohazards

Within the context of pipelines, geohazards comprise a subgroup of natural hazards associated with geotechnical, hydrotechnical, tectonic, snow and ice, and geochemical processes that can affect the safety of construction or operational personnel, impact construction schedules and costs, threaten the integrity of pipelines and associated infrastructure, and/or impact the environment. Most are natural processes triggered by storms or seismic activity, while others, such as the potential for cut and fill slope failures along a pipeline right-of-way, can be triggered or exacerbated by project construction and site remediation activities or third party activities.

A partial list of geohazards that may need to be accounted for in Canadian onshore pipeline development projects and in pipeline integrity management programs is provided in Table 1.

Ground movement hazards are a subset of geohazards. They include processes associated with the movement of soil, rock or water that can cause pipeline exposure and/or unintended loads on pipelines and thereby threaten pipeline integrity. Ground movement geohazards, and their potential to cause pipeline failure (exposure, deformation, and loss of containment (leak or rupture), are the focus of the remainder of this paper.

Table 1. Partial list of geohazards affecting Canadian onshore pipeline projects

| Hazard Class | Type, Name |
|---|---|
| Geotechnical Hazards | Frost Heave<br>Thaw Settlement<br>Solifluction<br>Rock Fall<br>Rock Slide/Creep<br>Earth Slide/Creep<br>Earth Flow<br>Debris Slide |
| Hydrotechnical Hazards | Debris Flow<br>Scour<br>Channel Degradation<br>Bank Erosion<br>Encroachment<br>Avulsion<br>Shoreline Wave Erosion |
| Seismic Hazards | Liquefaction<br>Lateral Spreading<br>Surface Fault Rupture<br>Strong Ground Motion<br>Volcanic Eruption |
| Snow and Ice Hazards | Snow Avalanche<br>Ice Fall and Ice Avalanche |
| Other Ground Movement Hazards | Surface Water Erosion<br>Groundwater Erosion<br>Ground Subsidence (Karst/Mines) |
| Geochemical Hazards | Acid Rock Drainage and Metal Leaching |

### 2.2 Spatial Frequencies of Geohazards Along Pipeline Corridors

Over the last 15 years, the authors have been involved in the implementation of geohazards integrity management programs for several major pipeline operators of gas and oil gathering and transmission pipelines systems. Over this time, inspectors have visited on the ground more than 13,500 individual geohazard sites spanning approximately 63,000 km of pipelines in Canada and the USA (Baumgard et al. 2014). These inspections have focussed on the geotechnical and hydrotechnical hazards listed in Table 1.

Approximately 70% (44,000 km) of the pipelines inspected as part of the program have been located in prairie terrain, and approximately 30% (19,000 km) in mountainous terrain (Table 2). For comparison, of the nearly 13,500 hazards visited, 60% of them are found in prairie terrain and 40% within mountainous terrain. Perhaps not too surprisingly, this suggests that, on a per kilometre basis, there are a greater number of geohazard sites in mountainous terrain than in prairie terrain.

Table 2. Approximate distribution of geohazard sites along pipelines in Canadian and US mountain and prairie terrain from BGC's geohazard management programs

| Physiographic Region | Total km | # of Sites |
|---|---|---|
| Mountainous | 19,000 | 5,744 |
| Prairie | 44,000 | 7,736 |
| Totals | 63,000 | 13,480 |

The average number of geohazards per kilometre of pipeline is shown in Table 3. The higher frequency of hazards in mountainous terrain is clearly demonstrated. Using these statistics, an operator who manages pipelines across both types of terrain might expect one geohazard requiring management for every 3 km of pipeline operated. This frequency will vary and has been observed to range between approximately a low of one geohazard site per 6 km of pipeline to a high of nearly one geohazard site per 2 km of pipeline (Leir 2012).

Table 3. Average number of geohazard sites per kilometre of pipeline from BGC's geohazard integrity management programs

| Physiographic Region | Average # of Sites per Kilometre | | |
|---|---|---|---|
| | All Hazards | Geotech. | Hydrotech. |
| Mountainous | 0.417 | 0.070 | 0.347 |
| Prairie | 0.208 | 0.021 | 0.187 |
| All | 0.305 | 0.044 | 0.262 |

### 2.3 Significance of Geohazard-Related Pipeline Exposures, Leaks, and Ruptures

Despite the relatively high spatial frequency of geohazard sites along operating pipelines, geohazard-related pipeline failure rates (in terms of loss of containment) in Canada, the United States, and Western Europe are typically rare events. However, where difficult ground conditions have not been properly accounted for in pipeline design, construction, and operation, geohazards may have an overriding influence on pipeline risk and reliability.

The relative significance of geohazards is often underestimated by the pipeline industry and a brief review of published western European and U.S. incident data indicates why. The European Gas Pipeline Incident Data Group (2011) reports that geohazards only accounted for 7% of all pipeline incidents in Western Europe between 1970 and 2010. External interference is cited as the leading cause (50%), followed by construction and material defects (17%), and corrosion (15%).

U.S. DOT (2013) summaries of all reported incident data for the period 1993 to 2012 indicate construction defects (26%), external interference (18%), and corrosion (18%), are leading causes of gas pipeline incidents in the

United States, with geohazards only contributing to about 6.8% of incidents.

Data published by the National Energy Board (2011) for Canadian Regulated pipelines indicates the leading cause of failure during the period 1991 to 2009 was Cracking (38%), followed by metal loss (27%), with geohazards contributing to about 5% of incidents.

These failure frequency statistics do not tell the whole story. Pipeline incidents caused by geohazards often result in larger leaks, greater property and environmental damage, and longer periods of service disruption than other hazard types. For example, geohazards are the second leading cause of pipeline *rupture* (as opposed to holes and pinhole-cracks) in western Europe (EGIG 2011). U.S. DOT data indicates that heavy rains/floods account for 1.5% of all failures but 16.8% of all costs related to failures.

The relative significance of geohazards is even more pronounced where pipelines are constructed in difficult terrain without full appreciation for the presence of geohazards. In South America, for example, the authors have been involved with several pipelines where geohazards are clearly the leading cause of failure, with failure frequencies between 2.5 and 5 per 1,000 km per year observed in extreme cases (Porter et al. 2004). These failure frequencies are about 2 orders of magnitude greater than experienced in western Europe (EGIG 2011).

Some pipeline operators define pipeline failure when the depth of cover on their pipeline is below a certain amount (i.e. 0.6 m) or is zero which results in an exposed pipeline. A review of pipeline exposure frequencies within the authors' geohazard management database suggests that, depending on geographic region, a pipeline operator can expect one new section of exposed pipeline every year for every 1,000 km of operating pipeline (Leir 2012). So, for a 5,000 km long pipeline system an operator can expect five new pipeline exposures from geotechnical and hydrotechnical geohazards every year. This exposure frequency is approximately 100 times more frequent than the estimates of rupture frequency made from a review of various regulator rupture databases (Leir 2012). Although influenced by the age of the pipeline system and geography, these guidelines can help forward-thinking pipeline operators budget for hazard mitigations.

Finally, geohazards can contribute to the disbondment of old pipeline coatings, aggravate corrosion, and may contribute to stress corrosion cracking. The contribution of geohazards to these types of failure mechanisms is not always recognized and may therefore be under-reported in the industry's failure statistics.

### 2.4 Pipeline Geohazard Risk Management Framework

In the authors' opinions, geohazards are best managed using a combination of industry best practices and a risk-based approach to prioritizing investigation, design, monitoring and mitigation efforts.

Canadian Standards Association (2011) CSA Z662 provides guidance on methods to estimate failure frequency and pipeline risk. Approaches to estimating failure frequency include:

- analysis of historical operational and incident data;
- fault and event tree analysis;
- mathematical modelling; and,
- judgement of experienced and qualified engineering and operational personnel, based on known conditions.

Porter et al. (2004) provides a summary of hazard and risk terminology and further guidance on the options available for estimating pipeline geohazard risk. Figure 1 provides a summary of our generalized risk management framework.

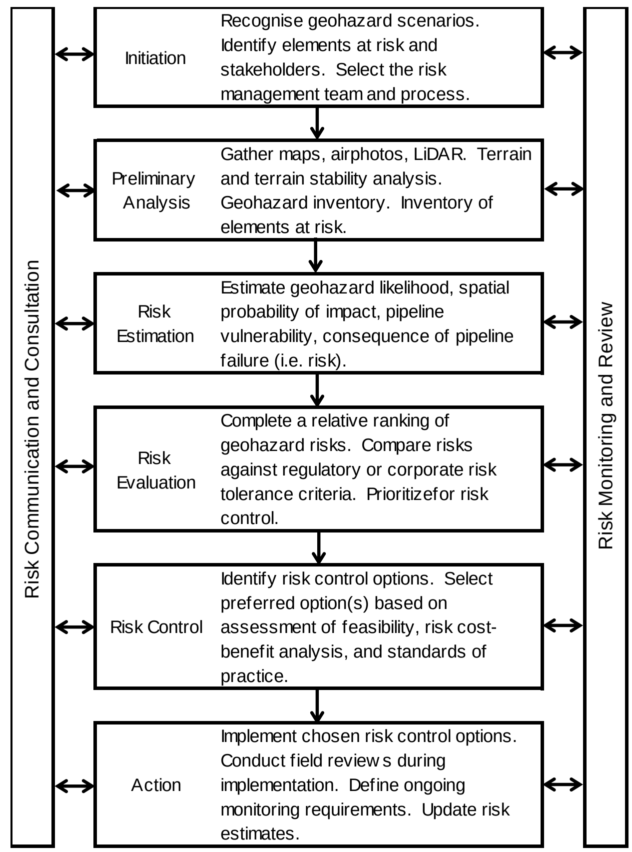


Figure 1. Pipeline geohazard risk management framework (after CAN/CSA Q850-97, MoF 2004, and ISO 2009)

## 3 PIPELINE DEVELOPMENT LIFECYCLE

Geohazard avoidance is one of the most effective and least expensive options to reduce pipeline geohazard risk. This is provided that geohazards are identified and characterized early enough in the pipeline development lifecycle that route adjustments can be made with minimal impact to cost and schedule.

Pipeline route selection is an iterative process by which one or more potential pipeline corridors are systematically reduced from an early conceptual corridor of about 10 km in width down to a final right of way that is about 50 m in width. As the project advances to narrower corridors, the project scale and the level of detail in the follow-on investigations increase. An idealized four-stage process to pipeline routing is outlined in Table 4, below. Each of the four stages provides guidance on the study scale, the nominal corridor width, the engineering design level, tasks and deliverables. The staged approach is a "road map" that helps all project participants understand how geohazards can be addressed in the pipeline routing process and summarizes the scope, deliverables, and limitations of each Stage.

Pipeline routing is a very dynamic process. Each stage is iterative as a considerable number of factors guide the route selection process including the political and regulatory process, environmental impact and permitting, economics, constructability, land acquisition, and terrain. A change in one of the factors may require that some of the other factors be re-evaluated and models be re-run. For example, if the pipeline route needs to be moved because a section of land cannot be acquired, then the re-route will need to be reviewed again by the appropriate experts to determine if any 'show stoppers' are present and if the re-route can be constructed. A 'show stopper' is loosely defined as a technical, social or environmental route constraint that is likely not feasible to overcome given criteria that have been established for the overall project schedule and budget.

In the early stages of a project the location of pipeline corridor or centerline will vary as frequently as every week. Any geohazard models that reference the pipeline corridor or centerline need to be built so they can easily accommodate frequent centerline changes over several years leading up to construction.

Table 4 and the subsections that follow outline an idealized and simplified pipeline development lifecycle and the steps that can be taken to effectively incorporate terrain and geohazard information into the process. As a guideline, each of the four stages often requires about a year to complete.

Table 4. Idealized Pipeline Development Lifecycle

| Stage | Corridor Width at End of Stage | Typical Map Scale and Terrain and Geohazard Data Sources |
|---|---|---|
| Preliminary Route Appraisal (Prefeasibility) | 10 km | 1:50,000 to 1:5,000,000 Published maps, satellite imagery, limited helicopter reconnaissance |
| Route Selection (Feasibility) | 2 km to 500 m | 1:10,000 to 1:50,000 Airphotos, field reconnaissance, limited topographic survey |
| Route Definition (Basic Engineering) | 500 m to 100 m | 1:2,500 to 1:20,000 LiDAR, topographic survey, geological surface mapping, subsurface geotechnical investigations at critical crossings |
| Route Optimization (Detailed Engineering) | 50 m | 1:500 to 1:5,000 Surface mapping and subsurface geotechnical investigations at select geohazard sites, crossings, and above-ground facilities |
| Construction | Width of RoW and temp. work space | Additional investigations following right-of-way clearing and grading, and geotechnical input during road pioneering, trenching, site remediation |
| Operation | See Section 4 for description of pipeline geohazard integrity management techniques | |

3.1 Preliminary Route Appraisal

The objective of the Preliminary Route Appraisal stage is to identify one or more pipeline corridors that are less than 10 kilometres wide in which it appears feasible to permit and construct the proposed pipeline. These corridors will be identified primarily on the basis of desk study and limited to no field reconnaissance by the routing team. The routing team would typically comprise specialists in pipeline hydraulics, pipeline construction and operations, environmental assessment, and terrain analysis.

Common sources of terrain and geohazard information would include published maps and reports. Increasingly common is use of tools such as Google Earth (e.g. Figure 2) to review publically available satellite imagery. This desk study review might be supplemented by brief vehicle or helicopter-supported field reconnaissance.

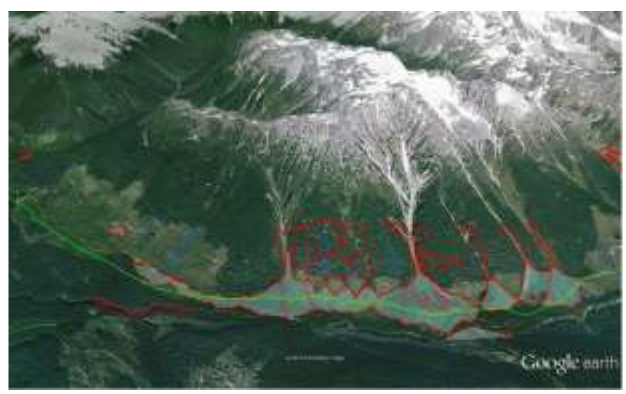


Figure 2. Example of preliminary terrain and geohazard information acquired through review of satellite imagery

From a terrain and geohazard perspective, the role of geotechnical engineers and geoscientists at the Preliminary Route Appraisal stage is to provide guidance on the types of terrain and geohazards likely to be encountered along each of the routes and a preliminary qualitative assessment of major river crossings and identified large-scale geohazard features that the proposed route centreline would cross. Potential geohazard 'show stoppers' are identified. The scope of the geotechnical and geohazard investigations that would likely be required in order to advance through the next stage (Route Selection) is identified.

### 3.2 Route Selection

The objective of the Route Selection stage is to identify a single preferred pipeline corridor that is less than 2 kilometres wide in which it appears feasible to permit and construct the proposed pipeline, and to gather enough information to support conceptual design and the development of a Class 4 cost estimate. This stage focuses primarily on three-dimensional positioning of the pipeline and related major infrastructure such as bridges, aerial crossings, and facilities (pumps and compressors stations).

Common sources of terrain and geohazard information would continue to include published maps and reports, and satellite imagery. These would be supplemented by review of historical government aerial photography at locations of major river crossings and additional vehicle or helicopter-supported field reconnaissance. Topographic surveys of major river crossings would be conducted. Individuals experienced in pipeline construction and routing would begin to traverse the corridor on the ground and by helicopter, and would provide feedback to the geotechnical engineers and geoscientists on observations and areas of concern.

From a terrain and geohazard perspective, the role of geotechnical engineers and geoscientists at the Route Selection stage is to:

- Identify and help route around geohazard ‘show stoppers’;
- Begin terrain and terrain stability mapping;
- Assign simplified terrain types to the corridor;
- Provide preliminary estimates of important costing parameters, such as quantities of ditch rock;
- Gather regional hydrology data to characterize flows in watercourse crossings;
- Gather regional seismic hazard data;
- Provide desk-study observations for proposed facilities such as compressor or pump stations;
- Identify locations requiring detailed geohazard, geotechnical and hydrotechnical investigations and support the site investigation permitting process; and,
- Support the development of the design basis for the project.

In some parts of western Canada, the permitting process to secure permission to conduct subsurface investigations is extensive, and can take six months or more to complete. This often means that permit applications are prepared while the pipeline centreline location is still in a state of flux. Considerable effort is often spent on securing Investigative Use Permits, Road Use Permits, and Water Use Permits for sites that become redundant as the route is refined, and basic engineering design is often completed without the benefit of subsurface investigation results at new watercourse crossing locations because of the permitting timeline. Considerable patience, flexibility, and communication are required from terrain and geohazard specialists when trying to balance the project data requirements with the dynamic nature of the pipeline routing and site investigation permitting processes.

Typically the environmental assessment process will commence near the end of the route selection phase. This will include desk and field studies for fish, wildlife, rare plants, archeology, soils and terrain stability, and numerous other factors. The terrain and geohazard requirements for pipeline routing and engineering design may differ than those required for the environmental assessment, but efforts should be taken to ensure the findings of the engineering and environmental geotechnical and geohazard studies are complementary.

### 3.3 Route Definition

The objective of the Route Definition stage is to support Basic Engineering, to prepare the environmental impact assessment, to facilitate commencement of a final investment decision on the project, and to commence the procurement of long-lead time items such heavy wall pipe. By the end of this stage, the pipeline corridor will be narrowed to less than 500 m (and typically to less than 100 m). This corridor will contain the proposed pipeline right of way and any required temporary workspace for construction.

Project-specific light detection and ranging (LiDAR) survey data and high-resolution ortho-photography would typically become available early in this project stage. Increasingly, these datasets form a key input to detailed terrain and terrain stability mapping activities, inventory and desk-study characterization of geohazards, and selection of conceptual crossing methods and preliminary design parameters for typical stream crossings.

LiDAR data are supplemented by terrain mapping field verification activities and focused field mapping efforts at areas of interest including:

- Stream crossings
- Geohazard and steep slope crossings
- Areas of shallow bedrock
- Areas of thick organic soils
- Locations of compressor or pump stations

Some of the key investigation, analysis and design tasks include:

- Developing a zone of river influence for all major watercourse crossings by estimating the flood and scour elevations for the project’s hydrological design event (typically the 100 or 200-year return period flood) and assessing bank erosion and channel avulsion potential;
- Commencement of Terrain Stability Field Assessments (TSFAs) on unstable and potentially unstable (Class IV and V) terrain in advance of clearing, right-of-way preparation, and construction permitting and activities.

Geotechnical subsurface investigations would be carried out at all crossings where trenchless (horizontal directional drilling (HDD) or micro-tunneling) or aerial/bridge crossings are proposed as the primary or secondary crossing methods. Subsurface investigations such as test holes, test pits, and geophysics are also carried out at the locations of proposed compressor or pump stations, select road, rail and pipeline crossings, and locations where the potential for liquefaction, lateral spreading or deep-seated landslides are suspected.

Few active faults have been identified in western Canada, but with the advent of LiDAR it is now becoming more practical to identify suspect lineaments that may represent faults that have been active since de-glaciation. Desk study inventory of suspect lineaments is followed by field reconnaissance. If field observations indicate that the lineaments have offset Holocene sediments, more detailed subsurface investigations can be subsequently conducted during Route Definition or the following Route Optimization stage to verify the presence of faults and their magnitude and direction of future movement.

While it does not constitute a ground movement geohazard, Route Definition is the stage at which assessment of acid rock drainage and metal leaching (ARD/ML) potential often commences. Desk study review is carried out to identify areas of potential ARD/ML. This is supplemented by field reconnaissance and laboratory testing of select rock samples. Additional review of ARD/ML potential is conducted as rock samples are retrieved from various geotechnical drilling programs. Concepts for managing potentially acid-generating rock that might be encountered during construction are developed.

### 3.4 Route Optimization

The objectives of the Route Optimization stage are to support detailed design, preparation of construction drawings, procurement of construction materials and contractors, and permitting for construction activities.

Several terrain and geohazard tasks that would get underway during Route Definition continue to be advanced through this stage, and other new tasks are introduced. Some of the key investigation, analysis and design tasks include:

- Ongoing predictions of scour and bank erosion potential for the atypical design of stream crossings;
- Ongoing subsurface investigations to support the detailed design of trenchless and aerial crossings;
- Foundation and anchor design for aerial crossings;
- Foundation design parameters for compressor and pump stations, valves, and other facilities
- Estimating soil reaction springs for use in pipe-soil interaction models for pipeline design;
- Hand or mechanized augering, and geophysical surveys to delineate muskeg, peat, or other soft soil areas and to support design of pipeline buoyancy control measures;
- Geohazard risk assessment and development and selection of risk control measures;
- Support for the design of known landslide and active fault crossings;
- Ongoing terrain stability field assessment on unstable and potentially unstable (Class V and IV) terrain in advance of clearing and right-of-way preparation activities;
- Development of specifications for cut and fill construction, and for permanent stabilization of slopes and road and RoW cuts and fills;
- Refinement or customization of erosion control plans; and
- Installation of instrumentation such as piezometers, slope inclinometers, and strain gauges where landslides must be crossed, to support ongoing monitoring and integrity management.

### 3.5 Construction

In reality, pipeline routing and the supporting geotechnical and geohazard assessment and design activities never proceed as linearly as outlined above. Some sections of the pipeline are relatively more straightforward and advance through each of the routing stages quickly, while others are more complex and route refinement activities will continue through construction. Furthermore, many geotechnical investigation activities are much more efficient to carry out during construction once access has been created, the right of way has been cleared, and grading and trenching activities have commenced. Examples of geotechnical and geohazard activities that often take place during construction include:

- Snow avalanche hazard management for winter construction activities;
- Additional terrain stability field assessments to support construction of access roads and the right-of-way construction platform;
- Geotechnical review of soil and rock cut excavations and provision of guidance on final cut and fill slope design;
- Additional geotechnical drilling at HDD crossings, such as at entry and exit points to support design of surface casing activities;
- Subsurface investigations and foundation designs for “last minute” positioning of valve stations;
- Field reviews for foundation construction;
- Field review and laboratory assessment of ARD/ML potential for rock encountered during construction;
- Field-fit design of erosion control and surface and subsurface water management measures;
- Field-fit design of measures to protect the pipeline and other infrastructure from impacts from rock fall, debris slides and debris flows;
- Installation of instrumentation such as piezometers, slope inclinometers, and strain gauges where landslides must be crossed, to support ongoing monitoring and integrity management; and
- Update of the geohazard inventory and risk assessment to support development of the integrity management program.

For many of the tasks outlined above to be of value, there needs to be flexibility in the construction contracts that allows for the inclusion of new geotechnical and geohazard information and field-fitting of permanent slope stabilization and other geohazard mitigation measures as construction proceeds.

## 4 GEOHAZARD MANAGEMENT FOR OPERATING PIPELINES

The Canadian Standards Association's publication Z662-11, Annex N (CSA 2011) provides guidelines for pipeline integrity management programs. Annex B of Z662-11 recommends a risk-based approach and provides guidelines for risk assessment for pipelines. Provincial and federal regulators of oil and gas pipeline facilities are increasingly relying on these guidelines as a framework for operational regulations and permitting, and they have become mandatory in Alberta and British Columbia (Zaleski et al. 2010). The risk management framework outlined by the authors in Section 2.4 is compatible with the Z662-11 guidelines.

Most pipeline operators recognize the need to include geohazards in their integrity management programs. A geohazard integrity management program begins with a review of historical records, the development of a detailed inventory of credible geohazards, baseline characterization, and establishing a mechanism for data storage and retrieval (usually an on-line database linked to a geographic information system) (Leir, 2004a, 2004b, Leir and Baumgard 2010, Leir 2012).

Initially this assessment can be office based and utilize historical records, pipeline specific records and general understanding of the geological setting that the pipeline traverses. With guidance from historical records or detailed understanding of pipeline failure modes such an office review can identify the most vulnerable geohazard sites, which would be the most likely to cause failures (Dooley et al. 2014), for early field verification.

Baseline characterization, during field inspections, is used to establish a screening level quantification of all geohazards that could affect the pipeline that were identified. The screening level assessment is used to establish the general scale of importance of the geohazard, both from a likelihood of occurrence and vulnerability standpoint. Once this screening level is completed then detailed assessment of a smaller number of geohazard sites can begin.

Risk-based concepts are used to prioritize geohazard sites for further review and ongoing inspection: some operators use a hazard-based approach for site prioritization while others use estimates of the potential for geohazards to cause pipeline failure. In the authors' experience, few Canadian pipeline operators currently use estimates of geohazard risk (which would include estimates of safety impacts or cost of a pipeline failure), although we anticipate that the industry may move in this direction over time.

The results of additional site surveys, geotechnical and hydrotechnical investigations, analyses, inspections, monitoring data, and other mitigation efforts are recorded in the integrity management database and used to update the site prioritization for subsequent inspections.

Many geohazard types change progressively over time and are well-suited to integrity management practices that rely on site inspections, stream flow monitoring, and monitoring of instrumentation such as piezometers, inclinometers and strain gauges. As changes in site conditions are observed, mitigation activities can be scheduled before the geohazards expose the pipeline or impose loads on the pipe that could threaten pipeline integrity.

Other geohazard types can occur rapidly and with little warning. Inspection and monitoring programs tend to be less effective in these cases and threats to pipeline integrity are best addressed by carrying out enough investigation and analysis to support refined estimates of the probability of pipeline failure (or risk), and by implementing risk control measures to reduce this probability (or risk) to below the Owner's acceptance criteria.

## 5 CONCLUSIONS

North American pipelines are exposed to a wide range of geohazard types and, on average, typically encounter geohazard sites that require some kind of management every 2 to 6 kilometers.

Although geohazards are spatially relatively common, they cause relatively few pipeline failures in comparison to other mechanisms such as corrosion and third party impacts. Typical pipeline exposure rates from geohazards are on the order of 1 new pipeline exposure every 1000 km per year, approximately 100 times more frequent than pipeline ruptures caused by geohazards.

A closer look at the pipeline failure statistics, however, reveals that geohazards cause a relatively high proportion of pipeline ruptures (as opposed to leaks and pinhole cracks) with associated elevated levels of pipeline failure consequence. Furthermore, pipelines constructed in mountainous terrain make up a relatively small percentage of pipelines in North America, but are exposed to a much higher frequency of geohazards than typical 'prairie' pipelines.

In many cases, geohazard avoidance is one of the most effective and least expensive options to reduce pipeline geohazard risk, provided that geohazards are identified and characterized early enough in the pipeline development lifecycle that route adjustments can be made with minimal impact to cost and schedule. This requires that geotechnical engineers and geoscientists participate in the early stages of pipeline routing and environmental assessment projects. A staged approach usually proves to be cost effective, with more intensive and costly subsurface investigations being carried out once the proposed pipeline corridor is reasonably well-defined. Ideally, the four main stages of pipeline routing would take place over approximately a 4 to 6 year period; however, many of the development projects currently underway in western Canada are attempting to compress all of these Stages into a 2 to 3 year period. As a result, heightened communication amongst the routing and environmental assessment teams is required, and construction contracts need to be developed in a way that allows for more of the geotechnical investigations to be carried out during the construction stage. It is a stressful time in the geohazard arena – new practices and innovation are required to keep pace with these aggressive schedules.

Pipeline integrity management programs are required for all operating hydrocarbon pipelines in North America. In British Columbia and Alberta, it is encouraged that these programs consider risk-based techniques, although at this time risk estimation is typically only carried as far as estimating the probability of pipeline exposure or rupture.

Most operators recognize the need to include geohazards in their pipeline integrity management programs. A geohazard management program begins with the development of a detailed geohazard inventory and baseline characterization. Many geohazard types occur progressively over time and are well-suited to management programs that rely on site inspections, stream flow monitoring, and monitoring of instrumentation such as piezometers, inclinometers and strain gauges. Other geohazard types, such as debris flows, can occur rapidly and with little warning – threats to pipeline integrity from these types of hazards are best addressed by carrying out enough investigation and analysis to support estimates of the probability of pipeline exposure or rupture, and by implementing risk control measures to reduce this probability to below the Owner's acceptance criteria.

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