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VULNERABILITY OF PIPELINES INSTALLED BY HORIZONTAL DIRECTIONAL DRILLING TO LANDSLIDES AND A PROPOSED FRAMEWORK FOR DEVELOPING PRELIMINARY NO DRILL ZONES FOR LANDSLIDE AVOIDANCE

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ABSTRACT

Horizontal directional drilling (HDD) is a method of trenchless pipeline installation which has been widely used in the Western Canadian Sedimentary Basin (WCSB) during the past 40 years to cross challenging terrain, including watercourses and slopes. In the case study presented, 7,952 pipeline slope crossings are considered, of which an estimated 14% are partially or fully crossed by HDD. Often the primary objective of the HDD installation at the time of construction was to cross a watercourse and adequate consideration was not always given to the possible presence of landslide terrain adjacent to the watercourse. Minimizing HDD cost often requires shallower and shorter installations, which combined with the practice of not always identifying existing landslide features resulted in an estimated 16% of HDD landslide crossings spatially intersecting landslides. Due to the increased stiffness and overburden stress of soil or bedrock with depth as well as other factors, pipeline vulnerability and hence probability of failure is significantly increased relative to shallower conventionally trenched pipelines. Within the case study inventory, the combination of historical HDD installations that did not effectively avoid landslides and the increased vulnerability of pipelines impacted by landslides at depth accounted for approximately 35% of landslide related pipeline failures within a recent 10-year period, a failure rate approximately 15 times that of conventionally trenched pipelines when adjusted for frequency of landslide intersection.

Many pipeline operators have recognized the disproportionate risk landslides pose to ineffective HDD installations and are prioritizing assessment and management accordingly. This paper proposes a screening framework to provide guidelines for evaluating the effectiveness of HDD installations avoiding landslides for both existing and planned installations.

Keywords: Horizontal directional drilling, landslides, Western Canadian Sedimentary Basin, no drill zone, pipeline vulnerability, failure rate.

NOMENCLATURE

N	Number of landslide intersections
N_H	Number of HDD landslide intersections
N_C	Number of Conventional landslide intersections
P_L	Probability of landslide presence
P_S	Probability of spatial impact
f	Pipeline failure frequency
F	Number of pipeline failures
H	Number of slopes in an inventory subgroup
h	Slope height
d	Pipeline depth
D	Pipeline diameter

1. INTRODUCTION

Horizontal directional drilling (HDD) for pipeline installation emerged as an important trenchless installation method in the 1970s thanks to advances in technology that allowed steerable downhole mud motors to drill paths precise enough for installation. By the 1980s HDD had become the dominant trenchless installation method for crossing water courses in the Western Canadian Sedimentary Basin (WCSB), an oil and gas producing region extending from Northeast British Columbia to Southwestern Manitoba, Canada.

The key drivers for determining when HDD was used as an alternative to conventional trenching (conventional) methods included cost, speed, and installation feasibility. Most commonly HDD was selected when conventional construction methods would have been complicated by natural terrain features such as rivers or slopes that would require significant additional work such as regrading, dewatering and river flow management. In more recent years another key driver has been regulation around environmental protection of riparian zones around watercourses which promote trenchless installation to avoid unnecessary disturbance to sensitive areas.

The slopes and watercourses crossed by HDD are potential geohazards that may damage or fail pipelines [1]. When properly planned and executed, HDD is a cost-effective installation method which has the potential to significantly reduce geohazard risk by spatially separating the pipeline from the hazards, however inadequate appreciation of geohazards can increase risk relative to conventional installations [2].

HDD installations may accomplish the key objectives of efficiently crossing challenging terrain without appreciating the presence of geohazards. This occurrence is more prevalent with landslides than watercourses because identifying landslides often requires specialist knowledge and data and may not have been apparent to the pipeline designers at the time. In the WCSB many of the slopes comprise valley slope-scale historic landslides, often hundreds or thousands of years old, deep-seated, and challenging to identify without the benefits of LiDAR [2]. Avoiding this type of landslide requires longer and deeper HDD installations than would be required to avoid the more easily identifiable watercourse hazards. A lack of awareness of this type of landslide hazard and the cost drivers for shorter drill paths contributed to the installation of some pipelines through existing landslides. Given that many of the pipelines in operation today are decades old, historical installation practices have impacts related to geohazard exposure of operating pipelines positioned in active landslides and subsequently operational risk, reliability, and safety. Additionally, the presence of landslides continues to be under-appreciated in pipeline routing and HDD design.

2. CASE STUDY: HDD CROSSINGS OF LANDSLIDES IN THE WCSB

The following case study reviews pipeline failures (loss of containment) where ground movement was an important contributing factor and compares failure rates from pipelines installed by HDD versus conventional trenching. The pipeline geohazard database (the database) used has existed for over 20 years and contains over four hundred thousand kilometers of pipeline from more than 25 operators, mainly in North America.

The scope of the study was restricted geographically to the portion of the WCSB in Alberta and Northeast BC (Figure 2-1) and includes pipeline failures involving landslide impact over a period of 10 years, between 2010 and 2019. This scope was selected based on a preliminary review of data quality and availability with the intention of maximizing the size and duration of the study without introducing significant uncertainty due to variable data quality. Since pipeline failures due to geohazards are infrequent, occurring at a rate of 0.02 per 1,000 km per year prior to 2016 [1], and failures where landslides are crossed by HDD are a subset of the total failures, the largest initial dataset possible was used to provide the most reliable quantification.

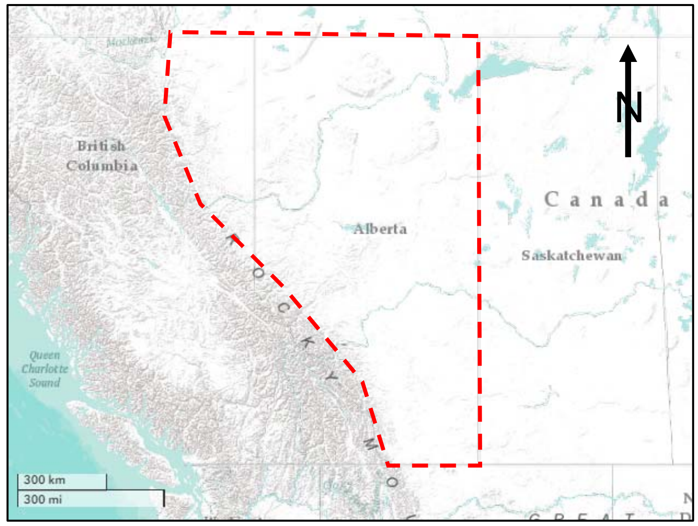

FIGURE 2-1: THE GEOGRAPHICAL SCOPE OF THE CASE STUDY INCLUDES PORTIONS OF THE WCSB IN ALBERTA AND NORTHEAST BRITISH COLUMBIA.

The study included 97,642 km of pipeline from 10 different operators comprising gathering, midstream and transmission pipelines with nominal diameters ranging from nominal pipe size (NPS) 3 to NPS 42. Each pipeline had an existing slope inventory study completed and in total 7,952 slope crossings were identified. Each slope crossing may have zero or multiple existing landslides.

The study provides an estimate of the frequency of HDD as an installation method for crossing slopes, estimates the frequency of HDD slope crossings intersecting landslides, and finally, compares the failure frequency due to landslide impact of conventionally installed pipelines to HDD installed pipelines.

2.1 Pipeline failures involving landslide impact from 2010 - 2019

A review was completed of pipeline failures during a ten-year period from 2010 to 2019 on the slopes within the study scope where ground movement impact from landslides was an important contributing factor. In total 17 landslide related failures were documented and 6 (35%) were on slopes where HDD was the method of installation (Figure 2-2). Of the HDD failures, 50% were partial drills that entered or exited mid-landslide, and 50% were drills that were too shallow to avoid landslide impact but the entry and exit points were not within a landslide.

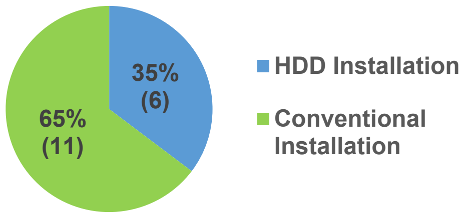

FIGURE 2-2: LANDSLIDE ASSOCIATED PIPELINE FAILURES FROM 2010 TO 2019 SUMMARIZED ACCORDING TO INSTALLATION METHOD.

The duration for the study was selected by maximizing the time-period providing confidence of the data quality could be maintained. Based on the authors' familiarity with the information and sources used to develop the failure database, the most recent ten-year period was selected, excluding 2020 and 2021 due to the potential for failure data reporting lag (e.g., ongoing failure causation assessments).

Extending the study record to earlier than 2010 would have magnified several potential sources of error, most importantly missing or undocumented failures and undocumented installation details. Given the low frequency of landslide related pipeline failures, missing or misclassifying even a few failures could have a significant impact on predicted failure rates, therefore a high degree of confidence in the failure database was desirable.

2.2 Proportion of slopes crossed by HDD

Estimating the proportion of the 7,952 slope crossings that were crossed partially or entirely by HDD is necessary to understand the frequency of failure from landslide impact to HDD installations versus conventional trenching. Some operators have installation as-built documents for every slope and watercourse crossing; however, it is more common for records to be unavailable for many reasons including the age of the pipeline systems or variable document control with the sale of pipelines over time. Given the lack of readily available documentation, the number of HDD slope crossings within the case study inventory needed to be estimated.

Three approaches were considered to develop this estimate. Method 1 reviewed the frequency of HDD crossings where installation method was documented within the database. In total 2,298 of the 7,952 slope crossings had installation method documented, and of this subset 15.1% were partially or fully crossed by HDD. This result may not be an accurate representation of the entire inventory because it is not a randomized sample and would be influenced by information availability bias (e.g., Transmission pipelines more commonly have as-built documents).

To improve the estimation, two additional approaches were considered.

Method 2 randomly sampled 800 slopes from the complete inventory, including slopes with known installation method (i.e., including the Method 1 population), and reviewed any available installation information to determine the installation method. From the randomized sample, as-built HDD pipe and ground profiles were available for 5% of the slope crossings and depth of cover information was available for approximately 50%. In addition to reviewing pipeline as-built documents and installation depth (where available), aerial imagery was reviewed to check for evidence of right-of-way clearing indicative of HDD installation, specifically cleared drill pads indicating HDD entry and exit points separated by a lack of cleared right-of-way along the pipe centerline. Using this methodology 14% of the slopes in the randomized sample were estimated to be crossed by HDD.

Method 2 has the benefits of randomized sampling but still relies on aerial imagery interpretation to compensate for incomplete information. To provide some quantification of the interpretation error, Method 2 was applied to a subset of known installation type. From a sample of 100 known HDD installations, 88 were correctly identified, while for a similar sample of 100 known conventional installations, 98 were correctly identified. Combining this performance with the observed frequency of HDD installations suggests that the range of potential error is around 3%.

Method 3 involved review of slope crossings with measured depth of cover to estimate installation method. A subset of the slope inventory with documented installation method and known depth of cover was used to develop a correlation between average depth of cover and number of slopes crossed by HDD. In total 1100 slopes had both documented depth of cover and documented installation method, while 190 of those were installed by HDD. The slopes with known installation methods were ordered from greatest to least in terms of average depth of cover, and the average depth of cover corresponding to the 190th slope was measured to be approximately 4.5 m. The number of slopes with an average depth of cover greater than 4.5 m was used to estimate the number of slopes crossed by HDD as a proportion of all slopes, resulting in an estimated 13.8% of the inventory likely installed by HDD.

Method 3 does not use a randomized subset and therefore would still have information availability bias, however the distribution of slopes with known depth of cover is more uniformly distributed across all operators, pipe diameters and geographical areas within the study area so the bias is expected to be less than with Method 1.

While the three methods all produced similar estimates (Figure 2-3), each method has limitations and uncertainty. Reducing the scope of the study to only slopes with known installation method is not desirable because of the low frequency of landslide pipeline failures related to HDD and the reintroduction of information bias. Conversely, obtaining reliable information for the entire inventory would be cost prohibitive, therefore adopting an estimation approach while appreciating there will be error is the most practical. Of the three methods presented, Method 2 is considered the best representation of the inventory due to the randomized sampling and the ability to quantify error.

For the remainder of this case study the proportion of the slope inventory estimated to have HDD as the installation method is 14%, or 1113 slopes, while conventional installation accounts for the remaining 86%, or 6839 slopes recognizing that a range of error of around 3% is possible.

Other installation types such as above ground pipe or other trenchless installation methods are rare enough in the dataset that they are statistically negligible. Only four cases of above ground pipe were identified, which we considered to be conventionally installed.

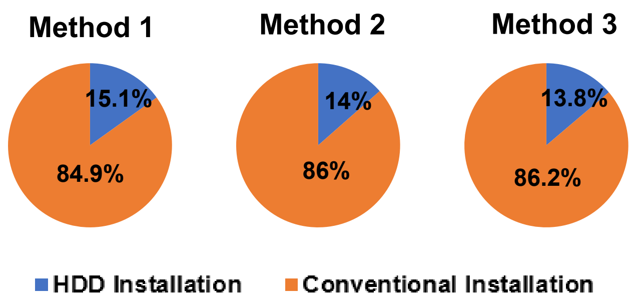

FIGURE 2-3: ESTIMATED PROPORTION OF SLOPES IN THE CASE STUDY WITH HDD INSTALLATION METHOD

2.3 An estimated frequency of landslide intersections by pipeline installation method

Comparing the failure frequency on slopes where HDD is the installation method (35%) (Section 2.1) to the frequency of HDD slope crossings (14%) (Section 2.2), results in a 3.3 times higher failure rate where HDD is the installation method. This observation highlights the potential for elevated risk when HDD is the installation method, however within the group of slopes crossed by HDD there is a much larger proportion with very low landslide risk because the installation depth is below the credible failure depth of the landslide (i.e., a lower rate of landslide intersection within the HDD group). Estimating the frequency of landslide intersections for both HDD and conventional installations provides a more precise estimate of the elevated risk because it accounts for variability between the two groups in terms of the likelihood of landslide presence and the likelihood of spatial intersection.

The expected number (N) of spatial intersections with landslides for each installation method group can be taken as the average probability of landslide presence (P_L) multiplied by the average probability of spatial intersection given a landslide (P_S) and the number of slope crossings in the group (H).

$$N = P_L \times P_S \times H \qquad (1)$$

The expected number (H) of slopes within each installation method group is provided in Section 2.2, 1113 slopes crossed by HDD, and 6839 slopes crossed by conventional trenching.

The presence of one or more landslides on a slope was documented as 91% of the slopes for HDD crossings, while conventional installations was slightly less, at 74%. The higher frequency of landslide presence amongst the HDD group could be explained by multiple factors including a construction preference towards HDD for challenging terrain, such as steeper uneven slopes likely to be landslides, or a high incidence of landslides on approach slopes to watercourses, which are also commonly crossed by HDD.

An estimate of spatial probability of intersection was documented in the database for each slope where a landslide was present. The estimates are based on integrating the best available pipeline installation and landslide depth data using professional judgement. For conventional installations the average probability of spatial intersection was 88%, meaning that nearly 9 in 10 landslides on slopes with conventionally trenched installations are expected to be deep enough to intersect the pipeline.

For HDD crossings, estimation of probability of spatial intersection was similarly adopted from evaluations of HDD effectiveness in the database. Where sufficient data was available to make an assessment (e.g., pipeline as-builts, LiDAR), each HDD was assigned to a probability of spatial impact bin (Table 2-1).

If the HDD entry or exit points are within the landslide extents at surface, or it was very likely based on other data that the HDD installation intersects a landslide (e.g., known landslide depth from subsurface instruments) a probability of 1 was assigned. In total 9% of the HDD slopes with landslides were in this bin. Installations that were assessed to be below the credible failure depth of the landslide were assigned a spatial probability of impact of 0.001. In total 50% of the HDD slopes with landslides were in this bin. The remaining 41% of installations were between these two groups and were assigned a spatial probability of impact of either 0.1 or 0.5 (Table 2-1) based on subjective assessment by a terrain specialist. Assessing probability of spatial impact was dependent on specialist experience and skill because only a small proportion of landslides are instrumented. Combining these frequencies and probabilities resulted in an estimated 16% frequency of HDD installations spatially intersecting a landslide, if present.

Frequency	Probability of Spatial Impact (P_S)	Expected intersections per 100 landslides
9%	1	9
7.5%	0.5	3.75
33.5%	0.1	3.35
50%	0.001	0.05

TABLE 2-1 A SUMMARY OF ESTIMATED PROBABILITY OF SPATIAL IMPACT DIVIDED INTO FOUR BINS.

In summary, for the 6839 slopes crossed by conventional trenching, 74% (P_L) are expected to have landslides present, and 88% of landslides are expected to spatially intersect pipelines (P_S), resulting in a total of 4,453 intersections of landslides with conventionally trenched pipelines (N_C), according to (1).

For the 1113 slopes crossed by HDD, 91% (P_L) are expected to have landslides present, and 16% of landslides are expected to spatially intersect pipelines (P_S), resulting in a total of 162 intersections of landslides with pipelines installed by HDD (N_H), according to (1).

2.4 Landslide related failure frequency by installation method

The failure rate per estimated number of landslide intersections in each installation method group was calculated according to (2), where f is failure rate, F is the number of installation group failures, and N is the number of landslide intersections.

$$f = \frac{F}{N} \quad (2)$$

For HDD installation, the failure rate is 6 failures from 162 estimated intersections, or 0.037. For conventional installations the failure rate is 11 failures from 4453 estimated intersections, or 0.0025. The ratio of HDD failure rate to conventional failure rate is 15, indicating a significantly higher failure frequency from the HDD group.

Assuming there is no significant difference in landslide activity or other influential factors between the two groups, the ratio of the failure rates provides one indication of the relative vulnerability. Vulnerability is defined as the conditional probability of pipeline failure given pipe impact by a landslide [3]. The high ratio between the two groups indicates that the vulnerability of pipelines to landslides is significantly increased when the impacted line is installed by HDD.

2.5 Other variables influencing group differences between HDD and Conventional installations

The failure rate comparison presented in Section 2.4 relies on the assumption that group differences between HDD and conventionally installed pipelines which are not accounted for have a negligible impact on pipeline failure rates. It is understood that the decision to choose HDD over conventional installation is not a random decision and would be influenced by terrain features such as slope grade, slope length, terrain irregularity proximity to large rivers and other factors which may also be correlated to landslide presence, activity, or pipeline vulnerability. A comparison between two important factors, slope length and probability of hazard occurrence (i.e., the annual probability of movement or activity), indicated that these factors were similar for both HDD and conventionally installed pipelines. Slope length is noted as the most important factor influencing pipeline vulnerability to ground movement [3], and active ground movement is necessary to cause ground movement related pipeline failure.

Average probability of occurrence and slope length for both installation types are summarized in Table 2-2 where they were available in the database. The average slope length between the two groups is very similar, 135 m for HDD and 133 m for conventional. Probability of hazard occurrence is also similar, 0.12 for HDD and 0.13 for conventional. In total 1303 sites in the inventory had these data.

	HDD	Conventional
Average Slope Length (m)	135	133
Probability of hazard occurrence	0.12	0.13

TABLE 2-2 A SUMMARY OF AVERAGE SLOPE LENGTH AND AVERAGE PROBABILITY OF HAZARD OCCURRENCE BY INSTALLATION METHOD.

It is possible that other factors which were not accounted for in this study would cause disparities between the groups, however those data were not available at the time of study and could be considered for refinement of HDD installation vulnerability estimates in the future.

3. REVIEW OF PIPE-SOIL INTERACTION AT DEPTH

This section provides a discussion of pipe-soil interaction at depth, comparing the factors influencing vulnerability of conventionally installed versus HDD installed pipelines, when impacted by landslides.

Compressive and tensile strain capacities for safe operation of pipelines are generally set below strain thresholds at which pipeline failure occurs. Pipe strains subject to operational loads (e.g., gravity, internal pressure, and temperature) are well below the strain capacities. The main contributor to pipe strain within a landslide is the pipe-soil interaction load, generated due to differential movement between the pipe and the surrounding soil. A differential movement along the pipe axis generates axial strain, and a differential movement transverse to the pipe axis generates bending strain. Landslides often have ground movement components both axial and transverse to the pipeline direction. The greatest differential movement between the pipe and the soil, and subsequently the greatest axial and bending strains on the pipe, usually occur where the pipeline enters and exits the landslide mass.

Numerous guidelines and papers have studied and formulated pipe-soil interaction loads (e.g., [4], [5]). Several factors affect pipe-soil interaction loads, including pipe parameters, soil parameters, and landslide parameters.

The pipe parameters (mainly pipe diameter and operating pressure) are generally similar for conventionally installed and HDD installed pipes. A greater wall thickness and an upgraded coating may be used over the segment of the pipe installed by HDD. Although these parameters may impact pipe strain capacity and vulnerability to ground movement, they do not directly impact the pipe-soil interaction loads.

The main soil parameters that affect pipe-soil interaction loads are soil strength and overburden stress at the pipe elevation, both of which generally increase with depth. In conventional installations, excavated material is usually used to backfill the trench after pipe installation with minimal compaction, whereas in HDD installations, the surrounding material is usually in-situ soil or rock, with much greater strength and stiffness. As an example, a 15% increase in soil friction angle from 35° to 40°, results in more than 50% increase in transverse pipe-soil interaction loads [5]. Increasing overburden pressure with depth also significantly affects the pipe-soil interaction loads. For example, increasing d/D (depth to diameter ratio) from 5 to 15, results in 6-to-9-fold increases in pipe-soil interaction loads [5].

HDD installations require an oversized borehole ("overcut") to facilitate dragging the pipe into place. The annulus between the overcut and the pipeline fills in over-time as the sediments in the drilling mud settle and through swelling, squeezing or sloughing of the surrounding formation (particularly in the WCSB). This could result in lower strength infill immediately proximate to the pipeline that would reduce initial pipe-soil interaction loads and potentially provide early protection from ground movement. After initial annulus deformation and with increasing ground movement, the pipe will become in direct contact with in-situ soil or rock and the full soil load will be mobilized on the pipeline. The analysis provided in Section 2 clearly demonstrates that the overcut is not sufficient to provide long-term protection from ground movement.

Finally, the main landslide parameters that affect soil-pipe interaction loads are the magnitude of movement, the length of transition zone between stable and moving ground, and direction of the moving ground relative to the pipeline axis. Except for the surficial soil, the magnitude and orientation of ground movement usually remains constant above the failure surface. However, at depth the transition between stable and moving ground usually occurs over a very short distance, whereas closer to the surface, the transition might occur over a longer distance. A short transition zone, results in a much greater differential displacement between pipe and surrounding soil or rock, and significantly increases soil-pipe interaction loads and subsequent pipe strains.

All contributing factors result in much greater loads and strains on a deep HDD installed pipelines compared to a conventionally installed pipeline. Pipe-soil interaction theory supports and provides a range of possible mechanical explanations for the observed significant increase in vulnerability of HDD installed pipelines.

4. A FRAMEWORK FOR ADDRESSING LANDSLIDE RISK TO HDD INSTALLATIONS

The preceding sections provide quantitative insight into the significant long-term risks that are incurred when HDD installations are completed within landslide masses. This underscores what is perhaps intuitively obvious, that HDD installations should not intersect landslide features, either by positioning entry or exit points on the landslide, or by intersecting a failure surface due to insufficient depth. There are however many existing HDD slope crossings that are within landslides, as demonstrated by the slope crossing database presented in Section 2, and in the authors' experience it continues to be a common practice in new pipeline construction. We propose a framework to help address this issue and lower risks on existing systems; and an approach to avoid creating these conditions on new pipeline projects. These approaches are outlined in the following respective sections.

4.1 HDD installations on existing pipelines

From the case study (Section 2) it was estimated that about 14% of pipeline slope crossings are installed by HDD. In half of these installations (50% of cases in Section 2.3) the HDD is a positive factor in lowering integrity risks and may even have been executed as a mitigation to safely avoid slope movements. Conversely, a subset of these installations significantly increased integrity risks by placing the pipeline within the slide mass (9% in Section 2.3). The remaining installations (41%) were in between these two bounds where further assessment would be required to determine if there was a credible threat.

For many operators, evaluating every HDD slope crossing would involve tens or hundreds of slopes. For these operators detailed assessments at each HDD installation would be onerous and time consuming particularly if site investigations are required. Effectively screening to identify the subset of sites where resources should be prioritized to assess risk and determine where risk reduction actions (e.g., mitigation) are required is critical. The distribution of spatial impacts from the case study (Table 2-1) suggests that in most cases a detailed assessment to evaluate probability of spatial impact is not warranted because the HDD installation either is sufficiently deep that intersection is very unlikely, or the HDD installation enters or exits within a landslide and intersection is known.

The flow chart on Figure 4-1 illustrates an approach to screen existing HDD installations by grouping installations according to an estimate of probability of spatial impact. This estimate is critical to establishing a risk-based ranking to prioritize sites requiring further assessment and ultimately determine where enhanced inspection, monitoring (e.g., instrumentation, inertial measurement unit (IMU), caliper ILI tools) or mitigation is warranted.

To facilitate efficient screening, geometric rules termed the "deep-effective" screening criteria are proposed to help identify installations which are deeply installed below the slope and therefore likely require less detailed attention. The deep-effective envelope is defined by a line drawn at 60 degrees to horizontal to a height (h) equivalent to the slope height, joined to a vertical line of height h/2 extending from the slope toe, as illustrated in Figure 4-1. A typical HDD path which avoids this envelope will extend well beyond the boundaries of the envelope due to HDD installation geometry restrictions and is very unlikely to intersect a landslide. Very unlikely is notionally defined as a probability of spatial impact less than 0.001.

The basis for the deep-effective criteria relies on professional judgement combining experience and an understanding of slope stability mechanics, and to a lesser degree landslide depth statistics. The landslide depth statistics required to quantify a very unlikely depth are limited for multiple reasons including:

- Deep landslides (i.e., with failure surfaces below the valley bottom) are a small fraction of the inventory.
- Unless a landslide is active, the failure surface depth cannot be measured. Less than 50% of deep-seated landslides are estimated to be active [6].

- Instruments which could provide confirmation of landslide depth (e.g., Slope inclinometers, shape accel arrays) are present on a small proportion of slopes (only 5% of the landslides in the case study inventory have subsurface deformation instruments).

Currently there is insufficient data available to statistically support the quantitative estimate, however, other observations from the database support the notion that impact below the deep-effective envelope is very unlikely. The database used for the case study contains over 20,000 landslides and there are no documented cases of ground movement exceeding the deep-effective criteria. Additionally, no known instances of landslide impact identified by IMU exceed the deep-effective criteria. Documentation of landslide impact to HDD installations detected by IMU may provide an improved estimate in the future once enough data has been acquired, reviewed and compiled.

The screening framework is outlined in the following steps:

1. Geohazard Assessment. A geohazard assessment should be completed to establish a slope inventory (if it doesn't exist) that includes all slopes that either contain landslide features, or where there is appreciable potential for instability to occur in the future. Existing papers such as [7] provide examples of best practices for creating a landslide hazard inventory.
2. HDD Inventory. An inventory of HDD installations should be assembled. For systems where HDD installations are not well documented, the methods outlined in Section 2.2 can be used to identify known or likely HDD sites. Where an installation partially or fully intersects a geohazard slope inventory site, the pipe and ground profile should be estimated as accurately as possible (as-builts, HDD reports, inertial measurement unit (IMU pipeline position, LiDAR slope topography, depth of cover surveys).
3. Apply Deep-Effective Screening Criteria. Screening criteria, such as the one illustrated on the inset cross section (Figure 4-1), should then be applied to evaluate whether the pipeline installation effectively avoids the hazard due to sufficient installation depth. To be considered deep-effective, both the potential for future crest retrogression and for horizontally extensive slip planes deeper than the water course or slope toe (valley floor) should also be evaluated. If potential for retrogression or failure planes below the valley floor exists, a site-specific assessment is required to evaluate the installation effectiveness.
4. Site-specific Assessment. If the pipeline does not meet the deep-effective screening criteria, a review of available desktop information would then be completed by a geohazard specialist to assign the installation to one of the four categories shown on Figure 4-1. It is noted that the simple criteria shown in the inset figure are conservative, and in many cases it is often not difficult to establish that the pipeline is installed well below the depth of potential ground movement even when it doesn't satisfy the simple screening criteria.

The four proposed categories are defined by probability of spatial impact (P_S) as follows:

$P_S = 0.001$
: The pipeline is located far enough beyond the estimated extent of the given hazard that spatial intersection is considered "very unlikely". Very unlikely is defined as a probability of less than 1 in 1000.

$P_S = 0.1$
: The pipeline is located beyond the estimated extent of the given hazard and spatial intersection is considered "unlikely", however compared to "very unlikely" there is reduced confidence due to factors such as a shallower installation depth, uncertainty regarding the characterization of the hazard. Unlikely is defined as a probability of less than 1 in 10 but greater than 1 in 1000.

$P_S = 0.5$
: The pipeline is located within the estimated depth range of the hazard and there is an even chance of intersecting the pipeline, or there is insufficient information available regarding the pipeline installation and/or to estimate the landslide depth.

$P_S = 1$
: The HDD depth is insufficient, and the pipeline is known to be or is likely intersected by the hazard.

It should be noted that probability of spatial impact is not an annualized probability.

5. Implement Action Plan for Higher Risk Sites. For sites in the highest risk category where the pipeline is clearly within the slide mass, mitigation may range from a reinstallation of the pipeline (e.g., deeper HDD, reroute) to careful monitoring of pipeline strain and slope movement (e.g., IMU for pipeline strain and a range of technologies for ground movement).

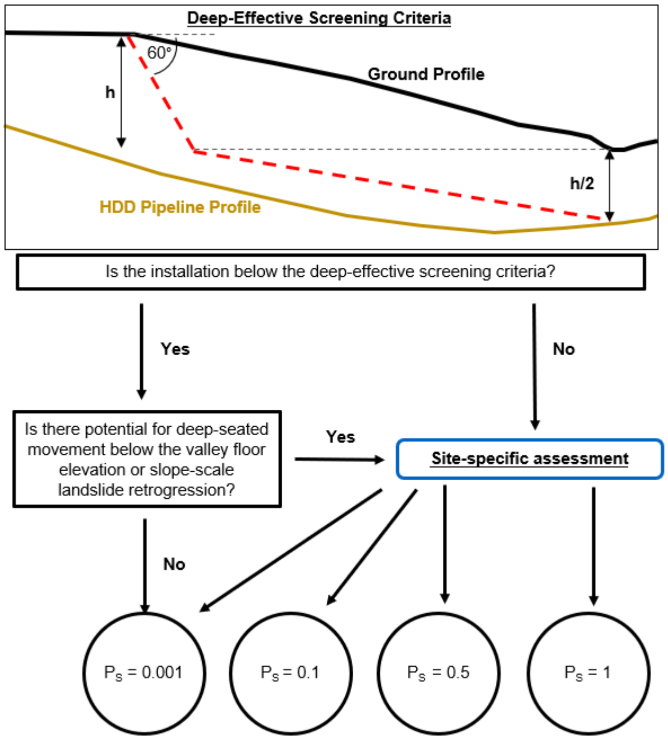

FIGURE 4-1 A FLOW CHART FOR SCREENING EVALUATION OF HDD EFFECTIVENESS FOR AVOIDING LANDSLIDES.

Following this methodology an operator within the case study scope recently reviewed their geotechnical inventory and identified 44 HDD crossings of landslides, of which 5 (11%) were determined to be above the operator's tolerable threshold for probability of failure due to intersecting (P_S = 1) or possibly intersecting (P_S = 0.1 or P_S = 0.5) a landslide. The next step of an action plan has been developed for each site based on the landslide characterization, uncertainties and available data. These actions range from obtaining and reviewing IMU to site investigation and may ultimately lead to management plans involving monitoring or mitigation.

4.2 HDD planning for new installations

The most effective means of minimizing long term integrity risks from slope geohazards on HDD installations is to rigorously address this issue at the planning and design stages of new pipelines. This involves a combination of planning HDD installations in the context of a comprehensive geohazard inventory, designing HDD installations to be safely below or outside of credible slope movement zones and collecting and maintaining good as-built data during construction that can be effectively accessed over the operational life of the pipeline by integrity groups.

An approach to support the planning and design of HDD installations to minimize future slope risks is outlined in Figure 4-2. Similar to the approach outlined above for existing installations, the intention is to provide a practical means to help operators focus resources on actual risk reduction. The same deep-effective criteria (Figure 4-1) are used as a screening tool to identify slope crossings where detailed investigative data for slope stability would not be of significant benefit. This would especially apply to smaller slopes where HDD drill paths can easily pass below the deep-effective criteria without significant cost impacts, where detailed investigative data on the landslide would not be of value. Geotechnical drilling would be important to aid in developing an optimized drill path that is feasible and addresses hydraulic fracturing risks but would not need the more detailed data on the landslide that can add significant cost and time for data collection.

For the small subset of cases where an HDD installation remains the preferred option, even though a drill path to avoid the risk of future movement is not feasible or practical, it is far better to recognize the issue upfront and make informed decisions at the planning stage, with monitoring and contingent actions identified. In the authors' experience, this is best achieved when an operator's integrity group is involved in the planning process for new pipeline construction.

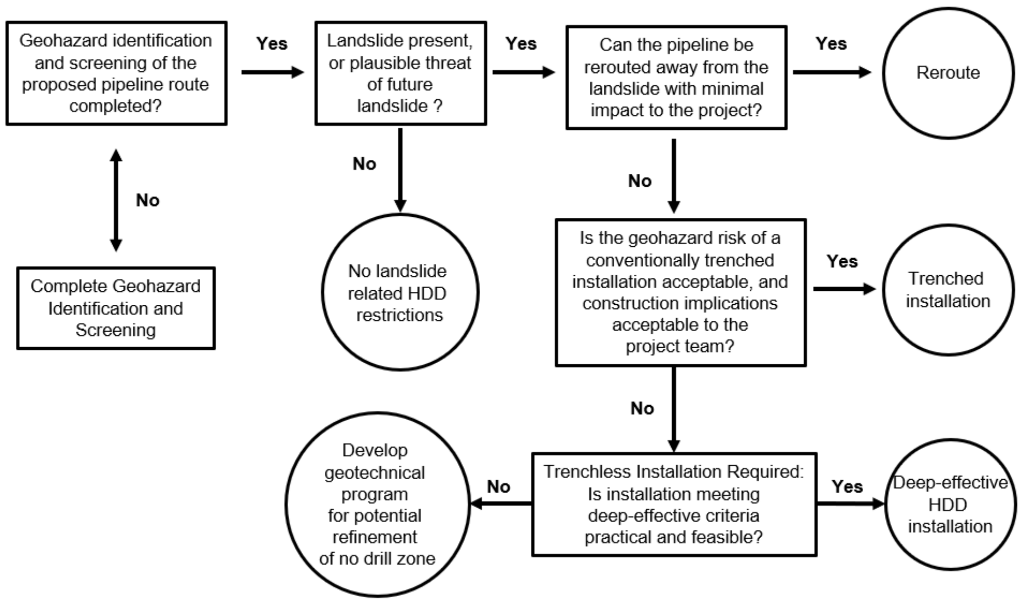

FIGURE 4-2 A FLOW CHART FOR SCREENING EVALUATION OF HDD EFFECTIVENESS FOR AVOIDING LANDSLIDES.

5. RESULTS AND DISCUSSION

The results of the case study indicate a strong relationship between increased pipeline failure rates from landslides and installation by HDD relative to conventional trenched installation. The construction practices, including frequency of HDD as a method for slope crossings, typical installation depth, and the frequency and characteristics of landslides in the WCSB are unique to the study area and would not necessarily reflect expectations for pipelines in other regions, however, the observation of significantly increased pipeline vulnerability when HDD installations are impacted by ground movement is expected in all regions. This expectation is consistent with pipe-soil interaction theory which indicates that loads on pipelines tend to increase with depth due to increased stiffness and overburden pressure of soil or rock, as well as differential movement distributed over a shorter distance (i.e., more distinct shear planes).

The data available for the case study was imperfect and will have introduced error and uncertainty, however it is likely the most comprehensive and robust dataset currently available. Given the expected error and uncertainty the 15-times increase in vulnerability indicated by the case study should not be applied as a precise number and would vary significantly from site to site depending on all the variables controlling pipe strain demand (e.g., pipeline properties, soil/rock properties, loading scenario). The appropriate application of the results of the case study is to recognize that pipelines installed by HDD are highly vulnerable to ground movement, and prioritizing geohazard management resources according to risk, such as through screening-level assessments, should shift focus towards these sites.

Similarly, for future pipelines, evaluating landslide risk for HDD installations as part of the planning and design process can significantly reduce the full life cycles costs where spending additional capital to avoid a landslide would eliminate the potential for expensive rupture response, loss of service and/or mitigation.

In addition to the significant increase in vulnerability of HDD installations relative to conventional installations, the consequences for HDD installations impacted by ground movement are often significantly greater. When conventionally trenched pipelines are impacted or fail due to ground movement, the available short-term mitigation options include daylighting, stress relieving, replacing or reinforcing the pipeline. Due to the depth of impact with HDD installations, these mitigation options are often not available, resulting in a complete loss of service for the HDD segment. An unforeseen loss of service could result in a prolonged shutdown of the entire pipeline as an above ground or trenched option may not be feasible and replacing the segment with a new HDD segment may take a long time.

In 2021 the authors provided geotechnical support for eleven instances of unplanned mitigation comprising stress relief or pipeline shut-in originating from the slopes within the case study. Of these eleven sites, six of them (55%) were installed by HDD. This anecdotal evidence is consistent with the statistical observations presented in this paper, but also demonstrates the value in allocating resources to assess and manage landslide risk to HDD installations. Since 2020 there are currently no known pipeline failures associated with landslide impacts to HDD installations from the same group but concerning IMU strains accounted for a disproportionate number of sites requiring risk reduction actions. This observation involves limited years of data and no failures but supports the notion that HDD landslide risk can be effectively managed following the framework outlined in this paper. It should be noted that IMU was a critical tool for assessing HDD impact in every case.

6. CONCLUSIONS

The presented case study estimates the frequency of HDD as an installation method for slope crossings and compares failure rates of pipelines on a per landslide intersection basis where installation method is HDD versus conventional trenching. The results for the case study indicated:

- HDD is a common form of trenchless pipeline installation in the WCSB, accounting for approximately 14% of slope crossings.
- Pipelines installed by HDD accounted for 35% of the landslide related pipeline failures over a ten-year period from 2010 to 2019, a failure rate several times higher than for conventional trenched pipelines.
- More than 50% of pipelines installed by HDD were estimated to avoid landslides through "deep-effective" installations while 9% were known to intersect and 41% require additional assessment. Ultimately 16% of existing drills within the case study were estimated to intersect landslides.
- The failure rate from pipelines installed by HDD and intersecting landslides is estimated to be 15 times higher than conventionally trenched pipelines. This indicates that pipeline vulnerability is significantly higher for pipes installed by HDD, an observation that is consistent with pipe-soil interaction mechanical theory.
- Given the elevated pipeline vulnerability of HDD crossings of landslides, assessment for landslide risk should be prioritized, both for existing and proposed pipelines.
- Given appropriate geohazard assessment, HDD can effectively avoid landslides reducing geohazard risk well below conventional installations.

A generalized framework for managing landslide risk to existing and planned HDD installations is proposed.

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