

Pipeline Integrity Management of Landslide Hazards

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Pipeline Integrity Management of Landslide Hazards

1 Scope

This recommended practice (RP) provides recommendations for the management of landslide hazards for operating onshore welded steel pipelines.

The recommendations in this document are applicable for onshore transmission pipelines conveying natural gas, hazardous liquids, and carbon dioxide. Offshore pipelines, pipelines containing products other than those listed above, and pipelines made of materials other than welded steel were not explicitly considered in the development of this document, however, it may provide useful guidance to these other applications. The recommendations provided herein are based on the physical, regulatory, and social environment of the United States, but could reasonably be applied in Canada and in other countries with due consideration for their regulatory requirements. The recommendations are for active pipelines and not intended for terminals, aboveground stations and appurtenances, or delivery facilities.

The intention of this document is to provide operators, contractors, and consultants with recommendations to manage landslide hazards. Landslide hazard management may include both consideration of active features and anticipating or avoiding features such as in design processes, route selection and/or planning of mitigative measures.

1.1 Application Notes

This document is an API recommended practice that is published to provide technical information and recommendations toward building a best practice. Different methodologies, improvements and new technologies may not have been included as part of the recommended practice. For this reason, the following notes are provided to guide users of the document:

- The RP was assembled by collecting experience- and good engineering practice-based recommendations from pipeline operators, trade associations and engineering service providers. Landslides are complex problems and specific scope and requirements in this document may not be sufficient for an effective solution to all scenarios and as such the RP user is encouraged to exercise their judgment.
- Alternate processes and tools found to be suitable by pipeline operators may be substituted for those included in the RP. The development of the RP does not suggest that it presents a comprehensive listing of all applicable processes or tools. For example, the user may elect to apply stress-based assessment tools, such as those in ASME B31.4, or strain-based assessment tools. It is the users' responsibility to be in compliance with design code, fabrication requirements, and applicable regulatory requirements.
- The levels of assessment presented in the RP provide a detailed listing of the types of data, analyses, and decision processes that they may involve. The intent of the RP is that the user may elect to customize the data, analyses and decision processes to suit their needs, data availability and assets.

1.2 Document Structure

This document is structured as follows:

- [Section 1](#) (this section) introduces the scope, limitations, and structure of the document.
- [Section 2](#) provides normative references pertaining to this document.
- [Section 3](#) provides the terms, definitions, acronyms, and abbreviations used in this document.
- [Section 4](#) provides recommendations for the overall structure and key components of a landslide management program for the purposes of pipeline integrity.

- [Section 5](#) provides the recommendations for threat assessment of landslides to pipeline integrity.
- [Section 6](#) provides recommendations for managing data relative to landslides in a pipeline context.
- [Section 7](#) provides recommendations for threat management, including classification and decision making (CDM) and implementation of landslide threat management measures.
- [Section 8](#) provides recommendations for evaluating and improving landslide management programs.
- [Section 9](#) provides recommendations for establishing a change management program.
- [Annex A](#) provides an overview of landslide types and processes.
- [Annex B](#) provides an overview of the methods used to conduct geologic and geotechnical assessment of landslides.
- [Annex C](#) provides a summary of the methods and considerations for performing landslide fitness-for-service (FFS) assessments from a pipeline perspective.
- [Annex D](#) provides examples of the implementation of the landslide assessment process.
- [Annex E](#) provides considerations and examples of landslide-specific data that could be stored and managed by an operator.
- [Annex F](#) provides considerations and guidance for implementing a landslide CDM program and examples of previously implemented CDM programs.
- [Annex G](#) provides considerations and guidance for implementing threat management measures.
- [Annex H](#) provides a listing of possible metrics that could be maintained to evaluate the progress and state of a landslide management program.
- [Annex I](#) provides a discussion of considerations in evaluating the impact of interacting threats with landslides.
- A bibliography is associated with this document. This bibliography is a sequential listing of references used in the main document and continues through the annexes. It also provides additional documents to support the user in identifying other relevant data sources.

2 Normative References

This document contains no normative references. A list of documents and articles associated with RP 1187 are included in the bibliography.

3 Terms, Definitions, Acronyms, and Abbreviations

For the purposes of this document, the following definitions, acronyms, and abbreviations apply.

3.1 Terms and Definitions

3.1.1

baseline assessment

The first Level 1 Assessment conducted for a pipeline segment or system.

3.1.2

bending strain

strain in the longitudinal direction of the pipe caused by bending.

3.1.3

capacity

Maximum amount of loading or deformation that a pipeline can withstand prior to a negative consequence, such as a leak, rupture, or change in the physical characteristics of the pipeline that may negatively affect its operation.

3.1.4

classification and decision-making system

A process used to establish the assessment that should be performed, the actions that should be taken once the assessment is completed, and the prioritization or timing of those actions.

3.1.5

compressive strain capacity

Maximum magnitude of compressive strain that pipe can support prior to the onset of yield, buckling or wrinkling limit condition (failure mode).

3.1.6

demand

Loading imposed on a pipeline by its operational and environmental conditions. May be expressed as load, stress, or strain.

3.1.7

displacement-controlled loading

Loading in which the amount of global deformation is not affected by the load-carrying capacity of the component/structure being subjected to the loading.

3.1.8

fitness-for-service assessment

FFS

Quantitative engineering evaluation performed to assess the suitability of a structure for its intended use over a defined time frame considering possible limit states.

3.1.9

geohazard

Hazard caused by ground movement or flowing water that occurs at discrete locations and may threaten the integrity of a pipeline or associated facility.

3.1.10

geomorphic assessment

Analysis of the characteristics of the ground surface to identify, characterize, and document geohazards and the processes that shape them, such as through review of remote sensing data or direct observations from the air or on the ground.

NOTE Sometimes referred to as geomorphological assessment

3.1.11

geophysical investigation

Imaging subsurface features using engineering geophysical tools (e.g. refraction seismology, reflection seismology, soil resistivity, ground-penetrating radar [GPR]).

3.1.12

geotechnical hazard

Threat to a pipeline that results from displacement of soil or rock. This group of hazards includes landslide, subsidence, seismic, heave, and volcanic events.

3.1.13**geotechnical investigation**

Evaluation of soil and rock conditions using in situ geotechnical engineering techniques such as geotechnical boreholes, test pits, dynamic cone penetration tests, and installation of slope inclinometers (SIs).

3.1.14**hydrotechnical hazard**

Threat to a pipeline that results from changes in a waterway or body of water, including but not limited to scouring, channel migration, bank erosion, avulsion, and other threats related to the movement of water.

3.1.15**landslide**

Type of naturally occurring or human-caused downslope movement of a mass of rock, debris, or earth in which much of the material moves as a coherent to semi-coherent mass with little internal deformation.

3.1.16**landslide management program**

A program implemented to minimize the likelihood of landslide hazards causing undesirable consequences to a pipeline, such as a leak, rupture, or impaired serviceability.

3.1.17**level 1 assessment**

Ranking or screening process completed as a desk top study to identify potential landslide hazard sites and evaluate their relative severity, often considered at a qualitative to semi-quantitative level.

3.1.18**level 2 assessment**

Assessment process applied to landslide sites based on site specific non-intrusive collected data to evaluate the relative severity and support preventative and mitigative measures, often considered at a semi-quantitative to quantitative level.

3.1.19**level 3 assessment**

Assessment process applied to a specific site based on detailed collected site data to evaluate the current and forecast threat to support preventative and mitigative measures, often considered at a quantitative level.

3.1.20**load-controlled loading**

Loading in which the magnitude of the loading is not affected by the amount of deformation or displacement.

3.1.21**longitudinal strain or stress****axial strain or stress**

The stress strain aligned with the pipe axis and comprises stresses or strains from pipe uniform extension/contraction and bending.

3.1.22**mitigation**

Physical or operational modification of a site or pipeline aimed at reducing the probability of a landslide negatively impacting a pipeline.

3.1.23**monitoring**

Collection of data for the continued assessment of the pipeline or the conditions near the pipeline.

3.1.24**movement (displacement) rate**

Estimated or measured magnitude of displacement per unit time.

3.1.25**pipeline geohazard management program****PGMP**

A set of practices and procedures used to systematically identify, assess, and manage geohazards with the intention of reducing the likelihood of pipeline damage and failures.

3.1.26**pipeline system**

All portions of the physical facilities through which gas, oil, or product moves during transportation.

NOTE This includes pipe, valves, and other appurtenances attached to the pipe, compressor units, pumping units, metering stations, regulator stations, delivery stations, breakout tanks, holders, and other fabricated assemblies.

3.1.27**preventative and mitigative measures**

Activities designed to reduce the likelihood of a pipeline failure or minimize or eliminate the consequences of a pipeline failure.

3.1.28**segment****line section**

A length of a pipeline or a part of a pipeline system having common characteristics.

3.1.29**Strain or stress capacity**

Strain or stress level beyond which there would be a negative consequence, such as a leak, rupture, or change in the physical characteristics of the pipeline that may negatively affect its operation.

3.1.30**Strain or stress demand**

Total strain or stress imposed on a pipeline by its operational and environmental conditions.

3.1.31**strain or stress demand limit**

The strain or stress level that is selected as the acceptable strain limit.

3.1.32**subject matter expert****SME**

Technical expert in a subject area with demonstrated training and experience.

3.1.33**tensile strain or stress capacity**

Strain or stress capacity in tension.

3.1.34**threat management measures**

Actions that reduce the likelihood of a landslide negatively impacting a pipeline.

3.2 Acronyms and Abbreviations

ALA

American Lifelines Alliance

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CDM	classification and decision making
CRES	Center for Reliable Energy Systems, LLC
CSA	Canadian Standards Association
CSC	(what does this stand for?)
DEM	digital elevation model
FFS	fitness for service
GPR	ground-penetrating radar
HDD	horizontal directional drilling
ILI	in-line inspection
ISO	International Organization of Standardization
JIP	Joint Industry Project
IMU	inertial measurement unit
IMP	integrity management program
INGAA	Interstate Natural Gas Association of America
InSAR	interferometric synthetic aperture radar
LiDAR	light detection and ranging
MAOP	maximum allowable operating pressure
MOC	management of change
MOP	maximum operating pressure
MTR	mill test report
NDT	nondestructive testing
PGMP	Pipeline Geohazard Management Program
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRCI	Pipeline Research Council International
PQR	(welding) procedure qualification record
ROW	right-of-way
SBA	Strain based assessment
SF	Safety factor
SI	slope inclinometer
SME	subject matter expert
TSC	Tensile strain capacity
WPS	welding procedures specification

4 Landslide Management Program

This section discusses the overall structure and key components of a landslide management program. The objective of a landslide management program is to minimize the likelihood of landslide hazards causing undesirable

consequences to a pipeline, such as a leak, rupture, or impaired serviceability. A landslide management program is intended to operate for the entire pipeline life cycle, which could span many decades.

A landslide management program manages landslides that have progressed to any of the following three stages:

- 1) A current or potential landslide condition exists along or near a pipeline.
- 2) The pipeline becomes engaged by the landslide, creating a demand on the pipeline.
- 3) The demand approaches the capacity of the pipeline, promoting the potential for pipeline failure.

4.1 Components and Processes

The landslide management program should comprise the following core components and processes, which can follow a “Plan-Do-Check-Act” process as outlined in API Recommended Practice 1173:

- Identification and assessment of landslide threats to pipeline integrity ([Section 5](#)).
- Data management, including storage, analysis, and retrieval of data ([Section 6](#)).
- Implementation of measures to assess landslide threats, including the process to decide which measures are appropriate to manage those threats ([Section 7](#)).
- Evaluation of the effectiveness of the program ([Section 8](#)).
- MOC following program implementation ([Section 9](#)).

These processes generally follow the Plan-Do-Check-Act processes described in API Recommended Practice 1173.^[8]

4.2 Administration of the Program

The landslide management program can be a part of the Integrity Management Program or Pipeline Geohazard Management Program (PGMP). A PGMP is a set of practices and procedures used to systematically identify, assess, and manage geohazards with the intention of reducing the likelihood of pipeline damage and failure. The PGMP should be administered under the umbrella of an operator’s integrity management program (IMP).

The landslide management program should be administered by a designated group with the necessary expertise, either internal or external to an operator.

4.3 Landslide Management Program Documentation

The landslide management program, including the core components (see [4.1](#)), should be documented. The level and type of documentation may vary according to the number and complexity of landslide hazards present across a pipeline system.

If an operator concludes there are no landslide threats potentially affecting their system, the rationale and evidence for coming to this conclusion should be documented.

4.4 General Considerations

While many elements of landslide management are similar to the management of other integrity threats, the list below summarizes unique characteristics that should be considered when developing a landslide management program. These considerations affect multiple aspects of landslide management.

- Landslide formation and movement can be episodic or consistent, and average landslide movement rates can range from less than inches per year to feet per second.^[15] Consequently, the effects on a pipeline can range from gradual strain accumulation over years to an instantaneous impact.
- The timing of landslide activity is difficult to forecast or predict. While factors such as precipitation and earthquakes are known to trigger or exacerbate landslide movement, correlating precipitation with landslide movement is challenging,^[16] and the timing, location, and magnitude of seismic activity cannot be reliably predicted at this time.
- Landslides have multiple modes of occurrence and behavior, which can affect pipelines differently. [Annex A](#) provides a summary discussion of landslide characteristics and processes, and how these can affect pipelines.
- Landslides can be caused by both natural processes and events and by human activities.
- Landslide activity leaves characteristic indications on the ground surface that can be identified through geomorphic assessment. The specific location of past or ongoing landslide movement can generally be proactively identified through direct observation using assessment tools discussed further in [Section 5](#).
- ILI data can provide critical information for understanding the effects of a landslide on a pipeline and can provide a supplementary method of identifying landslides that have affected a pipeline. ILI IMU data can be used to calculate bending stress or strain and changes in stress or strain (or pipe movement) by comparing two or more sets of IMU data. ILI caliper data may be used to identify local pipe wall deformations resulting from pipe wall compression. ILI data may also be used to understand elevated stress coincidence with girth and long seam welds or other pipe degradation.
- A pipeline has to be engaged by a landslide (e.g. the pipeline is within the mass of the landslide) to be affected by the threat. The level of impact on a pipeline, broadly termed “demand,” depends on the characteristics of a landslide and the process and nature of interaction between the landslide and the pipeline. The implications on pipeline integrity of a pipeline engaged by a landslide can vary greatly depending on the capacity of a pipeline.
- A pipeline that is not currently engaged by a landslide may need to be monitored or assessed to consider the progression of the hazard which may result in future engagement.
- The capacity of pipelines can vary greatly depending on the characteristics of materials and construction methods, including the methods used for welding and inspection. The capacity of the pipeline is also related to the pipeline’s operational conditions.
- The impact of interacting threats should be considered in the management of landslide hazards (See [Annex I](#)).

5 Landslide Threat and Integrity Assessment

The landslide threat to pipeline integrity should be assessed using a three-level framework¹, which is described in the following sections. In many instances, landslide threats can be assessed and managed without needing to progress through all levels. Operators can add additional levels to this framework if appropriate and include processes and tools suitable for their approach to landslide threat assessment.

The key components of this three-level framework are as follows:

- As the assessment progresses to a higher level, the degree of characterization of a landslide threat and pipeline integrity generally increases, and the number of landslide threats being assessed typically decreases because lower-level assessments have identified suitable actions for some hazards.

¹ In accordance with general practice as of the time of this document.

- Level 1 assessment should be performed on pipeline systems managed by the operator to develop an inventory of landslide threats across the entire system.
- The three-level framework should combine an assessment of the hazard with an assessment of pipeline integrity to produce an integrated assessment of the landslide threat. Hazard assessment is discussed in more detail in [Annex B](#), while pipeline integrity assessment is discussed in [Annex C](#). [Annex D](#) provides examples of landslide assessments using this three-level framework. The three-level framework can include:
 - Level 1—Ranking or screening process completed as a desk top study to identify potential landslide hazard sites and evaluate their relative severity, often considered at a qualitative to semi-quantitative level.
 - Level 2—Assessment process applied to landslide sites based on site specific non-intrusive collected data to evaluate the relative severity and support preventative and mitigative measures, often considered at a semi-quantitative to quantitative level
 - Level 3—Assessment process applied to a specific site based on detailed collected site data to evaluate the current and forecast threat to support preventative and mitigative measures, often considered at a quantitative level.
- Some form of CDM program should be developed and implemented throughout the assessment process to determine the level of assessment needed and ultimately the methods used to manage landslide threats. Threat classification is discussed further in [Section 7](#).

5.1 Level 1 Assessment

A Level 1 Assessment should fulfill the following main objectives:

- Identify possible landslide(s) along a pipeline. When conducted for a pipeline segment or system, such an assessment will help in developing an inventory of the potential landslide hazards along the pipeline.
- Evaluate the availability of data/information necessary to assess the threat each landslide poses to the pipeline system.
- For pipelines in landslide prone areas, evaluate the availability of data/information necessary to assess the resilience of a pipeline (such as stress or strain capacity).

5.1.1 Applications of Level 1 Assessment

A Level 1 Assessment should be conducted for a pipeline system(s) when one of the following conditions occurs:

- An existing pipeline system is acquired from another operator. If a Level 1 assessment is available from the previous operator, these data can be used instead of conducting a new assessment.
- A new pipeline system is introduced.
- Reactivation or preservation of an idle line that has not had a Level 1 assessment.
- Upon initiation of a PGMP.

If completing a Level 1 Assessment for an entire pipeline system during a single effort is not practical, a Level 1 Assessment can be broken up into regions or segments such that assessment of an entire system can be spread over multiple years. If the Level 1 assessment of the pipeline system is performed over multiple years, the priority and the timeline to complete each separate assessment should be developed prior to initiating the assessment. The prioritization method may vary, but it could be developed based on the severity of expected landslide conditions and other risk factors. The timeline for completing the Level 1 Assessment should be documented and justified in the landslide management program. The results of the Level 1 Assessment should be used to establish whether a Level 2 Assessment is needed.

5.1.2 Data and Analysis That May Be Include in a Level 1 Assessment

A Level 1 Assessment may consist of the following components:

- In forested or thickly vegetated areas where the ground surface is mostly or completely obscured, the most recent and relevant bare-Earth digital elevation models (DEMs) may be reviewed to identify geomorphic evidence of recent or historical landslide activity. See [Annex B](#) for further discussion on geomorphic assessment and delineation of potential landslide areas.
- In areas where the ground surface can be directly observed, it is preferred that bare-Earth DEMs be reviewed, but that review can be replaced or supplemented with a review of stereoscopic (3-D) aerial photographs, 2-D aerial photographs, or direct observation by a landslide-hazard-focused aerial reconnaissance.
- Identification, mapping, and documentation of areas of possible current and past landslide activity should be completed to include pipeline adjacent areas that may contain landslides with the future potential to impact pipeline integrity. The information recorded should meet or exceed the minimum requirements provided in [Section 6](#).

A Level 1 Assessment relies on a combination of original desktop geomorphic assessments and reviews of preexisting information. A Level 1 Assessment should incorporate the following additional information when such information is available to the operator ². Incorporating this information improves the results of the Level 1 Assessment and supports decision making on whether further assessment is needed.

- ILI data relevant to landslide assessment, that are continuously developing, may include among other information:
 - IMU bending strain data.
 - Caliper pipe wall deformation data.
 - Crack observations.
 - Wall thickness data.
- Previously collected ROW slope monitoring or pipe monitoring data.
- Pipeline stress or strain capacity, combined with stress or strain demand and the geomorphic assessment, the safety margin between the capacity and demand can be used to assist in decision making for prioritization and the need for further assessment. This can include identified changes in material properties.
- The locations of previous landslides and repairs performed at those locations, if known.
- Public or third-party records review could also be useful (e.g. collection of public LiDAR data, collection of public soil data, etc.).
- Other remote sensing data beyond the aerial photographs and LiDAR listed above, such as satellite-based interferometric synthetic aperture radar (InSAR).

It is not required to perform the assessments or collect the information described in the following list if not realistically available prior to initiating the Level 1 Assessment. This list is provided to identify items that may already be available to an operator, and if available, can enhance the accuracy and completeness of the Level 1 Assessment. This information, if available, can reduce the potential for not identifying a landslide and support

² Readers are cautioned that with the current state of technology and scientific understanding, considerable uncertainties often remain with respect to geohazard behavior, geologic materials, and safety margin even after the completion of detailed assessments. These uncertainties should be accounted for in the decision-making process.

decision making, such as the timing and prioritization of additional assessment. It is understood that for many pipeline systems, some or all this information might not be available at the time of a Level 1 Assessment.

A Level 1 Assessment may be sufficient for decision making for many landslide hazard sites. A CDM program should be used to determine when additional Level 2 Assessment is needed. The considerations for when a Level 2 Assessment is needed are discussed in more detail under “Decision Making” in [7.1](#).

5.2 Level 2 Assessment

A Level 2 Assessment is a site-specific investigation focused on specific, identified landslides.

A Level 2 Assessment is an investigation based on readily available or readily collected site-specific information and does not require intrusive investigations and analysis such as subsurface drilling, trenching, pipeline exposure, and testing. Conceptually, sites selected for Level 2 Assessment are based on the results of the Level 1 Assessment, but sites can also be identified from the results of regional monitoring or other identification of a potential landslide that occurs after the Level 1 Assessment.

A Level 2 Assessment should meet one or more of the following objectives:

- Confirm landslide terrain, location/size with respect to pipeline, and level of activity to potentially impact the pipeline.
- Gain a better understanding of the characteristics of the landslides (those confirmed or likely) and potential threats posed to a pipeline(s) to support decision making.
- Provide further information needed to support an FFS assessment.
- Reassess a previously evaluated landslide when some changes might have occurred, such as identification of movement or changes in pipeline strain from ongoing monitoring. Based on this reevaluation, determine whether additional actions are needed and, if so, the nature of those actions.

Depending on the objectives of the Level 2 Assessment, one or more of the following activities should be performed:

- A field geomorphic and geological or geotechnical reconnaissance, including approximating the pipeline location and depth of cover using a pipeline locator. The results of the reconnaissance should include confirmation of the landslide boundary where it occurs near the pipeline or has the potential to affect the pipeline, estimates of the thickness (depth) of the landslide, the type and behavior of landslide movement, its estimated age of last movement, and an estimate on the relationship of the landslide to the pipeline both vertically and horizontally.
- A detailed records review or other detailed desktop assessment or analysis, such as a review of construction records to confirm if the pipeline is below landslide depth or that prior mitigation had been performed. Public or third-party records review could also be useful, which could include the collection of public LIDAR data, or the collection of public soil data.
- An FFS assessment, including stress or strain capacity and demand from one or more sources supported by available data as described in [Annex C](#).

A Level 2 Assessment is often sufficient for decision making regarding landslide hazards. In instances where remaining uncertainty needs to be reduced for decision making or to design appropriate threat management measures, a Level 3 Assessment may be considered. The considerations for when a Level 3 Assessment is needed are discussed in more detail under “Decision Making” in [7.1](#).

5.3 Level 3 Assessment

A Level 3 Assessment is a detailed site-specific assessment. The specific methods used to conduct a Level 3 Assessment should be fit-for-purpose. The methods can vary based on landslide type, location, site-specific constraints, and degree of certainty needed for pipeline integrity assessment.

A Level 3 Assessment should meet one or more of the following objectives:

- Resolve or reduce uncertainties or potential risk remaining from prior assessments regarding the impact of a landslide on a pipeline.
- Acquire additional information or perform analyses needed to make or implement a risk-management decision regarding landslide hazards when such information cannot be generated from prior assessments.

Depending on the objectives of the Level 3 Assessment, one or more of the following activities could be performed:

- A detailed assessment of the subsurface conditions through measures such as geophysical investigations or subsurface geotechnical investigations.
- An FFS assessment that may include the current state of the pipeline and/or expected future increase in stress or strain demand and possible degradation of stress or strain capacity.

The operator should evaluate uncertainties and consider them with regards to the desired safety margin when conducting an FFS assessment. Sensitivity studies may be desirable to mitigate uncertainties.

In some instances, the results of a Level 3 Assessment might not fully meet the objectives of the assessment. In these cases, the Level 3 Assessment should continue with further data gathering and assessment until the objectives have been met or a conservative decision may be adopted. [Section 7.1](#) contains further discussion on decision making.

5.4 Reassessment

Natural and human-influenced conditions can change along a pipeline right-of-way (ROW), as can the availability of new and updated landslide hazard data and information. The capacity of a pipeline might also evolve over time, such as discussed in [Annex I](#) (interacting threats). As such, operators should periodically reassess their system/segments by conducting an updated Level 1 Assessment.

The specific assessment interval should be determined by the operator to manage the threat to the segment or site. Reassessment intervals could reasonably be set at 10 years or less. The frequency and justification for reassessment should be documented in the PGMP and may take into consideration other ongoing assessment and monitoring that might influence the need for and timing of reassessment.

In addition to periodic reassessment of a system/segment, individual sites might require reassessment at any level due to changing conditions.

6 Data Management

A landslide management program should have an efficient mechanism in place to capture, store, and sort data for integration as the data is generated.

There are two broad types of data that should be managed: spatial and nonspatial. Spatial data are types of data that have a physical location, such as the boundary of a landslide, pipeline centerline locations, depth of cover measurements, and the locations of monitoring instruments. Nonspatial data are types of data that may be tied to a specific map location or landslide but are not spatial in nature, such as report documents, and landslide characteristics.

Spatial data may be managed in a GIS platform where dimensional aspects of the data can be accessed and viewed. A GIS platform can be used to spatially display the following available data in map view, such as:

- Pipeline centerline locations and ROW, which may include as built and current, as available.
- The footprint or 2-D extent of each landslide.
- Locations of monitoring instruments, such as strain gauges, monitoring points, and Sis.
- Strain or stress and strain or stress change data derived from measurements or analysis.
- LiDAR data or aerial imagery and derived products.

Additional detailed site information may be maintained and made available within the GIS platform or linked to externally stored files through a unique landslide identifier. When the following data are available, they should be accessible for each landslide, as follows:

- A unique identifier for each landslide.
- The location of the landslide in latitude and longitude.
- Landslide characteristics that are relevant to the CDM process, which can include:
 - depth of the landslide surface of rupture,
 - amount of displacement,
 - width and length of movement zone,
 - age,
 - landslide movement direction relative to the pipeline,
 - movement rate, and
 - landslide type.
- The classification or threat ranking for each landslide.
- The date(s) of activities at the site, including identification, field assessment(s), mitigation, and monitoring.
- The type(s) of threat management measures implemented for the landslide.
- The type(s) and frequency of ongoing monitoring.

Nonspatial data can be linked with spatial data either in the form of direct file attachments that may be accessible through the GIS platform or as link(s) to other locations where the data are stored. The selected filing and access methods may vary based on the data format, the need for updates, and accessibility requirements.

The following data, when available, should be maintained for each site:

- Monitoring data results.
- ROW characteristics.
- Geotechnical information including detailed site inspections/surveys reports.

- Pipe survey data.
- Mitigation measure designs or as-builts including notes on previous maintenance activities, either geotechnical remediation or pipeline repair.
- Site and construction photographs.
- History of changes that may affect site stability, such as vegetation removal or site regrading.
- ILI data.

Pipeline data should be readily accessible for each site to use as needed. Pipeline information that might support evaluation of landslide threats includes the following:

- Pipeline characteristics.
- As-built details.
- Pipeline operating conditions.

Data management systems and considerations for their implementation are discussed further in [Annex E](#).

7 Threat Management

Landslide threat management measures are a component of general preventative and mitigative measures. The landslide threat management measures discussed in this document are largely preventative in nature, with the intention to reduce the likelihood of pipeline failure from a landslide. Landslide threat management measures consist of the following:

- Measures that provide monitoring of landslide or pipeline conditions.
- Physical measures that affect the likelihood of a landslide impacting a pipeline or further impacting a pipeline or that enhance the resilience of a pipeline to reduce the likelihood of negative consequences if the pipeline is impacted by a landslide.
- Interpretation and forecasting of measured data.

When these measures are implemented systematically, they reduce the likelihood of landslide damage to pipelines. The selection and implementation of appropriate threat management measures, individually or in combination, should be performed using a landslide threat CDM program.

7.1 Classification and Decision Making

A CDM program should be developed as part of the landslide management program. A CDM program should be used for three primary purposes:

- To determine whether to perform additional assessment or implement a threat management action following the performance of a Level 1, 2, or 3 Assessment.
- To determine the nature of that action.
- To determine the timing or order of conducting actions.

While the form of a CDM program varies may vary, each CDM program should contain the following:

- Requirements for the types of data needed to determine the threat classification, which should integrate with the requirements for assessment.
- A means to classify the perceived threat to a pipeline from landslides.
- A means to classify the resilience of pipelines against the impact of landslides, such as stress or strain capacity.
- A set of requirements or guidelines by which to perform additional actions and, if so, the type of actions and the timing in which to conduct each action based on the classification (see [7.2](#)).

Further discussion on CDM programs and consideration for their implementation are provided in [Annex F](#).

7.2 Threat Management Measure Selection

The CDM program should include guidelines for selecting appropriate threat management measures. These guidelines should consider the following:

- The behavior and characteristics of the landslide, such as size, type, orientation, direction, amount, and rate of movement.
- Whether the landslide has previously engaged or otherwise affected the pipeline. Where possible, this should include an estimate of the stress or strain demand imposed by the landslide.
- The resiliency of the pipeline to landslide movement. Where possible, this should include an estimate of the stress or strain capacity, or stress or strain demand limit of the pipeline.
- Uncertainties remaining from completed assessments. Typically, the more in-depth the assessments, the lower the uncertainty.

7.3 Monitoring

Landslide monitoring is the collection of data over time and should be performed for one or more of the following reasons:

- To act as a warning system to allow for preemptive intervention to reduce or eliminate the potential for future impact to a pipeline or associated facility.
- To act as a warning system to allow for preemptive intervention to reduce the consequence of an event (e.g. shutdown if a pipeline rupture is imminent).
- To further characterize a landslide or landslide susceptible area, such as for use in designing mitigation measures.
- To calibrate or validate strain demand predictions or geological models used to evaluate mitigation options and timing of implementation.
- To measure or assess the effect of landslide movement on a pipeline.
- To identify new landslides or changes to existing landslides.
- To confirm that mitigation measures are functioning as intended.
- To provide notification and information that an extreme weather or geologic event (such as an earthquake) has occurred to facilitate post-event assessment.

Monitoring encompasses a wide spectrum of technologies and approaches, ranging from simple visual observation to advanced satellite data. The landslide monitoring technologies selected and used should be fit-for-purpose.

A landslide management program should provide requirements for commonly used monitoring measures. These requirements should consider the following:

- Considerations for selecting monitoring methods and locations.
- Installation requirements (for monitoring that requires instrument installation).
- Resolution, sensitivity, and accuracy of measurement.
- Site conditions or site accessibility.
- Expected type of pipe response and magnitude of movement, stress or strains.
- Data collection methods.
- Duration of monitoring and frequency of measurements and analysis.
- Analysis methods.
- Reporting and distribution of monitoring results and analysis.
- Response thresholds for the implementation of further action and the type of action to be implemented upon threshold exceedance, when the purpose of monitoring is to act as a warning system.

Considerations for selecting and implementing appropriate landslide monitoring strategies are discussed further in [Annex G](#).

7.4 Mitigation Measures

Mitigation measures are a means to manage landslide threats by implementing physical methods to reduce the potential for a landslide to impact a pipeline and/or to reduce negative impacts to a pipeline from a landslide. Mitigation measures should accomplish one or both of the following objectives:

- Reduce stress or strain demand or reduce the potential for increase in stress or strain demand. Some examples include avoiding the landslide (such as through a reroute or horizontal directional drilling [HDD] below the slip plane), stabilizing the landslide, excavating for stress relief, or reducing the rate or extent of movement by lowering the groundwater table.
- Enhance the stress or strain capacity of a pipeline to reduce its vulnerability to the effects of a landslide: examples include reinforcing girth welds and applying stress- or strain-resistant design principles to replace sections of pipeline.^[17]

Although discussed separately, these mitigation measures are often combined with each other and with monitoring measures to reduce overall threat. Further discussion and considerations for selecting and implementing mitigation measures are provided in [Annex G](#).

The following should be considered when selecting and implementing mitigation measures:

- The characteristics of the landslide(s) being managed, such as soil or rock types, groundwater presence or elevation, direction of movement and movement rates, size, depth, orientation, and relationship to the area being protected.
- Timing and season of mitigation actions.

- Design life of the mitigated solution.
- Historic performance and experience with the deployment of mitigation options being considered.
- The feasibility of successfully implementing the mitigation measures given the landslide characteristics, location, and geography.
- The potential to cause or trigger additional landslide movement or worsen landslide movement during implementation.
- The constructability in the context of potential impacts to sensitive receptors, such as waterbodies or other environmentally sensitive areas, third parties, such as homes or roads adjacent to the ROW, workers, and other pipelines.
- Environmental restrictions or other land-use restrictions that could prohibit certain kinds of mitigation measures, such as mitigation that extends outside of the ROW.
- Stakeholders that may be involved in the selection of mitigation measure(s), such as geotechnical and pipeline integrity subject matter experts (SMEs), construction contractors, land and environmental permitting groups, and adjacent landowners and residents.
- Whether continuous monitoring is needed after implementation and, if so, the considerations to select appropriate monitoring. It is recommended that there should always be performance monitoring following mitigation implementation.
- Maintenance and potential failure modes of the mitigation measures.

Operators may wish to identify preferred mitigation methods and create typical designs that can be used for scoping. Because of significant variability between landslides and site conditions, using prescribed methods is not recommended. However, it could be appropriate to provide guidelines for using certain types of geotechnical mitigation measures where sufficient flexibility is built in to adapt to actual site conditions.

8 Program Evaluation

Operators should follow the general structure of API Recommended Practice 1160^{3, 4}, Section 13 for evaluation of their landslide management program. As stated in API Recommended Practice 1160, evaluation should be periodically performed to assess the effectiveness and completeness of the landslide management program and its effect on improving integrity management.^[7] Examples of landslide-specific metrics are provided in [Annex H](#).

9 Management of Change (MOC)

Per API Recommended Practice 1160, operators should develop a MOC process for their landslide management program.^[7] This MOC process should, at a minimum, address the following:

- New construction.
- Acquisition of a pipeline system.
- Major operational changes.
- Changes in pipeline status

³ API Recommended Practice 1160 is written for hazardous liquid pipelines, but the overall structure of the program evaluation recommendations can be applied to other types of pipelines covered in this document.

⁴ Effective way of compensating the effects of high-low misalignment include using properly design weld cap reinforcement and ensuring adequate weld strength ^[31, 32].

- Third-party changes to land use within the ROW or areas immediately adjacent that may influence or change the likelihood of landslide occurrence.

Recommendations for each of these aspects are discussed in [9.1](#) through [9.5](#).

9.1 New Construction

The following information should be recorded as part of new pipeline construction and integrated into the landslide management program:

- Pipe as-builts.
- GIS centerline and ROW locations.
- Depth of cover, trench and backfill condition, including as-builts and survey results that contain soil and rock conditions.
- Inventory of landslides (including preexisting landslides and those that occur during or after construction) and other geohazards such as mining.
- Mitigation measures performed for landslides including as-builts, photographs and designs for those mitigation measures.
- Locations and types of monitoring instrumentation installed for landslides.
- Records of landslide monitoring results.
- Mill test reports (MTRs) and any other line pipe characteristics and testing including coating type.
- Girth welding procedures specifications (WPSs) and procedure qualification records (PQRs).
 - Girth weld inspection records (results including feature types, sizes, locations along with nondestructive testing (NDT) procedures and acceptance criteria).
- Available post construction ILI and LiDAR data (such as IMU and caliper) with the dates of the inspection, construction completion and operations start.

If no landslides were identified during the design and construction process, include evidence that a landslide assessment was conducted. If a landslide assessment was not performed for the new pipeline prior to or during construction or acquisition, a Level 1 Assessment per the recommendations of [5.1](#) should be performed and documented.

9.2 Acquisition of Pipeline System

Upon acquisition of a new pipeline system, the records or inventories of landslides, including mitigation and monitoring measures and construction records as described in [9.1](#) (if available), should be integrated into the existing landslide inventory and PGMP.

A due diligence review of available records, data, and performance of the previous operator's program should be conducted. Depending on the results of this review, additional assessment may be needed to meet the recommendations of this document. If no landslide assessment has been completed for the acquired system, a Level 1 Assessment should be executed.

9.3 Major Operational Changes

Changes in operation shall trigger the MOC process and include the potential impact(s) on landslide management. Typical changes that may impact the program include but are not limited to:

- change in design basis (e.g. MAOP),
- change in commodity shipped,
- flow reversals, and
- similar changes that may affect a pipeline's stress or strain capacity or interaction with landslides.

Impacts and associated mitigation measures shall be documented as part of the MOC process.

9.4 Pipeline Status

Changes in operational status (such as a change from active service to abandoned) should be accounted for in the landslide management program. For instance, abandoning a pipeline that is being monitored for landslides could be justification for ending that monitoring.

9.5 Land Use Changes

Significant changes in land use or land condition that could meaningfully affect the likelihood of landslide occurrence should be accounted for in the landslide management program. For instance, the construction of new highways, open-pit mines, or other structures might reduce hillside stability. As additional examples, notable changes such as clearcutting or wildfires might change the surface water and groundwater regime in landslide-prone areas which may increase the likelihood of landslide occurrence. Such changes on or adjacent to the ROW can result in the need to increase monitoring frequency or implement additional monitoring measures.

Annex A

(informative)

Landslide Basics

A.1 Introduction

Pipeline systems cross a wide variety of topographic terrains and geologic conditions exposing them, in some cases, to geological areas of risk that may include landslides.

This annex addresses landslide types, terminology, classification, characteristics, potential triggers, causes, and the potential effects of pipeline–landslide interaction. These basics are to help provide operators and engineers with a consistent and common understanding of the potential threats that landslides pose to pipelines.

The concepts, definitions, and descriptions in this annex depend heavily on the work of McKenzie-Johnson et al., Wang et al., Cruden and Varnes, Highland and Bobrowsky, and West [12, 14, 15, 18, 19].

A.2 Landslide Overview

Landslides are complex, natural, geologic phenomena. They are a shift of soil and rock brought on by any number of causes due to their geomorphic and geologic environments as well as complex external causes, both manmade and natural. The variability and complexity of landslides contribute to the difficulty in identifying them and understanding their type, nature, location, extent, age, and time of occurrence.

Geologists, engineers, and other professionals often rely on unique and slightly differing definitions and descriptions of landslides, and this diversity in definitions reflects the complex nature of the many disciplines associated with studying landslide phenomena. Within the context of this document, the term “landslide” is a general term used to describe the downslope movement of soil, rock, and organic materials under the effects of gravity and the landform that results from such movement.

A landslide occurs when the downslope component of driving forces acting on the slope exceeds the resistance or strength of the materials underlying the slope often referred to as resisting forces. Driving forces can be increased by changes to the slope mass or geometry such as adding fill material at the top of the slope or by earthquake accelerations. Resisting forces can be reduced by mechanical and chemical weathering of the material underlying the slope which weakens the material and by increased or raised groundwater levels or pore water pressure in the slope.

Landslides range in thickness from shallow (at or near the ground surface) to deep-seated (several tens to hundreds of feet thick). They can move rapidly or slowly, and movement can occur continuously or episodically. Physical changes to the environment, such as intense precipitation events, earthquakes, undercutting and erosion by streams, and human activities can initiate or trigger landslides. The stability of a slope is directly related to the following:

- Material properties of the soil and rock underlying the slope.
- Surface water, groundwater, and pore water conditions within the slope and along landslide rupture surfaces, orientation of soil or rock layer structure.
- Slope surface loading effects.
- Slope geometry.
- State of stress and stress history of the slope.

A.3 Landslide Features and Terminology

Landslides have recognizable physical and geomorphic features that are used to identify the type of landslide and to document their dimensional, physical, and geometric characteristics. These individual features help to understand the location, nature, spatial extent (laterally and vertically), and magnitude of potential landslide effects relative to a pipeline. The typical features of a landslide are illustrated in [Figure A.1](#).

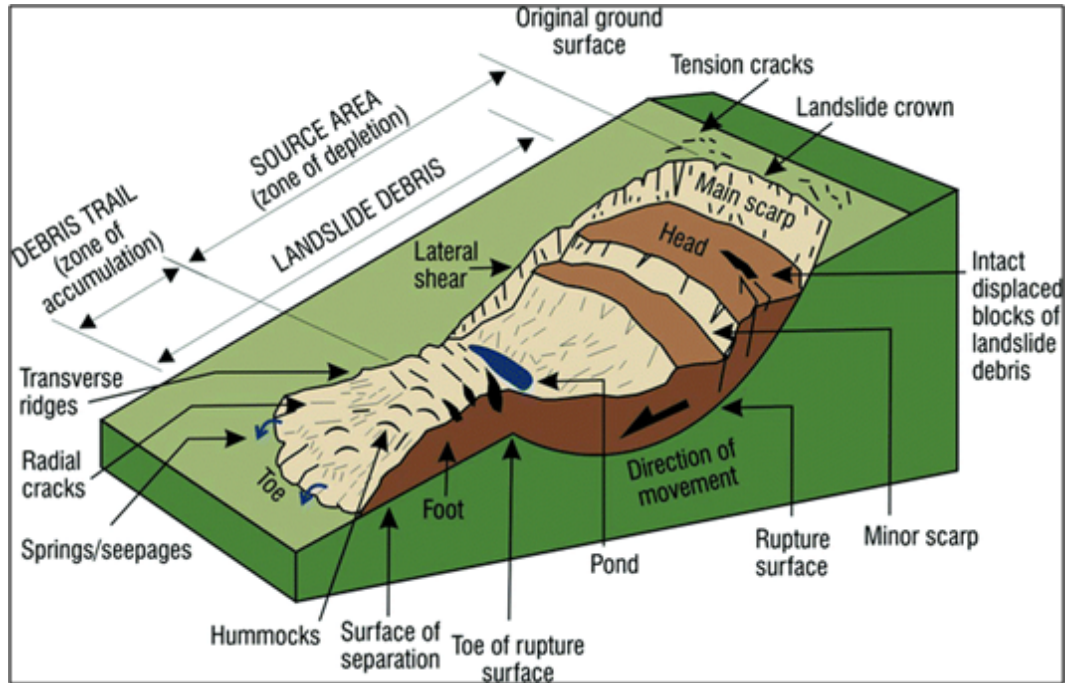


Figure A.1—Conceptual Landslide Diagram [Reference 20]

Almost all landslides have a zone of depletion, where the movement initiates and from which the landslide mass moves downslope, resulting in a zone of accumulation. There are lateral limits to a landslide called the flanks (also called “the lateral shears”). Looking down the slope, the right lateral shear is to the right and the left lateral shear is to the left. There is a main scarp at the upper limit of the landslide, alternatively termed the head scarp, which is generally oriented across the slope and perpendicular to the slope fall line or direction. The main body of the landslide is in the zone of depletion, and the foot (also called the “toe”) is in the zone of accumulation. There is often extension, back tilting, and internal deformation of the main body of the landslide, which can produce transverse scarps and closed depressions that could form sag ponds in larger landslides. The main body, as well as the toe can exhibit hummocky (rumpled and disturbed) terrain. Crown cracks (tension cracks) might also be present behind or upslope of the main scarp indicating possible enlargement of the landslide through uphill retrogression of the main scarp.

A.4 Landslide Types

Landslides can be classified based on the type of movement and the type of material involved. The material in a landslide mass is either rock or soil or both. Soil is described as either earth (if mainly composed of sand-sized or finer particles) or debris (if composed of coarser fragments). This type of movement describes the actual internal mechanics of how the landslide mass is displaced. There are five types of movement: fall, topple, slide, spread, or flow.

- **Falls** occur as a detachment of soil or rock from a steep slope on a surface with little or no shear displacement. The landslide material descends by free falling, bouncing, or rolling. The movement of falls is typically very rapid to extremely rapid.

- **Topples** are the forward rotation out of the slope of a mass of soil or rock about a point or axis. Topples commonly occur in basalt columns or metamorphic and sedimentary rocks with steeply dipping joints, metamorphic foliation, or bedding. The velocities of topples are commonly very rapid.
- **Slides** are the downslope movement of a soil or rock material that occurs primarily on surfaces of rupture or on thin zones of intense shear strain. Slides typically occur either as translational slides, where the zone of rupture is planar, or as rotational slides, where the surface of rupture is curved. Slides can also occur with a combination of translational and rotational movements. Rotational slides are often referred to as slumps by some practitioners, the term “slump” should not be used when describing landslides because there is no widely accepted definition for this ambiguous term.
- **Spreads** are defined as an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads usually occur on very gentle, low-angle slopes, or almost flat terrain where a stronger upper layer of rock or soil undergoes lateral extension and moves along an underlying softer, weaker layer. Spreads can result from liquefaction or from softer material squeezing out from underneath a harder more cohesive material.
- **Flows** are a spatially continuous movement in which there is significant internal deformation, and the material behaves like a viscous fluid. There is a gradational transition from slides to flows, depending on such variables as water content, mobility, and evolution of the movement. Slides can evolve into extremely rapid flows as displaced material loses cohesion, gains water, or encounters steeper slopes. The term “flow” can encompass landslide events such as debris avalanches, debris flows, debris torrents, lahars (volcanic debris flow), and earth flows.

Landslides are ultimately described based on their movement type and the predominant material in the landslide mass. For example, rockfall, debris flow, earth flow, and so forth. Landslides can also form a complex failure encompassing more than one type of movement (for example, a rotational slide-debris flow or translational slide-earth flow). For the purposes of this report, we treat type of movement as synonymous with landslide type. The following table (Table A.1) is a matrix of the terms used to describe landslides based on their movement type and the material making up the landslide.

Table A.1—Landslide Types and Material (based on Cruden and Varnes [Reference 15] and USGS [Reference 21])

Type of Movement	Material Type		
	Bedrock	Coarse Soil	Fine Soil
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock topple	Debris topple	Earth topple
Slide (rotational, translational)	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow
Complex	Combination of two or more movement types		

A.5 Landslide Velocity

Except for falls (which can have instantaneous, short-term velocities of hundreds of miles per hour), the velocity of landslides can vary from fractions of an inch per year to feet per second, depending on the landslide movement type, the properties of the soil and rock slope, the landslide water content, the slope angle, and the triggering event. Extremely slow movement (fractions of an inch per year) may still be referred to as slides, topples and flows despite their low rate of progression. Velocities associated with common landslide types are tabulated below ([Table A.2](#)).

Table A.2—Landslide Velocities [References 15 and 22]

Movement Velocity Class	Typical Velocity	Description	Common Landslide Types
7	>5 m/sec [>16.4 ft/sec]	Extremely Rapid	Falls, Topples, Debris Flows
6	3 m/min to 5 m/sec [9.8 ft/min to 16.4 ft/sec]	Very Rapid	Falls, Debris Flows
5	1.8 m/hr to 3 m/min [5.9 ft/hr to 9.8 ft/min]	Rapid	Falls, Debris Flows, Earth Flows, Slides, Spreads
4	13 m/month to 1.8 m/hr [42.7ft/month to 5.9 ft/hr]	Moderate	Slides, Earth Flows, Spreads
3	1.6 m/yr to 13 m/month [5.2 ft/yr to 42.7ft/month]	Slow	
2b ^a	160 mm/yr to 1.6 m/yr [0.5 ft/yr to 5.2 ft/yr]	Very Slow B	
2a ^a	16 mm/yr to 160 mm/yr [0.6 in/y to 0.5 ft/yr]	Very Slow A	
1	<16 mm/yr [<0.6 in/y]	Extremely Slow	Topples, Slides, Flows
^a Movement class Very Slow Velocity subdivided based on contribution of Porter ^[87] .			

A.6 Landslide Causes and Triggers

The common causes or triggers of landslides can be geological, morphological, physical, or human-caused. Many times, there is not a single cause or trigger for a landslide, but rather there are several triggering mechanisms. Experience along numerous pipeline systems in North America indicates that there is a common subset of triggering mechanisms that have caused landslides that have affected pipelines. These common triggering mechanisms are shown in bold italics in [Table A.3](#).

Table A.3—Landslide Causes and Triggers (modified from Cruden and Varnes [Reference 15] and USGS [Reference 21])

Cause or Trigger	Examples
Geological	Weak or sensitive rock or soil Weathered rock or soil Sheared, broken, jointed, or fissured rock or soil Adversely oriented rock structure Contrast in groundwater permeability Contrast in soil stiffness
Morphological	Tectonic or volcanic uplift Glacial rebound Fluvial (stream) erosion of slope toe Wave or glacial erosion of slope toe Erosion of lateral margins Subsurface erosion (piping, dissolution) Deposition loading on slope or crest Vegetation removal (fire, drought)
Environmental	Intense rainfall Rapid snowmelt Prolonged, exceptional precipitation Elevated groundwater Rapid drawdown (floods, tides) Earthquake shaking Volcanic eruption Thawing Freeze-thaw weathering Shrink-swell weathering
Anthropogenic	Excavation of slope or slope toe Loading (i.e. artificial fill) of slope or crest Reservoir drawdown Deforestation (clear-cutting) Irrigation Mining Artificial vibration Water leakage from utilities

A.7 Landslide-Pipeline Interaction

The potential risk to a pipeline from the effects of a landslide can be influenced by many factors, including the following:

- Characteristics of the pipe include pipe diameter, wall thickness, grade, manufacturing method of the steel, seam welding practice, and anticorrosion coating.
- Pipeline construction methods and girth welding and inspection practice.
- The dimensions and geometry of the trench and the trench backfill material properties.
- The presence of interacting anomalies.
- Landslide type, dimensions, material properties, moisture content, total displacement, and velocity of movement.
- Landslide depth relative to pipeline depth of cover.
- Pipeline location relative to the landslide.

— Pipeline orientation relative to the direction of landslide movement (axial, transverse, oblique).

Three pipeline-landslide interaction scenarios are illustrated in [Figure A.2](#). The landslide movement may be parallel (axial) to the orientation of the pipeline, oblique to the pipeline, or perpendicular (transverse). In the three scenarios depicted in [Figure A.2](#), the pipeline is engaged by the landslide.

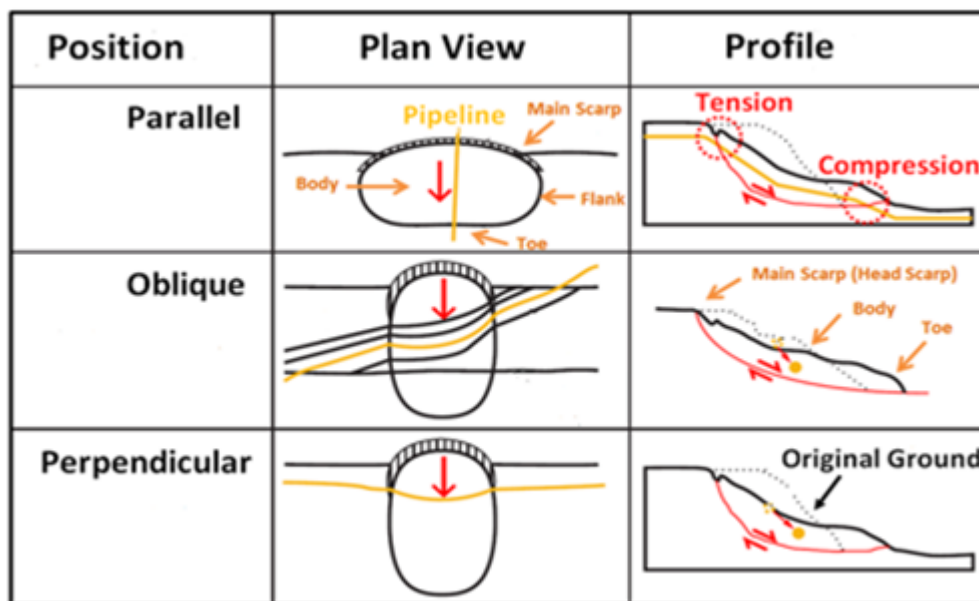


Figure A.2—Common Landslide-pipeline Interaction Scenarios [Reference 19]

In the parallel movement scenario, discrete sliding or slow flow puts tensile stresses on the pipeline at or near the top of the slope, while compressive stresses are induced at the toe of the landslide, and in this case, the base of the slope. Variations in the rate or direction of movement within the landslide mass could result in variable tensile and compressive stress on the pipeline within the landslide. The pipeline coating may also be damaged by movement of the landslide mass. It is noted that the pipeline can develop tensile and compressive stresses due to the landslide event in areas outside the landslide adjacent to the slip plane.

In the oblique movement scenario, landslide-induced loading on the pipeline would generally depend on the skew angle of the oblique movement relative to the pipeline. In addition to pipeline tensile and compressive stresses near the head and toe of the landslide, the pipeline can also experience lateral shear stresses where it traverses the lateral limits of the landslide and tensile and compressive stresses within the internal landslide mass. It is noted that the pipeline can develop tensile and compressive stresses due to the landslide event in areas outside the landslide adjacent to the slip plane.

In the perpendicular (transverse) scenario, discrete landsliding or slow flow movement induces shear at the slide flanks and results in complex shear, tensile and compressive stresses in the body of the landslide as the landslide mass extends downslope.

Annex B (informative)

Geologic and Geotechnical Assessment of Landslides

B.1 Introduction

As discussed in detail in [Section 5](#), the assessment of landslide hazards is typically conducted using a sequential three-level framework, progressing from an initial, more-regional screening assessment of landslides (Level 1) to a more focused assessment of landslide hazard areas and hazard sites (Level 2) and finally to a highly detailed, site-specific assessment of a particular landslide hazard (Level 3). The assessment level framework combines the geomorphic/geotechnical evaluation of landslide hazards with a fitness-for-service (FFS) assessment of pipeline integrity. Each of the three assessment levels is progressed through as needed to make decisions regarding management of landslide hazards that may affect a pipeline. The level of detail of landslide hazard characterization increases with each successive level of assessment. It is possible that data to support an assessment is not available, and this issue may become more acute for older pipeline systems. Typically, but not necessarily in all cases, the miles of pipeline or the number of landslide hazards being assessed decreases with each increasing level of assessment. This concept is illustrated in [Figure B.1](#).

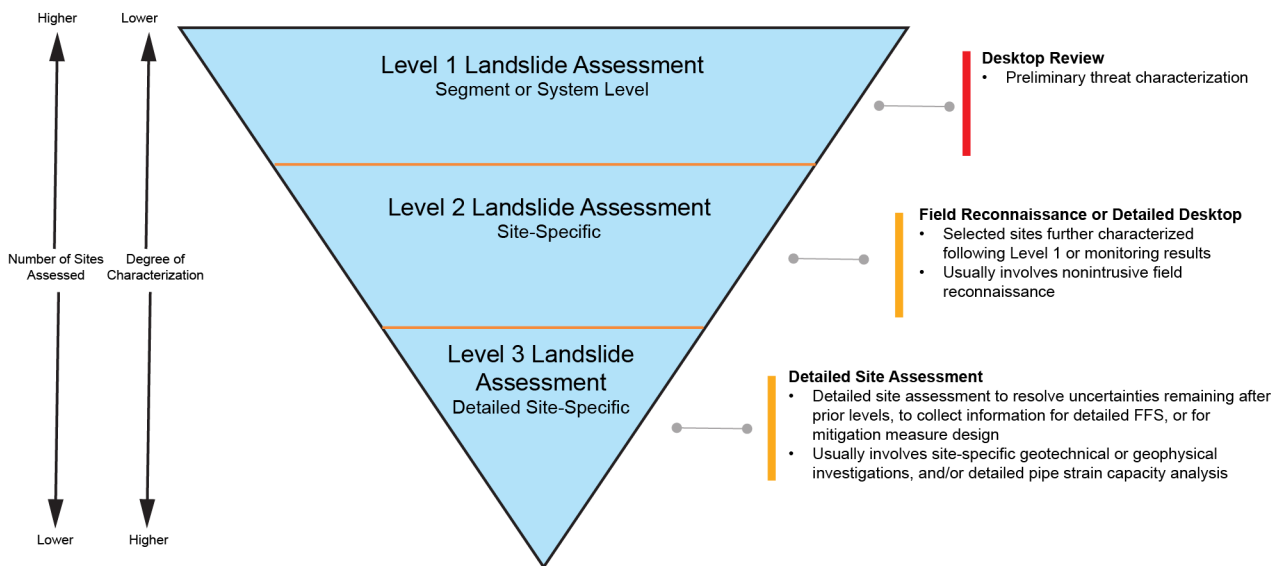


Figure B.1—The Three-level Framework for Landslide Assessment

The three-level framework has two interrelated and mutually supporting components: 1) a landslide hazards-focused assessment and 2) a pipeline integrity-focused assessment. The outcome of one component can help to make decisions about the need for and the refinement of the other component. The integration and order of landslide hazards- and integrity-focused assessments can be selected based on the circumstances of landslides and pipeline characteristics. It is not necessary to go through the entire processes for either type of assessment.

There are differences in the targeted outcomes and processes used when executing the two components. The primary objective of the landslide hazards-focused assessment is understanding the physical characteristics of the landslides and their impacts on a pipeline. The primary objective of the pipeline integrity-focused assessment is the safety margin expressed as a difference between capacity and demand. The process of establishing the safety margin is the FFS assessment. As the assessment level increases, the uncertainty related to landslide hazards generally decreases.

The precision of landslide hazards-focused assessments and pipeline integrity-focused assessments depends on the availability and quality of input data. As more data pertaining to geohazards and pipeline characteristics become available, the precision and certainty about the outcome of each type of assessment increases, respectively.

Level 1, 2, and 3 Assessments can be carried out on a pipeline system to develop a complete inventory of landslide hazards and assess landslide threats across the entire system. They can also be carried out at individual sites, whereby a new site of concern may be identified through a separate process (e.g. pipeline aerial patrol, third-party discovery), and then the site would proceed through the levels, as needed, in a focused manner (e.g. Level 1 desktop review of the site followed by a Level 2 site visit and possible Level 3 subsurface investigations, if needed).

In this annex, we describe common or typical geologic and geotechnical investigative processes, methods, techniques, and tools that are used to implement the geohazard assessment of landslides in each of the three assessment levels. The role, types, and data needs for FFS assessment in the three-level geohazard assessment is described in [Annex C](#).

The common geologic and geotechnical investigative techniques used in the three-level assessment approach reflect current landslide assessment technologies that have been found to be effective in identifying, characterizing, and evaluating landslide hazards for use in a Pipeline Geohazard Management Program (PGMP). As new geologic and geotechnical assessment technologies are developed and proven effective, they can be incorporated into pipeline landslide hazard assessments.

The information presented in this annex has largely been adopted from McKenzie-Johnson et al. ^[12, 86] with supporting information from Wang et al. ^[14]. Collective geologic and geotechnical engineering experience by the Joint Industry Project (JIP) team in landslide assessment, mitigation, and monitoring for numerous operators across North America also played a role in developing the information in this annex.

B.2 Landslide Assessment Investigative Processes, Methods, Techniques, and Tools

Operators have an extensive and comprehensive toolkit of landslide assessment methods and techniques that are appropriate to a sequential level assessment of a pipeline system or an as-needed assessment of a particular landslide. Typically, more than one technology or method may be used, and the methods may vary by region depending on many factors, such as the location, length, and configuration of the pipelines; the anticipated or known density of landslides in each region; and ongoing inspection and maintenance procedures. The use of multiple technologies provides context for the data collected and reduces the potential for landslide hazards to be overlooked. In turn, this allows for more informed decision making. Descriptions of common landslide assessment processes, methods, and technologies applied during the sequential level approach are summarized in [Table B.1](#).

Of the many landslide assessment processes, methods, and tools listed in [Table B.1](#), the implementation of a geographic information system (GIS) and the use of light detection and ranging (LiDAR) data are critical in a PGMP. A GIS provides the basic working tool to identify, map, and document landslide hazards and allows for the spatial integration of data from other sources and assessment techniques, including FFS, in-line inspection [ILI] inertial measurement unit [IMU] bending strain, mapped geology, LiDAR, aerial imagery, and mitigation and monitoring efforts at specific landslides. LiDAR should be a cornerstone technology for a Level 1 Assessment and in supporting Level 2 and 3 Assessments. The initial identification of landslides is the most consequential step in a PGMP because it guides all further actions within the program, and LiDAR is the most important tool to use for this purpose. With widespread commercial and public availability of high-resolution LiDAR data, the ability to identify landslide hazards is continually improving. If this step is skipped or if inadequate LiDAR data (e.g. outdated, low resolution, narrow focus) are used, key hazard locations might not be identified, resulting in uncharacterized or unknown threats.

Table B.1—Processes, Methods, Techniques, and Tools for Geologic and Geotechnical Assessment of Landslide Hazards

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where It Is Used
Geographic information system (GIS)	A GIS is a computer-based tool used to store, visualize, analyze, and interpret geographic, topographic, geologic, and geotechnical data. Geographic data (also called spatial or geospatial data) provide the geographic location of geomorphic, geologic, and geotechnical features relevant to landslide hazards. Geographic data includes anything that can be associated with a location on the globe (e.g. landslides) or, more simply, anything that can be mapped. A developed GIS landslide database is the core element and data source for implementing the PGMP.	Used in all three assessment levels but is established in Level 1 with the development of a landslide inventory for continued use in the following levels of assessment and in implementing the PGMP.
Detailed topographic maps and digital elevation model (DEM) data	Detailed topographic maps (1:20,000- to 1:25,000-scale, or larger) show large-scale geomorphic features and cultural features, such as disrupted terrain and closed depressions (e.g. sag ponds), that might relate to landslide hazards. DEM data (e.g. 10-m or larger) derived from cartographic topography can be manipulated to create shaded relief maps (hillshades) to accentuate geomorphic features and help identify landslide hazards. The identification of landslides from geomorphic features is based on looking for disturbed terrain in otherwise uniform topography, and such disturbed ground can be seen in disturbed, out-of-place contours on topographic maps and DEM hillshades.	Commonly used in Level 1 Assessments and for site information for Level 2 Assessments.
Regional and large-scale geologic maps and geology reports	Geologic maps may delineate landslides as distinct geologic units. Geologic maps and reports may tie specific geologic/stratigraphic units and structural conditions to landsliding. The geologic map data can be in the form of print copies, PDF files, or GIS databases. Geologic maps provide needed geologic background and context for understanding the nature and genesis of landslides for regions and site areas.	Used in Level 1 Assessments for overall regional and local geologic context and in Level 2 Assessments for site-specific geologic conditions.

Table B.1—Processes, Methods, Techniques, and Tools for Geologic and Geotechnical Assessment of Landslide Hazards (Continued)

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where It Is Used
Airborne light detection and ranging (LiDAR) data review	LiDAR is a remote sensing method that uses pulsed laser light from an aircraft to measure ranges (variable distances) to the Earth. LiDAR data can be processed to generate a bare-Earth DEM, which represents the elevation of the ground surface, free of vegetation, buildings, and other non-ground objects. The bare-Earth DEM can then be displayed in different forms (e.g. hillshade, slope derivatives, contours) intended to highlight different geomorphic features and disturbed terrain on the ground surface (e.g. landslides). In this way, LiDAR DEMs are used to identify and map landslides. Comparison of repeated LiDAR data for the same area can be used to examine changes related to landslide movement over time; this is known as LiDAR differencing. Examination and evaluation of LiDAR data and mapping of landslides are typically done in a GIS format so that the mapped landslide footprints are documented in a digital database for use in the PGMP.	Common to Level 1 and Level 2 Assessments and provide support in Level 3 Assessment. Can also be used for design of mitigation and monitoring.
Ground-based LiDAR (terrestrial laser scanning)	Ground-based LiDAR technology with high precision (e.g. Three millimeters) applies to monitoring landslides and detecting changes to landslide surfaces due to movement ^[23] . Ground-based LiDAR point-cloud data in high density can be obtained in a short time. To obtain a consistent landslide surface model, it is necessary to set up multiple scans with the ground-based LiDAR. After data preprocessing, a 3-D landslide surface model can be directly generated, and follow-up LiDAR scans can be integrated to produce LiDAR differencing, which highlights areas within the landslide that have moved and by how much.	Used in Level 3 Assessments. Can also be used for design of mitigation and monitoring.
Stereoscopic (3-D) aerial imagery	Federal and state/provincial agencies often have wide coverage of large-scale stereoscopic black-and-white and color aerial photographs that provide a 3-D view of the Earth's surface and are used in identifying geomorphic features indicative of landslide movement. Limited by thick, dense vegetation cover and typically used in arid and semi-arid regions with little vegetation coverage.	Used in Level 1 Assessments.
Two-dimensional (2-D) aerial imagery (including Google Earth™ historical imagery)	Historical or current low- and high-quality, aerial photography may indicate features and changes to the terrain that are the result of landslide movement or human development that might trigger landslides.	Commonly used in Level 1 Assessments.

Table B.1—Processes, Methods, Techniques, and Tools for Geologic and Geotechnical Assessment of Landslide Hazards (Continued)

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where It Is Used
Interferometric synthetic aperture radar (InSAR) (satellite-based)	InSAR data are typically gathered from satellite platforms. Scanning of the ground using InSAR produces data that allows for detection and monitoring of changes in the ground surface over large areas without the need to physically access an area or site. Technology has been used to detect and identify areas and individual features, as well as the magnitude of slope movement (landslides) when these locations have favorable orientations relative to the satellite's path. The technology is currently used primarily by government agencies and research institutions to prove its application. Different radar bands are available for InSAR, with C, L, and X bands being most prevalent. Each band has different abilities to detect land movement based on the terrain and vegetation. Satellites also have a range of image resolutions, and the selected satellite should have a resolution that can detect the size of landslide expected along the pipeline route. Satellite detection/accuracy can be enhanced using targets. — X Band—High resolution SAR (urban monitoring, little penetration into vegetation cover; fast coherence decay in vegetated areas) — C Band—SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence) — L Band—Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)	Used in Level 1 Assessments and for long-term monitoring.
InSAR (ground-based)	Unlike many other slope monitoring technologies, ground-based InSAR (GBInSAR) provides almost total coverage of an entire slope surface in near-real-time. The ability to see data nearly instantaneously is useful for many reasons. For example, steep, unstable slopes could present dangerous and difficult access for the placement of in situ monitoring devices. More importantly, GBInSAR is highly accurate while monitoring a slope from a safe distance. One of GBInSAR's unique abilities is its high-speed presentation of displacement rates allowing for identification of individual surface areas moving at different velocities on an unstable slope surface. At some locations, the radar has been able to identify areas of displacement long before disruptive surface deformation occurs, allowing for the placement of in situ technology in preferred locations.^[24]	May be used for monitoring of specific, active landslide sites or for Level 3 Assessments.