A Suggested Soil And/Or Rock To Pipeline Landslide Interaction Classification System

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ABSTRACT
Pipeline Fitness for Service (FfS) assessments are required when landslides impact pipeline rights-of-way and pipelines. FfS assessments may have to be done rapidly for higher velocity landslides triggered by extreme weather events or conversely may be more methodical engineering assessments for slow-moving deep-seated landslides. A system is presented that has 3 "geo-mechanical" categories: 1) non-interacting, 2) exposing and 3) interacting that are divided into 19 sub-types that follows the work of Wang et al. (2016). The system is based on the author's Western Canadian and Eastern US experiences. Non-interacting and exposing categories can be designated as lower priority while the appropriate attention is given to interacting landslides. A description of the preferred technologies and methods to detect and determine the FfS for each interaction subcategory is discussed. Additionally, limitations for the current state of practice are detailed.

RÉSUMÉ
Les évaluations de l'aptitude (FfS) au service des pipelines sont nécessaires lorsque des glissements de terrain ont un impact sur les emprises des pipelines et les pipelines. Les évaluations FfS peuvent devoir être effectuées rapidement pour les glissements de terrain plus rapides déclenchés par des phénomènes météorologiques extrêmes, ou inversement, il peut s'agir d'évaluations techniques plus méthodiques pour les glissements de terrain profonds et lents. Le système comprend 3 catégories "géomécaniques": 1) sans interaction, 2) exposition et 3) interaction, divisées en 19 sous-catégories basées sur les expériences de l'auteur dans l'ouest du Canada et l'est des États-Unis et suivant les travaux de Wang et al. (2016). Les catégories sans interaction et avec exposition peuvent être désignées comme ayant une priorité inférieure, tandis qu'une attention particulière étant accordée aux glissements de terrain en interaction. Une description des technologies et méthodes préférées pour détecter et déterminer le FfS de chaque sous-catégorie d'interaction est discutée. De plus, les limites de l'état actuel de la pratique sont détaillées.

1 INTRODUCTION

Recent advances in pipeline RoW surveillance and ground/pipe monitoring as summarized in Dewar et al. (2017) and detailed in Wang et al. (2006) and Rizkalla and Read (2019) have significantly improved the ability to detect, characterize and monitor landslides. The ability to detect landslide features has been revolutionized by the introduction of remote LiDAR and InSAR techniques. Additionally, recent advances in pipe monitoring may allow for actual quantitative assessments of FfS for slower moving landslides rather than using models, past experiences and/or judgments.

Once a landslide has been characterized, it is suggested that the presented system be used to classify the interaction into "geo-mechanical" categories: 1) non-interacting, 2) exposing and 3) interacting. These categories are then divided into 19 category subtypes. The purpose of the system is to allow for the prioritization of risk control and mitigative actions based on the geo-mechanical sub-category. This paper will use and modify terms presented in Cruden and Varnes (1996) but is applicable to any landslide classification system including those by WP/WLI (1993), and Hungr et. al. (2014).

The system allows for geotechnical engineers and/or geoscientists to characterize a potential landslide interaction and provide input to mechanical/structural specialists characterizing the interaction.

2 TERMINOLOGY

2.1 Interaction Areas

Dewar et al. (2017) states that soil to pipe interactions that could lead to either operating outside design/fitness for service limits or loss of containment/rupture occur in either:

1. *Areas of differential movement (ADM) include slide flanks, main scarps and toes where the pipeline transitions between stable and unstable ground. As a landslide becomes larger, there is an increased likelihood that there will also be ADMs within the slide mass including minor scarps and slide block boundaries.*
2. *Areas of accumulated movement (ACM) associated with flow type movements or zones of shear where the pipe is often roped. Maximum strains may occur at the center of the slide feature rather than at the boundaries. Generally, ACMs have significant horizontal components across a pipeline created by perpendicular/oblique movement.*

Figure 1 shows conceptual ADM's and ACM's within a deep-seated slow-moving landslide.

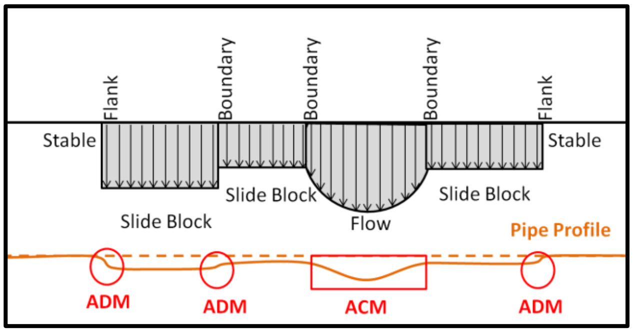


Figure 1. ADM and ACM examples represented on a plan view of a pipeline crossing a large landslide perpendicular to pipeline (from Dewar et al. 2017).

2.2 Activity

Definitions for activity of a landslide relating to pipeline interactions generally follows Cruden and Varnes (1996):

- *Active* refers to a landslide that is continuously moving or moves seasonally during wetter times of the year. In the case of rockfall, active refers to a minimum of 1 event/year with a mid-dimension of greater than 1 pipeline diameter (d_p) or 1/3 the pipeline depth of cover. The remainder of terms below fall under the classification of *inactive*.
- *Dormant* refers to a landslide that is inactive for at least one season.
- *Long Term Dormant* refers to a landslide that has not moved during the lifetime of the pipeline. It is expected to be unlikely that the slide will reactivate during the design life of the pipeline. There should be a minimum time frame to be considered long term dormant. A time frame of 20 years is suggested based on a typical minimal operating lifespan of a pipeline. Alternatively, timeframes could be classified as part of an operator's program, ex. Dormant 10, Dormant 20 etc. The term has been introduced because operating pipelines can have service life's exceeding 100 years; therefore, the term dormant may not be that useful when classifying soil/pipe interactions (Guthrie and Reid 2018).
- Abandoned refers to an inactive slide where the cause of the slide is not currently active. An example would be where a river has abandoned a channel that was previously eroding the toe of an unstable slope.
- *Stabilized* refers to a landslide that has either been stopped or slowed to an acceptable extremely slow rate of movement by revetment/stabilization works.
- *Relict* refers to a historic landslide that moved under different geomorphologic or climatic conditions. It is not conceivable, unless significant anthropogenic changes are made that the landslide could ever be reactivated.

2.3 Rate of Movement/Displacement

Crude and Varnes (1996) provide velocity classes for landslides. The actual rate of movement is less critical than the total displacement of a landslide interacting with the pipeline. Relevant rates of movement for landslides interacting with pipelines are summarized in Table 1.

Table 1: Rates of movement for pipeline interactions.

Rate of movement	**Typical velocity**	**Common landslide types**
Extremely rapid	>5 m/sec	Falls, Topples, Debris Flows
Critical	>1.6 m/yr to 5 m/s	Slides, Earth Flows, Spreads
Very slow	1.6 m/yr to 16 mm/yr	Slides, Earth Flows, Spreads
Extremely slow	<16 mm/yr	Slides, Earth Flows, Spreads

ADM interaction variables that influence the deformation of a pipeline commonly include the stiffness of the pipeline backfill/native soil, pipeline properties/geometry/features (such as bends and anchors) and the rate of movement. Typically, critical rates of movement are relatively low given that the critical displacement for a pipeline can broadly range from 0.5 to 10 d_p based on the variables described above. As an example, a ductile 6-inch pipeline buried in a 2 m wide pipeline trench backfilled with soft material being deformed by a landslide in a glacial lacustrine deposit would have far greater deformation capacity than a stiff 42-inch pipeline buried in a narrow bedrock trench crossing an active rock slide. Generally, pipelines tend to fail in ACM's either at interacting wall anomalies in tension and/or by buckling/wrinkling in bending/compression.

Where there is an ACM interaction the pipeline can often handle much larger accumulated displacements. The total displacement that a pipe can withstand would depend on the ductility of the pipeline and the uniformity of the accumulated movements. The total strain/overall deformation capacity of the pipeline would be expressed as a ratio of d_p/length. For example, a ductile small diameter pipeline buried within a 1000 m wide earth flow with a displacement profile as shown in Figure 1 could have up to 30 to 50 m of peak lateral movement without a loss of containment using the simplified calculation method presented in Oswell (2016). Generally, pipelines would tend to fail in tension at potential interacting wall/weld anomalies such as vintage welds.

2.4 Angle of Incidence

The angle of incidence is important for consideration when conducted stress analysis to consider the locating on a pipeline. Parallel or Perpendicular scenarios are often much simpler to model than oblique loading.

The angle of incidence of landslides are describe in Figure 2 to be categorized into parallel, oblique and perpendicular. The direction of the slide ± 22.5° in alignment with pipeline axis is considered parallel and conversely a slide ± 22.5° across is classified as perpendicular. The remaining angle of incidences are defined as oblique.

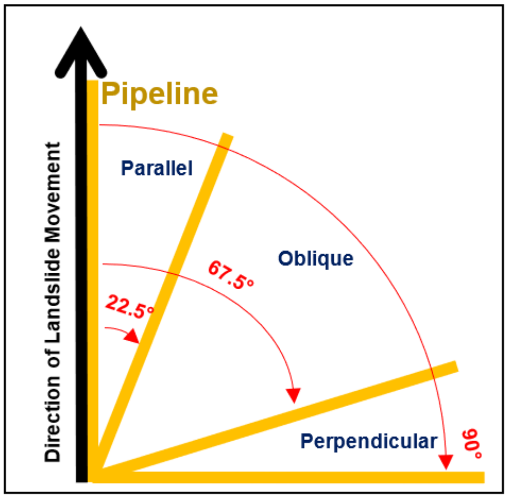


Figure 2: Suggested classification of angles of incidence.

3 INTERACTION TYPES

The system is divided into "geo-mechanical" categories: 1) non-interacting (NI), 2) exposing (E) and 3) interacting (I). These categories are then divided into 19 category subtypes generally ranked by there potential impact on a pipeline's fitness for service. The scheme developed enables real-time risk ranking of landslides from aerial patrols and ground inspections during extreme weather events as an advantage.

The purpose behind developing the scheme is to help risk rank landslides during aerial patrols and ground inspection during and after extreme rain events and as part of an overall geohazard management program. Classifying the interactions, or lack thereof, allows an operator and their representatives to put landslides into different buckets for risk control and mitigative measures. Based on regional experiences and characterises of regional landslides, operators and their consultants/specialists can develop lists of characteristic features that will allow for the reliable classification of interaction types. Additionally, having a classification system allows operators to rank hazards across an entire pipeline system rather than specific operating regions.

When classifying landslide interactions, it is recommended that the most conservative type of interaction is delimited when there are multiple options. Further work can verify the actual subtype.

3.1 Non-Interacting

Non-interacting (NI) type landslides are defined as landslides that have slip surfaces above and/or adjacent to a pipeline and do not alter the state of stress in the soils contacting a pipeline. NI landslides do not impart any stresses and/or strains on a pipeline. Therefore, NI landslides are not considered fitness for service issues but maintenance issues unless they enlarge or retrogress and change into an I landslide. Figure 3 provides a schematic of NI landslides. NI oblique (NI_{obq}) is not included in Figure 3 for brevity.

Table 2 provides a summary of ground/pipe monitoring methods applicable to detection and characterization of I landslides. Methods in Table 2 are described in Dewar et al. (2017).

Table 2: Application of ground/pipe monitoring methods for NI and E landslides.

Method /Technology	Detection of Landslide	Characterization of Landslide non-interaction
Aerial Patrol	Proven[1]	Contributes[2] - Triggers ground inspection
Ground Inspection	Proven	Contributes
Slope Inclinometers	Proven but typically not used	Proven but typically not used
Conventional and GPS Survey	Proven	Limited[3]
LiDAR	Contributes	Limited
InSAR	Contributes to Limited	Limited
Locates	Contributes	Contributes
Strain Gages/Fiber-Optic's	Limited	Proven but typically not used
ILI geometry wall anomalies	Limited	Proven
ILI IMU	Limited	Proven
ILI axial strain	Limited	Proven

[1]Proven - accepted method to accomplish goal
[2]Contributes - accomplishes goal when used in combination with another method
[3]Limited – likely will not accomplish or contribute to goal

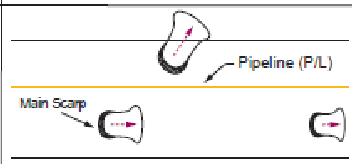
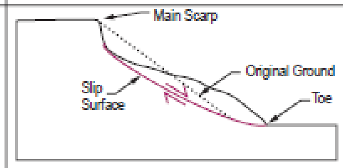
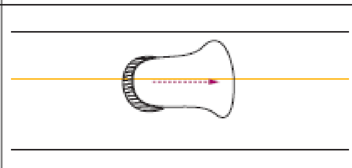
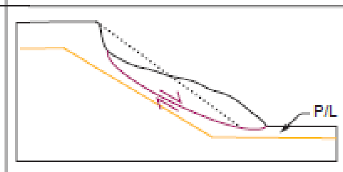
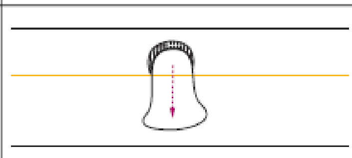
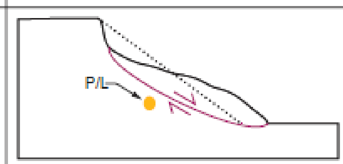
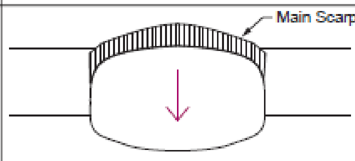
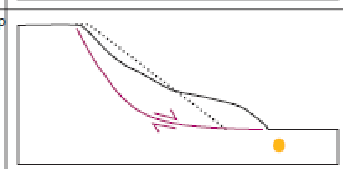
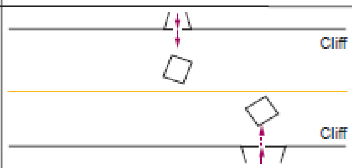
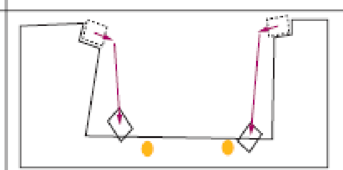
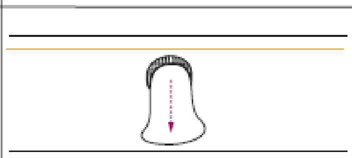
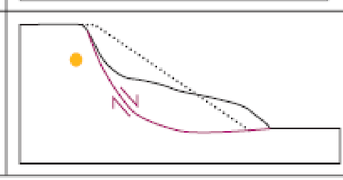
Landslide Interaction Type: Non-Interacting (NI)	Schematic Plan View	Schematic Profile View	Notes
NI_{RoW}: Slides/flows within or in proximity to pipeline RoW but do not expose or interact with pipeline			Shallow flows/slides within or adjacent to P/L RoW. May enlarge/retrogress to become either "E" or less likely "I" types.
NI_{para}: Slide/flow over pipeline parallel to pipe axis but does not expose or interact with pipeline			Shallow flows/slides parallel to P/L. May evolve into an E type. Typically invloves pipeline backfill.
NI_{perp}: Slide/flow over pipeline perpendicular to pipe axis but does not interact with pipeline			Shallow flows/slides perpendicular to P/L. May evolve into an E or I type.
NI_{dep}: Slide/flow deposits material within RoW but not on pipeline			Shallow flows/slides depositing material on P/L RoW.
NI_{imp}: Rockfall/topple impacts within RoW but does not interact with pipeline			P/L RoW outside of pipe trench is impacted by rock/debris fall. Additional movements may be an I type.
NI_{retro}: Slide/flow has potential to retrogress leading to pipeline exposure/interaction			Similar to NI, but much deeper movements that could retrogress to become an I_{perp} or I_{span} type.

Figure 3: Non-interacting landslide types.

3.2 Exposing

Exposing (E) landslide types are separated from NI and I landslide types as many regulations consider these to be out of compliance. As an example, the Onshore Pipeline Regulation Section 5.1.5 (NEB 2018) states that "unintended exposures of pipelines including in waterbodies (e.g. rivers, wetlands) and on land" are operating outside of design limits. E landslides are defined as landslides that have a slip surface that include the pipeline but do not impart significant stresses/strains because of soil to pipe interactions. E landslide types partially expose supported pipelines. Typically, E landslide types can involve some damage to pipeline coatings which is considered a maintenance issue typically handled by an operator's corrosion management program. Additionally, exposed pipelines may expose operators to additional hazards associated with 3rd parties which are typically managed under damage prevention programs. Figure 4 provides a schematic of E landslides. E_{obq} is not included in Figure 4 for brevity.

In many cases E landslides are due to seasonal construction during less desirable wetter and/or winter conditions where backfill is either placed in a soft saturated condition and/or as "Snirt" (snow/dirt). Table 2 in Section 3.1 is also applicable to E landslides.

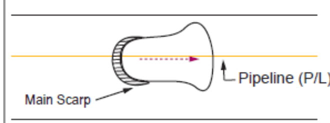
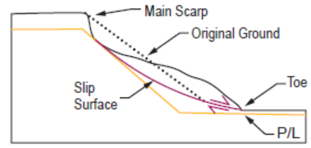
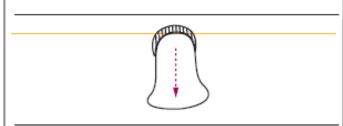
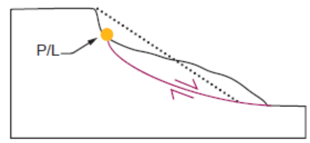
Landslide Interaction Type: Exposing (E)	Schematic Plan View	Schematic Profile View	Notes
E_{para}: Slide/flow causes perpendicular exposure of pipeline			P/L typically is partially exposed by slide/flow in pipeline backfill material. Further slide movements may cause an I_{para} type interaction.
E_{perp}: Slide/flow causes parallel exposure of pipeline			P/L typically is partially exposed by slide/flow across pipeline. Further movements may evolve into an I_{para}/I_{span} type interaction.

Figure 4: Exposing landslide interaction types.

3.3 Interacting

Interacting (I) landslides are defined as having a slip surface below a pipeline and/or ground deformation that interact with a pipeline. Figure 5 provides a schematic of I landslides. Note that for brevity only perpendicular free span scenario is shown for the I_{span} type. Parallel and to a much lesser extent oblique spans are less common. Typically, I_{span} parallel type exposures are caused by a combination of landsliding and erosion that may produce short free spans.

The fitness for service of a pipeline is typically determined by:

- Resultant ground deformations for I_{dep} and I_{imp} types,
- Rates of movement/displacement for I_{para}, I_{obq} and I_{perp} types,
- Pipeline resistance to buckling for I_{span} types, and
- Factors listed above, and potential vibration induced vortices/hydrodynamic loading for the I_{debris} type (Boultbee et al. 2006).

Pipeline related factors that should be considered in any interaction are:

- Pipeline features such as bends, tees, valves and/or property changes within an interacting landslide. As an example, one very common mode of failure of pipelines is the compressional buckling of horizontal directional drill tie-in sag bends interacting at the toe of a landslide (Murray and Guthrie, 2016).
- Interacting wall/weld anomalies that reduce the strain capacity of a pipeline. Wang et al. (2016) provides a detailed description of these anomalies.

Table 3 provides a summary of ground/pipe monitoring methods applicable to detection, characterization and fitness for service determinations for I landslides.

Table 3: Application of ground/pipe monitoring for I landslides.

Method / Technology	Landslide Detection	Interaction Character-ization	FFS Assessment
Aerial Patrol	Proven	Contributes	Limited
Ground Inspection	Proven	Contributes	Limited
Slope Inclinometers	Proven	Proven	Limited to contributes
Conventional and GPS Survey	Contributes	Limited	Limited
LiDAR	Contributes	Limited	Limited
InSAR	Contributes	Limited	Limited
Locates	Contributes to Proven	Contributes to proven	Contributes to Proven
Strain Gages	Contributes	Contributes	Contributes
ILI geometry	Contributes	Contributes	Contributes
ILI IMU	Contributes	Proven	Proven
ILI axial strain	Contributes	Proven	Proven
SCADA[4]	Limited	Limited	Indicates LoC[5]

[1]Proven - accepted method to accomplish goal
[2]Contributes - accomplishes goal when used in combination with another method
[3]Limited - likely will not accomplish or contribute to goal
[4]SCADA - refers to the system used to monitor and control flows and pressures within pipelines
[5]LoC – Loss of Containment

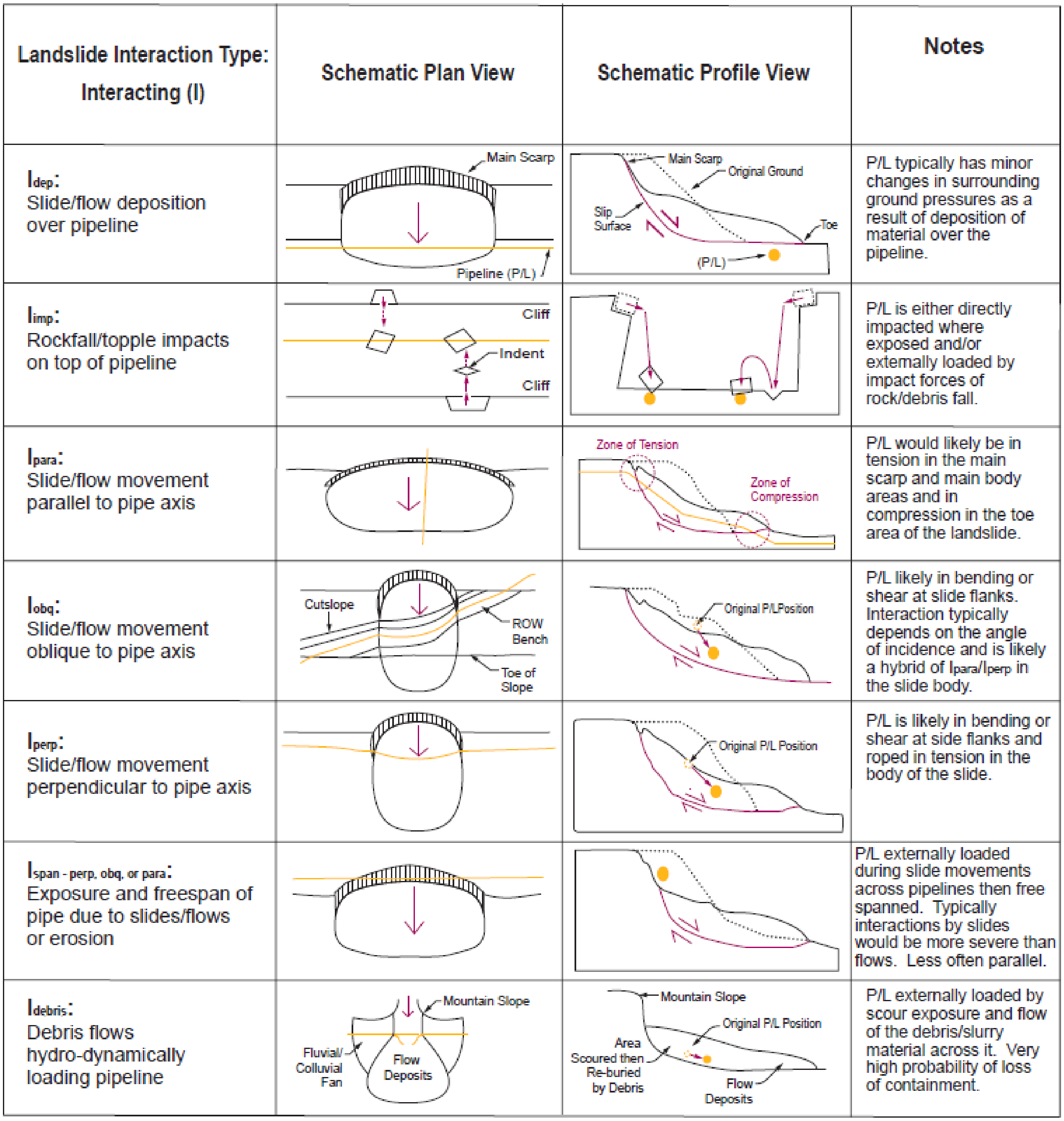


Figure 5: Interacting landslide types.

4 CURRENT STATE OF PRACTICE

4.1 Landslide Interaction Identification

Ground monitoring technologies have rapidly evolved over the last 20 years to include techniques that allow geotechnical engineers/geoscientists to strip away the vegetation which previously disguised landslide features. The rapid advancement of new area-based technologies including LiDAR and InSAR and the refinement of existing slope inclinometer/SAA and conventional/GPS survey monitoring techniques has allowed for reliable identification, characterization and monitoring of landslides.

Pipe monitoring has also rapidly evolved over the last 20 years but in most cases the technology needs refinement to be applied to geo-mechanical interactions. Specifically, inline inspection (ILI) geometry pigs are highly reliable at detecting features such as wrinkles, ripples and ovality which may be indicative of landslide interactions. ILI internal measurement unit (IMU) bending strain and run to run movement analysis can be a very reliable tool for detecting either anomalous bends across welds post construction and/or landslide induced deformations in pipelines when multiple runs are compared. ILI axial strain tools can reliably measure the state of longitudinal strain in a pipeline to delimit areas where outside forces are contributing to the strain demand on pipelines (Dewar, 2018). These technologies have been developed for other pipeline applications associated with traditional integrity programs. The application of these ILI technologies to geohazards is not as well developed. As an example, there are no current industry established methods to relate ILI IMU data to ground deformations. This information is typically interpreted by individual ILI vendors using different methodologies and thresholds. Significant deformations are seldom missed but subtle features which may provide early indications of landslide interactions are often remain unidentified.

Going forward the challenge for the pipeline industry is to combine/integrate ground monitoring, pipe monitoring and construction/operational/integrity experience to optimize landslide geohazard management programs. These successes will be because of better communications between construction, geohazard, integrity, operations and lands groups. Often smaller operators do not have in in-house geohazard department which may introduce additional challenges. It is believed that improved GIS systems will allow for the integration of information from multiple programs/groups to better detect and manage landslide interactions.

4.2 Fitness for Service Assessments

Generally, fitness for service assessments can be divided into 2 distinct categories:

- Calculation of fitness for service using estimated strain demands in relation to strain capacities of the pipeline based on either field or ILI measured deformations or strains.
- Modelling of fitness for service using traditional soil spring and/or finite/discrete element analysis.

There are advantages and disadvantages to both methods that are beyond the scope of the discussion in this paper. Regardless of the assessment approach, the greatest challenge to industry is verifying with actual data from historic loss of containment/fitness for service incidents. There are generally 4 reasons for this challenge:

- There is minimal geo-mechanical information available for a historic incident typically because there is no monitoring data for either the pipeline and/or the landslide.
- There is geo-mechanical information collected but is not available as an incident did not meet any threshold for regulatory reporting. There may be a reluctance from some operators to share information which may be beneficial to the industry.
- There is information available, but it is not in a format that it can be interpreted in any meaningful manner by geo-mechanical specialists to compare specific incidents to each other or model individual incidents.
- Regardless of data being available there is a finite number of incidents to model. Given the variations in parameters that determine fitness for service, the data set is simply too small.

A consistent categorization of landslide has potential to improve information sharing within industry by speaking a consistent language. Increased investment and information sharing by operators and consultants into assessment of landslides will develop more effective overall geohazard management programs.

5 CLOSURE

The observations, conclusions, statements and professional expertise expressed in this paper are derived from the experiences working with legacy Westcoast Energy Inc. and Pembina Pipeline Corporation. The author would like to thank all the contractors, consultants, vendors and internal operations staff that worked on landslide mitigation and monitoring projects. Lucy Swank is responsible for the classification system graphics. Subject matter expertise and industry experience contributors are Greg Van Boven, Ed McClarty, Drum Cavers, Yong-Yi Wang, Bill Liu, Will Webster, Kent Ryan and Don West. Nicki Lee Robertson provided outside document proofing including introducing the main author to a concept known as punctuation and the Queen's English.

6 DISCLAIMER

The opinions, statements and conclusions contained herein are those of the individual author and not those of Pembina Pipeline Corporation.

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