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Debris-flow risk assessment and mitigation design for pipelines in British Columbia, Canada

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Abstract

Pipelines in mountainous terrain in British Columbia, Canada often cross debris-flow fans and channels along valley bottoms and can be susceptible to various geohazard impacts, including debris flows. The design of new pipeline infrastructure and maintenance of existing pipelines necessitates debris-flow risk assessments and appropriate mitigation design. A methodology is presented for assessing debris-flow risk along pipeline routes that consists of estimating the probability of a debris flow causing a pipeline loss of containment or disruption in service. The methodology consists of estimating debris-flow frequency, scour potential, and the vulnerability of the pipeline to break if impacted. Debris-flow frequency is estimated based on field observations of debris-flow deposits, degree of vegetative growth on debris-flow deposits, evidence of debris-flow impacts on trees near the pipeline crossing, documented debris-flow events, review of historical air photos and terrain mapping based on LiDAR-generated topography. Debris-flow scour potential is estimated based on channel morphology, presence of bedrock and grain size distribution of channel bed material. Vulnerability is estimated based on flow width and velocity and can be modified for different pipe diameters and wall thicknesses. Mitigation options for buried pipelines include those intended to decrease the likelihood of bed and bank scour (e.g. rip rap bed and bank protection), decrease the likelihood of the pipeline being exposed (increasing the burial depth of the pipeline) and to increase the resiliency of the pipeline to debris-flow impacts if exposed, (e.g. increasing pipeline wall thickness, adding concrete coating to the pipeline). The final option is to prevent debris flows from reaching the pipeline by designing and installing debris-flow deflection berms or sedimentation basins. The methodology presented is embedded in risk-informed thinking where pipeline owners and regulators can define probability thresholds to pipeline exposure or rupture and the pipeline designer needs to show that the proposed mitigation measures achieve these threshold criteria in ways that honor the 'as low as reasonably practicable' (ALARP) principle.

Keywords: Risk assessment; pipeline; vulnerability

1. Introduction

Pipelines in British Columbia, Canada (BC) as in many other nations travel throughout variable physiographic terrains that can include prairies, mountain ranges, upland plateaus, and lowlands occupied by floodplains. Since most fossil fuel reserves in western Canada lie either in Alberta or eastern BC, those needing to reach the ocean will have to cross mountainous terrain against its regional north-south grain; a legacy of BC's tectonic history. The terrain between the BC coast and the western Canadian prairies is characterized by highly variable topography, climate and geology. As a result, a single pipeline may be exposed to numerous geohazards including landslides, rock avalanches, debris slides, rock falls, debris flows, debris floods, and scour and bank erosion from clear water floods.

Extreme environmental, economic and safety consequences can result from debris flows or other geohazards impacting and breaking a pipeline. An analysis of pipeline incident data in BC found geohazards to account for approximately 22% of failures (Porter et al., 2016). For example, a Pacific Northern Gas pipeline in BC was ruptured by a rock avalanche that transitioned to a debris flow and resulted in environmental damage to a pristine coastal ecosystem (Boultbee et al. 2006; Jakob et al., 2004). Another recent example is a debris flow, initiated from the area burned by the Thomas Fire near Montecito, CA that impacted a high-pressure gas line in a residential area and caused a large explosion which impacted numerous houses (Kean et al., in print). Numerous other cases could be quoted worldwide. The potentially catastrophic safety or economic consequences emphasize the importance of accurately

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characterizing the risks posed to a pipeline traversing rugged terrain, so that appropriate mitigation can be designed to minimize pipeline damages, loss of containment, and attendant consequences.

This paper describes methods for estimating debris-flow risks and selecting appropriate mitigation designs that have been applied to various pipelines throughout British Columbia, Canada.

2. Background

Due to the presence of existing right of ways and the logistical and geotechnically motivated desire to construct on shallow slopes, pipelines and other utilities are typically buried along valley bottoms. Where pipelines follow valleys, they will invariably intersect fans subjected by debris flows. Such fans are primarily depositional; however, channel scour is possible on parts of a fan during a debris flow. For example, a debris flow near the town of Hope, BC entrained most of its total volume in the colluvial channel extending through the debris-flow fan (Jakob et al., 1997) and Neff Creek near Pemberton, BC eroded approximately 80,000 m^3 of material from its fan (Lau, 2017). At locations where the pipeline crosses a mountain pass or traverses steep terrain, the pipeline may cross debris-flow channels where massive channel scour is possible. In BC, yield rates in colluvial channels have been reported to range from 6 to 28 m^3/m (Hungr et al., 2005). More recent cases have shown yield rates up to 350 m^3/m measured at Neff Creek (Lau, 2017). As highlighted by Jakob (2019, this conference), incorrect estimates of potential scour on fans prone to debris flow could lead to pipeline ruptures with highly disruptive outcomes to the environment, the pipeline owners and the design team. The question of when and by how much a debris flow can entrain versus deposit is highly complex and it appears that the mobilization of channel materials depends on pore water pressures of the channel base and banks (Iverson, 2011). Practically speaking, however, piezometers are not installed that could measure pore water pressures and antecedent moisture conditions to estimate if and how much debris flows could incise. Entrainment models have been proposed (Kang and Chan, 2018), but their practicality and application along pipeline corridors still needs to be tested.

Pipeline crossings of debris-flow channels are characterized as hydrotechnical hazards because the channel may have at least ephemeral clear water flows. However, debris flows in ephemeral channels pose a different hazard to a pipeline due to their potential to deeply incise channels during a single debris-flow event, transport large boulders many meters in diameter at high velocities and avulse and travel down paleochannels.

Pipeline design for watercourse crossings in BC is guided by the Government of British Columbia's Guidelines for Managements of Flood Protection Works in British Columbia (BC MoE, 1999), which state that the standard design flood is the flood having a 200-year recurrence period interval. Furthermore, a minimum depth of cover (DoC) of 1.2 m across watercourse crossings is typically adopted based on the Canadian Standards Association (CSA Z662-15). No such guidelines exist for debris flows which produce impact forces substantially higher than those exerted by hydrodynamic processes or by bedload mobilized through drag forces at the channel bed in rivers with alluvial beds. This realization necessitates a vastly different design approach for debris flows.

Some guidelines for assessing debris-flow hazards to pipelines are described in Jakob et al. (2004) and Porter et al. (2004). More recently, as part of the Trans Mountain Expansion Project, a pipeline proposed to connect Edmonton, Alberta to Vancouver, BC a plan has been developed to manage and mitigate geohazard sites that exceed specific risk tolerance criteria (Trans Mountain Pipeline ULC, 2017).

The design basis for protecting pipelines from debris-flow hazards can be hazard or risk-informed. In the former case, it consists of a design event scenario (e.g. to protect against a debris flow with a 200-year return period or probability of occurrence of 0.5% in any given year). In the latter case, a level of tolerable risk is identified by the owner or regulator. The pipeline designer is then to work towards achieving or exceeding such tolerable risk levels which is the focus of this contribution.

3. Risk Assessment Framework

Geohazard risk for pipelines can be calculated as the product of the annual probability of a geohazard, the spatial probability that the geohazard reaches the pipeline, the vulnerability of the pipeline to be damaged or broken by a geohazard and the consequence (CSA, 1997; AGS, 2000; Porter et al., 2004; 2017).

Total risk would include a systematic evaluation of the consequences of loss of containment such as health and environmental outcomes and may go as far as reputational loss to the pipeline operator, the entire industry and loss in share value. Evaluations of such consequences are outside the geotechnical realm and thus we focus on a narrower definition of pipeline risk which treats all pipeline failures as having equal consequence. Pipeline risk is defined here as the frequency of a loss of containment (FLoC) at a debris-flow crossing (Baumgard et al., 2016). The FLoC can be expressed as:

$$F_{LOC(i)} = I_{(i)} \times F_{(i)} \times S_{H(i)} \times S_{V(i)} \times V_{(i)} \times M_{(I,F,SH,SV,V(i))}$$

where:

- $F_{LOC(i)}$ is the frequency of loss of containment due to a debris flow or debris flood at location i, expressed as an annual frequency.
- $I_{(i)}$ is the occurrence factor of 0 or 1 expressing whether a potential debris-flow or debris-flood hazard has credible opportunity to occur at location i.
- $F_{(i)}$ is the frequency of occurrence of the debris flow or debris flood at location i expressed as an annual frequency.
- $S_{H(i)}$ is the spatial probability of horizontal impact; expressed as a conditional probability that a debris flow or debris flood would horizontally reach the pipeline at location i, given its occurrence.
- $S_{V(i)}$ is the spatial probability of vertical impact; expressed as a conditional probability that a debris flow or debris flood would erode vertically to the pipeline at location i, given its occurrence.
- $V_{(i)}$ is the vulnerability of the pipeline expressed as a conditional probability that a debris flow or debris flood would result in loss of containment, given that it occurs and reaches the pipeline at location i. The unmitigated case assumes standard pipeline construction and operation conditions.
- $M_{(SH,SV,V(i))}$ is the mitigation reduction factor, ranging from 0 to 1, that is associated with various detailed design measures. This reduction factor accounts for the decreased spatial probability of a hazard reaching the centerline and eroding to the pipeline (identified by the *SH* and *SV* subscripts) or decreased vulnerability due to a specific mitigation applied at location i (identified by the *V(i)* subscript).

Probability of Exposure (PoE) can be expressed as:

$$PoE = I_{(i)} \times F_{(i)} \times S_{H(i)} \times S_{V(i)}$$

To fully characterize the debris-flow risk at a pipeline crossing, estimates of FLoC should be completed for the active channel on a debris flow fan, potential avulsion paths and the fan surface (due to the possibility of a flow avulsing and reaching any part of the fan). Multiple calculations of FLoC at a single site may be required to evaluate risk associated with debris-flow scenarios at various frequencies and magnitudes. This is particularly important since it is the most frequent event leading to pipeline rupture that often provides the basis for total risk evaluations.

4. Methods for Estimating FLoC

FLoC can be estimated through combining desktop analysis, field investigations and data analysis. Desktop analyses of a debris-flow site may examine the following data sources, if available:

- Air photos and/or google earth imagery
- Digital Elevation Models (DEMs) derived from LiDAR data
- Geologic maps
- Documentation of previous debris flows at the site.

Field observations of debris flow channels may include:

- Grain size distributions in the debris-flow channel including maximum boulder size transported by previous debris flows
- Channel geometry, including channel width, channel depth, channel slope
- Observations of previous debris-flow deposits on the fan and along the channel
- Locations of previous avulsion channels
- The frequency of debris flows in the channel which may include:
    - presence and abundance of boulder impact tree scars
    - estimated ages of debris-flow deposits
    - estimated ages of vegetation in the channel and surrounding area

While detailed dendrogeomorphic methods or radiocarbon dating of organic sediments in natural outcrops or test trenches can be used to decipher accurate debris-flow frequencies, those are often not feasible to be conducted over hundreds of kilometers of pipelines within typical project development timelines. However, new methods have emerged to approximate debris-flow frequencies and corresponding magnitudes from fan areas alone (Jakob et al. 2016). The following sections describe how this data can be incorporated into estimating the variables in the FLoC equation.

4.1. Occurrence, $I_{(i)}$

Occurrence ($I_{(i)}$) indicates whether a debris-flow hazard exists at a given site. A debris flow is considered a hazard if it has the potential to scour down to at least the crown of the pipeline at a given location. As most of the pipeline length is not subject to debris-flow or debris-flood hazards; in these locations, $I_{(i)} = 0$. Where past debris flows led to the formation of a debris-flow fan and/or evidence of debris flows persist, $I_{(i)} = 1$.

Geologic maps may identify alluvial fans which may have been formed primarily by debris-flow processes. Air photo analyses may reveal evidence of past debris flows. Literature searches of debris flows in the region may provide site specific information for the crossing. Field observations of debris-flow deposits, levees and tree impact scars can also be used to identify if there is a credible debris-flow hazard at the crossing. Watershed morphology can also help to identify watersheds dominated by debris-flow processes. Typically, small, steep watersheds are most susceptible to debris flows and can be differentiated from watersheds dominated by debris floods and clearwater floods by plotting Melton ratio (defined as the watershed relief divided by the square root of the watershed area) against watershed length (Wilford et al., 2004).

4.2. Frequency of Occurrence, $F_{(i)}$

Frequency of occurrence ($F_{(i)}$) is defined as the annual probability of occurrence of a debris flow (hazard probability) at location i. This frequency has a temporal and spatial component, i.e. how often does the debris flow both occur and reach the pipeline. Although most debris may deposit on the proximal or medial regions of a fan, the fluid afterflow should be assumed to reach the fan margins, and fine-grained channelized debris flows may transport most of their debris load to the fan's margins. Channel incision that lowers the fan's base level or artificial over-steepening of the fan (for example by a highway or railroad cut) may further influence fine-grained flows and fluid afterflow to travel to the fan margins. Many pipelines cross fans in their distal portion for logistical and constructability reasons.

Frequency can be expressed either as a return period or as an annual probability of occurrence. For example, if five debris flows have occurred within a 100-year period, the average return period is 20 years and the annual probability is 0.05 (or a 5% chance that a debris flow may occur in any given year assuming data stationarity). Given the uncertainty associated with estimating debris-flow frequency at a site, frequency classes with minimum and maximum bounds may be used (e.g. 0.03 to 0.1 for a 10 to 30-year return period).

Frequency classification can be based on existing site conditions and site conditions for the historic period for which air photos are available. Debris-flow activity on a fan and the availability of erodible sediment in the upstream catchment is related to the frequency of a debris flow that may reach and impact the pipeline. An important consideration is that estimated frequencies based on historical data may differ from frequencies in the future due to changes in sediment supply by forestry-related instabilities or forest fires, or by changing hydroclimatic environments associated with climate change. The past is no longer a key to the future as it pertains to debris flows and debris floods (Jakob and Lambert, 2009, Jakob et al. 2018). In cases where the science has advanced sufficiently to allow for future changes in debris flow frequency, it should be adjusted accordingly. Likewise, observations of existing site conditions may be influenced by a recent, rare debris-flow event that may create bias towards interpreting the site as being subject to frequent debris-flow occurrence.

4.3. Spatial Probability of Impact, $S_{H(i)}$ and $S_{V(i)}$

The spatial probability of horizontal impact ($S_{H(i)}$) is defined in the case of debris flows as the probability that a given event at location i will reach the pipeline alignment. For input into the FLoC equation, only debris flows that cross the pipeline may be evaluated which would make $S_{H(i)}$ equal to one. As an alternative, empirical modeling such as Flow-R (e.g. Horton et al., 2013) or numerical modeling such as DAN3D (McDougall and Hungr 2004), FLO-2D (FLO-2D, 2007), RAMMS (RAMMS, 2017) or D-Claw (George and Iverson, 2014) may be used to evaluate the spatial probability of impact along a pipeline crossing of a debris-flow fan.

The spatial probability of vertical impact ($S_{V(i)}$), is defined as the probability that a given event at location i will vertically expose at least the top of the pipeline (termed, the "crown"). Predicting debris-flow entrainment of channel material is challenging as previously noted, and there are no time-tested methodologies for reliably predicting scour depth of a debris flow. Therefore, estimates for $S_{V(i)}$ should be based on field observations, analyses of channel and fan morphology and professional judgement.

Debris flows tend to scour channels upstream of the debris-flow fan apex, oftentimes removing all colluvium in the channel and possibly exposing bedrock. As such, pipelines that cross a debris-flow channel upstream of the fan apex (which is rare, but possible) are particularly prone to be exposed by debris flows and would be assigned a high (between about 0.7 and 0.9) value for $S_{V(i)}$.

Although debris-flow fans are dominated by debris-flow depositional processes, pipeline crossings of debris-flow fans may be subject to channel scour. In some scenarios, extreme scour (greater than about 10 m depth) on a fan is possible. For example, a watershed that has produced several small debris flows may deposit material near the apex of the fan, which steepens the fan gradient and makes it susceptible to extreme scour during a subsequent debris flow or debris flood. Research on debris-flow and debris-flood fan scour has shown that the average fan gradient and watershed area can give a first indication of fans that could be prone to extreme scour (Lau, 2017). Flume studies in low gradient creeks (2-4%) have postulated that buried infrastructure on alluvial fans are not likely to exposed if their depth is greater than 3.6 times the formative depth of a flood (Eaton et al., 2017). Although these studies are not directly applicable to estimating $S_{V(i)}$, they provide guidance for making appropriate estimates for the likelihood of channel scour on a fan to reach a pipeline at a given burial depth.

Figure 1 shows a pipeline crossing on a fan where material has been deposited on parts of the right of way, and channels have been eroded at other parts of the right of way. The erosion in this example, however, occurred likely due to fluvial material reworking, rather than due to the debris flow itself.

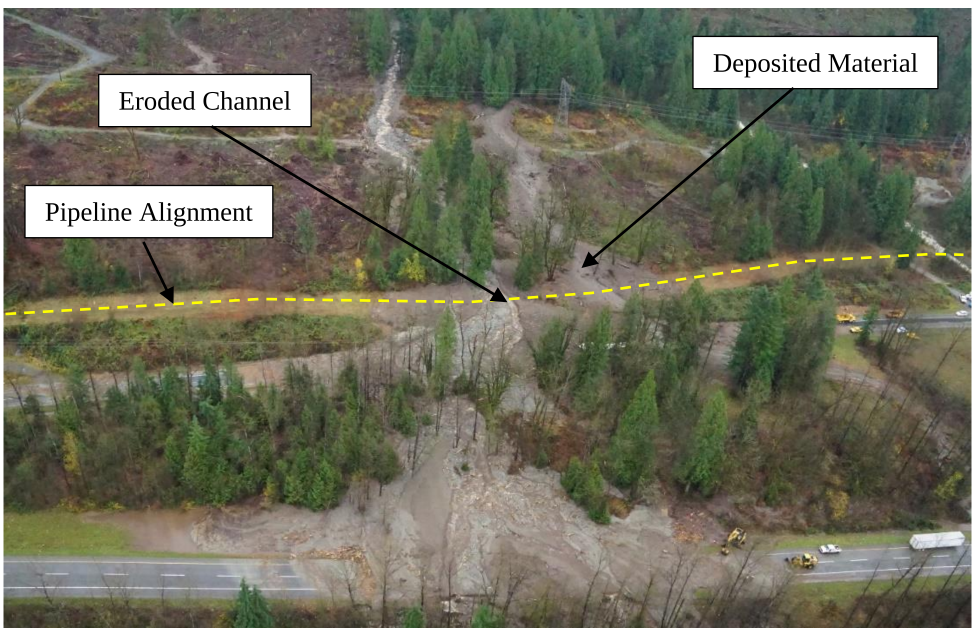

Fig. 1. A pipeline crossing of a debris-flow fan near Chilliwack, BC was both inundated with deposited debris-flow material and eroded by the debris flow or it's hyperconcentrated flow phase. Vehicles and road near the bottom of the photo are visible for scale. Photo taken November 2017 by BGC Engineering Inc.

The observed depths of active and abandoned channels on a fan can provide an indication of the flow depth of past flows. However, it could be overly conservative to conclude that this incision is attributable to a single event, and it may indeed be the legacy of fluvial reworking rather than attributable to debris-flow scour. Irrespective, field measurements of channel scour depths and/or lidar measurements of channel depths on a fan, can be used to evaluate total scour potential at the active or avulsion channels and arrive at an estimate for $S_{V(i)}$. This method assumes that the presence of at least one deeply incised channel on a fan and the inference that other deeply incised channels could form in previously unchannelized areas of the fan. These assumptions are conservative, which is justifiable due to the potentially high consequences associated with a loss of pipeline containment.

Some considerations for estimating scour potential on a fan include the position where the pipeline crosses the fan and the local channel geometry near the pipeline crossing. Scour depth can vary with respect to position on a fan with typically higher scour potential near the fan apex, where channel gradients are steeper, than at the distal part of the fan, where flows may be less confined by channel banks and travel over shallower gradients. Moreover, near the fan apex, there is less opportunity of streamflow to infiltrate into the coarse fan deposits. This implies higher degrees of channel bed saturation which enhances the likelihood of continued sediment entrainment and thus scour (Iverson, 2011). Therefore, higher estimates for $S_{V(i)}$ are likely for pipeline crossings at the fan apex than at the distal part of the fan.

Local channel geometry can lead to channel scour on fan when there is an abrupt increase in channel slope just downstream of the pipeline. At such locations, there is a possibility that a knickpoint (a sudden change in channel slope) may be exacerbated and migrate upstream and expose the pipeline. During construction of a pipeline, it is common for the right of way to be constructed with a cut and fill slope. The fill slope may create an over-steepened channel just downslope of the pipeline. As a result, future debris flows are likely to deposit material in the right of way cut and to erode the right of way fill material downslope. Figure 2 illustrates this scenario. Equally, when pipelines are constructed upstream of logging roads or highways, those have also been cut into the distal fan deposits, potentially leading to a knickpoint that is out of equilibrium with the natural channel slope.

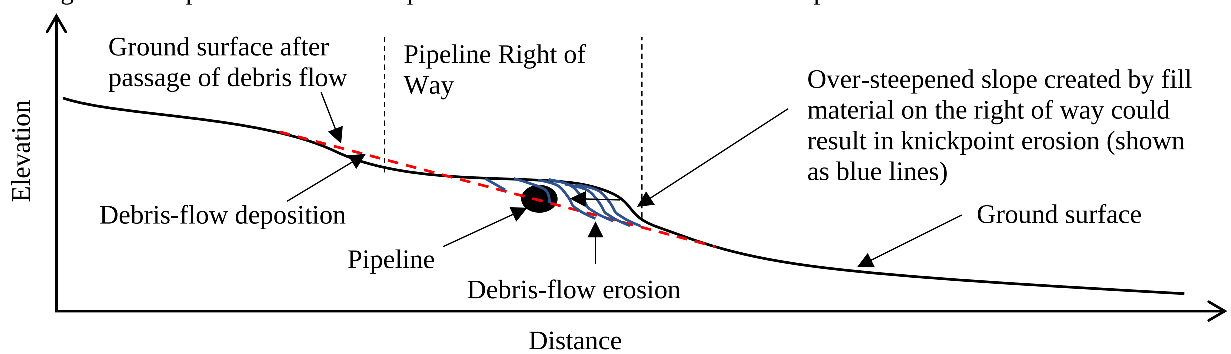

Fig. 2. Illustration of how knickpoint erosion during the passage of a debris flow may erode fill material of a pipeline right of way to expose the pipeline.

4.4. Pipeline Vulnerability, $V_{(i)}$

Pipeline vulnerability ($V_{(i)}$) is the vulnerability of the pipeline to loss of containment, given that the pipeline is exposed at location i. A loss of containment from a debris flow include may be caused by dynamic pressure on the pipeline or impact loading on the pipeline. For dynamic loading to break a pipeline, the passage of a debris flow exposes the pipeline and subsequent dynamic pressure of debris-flow material on the pipeline exceeds the resisting strength of the pipeline. For a pipeline to break due to impact loading, only the crown of the pipeline needs to be exposed for a boulder to impact the pipeline with a point load that exceeds the resisting strength of the pipeline.

Assessment of the vulnerability of a pipeline depends on the material strength of the pipeline which varies depending on pipeline wall thickness and pipeline diameter. Vulnerability can be assessed probabilistically using probability distributions of pipeline yield strength, debris-flow velocity, debris-flow density and grain size.

Debris-flow velocities can be estimated using superelevation of flow around a channel bend (Johnson, 1984) or runup against vertical barriers or adverse slopes (Iverson et al., 2016). However, sufficient field evidence for applying these methods may not be available and methods presented in Prochaska et al. (2008) may be applied with field estimates of debris-flow depth and measurements of channel slope. Grain size distributions can be estimated from field investigations of debris-flow deposits. Bulk density of debris flows in flume studies have ranged from 1400 – 2400 kg/m^3 and bulk densities of natural debris flows typically range from 1800 to 2300 kg/m^3 (Iverson, 1997).

4.5. *Mitigation Reduction Factor*, $M_{(SH,SV,V(i))}$

The mitigation reduction factor is a value from 0 to 1 that represents the reduction in the FLoC at a specific site due to a mitigation measure. Different mitigation measures could provide varying degrees of protection from impacts by changing either $S_{H(i)}$, $S_{V(i)}$, or $V_{(i)}$ at location i. Mitigations that decrease $S_{H(i)}$ include debris retention basins and deflection berms. Mitigations that can decrease $S_{V(i)}$ include increasing the depth of cover, adding rip rap or grouted rip rap channel protection, grade control structures. Mitigations that decrease $V_{(i)}$ include using pipeline with a thicker wall thickness or pipeline with a concrete coating.

Values for decreasing $M_{SH,SV,V(i)}$ range from zero to one and depend on the risk reduction the mitigation offers. For example, rerouting a pipeline or construction of a debris retention basin or deflection berm may have a significant reduction in the $S_{H(i)}$ variable and the associated mitigation reduction factor, $M_{SH(i)}$ may be low (e.g. approaching 0.01). Increasing depth of cover may have varying effects on risk reduction depending on how deep the pipeline is buried and the associated mitigation reduction factor, $M_{SV(i)}$ may have a broad range (e.g. from 0.1 to 0.9). Increasing pipeline wall thickness may have a marginal benefit to reducing risk at the pipeline and the associated mitigation reduction factor, $M_{V(i)}$ may be higher (e.g. approaching 0.9).

Accurate characterization of the mitigation reduction factors associated with different mitigation techniques allows for risk-informed design. A pipeline operator or regulatory body may choose a risk tolerance threshold for individual crossings, or a total FLoC for the entire pipeline. In the latter case, the sum of all geohazard FLoCs would need to be less than the total tolerable FLoC. At sites where the risk, as characterized by the estimated FLoC, exceeds such threshold the amount of risk reduction afforded by various mitigations can be quantified to demonstrate that risk has been reduced below that threshold. Alternatively, a PoE (probability of exposure) criteria may be chosen where the pipeline can have a given maximum annual probability of being exposed. Appropriate mitigations to reduce $S_{H(i)}$ and/or $S_{V(i)}$ could be applied until the PoE does not exceed this probability threshold.

If needed, a variety of mitigation techniques may be required to achieve the tolerable FLoC or PoE value. Figure 3 shows a site where channel erosion protection, grade control structures and increased depth of cover are present to protect the pipeline against an active debris flow channel. Where several mitigation methods are applied, multiple mitigation reduction factors can be integrated into the FLoC equation. Although complimentary mitigation measures provide greater risk reduction, engineering judgement needs to be applied to ensure that the combined mitigation reduction factors do not create an inflated level of risk reduction. Furthermore, detailed design of mitigation should incorporate detailed site-specific analysis of potential debris-flow magnitudes.

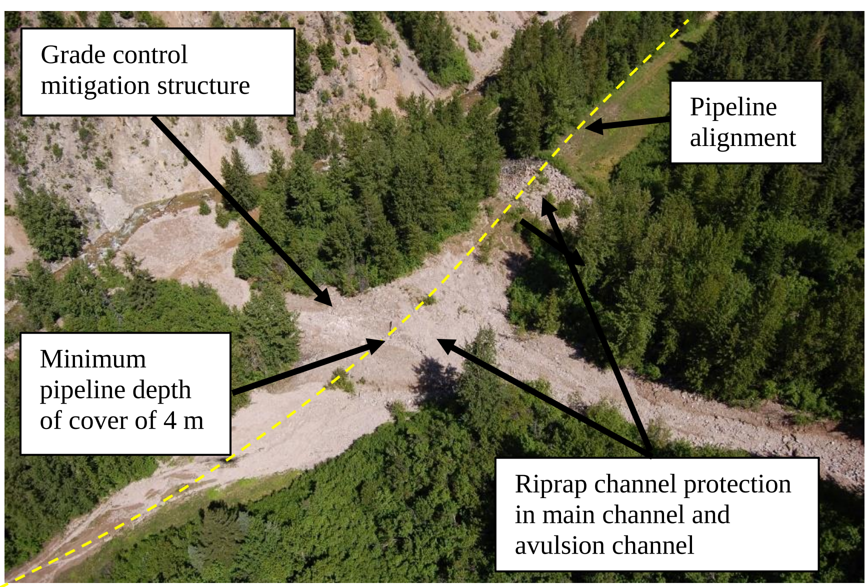

Fig. 3. Example of a combination of channel grade control and riprap erosion protection and increased depth of cover at a pipeline crossing of an active debris flow channel. Photo taken by BGC Engineering in May, 2016.

5. Summary

In this paper, a risk assessment methodology is presented suitable for quantifying debris-flow risk posed to pipelines. Risk is defined as the frequency of a loss of containment (FLoC). The method can also be applied to identify appropriate design measures to reduce FLoC or PoE to below a tolerable threshold set by either the pipeline owner or regulatory authority. Research is continuing to define best practices for quantifying debris-flow frequency-magnitude relationships, runout, scour and rheology as applicable to long linear infrastructure corridors. This methodology provides a framework that can be implemented with existing methods for debris-flow assessment and integrate scientific advancements in debris-flow research.

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