Recommended Practice for Pipeline Integrity Management of Landslide Hazards

Prepared for

INGAA, The INGAA Foundation, and a Group of Sponsors

Prepared by

Geosyntec Consultants, Inc.
Center for Reliable Energy Systems, LLC (CRES)

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This guideline was developed to provide technical background and a body of knowledge for pipeline operators, service providers, and interested public stakeholders on landslide hazards for onshore transmission pipelines conveying natural gas, hazardous liquids, and carbon dioxide. It was shared with the workgroup that developed API RP 1187, *Pipeline Integrity Management of Landslide Hazards* published on August 27, 2024 under the auspices of the American Petroleum Institute.

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TABLE OF CONTENTS

ANNEXES

1 INTRODUCTION

This document provides recommendations for the management of landslide hazards for operating onshore welded steel pipelines.

1.1 Scope and Limitations

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 are excluded. The recommendations provided herein are based on the physical, regulatory, and social environment of the United States. The recommendations are for operating pipelines (i.e., ones that have been constructed and are in service) and not intended for terminals, aboveground stations and appurtenances, or delivery facilities.

The intention of this document is to provide pipeline operators and the contractors and consultants supporting pipeline operators with recommendations to manage landslide hazards. If implemented appropriately, these practices will reduce the potential for landslides to damage pipelines and cause unintentional releases.

1.2 Document Structure

The document is structured as follows:

- Section 1 (this section) introduces the scope, limitations, and structure of the document.
- Section 2 provides normative references used in completing this document.
- Section 3 provides the terms, definitions, acronyms, and abbreviations used in the 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 management of change.
- Section 10 provides a list of references cited in this main document.
- 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 a pipeline operator.
- Annex F provides considerations and guidance for implementing a landslide CDM system and examples of previously implemented CDM systems.
- 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.
- Annex J provides the complete bibliography associated with creating this document. This bibliography is a sequential bibliography that starts with the references used in the main document and continues through the annexes, in order.

2 NORMATIVE REFERENCES

The recommendations contained within this document build upon a significant body of work, including published American Petroleum Institute (API) recommended practices, American Society of Mechanical Engineers (ASME) standards, International Organization of Standardization (ISO) standards, and prior guidance documents published by the Interstate Natural Gas Association of America (INGAA) Foundation, and the Pipeline Research Council International (PRCI). Key references used to complete this document are listed below.

2.1 Codes and Standards

- American Lifelines Alliance (ALA), *Guidelines for the Design of Buried Steel Pipe*[1]
- ASME B31.4, *Liquid and Slurry Piping Transportation Systems*[2]
- ASME B31.8S, *Managing System Integrity of Gas Pipelines*[3]
- ISO 20074, Petroleum and natural gas industry—Pipeline transportation systems—Geological hazard risk management for onshore pipeline[4]

2.2 Advisory Bulletins

- Pipeline and Hazardous Materials Safety Administration (PHMSA) Advisory Bulletin ADB-2019-02, *Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards*[5]

- PHMSA Advisory Bulletin ADB-2022-01, Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards[6]

2.3 Recommended Practices

- API Recommended Practice 1160, *Managing System Integrity for Hazardous Liquid Pipelines*[7]
- API Recommended Practice 1173, *Pipeline Safety Management Systems*[8]

2.4 Industry Reports

- ASME. *Pipeline Integrity Management under Geohazard Conditions*. Edited by M. Salama et al. ISBN: 978-07918-6199-8, ASME, New York, New York. 2020.[9]
- C-Core et al. *Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines Through Areas Prone to Landslide and Subsidence Hazards.* 2009.[10]
- Golder Associates Inc. *Mitigation of Land Movement in Steep and Rugged Terrain for Pipeline Projects: Lessons Learned from Constructing Pipelines in West Virginia*. 2016.[11]
- Mckenzie-Johnson et al. *Guidelines for Management of Landslide Hazards for Pipelines*. 2020.[12]
- Rizkalla and Read, eds. *Pipeline Geohazards: Planning, Design, Construction, and Operations*. 2019.[13]
- Wang, Y.-Y., et al. *Management of Ground Movement Hazards for Pipelines*, CRES Project No. CRES-2012-M03-01, Final Joint Industry Project (JIP) Report, February 28, 2017.[14]

3 TERMS, DEFINITIONS, ACRONYMS, ABBREVIATIONS

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

Bending strain, in the context of inertial measurement unit (IMU) reported strain, is the longitudinal strain in the pipe caused by bending.

3.1.3 Capacity

Maximum amount of loading that a pipeline can withstand prior to a negative consequence, such as a leak, rupture, or change in the physical characteristics of the pipeline (e.g., deformation of the pipe cross-section) that may negatively affect its operation. May be expressed as load, stress, or strain.

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

Strain capacity in compression.

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 deformation is not affected by the load-carrying capacity of the component/structure being subjected to the loading. Examples of displacement loading are bending a pipe on a mandrel and reeling-on a pipe string in spool-based installation.

3.1.8 Fitness-for-Service Assessment

Quantitative engineering evaluation performed to assess the suitability of a structure for its intended use. FFS assessment is often performed against possible limit states.

3.1.9 Geohazard

Geotechnical or hydrotechnical hazards that occur 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 landslides and landslide features, such as through review of remote sensing data (e.g., light detection and ranging [LiDAR], aerial imagery) or direct observations from the air (e.g., helicopter) or on the ground.

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, and volcanic.

3.1.13 Geotechnical Investigation

Evaluation of soil and rock conditions using 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. This hazard includes scouring, channel migration, avulsion, and other threats related to the movement of water.

3.1.15 Landslide

Naturally occurring or human-caused downslope movement of soil or rock material. Typically occurs either as translational or rotational slides. The term “landslide” encompasses a wide variety of processes, including falling, toppling, sliding, spreading, or flowing.

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 Landslide Assessment

An initial assessment intended to identify potential landslides and preliminarily evaluate their threat to a pipeline. Usually conducted by desktop review.

3.1.18 Level 2 Landslide Assessment

A site-specific investigation focused on specific, identified landslides and potential landslides. The investigation is conducted using readily available or readily collected site-specific information (such as visual observations from surface field examinations and in-line inspection [ILI] IMU data) and does not require intrusive investigations and analysis (such as subsurface drilling, trenching, pipeline exposure, and testing).

3.1.19 Level 3 Landslide Assessment

A detailed site-specific assessment. The specific methods used for the assessment should be fit-for-purpose (i.e., they should meet the intentions and needs for conducting the assessment). The methods can vary based on landslide type, location, site-specific constraints, and degree of certainty needed for pipeline integrity assessment. Methods may include detailed assessment of the subsurface conditions through measures such as geophysical or geotechnical investigations and FFS assessment.

3.1.20 Load-Controlled Loading

Loading in which the magnitude of the loading is not affected by the amount of deformation or displacement. Examples of load-controlled loading are dead-weight loading, soil load on a span, and internal pressure.

3.1.21 Mitigation

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

3.1.22 Monitoring

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

3.1.23 Pipeline Geohazard Management Program

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.

3.1.24 Pipeline System

Single or multiple pipeline segments that have defined starting and stopping points.

3.1.25 Preventative and Mitigative Measures

Activities designed to reduce the likelihood of a pipeline failure (preventative) and/or minimize or eliminate the consequences of a pipeline failure (mitigative).

3.1.26 Segment (line section)

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

3.1.27 Strain Capacity

Strain level beyond which there would be a negative consequence, such as a leak, rupture, or change in the physical characteristics of the pipeline (e.g., deformation of the pipe cross-section) that may negatively affect its operation.

3.1.28 Strain Demand

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

3.1.29 Strain Demand Limit

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

3.1.30 Subject Matter Expert

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

3.1.31 Tensile Strain Capacity

Strain capacity in tension.

3.1.32 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
CRES	Center for Reliable Energy Systems, LLC
CDM	classification and decision-making
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
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
SI	slope inclinometer
SME	subject matter expert
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 (i.e., routing, design, construction, operation, decommissioning), 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 exceeds the capacity of the pipeline, resulting in a pipeline failure.

4.1 Components and Processes

The landslide management program should comprise the following core components and processes.

- Identification and assessment of landslide threat to pipeline integrity (Section 5)
- Data management, including storage, analysis, and retrieval of data (Section 6)
- Implementation of measures to manage 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)

- Management of change following program implementation (Section 9)

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

4.2 Administration of the Program

The landslide management program should be a part of the Pipeline Geohazard Management Program (PGMP). The 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, either internal or external to an operator.

4.3 Landslide Management Program Documentation

The landslide management program, including the core components (Section 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 constant (i.e., creeping), 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 effectively 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 (e.g., precipitation, undermining by a stream, earthquakes) and by human activities (e.g., excavation and filling for infrastructure construction, forest clear-cutting, irrigation for agriculture).
- Landslide activity leaves characteristic indications on the ground surface that can be identified through geomorphic assessment (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. Thus, the specific location of past or ongoing landslide movement can generally be proactively identified through direct observation.

- A pipeline must be engaged by a landslide to be affected by the landslide. 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 resiliency of a pipeline (broadly termed as "capacity").
- The resilience of pipelines can vary greatly depending on the characteristics of materials and construction methods, including the methods used for welding and inspection.

5 LANDSLIDE THREAT AND INTEGRITY ASSESSMENT

The landslide threat to pipeline integrity should be assessed using a three-level framework,[1] which is described in the following sections. Operators can add additional levels to this framework if appropriate for their particular 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 landslide threat and pipeline integrity generally increases, and the number of landslide threats being assessed decreases.
- Each level should be progressed through as needed to make an informed decision on an appropriate response. At a minimum, desktop-level assessment (Level 1 Assessment) should be carried out on all pipeline systems managed by the pipeline operator to develop an inventory of landslide threats across the entire system. In many instances, landslide threats can be assessed and managed without needing to progress through all levels.
- The three-level framework should combine an assessment of the hazard (i.e., a landslide or landslide-prone area) with an assessment of the pipeline integrity to produce an integrated assessment of landslide threat to pipeline integrity. Hazard assessment is discussed in more detail in Annex B, while pipeline integrity assessment (i.e., FFS assessment) is discussed in Annex C. Annex D provides examples of landslide assessments using this three-level framework.
- Some form of CDM system 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:

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

- Identify possible landslide(s) along a pipeline. When conducted for a pipeline segment or system, this assessment results in developing an inventory of the potential landslide threats along the pipeline.
- Initially evaluate the threat each landslide poses to the adjacent pipeline(s).
- Initially evaluate the availability of data/information necessary to assess the resilience of a pipeline (such as strain capacity).

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 owner, these data can be used instead of conducting a new assessment).
- A new pipeline system is put into service following construction (if landslide data were compiled during the route selection, design, and construction, these data should be used to complete the assessment).
- Upon initiation of a PGMP. The first Level 1 Assessment conducted for a pipeline segment or system is considered the baseline.

If completing a baseline Level 1 Assessment for an entire pipeline system during a single effort is not practical (e.g., due to limited resources or the need to acquire data such as LiDAR), a baseline 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 baseline 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 (e.g., high consequence areas, criticality, strain tolerance level). The timeline for completing the baseline Level 1 Assessment should be documented and justified in the landslide management program. The results of the baseline Level 1 Assessment should be used to establish whether a Level 2 Assessment is needed.

A Level 1 Assessment should 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) should be reviewed to identify geomorphic evidence of recent or historical landslide activity. The bare-Earth DEM should be generated from LiDAR or similar technology that can generate high-resolution topographic data in vegetated areas. 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 (as described above), but that review can be replaced 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 within at least 100 feet of a pipeline centerline in a geographic information system

(GIS). The information recorded should meet or exceed the minimum requirements provided in Section 6. Larger assessment corridor widths may be needed where there is a reasonable potential of long run-out landslides that could affect a pipeline in a single event from more than 100 feet away.

A Level 1 Assessment relies on a combination of original desktop geomorphic assessment and review of preexisting information. As such, 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 results relevant to landslide assessment. As of the date of this document, this is typically IMU bending strain, which can be incorporated into the Level 1 Assessment process to help identify locations where the pipeline might have previously been strained by a landslide and provide an initial estimate of strain demand.
- Pipeline resiliency, such as strain capacity. Combined with 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.
- The locations of previous landslides and repairs performed at those locations, if known.
- Other remote sensing data beyond the aerial photographs and LiDAR listed above, such as satellite-based interferometric synthetic aperture radar (InSAR).

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 (such as visual observations from surface field examinations and ILI IMU data) 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 (e.g., repeat LiDAR, InSAR, IMU) 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 whether landslides and potential landslides identified during the Level 1 Assessment are indeed landslides (if there was initial uncertainty) and whether the landslides impact the pipeline(s).
- 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.

[2] 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 a pipeline operator, and if available, will enhance the accuracy and completeness of the Level 1 Assessment. . This information, if available, will reduce the potential for not identifying a landslide and support decision-making, such as the timing and prioritization of additional assessment. It is understood that for many pipeline systems, some or all of this information might not be available at the time of a Level 1 Assessment.

- 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 geologic 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 in close proximity to 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 (i.e., does it cross the pipe and, if so, is it above or below).
- 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.
- An FFS assessment, including strain capacity and strain demand from one or more sources supported by available data as described in Annex C.

In many instances, a Level 2 Assessment is 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 should be performed. The considerations for when a Level 3 Assessment is needed are discussed in more detail under Decision-Making in Section 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 (i.e., they should meet the intentions and needs for conducting the assessment). The methods can vary based on landslide type, location, site-specific constraints, and degree of certainty needed for pipeline integrity assessment. Geotechnical and FFS methods used for Level 3 Assessment are discussed in more detail in Annexes B and C.

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

- Resolve or reduce uncertainties 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 (e.g., geotechnical boreholes, test pits, dynamic cone penetration tests, installation of SIs)
- An FFS assessment that may include the current state of the pipeline and/or expected future increase in strain demand and possible degradation of strain capacity, as indicated by degree of uncertainty, safety margin, and readily available data

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. Section 7.1 contains further discussion on decision-making.

5.4 Reassessment

Natural and human-influenced conditions can and will change along a pipeline right-of-way (ROW), as will the availability of new and updated landslide hazard data and information. The resilience 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 interval should be selected by the operator to manage the threat to the segment or site, but intervals of 10 years or less are recommended. The frequency and justification for reassessment should be documented in the PMGP 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 sort, store, and integrate data as they are generated and to retrieve data as they are needed.

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, landslide characteristics (e.g., age and movement rate), and pipe characteristics (e.g., age, diameter, grade).

Spatial data should be managed in a GIS platform (i.e., a map-based platform such as ESRI ArcGIS, QGIS, or Google Earth) where dimensional aspects of the data can be viewed and accessed. A GIS platform should be used to spatially display the following available data (at a minimum) in map view:

- Pipeline centerline locations (i.e., displayed as lines)
- The footprint or 2-D extent of each landslide (i.e., displayed as a polygon boundary)

- Locations of monitoring instruments, such as strain gauges, monitoring points, and SIs (i.e., displayed as points)
- Strain features, such as IMU bending strain features (i.e., distinct pipeline segments displayed as line segments)
- Implemented threat management measure locations (e.g., drains, retaining walls)
- LiDAR data or aerial imagery used for landslide identification

Additional detailed site information should be maintained and directly available within the GIS platform (e.g., through attribute tables) or linked to externally stored files (e.g., spreadsheets) through a unique landslide identifier. When the following data are available, they should be accessible for each landslide:

- A unique identifier for each landslide
- The location of the landslide in latitude and longitude (e.g., the landslide centroid)
- Landslide characteristics that are relevant to the CDM (e.g., depth of the landslide surface of rupture, amount of displacement, age, 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 should be linked with spatial data either in the form of direct file attachments 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 (e.g., tabular, charts, reports), the need for updates (e.g., one-time data collection versus ongoing collection, manual collection versus automated data collection), and accessibility requirements (e.g., single versus many users/viewers, desktop versus online platforms).

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

- Monitoring data results (e.g., time-series data, such as from strain gauges, SIs, geodetic survey points, piezometers)
- ROW characteristics (e.g., landowner, permit)
- Geotechnical information (e.g., borehole logs, geotechnical lab testing, slope stability analyses)
- Pipe survey data (e.g., depth of cover, site features, benchmark)
- Mitigation measure designs or as-builts
- Site photographs
- ILI data (e.g., IMU strain plots, movement plots)

- Reports (e.g., assessment reports, including characteristics of the hazards and FFS)

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 (e.g., age, diameter, wall thickness, grade, girth welding procedure[s] and inspection practice, strain capacity, strain demand limit)
- As-built details
- Pipeline operating conditions (e.g., maximum operating pressure [MOP], maximum allowable operating pressure [MAOP], normal operating pressure, operating temperature)

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 the landslide or pipeline conditions to allow intervention prior to an impact occurring to a pipeline or to reduce the consequences of a landslide impact (i.e., monitoring measures)
- 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 (i.e., mitigation measures)

When these measures are implemented systematically, they reduce the risk of landslide impacts and incidents. The selection and implementation of appropriate threat management measures, individually or in combination, should be performed using a landslide threat CDM system.

7.1 Classification and Decision-Making

A CDM system should be developed as part of the landslide management program. A CDM system 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 (e.g., level, type, and scope of additional assessment; development and implementation of threat management measure[s]; type, location, frequency, and implementation of monitoring; or no further action)
- To determine the timing or order of conducting actions (i.e., the prioritization)

While the form of a CDM system varies by operator, each CDM system 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 and possible landslides
- A means to classify the resilience of pipelines against the impact of landslides, such as strain capacity
- A set of requirements or guidelines for whether to perform additional actions and, if so, the type of action (e.g., additional assessment, monitoring measures, or mitigation measures) and the timing in which to conduct each action based on the classification (see Section 7.2)

Further discussion on CDM systems and consideration for their implementation are provided in Annex F.

7.2 Threat Management Measure Selection

The CDM system 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 strain demand imposed by the landslide.
- The resiliency of the pipeline to landslide movement. Where possible, this should include an estimate of the strain capacity or strain demand limit of the pipeline.
- Uncertainties remaining from completed assessments. Typically, the more in-depth the assessments, the lower the uncertainty.[3]

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 (i.e., implementation of mitigation measures)
- 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

[3] Operators 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.

- 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 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 (e.g., InSAR analysis). The landslide monitoring technologies selected and used should be fit-for-purpose (i.e., the monitoring performed should provide the type of data needed at the frequency needed to address the purpose for the monitoring).

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

- Considerations for selecting a monitoring method
- Installation requirements (for monitoring that requires instrument installation)
- Resolution, sensitivity, and accuracy of measurement
- Data collection methods
- 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 of an impact and to reduce the negative consequences of an impact. Mitigation measures should accomplish one or both of the following objectives:

- Reduce strain demand or reduce the potential for increase in strain demand: examples include avoiding the landslide (such as through a reroute or horizontal directional drilling [HDD]), stabilizing the landslide, excavating for stress relief, or reducing the rate or extent of movement by lowering the groundwater table.
- Enhance the strain capacity of a pipeline to reduce its vulnerability to the effects of a landslide: examples include reinforcing girth welds and applying 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/rock types, direction of movement and movement rates, size, depth, orientation, and relationship to the area being protected
- 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 subject matter experts (SMEs), construction contractors, land and environmental permitting groups, and adjacent landowners and residents
- Whether monitoring will be needed after implementation and, if so, the considerations to select appropriate monitoring
- 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 budgeting and 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 are recommended to follow the general structure of API RP 1160[4] Section 13 for evaluation of their landslide management program. As stated in API RP 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.

[4] API RP 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.

9 MANAGEMENT OF CHANGE

Per the recommended structure in API RP 1160, operators should develop a management of change process for their landslide management program.[7] This management of change process should (at a minimum) address the following:

- New construction
- Acquisition of a pipeline system
- Major operational changes
- Changes in pipeline status
- Significant 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 the following sections.

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 location
- Inventory of landslides (including preexisting landslides and those that occur during or after construction)
- Mitigation measures performed for landslides including as-builts and designs for those mitigation measures
- Locations and types of monitoring instrumentation installed for landslides
- Records of landslide monitoring results
- Mill test reports (MTRs)
- Girth welding procedures specifications (WPSs) and procedure qualification records (PQRs)
- Girth weld inspection records (including nondestructive testing [NDT] procedures and acceptance criteria)

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, a Level 1 Assessment per the recommendations of Section 5.1 should be performed and documented.

In addition, the following information should be captured and integrated into the landslide management program as part of new pipeline construction:

- Trench and backfill condition, including as-builts and survey results that contain soil and rock conditions, particularly for pipelines constructed in landslide-prone regions
- Baseline ILI data (including IMU)
- Baseline LiDAR data

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 Section 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 management of change 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 strain capacity or interaction with landslides. Impacts and associated mitigation measures shall be documented as part of the management of change 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, increasing the likelihood of landslide occurrence. Such changes can result in the need to increase monitoring frequency or implement additional monitoring measures.

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Annex A
Landslide Basics

Annex A: Landslide Basics

A Introduction

Pipeline systems cross a wide variety of topographic terrains and geologic conditions and might be exposed to multiple threats from landslides.

This annex addresses landslide types, terminology, classification, characteristics, potential triggers and causes, and the potential effects of pipeline–landslide interaction. These basics are to help provide pipeline owners, operators, and pipeline 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-1 Landslide Overview

Landslides are complex, natural, geologic phenomena. Landslides are complex because there are numerous types of landslides and combinations of landslides, varied and complex geomorphic and geologic environments in which landslides occur, numerous causes or triggers of landslides, and varied sizes and behaviors of landslides. The variability and complexity of landslides contribute to the difficulty in identifying them and understanding their types, natures, locations, extents, ages, and timing of movement.

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 forces (driving forces) acting on the slope exceeds the resistance (strength) of the materials underlying the slope (resisting forces). Driving forces can be increased by changes to slope geometry (e.g., erosion or grading of the slope toe) or by increased loading on the slope (e.g., placing fill on the slope or earthquake shaking). 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 porewater pressure in the slope.

Landslides range in thickness from shallow (at or near the ground surface [i.e., only a few feet thick]) to deep-seated (several tens to hundreds of feet thick). They can move rapidly or slowly (e.g., timing of movement ranging from seconds to centuries), 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 porewater conditions within the slope and along landslide rupture surfaces
- Slope geometry
- State of stress and stress history of the slope

A-2 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 the following block diagram (Figure A-1).

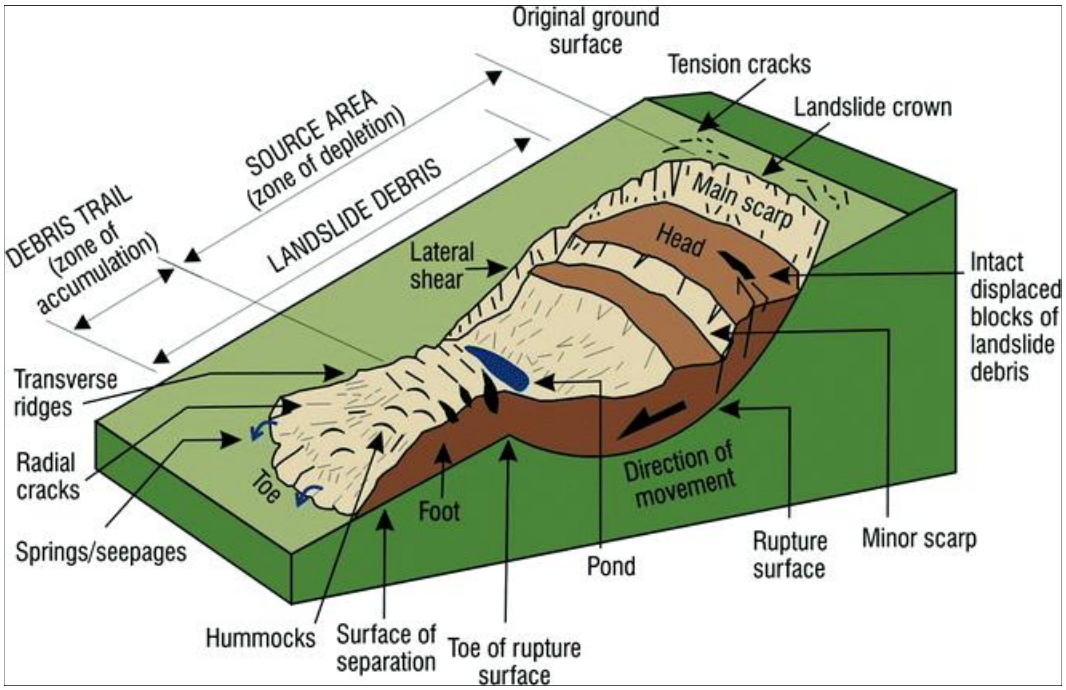

Figure A-1. Conceptual landslide diagram[20]

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-3 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). The 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, but it is recommended that the term “slump” 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

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		

Based on Cruden and Varnes[15] and USGS[21]

A-4 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) is often referred to as creep or soil creep. Typical velocities associated with common landslide types are tabulated below (Table A-2).

Table A-2. Typical landslide velocities

Movement Category	Typical Rate	Common Landslide Type(s)
Extremely Slow	< 1 foot per 5 years	Earth flow, soil creep
Very Slow	1 to 5 feet per year	Earth flow
Slow	5 feet per year to 5 feet per month	Earth flow
Moderate	5 feet per month to 5 feet per day	Lateral spread, translational slide, rotational slide
Rapid	5 feet per day to 1 foot per minute	Lateral spread, translational slide, rotational slide
Very Rapid	1 foot per minute to 10 feet per second	Rock topple, debris flow, rock fall
Extremely Rapid	> 10 feet per second	Rock fall, rock topple

Based on and modified from Varnes[22] and Cruden and Varnes[15]

A-5 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 fairly common subset of triggering mechanisms that have caused landslides that have affected pipelines. These common triggering mechanisms are shown in bold italics in the following table (Table A-3).

Table A-3. Landslide causes and triggers

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)***
Physical	• ***Intense rainfall*** • ***Rapid snowmelt*** • ***Prolonged, exceptional precipitation*** • ***Elevated groundwater*** • Rapid drawdown (floods, tides) • ***Earthquake shaking*** • Volcanic eruption • Thawing • Freeze-thaw weathering • Shrink-swell weathering
Human-Caused	• ***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***

Modified from Cruden and Varnes[15] and USGS[21]

A-6 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 including 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
- Dimensions and geometry of the trench and the trench backfill material properties (e.g., grain size, grain/particle shape, consistency and density, moisture content, and strength)
- Presence of interacting anomalies
- Landslide type, dimensions, material properties, moisture content, direction, total displacement, and velocity of movement
- Landslide depth relative to pipeline depth of cover
- Pipeline location relative to the landslide (i.e., whether the landslide crosses the pipeline and if not, distance from the landslide to the pipeline)
- Pipeline orientation relative to the direction of landslide movement (axial, transverse, oblique)

Three pipeline-landslide interaction scenarios are illustrated on 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 on Figure A-2, the pipeline is engaged by the landslide (i.e., the pipeline is within the moving landslide mass).

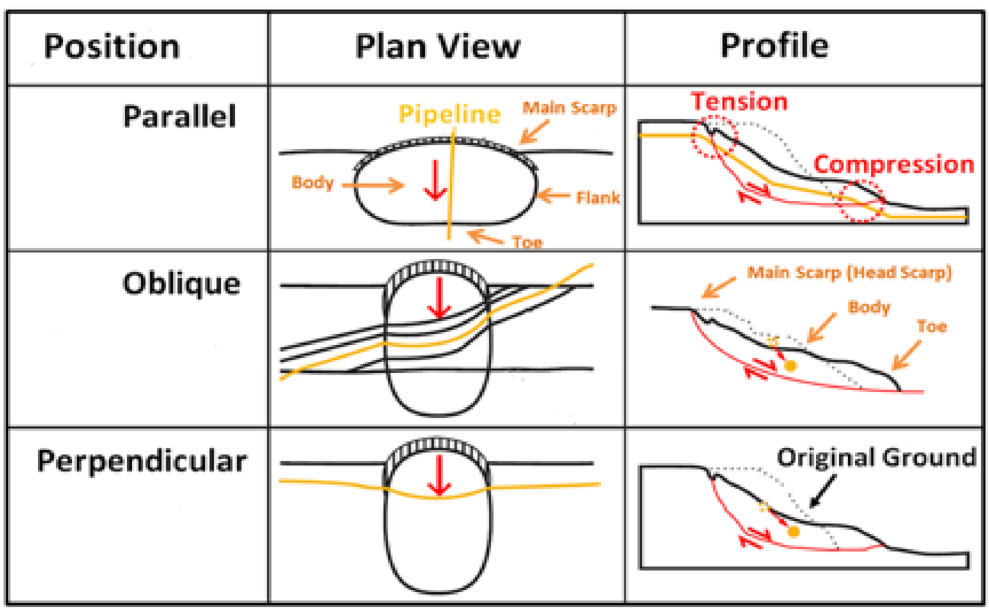

Figure A-2. Common landslide-pipeline interaction scenarios[19]

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.

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. The pipeline might experience lateral shear stresses where it traverses the lateral limits of the landslide and tensile and compressive stresses within the internal landslide mass.

In the perpendicular (transverse) scenario, discrete landsliding or slow flow movement typically 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

Geologic and Geotechnical Assessment of Landslides

Annex B: Geologic and Geotechnical Assessment of Landslides

B Introduction

As discussed in detail in Section 5 of this document, 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. 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.

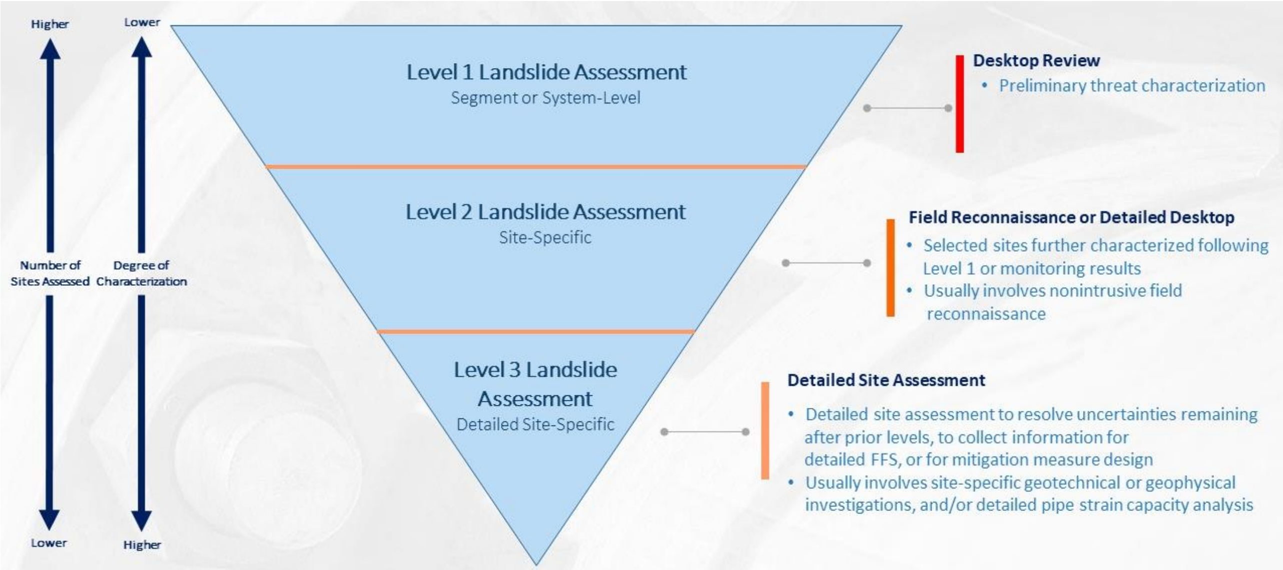

Figure B-1. The three-level framework for landslide assessment

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 as a whole 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 are 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] with supporting information from Wang et al.[14] In addition, collective geologic and geotechnical engineering experience by the Joint Industry Project (JIP) team in landslide assessment, mitigation, and monitoring for numerous pipeline operators across North America also played a role in developing the information in this annex.

B-1 Landslide Assessment Investigative Processes, Methods, Techniques, and Tools

Pipeline 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 a given 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 (FFS, in-line inspection [ILI] inertial measurement unit [IMU] bending strain, mapped geology, LiDAR, aerial imagery, mitigation and monitoring efforts at specific landslides, etc.). 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.

An example of the power of LiDAR data in identifying landslides in forested terrain is its use at the 2014 Oso Landslide in the state of Washington. In Figure B-2, the geomorphic nature and extent of the Oso Landslide (outlined in red) are clearly defined in the LiDAR shaded relief image. More importantly, the thickly forested valley walls are populated with many more landslides, which had not been identified prior to collecting these LiDAR data.

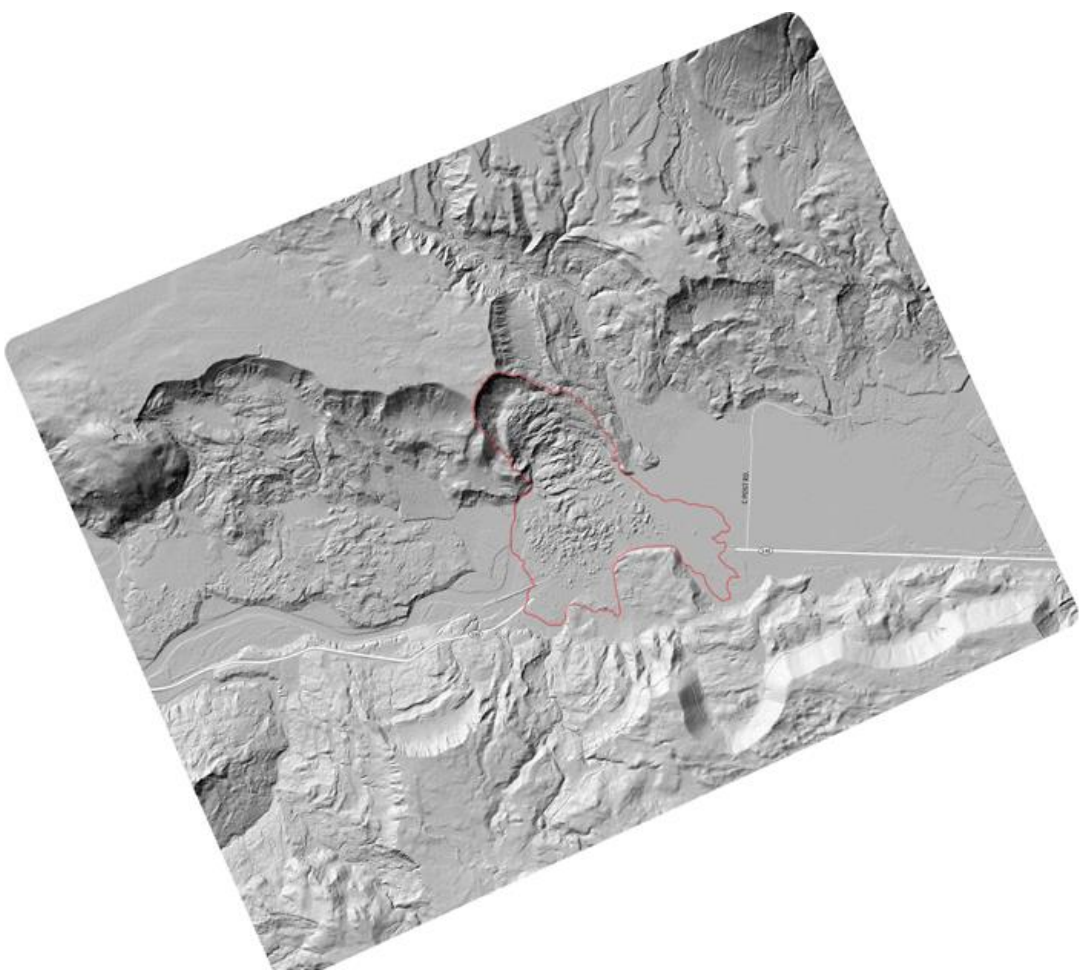

Figure B-2. 2014 Oso Landslide in the state of Washington

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 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-meter 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, .pdfs, 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.

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where 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., 3 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.
Interferometric synthetic aperture radar (InSAR) (satellite-based)	InSAR data are typically gathered from satellite platforms. Scanning of the ground using InSAR produces data that allow for detection and monitoring of	Used in Level 1 Assessments and for long-term monitoring.

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where Used
	changes in the ground surface over large areas without the need to physically access an area or site. The 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 must have a resolution that will detect the size of landslide expected along the pipeline route.	
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.
In-line inspection (ILI) inertial measurement unit (IMU) bending strain data, caliper tool, and to a lesser extent, magnetic flux leakage tool (MFL) dent/wrinkle indications	An IMU module is typically mounted on another smart ILI platform; thus, IMU monitoring can occur during any scheduled ILI assessment. When reviewing the IMU data, information collected on pipeline anomalies (e.g., buckles) should also be reviewed to either detect or monitor areas of pipeline deformation. Bending strain data can be used in Level 1 Assessments to identify locations that might be affected by landslide movement, and in later levels of assessment for monitoring along pipeline systems and segments when two or more IMU data sets are compared.	Used during Level 1, Level 2, and Level 3 Assessments.

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where Used
Aerial reconnaissance by a subject matter expert (SME)	Experienced, trained geologist and geotechnical professionals view the ground surface from an aerial platform—typically a helicopter, but also can be a fixed-wing aircraft. The reconnaissance is typically part of a Level 1 Assessment to develop a real-time knowledge of potential landslides along a right-of-way (ROW). The aerial reconnaissance may also be implemented following a significant event such as an intense storm (e.g., hurricane) or earthquake that might trigger landslides. Annual or periodic aerial reconnaissance by SMEs may be completed to verify conditions along the ROW or particular sections as part of long-term monitoring. In some cases, the SME may view video along the ROW collected by the pipeline operator.	Commonly done during a Level 1 Assessment, in response to significant natural events, or as a form of monitoring.
Aerial patrol by operator	Pipeline operator aerial observers, flying their regular patrols and trained to recognize basic geomorphic features of landslides, can detect and document new landslides that might occur along an ROW. With knowledge of the locations of existing landslides along the ROW (i.e., from a Level 1 Assessment), the aerial observers can also keep track of significant changes at known landslides.	An ongoing process within the PGMP used as a form of monitoring.
Ground reconnaissance and landslide mapping by SME	Detailed, nonintrusive, site-specific geomorphic and geologic mapping by trained and experienced geotechnical professionals. The purpose is to more completely identify the lateral limits of the landslide relative to the pipeline and to estimate the magnitude and rate of movement. This may include pipeline locating, including pipeline depth of cover, to evaluate whether the pipeline might have been engaged by landslide movement or whether the pipeline is deep and possibly below landslide movement.	SME ground reconnaissance and mapping are commonly conducted during a Level 2 Assessment. May also be done to support Level 3 Assessments and mitigation or monitoring planning and design.
Geologic cross sections	Geologic cross sections through the landslide based on landslide mapping can be used to describe the subsurface geometry of the landslide, including the estimated landslide thickness and depth of the rupture (failure) surface.	Commonly done in Level 2 and Level 3 Assessments.

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where Used
Precise global positioning system (GPS)/GIS mapping	Precise geologic/geotechnical mapping (sub-meter) of landslide features using smartphones, tablets, and similar devices that are GPS and GIS enabled. When applied to Level 2 ground reconnaissance and landslide hazards mapping by an SME, it allows for the precise spatial/geolocation of landslide features and geometry relative to the pipeline location and its depth of cover. Also used in Level 3 Assessments to document the location of exploratory boreholes, test pits, and geophysical explorations, as well as slope monitoring features.	Commonly applied in Level 2 Assessments and to support Level 3 Assessments.
Site-specific test pits	Test pits or test trenches allow for the examination of the near subsurface (to depths of 15 to 20 feet) geologic, geotechnical, and hydrogeologic conditions, particularly useful for a shallow landslide. The depth/thickness of the landslide relative to the pipeline can be investigated, and these data support the development of hazard mitigation options. Soil samples are often analyzed for geotechnical properties.	This intrusive, subsurface exploration tool is used for a Level 3 Assessment for site-specific geologic and geotechnical investigations of landslides.
Site-specific geotechnical boreholes	Subsurface geologic and geotechnical conditions to depths of tens to hundreds of feet can be investigated with geotechnical boreholes to document and evaluate the subsurface material properties and geometry of landslides. Additionally, samples of soil and rock can be collected from the boreholes for laboratory testing of material and geotechnical properties. The boreholes can also be used to install slope monitoring instrumentation, including slope inclinometers (SIs), shape-accel-arrays (SAAs), and piezometers.	Intrusive geotechnical boreholes are employed for a Level 3 Assessment where subsurface site-specific data are needed to confirm landslide depth or develop landslide mitigation.
Site-specific engineering geophysics	Various geophysical methods (e.g., ground-penetrating radar [GPR], seismic refraction, seismic reflection) can be used with favorable conditions to image the subsurface structure, stratigraphy, and geometry of landslides. This information can support the development of mitigation alternatives.	Geophysics are used for a Level 3 Assessment to typically provide additional spatial context beyond the limits of geotechnical boreholes and test pits.

Process/Method/ Technique/Tool	Description	Assessment Level or Area Where Used
Site geodetic topographic survey and installation of survey monitoring points	The collection and use of detailed, site-specific, traditional geodetic survey topographic data for developing a site topographic map. May include pipeline centerline survey with pipeline depths and specific points/features of the landslide. A detailed topographic base could also be obtained from site-specific LiDAR DEM. The installation of geodetic surface monitoring points around a landslide assists in understanding the lateral limits of deformation and the magnitude and rate of surface movement (x, y, z). A series of survey monitoring points can serve as a detection, characterization, or a monitoring tool.	Used for Level 3 Assessment and monitoring.
Pipeline alignment/depth of cover survey	Pipeline alignment locating with depth-of-cover data is used confirm the location (horizontal and vertical) of the pipeline relative to the landslide. It can also detect possible local deviations in the pipeline alignment and document the depth of cover in the area of deviation as well as the area outside.	Used for Level 2 and Level 3 Assessments and mitigation design.
Geologic and geotechnical engineering analyses of site-specific data	These analyses (e.g., geologic and geotechnical analyses, including slope stability modeling/analysis) and the data from the analyses can be used to understand critical/sensitive factors controlling slope stability. In addition, hydrotechnical analyses can support mitigation alternatives because surface water and groundwater also factor into slope stability.	Used in Level 3 Assessment and mitigation design.

Annex C
Fitness-for-Service Assessment in Landslide Management

Annex C: Fitness-for-Service Assessment in Landslide Management

C Introduction

Fitness-for-Service (FFS) assessment is a process that establishes the integrity of a pipeline impacted or potentially impacted by a landslide.[14, 25, 26] The focus of the assessment is the potential for loss of containment or loss of service.

Many landslides are time-dependent hazards that can affect a pipeline over many years. FFS assessment can be used to assess the integrity of a pipeline if the severity and behavior of a landslide can be measured, estimated, or postulated from geotechnical considerations. FFS assessment is for a given set of circumstances at a given time, and the assessment may need to be updated or conducted again as new information is gained or the site conditions change.

FFS assessment, including strain-based assessment (SBA), can serve a diverse array of purposes in a landslide management program:

- Setting priority for further assessment and mitigation as a part of an initial system-wide inventory and screening process.
- Assisting the execution of an emergency response plan after an unexpected landslide event.[27, 28]
- Setting segment-wide thresholds, which if exceeded, trigger further actions. The basis of the threshold is the strain capacity of the target segment and a selected safety factor (SF). The value established from the strain capacity and the selected SF is often referred to as the "strain demand limit." The strain demand limit is typically compared to the output of strain demand tools, such as inertial measurement unit (IMU) or strain gauges, to establish if further action may be needed.
- Conducting site-specific or girth-weld-specific assessment to assist operational and mitigation decisions. The assessment involves determining safety margins between strain demand and strain demand limit. The outcome can be used to make operational decisions (such as operational restriction) or site mitigation decisions (such as timing and method of mitigation).
- Supporting the specifications or selection of linepipes. In a pipe replacement project, SBA can be used for the selection of linepipe (e.g., from distributors, assuming a small quantity of linepipes would not entail a production run by a pipe manufacturer). In a new construction project, SBA can help to establish linepipe specifications.
- Assisting in the selection and specifications of welding procedures for girth welds. In parallel with considerations of linepipe properties and specifications, girth welding procedures can be selected for the construction of strain-resistant pipelines.
- Setting girth weld flaw acceptance criteria. SBA can be used to set a maximum allowable flaw size for a target tensile strain capacity (TSC) and pipe/weld mechanical properties. This information can be used to determine if a weld reinforcement or cutout is necessary.

- Setting acceptance criteria for interacting threats (see Annex I).
- Supporting a classification and decision-making system as described in Section 7 and Annex F.

When used correctly, FFS assessment can be a powerful tool in managing landslide hazards by optimizing the use of limited resources to mitigate landslides most likely to affect the integrity of the pipeline.

Some level of uncertainty exists in the outcomes of an FFS assessment due to the uncertainties associated with the input parameters used for the assessment and imprecisions in the assessment methods. It is possible to refine the assessment by improving the precision of the input parameters and continuing to develop and validate the assessment methods. For instance, having perspectives on the uncertainties of TSC requires understanding the factors affecting the TSC, such as the vintage of pipelines, linepipe properties, and construction methods, including girth welding practices, quality control, and inspection for weld flaws. Consequently, FFS assessment is best performed by subject matter experts (SMEs) with requisite knowledge and experience.

Some examples of applications of FFS assessment for landslides are provided in Annex D.

C-1 Possible Failure Modes and Limit States

Landslide loading can result in three possible failure modes for pipelines:

- Leak or rupture under tension
- Formation of wrinkles and buckles from compression, which may or may not lead to leak
- Bursting due to the interaction between landslides and other integrity threats

These failure modes are discussed below in the following sections.

C-1.1 Leak or Rupture under Tension

When a landslide imposes a longitudinal tensile stress/strain on the pipeline (i.e., demand), the primary concern is the integrity of the girth welds. When the strain demand is higher than the strain capacity of a girth weld, a leak or rupture occurs at the girth weld (Figure C-1).

Figure C-1. Example of a girth weld failure due to longitudinal stress/strain

C-1.2 Wrinkles and Buckles from Compressive Loading

When the longitudinal stress or strain imposed by a landslide is in compression, wrinkles and buckles can form if the stress or strain is sufficiently high (Figure C-2). The immediate consequence of the formation of a wrinkle or buckle can vary from a serviceability concern if no breach of the pipe wall occurs, to leaks due to the local high tensile strain in the vicinity of the severe wrinkle or buckle (Figure C-3). Large hoop strains generated in the vicinity of severe wrinkles and buckles can cause failures in seam welds with compromised properties. In addition to the potential for immediate loss of containment after a wrinkle formation, flaw initiation and growth is possible if the wrinkles and buckles are subjected to cyclic loads.

Figure C-2. Example of buckle formation at zero internal pressure

Figure C-3. Wrinkle formation near a girth weld and the resulting cracking of pipe wall at the apex of the wrinkle

C-1.3 Burst Due to Interacting Threats

Common threats to pipeline integrity, such as corrosion, can be affected by loads imposed by a landslide. For instance, compressive longitudinal stress can reduce the burst pressure of a corrosion anomaly. More details on interacting threats are given in Annex I.

C-2 Considerations for Selecting the Right Fitness-for-Service Assessment

The approaches to FFS assessment depend on the loading modes imposed by a landslide, possible modes of failure, time-dependence of anomalies, and applicability of certain FFS procedures.

- There are broadly two loading modes: (1) displacement-controlled loading and (2) load-controlled loading. Most loading modes involving geohazards are neither fully displacement-controlled or load controlled. Loading on a buried onshore pipeline in a slow-moving landslide event is primarily displacement controlled. The loading mode of a span is primarily load controlled.
- The possible failures modes are (1) tensile leak/rupture, (2) compressive wrinkle/buckle, and (3) burst.
- Anomalies, including volumetric features and planar flaws, are often contributors to failures involving landslides. Some of the anomalies, such as girth weld flaws, are formed during pipeline construction. There is little evidence of flaw growth during service. Other anomalies, such as corrosion and stress-corrosion cracking (SCC), may grow over time due to either static or cyclic loading. Cyclic loading can initiate and grow flaws at geometric discontinuities, such as at wrinkles and buckles.
- Most FFS assessment procedures developed to date, such as API 579 and BS 7910, are primarily stress-based. They are most suitable for integrity assessment under load-controlled loading when the applied stress is less than the yield strength of the materials. Stress-based methods tend to become overly conservative when the applied stress is greater than approximately 90% of yield strength or when the total longitudinal strain is greater than 0.15% to 0.20%. There are no rigid connections between the type of hazards and the appropriate FFS assessment procedure. For instance, buried onshore pipelines affected by landslides are best assessed by strain-based procedures, but spanning caused by a sink hole should be assessed by stress-based procedures.

Stress-based assessment procedures, such as API 579 and BS 7910, are well recognized and documented. Integrity concerns arising from landslide hazards typically involve strains greater than 0.2%. Therefore, using SBA is more appropriate than using stress-based assessment when addressing landslides.

C-3 Strain-Based Assessment

SBA is a process of integrity assessment that uses longitudinal (axial) strain to represent the condition of a pipeline.[29, 30] SBA typically focuses on the integrity of a pipeline under moderate to high levels of longitudinal (axial) strain. The effects of internal pressure are incorporated into the assessment process because it can affect the assessment outcome.

C-3.1 Concepts and Basic Elements of Strain-Based Assessment

SBA follows the same engineering process as a generic FFS assessment. An acceptable condition is when the strain demand is less than the strain demand limit:

$$\varepsilon_D < \varepsilon_{DL}$$

$$\varepsilon_{DL} = \frac{\varepsilon_C}{S_F}$$

where ε_D is strain demand, ε_{DL} is strain demand limit, ε_C is strain capacity, and S_F is safety factor that is greater than 1.0. The condition being assessed can be the current state of a pipeline or a state of pipeline projected into the future.

C-3.2 Determination of Strain Demand

Strain demand relevant to pipeline integrity is the total strain demand, which includes the strain demand prior to a geohazard event and additional strain demand imposed on a pipeline segment by a geohazard event. Strain demand can be caused by operational conditions (such as internal pressure or temperature differential) and external conditions (such as landslides).

There are broadly two categories of approaches to determine or estimate strain demand:

- Strains directly measured on the pipeline or from the pipeline, including strain gauges, IMU, and strain computed from surveyed pipeline profile
- Strains indirectly computed from the interaction between a landslide and a pipeline segment

The indirect method for strain demand determination consists of characterizing a landslide and estimating strain demand by modeling the interaction between the landslide and the pipeline. The indirect method usually consists of pipe-soil interaction modeling with various levels of assumptions about the characteristics of the landslide and mechanisms of interaction. Further details on methods of determining strain demand are given in Section C-4.

Public domain information on the relative accuracy of strain demand determination methods is scarce. Therefore, it is not prudent to associate an accuracy level with a particular strain demand method until the accuracy can be established through independent validation. Two levels of strain demand determination are organized with Level 2 (SD-L2) being viewed as having lower uncertainty than Level 1 (SD-L1):

- SD-L1: Strain demand from any single method without corroboration with other methods (e.g., strain gauge, IMU, pipe-soil interaction modeling)
- SD-L2: Strain demand from corroboration of two or more methods

C-3.3 Determination of Tensile Strain Capacity

When a pipeline is impacted by a landslide, the likelihood of pipeline failure varies greatly due to the possible large range of strain capacity of a pipeline. The displaced pipeline segment experiences bending and extension strains. One of the key drivers to the integrity of the pipeline is whether the strains imposed on the pipeline by the landslide are concentrated at girth weld(s). A leak or rupture could result with a small or moderate level of pipe movement if the strains are primarily concentrated at a weld. The susceptibility of a girth weld to such strain concentration can be caused or exacerbated by several factors:

- Actual strength of the weld being lower than the actual strength of the pipe
- High level of high-low misalignment at girth welds without proper compensation[5] for the misalignment. High-low misalignment is more likely to occur at tie-in welds and welds joining pipes and fittings of different wall thickness
- Heat-affected zone (HAZ) softening due to welding thermal cycles applied to the pipe
- Girth weld anomalies, particularly planar flaws such as hydrogen cracks and lack of sidewall fusion
- Low toughness
- Underfill or missing weld pass(es)

As stated above, the TSC of a pipeline is often controlled by the behavior of its girth welds. Frequently, the TSC of a pipeline is often referred to as “girth weld TSC” for this reason. The TSC of a girth weld is not the strain value measured across a girth weld at the initiation of failure (rupture or leak). The TSC of a pipeline, even when referred to as girth weld TSC, is the nominal strain or remote strain measured away from the local area of a girth weld at the beginning of a failure.

The magnitude or value of factors known to affect the TSC might not be available to pipeline operators, especially at the start of a landslide management program. A multilevel approach, in approximate order of increasing accuracy and precision, can be taken for the TSC determination. In most cases, the estimated TSC increases as the process moves to a higher level due to reduced uncertainty.

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

C-3.3.1 TSC- L1 Reasonable Lower-Bound Tensile Strain Capacity

There can be a large range in TSC among the girth welds in a pipeline segment. For instance, some vintage pipelines[6] have a highly varying level of girth weld anomalies, which can directly result in a large range in TSC.

For initial screening of a pipeline, having a reasonable lower-bound TSC is useful. This can be established based on the vintage of pipeline; construction practice (particularly girth welding and inspection practice); history of past failures, if any; and mechanical testing and anomaly inspections.

C-3.3.2 TSC- L2 Segment-Specific Tensile Strain Capacity

At this level, some knowledge about the major factors affecting TSC is necessary. Typically, knowledge of the pipe and weld characteristics, including pipeline alignment sheets, pipe mill test reports (MTRs), welding procedure specifications, and nondestructive testing practices for field welds is required to exercise this level. Characteristic distributions of pipe and weld mechanical properties from available records are used to derive a plausible range of TSC. A reasonable lower-bound TSC may be determined from the plausible range to facilitate initial integrity assessments.

Appropriately validated software/tool or case-specific analysis can be used to determine TSC at Level 2.

C-3.3.3 TSC- L3 Site/Girth Weld-Specific Tensile Strain Capacity

The type of information necessary for this level is similar to that of L2, except such information is specific to a site or weld. For instance, pipe-specific tensile properties from MTRs could be used to represent the pipe properties instead of a statistical distribution of an entire pipeline or segment. Information on weld flaws could be from site-specific or girth-weld-specific, in-ditch, nondestructive testing instead of using the generic workmanship flaw acceptance criteria.

Appropriately validated software/tool or case-specific analysis can be used to determine TSC at L3. Methods of determining TSC are further described in Section C-5.

C-3.4 Determination of Compressive Strain Capacity

Compressive strain capacity (CSC) associated with maximum load (CSC_{ML}) is often determined from equations published in various standards or recommend practices, for example Canadian Standard Association [CSA] Z662.[33] There are no recognized methods to determine the CSC associated with post-maximum-load (CSC_{PML}) behavior, although case-specific methods for determining CSC_{PML} have been published.[34]

CSC_{ML} is appropriate for primarily load-controlled loading. CSC_{PML} is appropriate for primarily displacement-controlled load.

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[6] Vintage pipelines, in the context of this document, are the pipelines (1) built with pipes before the thermomechanical control process (TMCP) steel-making processes with carbon content in steels greater than 0.2% and (2) before the widespread use of 100% X-ray for girth weld flaw acceptance (before ~1970 in the United States).

C-3.5 Difference between Uncertainty and Conservatism

When starting an SBA, information related to the determination of strain demand and strain capacity can be limited. Assessment may be done with a lower-bound strain capacity and upper-bound strain demand. This leads to underrepresentation of the safety margin (strain demand limit minus strain demand) and a high degree of uncertainty. As more relevant information is collected and assessments move to higher levels, using a greater value of strain capacity and a reduced level of strain demand may be justified, reducing the level of underrepresentation of safety margin. At the same time, the level of uncertainty is also reduced. From the viewpoint of safety margin, the lower-level outcome may be viewed as more conservative although it has a higher degree of uncertainty. A higher-level outcome could be less conservative but with a greater level of certainty. Therefore, depending on different approaches to SBA, the level of conservatism and uncertainty might not move in the same direction.

C-3.6 Determination of Safety Factor for Strain-Based Assessment

The appropriate value of an SBA SF depends on several considerations. There is no single SF that is suitable for all conditions. At a minimum, the following aspects should be considered when determining an appropriate SF.

- Level of bias built into determining or estimating strain demand and strain capacity, which in turn depends on the availability and reliability of the required input data for strain demand and strain capacity determination
- Geohazard characteristics and time frame for response
- Consequence and risk tolerance level

In most cases, both the strain demand analysis and the TSC analysis are biased toward conservative assessment outcomes. The level of conservatism varies with the analysis approach and available data. If both the strain demand analysis and the TSC analysis included significant conservatism, an SF close to 1.0 is justifiable. A greater SF may be justified if a failure event could have high consequences on life, property, the environment, and economics. Higher uncertainties in the required input data may also call for a greater SF.

C-4 Methods of Determining Strain Demand in Areas of Landslide Hazards

Strain demand from landslides can be estimated through review of the following:

- Current pipeline position compared to a known baseline position
- Direct measurement such as using strain gauges
- Landslide characteristics and its interaction with the pipeline
- IMU data

The following sections discuss these four methods, along with their limitations.

C-4.1 Estimation of Strain Demand from the Position of the Pipeline Segment

The process for estimating the strain demand from the position of the pipeline segment involves comparing the as-built location of the pipeline segment with the position of the pipeline after being displaced by the landslide.

The location of the pipeline segment prior to the landslide may come from the following:

- Construction alignment sheets
- Survey points established at the time of construction
- Records of prior line location
- IMU data

The location of the postconstruction pipeline segment may be determined by locating the pipeline through pot holing and surveying, conventional line locators,[7] or IMU (if an after-event IMU run is available).

Once the as-built location and the landslide-deflected location have been determined, they can be compared to establish the width (i.e., length along the pipeline) and the magnitude of the pipeline movement. Once the width and the magnitude of the lateral or vertical pipeline movement are known, the strain generated by the movement can be estimated using simple beam bending and extension theory.

The following factors should be considered in estimating the strain demand based on comparing the as-built and deflected position of the pipeline:

- Accuracy of survey and line locating techniques
- The restraint conditions at the span ends
- The strains from bending and longitudinal (axial) extension
- The baseline strain (without movement) (a default value of 0.1% could be used if no further information is available.)[14]
- The effect of temperature change if the temperature change is more than that assumed in the baseline strain calculation
- The effect of internal pressure, which is often less than that of temperature changes[14]

A review of analytical models for estimating strain demand from pipeline displacement profiles is given by Yu et al.[35]

C-4.2 Estimating Strain Demand from Strain Gauges

Strain gauges provide an accurate measurement of change in strain at the location of the installation and can be used for FFS assessment and long-term monitoring. There are three primary types of

[7] Although as a cautionary note, relatively small deflections or deflections over many feet might not be accurately resolved using standard line location equipment because of inherent inaccuracies in measurement.

strain gauges that can be used for monitoring pipeline strain: spot-weldable vibrating wire (VW), resistance-based, and fiber optic (FO). VW strain gauges are the most common type of strain gauge used for monitoring strain imposed on a pipeline from land movement.

The following factors should be considered at the time of strain gauge installation:

- Strain gauges should be installed at locations likely to experience the highest strain. Understanding the likely deformation pattern of the pipeline from the characteristics of the landslide and interaction between the landslide and pipeline is key to selecting the right locations.
- In addition to the consideration of pipe movement, girth welds of interest can also be considered when determining strain gauge locations.[8] For instance, manual tie-in welds tend to have lower strain tolerance than mainline welds. There have been cases of tie-in weld failures when the ground movement was many feet away from the tie-in welds.
- Because strain gauges only capture the strains from the time of their installation, any strain that occurred prior to strain gauge installation should be accounted for when estimating total strain demand.
- A minimum of three strain gauges around the pipe circumference is needed to fully resolve the strains from lateral bending and uniform extension/compression. A set of three or four strain gauges is usually installed around the pipe circumference at a given location along the pipe length (referred to as a strain gauge set). The fourth gauge provides some level of redundancy in the event of an unexpected failure of a strain gauge and helps rule out spurious readings. As an alternative to a fourth gauge, a duplicate set of gauges can be installed nearby (within a few feet) to provide redundancy.
- A set of three gauges may be installed at the 12, 4, and 8 o'clock positions or at the 12, 3, and 9 o'clock positions. A set of four gauges may be installed at the 12, 3, 6, and 9 o'clock positions or at the 1:30, 4:30, 7:30, and 10:30 clock positions. It is recommended that an operator pick an approach and use it for most or all installations for internal consistency and to reduce the potential for erroneous interpretation.
- The readings from individual strain gauges can be processed to determine the maximum strain, bending strain versus extensional/compressive strain, and the orientation of the bending.
- For FFS assessments, the strains at multiple locations along the pipe length may be used to determine the overall deformation pattern and the maximum strain over the entire affected segment.
- The maximum strain at any discrete location is not necessarily the maximum strain over the entire affected segment.
- The effects of temperature changes should be accounted for when analyzing the output from strain gauges.

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[8] Strain gauges should not be installed on the girth weld. When using strain gauges to monitor strains on a girth weld, gauges should be installed a few inches from the girth weld.

C-4.3 Estimation of Strain Demand from Landslide Characteristics

Pipe-soil interaction models can be used to determine the strain demand on an affected pipeline segment.[9] Pipe-soil interaction models often start with the characterization of the landslide and the geotechnical properties of the soil and rock that make up the landslide and surrounding area. Many factors affect the loads imparted on the pipeline by the landslide, which need to be accounted for in the pipe-soil interaction model. When selecting a model, the following are the most important factors related to pipe-soil interaction modeling.[36]

- Ability to simulate large relative displacement of a pipeline
- Correct modeling of the pipe-soil interface behavior
- Selection of appropriate constitutive models
- Accurate estimation of the soil constitutive parameters
- Proper consideration of loading rate effects
- Coupling effects from oblique pipe movement

Many pipe-soil interaction models use structural beam elements to represent the pipeline and spring elements to represent the resistance of soil to the pipe movement.[37] Pipe-soil interaction is captured by distributed nonlinear springs in the axial, lateral, and vertical directions of the pipe centerline. The formulation of soil springs has gone through several iterations,[1, 38, 39, 40] but generally requires some knowledge about the pipeline (outer diameter, coating type, depth of cover) and the surrounding soil (classification, unit weight, cohesion, internal angle of friction). In addition, an estimation of the soil movement profile at the depth of cover is needed to prescribe the loading condition on the pipeline.

More complex modeling techniques involve continuum pipe and soil modeling.[36, 41, 42] In a continuum model, the pipe is represented by shell or solid elements, such that complex pipe response (e.g., ovalization and wrinkling) can be properly modeled. The soil is modeled as a continuous medium, thus allowing proper representation of complex soil behavior, such as shear load transfer. In addition, continuum pipe and soil models properly represent variable circumferential and longitudinal pressure distribution.

The principal advantage of the structural pipe-soil interaction models is their computational efficiency; nevertheless, the force-displacement relationship representing the resistance of the soil is a simplification that could introduce modeling errors and prevent certain key processes from being properly modeled. In contrast, the continuum pipe-soil interaction models have the potential to provide more realistic representations of the physical mechanisms at the expense of computational efficiency. The two approaches also differ in the amount of input data required to establish an analysis. Continuum models tend to require extensive soil property data that can pose additional challenges to the integrity assessment process. The decision on which type of model to use (structural or continuum) should be based on the goal of the analysis, available data that

[9] Pipe-soil interaction models are not suitable for pipe-rock interaction.

support the analysis, and the desired turnaround time of the analysis. The uncertainties associated with a chosen model should be accounted for in presenting the FFS outcomes.

The pipe-soil interaction modeling approach to obtain strain demand is not as direct as using strain gauge or IMU data to obtain strain demand. The accuracy of the strain demand prediction is strongly affected by the assumed site and soil conditions. These properties should generally be provided by a geotechnical engineer. In the absence of site-specific data, it is important that any assumption about soil properties be considered in the context of integrity assessment. For example, the standard practice for most geotechnical engineering applications is to consider shear strength parameters that are lower than the average value of the measurements. This is considered conservative for foundation design and for landslide mitigation analysis and design. However, for pipe-soil interaction modeling, the use of low strength input values is not conservative because it reduces the load transferred to a pipeline by landslide movement. If conservatism is desired, soil conditions with values higher than the average value should be considered in the analysis (i.e., soil that is generally harder or denser than the likely conditions).

A review of pipe-soil interaction models and their limitations is provided by Yu et al.[35]

C-4.4 Estimating Strain Demand from Inertial Measurement Unit

The following are key considerations when interpreting and using IMU bending strain in FFS assessments:

- The bending strain is computed using the centerline profile of a pipeline segment when the centerline profile deviates from a straight line. The bending strain calculated includes strains from all events that caused the pipeline profile to change from a straight profile, including construction bends and all subsequent profile changes. The strain originating from construction bends is not relevant to the assessment of the potential tensile failure of girth welds; therefore, the contribution of those bends to the reported bending strain must be subtracted to assess the potential tensile failure of girth welds. Nevertheless, construction bends can influence the distribution of strains in the displaced segment if landslide movement were to continue. In addition, construction bends can reduce the buckling resistance of a displaced segment.
- For in-service pipelines that do not have the original pipe profile at the time of construction, determining the bending strains that are most relevant to integrity assessment is possible for segments of pipes that were straight at the time of construction. Locations with hot and cold bends can be identified by IMU based on their characteristic bending strain profiles. However, determining the magnitudes of strains caused by external loads at preexisting bends can be difficult unless the pipe position at the time of construction is known through surveys or IMU runs conducted prior to commissioning.
- IMU tools cannot detect uniform tensile or compressive strains that do not cause changes in pipe profiles.
- High-bending strains at locations near bends, wall thickness changes, valves, flanges, tees, or other fittings are often attributed to “chatter” by some vendors or reviewers. Strains from those locations are often excluded from assessment due to difficulties in determining the strain values relevant to landslides. Locations of tie-in welds or wall thickness changes tend to have higher stress and lower strain tolerance than other locations due to difficult

fit-up at the girth welds. Excluding these locations in strain feature analysis or FFS assessment could lead to unintentionally overlooking structurally critical locations.

- Bending strains can be induced from sources other than landslides and other geohazards, such as third-party impacts (an example would be anchor drag at waterbody crossings). The source of the bending strain and whether it results from static (such as the aforementioned anchor drag) or dynamic (such as landslides) causes should be understood and accounted for in the analysis.

C-5 Methods of Determining Tensile Strain Capacity

TSC is the strain level in tension beyond which there would be a negative consequence, such as a leak, a rupture, or change of the physical characteristics of the pipeline that may negatively affect its operation. A few essential concepts about TSC are given below.

- The tolerance to tensile loading/stress/strain of a pipe segment is largely influenced by how the necessary extension or bending caused by a landslide is distributed over the segment. For instance, if girth welds are stronger than the surrounding pipes, the elongation of the segment is distributed over the entire length of the segment. If the girth welds are weaker than the pipe, the elongation of the segment would be concentrated more in these welds than the rest of the segment, leading to low strain tolerance of the overall segment.
- Figure C-4 shows the evolution of the cross-weld strain in a girth weld (representing the averaged strain in the weld metal and the HAZ) and the strain in the pipe body (representing the nominal strain in the body of the pipe away from the girth weld) as a function of amount of lateral displacement over a 200-foot length of the pipeline traversing a landslide. Up to a lateral movement of about 4 feet, the materials remain elastic. The cross-weld strain and the strain in the pipe body are the same. With further increase of the lateral displacement, more strain goes into the weld area as shown by the increased level of cross-weld strain compared to the strain in the pipe body, leading to a very high level of strain in the weld at a displacement of 8 to 9 feet. Had the weld had the same strength as the pipe, the cross-weld strain would have stayed at the level of the pipe strain, much lower than the strain with the weld strength undermatching. The high strain concentration in undermatching girth welds leads to low strain tolerance.
- The TSC of a pipeline is often controlled by the behavior of its girth welds. Three groups of factors contribute to girth welds often being the controlling location: (1) existence of girth weld flaws, (2) weld strength undermatching (i.e., actual weld strength being lower than the actual strength of the pipe), and (3) unfavorable geometric profiles of a weld (e.g., high-low misalignment).
- Flaws or anomalies in the pipe body, such as circumferential SCC or corrosion with a large circumferential dimension, could become a controlling location, although historically such occasions have been rare. In the absence of flaws and anomalies in the pipe body, it is very difficult to have a failure in the pipe body under longitudinal/axial loading before other failure modes are initiated.
- The TSC of a pipeline is frequently referred to as girth weld TSC for the reasons stated above. It should be noted that the TSC of a girth weld is not the strain value measured

across a girth weld at the moment of failure (rupture or leak). The TSC of a pipeline, even when referred to as girth weld TSC is the nominal strain or remote strain in the pipe body measured away from the local area of a girth weld at the beginning of a failure.

- The current definition of TSC does not make a distinction between a leak or a rupture, nor is it possible to make such distinction on the basis of TSC alone. Reaching a TSC indicates an incipient failure that would lead to a loss of containment (leak or rupture). Other factors, such as the rate and duration of loading exerted on the pipeline segment and a material's resistance to flaw propagation in the hoop direction of a pipe, can affect whether a breach of the pipe wall would become a leak or rupture.

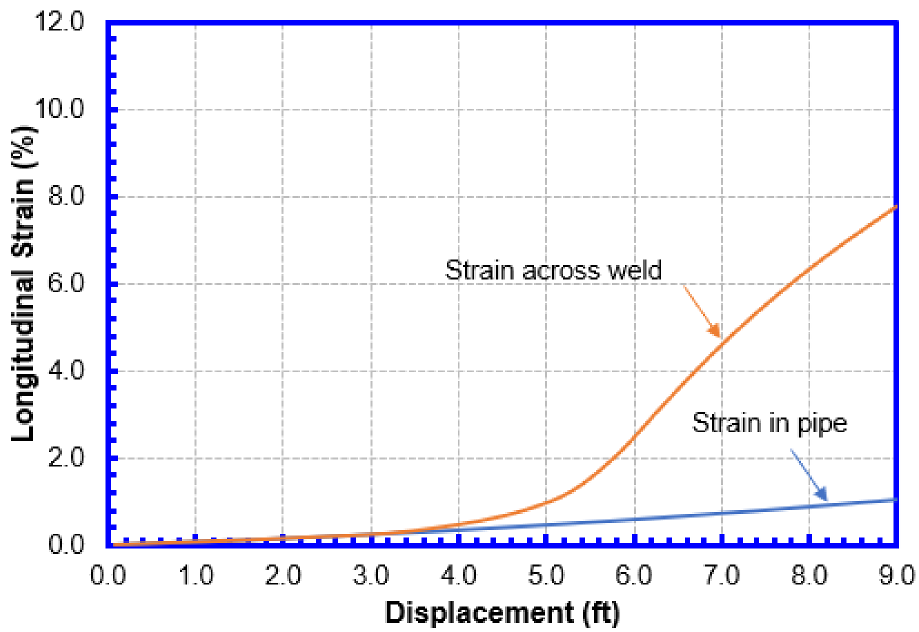

Figure C-4. Comparison of strain across a girth weld and strain in the pipe body in a weld joint with weld strength undermatching

The following factors have significant influence on TSC:

- Pipe wall thickness and diameter
- Strain hardening rate of the material, including pipe, weld metal, and HAZ
- Girth weld strength mismatch
- Extent and level of HAZ softening
- Girth weld profile
- Cap reinforcement
- High–low misalignment
- Girth weld bevel angle

- Girth weld flaws
- Type
- Location
- Dimensions
- Toughness
- Internal pressure

The large number of factors affecting TSC and the possible large range of some dominant factors, such as girth weld flaws, lead to large variations of TSC among different pipelines and even among different girth welds in the same pipeline. The observed TSC from field failures and experimental testing ranges from as low as 0.2% to well over 2.0%. [43, 44]

C-5.1 Dominant Factors Affecting Tensile Strain Capacity

Historical failure incidents and root cause analysis, including metallurgical and fracture mechanics analysis, indicate that the majority of tensile failures occur in pipeline girth welds driven by two dominant factors: (1) existence of weld flaws and (2) weld strength undermatching, including HAZ softening. The second-tier factors are toughness and weld profiles.[10] The impact of the dominant factors is further explained below.

C-5.1.1 Weld Flaw

For vintage pipelines constructed before the widespread use of X-ray for girth weld inspections and acceptance during construction, girth weld flaws are typically the predominant factor affecting the TSC. Figure C-5 shows exposed flaws after the fracture of a test specimen that contributed to low strain tolerance. Figure C-6 shows the in-service failure of a girth weld of a vintage pipeline containing girth weld flaws.

[10] For girth welds fabricated with certain no-longer-used welding techniques, such as oxy-acetylene welds, both weld toughness and weld profile could be major factors that could negatively contribute to low TSC in addition to weld flaws.

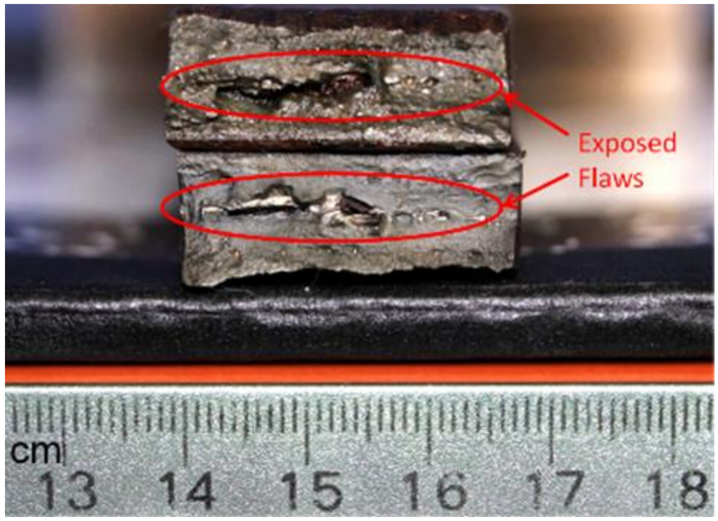

Figure C-5. Exposed flaws at the fracture surface of a girth weld after a cross-weld tensile test

Figure C-6. Failure of a girth weld of a vintage pipeline at low strain due to weld flaws

Figure C-7 shows the distribution of individual flaw lengths of 16 girth welds as reported by radiographic testing (RT) and phased array ultrasonic testing (PAUT).[45, 46] Although most of the flaws have a length of 4.0 inches or less, there is still a number of flaws with a length greater than 4.0 inches.

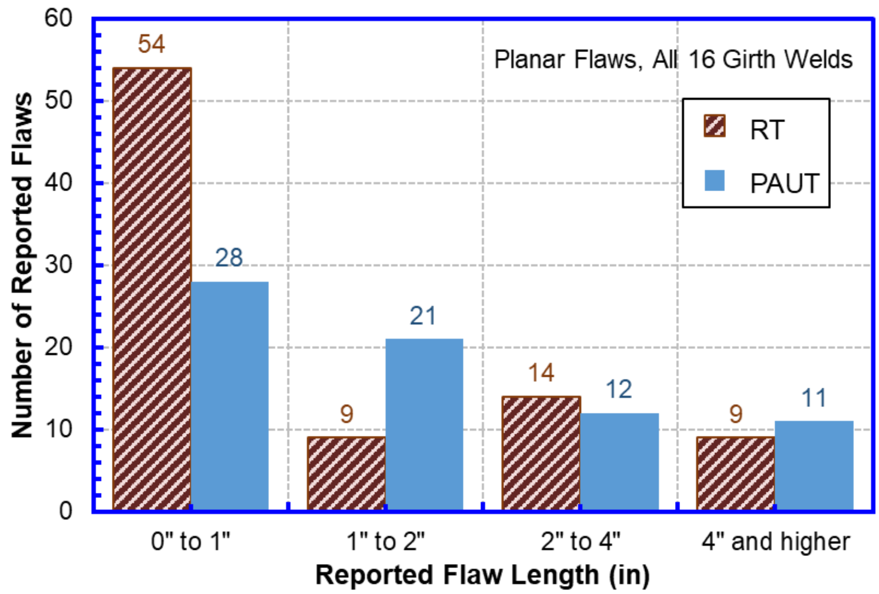

Figure C-7. Distribution of individual flaw length reported by RT and PAUT of 16 vintage girth welds[46]

C-5.1.2 Weld Strength Undermatching

For modern welds inspected and accepted by radiographic workmanship criteria during construction, the TSC of girth welds is predominantly affected by weld strength mismatch. Weld strength undermatching, which is permitted by relevant codes and standards, can lead to low strain tolerance.[47, 48, 49] Figure C-8 shows the failure of a girth weld with undermatching weld strength in the absence of weld flaws. Figure C-9 shows an in-service failure of a girth weld with undermatching weld strength.

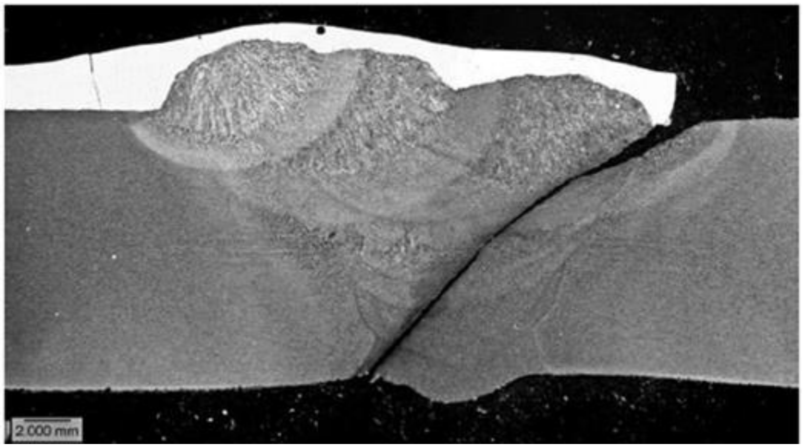

Figure C-8. Failure of a girth weld with weld strength undermatching in the absence of weld flaws

Figure C-9. In-service failure of a girth weld with weld strength undermatching

C-5.1.3 Determination of Tensile Strain Capacity

The determination of TSC may involve the following steps:

- Collect information on pipeline characteristics.
- Determine the most appropriate TSC procedure/models to use, guided by the requirements of TSC procedures/models, such as those shown in Tables C-1 and C-2 below.
- Collect available information on necessary parameters to exercise the TSC procedures/models. Frequently, not all information on necessary parameters is available. It might be necessary to obtain the information from pipelines of similar characteristics, such as vintage and construction practices by consulting either internal or external SMEs.
- Estimate TSC using the selected procedures/models.
- Conduct confirmation tests if possible. If not, consult internal or external SMEs about the suitability of the TSC values.

C-5.1.4 Procedures and Tools for Determination of Tensile Strain Capacity

A number of procedures and tools are available for determining TSC. Comprehensive reviews of these procedures and their limitations are available.[50, 51] The most versatile and validated procedures are the four-level PRCI-CRES models (alternatively termed ABD-1 models after the PRCI project code ABD-1[11]).[52–57] A special subset of the PRCI-CRES models is the TSC tool built for vintage pipelines with limited appliable range under a PRCI project SIA-1-7 (thus the tool is often referred to as SIA-1-7 model/tool).[58] A summary of the PRCI-CRES models with their features and intended applications is given in Table C-1. Further descriptions of the available models, including the CSA equations, is given in Table C-2. [59, 60]

[11] The PRCI-CRES tensile strain models have four levels. Levels 2 and 3 are in closed-form equation format. Many people refer those equations as the PRCI-CRES models or ABD-1 models. This notion is not complete as the formats of Level 1 and Level 4 are different from those of Levels 2 and 3. Level 4 is particularly versatile. It can be used to determine the TSC for a wide variety of linepipe and HAZ properties and girth weld configurations.

Table C-1. Features and intended use of the four-level PRCI-CRES tensile strain models and a special subset of the models (SIA-1-7)

Level of PRCI-CRES Models	Name of Subset Model	Format of the Model	Intended Application	Target Strain Demand	Range of Applicability		
					Linepipe	Girth Welding Process	Wall Thickness (inches)
1	N/A	Tabular (available in a report)	New pipeline construction (strain-based design)	≥ 0.5%	Modern	GMAW FCAW SMAW	≥ 0.5
2	N/A	Equations (available with a software tool)	New pipeline construction (strain-based design)	≥ 0.5%	Modern	GMAW FCAW SMAW	≥ 0.5
3	N/A	Equations (available with a software tool)	New pipeline construction (strain-based design)	≥ 0.5%	Modern	GMAW FCAW SMAW	≥ 0.5
4	N/A	Case-specific FEA	New pipeline construction (strain-based design) and existing pipelines (strain-based assessment)	≥ 0.15%	Modern and vintage	All	All
4	PRCI SIA-1-7	Software with limited range	Existing vintage pipelines (strain-based assessment)	≥ 0.15%	Vintage	SMAW	≤ 0.5

Table C-2. Features, intended use, and required input parameters of a few widely used tensile strain models

TSC Models/ Procedures		CSA Equations	PRCI-CRES Tensile Strain Models	PRCI SIA-1-7
Publication Year		2005–2007	2011–2012	2019–2020
Target application		TSC estimation of existing pipeline	**Levels 1–3** 1. New construction 2. Strain-based design 3. Linepipes made of modern microalloyed steels **Level 4** 1. New construction and existing pipelines 2. Strain-based design and assessment 3. All pipeline steels and welding processes	Assessment of existing vintage pipelines (prior to the use of microalloyed thermomechanical control process [TMCP] steels) with girth welds fabricated using SMAW processes and cellulosic electrodes
Permission for weld strength undermatching		No	No for Levels 1–3 Yes for Level 4	Yes
Parameters incorporated in the model	Pipe diameter	User selectable	User selectable	User selectable
	Pipe wall thickness	User selectable	User selectable	User selectable
	Internal pressure	Not user selectable, implicitly considered by setting limit on the maximum value of toughness	User selectable	User selectable
	Pipe Y/T ratio	User selectable	User selectable	User selectable
	Girth weld strength mismatch	Not user selectable	User selectable	User selectable
	HAZ softening or hardening	Not user selectable	User selectable (Level 4)	Not user selectable
	Toughness	User selectable	User selectable	User selectable
	Flaw Height	User selectable	User selectable	User selectable
	Flaw length	User selectable	User selectable	User selectable
	High–low misalignment	Not user selectable	User selectable	User selectable
	Girth weld bevel geometry	Not user selectable	User selectable	Not user selectable
	Girth weld cap reinforcement	Not user selectable	User selectable (Level 4)	Not user selectable

It is important to select the right tensile strain models for the determination of TSC. Tensile strain models developed for strain-based design pipelines for new construction have a set of assumed conditions that are different from those of most existing pipelines built without strain-based design considerations. For instance, strain-based designs usually start with more stringent specifications on linepipe properties than typical specifications without strain-based design considerations. The requirements on girth welding and inspection practice are also more stringent than typical requirements in most welding standards. One example is that girth weld strength undermatching is generally not permitted for strain-based design pipelines. Therefore, it is necessary to check whether the requisite conditions for using the tensile strain models developed for strain-based design are met if they are to be applied to existing pipelines built without strain-based design considerations.

With sufficient data support and the use of appropriate procedures/tools, the TSC of girth welds of interest can be predicted with reasonable accuracy as shown in Figure C-10 and Figure C-11.

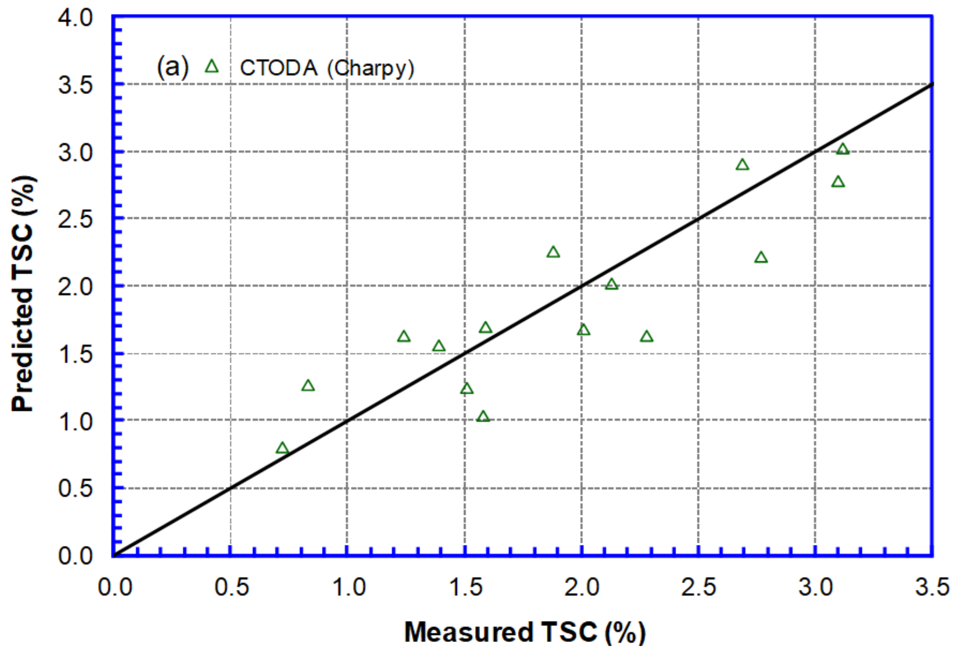

Figure C-10. TSC predicted by the Level 2 procedure of PRCI-CRES tensile strain model versus TSC measured from full-scale tests of mechanized girth welds[55]

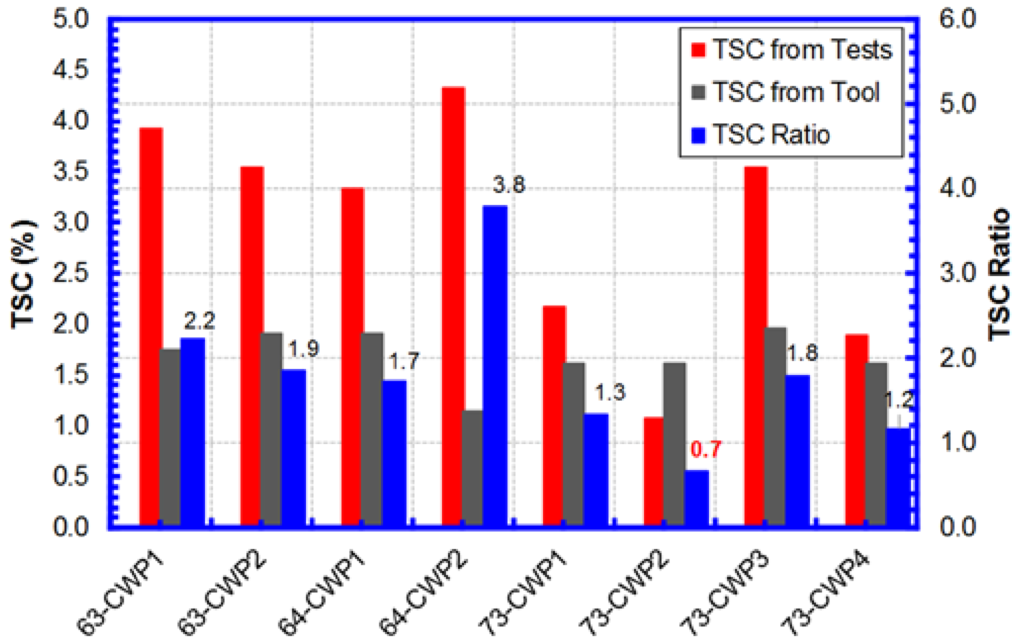

Figure C-11. Comparison of measured TSC from curved wide plate (CWP) tests of vintage girth welds and predicted TSC from the PRCI SIA-1-7 tool.[58] Specimen 73-CWP2 had a large preexisting flaw that was not identified prior to the test. This flaw led to the unexpected low TSC.

C-5.1.5 Proper Interpretation and Use of Tensile Strain Capacity

Given the wide range of possible TSC, it is often difficult to choose a value for integrity assessment. A typical TSC value for a pipeline can be substantially higher than a possible lower-bound value. On the other hand, choosing the absolute lowest possible value in a screening process could result in a large number of sites for further investigation. This can become impractical and lead to inefficient use of resources. In an initial screening process it is necessary to choose a reasonable lower-bound TSC value. Further investigation can be carried out depending on the outcome of the initial screening. Example D-3 in Annex D demonstrates this approach.

C-6 Methods for Determining Compressive Strain Capacity

CSC is related to the formation of wrinkles and buckles due to compressive strain on a pipeline segment. Compressive buckling is usually categorized as a serviceability limit state. This characterization is not complete and can be misleading. CSC in literature is often defined as the strain corresponding to the point of the maximum bending moment in a lateral bending test (CSC_{ML}). At the point of reaching CSC, pipes have a very minimal amount of bulging or wrinkles. The ovality of the pipe cross-section is small and does not impede the passage of in-line inspection (ILI) tools. The consequence of reaching CSC is related to events past CSC.

- If the loading is displacement controlled, as is typical of buried pipelines subjected to landslide loading,[12] reaching the CSC_{ML} generally does not negatively affect the pipeline service.
- If the loading is mostly load controlled, the pipe might collapse immediately after reaching CSC, possibly forming severe wrinkles. Wrinkles of large amplitude can also form when the displacement continues to increase in a displacement-controlled loading scenario when the strain continues to grow beyond CSC_{ML}. Large and severe wrinkles can lead to ruptures or leaks from high local tensile strains in either the hoop or longitudinal direction. If the wrinkles survive the initial formation, the long-term integrity of the wrinkles might be affected by possible fatigue damage and/or coating- or corrosion-related concerns.

The CSC_{ML} computed from equations available in standards and literature can be overly conservative for buried pipelines in which the movement of the pipelines is restrained by the surrounding soil. This CSC_{ML} may be viewed as a lower-bound value from a pipeline integrity viewpoint. A more relevant assessment is the behavior of the pipeline when the strain goes beyond CSC_{ML}. The CSC corresponding to the post-maximum-load behavior is defined as CSC_{PML}. A systematic assessment of various possible failure modes in a post-wrinkle environment is given by Liu et al.[34]

C-6.1 Factors Affecting Compressive Strain Capacity

The following factors are known to affect CSC:

- Pipe D/t ratio
- Pipe strain hardening behavior, sometimes represented by *Y*/*T* ratio or yield strength
- Shape of the stress-strain curve at the knee of the elastic and plastic part of the curves
- Internal pressure or external overpressure
- Geometric imperfection or features, including those in linepipe, girth welds, dents, mechanical damage, etc.
- Loading mode

C-6.2 Determination of CSC_{ML}

For load-controlled conditions, the relevant CSC is CSC_{ML}. The most commonly used models for estimating CSC_{ML} for onshore pipelines are CSA equations, the University of Alberta models, and the newly developed CRES models.[33, 61, 62, 63]

C-6.3 Determination of CSC_{PML}

There are no well-established procedures to estimate CSC_{PML}. One example of case-specific analysis used to justify a strain limit of 2.0% under displacement-controlled conditions is given by Liu et al.[34]

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[12] Exposing a pipe segment in an excavation can remove the restraint, causing an instability and creating a buckle. The excavation process effectively changes the loads from displacement-controlled to load-controlled conditions.

C-7 Collection of Data for Fitness-For-Service Assessment

A successful FFS assessment is critically dependent on the availability of relevant data as inputs for the assessment. The quality of the data also impacts the accuracy and precision of the outcome. Using incorrect or nonrelevant data could lead to overly conservative or nonconservative outcomes. The ability to locate and retrieve relevant data in a timely manner can determine whether an FFS assessment can be performed when the turnaround time is short.

It is highly recommended that opportunistic nondestructive testing (NDT) and mechanical testing of girth welds be conducted when the material becomes available. The mechanical testing must be organized to extract values for parameters that have major impacts on TSC. Customary testing meant to show code compliance is often insufficient.

This section highlights some of the necessary data for FFS assessment. A landslide management program can include plans to collect, sort, store, and retrieve such data in preparation for FFS assessment.

C-7.1 Material Property Data

The mechanical properties of linepipe and girth welds should be collected and properly grouped. MTRs might not be available for vintage pipelines. Data could be first collected from existing test reports (e.g., tests conducted in failure analysis or other integrity management programs). Dedicated testing of actual welds and pipe material might be necessary in some situations. The testing program should be designed to produce data relevant to applying TSC models.

C-7.2 Girth Weld Features

The geometric features of girth welds, such as weld cap reinforcement and high-low misalignment, can play a major role in the TSC of girth welds. Weld profiles are often related to welding practice at the time of weld fabrication. These features can be obtained through systematic documentation when welds are tested.

C-7.3 Girth Weld Anomalies

The type and dimensions of girth weld anomalies are often associated with welding processes at the time of fabrication. Older welds before the widespread use of X-ray inspection could have large volumetric flaws, such as porosity and slag. These anomalies tend to have a benign impact on the weld strain tolerance if they do not interact with surface-breaking flaws.

Reliable detection, sizing, and characterization of girth weld anomalies using ILI tools is not a mature field. Some tools may report girth weld anomalies, but often cannot characterize the nature of the anomalies. Ultrasonic testing (UT) tools targeting circumferential flaws can potentially detect planar girth weld flaws in liquid pipelines. However, detecting planar flaws by ILI tools in gas pipelines can be a challenge. Planar flaws tend to have more pronounced negative impact on the strain tolerance of girth welds than volumetric flaws do.

A more realistic approach to girth weld anomalies for welds fabricated before the wide use of X-ray is through accumulating relevant flaw information when destructive tests are conducted. Alternatively, girth welds can be inspected by in-ditch methods, such as X-ray or UT, when such opportunities exist (e.g., in integrity digs or recoating).[13] Such information can be collected, sorted, and archived in appropriate groups for conducting FFS assessments.

[13] Performing such opportunistic assessments can raise other issues that are beyond the scope of this section. If radiographic or UT inspections are performed on older welds on an opportunistic basis, there are no clear regulatory requirements or industry guidelines about the action needed if the welds do not meet current acceptance standards (such as whether cutting out and replacing the inspected welds or sleeving the welds might be needed).

Annex D
Landslide Assessment Examples

Annex D: Landslide Assessment Examples

D Introduction

This annex provides six examples of landslide threat assessments to provide context for the recommendations provided in Section 5. The focus of the examples varies between those with a balanced discussion of the hazard assessment component and fitness-for-service (FFS) component and those more heavily weighted on only one component. The examples more heavily weighted on one component reflect the experience of the authors with respect to the particular assessment process, but in all cases, these assessments were performed using the integrated assessment approach described in Section 5. The first four examples are based on actual work performed, while the last two are fictitious for illustrative purposes.

D-1 Landslide Assessment Example 1

This example demonstrates an integrated approach using both landslide hazard and pipeline integrity assessments to manage a landslide that occurred in the eastern United States. The information is taken from a paper by Nasrallah et al.[64] supplemented with information from the direct involvement of the authors.

D-1.1 Level 1 Assessment

In 2018 a Level 1 Assessment for approximately 300 miles of pipeline right-of-way (ROW) was conducted using light detection and ranging (LiDAR) data acquired in February 2018. Potential landslide hazards identified during this review were delineated and stored in a geographic information system (GIS)-based platform. The landslide that is the focus of this case study was identified and selected for ground reconnaissance (Level 2 Assessment) based on the size of the landslide and close proximity to the pipeline.

D-1.2 Level 2 Assessment

Following the Level 1 Assessment, a Level 2 Assessment consisting of a ground reconnaissance was conducted in November 2018, approximately 9 months after LiDAR data were collected. Based on observations made during the Level 2 Assessment, the landslide of interest had expanded laterally by about 5 feet, retrogressed uphill approximately 6 to 7 feet, and progressed downhill approximately 12 feet. The uppermost limits of the expanded landslide coincided with the pipeline trench. Based on the landslide morphology, the thickness of the landslide was estimated to be between 5 and 10 feet. The top of the pipeline was about 7 to 10 feet deep. At the time it appeared possible, but not known with certainty, that the landslide may have been engaging the pipeline, but with the information available at Level 2 the strain demand (if any) on the pipeline was unknown.

Following the Level 2 Assessment, the landslide continued to enlarge, with enlargement of the head and lateral scarps and the downslope movement progressing an additional 15 feet.

D-1.3 Level 3 Assessment

After the Level 2 Assessment, a number of uncertainties remained:

- Was the landslide engaging the pipeline?
- If so, what was the strain demand that had been induced?
- What was the strain capacity of the pipeline at this location?
- Did the pipeline need to be exposed (stress-relief excavation) or replaced, or could a less intrusive mitigation be performed?
- What was an appropriate long-term management strategy for this landslide?

Because these uncertainties needed to be resolved, a Level 3 Assessment was initiated. The Level 3 Assessment focused on both further characterization of the landslide hazard and the pipeline integrity assessment. The Level 3 Assessment consisted of the following:

- A depth of cover and pipeline position survey intended to compare the as-built weld locations of the pipeline through the landslide area with the current position of the pipeline to determine if pipeline movement had occurred
- A geotechnical investigation to characterize landslide depth, soil conditions, and extent using dynamic cone penetration investigation

D-1.3.1 Fitness-for-Service Pipeline Integrity Assessment

Based on the site survey, it appeared that the landslide was likely engaging the pipeline and might have resulted in increased strain demand on the pipeline. At the time of these activities (February 2019), information on the landslide and the site-specific pipeline properties was limited and still being collected. An FFS assessment was performed to help establish an appropriate course of action.

With the limited information available at the time of the initial FFS assessment, including the length of the pipeline experiencing the lateral movement and the maximum magnitude of the lateral movement, a preliminary assessment of the strain demand was completed with simplified analytical models (i.e., strain demand Level 1 [SD-L1]). This strain demand was compared with the tensile strain capacity (TSC) estimate from prior work for the same pipeline in 2016 (tensile strain capacity Level 2 [TSC-L2]).

Based on this analysis, the SD-L1 was lower than the lowest calculated strain capacity of all girth welds for the pipeline by a sufficient margin. It was concluded that immediate response actions, such as a stress-relief excavation or pressure reduction, were not necessary. In the early spring of 2019 when the assessment was performed, the ground was saturated. The conclusion about not needing immediate field work was critical. It meant that construction activities could be avoided during a time of poor ground conditions that could have led to further destabilization of the ground. System-wide TSC work previously conducted in 2016 allowed the safety margin to be determined quickly once the displaced profile of the pipeline was established.

In March and April 2019, additional information became available from the geotechnical investigation and site-specific pipeline properties. Refined pipeline-soil interaction modeling was performed and produced a strain demand lower than that found in the preliminary analysis. After a comprehensive review of the mill test reports (MTRs) and the welding procedure specifications (WPSs) for the affected pipeline joints and girth welds, a case-specific TSC analysis (TSC-L3) was performed on two manual tie-in girth welds. These two welds were chosen for analysis because other types of welds in the affected segment were expected to have a higher TSC. The TSC-L3 analysis produced a slightly higher TSC than the preliminary TSC estimates.

D-1.3.2 *Threat Management Measures*

The FFS analysis indicated that at the time of the analysis a stress-relief excavation of the affected segment was not necessary due to the large margin that existed between the strain capacity and the strain demand. A program of site stabilization work was selected that included diverting groundwater and installing strain gauges (for monitoring). Strain gauges were installed at strategically selected locations based on strain demand and strain capacity analysis to detect additional strains at those critical locations. The strain gauge locations were selected so that the same excavations performed for the strain gauge installation were also used for the work on groundwater management, thus minimizing the amount of excavation. Site-specific strain thresholds were established that if exceeded would trigger additional action.

D-2 Landslide Assessment Example 2

This example illustrates the considerations and processes for applying FFS assessment to two pipelines displaced by a landslide after initial identification and characterization through the Level 1 and 2 Assessment process. The contents of this example are an excerpt from Liu et al.[65] The example site was located in southwest Pennsylvania. The ROW was routed roughly perpendicular to the slope direction. Two gas transmission pipelines shared the ROW. Pipeline A is an NPS20 X42 pipeline constructed in the late 1970s. Pipeline B is an NPS24 X70 pipeline constructed in the early 2010s. The two pipelines were separated by 16 feet, with Pipeline A positioned higher on the slope. The depth of cover for the two lines was between 4.6 and 6.3 feet.

A Level 1 Assessment was conducted that used in-line inspection (ILI) inertial measurement unit (IMU) bending strain from an ILI run conducted in mid-2021 on Pipeline B. This Level 1 Assessment identified a strain feature with a peak bending strain of 0.44% in the pipeline body and 0.30% at the girth welds. The Level 1 Assessment used LiDAR differencing to identify a landslide extending 425 feet along the ROW and 226 feet along the slope at the bending strain location that had formed between the dates of acquisition of two different LiDAR datasets. A Level 2 Assessment confirmed movement of both pipelines due to a landslide within the identified area. Figure D-1 shows a schematic of the two pipelines and the boundary of the slide. Pipeline A was subsequently shut-in due to potentially large displacement indicated by the survey, while Pipeline B remained in operation.

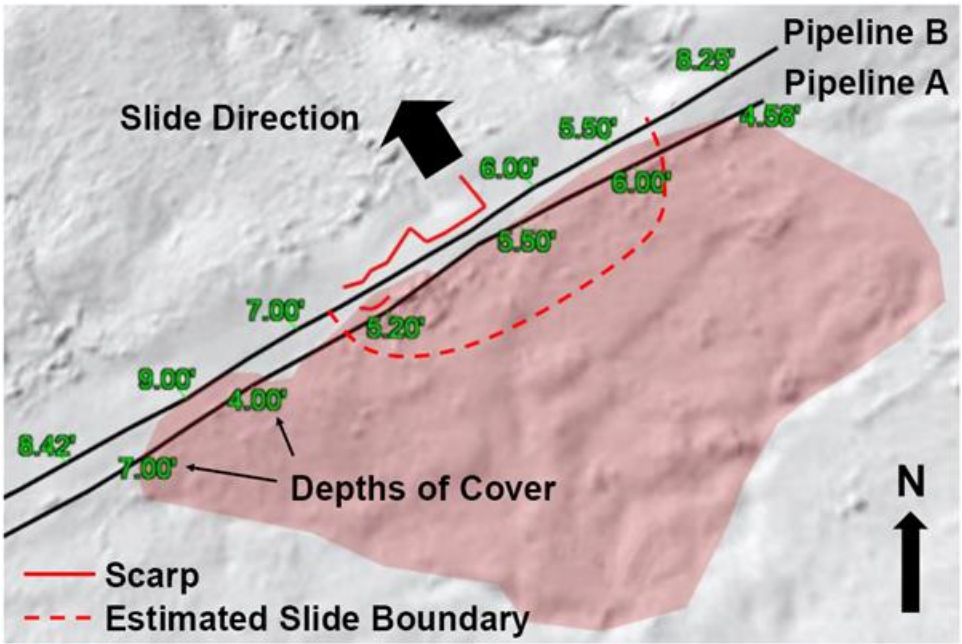


Figure D-1. Schematic illustration of the interaction between two pipelines and a landslide. The dashed line is the landslide boundary established by on-site survey. The pink shaded area is the landslide area identified by LiDAR.

D-2.1 Fitness-for-Service Assessments

Immediately after the pipeline movements were confirmed, an initial strain-based assessment (SBA) was performed. The strain demand was estimated with simplified profile analysis (SD-L1) and the TSC was determined with segment-specific material and geometry characteristics (TSC-L2). Neither pipeline passed the acceptance criterion, which stipulated that the ratio of TSC to strain demand must exceed 1.25: Pipeline A had a strain demand of 1.62% and a TSC of 1.97%, and Pipeline B had a strain demand of 0.78% and a TSC of 0.52%.

Upon completion of the initial SBA, different responses were determined for the two pipelines. For Pipeline A, a refined strain demand analysis was performed to reduce the potential conservatism in the initial strain demand estimate. For Pipeline B, since the strain demand was lower, the potential benefit from a refined strain demand analysis was deemed small. Instead, an in-ditch nondestructive examination (NDE) was performed at the girth weld closest to the peak strain location to verify the flaw condition to support a refined TSC analysis.

The refined strain demand analysis for Pipeline A was performed with pipeline-soil interaction analysis using soil characteristics provided by geotechnical subject matter experts and was verified against the IMU centerline (SD-L2). The refined strain demand for Pipeline A was 0.99%, consisting of 0.47% bending strain and 0.51% extensional strain. The bending strain was very close to the IMU peak strain of 0.44%, indicating the site had not moved significantly since the IMU run. Given the TSC at 1.97%, Pipeline A was considered safe at the time of assessment. Subsequently, the strain demand analysis was expanded by hypothetically increasing the amount of ground movement. The expanded analysis indicated that Pipeline A could tolerate at least an additional 3.0 feet of displacement before reassessment would be needed.

The in-ditch NDE of Pipeline B confirmed that the target weld was defect free. A refined TSC analysis (TSC-L3) was then performed, which increased the estimated TSC to 0.88%. Further, the bell hole excavation indicated that the weld location did not match the as-built record. The strain demand of the target weld at the confirmed location was less than 0.50%. The margin between the TSC and strain demand would allow at least 3.0 feet of additional pipeline movement before reassessment would be needed.

D-2.2 Threat Management Measures

Given the outcome of the SBA, both pipelines were returned to full service. A slide repair was implemented to minimize the likelihood of further ground movement at the site. No strain relief excavation was considered necessary.

D-3 Landslide Assessment Example 3

This example illustrates the considerations and processes for applying FFS assessment to one pipeline displaced by two landslides. The site is located in eastern Ohio. An NPS20 X70 gas transmission pipeline intersected with the boundaries of two adjacent landslides (Landslide 1 and Landslide 2) along the ROW separated by about 350 feet. The landslides and dimensions were initially identified through a Level 1 Assessment and confirmed with a Level 2 Assessment.

The ROW was routed roughly perpendicular to the slope. A pipeline locator survey in late spring 2020 confirmed pipeline movement at both locations. Landslide 1 affected a 160-foot-long segment of the pipeline with a maximum lateral displacement of 3.5 feet. Landslide 2 affected a 130-foot-long segment of the pipeline with a maximum lateral displacement of 2.0 feet.

An FFS assessment was immediately performed for girth welds at both locations. The strain demand was estimated with simplified profile analysis (SD-L1). The peak strain demands were 0.61% and 0.38% for Landslides 1 and 2, respectively. A review of the available MTRs indicated considerable scatter in the pipeline strength. As a result, joint-specific MTRs were used in the subsequent TSC analysis (TSC-L3). One girth weld closest to the peak strain demand location was analyzed for each landslide. Table D-1 lists the strain demand and TSC results, as well as the pipeline and weld material and geometry conditions considered. The TSC of the target weld at Landslide 1 was significantly greater than that at Landslide 2 due to a more favorable weld strength mismatch condition. This led to a greater margin between the TSC and strain demand at Landslide 1 and correspondingly additional tolerance for further displacement.

Following the FFS assessments, a stress-relief excavation was performed at Landslide 2. No stress relief was performed for Landslide 1. A slope stabilization and monitoring program was subsequently implemented at both locations.

Table D-1. Summary of FFS assessments at the two landslides

FFS Analysis Components	Landslide 1	Landslide 2
Peak strain demand (%)	0.61	0.38
Girth Weld TSC (%)	1.46	0.55
Pipeline ultimate tensile strength (UTS) (ksi)	87	100
Weld strength mismatch	0.98	0.85
TSC – strain demand (%)	0.85	0.17
Strain demand/TSC	0.42	0.69
Allowable additional displacement (feet)	4.0	1.0

D-4 Landslide Assessment Example 4

The following example is a summary of an application of the level assessment framework along a pipeline system in Ohio. The pipeline system consists of two pipelines: an 8-inch-diameter pipeline and a 12-inch-diameter pipeline. The level assessment resulted in identifying a specific landslide that progressed through all three assessment levels as well as threat management measures.

D-4.1 Level 1 Assessment

In the Level 1 Assessment, the pipeline operator obtained LiDAR digital elevation model (DEM) data at two different times during 2020 (late spring and fall). The late spring LiDAR data were acquired with leaf-on conditions, which resulted in low-quality DEM data. Nevertheless, LiDAR hillshade data were evaluated in the Level 1 Assessment during the summer to identify landslides and possible landslides. Although the LiDAR DEM data were low quality, a possible landslide was identified that appeared to cross the 8-inch-diameter pipeline with its right lateral flank.

An additional LiDAR mission was flown in fall 2020 in leaf-off conditions to obtain higher quality DEM bare-Earth data for use in the Level 1 Assessment. The higher-quality fall LiDAR DEM hillshades revealed that the landslide had distinct, young geomorphic features (headscarp, toe, and body) and was much larger than identified in the low-quality spring data. The fall data also showed that the landslide perpendicularly crossed both the 8-inch-diameter and 12-inch-diameter pipes. A Level 2 Assessment field reconnaissance was recommended to further define and confirm the limits and nature of the landslide.

D-4.2 Level 2 Assessment

A Level 2 Assessment field reconnaissance was implemented in the first part of 2021 to confirm the geomorphic limits of the landslide and to survey the locations of the 8-inch-diameter and 12-inch-diameter pipes relative to the landslide and the depths to the pipelines within the landslide limits. The conclusion from the Level 2 Assessment that the pipelines were likely impacted by the landslide led to the decision to conduct a Level 3 Assessment.

D-4.3 Level 3 Assessment

Due to uncertainty around the depth of the landslide slip surface after the Level 2 Assessment, a slope stability analysis was performed to estimate the landslide failure surface depth (i.e., the depth of the material moving downslope). The slope stability analysis indicated the land movement was likely pushing into the downslope overbend portions of the pipelines and that the pipelines were likely displaced and stressed by the landslide. As such, a subsurface investigation was completed through test pit excavations to explore subsurface conditions within the landslide. The test pit excavations revealed that groundwater, plastic clay, coal seams, and colluvium (unstable landslide-deposited soils) were present within the landslide. Hard bedrock was not present in the test pits within 15 feet of the existing ground surface. The test pit excavations also confirmed that the landslide failure plane was likely located below the pipelines and that the pipelines were likely displaced by the landslide.

D-4.4 Threat Management Measures

Because the results of the test pits confirmed that the pipelines were likely displaced and stressed by the landslide, stress-relief excavation and exposure of the pipelines was implemented to reduce the accumulated stress in the pipelines. Slope stability analyses indicated that draining groundwater in the landslide could potentially halt or slow the landslide movement. Therefore, French drains were installed at targeted locations within the landslide mass to intercept groundwater within the slope and divert it to the stream downslope. While the pipelines were exposed during the stress-relief excavation strain gauges were installed at multiple locations on each pipeline. After the site was restored, slope inclinometers (SIs) were installed between the pipelines to measure subsurface ground movement.

D-5 Landslide Assessment Example 5

This example is a fictitious scenario based on the following:

A pipeline owner-operator has recently purchased an existing pipeline system from another owner. The previous owner had not implemented a Pipeline Geohazard Management Program (PGMP) along the pipeline system, and there are no data in the previous owner's files regarding the presence of landslide hazards. The pipeline system traverses more than 300 miles of hilly and mountainous terrain of its total 500-mile length. The new owner-operator chooses to implement a sequential level landslide hazard assessment of the newly acquired pipeline to supplement its own PGMP and to address potential landslide hazards.

D-5.1 Level 1 Assessment

For the Level 1 Assessment, the operator decides to focus on the 300 miles of sloping terrain and institutes a desktop study of available data to identify landslides and potential landslides. Available topographic, DEM, and geologic data, as well as available public LiDAR data are acquired for use in the assessment. Although the topographic, DEM, and geologic data have comprehensive coverage of the pipeline alignment, the LiDAR data provide only partial coverage. Therefore, the operator initiates LiDAR data acquisition for the uncovered portion of the 300 miles of pipeline.

All these data are integrated into the operator's existing GIS and database in the PGMP. The data are reviewed by a subject matter expert contractor, and 12 landslides or potential landslides are identified in the Level 1 Assessment.

The landslides are primarily identified from the geomorphic review of the LiDAR data in GIS, their boundaries are mapped, and the landslides are initially characterized based on their geomorphic characteristics. The 12 landslides are threat classified based on their types, apparent age of movement (from geomorphic expression), and relative location with respect to the pipeline alignment (i.e., do they cross the alignment or are they in very close proximity). Of the 12 landslides, 2 are found to cross the pipeline alignment; therefore, these 2 are recommended for a site-specific field-based Level 2 Assessment to resolve whether they engage or potentially impact the pipeline.

D-5.2 Level 2 Assessment

In the Level 2 Assessment, a field team of two geohazard professionals visits the two landslides and completes geomorphic and geologic mapping of each to delineate the type of landslide, the lateral limits of the landslide, the landslide features (e.g., main scarp, lateral flanks, the toe area, the zone of depletion and zone of accumulation, the nature of the landslide mass and the vegetation growing on it), and the location and orientation of the pipeline crossing of the landslide (e.g., perpendicular, oblique, parallel). In addition, the pipeline alignment and depth of cover are documented through the landslides using field location surveys, and the pipeline position and depth are flagged in the field. All of these landslide features and locations are documented in field smartphones or tablets that are enabled with global positioning system (GPS) and GIS and then entered into the GIS database.

A review of the collected data reveals that one of the landslide types is a translational slide, and the pipeline crosses the toe area and is thus in the zone of accumulation. That means the landslide moved over the ground surface and is above the pipeline depth of cover, and the landslide does not engage or affect the pipeline. The second landslide is identified as a rotational slide, and the pipeline is located perpendicular to landslide movement in the zone of depletion. Through examination of the geometry of the main and lateral scarps and the nature of the landslide mass, the thickness of the landslide and the depth of the surface of rupture are estimated to be 10 feet. Pipeline location surveys indicate that there is a bend in the pipeline in the direction of the downhill movement of the landslide, and the depth of cover of the pipeline through the landslide varies from 3 to 5 feet. These data indicate that the rotational slide has engaged the pipeline, and the second landslide is recommended for a Level 3 Assessment.

D-5.3 Level 3 Assessment

For the Level 3 Assessment, four geotechnical boreholes are drilled—two within the landslide mass adjacent to the pipeline and two on either side of the pipeline crossing. The boreholes within the landslide are drilled to depths below (>10 feet below) the surface of rupture to identify and characterize the landslide material, the intact material below the landslide, and the depth of the surface of rupture. The two boreholes on either side of the landslide are drilled to characterize the undisturbed slope material. Samples of the material from all four boreholes are sent to the laboratory to test for geotechnical engineering properties (e.g., grain size, clay content and Atterberg limits, shear strength). SIs are installed in all four boreholes, along with vibrating-wire (VW) piezometers, to collect data on subsurface slope movement and groundwater conditions (both within and outside of the landslide). Refraction geophysical data are also collected from intersecting grid survey lines across the landslide to image the geometry of the base (rupture surface) of the landslide. All of the data from the Level 3 Assessment are used to inform decisions regarding mitigation approaches and design for this site and to develop and implement future slope monitoring plans.

D-6 Landslide Assessment Example 6

This next example is also a fictitious scenario, but it is based on the actual experiences of the authors. In this example, a natural gas pipeline operator commissions the performance of a Level 1 Assessment for an approximately 500-mile-long transmission pipeline system located in a forested, hilly area (such as Tennessee or New England) shortly after the initiation of their PGMP. This example, in contrast to the others provided, is intended to show the flexible nature of the leveled assessment structure and that for many locations, analysis does not need to be taken past a Level 1 Assessment.

D-6.1 Level 1 Assessment

For the Level 1 Assessment, the operator hires a LiDAR vendor to collect LiDAR data for the entire pipeline system, with the collection corridor being approximately 1,500 feet wide (750 feet to either side of the pipeline centerline) to allow for potentially large landslides to be identified. For optimal data collection, the LiDAR data is collected during the spring, after the snow has melted but before leaf-out occurs.

The LiDAR data, once collected, are processed and reviewed in GIS by a geotechnical consultant experienced with similar assessments. The geotechnical consultant also cross-compares the LiDAR data with public landslide mapping from state agencies, geologic maps, and the locations of IMU bending strain features.

The consultant identifies 10 likely landslides within the reviewed area, all more than 50 feet away from a pipeline centerline. Based on the location and size of the likely landslides, the consultant concludes that they are unlikely to affect the pipelines being assessed without significant expansion. The area is hilly but appears to be generally geologically stable with little regional landslide activity. This conclusion is supported by the lack of mapped landslides in the vicinity of the pipeline and the geologic mapping, which shows that the underlying bedrock (such as limestone and granite) is rarely associated with landslides.

Separately, the operator has previously collected IMU data analyzed by the ILI vendor for bending strain and reviews existing pipeline records to conduct an initial assessment of the pipeline resiliency to landslides. Based on the IMU data review, no bending strain features consistent with landslides are identified.

The consultant and operator review the results of the assessment and conclude that the overall exposure to landslides for this system is low and the pipeline does not appear to be impacted by landslide movement; thus, no Level 2 Assessment is needed.

D-6.2 Threat Management Measures

As summarized above, the exposure to landslides for the reviewed system is low, but not nonexistent (i.e., some landslides were identified in the vicinity of the pipeline segment in the

Level 1). The pipeline operator decides on a threat management program consisting of the following:

- Performing IMU bending strain analysis when ILI runs scheduled for other integrity threats are performed. The bending strain data is reviewed to evaluate whether the detected bending strain features are indicative of possible landslide movement.
- Conducting a Level 1 Assessment every 10 years. The repeat Level 1 Assessments evaluate whether new landslide hazards have developed that might pose a threat to the pipeline.

These measures allow the operator to assess whether there are changed conditions that would necessitate additional assessment.

The results of the Level 1 Assessment are stored in GIS and used to inform the operators internal risk model. The results are also available in the event of a regulatory audit to demonstrate that the operator has conducted a Level 1 Assessment and for use in justifying the threat management program, in accordance with the recommendations of this document.

Annex E
Data Management

Annex E: Data Management

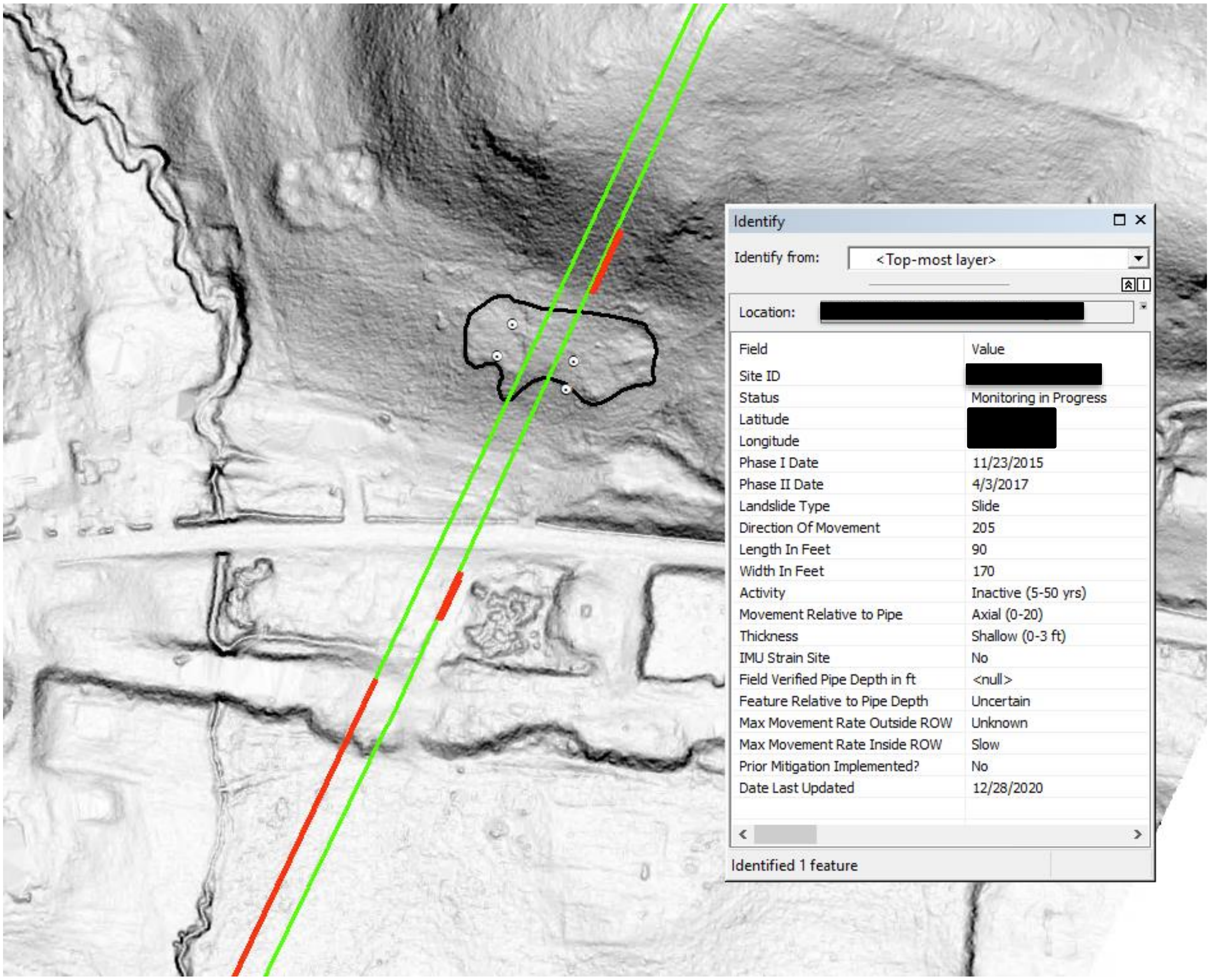
E Introduction

A well-developed landslide hazard management program will result in generating continuously expanding and evolving sets of data, with collected information varying widely in source, type, format, size, and date. Having efficient mechanisms in place to sort and store data as they are generated and to retrieve data as they are needed can limit rework, prevent overreacting or underreacting to scenarios as they arise or evolve, help with efficient and informed decision-making, and ultimately help minimize risk.

This annex discusses landslide-specific data relevant to pipeline systems. It is assumed that other types of data that may be relevant to analysis of landslide threats to pipeline systems, such as pipeline characteristics (e.g., diameter, wall thickness, grade, year of installation, coating type) and locations and characteristics of interacting threats are maintained as part of an operator's data management system (such as in a Pipeline Open Data Standard [PODS] database). These data, not being landslide specific, are not described herein.

E-1 Landslide Hazard Data

The most important component of data management for a landslide hazard management program is maintaining a comprehensive, up-to-date landslide inventory. This inventory should track potential landslide hazards (e.g., location, type, threat level) and document changes through time (e.g., changing hazard conditions or site activities, such as assessments or remediation that may be completed through time). As such, the landslide inventory should be established to maintain both spatial and nonspatial data, which both can be managed in some form of a geographic information system (GIS) platform (e.g., ESRI ArcGIS). Figure E-1 shows an example of spatial and nonspatial data in a GIS platform.



Note: In this image, spatial data include landslide boundary (black line), pipeline centerlines (green lines), inertial measurement unit (IMU) bending strain features (red lines), survey points (white points), and light detection and ranging (LiDAR) slope map (background imagery). Nonspatial data are presented in the inset table, which lists details for the landslide. The references to "Phase I" and "Phase II" are synonymous with the usage of "Level 1" and "Level 2" as described herein.

Figure E-1. Spatial and nonspatial data in a GIS platform

For landslide management, the following data are typically maintained in a GIS database:

- Delineated landslide hazard boundaries (e.g., mapped landslide footprints that can be viewed on a two-dimensional map).
- Information associated with each landslide hazard. These data could be embedded in a table tied to the spatial data. Table E-1 below provides an example list of key information that

could be beneficial to track for each identified landslide in the inventory. This list should be modified accordingly, to fit the operator's program.

- Observations and records from multiple events (e.g., aerial reconnaissance, ground visits, monitoring events), which track the site history. These data could also be embedded in a table and tied to the spatial data. Table E-2 below provides a list of key information that could be tracked for each event carried out at each site. This table could be set up whereby multiple events could be entered and tied to a single landslide hazard.
- Supporting documents and files (e.g., reports, photographs). These data sets could be directly uploaded and linked in the GIS platform or stored outside of the system in a separate filing system (e.g., private server, SharePoint) and linked with a hyperlink or directory path.

Table E-1. Suggested data to record for landslide hazard characterization

Field Name	Description
Hazard Identification (ID)	A unique, arbitrary ID assigned to each hazard feature.
Threat Classification	Hazard classification based on perceived threat to the pipeline.
Latitude	The latitude for the centroid of the hazard.
Longitude	The longitude for the centroid of the hazard.
County	The county in which the hazard is located.
State	The state in which the hazard is located.
Distance to Pipeline (feet)	The distance from the landslide to the pipeline. If the landslide crosses the pipeline, this should be listed as 0.
Field Verified Pipeline Depth (feet)	Depth to pipeline in feet within the landslide boundary or adjacent to the landslide (if landslide does not cross the pipeline) based on field measurement. May be presented as a range.
Landslide Mapping Confidence	The confidence of identification by the analyst.
Landslide Type	The primary type of landslide (e.g., slide, flow, fall).
Landslide Length (feet)	The maximum downslope length of the landslide.
Landslide Width (feet)	The maximum distance perpendicular to the line that defines the length.
Landslide Activity	An estimate of the current state of activity of the hazard (e.g., active, inactive, dormant).
Landslide Direction of Movement	The azimuthal direction of movement from 0° to 360°. If landslide has more than one major direction of movement, value should represent movement closest to pipeline.
Landslide Movement Relative to Pipeline	The direction of movement relative to a pipeline (i.e., transverse, oblique, axial).
Landslide Maximum Movement Rate (feet/year)	An estimate of the maximum rate of movement of the landslide. Can be based on instrument data or geomorphic observations.
Landslide Thickness in feet	The estimated maximum thickness at the pipeline centerline or closest point to the pipeline. Can be presented as a range.

Field Name	Description
Landslide Relative to Pipeline Depth	The estimated relationship of the landslide failure surface to the pipeline (e.g., above, below, uncertain) based on observed geomorphology, interpreted landslide type, slope geometry, etc., and/or direct instrument measurements (e.g., inclinometers) or modeling.
Inertial Measurement Unit (IMU) Strain Site	Indicates if an IMU bending strain feature is within or near the landslide.
Mitigation Status	Indicates if mitigation measures have been implemented at the site (e.g., none planned, planned, ongoing, completed).
Monitoring Status	Indicates monitoring status at the site (e.g., none planned, planned, ongoing, completed).
Summary	A complete description of the landslide hazard, based on data collected during all assessments completed to date at the site.

Table E-2. Suggested data to record for events related to individual landslides

Field Name	Description
Hazard Identification (ID)	A unique, arbitrary ID assigned to each hazard feature (i.e., used to tie tabular data herein to the landslide shape and other tabular data).
Event Type	Type of event (e.g., Level 1, Level 2, Level 3, aerial reconnaissance, mitigation, monitoring, inertial measurement unit [IMU] bending strain review, light detection and ranging [LiDAR] change analysis).
Event Date	Date on which event was completed.
Event By	The name of the company and individual(s) that conducted the event.
Event Comments	A description of the activities completed and observations of the hazard during the event (or before and after if changes to the site are made during event).
Hazard Classification Prior	Hazard classification based on perceived threat to the pipeline.
Hazard Classification After Event	Hazard classification based on perceived threat to the pipeline (i.e., can be the same as Hazard Classification Prior if nothing has changed).
Justification for Hazard Classification Change	If hazard classification is updated as a result of the event, provide comments justifying change.

The following are additional items to consider when developing a landslide hazard inventory data set:

- It is critical to establish a unique Hazard Identification (ID) for each feature in the inventory and use this as the primary reference name for the site. The Hazard ID can be used to tie together all types of data for the individual site and allows for an organized filing system both internal and external to the GIS platform.
- If a mapped landslide is at any point determined not to be a landslide, it should remain part of the inventory in some form, and it should be documented why the site was concluded to not be a landslide. The features can be kept in the same data set and denoted as "not a landslide" or pulled into a separate data set. This process maintains a record of the location so that it will not be misidentified again in the future. Similarly, landslides that have been remediated or mitigated should be maintained in the inventory.
- It will likely save time and effort to set up a complete landslide hazard inventory data set at the start of a program to make sure data are collected in a comprehensive and consistent manner. If a program is already underway, existing data sets can be consolidated into a comprehensive and consistent data set, which can then be used going forward, even if not all information is available for historical data.
- Each event at a location should be tracked, even if to say the site was visited on a certain date and no changes were noted from the last visit, which can be helpful to constrain the timing of activities that occur between events.
- Historical data pertaining to specific sites (e.g., prior boundaries, site history) should be maintained in some form.

E-2 Monitoring Instrumentation Data

Monitoring data collected from various types of instruments are critical to a landslide hazard management program where monitoring is used as a method for risk reduction. Similar to landslide hazard data, a monitoring instrument inventory should be maintained to track locations and key information about monitoring. The monitoring inventory should be linked to the landslide hazard inventory, either directly or indirectly, via the landslide Hazard ID. The key components for the monitoring instrument inventory are as follows:

- Spatial location (e.g., plotted as a point or shape in GIS) of each instrument
- Type and characteristics of the instrument, such as instrument type, depth, and installation date
- Nature of the monitoring, such as manual versus automated data collection and frequency of monitoring

Table E-3 below provides a list of key information that could be tracked for each monitoring instrument in the inventory.

Table E-3. Suggested data to record for monitoring instrument inventory

Field Name	Description
Hazard ID	A unique, arbitrary ID assigned to each hazard feature (i.e., used to tie tabular data herein to the landslide shape and other tabular data)
Instrument ID	Unique instrument ID
Instrument Type	Instrument type (e.g., strain gauge, inclinometer, shape-accel-array [SAA], extensometer, piezometer, remote monitoring unit [RMU])
Date Installed	Date of installation
Installer	Company that installed the instrument
Status	The status of the instrument (e.g., in service, not in service)
Latitude	The latitude of the instrument
Longitude	The longitude of the instrument
Data Collection Type	Method of data collection (e.g., manual, automated)
Data Collection Frequency	Frequency of data collection (e.g., hourly, daily, weekly, monthly)
Comments	Anything of note specific to the instrument
Date Last Monitored	Date of last recorded measurement
Date Abandoned	Date deactivated or abandoned

In addition to tracking where and how monitoring is occurring, it is also important to maintain the actual results of the monitoring (such as microstrains over time collected from strain gauges). These results should be collected and stored in such a way that the data can easily be tied back to the instrument inventory data and hazard site to provide appropriate context for results. Each type of monitoring instrument data should be recorded and maintained in the manner appropriate for the data type and collection frequency. If awareness or action thresholds are set for monitoring results, these should be identified with the results for quick identification of exceedances or set up with automated alerts to notify preset parties of exceedances in real time.

E-3 Mitigation Data

When mitigation measures are implemented at a landslide hazard site, details of the mitigation measures should be recorded and maintained in a mitigation inventory. The mitigation inventory should be linked to the landslide hazard inventory, either directly or indirectly, via the landslide Hazard ID. The key components for the mitigation inventory are as follows:

- Spatial location (e.g., shown on an as-built drawing, plotted as point(s) or shape(s) in GIS, or presented in a latitude and longitude table) of installed mitigation measures, if available and applicable
- Type and characteristics of mitigation measures (e.g., type, depth, and installation date)
- Objectives of mitigation (e.g., the mitigation plan included stabilization of the landslide to reduce further strain demand on the pipeline, or the mitigation plan included a stress-relief excavation to reduce the existing strain demand on the pipeline)

- Conceptual drawings or as-built drawings
- Photographs
- Field notes collected during installations (e.g., daily field reports)
- Other forms of supporting documentation produced before, during, or after mitigation is implemented

E-4 Bending Strain

Inertial measurement unit (IMU) bending strain data collected during in-line inspection (ILI) runs can provide key information for understanding whether a pipeline has been impacted by a landslide hazard and, if so, to what degree. IMU data can be used to identify landslide hazards (e.g., in the case where a landslide hazard is not known to exist at a location but is identified through review of IMU bending strain features) and to evaluate if known landslide hazards appear to have impacted a pipeline and to what degree (e.g., in the case where a known landslide hazard location coincides with a detected bending strain feature). As with other relevant data types, a comprehensive inventory of all IMU bending strain data can be helpful for landslide hazard management, including both spatial and nonspatial information.

The spatial data (e.g., GIS lines) associated with IMU bending strain features are best represented by a line segment representing the total length of the segment of pipeline over which strain is detected as well as the point location of the detected peak strain. When overlain with landslide footprints, IMU locations can provide context as to whether the detected bending strain could be related to landslide movement or to a separate cause and only coincidently collocated with a landslide.

Table E-4 below provides a list of key information that could be tracked for each IMU bending strain feature.

Table E-4. Suggested data to record in an IMU bending strain inventory

Field Name	Description
Import data provided by the in-line inspection (ILI) vendor as-is (e.g., strain magnitudes, strain direction, absolute distances)	
Bending Strain Feature	A unique, nonrepeating ID assigned to each bending strain feature
Date of Prior Run	Date of the prior run
Date of Current Run	Date of the current run
Year of Current Run	Year of current run
Tool Combo Prior	The tool combo of the prior run
Tool Combo Current	The tool combo of the current run
Vendor Prior	ILI vendor of the prior run
Vendor Current	ILI vendor of the current run
Contract	Contract number from the ILI vendor (for tracking and cross-referencing)

Field Name	Description
Pipeline Name	The pipeline name
Strain Demand Limit Pipe	The strain demand limit for the pipeline body (this can be the same as the strain demand limit for the welds if these have not been separately calculated)
Strain Demand Limit Weld	The strain demand limit for welds (this can be the same as the strain demand limit for the pipeline if these have not been separately calculated)
Length	The length of the bending strain feature (calculated because some ILI vendors do not report this detail)
Geomorphic Review Comments	Text description of the geomorphic review of the site
Bending Strain Plot Review Comments	Text description of the bending strain plot review
Strain Type	The strain type (e.g., unlikely external force, likely external force, uncertain)
Hazard ID	Landslide ID. Input landslide ID if strain site is within or close to previously identified landslide. The term “close” is subjective, but generally should be within about 20 feet of the landslide.
Location	The location of the strain site. The order of precedence is landslide, crossing (road, stream, railroad, etc.), and noncrossing areas (fields, forests, wetlands, etc.)
Reviewed By	The company or entity that performed the review

It can often be useful to have a spatial index data set for IMU runs that provides the map footprint for pipeline segments with available IMU run data along with run dates for available data. This allows for a quick determination of data availability at any given location. For example, the absence of an IMU feature at a given landslide location might be because IMU data have not been collected for the pipeline segment or might be because there is no detected strain at that location. Likewise, if multiple IMU runs have been conducted for a single segment, an understanding on the timing of formation of detected strains may be possible.

E-5 Remote Sensing Data

Remote sensing data, such as light detection and ranging (LiDAR) data, interferometric synthetic aperture radar (InSAR) data, or aerial imagery, can be useful for several purposes in landslide hazard management, including the following:

- Initially identifying and delineating landslides
- Understanding the history of a site, where data sets are available from multiple dates (e.g., it might be possible to discern when a landslide first formed, when it last moved or expanded, and if it has been mitigated)
- Monitoring known landslide locations for movement through time

- Modeling the site (e.g., slope stability), developing monitoring and mitigation designs, and planning implementation (e.g., site access, identifying work areas)

Remote sensing data may be available both through public sources (e.g., the United States Geological Survey [USGS] or state agencies) or through operator-specific data collection. Whether the data is public or private, it is important to pay close attention to the date of acquisition because landslides are dynamic in nature and can continue to change through time. Thus, what is reflected by remote sensing data might have changed since the date of collection.

Because remote sensing data are useful for several purposes, it can be highly valuable to have the data readily available for viewing and use, along with the landslide inventory. LiDAR data should be available and viewable as a bare-Earth digital elevation model (DEM), along with derivatives that help highlight geomorphic features (e.g., hillshades, slope maps).

It can often be useful to have a spatial index data set that provides the map footprint for available remote sensing data along with key aspects of the data, such as the type of data, acquisition date, resolution, and source, to allow for a quick determination of data availability at any given location.

E-6 Other Supporting Information

Other types of data that are useful to track and maintain for each landslide hazard site, when available, include the following:

- Site photographs, which should be filed by date and tracked by landslide Hazard ID
- Pipeline as-built data or alignment sheets from construction
- Site-specific investigations, such as reports or stand-alone subsurface data, laboratory data, pipeline characteristics

E-7 Program Management and Execution Support

Aside from the landslide inventory and other associated inventories described above, the data management system can be used to support program management and execution. For these purposes, data sets such as the following can be useful to develop and maintain:

- Tracking of large-scale (i.e., non-site-specific) assessments, including details on the following:
  - Segments covered by these assessments
  - Hazards considered under these assessments
- Intervals at which non-hazard-specific monitoring is conducted (such as repeat ILI or remote monitoring)
- Scheduled date of the next reassessment
- Tracking/task lists
- Planned activities and due dates, with built-in, automated reminders.

Annex F
Classification and Decision-Making Systems

Annex F: Classification and Decision-Making Systems

F Introduction

This annex provides guidance and considerations for implementing or improving a landslide threat classification and decision-making (CDM) system for landslide hazard management. A CDM system is the process by which data collected from assessment or monitoring is used to determine the following:

- Whether to perform additional assessment or implement a threat management action
- If an action is to be performed, the nature of that action (e.g., whether to conduct additional assessment, implement mitigation measures, implement monitoring, perform a combination of these actions, or conduct no further action)
- The timing or order of conducting actions (i.e., the prioritization)

F-1 Landslide Classification and Decision-Making Overview

At the time of this publication, there are no universally accepted pipeline landslide CDM systems, although there have been various attempts (such as the ones provided as examples in ISO 20074, McKenzie-Johnson et al., Wang et al., Herr and Atkinson, and Joehan et al.). [4, 12, 14, 66, 67] The reason for this lack of a universal CDM system pertains to the variety of landslides that can occur and the variety of ways in which these landslides can interact with a pipeline. In addition, there are varying regulatory environments, local land uses, and pipeline operator and owner internal structures and cultures that can affect the feasibility of various risk-management measures.

In the absence of a universal standard, it is up to each pipeline operator to establish its own CDM system. The CDM system is interlinked with most of the other major processes described in this document.

While the form of a CDM system varies by operator, each CDM system should contain the following:

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

F-1.1 Classification and Decision-Making Strategies

As discussed above, CDM systems are the process by which decisions are made on how to manage landslide threats. These decisions are informed by the CDM system, which uses data collected during the assessment and monitoring processes. CDM systems range from a process with no predefined criteria (referred to herein as a "case-by-case strategy") to ones where actions are prescribed based on predetermined criteria (referred to herein as a "prescriptive or semiprescriptive" system).

In a case-by-case strategy, the process may be defined for decision-making (e.g., who reviews collected data and who makes the decisions), but no predetermined or preestablished requirements dictate or recommend whether to take additional action, what action to take, or when to take it. The major disadvantages of the case-by-case strategy are that it can be time and labor intensive, the determinations made tend to reflect the risk tolerance of individual(s) rather than risk tolerances of a group or owner, and it can be difficult to establish consistency of action over time. Nevertheless, a case-by-case strategy for decision-making can be appropriate when an operator has only a small number of landslides and landslide-prone areas to address, and thus it can be unduly burdensome to prepare a CDM with predefined response criteria prior to implementing action.

If a pipeline system has numerous landslides and landslide-prone areas, establishing a prescriptive or semiprescriptive CDM system generally improves efficiency and consistency (both within the pipeline operator and between consultants supporting the operator). It also allows the overall risk tolerance of the pipeline operator rather than the individual to be accounted for in decision-making.

A key consideration for a prescriptive or semiprescriptive system is defining what level of quantification and prescriptiveness the system will have. The degree of quantification can be conceived of as a sliding scale from qualitative, where threat classification is entirely dependent on subject matter expert (SME) judgment, to quantitative, where classification is entirely determined by statistical or mechanical models, with no judgment component other than that used to create the original models.

Prescriptiveness can also be conceived of as a sliding scale ranging from wholly nonprescriptive to wholly prescriptive. That is, prescriptiveness ranges from decision-making on a case-by-case basis (discussed previously) to entirely predetermined and preestablished decisions. The advantage of a wholly prescriptive system is that it transfers the decision-making from individuals to the approach that the company has set. This ultimately increases efficiency and the likelihood of consistency of practice. The primary disadvantage of a wholly prescriptive system is that it either lacks the flexibility to accommodate the natural variability associated with landslides or, to account for all possible permutations, it becomes highly convoluted, overly conservative, or difficult to execute.

This guideline recommends a semiprescriptive, semiqualitative approach that is referred to as the "95-percent concept" for implementing a CDM system, originally discussed in McKenzie-Johnson et al.[12] The 95-percent approach is a conceptual idea that in most cases (e.g., 95%) the vast majority of landslide and pipeline scenarios will fall into a manageable number of options and can be managed prescriptively. The exceptions to these scenarios (e.g., 5%) can be managed on a case-by-case basis.

The advantage of the 95-percent concept is that it allows for most landslide hazards to be addressed prescriptively, making the process of determining response actions fast, efficient, and consistent. However, there is flexibility to address situations that do not fall under predetermined criteria. This approach streamlines the decision-making process and enables landslides to be managed over the long distances traversed by pipeline networks.

The following are key requirements of the 95-percent concept:

- Landslide hazards should be classified into categories or buckets based on common characteristics (e.g., the estimated displacement of the landslide, estimated typical rate of displacement, estimated depth of rupture surface, landslide movement direction relative to the pipeline, distance from the pipeline, preexisting pipeline strain induced by the landslide, whether the landslide is active or inactive, pipeline characteristics). The characteristics of the landslide and the pipeline determine the response; thus, applicable landslide and pipeline characteristics should be included in the classification system.
- Hazard and threat classification categories or buckets should be tied to response options and possibly supplemented by a ranking or probability-of-failure (POF) value. By tying the response options to the classification, the decision-making process is simplified and made more consistent than in a case-by-case approach.
- The buckets should be developed with a focus on those landslide and pipeline scenarios likely to affect the operator's pipeline network, consistent with the 95-percent concept. The buckets should not be designed to account for all situations that could be encountered.
- The CDM system can be revised if new pipelines are added or if information is acquired that necessitates additional categories.

F-1.2 Classification and Decision-Making Considerations

When designing a CDM system, the operator should consider the following:

- The extent to which the landslide CDM system should be similar to preexisting systems for other hazards managed by the operator (e.g., other geohazards, corrosion, and stress-corrosion cracking [SCC]). Having a similar approach and terminology, to a reasonable degree, will help integrate the CDM system within the operator's integrity management programs.
- The types of landslide hazards likely to affect the operator's pipelines.
- The degree or level of prescriptiveness required by the system.
- The group responsible for implementing the CDM system (i.e., which group is responsible for classifying hazards and deciding what actions to implement).
- The data requirements needed to implement the CDM system. These data are collected during the assessment process (Section 5 and Annexes B and C); thus, these processes should be interlinked with the CDM system.
- The type of consequences and extent to which these consequences are incorporated into the CDM system.

- The operator's risk tolerance and resource availability. This informs the decision-making component of a CDM system in that the actions specified or suggested under the CDM system should be realistic for the operator to implement.

F-1.3 Implementation of Classification and Decision-Making

When a CDM system is implemented, three parts of landslide hazard management are affected:

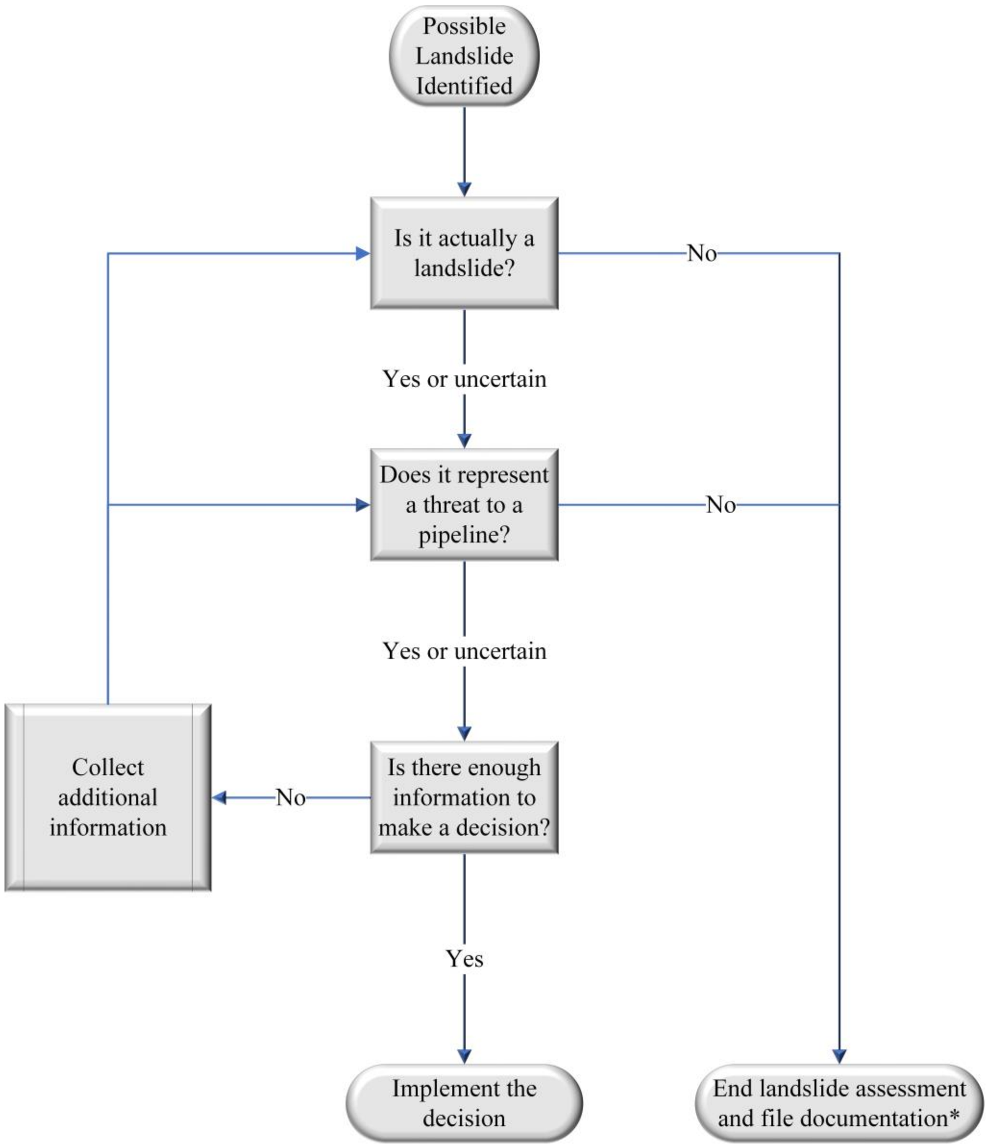
- Assessment of newly identified landslide hazards or possible landslide hazards. Here, the CDM system serves to establish the level and type of information needed to make a decision and to allow for a decision to be made and implemented once enough information has been collected.
- Establishment of the type of threat management actions to take once sufficient information has been collected. Here, the CDM system serves to establish the type(s) of threat management measures to be implemented.
- Ongoing monitoring of previously identified landslide hazards. Here, the CDM system serves to determine whether additional action is needed based on monitoring results and to establish the type of action(s) to take if additional action is needed.

F-1.4 Classification and Decision-Making for Newly Identified Landslides or Possible Landslides

The CDM system addresses three key points at each level of the assessment process:

1. Verification of the landslide
2. Evaluation and refinement of the understanding of the landslide threat to the pipeline system
3. Indication of whether sufficient information has been collected to determine a response or whether additional information is needed

This process is conceptually shown in Figure F-1.



* The result of the assessment may conclude that the site is not a landslide but could be a separate type of geohazard (e.g., subsidence feature) or other possible integrity threat. In such a case, appropriate further assessment for the type of integrity threat should be performed.

Figure F-1. CDM flowchart for newly identified possible landslides

Once enough information is collected to determine a response, there are two broad categories of options: (1) acceptance or (2) implementation of threat management measures.

Acceptance is an informed decision that current preventative and mitigative measures are adequate, and no additional action is required prior to the next scheduled assessment.

Threat management measures either reduce the likelihood of negative event occurrence or reduce the consequence from such an event or both. Threat management measures are commonly divided into two large groups: (1) monitoring measures and (2) mitigation measures.

Monitoring is usually the preferred approach when there would be sufficient time to respond (e.g., situational mitigation or consequence reduction) to anomalies before there is a negative consequence. Mitigation measures are usually the preferred approach when monitoring would not give sufficient time to implement measures to reduce threat to an acceptable level in the event of landslide movement or occurrence.[14]

Once enough information has been collected to determine a response, the decision-making process is essentially as follows (Figure F-2):

1. Step #1: Is the threat from the landslide or landslide hazard area sufficiently high to warrant further action? If no, then implement acceptance. If yes, then proceed to Step #2.
2. Step #2: In the event of further or new landslide movement, can the landslide be managed through monitoring? If yes, manage the landslide through monitoring. If no, proceed to Step #3.
3. Step #3: Manage the landslide through mitigation measures.

Once it has been determined whether to manage a landslide through monitoring or mitigation measures, the CDM system prescribes or recommends a particular monitoring or mitigation approach. In general, it is easier to prescribe monitoring approaches than mitigation approaches because there are fewer viable monitoring options than mitigation options and fewer factors need to be considered when implementing monitoring.

For most landslide-prone areas, there will usually be more sites monitored than mitigated. Thus, it is recommended that the CDM system have semiprescriptive elements for selecting monitoring approaches, while mitigation decisions be made on a case-by-case basis.

[14] The individual operator is to determine what the operator defines to be "sufficient time" or an "acceptable threat level" based on the characteristics of an operator's pipeline system and an operator's risk tolerance. Because there are no regulatory requirements that prescribe what constitutes a "high" landslide risk or "sufficient" time, these are defined by each operator. With respect to time-based decision-making (e.g., "sufficient" time), the operator should consider what monitoring options are realistic for that operator. Monitoring that is conducted daily may have a different threshold for sufficient time for response than monitoring that is conducted once every 2 years.

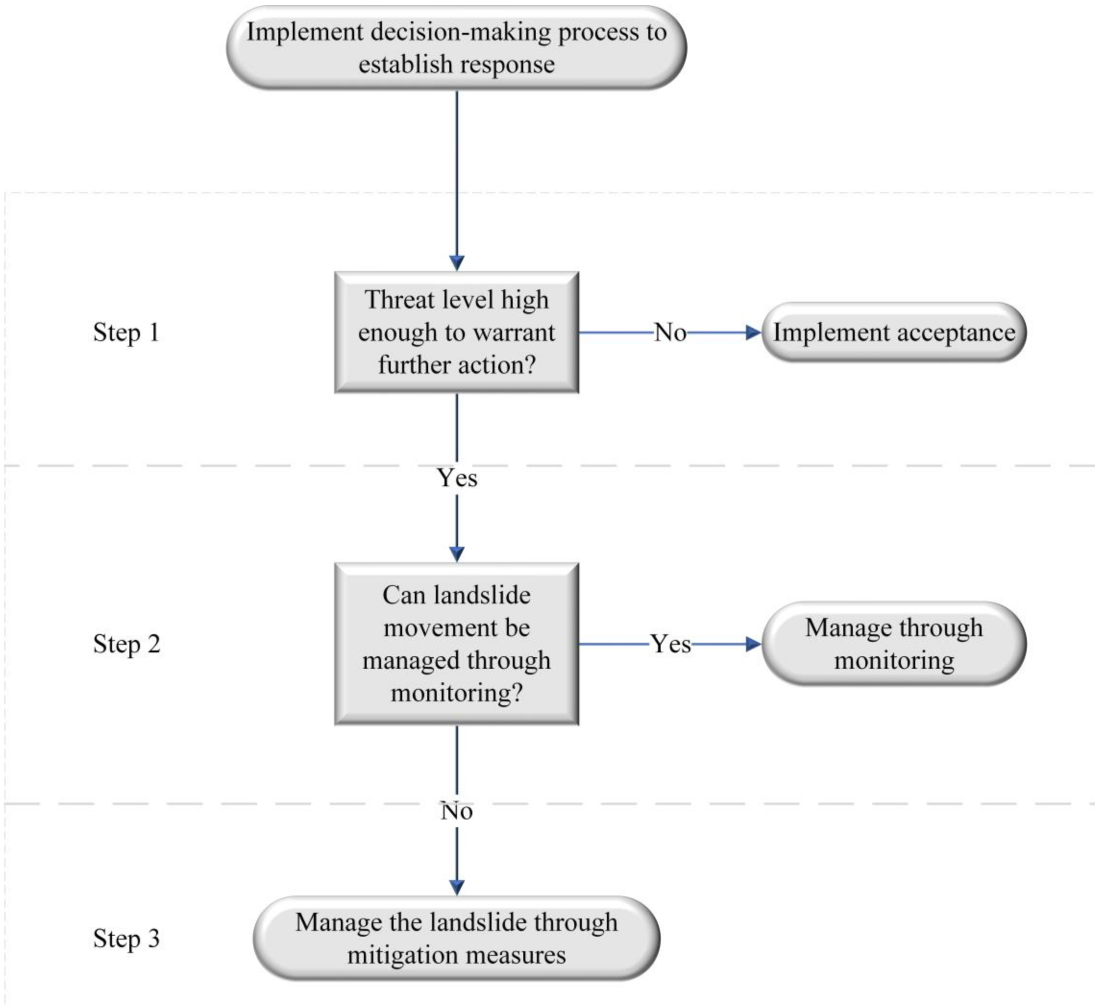


Figure F-2. Decision-making process for implementing a landslide management response

F-1.5 Decision-Making for Ongoing Monitoring

From the perspective of a CDM system, monitoring should be accompanied by qualitative or quantitative thresholds that trigger recommended or prescribed additional actions. These additional actions may include one or more of the following:

- Evaluating (or reevaluating) a possible or known landslide site (such as through a Level 1, 2, or 3 Assessment)
- Collecting or reviewing other monitoring data for comparison (if available)
- Increasing (or decreasing) the frequency of monitoring
- Installing or implementing additional types of monitoring
- Implementing risk reduction measures, such as reducing pressure or shutting-in a section of line
- Developing and implementing physical mitigation measures, such as installing geotechnical mitigation measures

The types of action to be taken depend on the type of monitoring, the results of that monitoring, and the risk tolerance of the operator. Multiple monitoring methods should be cross-compared whenever possible to formulate stronger and more accurate decision-making.

The general decision-making process for response to monitoring data is as follows (Figure F-3):

1. Step #1: Review and cross-compare with other monitoring data (if available). Do the results of the monitoring data indicate an imminent threat to a pipeline? If yes, implement threat-reduction measures. If no, proceed to Step #2. If uncertain, proceed to Step #4.
2. Step #2: Do the results of the monitoring data indicate a higher level of threat than previously understood? If yes or uncertain, proceed to Step #3. If no, continue with monitoring as before.
3. Step #3: Is the higher level of threat manageable with additional or more frequent monitoring? If yes, implement additional or more frequent monitoring. If no, implement mitigation measures.
4. Step #4: Conduct an additional evaluation and return to Step #1.

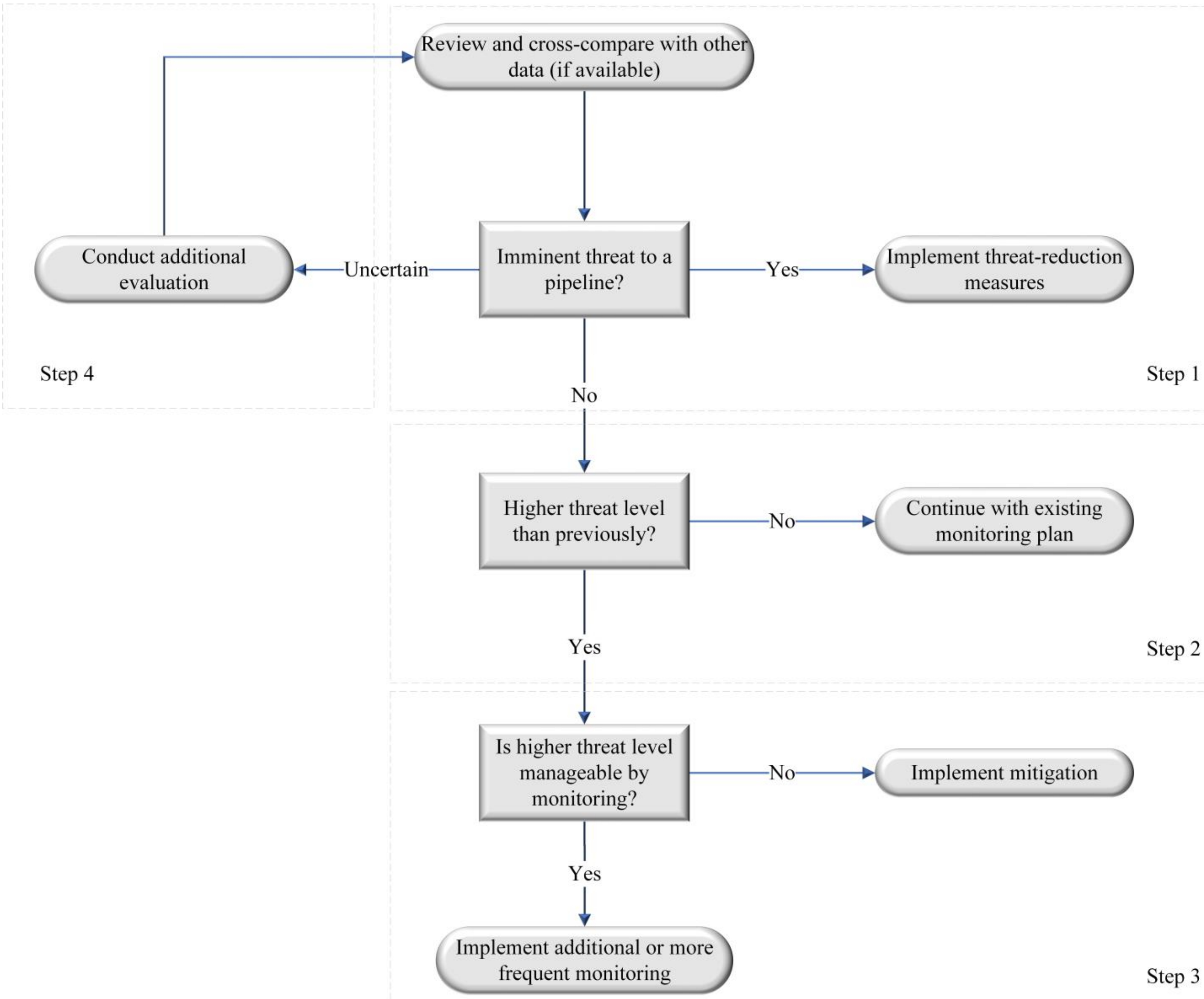


Figure F-3. CDM flowchart for ongoing monitoring

F-2 Prioritization

Prioritization in the context of landslide hazard management is the decision on when to implement actions and in what order. As discussed previously in the overall discussion around CDM systems, there is no universal or generally accepted prioritization system for landslide hazards. The decision on how to prioritize is operator-specific and may consider one or a combination of the following:

- Likelihood of failure or risk ranking (addressing the highest hazards first)
- Consequence of a loss-of-containment event or other impact from a landslide
- Consequence of pressure reduction or removal of pipeline from service until action can be completed

- Time to complete the action
- Resource availability

The inputs to a CDM system can be used to prioritize action. For instance, in Example 3 (below) of the CDM systems, the combination of landslide characteristics and strain demand versus strain capacity are used to decide on an action; these can also be used to assign a priority of response, where certain actions would be prioritized over other actions. If consequence is added as a third axis to the decision-making matrix, sites with a certain set of characteristics in areas with higher consequence could be prioritized over similar sites in areas with lower consequence.

F-3 Example Classification Decision-Making Systems

The following sections provide examples of landslide CDM systems that have been used by pipeline operators. It is important to note that these are provided as examples only and the authors' do not endorse one system over another. As described above, CDM systems should address the specific types of landslides present along a given system and the variety of ways in which these landslides can interact with a pipeline, as well as regulatory environments, local land uses, and pipeline operator and owner internal structures and cultures that can affect the feasibility of various risk-management measures. As such, it is expected that CDM systems vary between operators.

In the interest of space, the CDM system examples presented below have been simplified and condensed and do not contain all components, such as identifying how many levels of assessment should be performed for specific situations or response to monitoring data. The provided examples should not be construed to be complete CDM systems.

F-3.1 Example 1: Fitness-for-Service Performance-Based Approach

This example CDM system provides decisions on how to respond to landslide-induced strain based on girth weld strain demand compared to a defined strain demand limit state and can be considered a fitness-for-service (FFS) performance-based approach. Strain demand limit is based on estimated strain capacity with a safety factor applied, as described in Annex C and Wang et al.[14] In this system, girth weld strain demand is considered to be total strain demand as described in Annex C.

This example CDM system may be useful for operators where the information needed to perform detailed FFS assessments is generally available. Criteria for this method are as follows:

- Category 1 (Halt Operation and Immediate Mitigation): Girth weld strain demand exceeds 70% of girth weld strain demand limit (SDL) or is within 0.1% strain of girth weld SDL. The pipeline should be taken out of service as soon as possible. Before operations are resumed, mitigation should be performed and monitoring should be installed. Mitigation should, at a minimum, return the site to a Category 3 classification.
- Category 2 (Planned Mitigation): Girth weld strain demand exceeds 50% of girth weld SDL or is within 0.15% strain of girth weld SDL. Monitoring should be performed or continued, and monitoring and mitigation plans should be developed to identify mitigation scope, required timing of completing mitigation, and type and frequency of monitoring. Mitigation should, at a minimum, return the site to a Category 3 classification.
- Category 3 (Targeted Monitoring): Girth weld strain demand exceeds 30% of girth weld SDL or is within 0.2% strain of girth weld SDL. In this case, the landslide should have a

documented monitoring and reassessment plan that identifies the type of monitoring to be performed and the frequency of analysis.

- Category 4 (Case-by-Case): Girth weld strain demand is unknown, girth weld SDL has not been calculated, or the site does not fit within one of the categories above, but the hazard to the pipeline is judged to be unacceptable based on geohazard review or other SME assessment. In this scenario, the decision on how to address monitoring and mitigation needs are determined on a case-by-case basis or by an alternative method.

F-3.2 Example 2: Subject Matter Expert Judgment-Based Approach

The following example uses a method where the classification of landslide threat is largely based on SME judgment. This method is useful when the strain demand and strain capacity are unknown and cannot be established before a decision on how to manage a landslide threat has to be made. If a landslide site fulfills more than one of the definitions listed in Table F-1, the highest classification is selected.

Table F-1. Example SME judgment system

Hazard Class	Landslide Characteristics	Response and Timeline (Once Feature is Considered Fully Assessed)
1	An active or possibly active landslide that intersects the pipeline (both laterally and vertically at depth), where ongoing or future movement is expected to be at a rate where monitoring would not provide sufficient time for safe response.	Mitigate Immediately
2	Landslide with geomorphic or instrumental evidence of disturbance in close proximity to the pipeline centerline, where ongoing or future movement is expected to be at a rate where monitoring would provide sufficient time for safe response in the short term.	Enhanced Monitoring Until Mitigation is Complete (within 1-2 years)
3	Landslide with geomorphic or instrumental evidence of disturbance proximal to the pipeline centerline, where ongoing or future movement is expected to be at a rate where monitoring would provide sufficient time for safe response.	Monitoring
4	Landslide located distal to the pipeline centerline, where future expansion is not anticipated to impact the pipeline prior to the next planned reassessment.	Limited Monitoring

Note: the terms “close proximity,” “proximal,” and “distal” are intentionally undefined because these may vary based on geography and local landslide characteristics and should thus be defined by the operator.

F-3.3 Example 3: Matrix-Based Approach

The following example (Table F-2) is a matrix-based approach that combines concepts of both geomorphic and FFS assessments to support decision-making. In this approach, threat classification is assigned by populating the matrix with three geomorphic factors:

- Proximity of the landslide to a pipeline centerline
- The activity of the landslide
- The landslide's inferred or measured movement rate

These geomorphic factors are then cross-compared to the pipeline vulnerability through the ratio between estimated strain demand (typically from inertial measurement unit [IMU] bending strain) and a preestablished strain demand limit.

Table F-2. Example matrix-based landslide threat classification

Proximity	Activity	Movement Rate	Strain (S) and Risk (R) Level				
			S-0	S-1	S-2	S-3	S-4
Crosses the centerline (CC)	Active	Moderate	R5	R5	R5	R6	R7
		Slow	R3	R3	R4	R5	R7
	Inactive	Not Applicable	R3	R3	R4	R5	R7
ROW Crosscuts (RC)	Active	Moderate	R3	R3	R5	R6	R7
		Slow	R2	R2	R4	R5	R7
	Inactive	Not Applicable	R2	R2	R3	R5	R7
Proximal (P)	Active	Moderate	R3	R3	R3	R3	R [(1)]
		Slow	R2	R2	R2	R2	R [(1)]
	Inactive	Not Applicable	R2	R2	R2	R2	R [(1)]
Distal (D)	Active or Inactive	Not Applicable	R1	R1	R1	R1	R [(1)]

1: Case-by-case response

F-3.3.1 Matrix Inputs

The inputs to the matrix are defined as follows:

Proximity

- Crosses Centerline (CC): The landslide crosses the centerline of a pipeline (i.e., there is evidence of postconstruction disturbance resulting from the geohazard across the pipeline centerline).

- ROW Crosscuts (RC): The ROW crosscuts the landslide with no visual indicators of postconstruction landslide impact to the ROW.
- Proximal (P): Landslide is within 50 feet of the nearest pipeline centerline but does not cross the centerline, or the landslide is clearly above the pipeline(s) and does not intersect or engage the pipeline in cross section, even if intersecting the centerline in plan view.
- Distal (D): Landslide is more than 50 feet from the nearest pipeline centerline.

Activity

Active: A landslide where one or more of the following conditions apply:

- Fresh, sharp landslide geomorphic features and exposed soil indicate recent movement.
- There are quantitative measurements of movement within the last 5 years (e.g., from monitoring data).
- There is visual evidence of movement within the last 5 years (e.g., from direct observations of movement).
- Site conditions have appreciably changed indicating possible landslide reactivation in the near future (e.g., stream migration beginning to undermine the toe of a landslide).

Inactive: A landslide where the following conditions apply:

- There are rounded, weathered-appearing landslide geomorphic features with no exposed soil.
- Monitoring and other data (as available) indicate that the landslide has not moved or developed further in the past 5 years.
- Site conditions that caused the prior landslide movement have appreciably changed (such as removal of a slope) and reactivation or further movement is not likely, even if the prior movement was within the last 5 years.

Movement Rate

Landslide movement rate is defined as an estimated or measured maximum rate of movement based on historical or current activity. Quantitative measurements from instruments, direct observations, or regional monitoring (e.g., repeat light detection and ranging [LiDAR] or interferometric synthetic aperture radar [InSAR]) are the preferred methods of determining movement rate. In the absence of quantitative means, movement rate is estimated using qualitative assessment of the landslide during field assessment.

Definitions for movement rate are as follows:

- Slow: <2 feet per year of movement at the surface
- Moderate: 2 to 10 feet per year of movement at the surface
- Rapid: >10 feet per year of movement at the surface

Strain

Pipeline strain is a total strain demand typically determined using maximum magnitude from IMU bending strain review or previously installed pipeline strain gauges. It can also be determined by finite element analysis. If the landslide incorporates multiple bending strain features (such as crossing multiple pipelines), the highest overall bending strain magnitude associated with the landslide is applied. The SDL shall be determined prior to applying the strain classification and assumes that SDL is greater than 0.3%. Definitions for strain classifications are as follows:

- S-0: No reported bending strain
- S-1: <0.2% strain
- S-2: 0.2%–60% of SDL
- S-3: 60% of SDL to SDL
- S-4: >SDL

If the SDL is less than 0.3%, the above system does not apply.

F-3.3.2 Response Actions

Once the threat classification has been assigned, a response level is assigned. A simplified summary of the actions to take for each response level is as follows:

- R7: Mitigation within 2 years after threat classification, near real-time monitoring (daily) until mitigation implemented
- R6: Mitigation within 2 to 5 years after threat classification, near real-time monitoring (daily) until mitigation implemented
- R5: Near real-time monitoring (daily), mitigation on case-by-case basis
- R4: Annual landslide-specific monitoring
- R3-R2: Routine monitoring by IMU bending strain or LiDAR differencing
- R1: No further action (from geohazard perspective) unless changed condition occurs

Annex G
Landslide Threat Management Measures

Annex G: Landslide Threat Management Measures

G Introduction

This annex provides guidance and considerations for implementing landslide threat management measures. Landslide threat management measures consist of two broad categories: (1) monitoring measures and (2) mitigation measures. Both approaches are used to reduce the likelihood of landslide-caused loss of containment from a pipeline or other negative consequences. Monitoring measures indirectly reduces the likelihood of landslide impact by providing information for timely implementation of mitigation measures. The process to select whether a landslide should be managed through monitoring, mitigation measures, or a combination of both is discussed in Section 7 and Annex F.

Threat management measures are discussed extensively in multiple resources, including C-Core et al., McKenzie-Johnson et al., Wang et al., and Johnson et al.[10, 12, 14, 68] This annex does not reproduce the information contained in these resources; instead, it focuses on considerations in the selection and usage of appropriate threat management measures.

G-1 Landslide Hazard Monitoring

Landslide hazards can be monitored by geotechnical monitoring of landslides and their adjacent areas (landslide monitoring), structural monitoring of pipelines (pipeline monitoring), or both. Landslide monitoring provides information about the movement of the landslide itself. Pipeline monitoring provides specific information about whether a landslide is affecting the pipeline and to what extent. An integrated approach to monitoring both the landslide and the pipeline provides context for the interpretation of the monitoring results and provides for more robust and reliable decision-making than focusing on only landslide monitoring or only pipeline monitoring.

Monitoring is 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 (e.g., implementing mitigation measures)
- 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 for use in designing mitigation measures
- To measure or assess the effect of landslide movement on a pipeline
- To confirm that mitigation measures are functioning as intended
- To provide notification that an extreme weather or geologic event (such as an earthquake) has occurred to facilitate post-event assessment

G-1.1 Types of Landslide Hazard Monitoring

The following sections provide a generalized discussion on landslide monitoring strategies and options. More in-depth discussions of monitoring options can be found in McKenzie-Johnson et al., Wang et al., and Johnson et al.[12, 14, 68] For the purposes of this document, the three main landslide hazard monitoring strategies and options are regional monitoring, site-specific landslide monitoring, and pipeline monitoring.

G-1.1.1 Regional Monitoring

Regional monitoring is used to monitor large areas of ground along and near a pipeline right-of-way (ROW). In most cases, regional monitoring is used to monitor multiple landslides or areas where the underlying geology is susceptible to landslides and has the potential to form new landslides. Regional monitoring can also be used to monitor individual locations, such as large landslides that extend well beyond the ROW limits. Regional monitoring methods typically are the most cost-effective and efficient methods to monitor large areas.

Regional monitoring provides information related to landslide movement such as amount, rate, and direction of ground movement in newly developed landslides or in known landslides. Regional monitoring methods do not provide specific information about the depth to the rupture surface or changes in subsurface conditions (however, the depth of the slip surface can be estimated from the landslide geometry in these methods). Frequency of data collection ranges from weeks (such as interferometric synthetic aperture radar [InSAR]) to months or years (such as aerial patrol/reconnaissance, ground patrol/reconnaissance, light detection and ranging [LiDAR], aerial photography, and in-line inspection [ILI]). Regional monitoring methods are often combined with landslide- and pipeline-focused monitoring methods to provide context for the results of these more site-specific monitoring methods. No instruments are installed within or on the landslide(s) or pipeline to conduct regional monitoring.

The following are common regional monitoring types or methods:

- **Aerial Patrol/Reconnaissance**: Aerial patrol includes regularly scheduled patrol of the ROW for pipeline operations (using trained observers) and regularly scheduled (e.g., annual) subject matter expert (SME) aerial reconnaissance. This also includes event-driven operator aerial patrol and SME aerial reconnaissance following significant storm events, intense rainfall events or seasons, or a significant earthquake. Routine, scheduled operator aerial pipeline patrol is often completed with a fixed-wing aircraft. A helicopter platform is preferred for SME landslide hazard reconnaissance because its lower speed and ability to fly closer to the ground allow for more reliable detection and identification of landslide features. In most cases, aerial reconnaissance is only able to identify coarse changes (e.g., feet to tens of feet), and should not be expected to resolve subtle or small terrain changes (less than a foot) resulting from landslide movement.
- **Ground Patrol/Reconnaissance**: Ground patrol includes regular examination of the ROW in landslide areas of concern by trained pipeline operator personnel or by SMEs conducting geomorphic reconnaissance. Ground patrol may also be conducted following significant meteorological or seismic events. Ground patrol can be used to confirm the observations from other monitoring techniques. For instance, if possible new landslides are identified

via remote sensing, ground patrol might be performed to confirm the new landslides and to collect additional information.

- **Remote Sensing**: Remote sensing methods collect information using a sensor from a distance, usually from an aircraft or a satellite platform. The sensor can either be passive, in that it relies on reflected energy off the ground (i.e., aerial photography), or active, in that the sensor emits a signal and measures the reflection of that signal (e.g., airborne LiDAR or satellite InSAR).
- **In-Line Inspection**: ILI tools can also be considered a regional monitoring method in that they measure the condition of a pipeline over long distances. The ILI tool overlaps with pipeline monitoring, which is discussed further in G-1-1.3.

G-1.1.2 Site-Specific Landslide Monitoring

In the context of this document, site-specific landslide monitoring refers to monitoring a mapped landslide or landslide-prone area by installing instruments on the ground surface or in the subsurface. It is distinguished from regional monitoring where there are no installed instruments and pipeline monitoring where instruments are installed on the pipeline. Landslide monitoring instruments do not directly monitor the impacts on a pipeline but can be used to infer or model those impacts by providing site-specific ground movement information and data and physical and geometric characteristics of a landslide.

Landslide monitoring is conducted using a family of monitoring systems broadly referred to as geotechnical instrumentation. Geotechnical instrumentation has many applications outside of the pipeline industry that can be applied to monitoring landslides along pipelines.

Depending on the type(s) of instruments used, the following information can be collected:

- Extent, amount, rate, and direction of landslide movement (to a high level of accuracy usually measured in fractions of an inch)
- Depth of landslide rupture surface (slip surface)
- Changes to physical parameters that influence landslide behavior (e.g., porewater pressure)
- Warning of impending or accelerating movement

Geotechnical instrumentation is usually installed at specific points on or near a landslide. Accordingly, before the instruments are installed, it is important that the landslide or landslide-prone area has been defined or delineated through the assessment process (Section 5), such that the landslide boundaries and general physical and geometric characteristics have been defined, allowing for optimal placement of geotechnical instrumentation. For example, if slope inclinometers (SIs) are to be installed, it would be beneficial to locate them where the greatest observed movement of the landslide has occurred relative to the pipeline location within the landslide. This would provide information and data on maximum landslide movement and direction. SIs could also be placed near the pipeline to monitor landslide movement proximal to the pipeline.

When installing instrumentation that measures the depth of movement, Level 3 Assessment subsurface investigations and instrument installation can be conducted contemporaneously (e.g., the instruments can be installed in the same borehole[s] used to conduct the investigation).

The following are common types of landslide monitoring.[12, 68] This list is not exhaustive:

- Survey Monuments: Survey monuments are instruments used as reference points for measuring surficial movement of a landslide. Survey monuments can be monitored manually by a survey crew or automatically using a global navigation satellite system (GNSS) positioning units.
- Tilt Monument: Tilt monuments or posts are instruments used to measure the tilt of installed posts due to surficial movement of a landslide. Tilt monuments can be monitored manually or automatically using a tiltmeter.
- Visual Survey Markers/Monuments (VSMs): VSMs are aboveground monuments that can be visual references to assess landslide movement from the ground or air. VSMs usually consist of vertical pipes or posts that are installed in a straight line perpendicular to the direction of expected landslide movement. If the VSMs are displaced from a straight line, it may indicate movement of the landslide.
- Slope Inclinometers: SIs are high-precision instruments typically installed in geotechnical boreholes to measure movement of a landslide, including the amount, direction, and the depth at which the movement occurs. SIs can reliably measure movement to tenths or hundredths of an inch. SIs provide more-precise measurement of movement than survey monuments, but require the additional effort of installation in boreholes, which usually requires specialized drilling equipment. The SIs can be monitored manually or can be automated.

Other site-specific monitoring focuses on factors that trigger landslides, such as changes in groundwater elevation, rainfall, or earthquake ground motion. These provide supplemental information that can be used to better understand the conditions under which landslide movement occurs (or accelerates) or to confirm the efficacy of measures to reduce the impact of the triggering factors (e.g., use of piezometers to monitor drawdown or rising groundwater). However, since these types of monitoring do not directly measure landslide movement, they should not be used in place of other methods when the goal of monitoring is to measure and quantify landslide movement.

G-1.1.3 Pipeline Monitoring

Pipeline monitoring can be divided into two categories: on-pipeline strain gauges and ILI tools. There are other types of instruments that could be used to monitor the pipeline, such as fiber optic cables or on-pipeline survey monuments (see more information in C-Core et al.[10] or Wang et al.[14]). However, these are not discussed herein because they are not commonly used in North America at the time of this document.

Strain gauges and ILI tools provide information about whether a landslide is inducing strain on the pipeline (i.e., strain demand). Strain gauges provide strain measurements at discrete locations and can report frequent data (e.g., daily) using an on-site telemetry station, on-site data loggers, or manual measurement. ILI tools provide information over entire pipeline segments where ILI is run. The primary ILI technology used for landslide monitoring is IMU bending strain analysis, but this does not preclude the use of other ILI technologies (such as caliper and magnetic flux leakage [MFL]), as appropriate.

Both strain gauges and ILI tools have distinct advantages. Strain gauges can provide near real-time reporting of pipeline strain at the location of strain gauges, making them ideally suited for tracking trends over time and as an early warning system. ILI tools can provide information over pipeline segments and are useful for tracking and analyzing landslide effects on pipelines where multiple landslides are a concern.

Both also have disadvantages. Strain gauges provide the pipeline strain only at distinct locations and provide the changes in pipeline strain only from the time of installation. Their installation requires exposure of the pipeline in a pothole or trench (e.g., during a stress-relief excavation). ILI tool runs are relatively expensive and are generally infrequently run (time between measurements is usually years).

Like many other methods and technologies discussed herein, strain gauges and ILI tools can be complementary and integrated methods of monitoring.

G-1.1.4 Monitoring Summary

Table G-1 provides a summary of the monitoring types discussed above, their typical applications, and usual frequency of data collection. Note that the frequencies provided in Table G-1 should be considered typical, but more or less frequent measurement can be performed in some applications.

Table G-1. Summary of commonly used landslide monitoring methods for pipelines

Monitoring Type	Monitoring Focus	Instruments Installed	Typical Frequency of Data Collection
Aerial Patrol/Reconnaissance	Regional conditions (visual surface movement)	No	Weekly to annually, and event driven
Ground Patrol/Reconnaissance	Regional to site-specific conditions (visual surface movement)	No	Twice annually to annually, and event driven
Remote Sensing	Regional conditions (surface movement)	No	Annual to multiyear (airborne photography and LiDAR) Weekly to annually (InSAR), dependent on satellite
Survey Monuments	Site-specific landslide (near-surface movement)	Yes	Monthly to annually (manually), and event-driven Hourly to daily (automated)

Monitoring Type	Monitoring Focus	Instruments Installed	Typical Frequency of Data Collection
Visual Survey Markers/Monuments	Site-specific landslide (near-surface movement)	Yes	Monthly to annually, event driven
Tilt Post	Site-specific landslide (near-surface movement)	Yes	Monthly to annually (manually), and event driven Hourly to daily (automated)
Inclinometer	Site-specific landslide (movement from surface to depth of inclinometer)	Yes	Monthly to annually (manual) Hourly to daily (automated)
Piezometer and Rain Gauge	Landslide-triggering factors; surface water and groundwater conditions	Yes	Monthly to annually (manual) Hourly to daily (automated)
Strain Gauge	Site-specific pipeline; changes in strain	Yes	Monthly to annually (manual) Hourly to daily (automated)
ILI (e.g., IMU bending strain)	Site-specific and regional pipeline; bending strain and other conditions	No	Annually to multiyear

G-1.2 Guidance for Selection of Monitoring Methods

Monitoring methods should be selected and designed by engineering or geological SMEs to address the objective(s) of the monitoring program. The following are recommended considerations in the selection, design, and implementation of a monitoring program.

- Prior to initiating monitoring, a geohazard monitoring plan should be developed that may include (1) objectives of monitoring, (2) methods used for monitoring, (3) monitoring frequency, (4) threshold levels (if the monitoring is being used as an early warning system), and (5) response to threshold exceedance (if the monitoring is being used as an early warning system).
- The monitoring objectives should be defined prior to establishing a monitoring approach. By defining the objectives of monitoring, an appropriate monitoring approach can be implemented. Note that depending on the objectives, more than one monitoring episode may be needed to fulfill the objectives.
- The threat level of the landslides or areas to be monitored should be incorporated into selection of the monitoring approach. Operators should consider incorporating an overall monitoring approach into their classification and decision-making (CDM) system. This

will allow for consistent selection of monitoring types and appropriate prioritization of monitoring of landslides where the risk-reduction benefit is greatest.

- The target of the monitoring should be defined from the start (i.e., whether monitoring is focused on a single site or many sites within a given area[s]). If the intention is to monitor many landslides or large areas where landslides might occur, regional landslide monitoring techniques are needed. If the intention is to monitor certain, discrete locations that have been previously identified, then site-specific landslide and/or pipeline monitoring techniques are needed. In many cases, a combination of techniques may be required.
- For site-specific monitoring, the characteristics of the landslide(s) being monitored should be understood. Landslide features such as lateral limits, internal shear zones and scarps, and the thickness and depth (if known or estimated) and characteristics such as movement type (continuous versus episodic) and rate should be considered when developing a monitoring approach and design.
- Measurement limits should be accounted for when selecting monitoring methods. All monitoring methods have lower limits (i.e., resolution), and many have upper limits (operating range). These limits should be understood and compared to the monitoring objectives and resolution needed when selecting monitoring methods.
- Similarly, frequency of measurement should be accounted for when selecting monitoring methods. Depending on the monitoring method selected, frequency of measurement can range from seconds to multiple years between measurements. Measurement frequency should be understood and selected appropriately to meet the monitoring objectives.
- The expected duration for monitoring should be incorporated into the selection and design of instrumentation. It is important for the selected instrument(s) to meet the target lifetime of the monitoring program. The monitoring approach should also account for the difficulty of replacing instruments if they stop working; it may be prudent to install redundant instruments, use more robust equipment, or implement protective measures (e.g., placing bollards or fencing around instruments) in locations where instrument replacement is difficult or expensive.
- More conservative monitoring methods can be selected when situationally appropriate, such as in areas where the consequences of a loss of containment are potentially more severe than in typical locations.
- Site access constraints and topographical conditions will affect the types of instruments that can be realistically used and the frequency at which they can be monitored. A site with difficult access could limit feasible options for installing and monitoring the instruments. For a remote site, the cost of manual monitoring, surveying, and maintenance can be significant. In this case, a monitoring system with the capability of collecting data using a self-powered, automated data acquisition system (i.e., a remote monitoring unit or a telemetry station) could be a feasible solution. However, remote sites may also be exposed to vandalism and theft.
- The desired frequency of data collection, reporting, and interpretation should inform which monitoring method or instruments are selected. Reporting format and frequency depend on the type of monitoring system, the frequency of data collection, and the methods of

transmitting/reporting the collected data. It is important to note that the frequency of data collection may vary from the frequency of data reporting; both aspects should be considered when designing and implementing a monitoring system. For example, an IMU data report might become available weeks or months after the data collection is complete.

Table G-2 provides general guidance on selecting the monitoring methods and their frequency, based on the purpose of monitoring, the expected movement rate, and the ratio between strain capacity and strain demand. The guidance is general and intended to provide an overview of monitoring options. Additional guidance in selecting and interpreting monitoring data can be provided to operators by SMEs.

This guidance also assumes that the landslides and landslide-susceptible areas being monitored have been characterized through a landslide assessment process as described herein. Note that terms like “slow,” “moderate,” “low,” and “high” are subjective and are not rigidly defined. These terms are provided to establish the concepts rather than provide strong requirements.

Table G-2. Guidance on selection of monitoring approaches

Monitoring Purpose	Landslide Movement Rate	Ratio Between Strain Capacity and Strain Demand	Minimum Recommended Monitoring Strategies	Possible Frequency
Landslide crosses pipeline centerline and is below pipeline burial depth	Slow	Low	Regional landslide monitoring, site-specific landslide monitoring, and /or pipeline monitoring	Monthly to annually, and event driven
	Slow	High	Site-specific landslide monitoring and pipeline monitoring	Daily
	Moderate or rapid	Low to high	Site-specific landslide monitoring and pipeline monitoring	Daily
Landslide does not currently cross pipeline centerline, but could with further movement	Slow	Low	Regional landslide monitoring or site-specific landslide monitoring	Monthly to annually, and event driven
	Slow	High	Site-specific landslide monitoring and/or pipeline monitoring	Monthly to annually, and event driven
	Moderate or rapid	Low to high	Site-specific landslide monitoring and pipeline monitoring	Weekly to monthly, and event driven
Landslide in vicinity of pipeline, not likely to cross centerline	Slow to rapid	Low to high	Regional landslide monitoring and/or regional pipeline monitoring (i.e., ILI IMU)	Annually to multiyear

Monitoring Purpose	Landslide Movement Rate	Ratio Between Strain Capacity and Strain Demand	Minimum Recommended Monitoring Strategies	Possible Frequency
Characterization of landslide for mitigation design	Slow to rapid	Low to high	Site-specific landslide monitoring	Project specific
Large area monitoring (landslide-susceptible areas)	Slow to moderate	Low (e.g., for pipeline with high-strain capacity)	Regional landslide monitoring and regional pipeline monitoring (i.e., ILI IMU)	Annually to multiyear, and event driven
		High (e.g., for pipeline with low strain capacity)	Regional landslide monitoring	Monthly to quarterly, and event driven
	Rapid	Low to high	Regional monitoring	Monthly to quarterly
Post-mitigation measure implementation	N/A	N/A	Project-specific determination	Project-specific determination
Extreme weather or geological event notification	N/A	N/A	Regional to site-specific landslide monitoring[1]	Following event
Non-landslide-susceptible area[2]	N/A	N/A	Regional monitoring	At reassessment interval for Level 1 Assessment

1: Notification from the United States Geologic Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS) or similar public agency

2: Based on results of Level 1 Assessment (at a minimum)

G-2 Mitigation Measures

Mitigation measures are a means to manage landslide threat by implementing physical measures to reduce the likelihood of occurrence of a negative consequence, such as loss of containment of a pipeline.

Mitigation measures can be broadly divided into the following actions:

- Actions that reduce or eliminate the potential for strain demand to be imposed on a pipeline by a landslide (G-2.1 strain demand reduction measures)
- Actions that enhance the strain capacity of a pipeline, to reduce its vulnerability to a landslide impact (G-2.2 strain capacity enhancement measures)

Although discussed separately, these measures are often combined and implemented with monitoring measures to reduce landslide threat.

This section presents a relatively brief overview of mitigation measures for landslides that might impact pipelines. More discussions on potential geotechnical mitigation measures can be found in the 2009 Pipeline Research Council International (PRCI) guidelines on construction in areas prone to landslide and subsidence, the Joint Industry Project (JIP) document regarding management of ground movement hazards, the 2016 Interstate National Gas Association of America (INGAA) Foundation document on construction of pipelines in West Virginia, and the 2020 INGAA Foundation's guidelines on landslide management for pipelines.[10, 11, 12, 14]

The discussion herein assumes that the operator has proactively collected and analyzed data (as described in Section 5) and then applied a systematic CDM process (as described in Section 7).

This section is largely centered around mitigation measures for existing pipelines, not new construction, although many aspects of this discussion also apply to new construction. Note that the feasibility and cost of some of these measures differ greatly between planned construction and existing pipelines. For example, avoiding a landslide via rerouting can be a relatively small cost before a pipeline has been built, but it can be a major cost for an existing pipeline.

G-2.1 Strain Demand Reduction Measures

Strain demand reduction measures:

- Reduce the existing strain incurred on a pipeline from a landslide
- Reduce the likelihood for strain demand to be incurred
- Eliminate the potential for strain demand accumulation

Strain demand reduction measures include the following. This is not an exhaustive list:

- Avoiding a landslide through rerouting, deep burial (e.g., horizontal directional drilling [HDD]), or aboveground span to eliminate the future strain demand
- Conducting a stress-relief excavation to reduce the existing strain demand
- Modifying a pipeline alignment within a landslide to a more favorable alignment to reduce the exposure to the landslide
- Improving the cross-section geometry of a pipeline trench using a wider, lower-angle trench configuration than standard pipeline construction
- Shallowing the burial depth of the pipeline to reduce the load transfer to a pipeline
- Installing select backfill to reduce load transfer to a pipeline
- Installing low-friction coating or geosynthetic wrapping around a pipeline to reduce frictional load transfer to a pipeline
- Stabilizing the landslide or ROW through geotechnical measures, such as toe buttress, rock shear key, soil nails, retaining walls, or regrading

- Lowering or controlling surface water and groundwater to reduce the likelihood or rate of landslide movement to reduce the magnitude and rate of increase in strain demand
- Protecting the bottom of a slope or landslide from toe erosion triggered by stream undercutting

Typical strain demand reduction measures are discussed in the following sections.

G-2.1.1 Avoidance Mitigation Measures

From a threat management perspective, the optimal approach to mitigating a landslide hazard is to avoid it altogether. Avoidance can be achieved through various means, including but not limited to the following:

- Rerouting to avoid the landslide
- Relocating the pipeline below the failure plane of the landslide (e.g., via deep burial or HDD)
- Relocating the pipeline on or above ground (e.g., directly on the ground surface, on ground supports, or on bridges)

Avoidance can result in eliminating the landslide threat (such as rerouting from a landslide-prone area to a non-landslide-prone area). Avoidance can also be used as a threat-reduction measure (such as routing from a high-hazard area to a lower-hazard area). In principle, avoidance is simple, but the following should be considered prior to implementation:

- When selecting a reroute option, the route(s) being considered should be carefully reviewed using the assessment approach described in Section 5 to reduce the potential that the new route has similar or worse landslide hazards. Additionally, although this document focuses on landslides, the preferred reroute should consider other geohazards as well, such as stream bank erosion. The routing should also consider other non-geohazard constraints that could affect the suitability of the preferred reroute options, such as permitting or constructability.
- When selecting to relocate the pipeline above, below, or around a landslide, it is critical that the current extent of the targeted landslide (i.e., aerial boundaries and depth) is defined and that the landslide has been characterized to the extent that future activity and expansion of the landslide can be predicted. The extent of the relocation should account for future activity and expansion.
- Deep burial through conventional trenching can carry considerable risk during construction because the deep trench might destabilize or worsen the landslide stability. In addition, deep burial limits future access to the pipeline. Design and construction activities for this option should be overseen by a geotechnical SME.

G-2.1.2 Stress-Relief Excavation

Stress-relief excavation is a mitigation measure commonly used for pipelines impacted by landslides.[15] Stress-relief excavations consist of reducing a portion of the accumulated elastic strain on a pipeline by excavating the soil above and around a pipeline to allow the pipeline to rebound in the affected area. The exposure of the pipeline relieves a portion of the accumulated elastic strain, typically between about 30% to 60% of elastic strain or about 500 to 1,300 micro strains.[69]

A stress-relief excavation by itself is usually considered a temporary mitigation measure because it does not prevent future landslide movement and does not increase the capacity of the pipeline. The landslide activity might continue and result in the need to conduct additional stress-relief excavations.

Stress-relief excavation is an appropriate choice of mitigation in the following circumstances:

- The ground movement is slow (e.g., less than 2 feet per year of movement at the surface).
- The existing bending strain incurred on the pipeline is moderate (e.g., less than 0.3% bending strain).
- The strain accumulation in the pipeline occurs over several years (e.g., strain accumulation of less than 300 to 500 micro strain [0.03% to 0.05% strains] per year based on IMU bending strain analysis or from strain gauges installed on the pipeline).

Stress-relief can also be an appropriate choice if the above conditions are not met, as long as the stress-relief excavation is combined with other mitigation methods to stabilize the landslide.

Stress-relief excavations can be combined with other mitigation measures to increase the time between excavations or to eliminate the need for repeat excavations. The following are some other mitigation methods that are commonly performed with stress-relief excavations:

- Placing select backfill in the pipeline trench following the excavation
- Improving drainage to the pipeline trench
- Improving drainage to the landslide and contributing area to reduce landslide movement
- Replacing the affected section of pipeline with pipeline segment of higher strain capacity

If other mitigation measures have been implemented on the slope or around the pipeline in the past, considerations around how to minimize disturbance to the existing measures should be made before starting the stress-relief excavation.

Stress-relief excavations might not be a suitable mitigation option for all landslides. Stress-relief is generally not appropriate where there is a high potential for sudden pipeline failure. Stress-relief excavations can also be impractical to implement where the pipeline is deeply buried (e.g., generally more than 10 to 15 feet) or where it is located on a very steep slope; both scenarios can

[15] Stress-relief excavations are also commonly referred to as "strain-relief excavations." However, because they only relieve a portion of the elastic strain, not plastic strain, referring to them as strain-relief excavations may misleadingly imply that they relieve all accumulated strain.

lead to slope instability during excavation, pose unsafe work conditions, or make stress-relief an infeasible mitigation option. Stress-relief excavations might not be a suitable option when the strain demand on the pipeline is relatively close to the strain capacity of the pipeline.

The following are recommendations for implementing a stress-relief excavation:

- The orientation of the landslide movement relative to the pipeline should be considered. As described in Ahmadipur et al., stress-relief excavation is generally most effective when the landslide movement is perpendicular to the pipeline long axis. [69] Caution should be used when performing stress-relief excavations when the direction of motion is oblique or axial to the pipeline.
- The strain state of the pipeline should be considered before performing the excavation. In particular, the potential for transferring or concentrating strain (and thus to possibly cause conditions such as buckling) should be considered and accounted for during planning.
- Stress-relief excavation in a complex landslide geometry that is not well defined might be ineffective and could result in an inadvertent increase in the pipeline strain during excavation.[69] For example, if the elevation of the pipeline varies significantly along a landslide, excavating the pipeline can cause unintended rebound of the pipeline because of additional gravity load from the pipeline weight, reduction in pipeline constraint due to removing soil above or around the pipeline (i.e., the soil below the pipeline is not excavated), and thermal expansion (i.e., if the ambient temperature is significantly different than the pipeline operational temperature).
- If the pipeline will be exposed for long periods of time before reburial (months to years), the thermal management of the exposed pipeline and potential for coating deterioration should be considered and appropriately managed.
- When planning the excavation, the limits of the excavation should include the stressed length plus some additional length on both sides to allow the pipeline to maximize the effectiveness of the stress relief. If the stressed length is unknown or poorly constrained, the limits of excavation should typically be the length of the pipeline crossed by the landslide, including appropriate additional length on both sides of the planned excavation. A suggested approach is to plan for slightly more than the anticipated need to facilitate permitting and planning. The actual excavation may not necessarily proceed this far (see next bullet) but planning for more than needed will reduce the potential for emergency permitting and land acquisition.
- If the pipeline has accumulated strain, pipeline rebound should occur. In this approach, a minimum length of stress-relief excavation is planned. Due to uncertainties in boundaries of the impacted pipeline, planning for the stress-relief excavation should include a mechanism for potential additional excavation to confirm that sufficient rebound has occurred to meet the objectives of the excavation. For example, one approach to confirming that sufficient rebound has occurred is to place survey lathes or other visual markers vertically at the 3 and 9 o'clock positions at locations along the pipeline as they are first exposed to facilitate measuring pipeline rebound (Figure G-1). In this approach, the excavation encompasses the stressed pipeline length plus some distance (such as 40 feet) beyond the point at which minimal pipeline rebound occurs (such as less than 0.1 feet of movement from the as-exposed location), at which time the excavation would be

terminated. Another approach is to use strain gauges to confirm that the excavation has relieved strain.

- The optimal starting point for the excavation (e.g., from one end or from the center) depends on how the pipeline is being loaded by the landslide. Consideration should be given to the potential to increase stress in other areas during the excavation, possibly inducing buckling, concentrating, or transferring stress to a weak weld (such as a tie-in weld at a bend). The excavation should be planned to avoid these possibilities.
- Stress-relief excavations could destabilize upslope areas. Care and caution must be exercised when other pipelines, infrastructure, or structures are located upslope of the excavated area. The excavation and surrounding slope should be inspected daily for evidence of cracking or landslide movement. In regions with dry and wet seasons, the excavation should generally be performed during the dry season (if possible). In some cases, it could be necessary to install temporary shoring.
- The placement of excavated material and stockpiles should be considered before excavation begins. The location and height of the soil stockpiles must be planned before beginning excavation. Stockpiling material in the wrong location could further destabilize the slope. If adequate stable workspace is not available, the excavated soil might need to be removed rather than stockpiled at the site.
- The pipeline operator must determine whether the stress-relief work can be performed safely while the pipeline is under pressure, otherwise the pipeline should be depressurized. If the work can be safely performed with pressure in the pipeline the operator should consider applicable regulations, such as Code of Federal Regulations (CFR) 195.424, operator-specific health and safety requirements, a conservative geotechnical engineering design for excavation, and comprehensive landslide monitoring (e.g., survey monuments) or pipeline monitoring (e.g., strain gauges).

Figure G-1. Stress-relief excavation of a natural gas pipeline showing pipe rebound and survey lathes placed to provide a visual reference to measure pipe rebound

G-2.1.3 Pipeline Alignment Modification

Modifying pipeline alignment consists of adjusting the alignment across the landslide area to reduce the strain demand induced by ground movement. In other words, orienting the pipeline such that the strain demand induced by the landslide on the pipeline is lessened. Such modifications could include shortening the length of pipeline exposed to the landslide, eliminating elbows, reducing bends within the landslide, or changing the orientation of the pipeline from perpendicular to the landslide movement to axial to the movement.

G-2.1.4 Improved Trench Geometry

Improving the trench geometry consists of using a wider, shallow, and lower-angle trench configuration to reduce the strain induced by horizontal ground movement. This approach can be useful when the native soil or rock is relatively hard or dense (such as glacial till and clay soils) and is best when combined with installing select, deformable backfill to reduce the load transfer to the pipeline.

G-2.1.5 Shallow Burial

Shallow burial, as the name implies, consists of shallowly burying the pipeline to reduce load transfer to the pipeline from ground movement. Modeling by Fredj et al. has shown that an increase in burial depth can result in significant increases in tensile strain transferred to the pipeline from landslide movement.[70] Based on Fredj et al., an increase in burial depth of a 24-inch-diameter pipeline from about 5 feet to 6.8 feet resulted in increased axial strain of almost 0.5% for landslide movement of 9.8 feet (from 1% axial strain to 1.5% axial strain).[70]

G-2.1.6 Select Backfill

Select backfill refers to loosely placed, cohesionless sand or rounded sand or fine gravel with a low fines content (< 5% silt or clay). This type of backfill is commonly used when a landslide occurs in clayey soil or in rock to reduce the load transfer from a landslide mass to a pipeline and to improve subsurface drainage within the pipeline trench. In most cases, select backfill is separated from the native soils by a geotextile fabric (to prevent clay particles from migrating to the select backfill). Installation of a select backfill is commonly combined with improved trench geometry and stress-relief excavations.

G-2.1.7 Geotechnical Mitigation Measures

Geotechnical mitigation includes implementing engineered construction measures to a landslide, landslide-prone area, or area adjacent to a landslide for one of the following reasons:

- To stabilize the landslide mass through excavation, recompaction, and/or grading
- To stabilize a landslide or an affected (or potentially affected) portion of a ROW by installing structures or incorporating soil improvement techniques
- To reduce the likelihood of future landslide movement or acceleration of landslide movement or to slow movement to a manageable level by removing or reducing triggering mechanisms, such as lowering the groundwater table, controlling surface water, and toe erosion.

These measures, if performed successfully, could either eliminate a landslide as a hazard or reduce the likelihood of landslide impact.

The selection of a geotechnical mitigation measure(s) in many cases requires input from several entities, including the operator, geotechnical SMEs, construction contractors, environmental SMEs, and affected stakeholders.

Operators should consider identifying preferred methods and creating typical designs that can be used for budgeting and scoping. Because of significant variability between landslides and site conditions, the use of 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 allowed to adapt to actual site conditions.

G-2.1.8 Landslide Stabilization Using Earthwork

Stabilization of a landslide hazard can be performed by the following:

- Regrading a slope to a flatter angle, removing the unstable soil, and replacing it with more stable soil
- Removing soft soil and recompacting to stronger and more stable soil conditions
- Constructing a rock shear key, rock toe key, or slope toe buttresses or berms

If performed correctly, the stabilization of a landslide requires limited postconstruction monitoring or maintenance.[10,14] This method is only applicable to relatively small landslides where it is feasible to remove or regrade enough soil to stabilize the slope. The following parameters should be considered when selecting this mitigation option:

- The limits of ground disturbance and required construction area that would extend beyond the ROW limits
- The potential that the landslide could be activated during construction (i.e., developing a sequence of construction is critical)
- The financial cost associated with removing and exporting unstable soil and/or importing stable fill
- Potential environmental impacts and environmental restrictions

G-2.1.9 Landslide Stabilization Using Mechanical Reinforcement

The objective of landslide stabilization is to reduce the adverse impact of landslide movement on the pipeline. A landslide or a portion of the landslide where it crosses or intersects the ROW can be stabilized through mechanically reinforcing a slope. Examples of mechanical stabilization of a landslide include soil nail and mesh systems, soil nail wall, anchored block walls, soldier beam wall, and drilled shaft walls.

In some cases, stabilization of the entire landslide is not feasible, due to permitting, land use issues, the size of the landslides, or other constraints. Therefore, the focus is to stabilize the portion of the landslide or ROW that impacts the pipeline. When stabilizing only a portion of the landslide, ground movement due to landslide activity may continue upslope or downslope of the ROW.

G-2.1.10 Reduction of Landslide Movement Rate

Measures to reduce the rate of landslide movement (for landslides that move more or less continuously) or reduce the likelihood of movement (for landslides that move episodically) usually involve methods to control surface water and/or groundwater. These measures reduce the rate and/or likelihood of landslide movement by addressing one or more of the following:

- Lowering the piezometric surface (groundwater table) or avoiding its rise within the landslide. Elevated groundwater and saturation of soil is a common cause of landslide formation and movement. By lowering the piezometric groundwater surface, the effective stress acting on a potential slip surface increases, and thus, the overall resistance of the soil mass increases. Increasing the resistive force at the slip surface(s) will reduce the potential for landslide movement and/or reduce the rate of movement. Examples include subhorizontal drains, curtain drains, drainage tunnels, wells, and drainage trenches (e.g., French drains).[71]

- Diverting or controlling surface water. These measures divert or channel surface water away from a landslide or potentially unstable slope to reduce the amount of groundwater infiltration and, in some cases, to reduce erosion caused by surface water flow. These measures range from simple, standard pipeline construction practices, such as installing slope breakers (water bars), to more sophisticated designed measures, such as constructing rock-lined drainage channels. Careful consideration should be made as to where to direct or discharge the diverted water so as not to cause water-related issues or slope failures elsewhere.
- Protecting a landslide from erosion. Another common cause of landslide formation and movement is erosion. Slope instability from erosion can occur where the toe of a slope is undermined by a stream or where overland flow erodes the surface of the slope. The potential for further movement of a landslide can be reduced by buttressing and/or armoring areas subject to erosion.

The effectiveness of these methods will vary by geotechnic, geologic, hydrogeologic, hydrologic, and climatic conditions.[71] Depending on the site conditions and desired outcome, additional investigation and characterization might be needed. A one-size-fits-all approach should not be used because there are considerable variations in geotechnical, geological, hydrogeological, and hydrological conditions that cannot be accounted for without a site-specific design. For instance, subhorizontal drains might work well for soil predominantly composed of sand but might not work well for fine-grained soil dominated by clay and silt size particles.[72]

G-2.1.11 Combined Geotechnical Mitigation Measures

The discussions above have categorized various individual geotechnical mitigation measures. It is common to combine multiple mitigation measures, based on site-specific circumstances. For instance, a landslide mitigation project may involve regrading (Section G-2.1.8), installing soil nails (Section G-2.1.9), lowering the groundwater table through drainage wells, and armoring the landslide toe where it is crossed by a stream (Section G-2.1.10). When multiple mitigation measures are combined, each is chosen for a specific purpose, but their mutual impacts and interrelationships with each other should be considered carefully in the planning and selection process.

G-3 Strain Capacity Enhancement

Strain capacity enhancement measures reduce the vulnerability of a pipeline to future loading from a landslide(s). Strain capacity includes both tensile strain capacity (TSC) and compressive strain capacity (CSC). The determination of whether to enhance TSC or CSC should be made based on the type of expected loading from the landslide being addressed (i.e., whether the landslide would primarily induce tension or compression). In some instances, both TSC and CSC might need to be enhanced.

The mitigation options in the context of this section may be viewed as a part of pipeline repair in broad industry terms. Consequently, the term “repair” is used interchangeably with mitigation, mitigation options, and enhancement options.

Executing strain capacity enhancement may be viewed as a pipeline repair or pipe replacement project. Such a project often requires coordinating various relevant parties involved in the design, material section, permitting, mobilization of field crews, safety, performing repairs, inspection, documentation, etc. The focus of this section is on elements specific to enhancing strain capacity, not all aspects of executing a repair or pipe replacement project. It is assumed that established company procedures covering customary repairs would be followed when executing a repair. The content of this section can be viewed as supplementary considerations and/or requirements necessary for enhancing strain capacity.

G-3.1 Enhancing Tensile Strain Capacity

Measures to enhance TSC include pressure reduction, pipe replacement, Type B sleeves, composite sleeves, and Type A sleeves. These measures are discussed in the following sections.

G-3.1.1 Pressure Reduction

Pressure reduction can be a temporary method to increase TSC unless the pressure reduction becomes permanent. This increase of TSC is reversed when the pressure is increased.

Based on deduction from prior analytical and experimental testing, a pressure reduction to a level lower than approximately 50% specified minimum yield strength (SMYS) leads to an increase of TSC. A pipeline that is operating above approximately 50% SMYS can expect an increase of TSC by a factor of 2 if the pressure is lowered to near zero. The TSC increase between a pressure of approximately 50% SMYS to zero pressure can be treated as a linear relationship.[52– 55, 73–77]

G-3.1.2 Pipe Replacement

Pipe replacement as a strain capacity enhancement measure should be implemented following the philosophy of building strain-resistant pipelines, which involves selecting appropriate linepipe, girth welding procedures, and inspection practices as described in Wang et al. and Wang and Jia.[32, 78, 79] The major components of strain-resistant pipeline construction are as follows:

- Reduce and limit the level of weld strength undermatching by (1) setting an upper limit for pipe strength in the longitudinal direction and (2) increasing the weld metal strength.
- Reduce and limit the level of the heat-affected zone (HAZ softening) by (1) setting an upper limit for pipe strength as a function of the steel's hardenability[16] and (2) limiting girth welding heat input.

It should be recognized that pipe replacement without following the processes of strain-resistant construction can lead to poor TSC or reduced TSC in comparison with the TSC of the pipeline segments being replaced, even when the minimum requirements in modern standards are met.

G-3.1.3 Type B Sleeve

Type B sleeves, when selected and installed correctly, can increase the TSC of a pipeline segment. The effectiveness of Type B sleeves in enhancing TSC is demonstrated in PRCI project SBD-1-6.[79]

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[16] The hardenability of a modern TMCP (thermomechanical control process) steel may be represented by Pcm, a form of carbon equivalent.

When sleeves are installed on a vintage pipeline (carrier pipe) with high carbon and high carbon equivalent (CE), the primary risks are hydrogen cracking due to fast cooling of in-service welding and burn-through for thin wall carrier pipes. Most in-service welding procedures are designed and qualified to mitigate those risks.

When installing Type B sleeves to enhance TSC, it should be understood that the pipeline segment after the sleeve installation could still experience moderate to high longitudinal/axial tensile strains. Furthermore, there could be a diminished possibility that the carrier pipe could leak if further strained after sleeve installation. The Type-B sleeve must be able to sustain both internal pressure and future axial load even when there is a leak in the carrier pipe.

The combination of internal pressure and axial/longitudinal load can generate high stress concentration in the carrier pipe adjacent to the fillet weld (Figure G-2). If the annulus of the sleeve were to be pressurized due to a leak, high strains/stresses are generated in the fillet weld (Figure G-3).

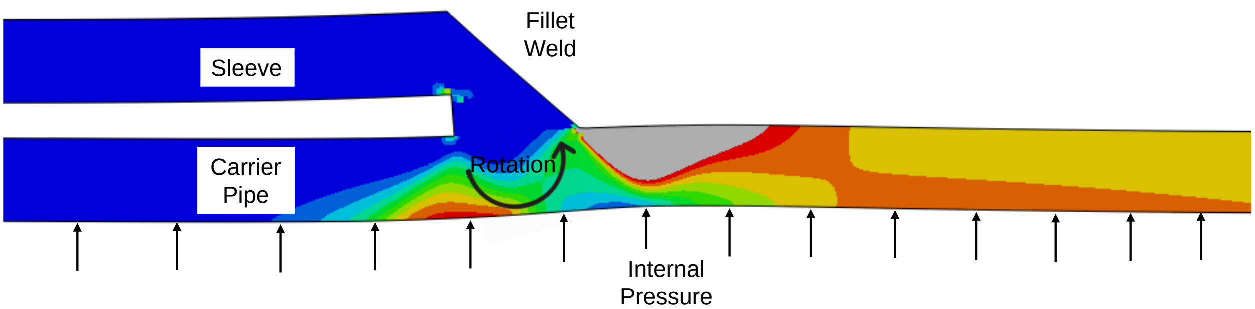

Figure G-2. Contour of equivalent plastic strain on deformed sleeve assembly under internal pressure and axial/longitudinal load when the annulus is not pressurized. The rotational deformation in the carrier pipe to the right of the fillet weld is evident. The gray areas represent the areas of the highest strains/stresses[80]

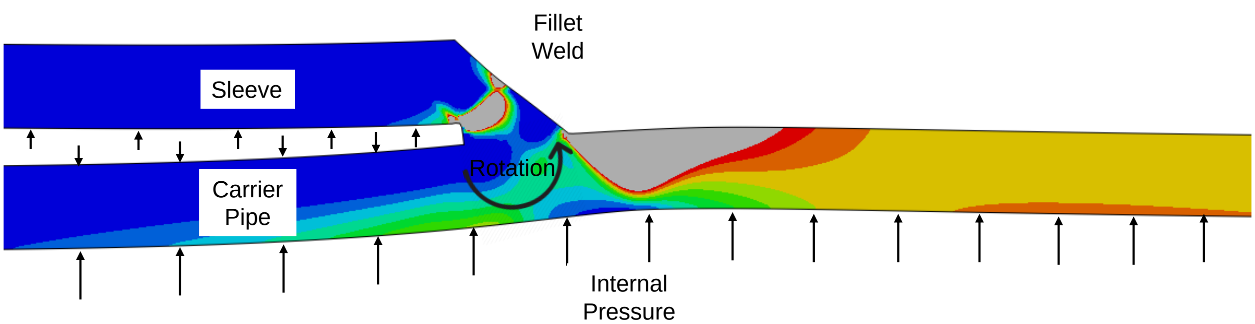

Figure G-3. Contour of equivalent plastic strain on deformed sleeve assembly under internal pressure and axial/longitudinal load when the annulus is pressurized. The pry-opening against the fillet weld is evident when the surfaces bounding the annulus are compared between this figure and Figure G-2.[80]

The following recommendations have been developed in PRCI project SBD-1-6[80] to ensure the integrity of the sleeve assembly.

- The fillet weld dimensions should target the higher end of the allowable size.
- The fillet weld strength must not be the lowest among the carrier pipe, sleeve, and the fillet weld. The actual strength, not the specified minimum strength, must be considered in meeting this requirement.

In addition to the above considerations, HAZ softening of the carrier pipe made of modern thermomechanical control process (TMCP) steels with low carbon and CE is a possibility if sleeves are installed in a non-flow or low-flow conditions, especially for natural gas pipelines. Figure G-4 shows the microhardness map of the fillet weld area of a sleeve assembly. The sleeve was installed on a modern TMCP low hardenability carrier pipe under an in-air condition with a high-end heat input of possible heat input range for a fillet weld. The softened HAZ in the carrier pipe is visible.

The HAZ softening in conjunction with the local high stresses/strains created at the toe of the fillet welds can reduce the strain tolerance of the completed sleeve assembly (PRCI Project SBD-1-6A).

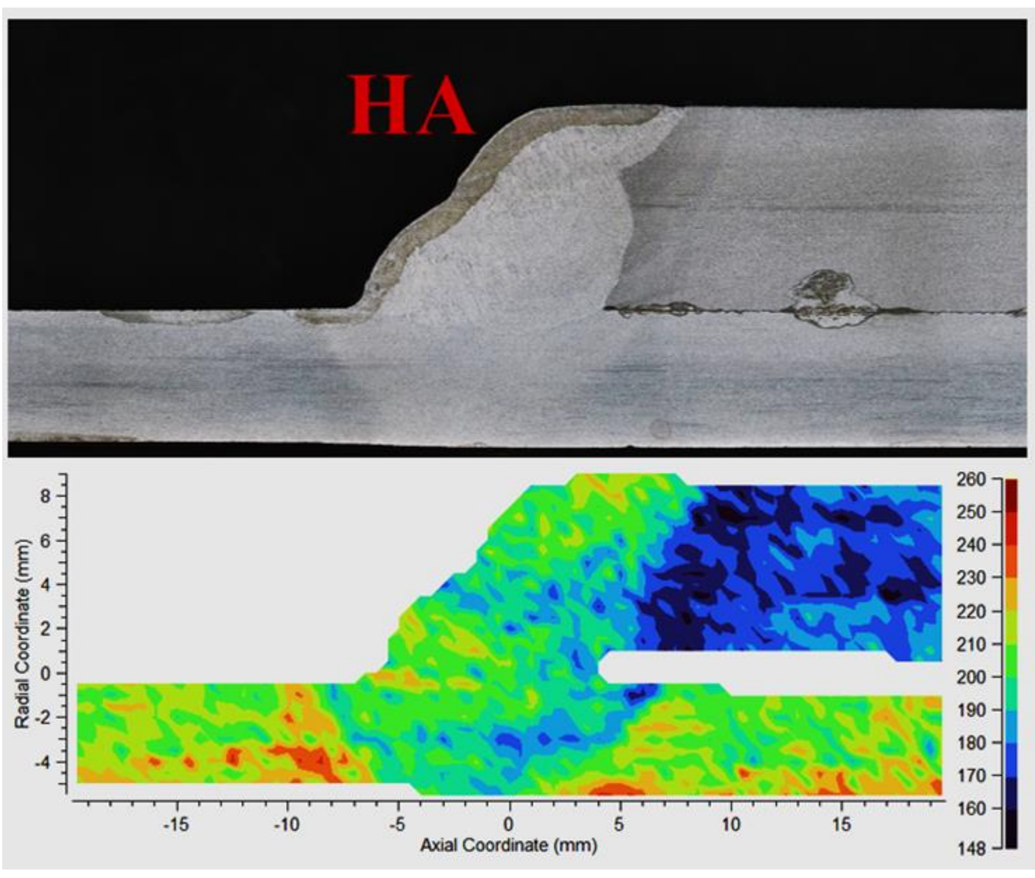

Figure G-4 Microhardness map of a fillet weld region of a sleeve assembly. The sleeve is installed on a modern TMCP pipe with low hardenability using high heat input under an in-air condition (HA).

G-3.1.4 Non-Pressure-Containing Sleeves

Sleeves that are designed to provide structural reinforcement, but not contain pressure if the carrier pipes were to have a leak, include composite sleeves and Type A sleeves (epoxy filled sleeves and compression sleeves). The following factors should be considered when selecting those sleeves:

- Loading mode (e.g., predominantly bending or uniform tension)
- Impact of internal pressure at the time of installation
- Effects of pressure cycles, including full pressurization and depressurization
- Possible degradation of material properties over time, including the effects of moisture and temperature

It is expected that the stresses/strains imposed on the carrier pipe after the installation of the sleeves would be lower than those without the sleeves. However, some increase in the stresses and strains is still possible. Such an increase must be less than the margin of the stress and strain needed to create a leak.

G-3.2 Enhancing Compressive Strain Capacity

CSC can be increased through pipe replacement by the following:

- Using low D/t ratio pipes
- Using low Y/T ratio pipes
- Replacing pipes having low-quality seam welds with pipes having high-quality seam welds
- Modifying the pipeline route in areas expected to experience large compressive strains/stresses (e.g., at the toe of a slope when a pipeline segment is running in the same direction as the slope) so it would not coincide with other detrimental factors (e.g., wall thickness transition or bends) when possible

G-3.2.1 Caution on Effects of Compressive Strain Capacity When Reducing Pressure

Pressure reduction usually reduces CSC. In some cases, pressure reduction has contributed to the formation of wrinkles and buckles when a pipeline segment is already under a high compressive load. Therefore, a pressure reduction should not be considered a mitigation option for enhancing CSC apart from the perspectives of safety and reduction of possible negative consequence if a loss of containment were to occur.

G-3.3 Guidance for Mitigation Measure Selection

The decision on the type, location, and scale of mitigation measures depends on many factors:

- Regional, local, and site-specific landslide and geologic conditions (e.g., one landslide versus many)
- Geologic, geotechnical, and topographic conditions
- Surface hydrologic and groundwater conditions

- Climatic conditions, including short-term and long-term climate condition over the anticipated lifetime of the pipeline system
- Landslide characteristics (e.g., type, direction of movement, rate of movement, footprint, landslide-pipeline interaction)
- Objectives (e.g., elimination of landslide hazard or reduction of potential effects)
- Site location and access
- Anticipated life of mitigation (i.e., short term versus long term)
- Proximity to human and environmental receptors
- Environmental and regulatory considerations
- Ongoing site monitoring
- Landowner restrictions (e.g., access, aboveground or underground structures)
- Land use restrictions
- Construction equipment access and weather constraints
- Pipeline operating conditions (current and future)
- Pipeline characteristics (strain capacity)
- Pipeline strain conditions (current and future strain demand)
- Constructability (e.g., geotechnical instability)
- Availability of construction material (e.g., rock for construction of a shear key)
- Budgetary constraints

Selecting appropriate mitigation measures for landslides involves a complex interface of technical, logistical, permitting, risk, and financial factors that, at a minimum, should consider the following:

- The characteristics of the landslide(s) being mitigated. These include: landslide type; soil and rock types; movement amounts, rates, and direction; landslide size; slip surface depth; depth of groundwater and piezometric pressure; direction of groundwater flow; pipeline location orientation and burial depth within the landslide; and relationship to the area being protected. These characteristics (not all applicable to a specific mitigative measure) should be well understood before implementing mitigation measures. Incomplete characterization can render installed measures less effective than planned or not effective at all.
- The feasibility of successfully implementing mitigation measures given the landslide characteristics. For instance, based on the landslide size or type, it might be financially infeasible to stabilize the landslide or to reduce the likelihood of recurrence. In these circumstances, an alternative approach to mitigation, such as avoidance or pipeline vulnerability reduction, might be a better option.
- The potential to cause or trigger additional landslide movement or worsen landslide movement during implementation. Landslide-prone areas are inherently unstable, and construction-related work has the potential to cause further destabilization. Selection and

design of mitigation measures should consider 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.

- The selected mitigation design should not pose the risk of destabilizing or worsening the landslide during or after construction. The design and construction plans should include appropriate measures to manage such risks (e.g., frequently monitoring slopes during construction, sequencing construction activities based on geotechnical analyses).
- The location and geography where the mitigation measures are to be performed. Location and geography strongly shape the feasibility of the mitigation option(s) being considered. For instance, an option that is feasible at a landslide location accessible by public roadway with no structures or other infrastructure (other than the roadway) in the vicinity might be financially infeasible for a remote location in proximity to other pipelines where access needs to be constructed.
- Environmental restrictions or other land use restrictions that could prohibit certain kinds of mitigation measures, such as mitigation that extends outside of the ROW. The selection of geotechnical mitigation measures should consider whether workspace outside of an existing ROW is needed and, if so, the time and cost to acquire this additional workspace.
- Permanent or temporary workspace outside of the ROW might need to be acquired. If this is not an option, alternative stabilization designs or mitigation approaches might need to be considered.
- The design should consider location and logistics to mobilize equipment to the site. This is particularly important when considering landslide stabilization because the equipment to conduct this work is often specialized, and some locations could be infeasible for some equipment.
- Constructability should be evaluated. For example, installing a retaining structure such as a sheet pile wall in granular soil is relatively difficult if not impossible or installing a deep curtain drain within a landslide might impose additional instability risk.
- The typical weather conditions at the time of year that construction will likely occur. For instance, in many areas, large earthwork projects might not be feasible (because of excessive soil moisture and/or frozen soil and snow cover) during the winter months, and alternative methods might be needed if the construction needs to occur during that time of year.
- The design should also consider the desired lifetime of the landslide stabilization. Pipeline operators should select a design lifetime, which can depend on the operational plans for the pipeline, as well as cost comparison and complexity of short-term versus long-term solutions. The design lifetime affects the selection of materials and methods to account for threat factors that can persist or evolve through time.

Table G-3 provides examples of possible mitigation measures that could be used for several scenarios involving landslides. Table G-3 is provided for illustrative purposes to assist in decision-making, and is not intended to be an exhaustive list, nor to preclude the use of other mitigation measures not listed. The table assumes that the pipeline operator has already decided that some form of mitigation measure is needed, and thus does not include the criteria for determining whether mitigation measures should be used as a threat management method.

The table also assumes that the objective of the mitigation measures include reducing to as low as reasonably possible (ALARP) the likelihood of impact (or further impact) to a pipeline or associated facility and that the selection of mitigation measures will be informed by input from an SME. Mitigation measures where the operator knowingly accepts some risk above the ALARP threshold are not listed. The table is focused on pipeline integrity and does not include measures that might be implemented for non-pipeline integrity reasons, such as to protect sensitive environmental areas or third parties. As previously discussed, the selection of mitigation measures depends on multiple characteristics, including technical feasibility, accessibility, land use restrictions, and environmental requirements, which, because of the many variations that can occur, cannot be easily captured in a single table.

The following are a few other notes to consider:

- Drainage improvements (within the pipeline trench or along the slope) can be used in combination with other mitigation measures and can potentially improve the stability of a landslide. These mitigation measures are only specifically called out in Table G-3 when they are preferred mitigation measures.
- Because of the difficulties in securing new ROW or conducting measures like HDD, avoidance is typically not a preferred option, unless all other options are infeasible.
- Landslide stabilization can include stabilization of all or a portion of a landslide that is adversely affecting the pipeline. Therefore, it can be feasible that only a portion of the landslide (e.g., pipeline ROW) be stabilized while the effect of the future ground movement within the area that was not stabilized is monitored.
- Landslides vary greatly in size and behavior. There are many landslides that cannot reasonably be stabilized or slowed with present day technology and resource availability. While there are many considerations that can shape the specific mitigation measures that are implemented, the measures selected must be technically feasible (as in, they must meet the objective of the mitigation measures). It should not be assumed that landslides can be managed through stabilizing or by eliminating all landslides that could affect a pipeline or pipeline ROW.
- The descriptions of landslides as small and large are relative. A small landslide can be one in which it is technically feasible that the entire landslide can be either eliminated through grading or stabilized through geotechnical measures. A large landslide, in contrast, is one that is too large to be feasibly stabilized using the resources of a pipeline operating company or only the portion of the landslide that is affecting the pipeline can realistically be stabilized.
- Similarly, the descriptions of landslides as fast and slow are relative. A fast landslide is one that has the potential for rapid movement with insufficient time for response, while a slow landslide is one in which the movement can be recognized, and the response time planned and implemented over months or years.

Table G-3. Guidance on selection of mitigation measures

Situation	Landslide Relationship to Pipeline	Possible Landslide Mitigation Measures	Considerations
Small, slow landslide	Crosses pipeline centerline and engages the pipeline	Stabilization using earthwork, stabilization using mechanical reinforcement, periodic stress-relief excavations, girth weld reinforcement, or other strain capacity enhancement measure combined with ongoing monitoring (to evaluate whether additional mitigation measures are needed)	These types of landslides, being relatively small and slow moving, allow for the use of essentially all mitigation measures to manage.
	Does not cross pipeline centerline	Stabilization using earthwork, stabilization using mechanical reinforcement, surface and trench drainage improvements combined with ongoing monitoring (to evaluate whether additional mitigation measures needed)	For small, slow landslides that do not currently cross a pipeline, if mitigation measures are deemed necessary, the preferred approach is to preemptively stabilize the landslide.
Small, fast landslide	Crosses pipeline centerline and engages the pipeline	Stabilization using earthwork, stabilization using mechanical reinforcement, surface and trench drainage improvements combined with ongoing monitoring (to evaluate whether additional mitigation measures needed)	In the fast scenario, there may be insufficient time to manage the landslide through repeat stress-relief excavations and thus the preferred option may be to stabilize the landslide.
	Does not cross the pipeline centerline	Stabilization using earthwork, stabilization using mechanical reinforcement, surface drainage improvements, stabilization of ROW (isolation or protection of the ROW), landslide monitoring	Similar considerations apply for this scenario, but since the landslide does not currently cross or impact the pipeline, it might also be a type of landslide that is located outside of the ROW, and thus outside of the pipeline operator's ability to stabilize or eliminate (such as a debris flow channel). In this case, the mitigation measures may consist of preemptive measures to isolate or protect the ROW from the impact of the landslide.

Situation	Landslide Relationship to Pipeline	Possible Landslide Mitigation Measures	Considerations
Large, slow landslide	Pipeline crosses through head or along flanks of the landslide	Stabilization of the ROW (isolation from the landslide), periodic stress-relief excavations, placement of deformable backfill to reduce pipeline-soil interface friction, girth weld reinforcement or other strain capacity enhancement measure combined with ongoing landslide/pipeline monitoring (to evaluate whether additional mitigation measures are needed)	In this scenario, while stabilization of the landslide might not be realistic, it might be possible to stabilize the ROW (or isolate the ROW from the landslide). Alternatively, if the landslide behavior is predictable with slow strain demand accumulation, periodic stress-relief excavations may be considered.
	Pipeline crosses through the body or toe of the landslide	Periodic stress-relief excavations, placement of deformable backfill to reduce pipeline-soil interface friction, girth weld reinforcement or other strain capacity enhancement measure combined with ongoing strain gauge or other pipeline strain monitoring (to evaluate whether additional mitigation measures are needed), avoidance	In this scenario, stabilization of the landslide or isolation of the ROW from the landslide is not realistic. If the behavior of the landslide is predictable and strain demand accumulation is slow, it can be managed through periodic stress-relief excavations, potentially combined with strain capacity enhancement measures to increase the time between excavations.
	Does not cross the pipeline centerline	Stabilization of the ROW (isolation from the landslide), drainage improvements, strain capacity enhancements	In this instance, the pipeline is not currently affected by the landslide, but could be with further movement. In this scenario, the focus is generally on reducing the likelihood of impact to the pipeline, and if impact does occur, to reduce the likelihood of a loss of containment.
Large, fast landslide	Pipeline crosses through head or along flanks of the landslide	Stabilization of the portion of the ROW affected by the landslide (isolation from the landslide), avoidance	In this scenario, while stabilization of the landslide might not be realistic, it might be possible to stabilize the ROW (or isolate the ROW from the landslide). If isolation is not possible, then avoidance would generally be the preferred method of threat management. Stress-relief excavation is not a recommended option.

Situation	Landslide Relationship to Pipeline	Possible Landslide Mitigation Measures	Considerations
Large, fast landslide (cont.)	Pipeline crosses through the body or toe of the landslide	Avoidance	In this scenario, the landslide is too large to stabilize and there is insufficient time to respond in the event of landslide movement, making measures like stress-relief excavations or strain capacity enhancements not appropriate. Avoidance would generally be the only feasible option in this scenario.
	Does not cross the pipeline centerline	Stabilization of the ROW (isolation from the landslide), avoidance	In this scenario, while stabilization of the landslide may not be realistic, it may be possible to isolate the ROW from the landslide. If isolation is not possible, then avoidance would generally be the preferred method of threat management.
Rockfall	Shallow pipeline, exposed pipeline, aboveground pipeline, or aboveground facilities	Rockfall fencing, armoring, tensioned wire mesh, catchment walls	Typically, rockfall is not a major threat to pipelines, unless the pipeline is exposed at the surface, shallowly buried, or for aboveground facilities, such as pipeline racks at flare pads or other facilities installed at the toe of deeper cut slopes. In these cases, the rockfall threat can be managed through standard rockfall protection measures, similar to those used for highways and other facilities potentially exposed to rockfall.

G-3.4 Post-Mitigation Monitoring

In most cases, monitoring should be conducted after implementing mitigation measures. Monitoring is intended to confirm the efficacy of the mitigation measures and determine if additional actions are needed (e.g., increased monitoring or implementing additional mitigation measures). The length, frequency, and type of monitoring to be conducted after mitigation measures is site specific. Operators should implement an appropriate post-mitigation monitoring plan using the considerations and approaches discussed in Section 7 and this annex.

Annex H
Landslide Program Evaluation Metrics

Annex H: Landslide Program Evaluation Metrics

H Introduction

Operators should periodically measure and evaluate the effectiveness of their landslide management program (Section 8). The evaluation of the effectiveness of the program should be performed annually. Examples of landslide-specific program metrics[17] that may be useful for program assessment include the following:

- Landslide Inventory Summary
  - Number of landslides that cross and/or are within a certain distance of the pipeline
  - Number of landslides that have evidence of a previous impact on a pipeline
  - Number of landslides that have moved/changed since construction or completion of the last assessment
- Landslide Assessment Summary
  - Number and level or type of assessments performed (summarized by year)
  - Miles or percentage of system assessed to Level 1
  - Sites assessed at Levels 2 and 3
  - Sites scheduled for Level 2 and 3 Assessments
  - Response actions scheduled as the results of assessments
- Incident Summary
  - Number of incidents resulting from landslides, such as leak, rupture, emergency response, line shutdown, or pressure reduction
- Monitoring Summary
  - Mileage of pipeline and/or number of landslides monitored by wide-area monitoring (e.g., repeat light detection and ranging [LiDAR]/inertial measurement unit [IMU] bending strain, interferometric synthetic aperture radar [InSAR]) and frequency of that monitoring
  - IMU bending strain assessment miles and whether they are first-run or repeat assessments
  - Miles scheduled for IMU bending strain assessment
  - Number of landslides that are monitored by on-site instrumentation and frequency of monitoring

[17] These possible metrics are supplements (not in lieu of) to the metrics normally collected to assess effectiveness of an integrity management program, such as the ones listed in API RP 1160.

  - Number of monitoring instruments installed for each instrument type
  - Number of sites scheduled for monitoring instrument installation, but not yet completed
  - Sites where thresholds were exceeded and that proceeded to mitigation or other action
  - Cost or effort (if completed in-house) for monitoring design, installation, maintenance, and analysis

- Mitigation Summary
  - Number of landslides that have been mitigated and mitigation type
  - Number of landslides where prior mitigation required maintenance (effectiveness of mitigation)
  - Number of sites scheduled for mitigation, but not yet completed
  - Cost or effort (if completed in-house) for mitigation design and implementation

Annex I

Interacting Threats in Landslide Integrity Management

Annex I: Interacting Threats in Landslide Integrity Management

I Introduction

An interacting threat is a threat that interacts with one or more other threats resulting in the compounding effects of further reducing the pipeline's integrity compared to that from a single threat. In the context of landslide management, interacting threats are those threats that potentially aggravate the impact of a landslide to a pipeline.

Since the integrity of a pipeline is determined by the difference between capacity and demand (i.e., safety margin), any threat that can affect the capacity or demand or both can potentially impact pipeline integrity.

I-1 Impact of Interacting Threats

Threats interacting with landslides can result in either one or both of the following:

- A reduction in capacity, such as strain capacity
- A reduction in burst pressure

Longitudinal stresses imposed by a landslide can affect the burst pressure of pipeline segments containing anomalies, such as corrosion or mechanical damage. For instance, compressive longitudinal/axial stress can reduce the burst pressure of a pipe containing corrosion anomalies in comparison to a situation with zero stress or tensile longitudinal/axial stress.[81, 82] This impact on burst pressure is expected to be addressed when these anomalies are assessed and are therefore excluded from further discussion in this document.

In the context of landslide management, interacting threats associated with potential reduction of capacity include the following:

- Corrosion with substantial circumferential extent, either in pipe body or girth welds
- Circumferentially oriented stress corrosion cracking (C-SCC) in pipe body (Figure I-1)
- Spirally oriented SCC (S-SCC) in pipe body with spiral angles aligning with the spiral tape coating or pipe seam weld (Figures I-2 and I-3)
- Other SCC with substantial circumferential extent
- Mechanical damage, without or with gouges

Girth weld anomalies technically can be considered an interacting threat. However, since those anomalies are almost always considered in the integrity assessment for landslide management, they are not listed here as an interacting threat.

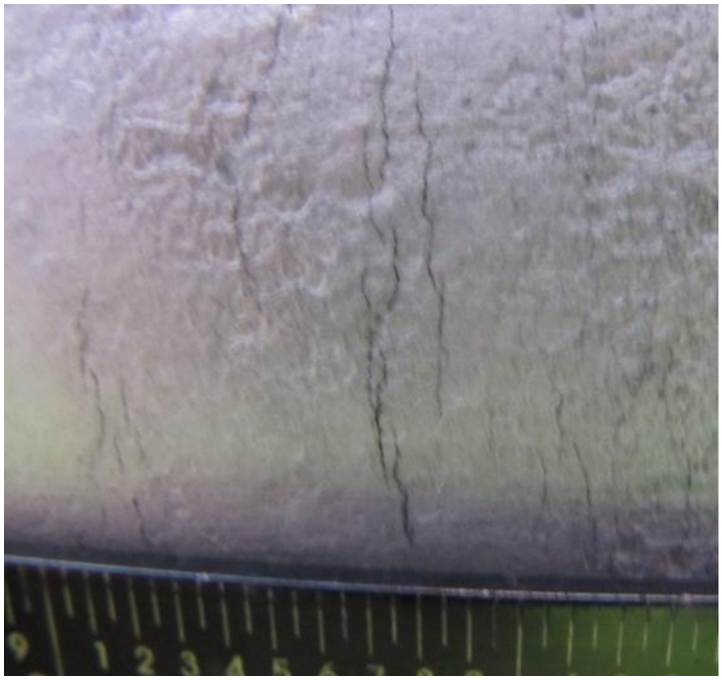

Figure I-1. Example of a C-SCC cluster

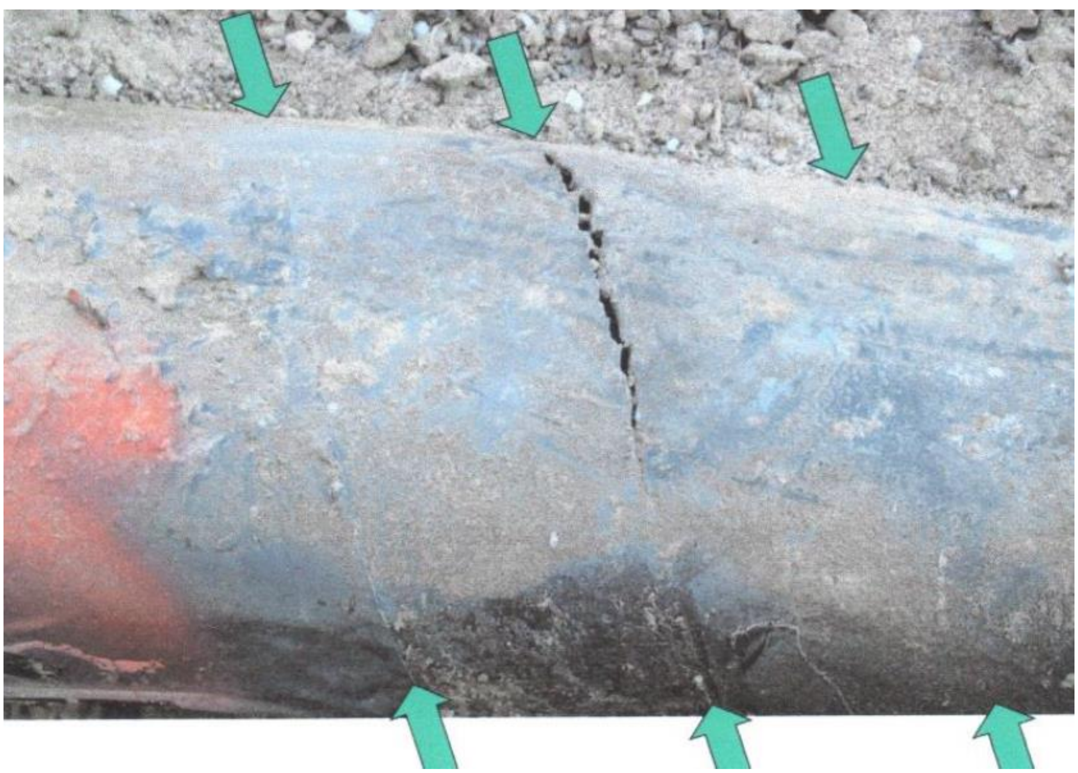

Figure I-2. Example of a S-SCC aligned with tape coating that resulted in a leak

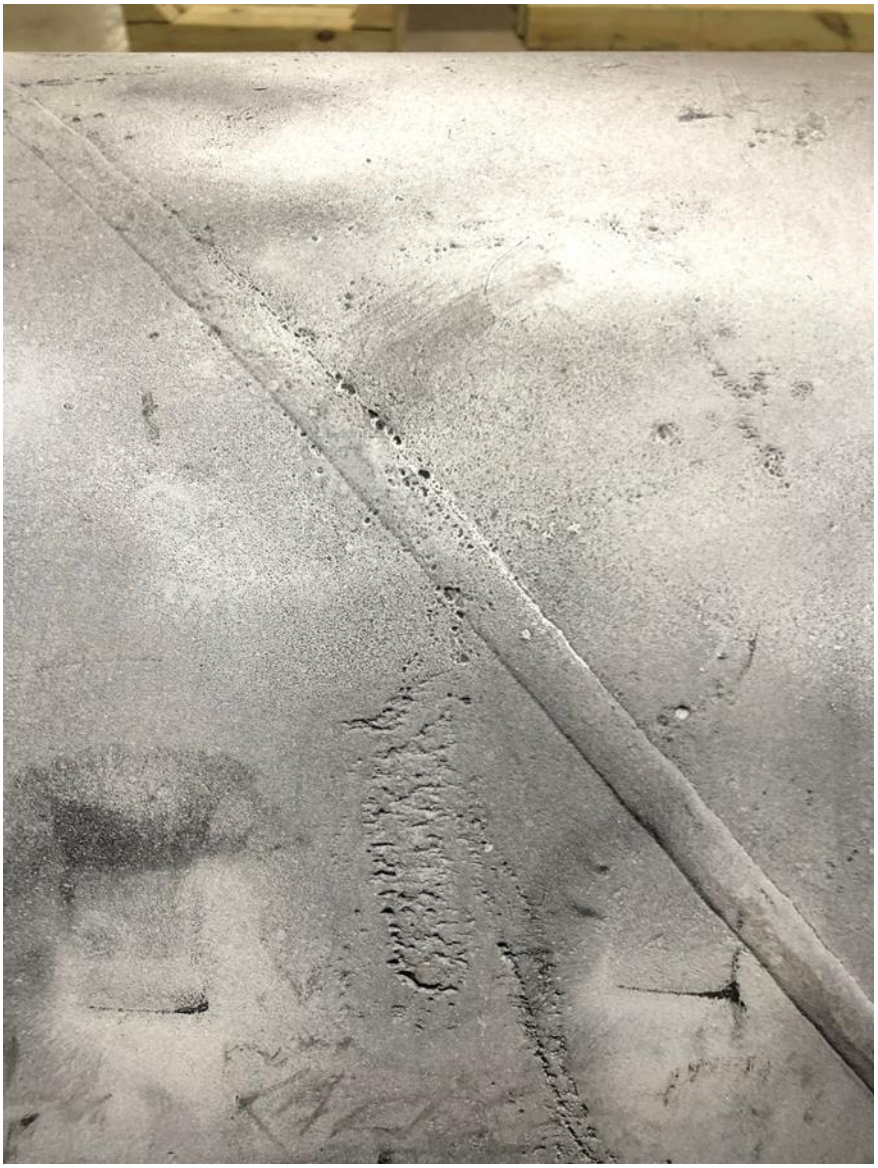

Figure I-3. Example of corrosion and SCC near a spiral weld

I-2 General Trends in the Potential Impact of Interacting Threats

The impact of interacting threats can be summarized as follows:

- Corrosion, especially corrosion with substantial circumferential extent in pipe body or girth welds, can reduce the tensile strain capacity (TSC).
- Dents without gouges can reduce the compressive strain capacity (CSC) but has little impact on TSC.
- Dents with gouges can reduce both CSC and TSC.
- C-SCC, S-SCC, and other SCC with substantial circumferential extent can reduce TSC.

- Compressive longitudinal stresses caused by landslides can reduce the burst pressure of pipes with corrosion and other anomalies.

I-3 Management of Interacting Threats

The landslide management program should consider the influence of interacting threats on strain capacity and the ability to contain internal pressure.

In order to manage interacting threats (referred to as "features" below in line with typical in-line inspection [ILI] and nondestructive examination [NDE] practice), the following information is needed:

- Location of the features
- Characterization of the features (what they are) and size (dimensions)
- Forecast or prediction of growth of the features if they were to grow over time
- Assessment of the impact of the features to strain capacity or strain demand

The management of each of the previously identified interacting threats is briefly discussed below.

I-3.1 Corrosion with Large Circumferential Extent in or near a Girth Weld or in Pipe Body

The impact of corrosion on the TSC and CSC can be evaluated using the methods in Liu et al., Zhou et al, and Zhou et al.[83, 84, 85]

I-3.2 Dent without Gouge

Dents can be located and sized by high-resolution geometry ILI tools. Dents are typically treated as a nongrowth threat. Their impact on CSC can be assessed using procedures similar to those described in the Zhou et al., and Liu et al.[82, 83]

I-3.3 Dent with Gouge

Dents with gouges can be identified by ILI tools. However, sizing the severity of the gouge can be difficult. In addition, there could be cracks initiated at the bottom of gouges. These cracks may not be reliably detected and sized with existing ILI technology, especially for natural gas pipelines.

There are no established methods to assess the impact of dents with gouges on either TSC or CSC. Case-specific analysis using the Level 4a procedure of Pipeline Research Council International-Center for Reliable Energy Systems (PRCI-CRES) tensile strain models can be performed to determine TSC.[53–55] Similarly, case-specific finite element analysis can be done to determine CSC.[62, 63]

I-3.4 C-SCC, S-SCC, and other SCC with Substantial Circumferential Extent

Reliably locating, characterizing, and sizing C-SCC, S-SCC, and other SCC with large circumferential extent is a challenge, especially for natural gas pipelines. In addition, SCC must generally be treated as time-dependent (i.e., they might grow over time). However, their growth rates can vary greatly, and it is generally difficult to estimate growth rates.

In the absence of ILI tools for locating and sizing SCC, integration of data from multiple sources can provide a susceptibility ranking among different pipelines and various locations along a pipeline. Three conditions must exist for the initiation and growth of SCC: (1) susceptible microstructure; (2) certain environmental conditions, including soil/moisture conditions and pipe coating; and (3) stresses. The first condition, susceptible microstructure, is almost always met for steel pipelines because most pipeline steels are susceptible to SCC. The remaining conditions to be examined are soil conditions surrounding the pipeline, health of the pipeline coating, and stresses. Pipelines with tape coating and girth welds with shrink sleeves are known to be susceptible to SCC. For SCC to have substantial circumferential extent, longitudinal/axial stresses must be present. These stresses can come from landslides, other types of geohazards, settlement stresses from pipeline construction and maintenance, and residual stresses from field bending of linepipe. More information on SCC susceptibility can be found in API RP 1176.

It is understood that C-SCC and S-SCC can reduce the TSC of a pipeline. The impact on TSC can be assessed using the Level 4a procedure of PRCI-CRES tensile strain models if the SCC can be located and sized.[53–55]

I-4 Prioritizing the Assessment of Interacting Threats

The assessment of landslides interacting with other pipeline threats is a maturing field. Rigorous processes and procedures are not yet readily available for routine assessment, although case-specific analysis may be performed. When it is necessary to prioritize the assessment of interacting threats, high priority should be placed on those threats that can grow and lead to reduced TSC over time. Specifically, corrosion near or in girth welds, C-SCC, and S-SCC, are recommended to generally be prioritized for assessment over other interacting threats.

Annex J
Bibliography

Annex J: Bibliography

J Introduction

This Annex provides all of the documents used to create this guidance. The items numbered in Section J.1 are documents cited. The items listed in section J.2 were reviewed for this project but not cited within the document. The items in Section J.2 are provided as other possible reading.

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