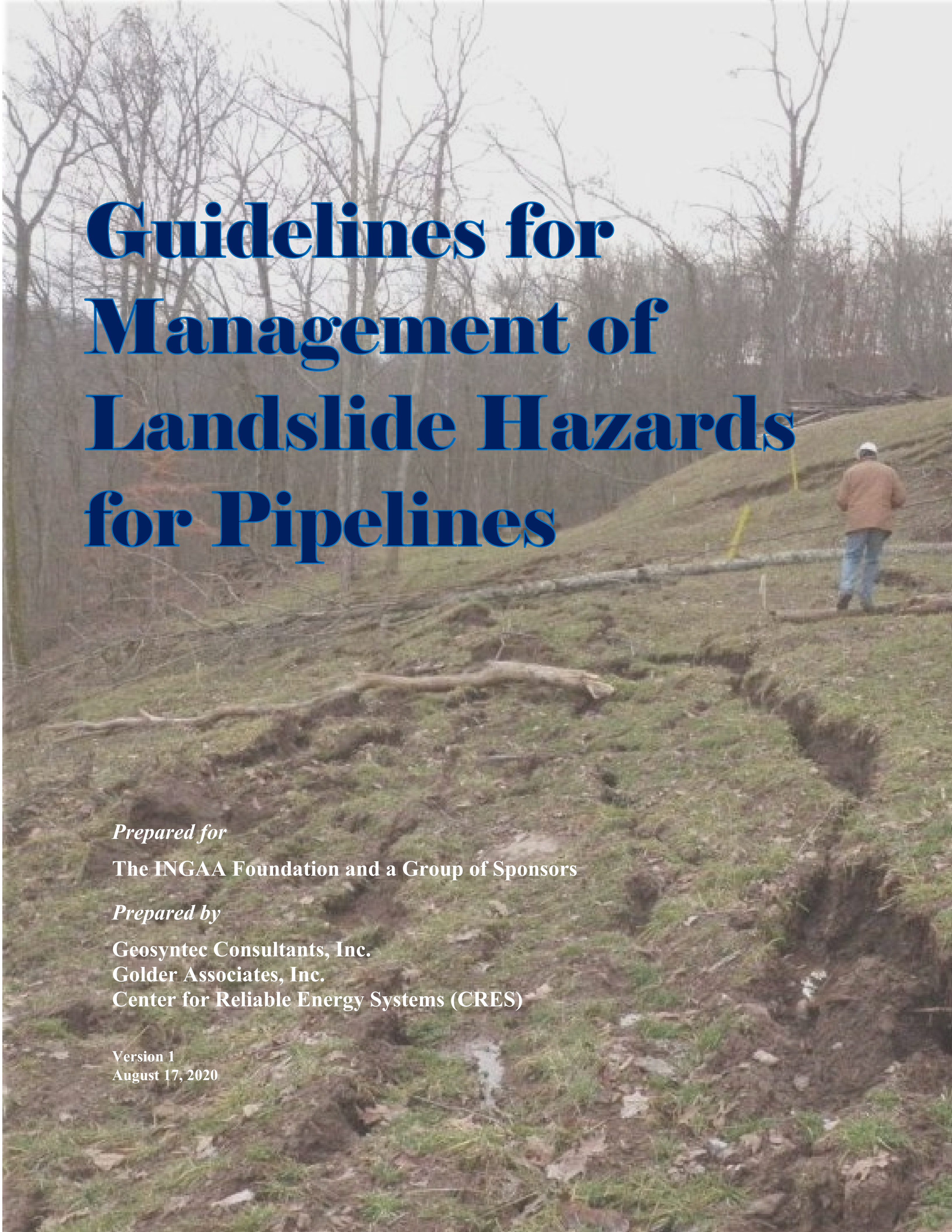

Guidelines for Management of Landslide Hazards for Pipelines

Prepared for

The INGAA Foundation and a Group of Sponsors

Prepared by

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

Version 1
August 17, 2020

Guidelines for Management of Landslide Hazards for Pipelines

This guidance document was prepared for The INGAA Foundation and a group of sponsors.

This guidance document was sponsored by Enbridge Inc. (JIP Lead), Boardwalk Pipelines, Dominion Energy, DTE Energy, Enable Midstream Partners, Energy Transfer, Kinder Morgan Inc., Marathon Pipe Line LLC, National Fuel Gas Company, Pacific Gas & Electric (PG&E), Phillips 66, Plains All-American, SoCalGas, Tallgrass Energy, TC Energy, and Williams.

This guidance document was prepared by Geosyntec Consultants, Inc.; Golder Associates, Inc.; and the Center for Reliable Energy Systems (CRES).

The authors of this guidance document are Alexander McKenzie-Johnson[1], Bailey Theriault[2], Yong-Yi Wang[3], Dunji Yu[3], Don West[2], Ali Ebrahimi[1], Martin Derby[2], Anthony Rice[1], and Alexander Greene.[1]

1: Geosyntec Consultants, Inc. 2: Golder Associates, Inc. 3: Center for Reliable Energy Systems (CRES)

Version 1
August 17, 2020

Acknowledgements

The development of any guideline document is by necessity a team effort. The lead authors of these guidelines, Alexander McKenzie-Johnson of Geosyntec Consultants Inc.; Bailey Theriault of Golder Associates Inc., and Yong-Yi Wang and Dunji Yu of Center for Reliable Energy Systems (CRES), would like to thank the following:

- Kurt Baraniecki of Enbridge for initiating the idea behind this Joint Industry Project (JIP) and organizing the JIP Committee.
- Doug Cook, also of Enbridge, for acting as the JIP lead and providing needed guidance and direction as the JIP progressed.
- Christopher Osman of INGAA and Michael Istre of the INGAA Foundation for providing the financial and administrative organization to make this JIP possible.
- All of the JIP Committee members who participated in the meetings, provided information on their landslide management programs, and contributed valuable review comments. Special thanks to Justin Brooks, Patrick Fleck, Jonathan Bell, David Johnson, and Doug Cook who carefully reviewed the first draft of this document and whose comments have greatly benefited the final outcome. The complete list of JIP participants is on the following page.
- All of our colleagues and co-workers who contributed to completion of these guidelines, including Anthony (Tony) Rice, Alexander Greene, Ali Ebrahimi, Rodolfo Sancio, Tim Cramer, and Colby Reece at Geosyntec; and Don West and Martin Derby at Golder.
- Finally, a special thanks to the many long hours put in by Laura Leighton of Geosyntec, who provided tireless technical editing and organization.

JIP Committee Participants

Operator	JIP Participants
Boardwalk Pipelines	Tony Rizk, Darral Ward, Rodney Clayton, Micheal Preuit
Dominion Energy	Tim Gawenus
DTE Energy	Richard Wyman, Thomas Stack
Enable	Cary Windler, Ren Oslica
Enbridge (JIP Lead)	Doug Cook, Kurt Baraniecki
Energy Transfer	David Johnson, Brian Jimenez, Matt Florian, Jason Becker, Nicholas Berkholz
Kinder Morgan	Justin Brooks, Munendra Tomar, Arash Mosaiebian
Marathon	Patrick Fleck
National Fuel	Brent Hoover
Pacific Gas & Electric (PG&E)	Bennie Barnes, David Xu
Phillips 66	Justin Samuel, Fan Zhang
Plains All-American	Tiffany Doan, Erol Alavi
SoCal Gas	Karineh Gregorian
Tallgrass	Paul Whitty, Kale Stanton
TC Energy	Justin Taylor
Williams	Jonathan Bell

PREFACE

Geohazard-related pipeline concerns, and certainly pipeline failures, are rare, one-off events that happen to other operators: those whose pipelines go up and down the hillsides in Appalachia or who have to deal with the earthquakes and mudslides on the west coast. When you get surprised by your first one, there's a tendency to treat it as a "black swan," something that you didn't realize even existed in your world. In thinking about the growing awareness of geohazard threats to pipelines, I am reminded of the advent of awareness of stress-corrosion cracking (SCC) several decades ago. First, it didn't exist. Then, it was somehow geographically limited to only north of the 49th parallel, making it a Canadian problem. Poor Canadians—glad we don't have that! And the United States operators were fine, until they weren't. Then, for a time, there were two kinds of operators: those who knew they had to deal with SCC, and those who hadn't yet realized they had to deal with SCC. Now it occupies its own place on pipeline failure reporting forms and has been the subject of a broad and robust and ongoing program of study. Addressing the threat that geohazards pose to pipelines seems to have followed a similar arc.

Fortunately, we are probably further along, as an industry, in our understanding of and our responses to geohazards than we perhaps realize. Our regulatory agencies have been encouraging us to account for these hazards for some time. The Pipeline and Hazardous Materials Safety Administration (PHMSA), Canada Energy Regulator (CER), Pipeline Research Council International (PRCI), the trade organizations, and professional societies have all sponsored research, reviewed some of the practices, and conducted meetings and symposia dealing with various aspects of geohazards. Further attention was focused on the issue when PHMSA published their advisory bulletin ADB-2019-02, *Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards*, on May 2, 2019. But it has been a daunting task for an individual or a single operator to digest all of these reports, papers, presentations, and symposia proceedings and synthesize them into a rational, coherent, integrated approach to geohazard management.

A few years ago, a group of interested operators initiated a Joint Industry Project (JIP) to develop best practices for managing ground movement hazards (i.e., landslides and ground settlement) (Wang et al. 2017). More recently, operators who were initially invited by Enbridge met to consider the value of another JIP to share experiences with landslide hazards—their identification, risks, and management—on pipelines already in operation. Those operators who chose to participate in this JIP collectively decided to engage a consortium of subject matter experts (SMEs), organizations that many of the participants had experience with, to assist and facilitate the collection of JIP members' experiences and approaches; review existing available research and guidance in the pipeline industry as well as other primarily linear infrastructure segments; and, with their insights and knowledge, provide a summary and a framework that pipeline operators could use in the development and implementation of their landslide hazard management programs or in the improvement of their existing programs.

It has been encouraging to note the continued interest, enthusiasm, and openness of the participants as this work progressed. The final work product, this document, should prove to be an extremely useful resource to almost any operator who is dealing with or has a growing interest in or concern about landslide hazards.

First, a couple of words about what this document is not. It is not overly prescriptive. It does not presuppose a particular level of knowledge or expertise. It does not attempt to tell the reader how to do everything that is discussed. It does, however, provide a methodical approach that each operator can tailor to its own circumstances and risk management structure. It provides guidance on the decision-making process that continues throughout landslide hazard management—recognition, identification, classification, assessment, monitoring, and remediation. Throughout, there are factors and information for the operator to consider in its decision-making process, but not what those decisions should be. It is also well referenced. The user has access to a wealth of detailed information on data, experiences, technologies, assessments, and even decision-making that are noted throughout.

This report will not solve all your landslide hazard problems for you. But if an operator commits to the framework and approach described and scales this approach to its particular system, environment, and needs, I am convinced that it will produce positive results for perhaps 90% of an operator's landslide hazards. Additionally, if embraced and used by a broad spectrum of operators, it also provides consistency of approach and a common terminology. This will likely be particularly beneficial in instances of multiple operators whose lines are in close enough proximity that they may be affected by the same landslide hazards.

The pipeline industry faces increasing technical challenges in general, including from landslide hazards, as well as increasing expectations from regulatory agencies and the public. We, as the pipeline industry, need to have a deeper understanding about the risks to our pipelines, which translate to risks to people, property, and the environment around our pipelines, and how to manage and mitigate those risks. This report provides an excellent common framework to help meet those challenges. I am happy to have had the opportunity to participate in its creation. I hope that it will be embraced broadly across the industry.

Dr. David Johnson
Director, Pipeline Safety (Energy Transfer) (retired)
PRCI Distinguished Service Award
PRCI – past Board of Directors member and Executive Committee Chair, past Corrosion Control Committee chair
GTI – past Board of Directors member
International Gas Union – past US delegate
INGAA – past Pipeline Safety Committee chair

David Johnson's 41 year career as a pipeline metallurgist begin in 1979 when he joined Northern Natural Gas. Over his career, he worked on failure investigations of pipe and equipment, pipe and welding specifications, process development, corrosion control, engineering project management, permit and right-of-way acquisition, regulatory development and compliance, risk assessment, and integrity management. Throughout his career, he has represented his employers and the pipeline industry in research and development related to pipeline safety and in the crafting of related regulations. We are fortunate to have had Dave's insight, humor, and experience in the development of these guidelines.

EXECUTIVE SUMMARY

This report, *Guidelines for the Management of Landslide Hazards for Pipelines*, provides a summary of recommended and suggested processes and steps that pipeline operators can use to provide a consistent framework for proactively managing landslide hazards that can or may affect their pipeline systems. The management guidelines help operators to identify, characterize, mitigate, and monitor actual and potential landslide hazards as well as provide guidance to perform fitness for service (FFS) assessments of pipelines affected or potentially affected by landslide movement.

Ten primary sections comprise the bulk of guidance contained in the report. The primary sections are followed by four brief secondary sections, which describe considerations for landslide data management, landslide hazard training and awareness for pipeline personnel, quality assurance, and the management of change and improvement. The following are descriptions of the contents of the 10 primary sections of the report.

In Section 1, Introduction, the objective and intent of the report is laid out to provide guidelines and a framework for implementing and improving landslide hazard management programs for pipelines, with the expectation that this will reduce landslide-related damage to pipelines and associated facilities. The introduction also includes a problem statement, which describes the background of the importance of landslide hazards as they relate to pipeline releases and ruptures, which drive the development of the guidelines. There is also a discussion of the limitations of the guidelines.

Section 2, Regulatory Guidance and Standards, outlines the regulatory framework and standards governing landslides and pipelines in the United States, Canada, and internationally. In the United States, the regulations are administered by the Pipeline and Hazardous Materials Safety Administration (PHMSA); in Canada, by the Canadian Energy Regulator (CER); and for international pipelines, by the International Organization for Standardization (ISO) standards, while nonmandatory and nonspecific American Society of Mechanical Engineers (ASME) standards may also apply. An important point for North American pipeline operators is that the regulatory guidance for management of landslide hazards is generally performance-based, with few prescriptive requirements.

In Section 3, Summary of Prior Work, the focus is on a brief review of the 2017 Joint Industry Project (JIP) (Wang et al. 2017), which was to develop best practices for managing ground movement hazards (i.e., landslides and ground settlement). The intention of the 2017 JIP was to address nearly all major elements necessary for managing landslides and settlement hazards using an integrated approach. It is noted in the section that the guidelines of this document should be considered complementary to the 2017 JIP and are intended to build upon the work of Wang et al. (2017). The section ends with a table that provides a brief review of the contents of 11 additional reports and documents that are deemed relevant to landslide hazard management for pipeline operators.

Section 4, Management Framework for Landslides, first lists key driving elements for integrity management of onshore pipelines, which translate to landslide hazard management. The section then delves into the landslide management process, wherein core processes are listed and explained, including the identification and threat classification of landslides of concerns, an FFS assessment, and a mechanism to manage, store, analyze, and retrieve information and data on landslides of concern. This is followed by recommendations for a pipeline operator in implementing a landslide hazard management program or for an operator looking to improve an existing program. The section ends with a discussion of considerations that are important in a landslide management program, particularly that it should be proactive and have a complete life-cycle approach.

Section 5, Identification and Characterization of Landslides, notes that identifying and characterizing landslide hazards is the foundation for a pipeline landslide hazards management program. That is, landslide hazards can only be addressed in a hazard management program if they are known, and decision-making around how to respond to the hazards should be centered around a complete understanding of the potential current and future landslide threat(s) imposed on the pipeline(s) by each landslide. The means to identify and characterize the landslides of concern along a pipeline system is a phased approach that is used to systematically identify, characterize, classify, and document in order to develop an inventory of possible landslide threats that might affect the system. There are three phases discussed in the section, and important elements and data requirements of each are described. The three phases allow for zeroing in on the landslides of concern that need or may require action by the operator. The section concludes with descriptions of applicable landslide identification and assessment technologies and methods as well as a brief discussion of addressing unplanned landslide identification that may have been brought by the public.

In Section 6, Fitness for Service Assessment of Pipelines Potentially Impacted by Landslides, the process of the FFS assessment is described, including its role in landslide hazard management. Whereas Section 5 focused on the landslide (hazard), the FFS assessment is a process by which the integrity of a pipeline is evaluated to establish whether the pipeline is at risk based on the information available to conduct the assessment and is focused on the potential for pipe loss of containment (LOC) or loss of service (LOS). Possible pipe failure modes and limit states are discussed along with the potential impact of pipe and weld conditions on landslide hazard management decisions. The majority of Section 6 is devoted to the discussion of strain-based assessment as the foundation of the FFS assessment. Estimating strain demand from landslide ground movement is discussed along with determining tensile and compressive strain capacity of the pipelines. The section concludes with descriptions of recommended data to be collected for the FFS assessment and the uncertainties and limitations of an FFS assessment.

Section 7, Classification and Decision-Making (CDM), provides guidance for the threat classification of landslides and for the decision-making process for landslide hazard management. CDM is used for three primary purposes: 1) to determine whether to perform action(s) throughout the identification and characterization process, 2) to determine the nature of such action(s) (i.e., whether to conduct additional assessment, implement mitigation, or implement monitoring), and 3) to determine the timing or order of conducting actions (i.e., the prioritization). The section also discusses the two major strategies for the CDM process: case-by-case and prescriptive or semi-prescriptive, with the semi-prescriptive strategy being recommended. Important CDM considerations for a pipeline operator are addressed along with the recommended approach to classification and decision-making. Implementation of the CDM process is thoroughly discussed, including how it is applied to newly identified or possible landslides and how it works for ongoing landslide or pipe monitoring. The section concludes with a brief discussion of prioritization.

Section 8, Mitigation of Landslide Hazards, describes the means to manage landslide risk through implementing physical methods to reduce likelihood of adverse impact, including 1) avoid landslide hazards, 2) reduce the vulnerability of a pipeline to the adverse effects of landslide movement, or 3) eliminate, stabilize, or reduce the likelihood of landslide movement and its impact on the pipeline. There are two main strategies for landslide risk control, though they are often combined: 1) proactive mitigation, and 2) monitoring. The section includes a discussion of geologic, geographic, topographic, and operational considerations and factors that play into the selection of mitigation, which guide the type, location, and scale of mitigative methods employed. Mitigation methods discussed include hazard avoidance measures, pipeline and pipeline trench-focused measures, and landslide-focused measures. The section concludes with a recommendation for post-mitigation monitoring.

Section 9, Monitoring Landslide Hazards, explains that monitoring landslide hazards can be conducted by monitoring the landslide, the pipeline, or both. Landslide monitoring provides information about the movement of the landslide itself, while 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 is recommended, which provides context for the monitoring results and provides for stronger, more reliable decision-making. Landslide monitoring is used for four main purposes:

1) to further characterize the landslide(s) and its relationship and threat to the pipeline
2) to act as a warning system to allow for preemptive intervention prior to the occurrence or reactivation of a landslide that could exceed a pipeline's strain capacity
3) to confirm that the mitigation measures are functioning as intended
4) to identify landslide movement caused by a significant natural event, such as an earthquake or storm event

The section provides in-depth discussion of considerations for monitoring selection and the three main types of monitoring strategies that can be used to monitor landslide/pipeline interactions: regional-scale monitoring, landslide-focused monitoring, and pipeline-focused monitoring.

Section 10, Landslide Emergency Response, provides a framework for a landslide emergency response plan. It includes a review of critical decisions to make after a landslide event, which include pipeline integrity, public health and safety, and operational considerations. The response plane includes three primary stages:

1) Stage 1. Initial Response
2) Stage 2. Follow-On Assessment and Actions
3) Stage 3. Long-Term Management

The elements of each stage are discussed in detail. The section ends with a discussion of the information likely needed to develop and execute a landslide emergency response plan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

.

LIST OF APPENDICES

ACRONYMS AND ABBREVIATIONS

Acronym	Definition
ALOS	Advanced Land Observing Satellite
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BS	British Standard
CDM	Classification and decision-making
CER	Canada Energy Regulator
CFR	Code of Federal Regulations
CRES	Center for Reliable Energy Systems
CSA	Canadian Standards Association
CSC	Compressive strain capacity
CWP	Curved wide plate
ERW	Electric resistance welded
FFS	Fitness for service
FO	Fiber optic
GIS	Geographic information system
GMAW	Gas metal arc welding
GPS	Global positioning system
HAZ	Heat-affected zone
HDD	Horizontal directional drilling
ID	Identification
ILI	In-line inspection
IMU	Inertial measurement unit
INGAA	Interstate Natural Gas Association of America
InSAR	Interferometric synthetic aperture radar
ISO	International Organization for Standardization
JIP	Joint industry project
JSA	Japanese Space Agency
ksi	Kilopound force per square inch
LiDAR	Light detection and ranging
LOC	Loss of containment
LOS	Loss of service
MFL	Magnetic flux leakage
MTR	Mill test report
PGMP	Pipeline geohazard management program

Acronym	Definition
PHMSA	Pipeline and Hazardous Materials Safety Administration
POF	Probability of failure
ppsm	Points per square meter
PRCI	Pipeline Research Council International
PSL	Product Specification Level
RASD	Robust allowable stress design
ROW	Right-of-way
SBA	Strain-based assessment
SCADA	Supervisory control and data acquisition
SCC	Stress-corrosion cracking
SDL	Strain demand limit
SI	Slope inclinometer
SMAW	Shielded metal arc welding
SME	Subject matter expert
SMYS	Specified minimum yield strength
TDR	Time-domain reflectometry
TMCP	Thermo-mechanical control process
TSC	Tensile strain capacity
USGS	United States Geological Survey
UT	Ultrasonic testing
VW	Vibrating wire
WPS	Welding procedure specification

GLOSSARY OF TERMS

Curved wide plate (CWP): A specifically designed test specimen cut from a pup with its curvature in place. The gauge width of the test specimen is usually 12 inches ± 3 inches.

Fitness for service (FFS): A practice used by the oil and gas and chemical process industries for in-service equipment to determine its fitness for continued service.

Geomorphology: The study of the origin and evolution of landscapes, which includes the physical, chemical, and biological processes at or near the surface of the Earth.

Heat-affected zone (HAZ): The area of base material that is not melted but has had its microstructure and properties altered by thermal cycles of welding or other heat-generating operations, such as cutting.

Inertial measurement unit (IMU): An electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers. In the context of this report, an in-line inspection tool.

Kilopound force per square inch (ksi): A unit of stress resulting from a force of one thousand pound-force applied to an area of one square inch.

Landslide: The naturally occurring or human-caused downward (or downslope) movement of a mass of soil or rock due to gravity. The term "landslide" encompasses a wide variety of processes that result in the downward movement of soil or rock. These materials may move by falling, toppling, sliding, spreading, or flowing.

Mill test report (MTR): A quality assurance document that certifies a material's chemical and physical properties and states a product made of steel complies with an international standards organization's specific standards.

PHMSA Significant Incident: A pipeline-related incident as defined by PHMSA as including one or more of the following conditions: 1) Fatality or injury requiring in-patient hospitalization; 2) $50,000 or more in total costs, measured in 1984 dollars; 3) Highly volatile liquid releases of 5 barrels or more or other liquid releases of 50 barrels or more; 4) Liquid releases resulting in an unintentional fire or explosion.

Strain capacity: The strain level a pipe segment can sustain without negative consequences. The negative consequences could be a leak, a rupture, or any other change of the physical characteristics of the pipeline that an operator may deem unacceptable.

Strain demand: The strain imposed on a pipeline by its operational and environmental conditions (such as a landslide).

Strain demand limit (SDL): An assigned upper limit that the strain demand is allowed to reach on a pipeline.

Shielded metal arc welding (SMAW): A manual arc welding process that uses a consumable electrode covered with a flux to lay the weld.

Specified minimum yield strength (SMYS): The specified minimum yield strength for steel pipe manufactured in accordance with a listed specification such as American Petroleum Institute (API) 5L.

Thermo-mechanical control process (TMCP): Thermo-mechanical control process is a microstructure control technique that combines rolling (thermo-mechanical rolling) and controlled cooling (accelerated cooling).

Ultrasonic testing (UT): A nondestructive testing technique based on the propagation of ultrasonic waves in the object or material tested.

Welding procedure specification (WPS): A formal written document describing welding procedures that provides direction to the welder or welding operators for making sound and quality production welds as per the code requirements.

1 INTRODUCTION

The intent of this document is to provide guidelines and a framework for implementing and improving landslide hazard management programs for pipelines. This document is the result of a collective effort of pipeline industry operators and consultants, representing a diverse array of industry expertise and experience, particularly in the management of landslide hazards. Geologists, civil and geotechnical engineers, mechanical engineers, metallurgists, and pipeline integrity analysts participated in the preparation of this document.

1.1 Problem Statement

Landslides are a significant and persistent contributing factor to pipeline failure for operators in North America, in general, and in the United States, in particular. Based on a review of the Pipeline and Hazardous Materials Safety Administration (PHMSA) significant incident database[1] (for natural gas transmission, natural gas distribution, and hazardous liquids pipelines), long-term trends for the number of reported pipeline significant incidents due to landslide movement have remained relatively unchanged since 1986 (despite significant year-over-year variability). Approximately the same number of reported landslide-related incidents occurred in the 10-year period from 1986 to 1995 (23 incidents) and the 10-year period from 2010 to 2019 (22 incidents).

From an operator-specific perspective, review of 15 years of release and rupture experience (1984 to 1999) from a gas transmission operator in the northwestern United States showed that nearly one-third (29%) of the reported pipeline failures were due to landslide movement. As such, it is apparent that pipeline failures from landslide movement can be a significant issue to address in pipeline hazard management. Therefore, guidance to operators for implementing and improving landslide hazard management programs is needed and, if adopted, is anticipated to reduce the number of landslide-caused incidents.

The need for such guidance has been highlighted following several landslide-related ruptures of pipelines in the Appalachian region of the eastern United States in the past decade. During the process of responding to these ruptures, it became clear to the operators that there were no widely accepted comprehensive guidelines for managing landslide hazards. This document is intended to fill that gap by providing a set of practical guidelines for effective landslide hazard management.

1.2 Limitations of this Guidance Document

This guidance document is intended to be used by pipeline integrity and engineering staff tasked with managing landslides and by the consultants, contractors, and other pipeline staff providing support for integrity and engineering staff. This document is intended for existing pipeline systems, not planning or construction of new pipelines. This document is not intended to be an exhaustive summary of landslide types and processes nor of all methods to identify, assess, mitigate, or monitor them; such topics are covered by other resources, many of which are cited in this document and summarized in Section 3.2.

[1] The PHMSA significant incident database was selected because of its relatively long period of record. Only incidents after 1986 were included in this analysis because, prior to 1986, descriptions were not included for hazardous liquid incidents. These trends are not necessarily reflective of non-United States pipelines nor of pipelines not regulated by PHMSA. PHMSA significant incidents are defined in the glossary.

2 REGULATORY GUIDANCE AND STANDARDS

Regulatory guidance for management of landslide hazards by North American pipeline operators is generally performance-based, with few prescriptive requirements. In other words, operators are expected to manage landslide hazards, but the means and methods by which they do so are not specified and are left up to the individual operators to determine. The following section discusses the regulatory requirements for landslide management by the United States and Canada and internationally.

2.1 General United States Regulatory Guidance

In the United States, pipeline operators are required by regulation to appropriately manage landslide hazards, but the specifics of how to do this are left up to the individual operating companies. This concept and the regulatory justification behind it are summarized in PHMSA Advisory ADB 2019-02: *Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards* (PHMSA 2019).

The PHMSA (2019) advisory provides a regulatory rationale for proactively managing landslide hazards during new project construction and operation. As cited in the advisory, 49 Code of Federal Regulations (CFR) 192.103 (Natural Gas) and 49 CFR 195.110 (Liquids) require that, during project design, operators consider loads that might be imposed by geological forces.

The PHMSA advisory reminds operators that once a pipeline is operational, 49 CFR 192.317 states that

> *"The operator must take all practicable steps to protect each transmission line or main from washouts, floods, unstable soil, landslides or other hazards that may cause the pipeline to move or to sustain abnormal loads."*

The PHMSA advisory states that under 49 CFR 192.705, a primary reason for having a patrol program is to "*monitor geological movement, both slowly occurring or acute changes,"* and that under 49 CFR 192.613, each operator shall have a procedure for continuing surveillance and appropriate action for unusual operating and maintenance conditions. The advisory states that

> *"Land movement, severe flooding, river scour, and river channel migration are the types of unusual operating conditions that can adversely affect the safe operation of a pipeline and require corrective action under 49 CFR 192.613 (a) and 49 CFR 195.401 (b)."*

The advisory further states that when an operator discovers a condition covered under the integrity management requirements of 49 CFR 195.452 or if a segment of pipeline is determined to be in unsatisfactory condition per 49 CFR 192.613 [b] (in the context of this advisory, a landslide), that 49 CFR 192.935 and 49 CFR 195.452 (i) require

> *"…an operator to take additional preventative and mitigative measures to prevent a pipeline failure and to mitigate the consequences of a pipeline failure that could affect a high consequence area…if an operator determines there is a threat to the pipeline, such as outside force damage (e.g. earth movement, floods), the operator must take steps to prevent a failure and to minimize the consequences of a failure under these regulations."*

In summary, PHMSA advisory ADB 2019-02 provides a justification for a performance-based requirement to actively manage landslide hazards under existing regulation. Thus, under this interpretation, operators are required to identify and manage landslide hazards, but the means and criteria to meet the requirements are left up to the individual operators.

The PHMSA advisory provides four recommended actions (not requirements) for proactive management of landslide hazards:

1. Identify areas prone to earth movement (i.e., landslides).
2. Use geotechnical engineers during design, construction, and operations to avoid or minimize the impact of earth movement on a pipeline system.
3. Develop monitoring and staff training plans in areas prone to earth movement.
4. Use appropriate mitigation measures as needed.

The PHMSA advisory also provides the following recommended monitoring measures:

- Aerial patrol
- Survey benchmarks
- Inclinometers
- Piezometers
- Strain gauges
- Stress/strain analysis using in-line inspection (ILI)
- Light detection and ranging (LiDAR)

The recommended mitigation measures in the PHMSA advisory include the following:

- Rerouting
- Horizontal directional drilling (HDD)
- Drainage improvements
- Regrading
- Retaining systems
- Trench breakers and slope breakers
- Soil drying
- Spanning
- Reducing operating pressure or shutting-in an affected section of line

Finally, the advisory closes with notification that if a pipeline has suffered damage or is shut-in as a precautionary measure due to earth movement or other geologic hazards, PHMSA should be advised before returning the pipeline to service or increasing pressure. PHMSA may propose additional safety measures, such as testing the pipeline or changing the design to address loads imposed by the ground movement. There may also be safety-related reporting conditions as prescribed in 49 CFR 191.23 and 195.55.

2.2 International Organization for Standardization (ISO) 20074 Standard

ISO 20074: "Petroleum and natural gas industry – Pipeline transportation systems – Geological hazard risk management for onshore pipeline" was published in 2019. This international standard provides a high-level framework for implementing and improving geohazard management programs for onshore pipelines. The standard is applicable to all geohazards, including landslides.

The standard espouses a complete life-cycle approach, meaning that an operator's pipeline geohazard management program (PGMP) should cover the entire lifespan of the pipeline from conception and design to construction, operation, and decommissioning. The standard envisions that all operators would have an in-house PGMP implemented by an in-house team, unless the operator could demonstrate that a PGMP was not necessary.

A PGMP covers four interlinked processes that are performed through the pipeline life cycle:

- Identification of geohazards
- Evaluation of geohazards
- Mitigation of geohazard threats
- Long-term management of geohazards through monitoring and periodic reevaluation

Each process is then linked to the four main phases of the pipeline life cycle: preliminary engineering and route selection; detailed design; construction; and operation and maintenance.

The standard provides workflows and recommendations for executing each process within each project phase, but generally avoids prescriptive requirements, other than that operators should create and implement a PGMP.

The standard also provides recommendations and discussion for the following elements:

- Steps for building a geohazard inventory
- Methods for desktop and field investigation (including a discussion on LiDAR and remote sensing analysis)
- Geohazard risk assessment method and assessment systems, including the relative strengths and weaknesses of qualitative, semi-quantitative, and quantitative systems
- Data management, including recommended elements for geohazard databases
- Sample classification systems

The ISO 20074 standard provides a generic framework for geohazard management, which in many ways is like the guidelines provided in this document. Elements from ISO 20074, as appropriate, are incorporated into this guidance.

2.3 CER SA-2020-01

The Canada Energy Regulator (CER) recently released a safety advisory related to the low-strain failure of girth welds in newly constructed pipelines.

> *"The CER expects that regulated pipeline companies design welded pipelines to withstand those loads that result in longitudinal strains in meeting the requirements of Clause 4.2.4 of CSA Z662-19, and that companies can demonstrate they are in compliance with those requirements of the Clause."*

Clause 4.2.4 of Canadian Standards Association (CSA) Z662-19 notes that the stress design requirements in the standard are specifically limited to design conditions for operating pressure, thermal expansion ranges, temperature differential, and sustained force and wind loadings. However, the designer is required to determine whether supplemental design criteria are necessary for loadings not specifically addressed in Z662-19 and whether additional strength or protection should be provided. The clause provides several examples of additional loading that could be considered, including slope movement (i.e., landslides).

Thus, similar to the United States regulations described in Section 2.1, the Canadian standards require designing pipelines to withstand loads imposed by landslides but do not specify the means by which this should be performed.

2.4 ASME B31.8S-2018

The American Society of Mechanical Engineers (ASME) B31.8S-2018 standard, "Managing System Integrity of Gas Pipelines" provides very little specific guidance on the management of landslides. In nonmandatory Appendix A in the ASME standard *Threat Process Charts and Prescriptive Integrity Management Plans*, Section A-10 covers weather-related and outside force threats, including earth movement (i.e., landslides), heavy rains or floods, cold weather, and lighting. The appendix proposes that the risk level should be elevated if a pipeline is susceptible to "extreme loading," including that caused by ground movement. For areas of elevated risk levels, an integrity assessment is recommended, but this is not required, and the components of what the integrity assessment should consider are not included.

3 SUMMARY OF PRIOR WORK

The following section is a summary of prior work on landslides and landslide hazard management for pipelines. The summarized documents supplement the material covered in these guidelines in subsequent sections and can be referred to for additional detail, background, and context.

3.1 Management of Ground Movement Hazards for Pipelines Joint Industry Project (JIP) (2017)

The overall objective of the 2017 JIP (Wang et al. 2017) was to develop a document that would provide best practices for managing ground movement hazards. The hazards of focus were landslides and ground settlement, including mine subsidence. The intention of the 500+-page, 2017 JIP report, which had 16 industry sponsors, was to address nearly all major elements necessary for managing landslides and settlement hazards.

One unique feature of the 2017 JIP is that it presents an integrated approach for managing ground movement hazards. This approach covers the hazards that impose strains on pipelines (strain demand) and the capacity of the pipeline to tolerate such strains (strain capacity). The balance of the strain demand and strain capacity determines the integrity of an affected pipeline segment. Comprehensive landslide management should include reducing strain demand or enhancing strain capacity or both.

The following are primary subjects covered in the 2017 JIP:

- **Identification and Assessment of Ground Movement Hazards**: The methods and processes for identifying, characterizing, assessing, and evaluating landslide and settlement/subsidence hazards are comprehensively and broadly covered.
- **Determination of the Longitudinal Stresses/Strains Acting on Pipelines**: Most forms of stresses/strains acting on pipelines are covered, from linepipe manufacturing and construction to operation. The stresses/strains acting on girth welds are a major focus because girth welds tend to be the weakest link for pipelines subjected to ground movement hazards. The baseline stresses/strains under normal operation conditions (i.e., in the absence of ground movement hazards) are also covered. Such information is useful when computing total strain demand from inertial measurement units (IMUs) bending strains. Various methods for measuring and estimating stresses and strains in pipelines are introduced.
- **Fitness for Service (FFS) Assessment and Supporting Information/Data/Tools**: The FFS assessment involves the comparison of strain demand and strain capacity. A pipe segment or a weld is considered safe when the strain capacity is higher than the strain demand by a sufficient margin. FFS procedures address applicability and limitations, fundamental basis, key considerations and key parameters, and example applications of the FFS process.
- **Mitigation and Monitoring of Landslide and Settlement Hazards**: Hazard mitigation is acknowledged to take many forms, including avoiding the hazard, stabilizing and controlling the hazard, reducing the effects of the hazard on the pipeline, and/or increasing pipe strain capacity. Monitoring is described as incorporating a combination of strategies

and methods with the focus on 1) verifying there is no or minimal ground movement once mitigation has been implemented, 2) tracking the movement of the hazard to identify when the hazard has diminished or has been minimized, or 3) tracking the response of the pipeline to landslides and settlement (i.e., pipe monitoring).

- **Overall Hazard Management Process**: This is a description of a quantitative assessment using FFS principles that could be applied to prioritize mitigation activities and assist with deciding on proper mitigation methods. The assessment is broadly divided into two categories: 1) screening or ranking the landslide or settlement locations of interest, and 2) conducting site-specific assessments to determine the risk of failure and mitigation measures.
- **Differences in Managing Internal Pressure and Loads Imposed by Ground Movement**: There are important differences in the ways the pipeline industry manages internal pressure and loads imposed by ground movement. The loads of primary concern, caused by ground movement, act in the length direction of the pipelines (customarily termed "longitudinal direction"). Traditional pipeline designs primarily focus on pressure containment through limiting the hoop stress to a certain percentage of the specified minimum yield strength (SMYS). Pipeline design and construction projects primarily focus on stress in the hoop direction and with limited focus on longitudinal loading.

Various methods to determine pipe stresses and strains are extensively covered in the 2017 JIP document. This includes discussion of working principles, limitations, accuracy, reliability, field experience, and cost. The methods described include 1) established methods with mature technology, such as strain gauges on the pipe and IMU; 2) maturing technologies with limited successful applications, such as fiber optic (FO) cables; and 3) new technologies under development with underlying working principles either proven or being validated.

The JIP also provides clarifications in response to a few common misconceptions.

- Pipelines built with modern linepipes and girth welding do not necessarily have better strain capacity than older pipelines. Older pipelines do not necessarily have poor strain capacity. The strain capacity of pipe segments with American Petroleum Institute (API) 5L compliant linepipe and API 1104 compliant girth welds can vary from as low as 0.2% to well over 2%.
- ASME B31.4 and B31.8 permit pipelines to be designed to be subject to strain up to 2%, provided conditions stated in the standards are met. This allowable design strain limit is often misinterpreted to mean that pipelines have a minimum longitudinal strain capacity of 2%. The actual minimum longitudinal strain capacity is likely to be variable, as explained in the prior bullet.
- Hydrostatic test pressure alone is not an effective way to weed out poor-quality girth welds unless the girth welds already have a leak path or are very close to failure under normal operational conditions. The incremental increase in longitudinal stress (which could cause a leak or rupture) due to the internal pressure increase from operating pressure to hydrotest pressure is quite small.

The guidelines in this document should be considered complementary to the 2017 JIP and are intended to build upon the work of Wang et al. (2017).

3.2 General Literature Review

In addition to the comprehensive treatment of ground movement hazards and pipelines in the 2017 JIP (Wang et al. 2017), there are several additional key references that cover landslide hazards and the management of geohazards including landslides. A summary of the content in these references is listed in Table 3-1.

Table 3-1. Summary of Recommended Relevant References

Reference	Summary
Transportation Research Board Special Report 247: Landslides Investigation and Mitigation (1996) (Turner and Schuster, eds)	For many years, this collection of articles published in 1996 by the Transportation Research Board has been considered one of the seminal references on applied geology and engineering for landslides. The references contained in this book do not specifically apply to pipelines (or any industry), but they do provide a good overview of landslide principles as well as an overview of investigating, analyzing, and mitigating landslides. Some of the technological references are outdated, and some current technologies are not included (such as LiDAR and interferometric synthetic aperture radar [InSAR]), but, overall, this is an excellent reference and framework for understanding landslide processes and methods of landslide investigation, analysis, and mitigation. Chapter 3 of this book, "Landslide Types and Processes" by Cruden and Varnes (1996) has long been considered one of the fundamental references in describing and classifying landslides.
The Landslide Handbook-A Guide to Understanding Landslides: USGS Circular 1325 (2008)	This 147-page handbook by Lynn Highland and Peter Bobrowsky is intended to be a general resource for communities and industries affected by landslides (e.g., pipeline operators) to acquire basic information about landslides, including their types and their behaviors, where they tend to occur, what their triggers are, and what their effects and consequences are. Also included are landslide mitigation concepts and approaches. The handbook helps industry, community and emergency managers, and decision makers to take positive steps to encourage awareness of available options and recourse regarding landslide hazards.
PRCI: Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines Through Areas Prone to Landslide and Subsidence Hazards (2009)	This comprehensive, 219-page report by C-Core, D.G. Honegger Consulting, and SSD, Inc. was published by the Pipeline Research Council International (PRCI) in 2009. This report is focused on landslide and subsidence hazards as they pertain to pipelines. It contains detailed descriptions of methods for hazard mapping and hazard analyses and discussions on qualitative vs. quantitative methods of analysis. This report contains discussions on modeling strain demand induced by ground movement on pipelines using soil springs. The report contains a detailed and extensive discussion of methods for landslide and subsidence mitigation and monitoring. The references to mitigation and monitoring are cited in subsequent documents, including the 2017 JIP discussed in Section 3.1 and this document.
Clague and Stead [eds]: Landslide Types, Mechanisms, and Modeling (2012)	This collection of papers on landslides has a largely academic focus and provides a useful overview of the variety of landslide processes, methods to identify and assess landslides, and some discussion of landslide mitigation methods.

Table 3-1. Summary of Recommended Relevant References

Reference	Summary
Cruden and VanDine: Classification, Description, Causes and Indirect Effects; Canadian Technical Guidelines and Best Practices related to Landslides; a national initiative for loss reduction (2013)	The classification system presented in the 22-page report is based on the International Union of Geological Sciences Working Party on World Landslide Inventory classification system with some minor additions and modifications. Cruden and VanDine note that other landslide classification systems exist but might be focused on selected landslide types. The report includes a general discussion of landslide size, intensity, travel angles, causes, and indirect effects. This report complements Cruden and Varnes (1996) and Highland and Bobrowsky (2008).
Hungr, Leroueil, Picarelli: The Varnes classification of landslide types, an update (2014)	This paper is included because it provides an updated and simplified method of describing landslides from the aforementioned Cruden and Varnes (1996), dividing them into 32 distinct types based on the type of material that makes up the landslide and the behavior of the landslide. For both the landslide expert and nonexpert, the paper includes excellent examples of various landslide types using color photographs and diagrams.
Golder (sponsored by INGAA): Mitigation of Land Movement in Steep and Rugged Terrain for Pipeline Projects: Lessons Learned from Constructing Pipelines in West Virginia (2016)	This white paper prepared by Golder Associates Inc. for the Interstate Natural Gas Association of America (INGAA) foundation provides a summary of Golder's experiences identifying and mitigating landslides in West Virginia for pipeline projects. The paper provides a summary of methods of landslide identification in Appalachia, with the bulk of the paper focused on methods to mitigate landslide hazards. The mitigation guidelines focus largely on methods of controlling and managing water to minimize the triggering effects of water on slope instability. The paper also provides a number of highly detailed typical designs for various scenarios, largely focused on grading and water control.
PRCI: Pipeline Seismic Design and Assessment Guideline (2017 Revision) (Honegger and Nyman)	This report published by PRCI in 2017 is an update for the previously prepared 2004 guidelines for pipeline seismic design and assessment. Although largely focused on assessment of seismic hazards, this report contains useful discussions of seismically triggered landslides, including methods of assessing magnitude of seismically triggered landslides and methods to reduce risk from these landslides.
PRCI: Guidelines for Management of Geohazards Affecting the Engineering and Construction of New Oil and Natural Gas Pipelines (2018) (Sancio et al.)	This report published by PRCI in 2018 and prepared by Geosyntec Consultants, Inc., provides a high-level guidance document for managing geohazards (including landslides) for new pipeline construction. This document addresses many of the topics discussed in other references, including geohazard basics, identification, characterization, mitigation, and monitoring. It also includes a discussion of the contractual relationship between owner and consultants/contractors and how that affects geohazard management. The document is intended to be accessible to nonexperts.

Table 3-1. Summary of Recommended Relevant References

Reference	Summary
Rizkalla and Read [eds]: Pipeline Geohazards: Planning, Design, and Construction (2019)	This 799-page volume edited by Moness Rizkalla and Rodney S. Read brings together a variety of papers focused on pipeline geohazards (including landslides) for the entire pipeline life cycle (planning, design, construction, and operations). Topics covered include terrain analysis methods for geohazards, data management, geotechnical engineering, construction of pipelines in areas subject to geohazards, and assessment and management of geohazards for existing pipelines. This collection of papers provides information and techniques on conditions not addressed in most other sources, such as permafrost-related geohazards.
ASME: Pipeline Integrity Management Under Geohazard Conditions (2020)	This 412-page collection of papers edited by Salama et al. addresses several aspects of managing ground movement hazards with a focus on landslides and subsidence. The papers cover topics of geohazard impact on pipelines, the characterization of geohazards, geohazard mitigation and monitoring, the management of geohazards, pipeline strain capacity and management, aboveground and in-line strain monitoring, and pipeline structural reliability and risk assessment.

4 MANAGEMENT FRAMEWORK FOR LANDSLIDES

Integrity management for onshore pipelines is usually considered to consist of the following key elements (modified from PHMSA 2020):

- Identifying hazard locations
- Assessing the hazard and its effect on the pipeline through ILI and other means
- Integrating the assessment results with other relevant information to determine a response
- Repairing pipeline defects induced by the hazard (as needed)
- Analyzing risk to identify the most significant pipeline threats
- Identifying additional measures to address the most significant threats, such as actions to prevent releases and mitigate release consequences above and beyond repair of defects
- Regularly evaluating available information about the pipeline and its location-specific integrity threats to determine when future integrity assessments should be performed and how they are performed
- Periodically evaluating the effectiveness of the integrity management program and identifying improvements to enhance the program

Management of landslide hazards broadly fits into this framework, with some unique aspects that need to be considered, including the following:

- Integrity management programs typically group hazards into time-dependent threats (e.g., corrosion and stress-corrosion cracking [SCC]), stable threats[2] (e.g., manufacturing and construction defects), and time-independent threats (e.g., third-party damage). Landslides exhibit characteristics of both time-dependent and time-independent hazards in that the movement rate of landslides can range from millimeters per year to meters per second (Cruden and Varnes 1996).[3] Consequently, the effects on a pipeline can range from gradual strain accumulation over years (a time-dependent hazard), to effectively instantaneous damage (a time-independent hazard). A landslide management program needs to consider this range of potential behavior.
- The timing of landslide activity is difficult to predict. While factors such as precipitation and earthquakes are known to trigger or exacerbate landslides, correlating precipitation with landslide movement is challenging at best (e.g., Iverson et al. 2015), and seismic activity cannot be reliably predicted at this time.
- Landslide hazard areas can almost always be identified through geomorphic assessment (discussed further in Section 5) and do not need to be identified by ILI (although the use of ILI can provide additional information useful for understanding effects of a landslide on a pipeline). Thus, while the timing of landslide activity is difficult to forecast, the specific

[2] Also referred to as resident threats.

[3] Although, most literature considers geohazards (including landslides) to be time-independent (e.g., Muhlbauer 2019).

location of past or ongoing landslides can be proactively identified through direct observational methods. These locations are generally the most prone to future landslide movement.

- Landslide hazards range from those that currently cross a pipeline and have been affecting the pipe for years to those that do not yet cross a pipeline, but in a single event could impact the pipe. As above, this range of possible behaviors should be considered under a landslide hazard management program.
- 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). A landslide hazard management program should thus account for both natural and human causes.

These considerations shape the approach to landslide hazard management, as presented in this document.

4.1 Landslide Management Processes

Integrity management for landslides consists of the following core processes, which are related to the general framework for integrity management provided earlier:

- A process to identify and characterize individual landslides of concern and areas susceptible to landslide hazards (Section 5)
- A process for conducting an FFS assessment for pipelines impacted or potentially impacted by landslides (Section 6)
- A mechanism for landslide threat classification and decision-making (CDM) to determine appropriate actions to manage landslide hazards once the identification and assessment processes are completed (Section 7)
- Implementation of activities (e.g., monitoring and/or mitigation) to manage and reevaluate the landslide hazards (Sections 8 and 9)
- A process to plan for and respond to unanticipated landslide events (Section 10)
- A mechanism to manage, store, and analyze data generated throughout the processes and activities described above (Section 11)
- A mechanism to train personnel, as needed, to support the landslide hazard management program (Section 12)
- A process to continuously evaluate the effectiveness and completeness of the landslide hazard management program (Section 13).

Integration and execution of these processes is the primary subject of this guidance document and form the essential integrity management framework for landslide hazards. These core processes and how they integrate with each other are discussed in subsequent sections.

4.2 Landslide Management Personnel

The level of resources dedicated to landslide hazard management is pipeline operator-specific and can be quite varied. However, it is recommended that operators have an in-house individual or group responsible for landslide hazard management, where personnel and effort can be scaled based on an operator's exposure to landslide hazards. Likewise, the use of external resources can be scaled, as needed.

There are benefits to having a dedicated individual or group responsible for landslide hazard management:

- Completeness and consistency in implementing and executing the landslide hazard management processes listed in Section 4.1
- Completeness and consistency in managing data and centralizing information concerning landslide hazard management
- Knowledgeable liaison between internal or external technical staff responsible for executing the landslide hazard management processes and others within the pipeline operator organization, such as senior management, project management teams, and engineering teams
- Long-term planning and follow-through to address, monitor, and manage landslide hazards
- Using previously acquired knowledge on landslide-prone areas specific to the operator's pipeline system to support planning decisions for new pipelines and facilities

Depending on organizational structure, the technical and managerial staff responsible for landslide hazard management may be the same individual or different people.

The individual or group(s) responsible for landslide hazard management is operator-specific but is typically a subset of the pipeline integrity group or the engineering group or both. If both groups contribute, typically those in the integrity group are responsible for acting as internal subject matter experts (SMEs), implementing long-term planning, and undertaking data management; those in the engineering group are usually responsible for executing the work.

4.3 Landslide Hazard Management Program Implementation

The following are recommendations for a pipeline operator implementing a landslide hazard management program or for an operator looking to improve an existing program. Depending on the maturity of an operator's landslide management program, some of these steps may have already been completed. The following list outlines a simplified, conceptual representation of the steps to implement a landslide hazard management program. Some processes (such as a quality assurance program) are assumed to be conducted throughout and are thus not explicitly called out. Other processes, such as establishing response plans or training programs, can be implemented at any time and do not need to be performed in a specific sequence.

1. Identify an individual or group responsible for the landslide hazard management program.
2. Establish a preliminary process for landslide hazard identification and characterization and approaches to threat CDM.

3. Establish a data management system (if a suitable system does not already exist). This system should be used to record data and support analysis and decision-making throughout the landslide management process. It can continue to evolve throughout the program.
4. Conduct a pilot program on a pipe segment or system likely to have landslides (one may want to consult with an SME to identify a suitable segment).
5. Refine the identification and characterization and FFS processes and CDM approach, if needed, based on conditions encountered, company risk-tolerance, and resource availability.
6. Continue with the identification and characterization program for the entire pipeline or system. Further refine the identification and characterization and FFS processes and CDM approach as needed.
7. Implement mitigation and monitoring actions (as needed) based on the identification and characterization results and the CDM approach.

At this point, the program should be considered mature, and landslide hazard management processes transition to a continuous cycle of monitoring, reassessment, and response. Additional assets that are acquired or constructed should be subjected to this process, and, periodically (such as every 5 to 10 years), previously evaluated assets should be reevaluated to assess if changes have occurred that would change the initial results.

4.4 Landslide Management Considerations

The following list provides a set of recommendations for pipeline operators to consider when implementing a landslide hazard management program.

- A complete life-cycle approach to landslide hazard management produces the lowest overall risk to a pipeline operator. While the focus of this document is on the operational portion of the pipeline life cycle, the decisions and actions made during routing, design, and construction largely determine landslide threat during operation. Thus, a comprehensive landslide management program considers all aspects of the pipeline life cycle.
- The identification and characterization process should be performed to at least a desktop level (i.e., the Phase I assessment process described in Section 5) for the entire operating pipeline system. Landslides are present in all North American states and provinces; thus, all pipelines can potentially be subject to landslide hazards. Note that this process should be scaled in effort and use appropriate resources, data, and methods based on the anticipated presence of landslide hazards for a given area. A Phase I assessment does not have to be labor intensive and, in many areas of North America, can be conducted rapidly.
- Multiple technologies and approaches should be used and integrated in the identification and characterization, FFS, and monitoring processes. 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.
- A landslide hazard management program is intended to operate for the entire pipeline life cycle, which could span many decades. Thus, the program should plan for staff and third-

party transitions and succession. The resiliency of the program to personnel and technology transitions should be considered.

- Decisions on budgets, risk tolerance, and thresholds for response (such as whether to mitigate or monitor a location) are the responsibility of the pipeline operator. Third-party consultants and contractors should implement actions of the landslide hazard management program in accordance with operator standards and expectations. Decisions involving risk and finances should be made by the operator, not by third parties, and, in most cases, most of the risk should be borne by the operator.
- A proactive approach to landslide hazard management, regardless of the details, will reduce risk. The specific form or nature of a landslide hazard management program is less important than simply having a program.

5 IDENTIFICATION AND CHARACTERIZATION OF LANDSLIDES

Identifying and characterizing landslide hazards is the foundation for a landslide hazards management program. Landslide hazards can only be addressed if they are known, and decision-making around how to respond to known landslide hazards should be centered around an understanding of the potential current and future threat(s) imposed on the pipeline(s) by each landslide. Although certain regions are more prone to landslides than others, landslides can occur anywhere with topographic relief. As such, it is a best practice for operators to systematically review their entire pipeline systems for potential landslide hazards.

However, not every landslide located within the vicinity of a pipeline poses the same level of current or future threat. Once identified, each landslide requires varying levels of necessary evaluation and characterization to formulate an appropriate response. Additional evaluation can range from no further assessment to highly site-specific and detailed assessment. It is recommended that a phased approach be followed to identify and characterize landslides, whereby more effort can be focused on sites that represent more significant threats to the pipeline.

The phased assessment approach discussed in this section is focused primarily on identifying and characterizing landslide hazards. The assessment of the impact to pipelines from landslides is discussed in Section 6, Fitness for Service.

5.1 Phased Assessment Approach

To develop an inventory of possible landslide threats that might affect a pipeline, potential landslide hazards should be systematically identified, characterized, classified, and documented for all pipeline systems. A phased approach to landslide hazard assessment incorporates the general process of identifying, characterizing, assessing, and, if necessary, mitigating and monitoring landslide hazards and allows for scaling assessments from regional to site-specific efforts (e.g., Wang et al. 2017). The phased approach should be carried out on proposed and existing pipelines. Some form of qualitative, semi-quantitative, or quantitative threat classification should be developed and assigned throughout the process to help determine the appropriate level of assessment for a given landslide hazard and to aid in selecting and prioritizing mitigation and monitoring options for specific landslide hazards. Threat classification is discussed further in Section 7.

The phased approach summarized in this section provides recommended guidance for pipeline operators to develop the list of landslides of concern that are ultimately tracked and addressed through their landslide hazard management program. This phased approach is based on the experience of the authors and many pipeline operators who have employed a three-phased approach to identify, assess, mitigate, and monitor landslide threats to their pipelines (e.g., Wang et al. 2017, Newton et al. 2020). Some operators have used a four-phased approach to deal with landslide hazard management, and Herr and Atkinson (2020) describe such an approach. Ultimately, it is up to the operator to decide the nature and number of phases, often with input from third-party SMEs.

Regardless of the number of phases, each process addresses the same needs for landslide identification, assessment, mitigation, and monitoring to manage the landslide hazard. The phases are listed as follows and described in more detail in the following sections.

- **Phase I Assessment:** A desktop assessment intended to initiate the process to systematically identify and characterize individual landslides of concern along an existing pipeline right-of-way (ROW) or a proposed, new-build pipeline alignment. A landslide inventory for the pipeline or proposed pipeline is developed and forms the framework for follow-on phases of assessment.
- **Phase II Assessment:** A nonintrusive, site-specific field investigation of a subset of landslides of concern identified from the Phase I assessment (e.g., typically those classified as posing more significant potential threats to the pipeline). The additional assessment is intended to further characterize sites and the potential threats that they might pose to the pipeline.
- **Phase III Assessment**: Site-specific detailed investigation, typically targeted at subsurface conditions, to further characterize a subset of landslides of concern where additional detailed information is necessary to determine appropriate response or to develop necessary mitigation plans. Assessments typically involve intrusive, subsurface geologic, geotechnical, and geophysical investigations as well as engineering analyses. This is typically the last phase of assessment, wherein enough information has been collected to make decisions on next steps and to develop mitigation options and/or short- or long-term monitoring plans, including response plans if adverse effects of landslide movement occur.

The phased approach to identifying, characterizing, and evaluating potential landslide hazards involves using many and varied investigative tools, techniques, and resources. The information and data to implement these tools and techniques might be publicly available or published and come from federal, state/provincial, and local agencies, institutions, and professional organizations; they might be operational and maintenance data from the pipeline owner/operator; and, most importantly, they should include remote sensing data that come from public and private sources or the pipeline owner/operators.

The available tools and techniques used to conduct each assessment phase vary in their purposes, strengths, and weaknesses. The suitable tools and techniques to complete each phase vary based on things such as program objectives, scale, location, regional conditions, the anticipated landslide prevalence in a given area, and other program components/activities. Common landslide assessment technologies and methods are discussed in Section 5.3.

5.1.1 Pre-assessment Considerations and Planning

The idea of conducting a detailed landslide hazard assessment along every mile of pipeline in an operator's system can be daunting, particularly for operators with tens of thousands of miles of pipes that might cross through many states with varying geologic, geographic, and topographic conditions. As such, particularly for larger pipeline systems, it can be beneficial to take the time for some pre-assessment planning. Pre-assessment planning would include assessing at a high level the possible landslide conditions regionally across the system to develop a detailed assessment approach that aligns with expected conditions (i.e., spending more time and effort on areas with higher anticipated landslide occurrence). Likewise, an upfront assessment on the need to use and/or acquire remote sensing data, including assessing whether ground conditions warrant the use of LiDAR data (i.e., if vegetation is dense, landslides are prominent, and sources of public imagery appear insufficient for review) and assessing availability and quality of public LiDAR data. Once an understanding of general landslide conditions and data availability is established, a plan to complete the system-wide Phase I assessment can be developed, in terms of approach and schedule.

5.1.2 Phase I Assessment

A Phase I assessment (Phase I) is a regional-scale evaluation that is intended to provide an initial assessment of landslide hazards along a proposed or existing pipeline system. The primary purpose of a Phase I, which should be completed for all pipeline systems, is the development of a baseline inventory of landslide hazards for further consideration by the pipeline operator. The Phase I also serves at a high level to provide operators an understanding of how landslide hazards are distributed across their system as a whole; that is, where there are a lot of landslides versus where there are very few or no landslides. This understanding is critical for operators to properly distribute resources such that the primary focus is on areas with the highest risk from landslide hazards.

The three main objectives of a Phase I are as follows:

1. Identify and characterize landslides and possible landslides along or adjacent to an existing or new-build pipeline system that could negatively impact the pipeline system. Possible landslides include areas with geomorphic features that likely or possibly suggest the presence of a landslide, but where there is uncertainty and possible alternative explanations exist for the observed features; possible landslides require additional assessment to be confirmed as landslides, for example, ground-based assessment.
2. Build an initial inventory of the landslides and possible landslides identified and being assessed (or, once a program is mature, to refresh and reexamine the initial inventory).
3. Complete an initial threat classification and screening of the identified landslides and possible landslides to establish whether and which landslides will receive additional geologic and engineering assessment (i.e., Phases II and III) in order to reach decisions regarding mitigation and/or monitoring of the targeted landslides (Sections 7, 8, and 9).

Phase I is primarily a desktop evaluation of available data, including the following:

- Public data (e.g., maps of geology, topography, and soils; reports or published datasets on local landslide conditions)
- Owner data (e.g., information on known hazard sites; available monitoring data, including site-specific or system-wide; as-builts or construction reports that highlight landslides)
- Remote sensing data (e.g., LiDAR data, aerial photography, InSAR)

The Phase I should include a geomorphic assessment of remote sensing data during which the locations and limits of landslides and possible landslides (unconfirmed landslides) are identified relative to the pipeline centerline.

As described above in Section 5.1.1, a preliminary review may be necessary before a remote sensing review in order to select the most suitable remote sensing data (e.g., LiDAR data or aerial imagery) for the existing ground conditions, which may vary by region. The use of high-resolution LiDAR data is a cornerstone in the detection and identification of landslide morphology, particularly in thickly vegetated areas. Publicly available LiDAR data and aerial imagery vary in availability, acquisition dates, resolution, and quality; therefore, desired data might not always be available or suitable in some or all areas, and project-specific data may need to be acquired. If project-specific remote sensing data will be acquired, the following recommendations are provided to obtain useful high-resolution data so that landslide features can be easily identified and initially characterized:

- **High-Resolution LiDAR**: The United States Geological Survey (USGS) LiDAR Base Specification Quality Level 1 requirements[4] can be used as the general guideline for LiDAR data specification and collection. A few additional guidelines to consider include the following:
  - Corridor Width: The initial round of LiDAR data collected along a pipeline should ideally be a minimum of 1,000 feet wide, centered on the pipeline (at least 500 feet to either side of the centerline). Wider corridors could be considered if there are other drivers/purposes for the data, such as alternate routes for new pipelines. Nevertheless, the 1,000-foot corridor width is recommended because it optimally captures landslides, which can often encompass large areas that extend away from the pipe, and because it allows for full characterization and understanding of the overall behavior of a landslide and the threat that it poses to a pipeline. Subsequent LiDAR data collection might encompass a narrower corridor width (recommended to be no less than 600 feet wide centered on the pipeline) as the focus of the LiDAR data review moves from full hazard characterization to characterizing ongoing movement in the vicinity of the pipeline.
  - Point Density: The minimum point density for data collection in vegetated areas should be 15 points per square meter (ppsm) during leaf-off conditions and 20 ppsm during leaf-on conditions. In areas with limited to no vegetation (e.g., desert settings), point densities as low as 10 ppsm may suffice.
  - Timing: In areas with deciduous vegetation, LiDAR data will be of highest quality if collected during leaf-off conditions. If data collection is necessary during leaf-on conditions, a higher point density should be considered. In areas that receive snowfall, LiDAR data should be collected during periods with no snow cover, if possible. Due to the limited window of ideal ground conditions in many areas, upfront planning and scheduling for LiDAR data collection is considered a critical step to obtaining the best dataset possible.

- **High-Resolution Aerial Imagery**: The USGS Digital Orthoimagery Base Specification[5] can be used as the general guideline for aerial imagery data collection. A few additional guidelines to consider include the following:
  - Corridor Width and Timing: These should follow the same guidelines as those provided above for LiDAR. In addition, time of day for data collection should be considered for aerial imagery collection, to minimize shadows especially within the ROW, which can obscure landslide features.
  - Resolution: The resolution should be 6 inches or better.

---

[4] Accessed here: https://www.usgs.gov/core-science-systems/ngp/ss/lidar-base-specification-online
[5] Accessed here: https://pubs.er.usgs.gov/publication/tm11B5

Publicly available historical aerial imagery, which can be used as a supplement to LiDAR data and/or other aerial imagery data sources or in lieu of other data sources where ground conditions permit, is critical in the review and understanding of historical changes to the ground surface over time at and surrounding landslide sites.

Figure 5-1 illustrates the output of the Phase I desktop geomorphic assessment of LiDAR data to identify and map landslides and possible landslides. While the landslides are clearly delineated in the LiDAR slope map (Figure 5-1), they are not visible in the aerial imagery because of the dense tree cover.

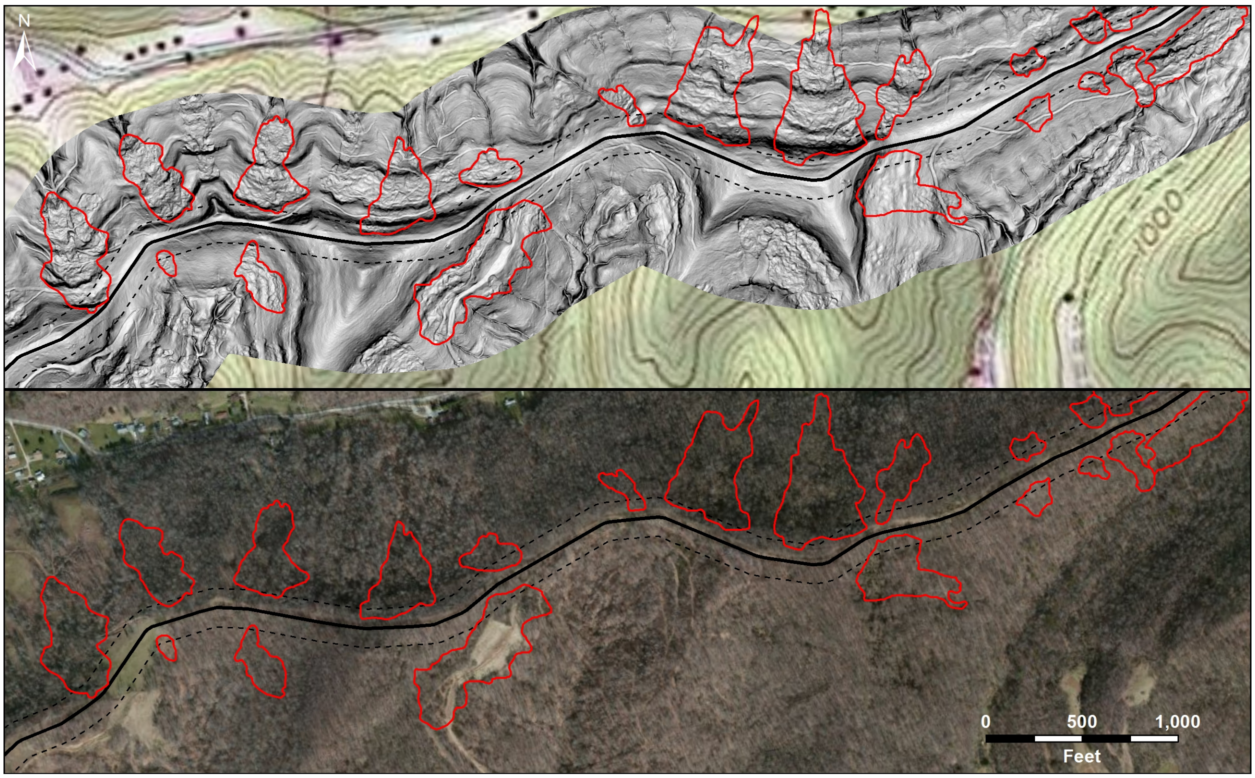

Figure 5-1 Example of landslide mapping (red outlines) along a 200-foot-wide corridor (black dashed line) centered on a pipeline (black line). This view is from a remote sensing review of LiDAR data (gray shaded slope map overlain on USGS topographic map in top photograph) and aerial imagery (bottom map). Note the lack of visible geomorphic features in aerial imagery in this area due to dense tree cover.

Available data that indicate whether an assessed pipe segment might already be impacted by a landslide should be incorporated into the desktop assessment. For example, ILI IMU bending strain data may indicate that a landslide is engaging the pipeline. Likewise, if individual landslide hazards have been previously identified through other avenues and have instrumentation (e.g., strain gauges, inclinometers), these data can be used to better define the threat at the given location.

An important step in the Phase I process is delineating the area or envelope of study, which encompasses the pipeline centerline. Because landslides that originate outside of the ROW can still impact a pipeline, the area of study should include a certain distance beyond the ROW limits. For existing pipelines, the envelope of study should include an area extending at least 100 feet to either side of the centerline (i.e., a 200-foot-wide swath). This corridor width may need to extend farther in areas with rapidly moving or expanding landslides. It should be noted that any landslide with any portion extending into the study corridor should be included, and its full footprint should be mapped; as such, many landslides identified in the Phase I will extend beyond 100 feet from the centerline. It is important to map each landslide in its entirety, to the extent possible, in order to properly characterize the landslide and assess its potential threat to the pipeline.

For new-build pipelines, the envelope of study should be wider than 200 feet and should typically range from 200 to 500 feet to either side of the centerline alignment to account for uncertainties in final centerline alignment and the area disturbed by construction. The defined study area then becomes the area for collecting new or existing LiDAR data and aerial imagery.

The available data (spatial and textual) from the Phase I are compiled into a geographic information system (GIS) database (Section 11), and the geomorphic assessment to identify landslides is completed in GIS, where each landslide is assigned a unique identifier. The unique identification (ID) will follow the landslide as it evolves and is managed (e.g., mitigated and monitored).

Landslide hazards are then classified to assign hazard threat levels based on criteria developed for the specific project or pipeline system or based on preexisting systems developed by the owner (classification is described in detail in Section 7). For new pipelines, where landslide hazard mitigation may be implemented during construction, possible mitigation response categories may be developed (in place of threat classifications) that define the appropriate level of mitigation response to the mapped landslide threat (e.g., Golder 2016).

A Phase I is commonly supplemented by an aerial reconnaissance to evaluate the current conditions along the existing pipeline ROW or proposed alignment and to confirm the landslide mapping from the desktop assessment. A helicopter platform is recommended for the aerial reconnaissance instead of a fixed wing aircraft, when possible, because a helicopter allows for flying at slow speeds and low to the ground along the alignment to view landslide-disturbed ground features. In addition, a helicopter can land on the ROW to quickly visit critical landslides that might be imminent threats to the pipeline but were not visible in the desktop assessment. The aerial reconnaissance becomes more important for the Phase I if new LiDAR data or new aerial imagery have not been acquired and used.

The results of the Phase I include an inventory of potential landslide hazards in a GIS platform. For proposed or existing pipelines, the inventory and the various threat classifications are used to identify landslides of concern and establish the scope for more detailed investigations if necessary. Typically, landslides or possible landslides that are considered to pose a higher threat to the pipeline will be included in the Phase II assessment (Phase II), whereas those where the perceived threat is considered low will not be included but will remain a part of the complete inventory in the event that conditions change in the future.

A Phase I landslide assessment is updated or redone periodically to capture new information and data about landslide hazards that may have developed since the original Phase I was completed. The periodic Phase I update for landslide hazards is completed to 1) identify any new landslide hazards or changes to existing landslide hazards that have occurred since the original assessment was completed, and 2) review any new sources of data that have become available since the prior assessment and which might affect the results or conclusions of the previous Phase I. In the authors' experience, the Phase I update for landslide hazards should be conducted approximately every 5 to 10 years, depending on the density of mapped landslides, the nature of their behaviors, and their levels of activity, although shorter or longer intervals may be justifiable.

5.1.3 Phase II Assessment

A Phase II is a detailed, site-specific evaluation of the higher priority/threat landslide hazards identified in the Phase I. The landslides and possible landslides of concern studied in a Phase II are a subset of the total landslide inventory identified during Phase I. Phase II is a nonintrusive (i.e., no subsurface exploration drilling or excavating conducted) field geomorphic and geologic reconnaissance of the landslides and possible landslides of concern. Phase II is intended to confirm whether features identified in Phase I are actual landslides and, for those that are confirmed as landslides, to gain a better understanding of the location, nature, extent (footprint and depth), age (timing of most recent activity), type and rate of movement, and potential effect(s) of a landslide on the pipeline. Features that are confirmed to be something other than a landslide during the Phase II should be clearly noted as such, and no further landslide assessments or landslide hazard management are necessary for such features. Features where uncertainty remains might require further assessment to be confirmed as landslides, or a feature might be deemed to represent a low hazard regardless of its true nature, and, thus, the uncertainty is deemed acceptable.

When planning for a Phase II, the following items should be considered:

- The time of year: The optimal time of year to conduct a Phase II is when vegetation is at a minimum, there is no snow cover on the ground, and there is no local flooding (which can impact access and visibility of the landslide if it is located on a submerged stream bank/valley slope). This is typically in early spring or late fall in most locations.
- Vegetation conditions: Vegetation can easily obscure small ground disturbances as well as large disturbances in some instances. If a site must be visited when and where vegetation is thick, consider having vegetation cleared before the visit. If this is not possible, note that vegetation can obscure surface evidence of ground movement and other landslide indications. Thus, if the site is thickly vegetated, the characterization might not be complete or accurate upon completion, and the site might need to be revisited later.
- Site access: All site access should be cleared with landowners prior to conducting site visits. The timing of site visits may be limited by landowner constraints (e.g., no access during hunting season, harvest season), and there may be specific access guidelines (e.g., point of entry, time of day, prearranged date and time). Access may also be limited by ground conditions, such as during flooding events.

An example of a landslide adjacent to a ROW and mapped in the field during a Phase II is shown in Figure 5-2.

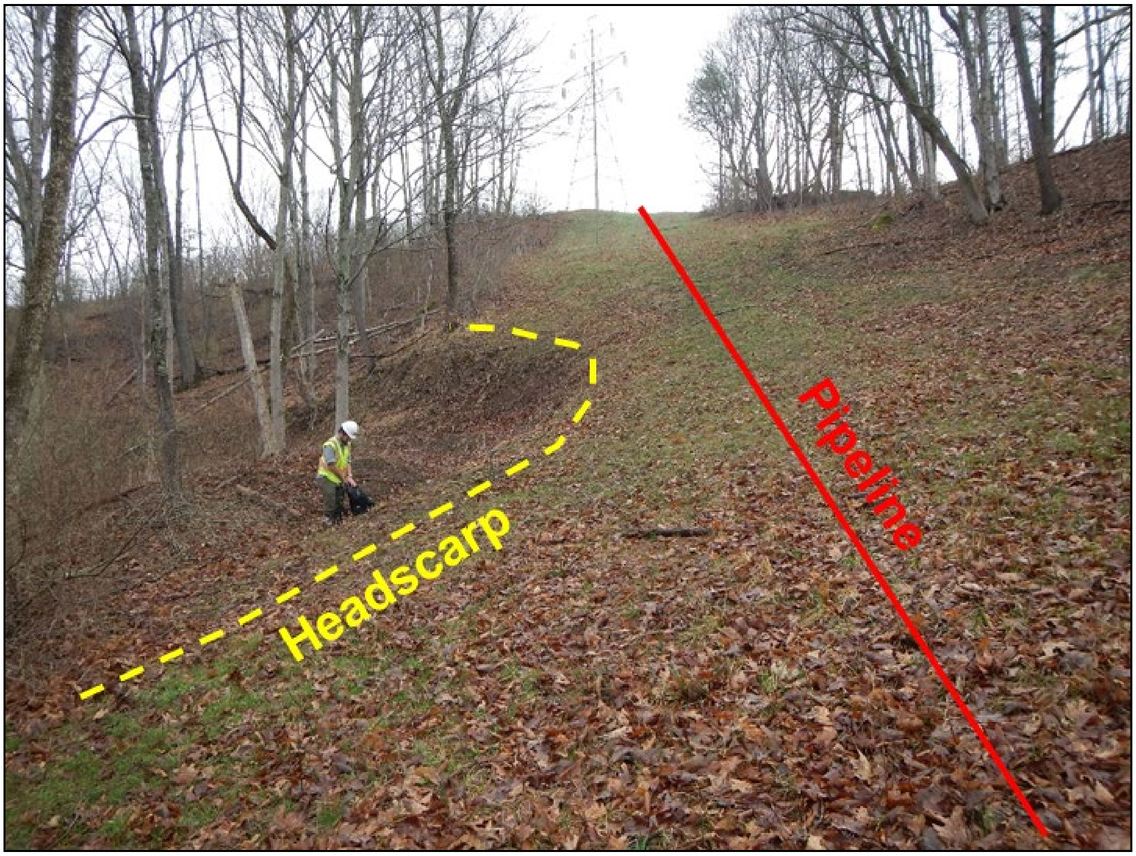

Figure 5-2. View showing a landslide headscarp (mapped during a Phase II) encroaching into the cleared ROW and approaching the pipeline centerline.

A Phase II should be completed by an individual or team of individuals experienced in geomorphic landslide identification and characterization and should consist of the following activities:

- Confirming the identification and characterization from Phase I.
- Taking notes and photographs to document geomorphic and geologic conditions at the time of the field visit. Conditions within and adjacent to the ROW should be recorded to provide a better understanding of the landslide as a whole.
- Using sub-meter location accuracy global positioning system (GPS) units to record locations of key landslide features and pipeline positions and depths (if field-located) and to confirm or revise the boundaries of confirmed landslide areas.
- Observing and recording landslide characteristics at sites where landslides are confirmed to be present. These characteristics typically include relative activity level (age), feature measurements (headscarp, toe, etc.), and other pertinent information relevant to evaluating the landslide and its potential interaction with a pipeline. In addition to direct landslide characteristics, vegetation conditions (e.g., tall/dense vegetation that may obscure features, vegetation indicating ground movement such as downed or curved trees, and presence of water loving plants, which may indicate water sources) and presence of water on the slope (e.g., sag ponds, seeps, springs) should also be recorded.

Information and data collected during the Phase I and Phase II should be compiled and used together to construct a more complete assessment of the hazard. For example, ground observations should be tied in with geomorphic features observed in LiDAR data to better understand overall site features and landslide characteristics. As another example, ILI IMU bending strain data should be further examined against field observations to evaluate if a strain feature appears to be associated with landslide movement or if it appears to be caused by something else (e.g., construction). Where an IMU bending strain feature's proximity appears related to ground movement, an FFS assessment (Section 6) should be conducted to evaluate current pipe conditions and assess the current threat level.

The additional information collected and assessed during a Phase II should ultimately be used to confirm or refine the preliminary landslide hazard mapping and boundaries, landslide characterization, and threat levels (or mitigation response level for new pipelines) assigned during the Phase I. The GIS database containing the landslide inventory developed during the Phase I should be updated based on the information collected during the Phase II.

The results of a Phase II should be used for proposed pipeline projects to make additional route adjustments and for proposed and existing pipelines to determine if and how to proceed with mitigation and monitoring or if further subsurface landslide investigation is needed to determine if and how to proceed with mitigation and monitoring (i.e., a Phase III assessment [Phase III]). Most landslides do not require additional assessment beyond the Phase II; therefore, only a small percentage of the total landslides typically proceed to the Phase III level of assessment.

5.1.4 Phase III Assessment

A Phase III is completed to further characterize and assess specific landslide hazards to remove uncertainties remaining after Phase II and to support development and implementation of mitigation design options. A Phase III generally consists of detailed, site-specific investigations based on site and hazard conditions and may include activities such as detailed surface mapping, geophysics, intrusive subsurface geotechnical investigations (e.g., drilling, test pits, dynamic cone penetration tests), or installation of monitoring instruments intended to further characterize the landslide (e.g., an inclinometer to evaluate depth of movement; see Section 9 for a detailed overview of monitoring techniques). The objectives are typically to more closely define landslide limits and depth relative to the pipeline and to characterize subsurface soil and water conditions that can be directly used when developing mitigation and monitoring plans (if deemed necessary). The images in Figure 5-3 show how a test pit is used to identify the landslide slip surface and provide data on landslide thickness relative to the burial depth of the pipeline to provide input into potential mitigation alternatives and monitoring plans.

Figure 5-3. Test pit completed at a landslide site during a Phase III. Left image shows excavator prepping for excavation. Center image shows completed test pit. Right image shows the SME-interpreted subsurface boundary between landslide material (top, light brown soil) and stable material (bottom, dark red-brown soil).

The following items should be considered when planning for a Phase III:

- The time of year. As Phase III efforts often involve use of heavy equipment and lead to slope disturbance, the timing of site activities can be important. For example, completing excavations on the slope during very wet/soft ground conditions can be difficult and possibly unsafe and could lead to slope instability, exacerbating preexisting landslide conditions. If the timing of activities is not flexible, the investigation approach may need to be altered based on site conditions.
- The characteristics of the landslide based on Phase I and Phase II results. For example, the estimated depth and landslide limits and the estimated pipeline location and depth will likely influence the selected Phase III approach (e.g., drilling vs. test pitting, use and selection of geophysics approach).
- Site access. Similar to considerations for a Phase II, all site access and planned activities should be cleared with landowners prior to conducting site visits, and activities and timing may be impacted by landowner restrictions. In addition, as Phase III work could include mobilization of heavy equipment (e.g., excavators, drill rigs). Considerations for how the location will be accessed may guide the selection of subsurface exploration methods.
- Permits. Permitting for site grading and environmental clearance (at a minimum) will likely be needed.

The information collected during a Phase III should be used in tandem with the information collected in the Phase I and Phase II to collectively improve upon the characterization of the landslide and the understanding of the threat potential. For example, if it is confirmed during the Phase III that a landslide slip surface is below the pipe depth at a location where there is an ILI IMU bending strain feature, the IMU data can be used for FFS assessment (as discussed in Section 6) to evaluate the current pipe conditions and assess the current threat level. The additional information collected and assessed during the Phase III should ultimately be used to confirm or refine the previous landslide hazard characterization and threat level (or mitigation response level for new pipelines) assigned during the Phase I and Phase II. The GIS database containing the landslide inventory developed during the Phase I and updated during the Phase II should be updated again based on the information collected during the Phase III.

A Phase III is typically the last step in the phased approach where the paths forward for individual landslides of concern are determined, and where long-term landslide hazard management plans are developed for each landslide or group of landslides (Section 7).

5.2 In-Line Inspection Inertial Measurement Unit Bending Strain Data

The use of IMU results to identify areas of bending strain is an established process offered by many ILI vendors. A bending strain analysis identifies areas of anomalous (i.e., not designed) bending that may result from original construction, subsequent maintenance and inspection activities (such as anomaly digs or pipe replacements), or by post-construction bending from an external force such as a landslide or third-party activities (such as anchor drag at water crossings). IMU review is discussed separately from the phased assessment process because it can be conducted at various times relative to the phased assessment process (before, during, or after, as discussed below). Some operators consider IMU review to be a separate, stand-alone phase within the phased assessment process.

IMU bending strain data can only be acquired on piggable pipeline segments, and acquisition of such data may be tied to schedules outside of the landslide hazard management program. As such, the timing on the review of IMU bending strain data throughout the phased assessment process may vary between operators and across a pipeline system for a single operator. If available, IMU bending strain data can be used during a Phase I to help identify landslide locations and to help characterize the hazard threat level. If the data become available later, they can be overlain with an existing landslide inventory and used to update threat classifications, as needed. IMU bending strain data can also be used at a more detailed level, during a Phase II or III, to more fully characterize the landslide-pipeline interaction, perceived threat, and FFS. Finally, IMU bending strain data can be used long term as a form of monitoring (discussed further in Section 9), which can be particularly useful in high-density landslide regions, where the data can be used to identify new landslide hazards or new or increased pipe strain related to existing landslide hazards.

Both single-run data and run-to-run comparison data are useful for managing landslide hazards. Single-run data provide indications of past pipeline/landslide interaction and a measure of the total magnitude of the bending from past landslide movement. Run-to-run data identify changes that occur between runs. This data can be used to track/monitor landslides that are actively impacting the pipeline between runs and provide an indication on the rate of strain increase resulting from landslide movements.

As shown by Theriault et al. (2019), most bending strain features reported by ILI vendors are not associated with geohazards (i.e., defined in the study as landslides or river crossings). In a review of 4,618 single-run bending strain features from known landslide prone areas, only about 6% were found to spatially correlate to geohazards. A large number of bending strain features reported by the ILI vendors appeared more likely to be induced during original construction (both intentional and unintentional bends). Thus, distinguishing between bending strain features caused by geohazards and those originating from other sources is an important component in the review of bending strain features. The following are indications of likely landslide origins (see Figure 5-4 for an example):

- Long length (spanning one or more girth welds) with the pipeline being deflected into a sinusoidal curvature shape. This shape is sometimes referred to as a "W-shape," with one dominant curvature lobe (centered on the likely source of movement) and two lesser side-lobes with curvature in the opposite direction (Wang et al. 2017).
- Intersection or proximity of bending strain features to known landslide hazards. Comparison of bending strain features to known (or likely) landslide hazards is a strong indication that the bending strain feature may have been caused by the landslide hazard. Thus, to the extent possible, bending strain feature locations should be reviewed against an existing landslide hazard inventory or reviewed during the initial geomorphic review.
- High overall strain magnitude. As demonstrated by Theriault et al. (2019), the higher the overall strain magnitude reported by the ILI vendor, the more likely the bending strain feature is to be associated with a landslide hazard. In the above-referenced dataset, at and above a reported bending strain magnitude of 0.35%, the correlation between bending strain features and likely geohazards was about 50%, and above a bending strain magnitude of 0.42%, the correlation was over 90%.
- High horizontal strain magnitude. Also as demonstrated by Theriault et al. (2019), in the reviewed dataset, the horizontal component[6] of bending strain was highly predictive of geohazard correlation. When the horizontal component of bending strain exceeded 0.14%, the correlation between the reviewed bending strain features and likely geohazards was greater than 50%, rising to 100% correlation when the horizontal magnitude exceeded 0.36%.

[6] ILI vendors typically report the maximum (or overall) strain magnitude and then separately report a maximum vertical and maximum horizontal component of bending strain.

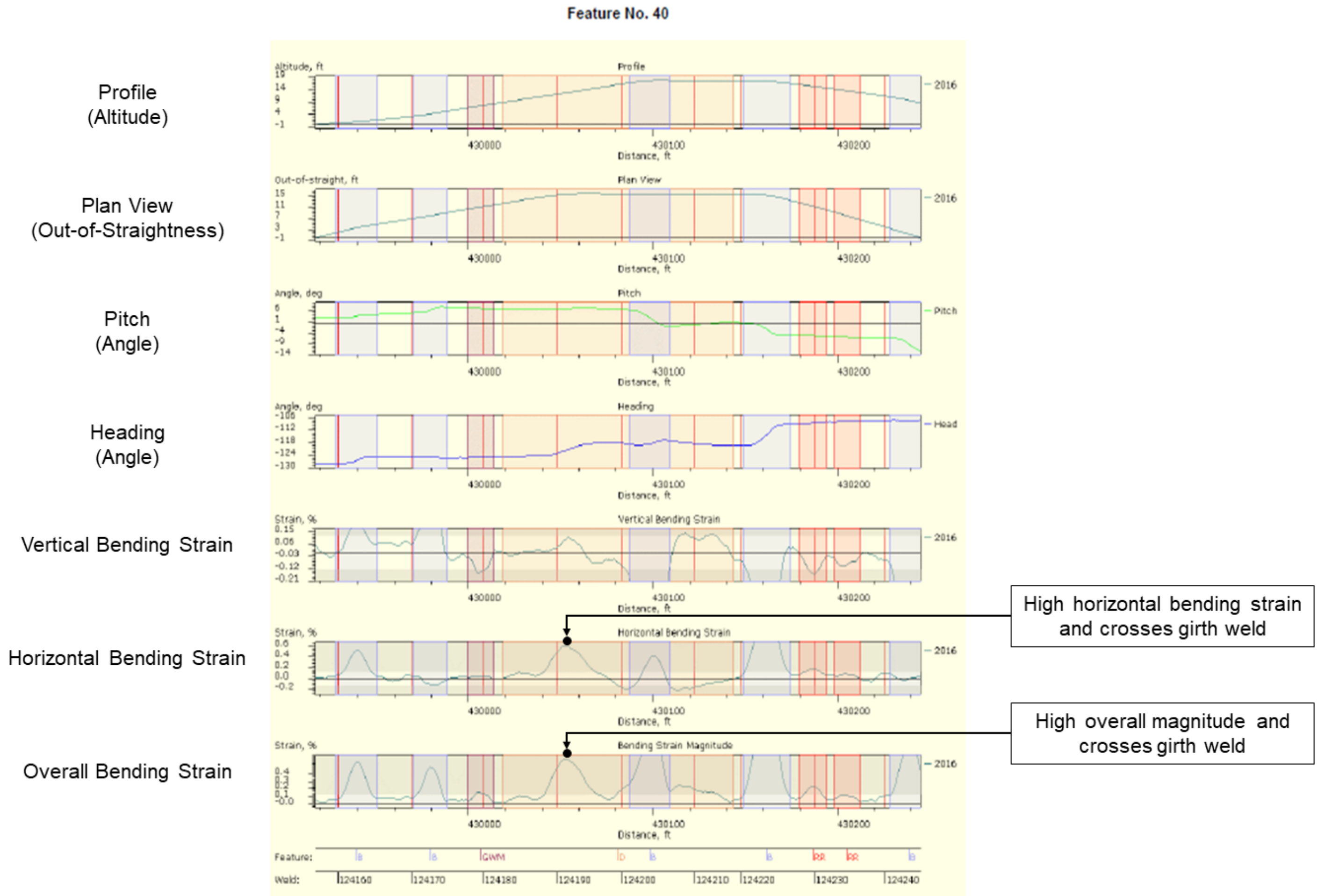

Figure 5-4. Example single-run bending strain report provided by ILI vendor showing how IMU bending strain can be used both to identify possible landslide effect on a pipeline and approximate magnitude of that effect. In this example, vertical red lines represent girth welds. The bending strain feature has several indications of possible geohazard origin, including long length (crosses more than one girth weld), relatively high overall magnitude, and high horizontal magnitude.

5.3 Landslide Identification and Assessment Technologies and Methods

There are many technologies and methods that can be used to identify and assess landslide hazards throughout the phases of assessment described above. Typically, more than one technology or method may be used by a company, and the methods may vary by region depending on many factors, such as the location, length, and configuration of the companies' pipelines; the anticipated or known density of landslides in a given region; and ongoing inspection and maintenance procedures (that may serve multiple purposes). Descriptions of common technologies and methods applied during the three phases of assessment are summarized in Table 5-1. The pros and cons (or limitations) of each method are also listed. Monitoring instrumentation (e.g., inclinometers, piezometers, strain gauges), which can also be used to characterize and assess landslide hazards, are described separately in Section 9.

5.4 Unplanned Identification

Sometimes, a member of the public or a regulatory body becomes aware of a landslide or possible landslide across or closely adjacent to a pipeline, and they will inform a pipeline owner of the situation. The response by the pipeline owner should include the following:

- Obtain as much information as possible on the location and characteristics of the reported landslide to initially assess the nature, severity, and immediacy of the landslide threat to the pipeline and the public. This would include communicating with the person or organization that provided the initial report of the landslide to obtain their firsthand information. Cross-referencing the reported landslide with the pipeline operator's existing landslide hazard database would be done to ascertain whether the reported landslide has already been identified in the system.
- Deploy aerial or ground patrols (or both) to the location of the landslide to gather more information and detail to inform owner decisions on whether to engage SME geologic and geotechnical professionals and whether modified pipeline operations (e.g., reduced pressure) need to be implemented while the landslide threat level is evaluated.
- If SMEs are engaged, begin with a Phase II landslide assessment to ascertain the type, nature, and behavior of the landslide and its relationship to the pipeline. If the information and data from the Phase II can support the development of hazard mitigation and/or monitoring, then the owner would proceed with those activities.
- If the results of an SME Phase II indicate more site-specific data are needed to support the development of mitigation design and/or monitoring plans, then implement a Phase III landslide assessment.

Table 5-1. Common Data Sources, Technologies, and Methods Used for Landslide Hazard Assessment

Method	Description	Areas Where Most Useful	Pros	Cons
Detailed topographic maps and digital elevation model (DEM) data	Detailed topographic maps (1:20,000- to 1:25,000-scale) show large-scale geomorphic features such as disrupted terrain and closed depressions (sag ponds) that might relate to landslide hazards. DEM data (e.g., 10-meter or larger) can be manipulated to create shaded relief maps (hillshades) to accentuate geomorphic features and help identify landslide hazards.	- Commonly used in Phase I assessments - In Phase II assessments, they support site access evaluations	- Topographic maps and DEM data depict areas and steeper terrain where landslides might be more likely	- Only useful for large-scale landslides because of the relatively small scale of the topographic maps and low resolution of the DEM data
Regional and large-scale geologic maps and geology reports	Geologic maps may delineate landslides as distinct geologic units. Geology maps and reports may tie specific geologic units to landsliding. The geologic map data may be in the form of print copies, .pdfs, or GIS databases.	- Used in Phase I assessments for overall regional and local geologic context and in Phase II assessments for site-specific geologic conditions	- Provides needed geologic background and context for understanding nature and genesis of landslides for region and site area - May identify typically large, distinct landslides	- Landslides are often not mapped on regional geologic maps - Large-scale geologic maps may also not show landslides because maps may be focused on bedrock geology
Airborne LiDAR data review	LiDAR, which stands for light detection and ranging, 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 features on the ground surface (e.g., landslides). Comparison of repeated LiDAR data for the same area/location can be used to examine changes to the DEM related to landslide movement; this is known as LiDAR differencing.	- Thickly vegetated areas - High-density landslide areas - Remote or difficult-to-access areas - Commonly used in Phase I and Phase II assessments	-High-resolution data allow for higher certainty in landslide identification, delineation, and initial characterization - Useful in areas with high densities of landslides - Can reduce the need for site visits - LiDAR differencing (change detection) can be used for landslide monitoring and identification of new landslides that form through time - Many areas/regions have high-resolution, publicly available LiDAR data that reduce the need for project-specific data collection	- Generally limited window to acquire highest quality data each year (e.g., leaf-off conditions) - Relatively long period for data processing and review (i.e., weeks to a few months) - Requires trained companies/personnel to acquire, process, and review the data - Publicly available data may be limited by acquisition date, quality, and footprint - Project-specific data may not be considered feasible
Stereoscopic aerial imagery	Federal and state/provincial agencies often have wide coverage of large-scale stereoscopic black-and-white and color aerial photographs, which are used in identifying geomorphic features indicative of landslide movement.	- Useful in detecting and identifying landslides in semi-arid and arid environments where vegetation cover is minimal - Commonly used in Phase I assessments	- Stereoscopic imagery provides 3D morphology from aerial photographs making landslide identification straightforward - Relatively inexpensive to acquire compared to LiDAR data and much less data processing required - Current technology and software allows for review of stereophotos digitally, so mapping can be conducted directly in a GIS platform	- Not reliable for complete/comprehensive landslide identification in forested/thickly vegetated environments - Publicly available data may be limited by acquisition date, quality, and footprint
Aerial imagery	Historical or current low- and high-quality aerial photography may indicate features and/or changes that are the result of landslide movement or human development that may trigger landslides.	- Commonly used in Phase I assessments to identify and characterize landslides	- Several public sources of imagery (Google Earth, ESRI, states, etc.) - Inexpensive, and historical imagery allows for review of landscape changes over time	- Often no 3D capability to detect landslide morphology, particularly in vegetated terrain - Not reliable for complete/comprehensive landslide identification in forested/thickly vegetated environment
InSAR	InSAR stands for interferometric synthetic aperture radar. Ground scanning using InSAR can detect and monitor changes in the ground surface over large areas, without the need to physically access a site. The technology has been used to identify areas and magnitudes 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 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.	- Satellite-based InSAR data can provide information on the location, magnitude, and rate of ground movement for landslides - Can be used in Phase I assessments for landslide identification and characterization and for long-term monitoring	- InSAR data of the same location may be collected frequently depending on the satellite (repeat imagery ranges from 4 to 46 days depending on the satellite) - Historical data may exist depending on the band and satellite chosen - Can be used to monitor same location into the future - Large images can capture many landslide features - Large images may capture multiple pipeline routes	- Requires multiple pass analysis - Image acquisition is expensive - Might not detect landslides with north or south movement directions - Might not detect very fast or very slow landslide movement - Most InSAR bands (except L-Band) cannot effectively resolve movement in thickly vegetated areas without pre-placed corner reflectors or existing hard structures -Does not identify landslides that occurred prior to beginning of monitoring -Limited control over future tasking of satellite resources

Table 5-1. Common Data Sources, Technologies, and Methods Used for Landslide Hazard Assessment

Method	Description	Areas Where Most Useful	Pros	Cons
ILI IMU bending strain data	An IMU module is typically mounted on another smart pig platform; thus, IMU monitoring can occur during any scheduled assessment. When reviewing the IMU data, information collected on pipeline anomalies (e.g., buckles) should also be reviewed to evaluate features that could reduce strain capacity and/or indicate past impacts from a landslide.	IMU data can provide the following information: - Evidence of high strains - Evidence of pipe movement from run-to-run analysis – comparing the positions of the pipeline from a baseline run to the current run to determine if there is any lateral displacement. Used in all three phases of landslide assessment.	- Can be used for long segments of pipeline - Can indicate landslide interaction with pipe - ILI IMU data can be used to detect pipe geometric anomalies and bending strains, and, during successive runs, data can be used to determine pipeline areas of apparent strain or displacement related to landslides - When there are multiple runs, the baseline run can be compared to provide incremental displacement data - Can be used for quantitative FFS assessment along with strain capacity determination	- Only applicable for piggable segments - Can be long delays between data collection and delivery of results - Can produce strain sites that may not be related to landslides, which must be filtered out - Determining strains caused by landslide in pipe segments with hot and cold bends can be difficult
Aerial reconnaissance by SME	Experienced, trained geotechnical professionals view the ground surface from an aerial platform, typically a helicopter, but also can be a fixed-wing aircraft.	The aerial reconnaissance provides a current, close-up, synoptic view of the terrain along the pipeline ROW so that the current geomorphology can be viewed for evidence of ground disturbance related to landslides. The reconnaissance can be conducted with helicopter or fixed-wing aircraft. Used in all three phases of landslide assessment.	- While other tools may provide only snapshots in time of the terrain or potential landslide morphology, aerial reconnaissance provides a real-time view of the terrain - If the reconnaissance is conducted with a helicopter, then ground checking of suspicious features can be done at the same time - Can be employed after an intense storm to detect whether landslides have been triggered or after a significant seismic event to see if ground shaking has triggered landslides	- Helicopters are expensive compared to fixed-wing aircraft - Fixed-wing platforms, while less expensive, fly at higher speeds, which may allow for missed detection of subtle landslide features - Features may be obscured by vegetation
Ground reconnaissance by SME	Detailed, nonintrusive, site-specific geomorphic and geologic mapping by trained and experienced geotechnical professionals to more completely identify the lateral limits of the landslide relative to the pipeline and estimate the magnitude and rate of movement. This may include pipeline locating, including pipe depth, to evaluate whether the pipeline might have been engaged by landslide movement or whether the pipe is deep and possibly below landslide movement.	SME ground reconnaissance is commonly conducted during a Phase II assessment and may also be done to support Phase III assessments.	- The field mapping and data points are recorded and plotted on GIS-based GPS tablets and handheld units so that the field data can be easily entered into a landslide GIS database - Applicable to examining multiple landslides along an alignment or a single landslide of concern	- Necessitates mobilization of experienced landslide mapping team(s) - Requires landowner permission - Site access can be difficult - Features may be obscured by vegetation
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 and geotechnical conditions, particularly useful for a shallow landslide. The depth/thickness of the landslide relative to the pipe 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 at the Phase III assessment level for site-specific investigations of landslides.	- Test pits are relatively inexpensive compared to drilling exploratory boreholes - Provides geologic context in the form of an outcrop (the exposed walls of the test pit) compared to point data from a borehole	- Limited depth for exploration - Create a larger area of disturbance than drilling
Site-specific geotechnical boreholes	The 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 instrumentation, including slope inclinometers and piezometers.	Geotechnical boreholes are employed at the Phase III assessment level where site-specific data are needed for landslide mitigation.	- Provides detailed, subsurface geologic and geotechnical information and data on the landslide - May be combined with other tools like inclinometers or piezometers	- Relatively expensive and logistically intensive
Site-specific geophysics	Various geophysical methods/techniques (e.g., ground-penetrating radar [GPR], electromagnetic induction [EMI], seismic refraction, seismic reflection) can be used, with favorable conditions, to image the subsurface structure, stratigraphy, and geometry of landslides, and this information supports the development of mitigation alternatives.	Geophysics are used at the Phase III assessment level, typically to provide context to the point data of geotechnical boreholes.	- Depending on the geophysical technique, the landslide slip surface can be imaged to provide detail to landslide geometry - Fills-in data gaps between geotechnical boreholes - Relatively inexpensive and fewer logistical concerns than intrusive methods	- Interpretations from geophysical data might be uncertain and inconclusive

6 FITNESS FOR SERVICE ASSESSMENT OF PIPELINES POTENTIALLY IMPACTED BY LANDSLIDES

6.1 Role of Fitness-for-Service Assessment

FFS assessment is a process by which the integrity of a pipeline is assessed to establish whether the pipeline is safe at the state and time that are being assessed based on the information available to conduct the assessment. In contrast to Section 5, which focused largely on landslides (i.e., the hazard), FFS assessment focuses on the integrity of the pipe—the potential for pipe loss of containment (LOC) or loss of service (LOS).[7]

Many landslides are time-dependent hazards that can affect a pipeline over many years. FFS assessment does not directly address the time-dependent nature of landslides. Instead, FFS assessment can be used to assess the integrity of a pipeline if the severity and behavior of a landslide can be predicted 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. Examples of applications of FFS assessment for landslides are provided in Appendix A.

Some level of uncertainty exists in the outcomes of FFS assessments due to the uncertainties associated with the input parameters used for the assessment and uncertainties associated with the methods of assessment. Refinements of the assessment are possible with improvements in the precision of the input parameters and continued development and validation of assessment methods.

FFS assessment can be incorporated into any component of a landslide hazard management program:

- During pipeline construction, including pipeline replacement programs, FFS assessment can be used for the selection of pipes and welding procedures, setting welding procedure qualification requirements, and field inspection criteria. It can also be used to assign threshold strain values below which the pipe segment is safe if the segment were to be affected by a landslide in the future.
- After an unexpected landslide event, FFS assessment can assist the execution of an emergency response plan as described in Section 10. FFS assessment can provide inputs to determine whether immediate mitigation is necessary and estimated tolerances for additional movement when information for such assessment is available.
- FFS assessment can be used to support a classification system as described in Section 7. FFS assessment addresses the strain capacity component of a classification system, such as the example system provided in Appendix B.
- FFS assessment can be a part of a screening system for the identification of high-priority sites that require mitigation. With the increased use of ILI IMU bending strain analysis to establish strain demand, FFS assessment completes the integrity assessment picture by

[7] Such as through inducing a buckle or wrinkle, that while it may not result in LOC, may impede the safe operation of the pipeline.

bringing together strain demand and strain capacity, improving the ability to estimate the likelihood of a failure at a given state and time.

When used correctly, FFS assessment can be a powerful tool in managing landslides by optimizing the use of limited resources to mitigate landslides most likely to affect the integrity of the pipeline. An overview of the application of FFS assessment for the management of ground movement hazards, including basic concepts and approaches, is given by Wang et al. (2017).

Unless noted otherwise, the strains of interest in this section are strains in the longitudinal (axial) direction of a pipe segment.

6.2 Possible Failure Modes and Limit States

FFS assessment focuses on possible failure modes of an affected pipe segment after a landslide event. These failure modes are briefly described in this section.

6.2.1 Leak or Rupture under Tension

When a pipeline is subjected to longitudinal tensile stress/strain, the primary concern is the integrity of the girth welds. If the tensile strain demand is higher than the strain capacity of a girth weld, a leak or rupture may occur at the girth weld as shown in Figure 6-1. Leak or rupture under tension is an ultimate limit state.

Figure 6-1. An example of girth weld failure

6.2.2 Buckles and Wrinkles from Compressive Loading

When the longitudinal stress/strain is in compression, wrinkles or buckles may be formed in a pipe segment if the stress/strain is sufficiently high, as shown in Figure 6-2.

The immediate consequence of the formation of a wrinkle or buckle can vary from a benign 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, as shown in Figure 6-3.

In addition to the immediate integrity concerns, large hoop strains generated in the vicinity of severe wrinkles and buckles may cause failures in seam welds with compromised properties (e.g., certain electric resistance welded [ERW] pipes with anomalies). Severe wrinkles can also cause damage to anticorrosion coating, leading to other possible failure modes associated with the loss of the coating. Additional structural integrity concerns include possible flaw initiation and growth through fatigue mechanism at the wrinkles and buckles.

Figure 6-2. A severe buckle formed at zero internal pressure

Figure 6-3. Wrinkle formation near a girth weld and the resulting cracking of pipe wall at the apex of the wrinkle

Compressive buckling is usually categorized as a serviceability limit state. This characterization can be misleading. The impact of reaching the customarily defined compressive strain capacity (CSC) can vary.

- If the loading is displacement-controlled, as is typical of buried pipelines subjected to landslide loading, reaching the CSC generally does not negatively affect the pipeline service. The bulging and ovalization of the pipe's cross section is so small that inspection pigs should be able to pass.
- 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. A systematic assessment of various possible failure modes in a post-wrinkle environment is given by Liu et al. (2016).
- 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.

6.3 Potential Impact of Pipe and Weld Conditions on the Landslide Hazard Management Decisions

When a pipeline is impacted by a landslide of given magnitude, the likelihood of pipeline failure varies greatly due to the varying level of strain tolerance of a pipeline. The displaced pipe segment experiences bending and extension strains. One of the key drivers to the integrity is whether the pipe strains imposed by the landslide are concentrated at a girth weld(s). For instance, a lateral movement of 5 feet over a span of 300 feet can be easily accommodated by a pipeline segment if the strains are distributed (shared) by the pipe and there is no gross strain concentration in the weld area. However, the same level of pipe movement could cause a leak or rupture if the strains are primarily concentrated at a susceptible weld. The susceptibility of a weld to such strain concentration can be caused or exacerbated by several factors:

- Weld strength being lower than the actual strength of the pipe
- High level of high-low misalignment, more likely to occur at tie-in welds and welds joining pipes/fittings of different wall thickness
- Heat-affected zone (HAZ) softening due to welding thermal cycles applied to the pipe
- Weld anomalies, particularly planar flaws such as hydrogen cracks and lack of sidewall fusion
- Low toughness
- Underfill or missing weld pass(es)

The welding community has put major focus on weld anomalies from prevention to detection through nondestructive examination and repairs. Prior to the 1940s, some onshore pipelines were constructed using Acetylene girth welding techniques which can have low toughness. Most onshore pipeline girth welds since the 1940s have adequate toughness under normal service conditions. There are gaps in the pipeline industry in the understanding and characterization of the first three factors (weld strength, misalignment, and HAZ softening). These factors can have a significant effect on the strain tolerance of a girth weld.

It is important to highlight some characteristics of linepipe and girth weld properties and their implications on tensile strain capacity (TSC) in contrast to a few persistent misconceptions in the industry:

- Linepipe of the same grade does not have the same strength. The grade only indicates the minimum yield strength measured typically in the hoop direction. For API 5L Product Specification Level (PSL) 2 pipes, the upper bound yield strength of a given grade is typically 22–23 kilopound force per square inch (ksi) above the SMYS. The upper bound ultimate tensile strength can be as much as 30 ksi above the specified minimum tensile strength. API 5L PSL 1 pipes do not have limits on upper bound strength. It is not uncommon to see a pipe with actual strength 20 ksi above the specified minimum values.
- Pipes of the same grade are not manufactured in the same way. Pipes of the same grade can have different characteristics that affect their interaction with girth welding thermal cycles, leading to different mechanical properties and, thus, differing strain tolerance levels.

- Current girth welding requirements do not have provisions to ensure weld strength is above the actual strength of the pipe. The weld strength is only required to match the specified minimum strength of the pipe. Since the actual pipe strength is almost always higher, sometimes significantly higher, than the specified minimum strength, the weld strength in many cases undermatches the actual strength of the pipe. Weld strength undermatching is permitted by most welding standards such as API 1104 and CSA Z662.
- Unless pipelines are designed specifically to accommodate strain using strain-based design concepts, pipeline design does not require the weld strength to be greater than the actual pipe strength.
- Weld strength undermatching the actual strength of the pipe is fairly common in manual welds.[8] However, this condition does not necessarily lead to low strain tolerance (low strain capacity). A high level of weld strength undermatching, however, can severely reduce the strain tolerance of a girth weld.
- The vintage of a pipeline is not a reliable predictor of the strain tolerance of a pipeline.

In summary, the likelihood of a failure when a pipeline is impacted by a landslide depends on the severity of the landslide and the strain tolerance of the pipeline, which can vary greatly from one location to another. As discussed in Section 7, it is recommended that a ranking or classification system in a landslide hazard management program consider both the severity of a landslide and a pipeline's tolerance to such an event.

6.4 Pipeline Design vs. Actual Field Condition

For traditional stress-based design pipelines, the longitudinal stresses and combined stresses are limited to 90% SMYS or less in ASME B31.4 and B31.8[9] (Wang et al. 2016a). ASME B31.4 and B31.8 also permit pipelines to be designed for strain up to 2%, provided conditions stated in the standards are met. The standards, however, do not state how these conditions can be met. This 2% allowable design strain limit is often misquoted and misunderstood to mean that all pipelines have a strain capacity of 2%. The vast majority of pipelines are designed to a longitudinal stress of 90% SMYS or less (i.e., approximately 0.2% strain), not to 2% strain. The actual strain capacity can vary from 0.2% to well over 2.0%.

In contrast to internal pressure, longitudinal stresses in pipelines are difficult to manage. The level of longitudinal stresses is often not known. Recent IMU surveys indicated that there could be many locations in a pipeline with longitudinal strains exceeding 0.2% strain. From the perspectives of managing landslides, it is the actual field conditions that must be considered, regardless of the original design conditions.

---

[8] The current industry practice is such that the deposited weld metal strength is typically higher than the actual pipe strength for pipes up to grade X80 when welds are made with mechanized gas metal arc welding (GMAW) processes. However, the weld strength requirements in welding procedure qualification specifications is the same for mechanized and manual welds. Weld strength undermatching is permitted for mechanized welds.

[9] This is only true for pipelines designed after ASME B31.4 and B31.8 were adopted and widely used in the design and construction of those pipelines. It is not clear whether there was longitudinal stress or combined stress limited before the adoption of ASME B31.4 and B31.8.

6.5 Strain-Based Assessment

Commonly used FFS assessment procedures, such as those in British Standard (BS) 7910 and API 579, were developed principally for stress-based assessment (i.e., when the nominal longitudinal strain is less than 0.2% in the context of pipeline integrity assessment). Integrity concerns arising from landslide hazards typically involve strains greater than 0.2%. Therefore, using strain-based assessment (SBA) is more appropriate than using stress-based assessment when addressing landslides.

SBA focuses on the integrity of a pipeline under moderate to high levels of longitudinal (axial) strain. The internal pressure is incorporated into the assessment process because it can affect the assessment outcome under the same level of longitudinal strain.

SBA encompasses at least two limit states: tensile rupture and compressive buckling. Tensile rupture is an ultimate limit state, which is related to the breach of the pressure boundary (i.e., leak or rupture). The compressive buckling could be either a service limit state or an ultimate limit state.

6.5.1 Key Concepts and Terms in Strain-Based Assessment

The following are key concepts and terms that apply to SBA:

- Strain Demand: Strain demand is the strain imposed on a pipeline by its operational and environmental conditions. An example of an environmental condition is a landslide.
- Strain Capacity: Strain capacity is the strain level a pipe segment can sustain without negative consequences. The negative consequences could be a leak, a rupture, or any other change of the physical characteristics of the pipeline that an operator may deem unacceptable. For instance, it can be an operational limit, such as preventing the passage of inspection pigs, or a condition that may lead to future integrity concerns, such as coating damage, fatigue after the formation of wrinkles, etc.
    - Tensile Strain Capacity (TSC): TSC is the strain capacity in tension.
    - Compressive Strain Capacity (CSC): CSC is the strain capacity in compression.
    - Strain Demand Limit (SDL): SDL is the limit the strain demand is allowed to reach. SDL is obtained by one of two ways: 1) multiplying the strain capacity by a safety factor that is less than 1.0, or 2) subtracting a finite number from the strain capacity.
- Acceptable Condition: Acceptable condition is when the strain demand is less than the SDL. An acceptable condition is only relevant to the condition being assessed with the corresponding input data for such assessment. If strain demand or strain capacity were to change from the conditions being assessed, reassessment might be necessary.
- Load-Control vs. Displacement-Control: Both displacement-controlled and load-controlled conditions are possible on a pipeline. A loading is considered load-controlled if the magnitude of such loading is not affected by the amount of deformation or displacement. Examples of such loading are dead weight loading, soil load on a span, and internal pressure. A loading is considered displacement-controlled if the amount of deformation is not affected by the load carrying capacity of the component/structure being subjected to the deformation. Examples of displacement loading are pipe bending by a

mandrel and reeling-on a pipe string in spool-based installation. Most loadings on pipelines are a combination of displacement- and load-controlled. A slow-moving ground movement against a small-diameter pipe is primarily displacement-controlled. However, a slow-moving ground movement of loose sandy soil against a large diameter pipe may potentially not be displacement-controlled because the soil may flow around the pipe.

6.5.2 Determination of Strain Demand in Areas of Landslide Hazards

The strain demand from a landslide includes at least two components:

- Strains on the pipeline segment prior to an event
- Additional strains imposed on the pipeline segment by the landslide

6.5.2.1 Estimation of Strain Demand from the Location of the Pipeline Segment

The process for estimating the strain demand from the location 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 sheet
- Survey points established at the time of construction
- Records of prior line location
- IMU runs

The location of the post-construction pipeline segment may be determined by locating the line through pot holing and surveying, conventional line locators,[10] or IMU (if an after-event IMU run is available).

The comparison of as-built location with the landslide deflected location should enable the establishment of the span and magnitude of the movement. When the span length and the magnitude of the lateral or vertical 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 (Wang et al. 2017).

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

- The effect of temperature change if the temperature change is more than that assumed in the baseline strain calculation.
- The effect of internal pressure. The effect of internal pressure on strain demand is often less than that of temperature changes (Wang et al. 2017).

A review of analytical models for estimating strain demand from displacement pipe profiles is given by Yu et al. (2020).

6.5.2.2 Estimating Strain Demand from Strain Gauges

Strain gauges (sometimes spelled “gages”) monitor pipe strain induced by change in temperature, operating pressure, or external landslide stresses. Existing strain of the pipe before the strain gauge installation cannot be estimated using the strain gauges. Strain gauges provide accurate measurement of change in strain at the location of the installation and can be used for FFS assessment and long-term monitoring (see Section 9.4.1).

There are three primary types of 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 type most commonly used for pipe monitoring and the type recommended for most applications.

VW strain gauges are typically attached to the pipe using low-energy spot welds (i.e., 20 to 40 joules, equivalent to 1/100th of the energy of an arc weld). Most post-installation failures of VW strain gauges are related to surface preparation prior to installation (the surface should be prepared by grinding versus sand blasting), incorrect installation, or damage after installation, such as cables being damaged by animals. There have been anecdotal concerns about the longevity of these instruments when exposed to the magnetic field of a magnetic flux leakage (MFL) ILI tool. However, many operators have reported that they have not observed changes to strain gauge behavior resulting from MFL.

The cost of installing VW strain gauges is relatively low if no excavation is required, such as during the installation of new pipes or replacement pipes. The installation cost increases when excavating to expose an existing pipe and preparing the pipe surface for installation of the strain gauges. The cost of installing strain gauges (material and labor) is typically less than 10% of the excavation cost. Therefore, installing additional strain gauge sets (for additional monitoring or for redundancy) might only slightly increase the project cost.

Resistance-type and FO strain gauges are only recommended for relatively short-term or specialized applications because prior experience has shown that they tend to have much shorter field longevity than VW strain gauges. A longer discussion of the resistance-type and FO strain gauges can be found in Wang et al. (2017).

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.[11] 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.
- Strain gauges only capture the strains from the time of strain gauge installation. The prior strain at the time of strain gauge installation should be accounted for when estimating total strain demand.
- A minimum of three strain gauges around the circumference is needed to fully resolve the strains from lateral bending and uniform extension/compression. A set of three or four strain gauges are 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 unexpected failures of a strain gauge and to help 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 at the 12, 3, 6, and 9 o'clock or at the 1:30, 4:30, 7:30 and 10:30 o'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 vs. 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.
- It is important to note that 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.

6.5.2.3 Estimation of Strain Demand from Landslide Characteristics

Pipe-soil interaction models[12] can be used to determine the strain demand on an affected pipeline segment. The pipe-soil interaction models often start from 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. These factors are taken into account in the pipe-soil interaction models to various degrees. The following are the most important factors related to pipe-soil interaction modeling (C-Core 2003):

- Ability to simulate large relative displacement of a pipeline

---

[11] For the purpose of monitoring strains on a girth weld, strain gauges can be installed on the pipe a few inches from the girth weld. Strain gauges should not be installed on the girth weld.

[12] These models are not suitable for pipe-rock interaction.

- 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

The most widely used pipe-soil interaction models use structural beam elements to represent the pipe and spring elements to represent the resistance of soil to the pipe movement (C-Core 2008). Potentially more accurate modeling techniques involve continuum pipe-soil interaction models (C-Core 2003).

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, variable circumferential and longitudinal pressure distribution can be properly represented in such models.

The principal advantages of the structural pipe-soil interaction models are their computational efficiency. However, the force-displacement relationship representing the resistance of the soil is a simplification that could introduce modeling errors and prevent certain key features from being properly modeled. In contrast, the continuum pipe-soil interaction models provide more realistic representations of the physical mechanisms at the expense of computational efficiency. The decision on which type of model to use (structural or continuum) should be based on the goal of the analysis, available data that support the analysis, and the time constraint on the turnaround time of the analysis. The uncertainties associated with a chosen model should be accounted for in presenting the FFS outcomes.

In comparison with the use of strain gauge or IMU data, pipe-soil interaction modeling is an indirect approach to obtain strain demand. The accuracy of the strain demand prediction is strongly affected by the accurate characterization of the site soil conditions, and these properties should generally be provided by a geotechnical engineer. Most pipe-soil modeling assumes one set of uniform soil properties along the length of the affected segment, which does not accurately represent the actual soil conditions and is generally a representation of the conditions at the time the soil samples were taken, not necessarily when the landslide occurred.

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 to be a conservative approach for foundation design and 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, then 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 limitation is provided by Yu et al. (2020).

6.5.2.4 Estimating Strain Demand from IMU

The use of IMU bending strain as a tool for landslide identification, FFS assessment, and long-term monitoring is discussed in Section 5.2. From an FFS assessment perspective, IMU is primarily useful as a means of estimating the strain demand induced by a landslide on a pipeline segment. However, this should be understood to be an estimate and not to be equivalent to total strain. 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 pipe segment when the centerline profile deviates from a straight line. The bending strain calculated includes strains from all events that caused the pipe 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 in order to assess the potential tensile failure of girth welds. However, construction bends may influence the distribution of strains in the displaced segment if a landslide 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 for the ILI vendors to accurately determine 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.

6.5.3 Determination of Tensile Strain Capacity

TSC (alternatively termed "tensile strain limit") refers to the highest tensile strain a pipe or weld can sustain without a leak or rupture. The TSC of a pipeline is often controlled by the TSC of its girth welds. There could be strain concentration at the welds due to geometric profiles (e.g., high-low misalignment, weld reinforcement, change in wall thickness), welding imperfections (e.g., cracking, lack of fusion or penetration), and mechanical properties (e.g., weld strength being lower than the actual strength of the pipe, low toughness).

Factors having significant influence on TSC are as follows:

- Pipe wall thickness and diameter
- Strain hardening rate
- Weld strength mismatch
- Extent and level of HAZ softening
- Girth weld profile
    - Cap reinforcement
    - High-low misalignment
    - Bevel angle
- Girth weld flaws
    - Type
    - Location
    - Dimensions
- Toughness
- Internal pressure

Some of these factors, such as pipe wall thickness, pipe diameter, and internal pressure, are generally known to pipeline operators. Most other factors may not be known without further examination and testing.

6.5.3.1 Understanding Tensile Strain Capacity in the Environment of a Landslide

The TSC of the pipe segment affected by a landslide is measured by its nominal strain in the entire segment, not the strain across the narrow width of girth welds. If the girth welds are stronger than the pipe, the elongation of the segment is distributed over the length of the pipe. If the welds are weaker than the pipe, the elongation of the segment can be focused in these welds, leading to low strain tolerance of the overall segment. For instance, an elongation of 1 inch over a 40-foot joint produces a strain of 0.21% which can usually be easily tolerated by the pipe and girth welds. However, if most of the 1-inch elongation were to occur in a girth weld, the weld would fail.

6.5.3.2 Possible Range of Tensile Strain Capacity

Figure 6-4 shows the strain at failure (y-axis) as a function of normalized flaw area (x-axis) from testing of over 200 curved wide plates (CWPs) (Wang et al. 2002). The parameters on the x-axis are dimensions of the wide plate and flaws:

- W: width of the reduced section of CWP
- t: wall thickness of the CWP
- l: length of the flaw
- h: height of the flaw

It is evident from Figure 6-4 that the failure strain is affected by more factors than flaw dimensions. For a given normalized flaw dimension, the failure strain can be as low as 0.2% to as high as more than 2%.

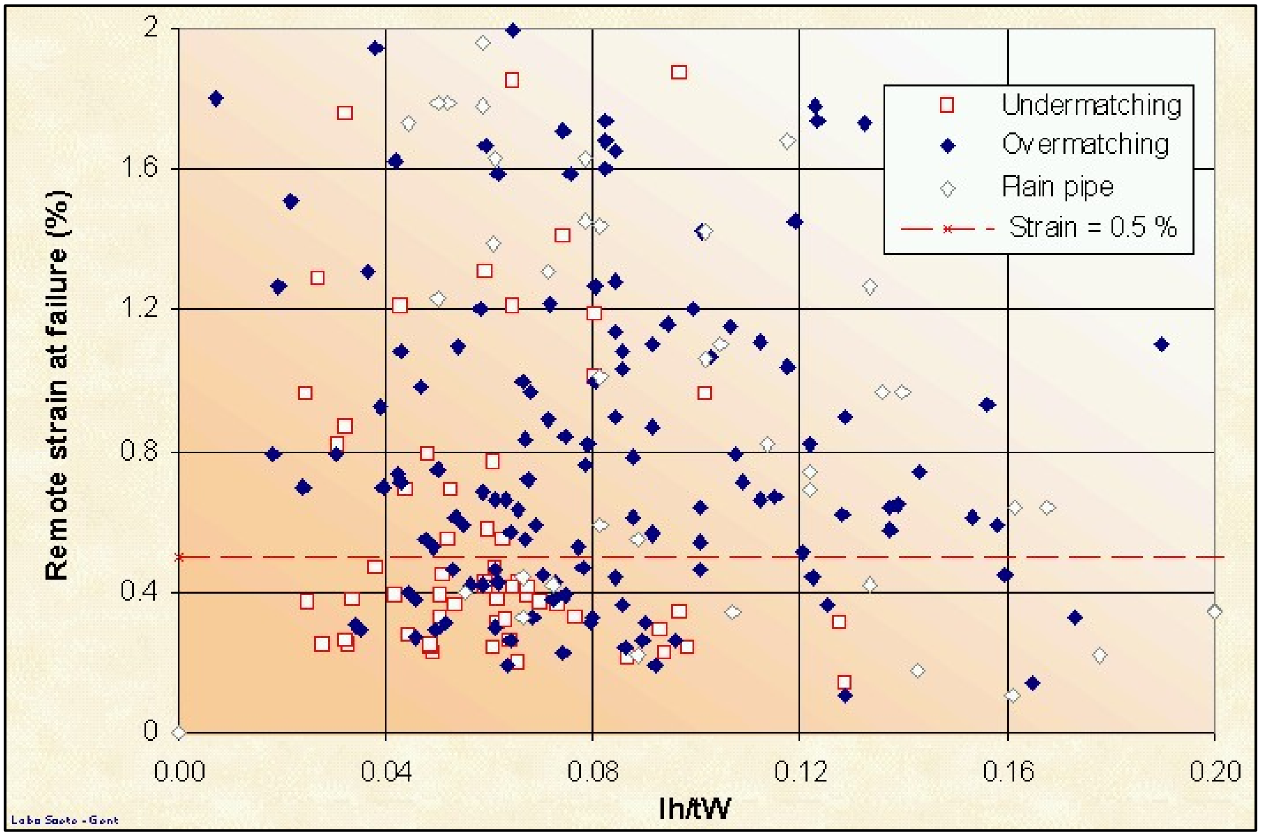

Figure 6-4. Failure strain distribution of over 350 CWP tests with different flaw dimensions (Wang et al. 2002)

6.5.3.3 Estimating Tensile Strain Capacity

As previously discussed, the TSC of a pipeline is often controlled by the TSC of its girth welds. Most tensile strain models focus on of girth welds. The TSC of a girth weld can be estimated in multiple ways, including the following (in approximate order of increasing accuracy and precision):

- Past experience or test data
- Software tools for generalized analysis
- Case-specific analysis

More information is needed when moving from low- to high-tier analysis with the benefits of increased accuracy and precision.

Estimation from past experience or test data can be a good starting point, but the large variations of TSC shown in Figure 6-4 and the many factors affecting TSC must be kept in mind. Most of the test data in this subject area were obtained under conditions that were not well-controlled, and, thus, their predictive value can be limited. Applying a single conservative value for TSC, if not tailored to specific classes of girth welds, can be overly conservative or not sufficiently conservative for some welds.

Another approach is using available software tools to estimate TSC. To use the tools correctly, one must understand the differences in linepipe manufacturing processes and the resulting linepipe properties as well as the different welding processes, consumables, and likely properties achieved by those welding processes and consumables.

- The tools must be used for the intended vintage of linepipes and girth welding methods.
- The applicable ranges of input parameters must be observed.
- When values of required parameters are not available, approximations from alternative data must be justified.

Case-specific analysis requires site-specific information about linepipes; girth welding processes, including consumables; and weld inspection practices and criteria. Such analysis can start from linepipes mill test reports (MTRs), girth welding procedure specifications (WPSs), and inspection procedures and report. When such information is available, case-specific analysis can produce quite accurate TSC estimates.

Case-specific analysis requires significantly more effort than estimating from prior experience or using software tools to provide generalized estimates and is thus usually used for specific-sites where the outcome from the analysis is meaningful in determining action. For instance, case-specific analysis might be used for a site that is difficult to access and where remediation may involve significant negative side effects and the risk of pipeline failure at either the current condition or a future postulated condition needs to be well understood before deciding to proceed or not proceed with this remediation.

6.5.3.3.1 Modern Mechanized Girth Welds

Modern mechanized girth welds here refer to welds made to modern microalloyed thermo-mechanical control process (TMCP) steels with mechanized GMAW processes. These modern steels were made with TMCP processes with low carbon content (typically below 0.08%) and addition of microalloying elements. The low-hydrogen welding processes permit the use of higher strength welding consumable without the risk of weld metal cracking. Weld strength matching or overmatching is typically achieved with current welding consumables for pipe grades up to X80.

The initial development of TSC models in the last 15 years focused on anticipated new pipeline projects traversing areas of unstable ground support, such as discontinuous permafrost. One of such efforts is a United States Department of Transportation PHMSA and PRCI jointly funded project which resulted in the publication of the PRCI-CRES tensile strain models (Wang et al. 2012a, Liu et al. 2012a, Liu et al. 2012b, Wang and Liu 2013). The models have a four-level structure for the maximum flexibility and varying degree of the availability of material data and design parameters. The Level 1 models are in tabular format and are intended for quick estimations of likely TSC for selected pipe dimensions, material properties, and flaw size. The Levels 2 and 3 models are in an equation format that can use either initiation-control or instability as the limit state. The Levels 1–3 models are primarily targeted for mechanized GMAW welds. The Level 4 models can be applied to any linepipes and welding processes and are typically used for case-specific analysis. The Levels 2 and 3 models have been implemented in a PRCI software suite for easy application (Wang et al. 2019).

6.5.3.3.2 Modern Manual Girth Welds

Modern manual girth welds here refer to welds made to modern microalloyed TMCP steels by manual processes, such as shielded metal arc welding (SMAW) processes with cellulosic electrodes, SMAW processes with low hydrogen electrodes, and semiautomatic flux-cored arc welding processes. These steels react to welding thermal cycles differently than vintage steels. This difference affects the weld's tolerance to strains in pipelines.

There is currently no software tool for modern manual welds. However, the Level 4 process of the PRCI-CRES models can be used to estimate the TSC using case-specific analysis. Examples of such applications can be found in Wang et al. (2019).

6.5.3.3.3 Vintage Manual Girth Welds

Pipeline operators have different ways of defining vintage pipelines. One way is to use 1970 as a time marker separating vintage from modern pipelines. This definition is most relevant to inspection practice but not necessarily relevant to pipe and weld properties. Pipelines constructed prior to 1970 typically did not have nondestructive testing conducted on all their completed girth welds.

Vintage welds here refer to welds fabricated by manual SMAW processes with cellulosic electrodes made to pre-1970 vintage pipelines. The steels of vintage pipelines were typically hot-rolled with normalized microstructure and carbon content greater than about 0.20% in North America.[13] Earlier girth welding processes, such as uncoated electrodes or oxy-acetylene welds, are not within the scope of this section.

The pipe properties are related to the steel-making practice and pipe-manufacturing process. The weld properties are related to welding processes, welding consumables, and pipe steels' response to welding thermal cycles. Evidence suggests that the properties of the deposited weld metal of SMAW processes using cellulosic electrodes did not go through drastic changes around 1970. On the other hand, pipe and HAZ properties would have gone through changes when microalloyed steels were introduced around this time (Wang et al. 2016a). The mechanical properties and flaw characteristics of the vintage welds fabricated in the 1940s to 1960s have been documented (Kotian and Wang 2016, Wang et al. 2017, Jia et al. 2020).

A tool for estimating TSC of vintage girth welds with limited validation is available (Wang et al. 2020a).

6.5.4 Determination of Compressive Strain Capacity

CSC is often defined as the strain corresponding to the point of the maximum bending moment in a lateral bending test, CSC_{ML}. In most cases, pipes have a very minimal amount of bulging or wrinkle at this point of loading (i.e., maximum moment). In a displacement-controlled loading scenario, reaching the CSC_{ML} does not negatively affect the pipeline service. The ovalization of the pipe's cross section is small and does not impede the passage of inspection pigs.

[13] Pre-1970 linepipe steels with carbon less than 0.2% have been found in pipelines in Europe.

If the loading is load-controlled, the pipe may collapse immediately after the maximum bending moment is reached, possibly forming severe wrinkles. 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 corresponding to the post-maximum-load behavior is defined as CSC_{PML}.

6.5.4.1 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 curves 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

6.5.4.2 CSC under Load-Controlled Conditions

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 (CSA 2011), the University of Alberta models (Dorey et al. 2006), and the newly developed CRES models (Liu et al. 2013a and Liu et al. 2013b).

6.5.4.3 CSC under Displacement-Controlled Conditions

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. (2016).

6.6 Collection of Data for Fitness-For-Service Assessment

In addition to having the appropriate assessment procedures as outlined in Section 6.5, 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 if an FFS assessment can be performed when the turnaround time is short. 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.

6.6.1 Material Property Data

The mechanical properties of linepipe and girth welds should be collected and properly grouped. MTRs may 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.

6.6.2 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 and the time of weld fabrication. These features can be obtained through systematic documentation when welds are tested.

6.6.3 Girth Weld Anomalies

The type and dimensions of girth weld anomalies are often associated with welding processes and 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's 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.

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).[14] Such information can be collected, sorted, and archived in appropriate groups for conducting FFS assessments.

6.7 Uncertainty and Limitations in FFS Assessment

As described above, the largest limitations of applying FFS assessment include the lack of data and TSC models appropriate for the vintage of pipelines of interest. The level of uncertainty is directly related to the accuracy of the input parameters used for the FFS assessment. There can be a high level of uncertainty if little information is available for the pipes and welds of interest.

Understanding of the linepipe metallurgy and manufacturing process, welding processes, and the interaction of weld flaws and materials is important to apply the TSC models/tools correctly. Consequently, case-specific FFS assessment for critical locations is best performed by SMEs with requisite knowledge and experience.

[14] It should be noted that 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).

7 CLASSIFICATION AND DECISION-MAKING

This section provides guidance for the CDM[15] process for landslide hazard management. CDM is used for three primary purposes:

- To determine whether to perform action(s) throughout the identification and characterization process (discussed in Section 5) and following FFS assessments (Section 6)
- To determine the nature of that action (e.g., whether to conduct additional assessment, implement mitigation, or implement monitoring)
- To determine the timing or order of conducting actions (i.e., the prioritization)

There are two major strategies for this process: 1) case-by-case, and 2) prescriptive or semi-prescriptive.

This guideline recommends a semi-prescriptive CDM approach, which is explained in more detail below. Situations in which case-by-case decision-making might be appropriate are also discussed briefly.

In a true case-by-case strategy, there are no predetermined or preestablished requirements that dictate or recommend whether or not 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 the 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 owner/operator has only a small number of landslides and landslide-prone areas to address.

If a pipeline system has numerous landslides and landslide-prone areas, establishing a prescriptive or semi-prescriptive CDM system generally improves efficiency. For the purposes of this guideline, it is assumed that an owner/operator has multiple, rather than a few, areas potentially subject to landslide hazards. For the purposes of these guidelines, it is considered a leading practice to establish a CDM system.

7.1 Landslide Classification and Decision-Making Overview

At the time of this publication, there is no universally accepted pipeline landslide CDM system, although there have been various attempts (such as the ones provided as examples in ISO 20074, Herr and Atkinson 2020, Joehan et al. 2020, and Wang et al. 2017). The reason for this lack of a universal CDM system likely 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 widely varying regulatory environments, local land uses, and pipeline operator/owner internal structures and cultures.

---

[15] In this context, the classification part of CDM refers to assigning a category to a landslide based on its characteristics and known or possible effects on a pipeline. This category can be explicitly tied to threat (such as a high, medium, or low threat) and/or a probability (such as probability of occurrence or probability of damage), or it can be more general in that it simply provides a category to establish a recommended action(s).

The widely used Hungr et al. (2014) simplified landslide classification system contains 32 separate types of landslides. However, the simplified landslides classification scheme does not consider factors such as land use, climate, pipeline characteristics, product type, potential consequences, and so on. If all possibly influential factors were to be considered such that the system could be used universally by anyone and in any location, potentially thousands of permutations would exist in the CDM system, and the system would be unwieldy.

In the absence of a universal standard, it is up to each pipeline operator to establish its own CDM system. In the practice that is recommended in this guideline, the CDM system is interlinked with most of the other major processes described herein. The CDM system is used to determine if sufficient information has been collected to decide which type of activity to implement and the timing of that implementation. Thus, a CDM system is the tangible reflection of the operator's risk tolerance, resource availability, and company approach toward landslide hazard management.

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
- A means to confirm the presence of landslides and landslide-prone areas based on available information, such as that collected during the identification and characterization, FFS, and monitoring processes
- A means to classify the perceived threat to a pipeline from landslides and possible landslides
- A set of requirements or guidelines for whether to perform additional actions and, if so, the type of action and the timing in which to conduct that action (i.e., the decision-making component of the CDM system), based on the classification

7.2 Classification and Decision-Making Considerations

For the reasons discussed in Section 7.1, each operator will need to establish its own CDM system, although those created by others can be used or modified, as appropriate. 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 SCC). Having a similar approach and terminology, to the degree reasonable, 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 (discussed further in Section 7.3).
- 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 generated during the identification and characterization and FFS processes (Sections 5 and 6); 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.

7.3 Recommended Approach for Classification and Decision-Making

A key consideration in designing and implementing a CDM system is defining the level of quantification and prescriptiveness of the system. In this document, the degree of quantification can be conceived as a sliding scale from wholly qualitative, where classification is entirely dependent on SME judgement, to wholly quantitative, where classification is entirely determined by statistical or mechanical models,[16] with no judgement component (other than that used to create the original models).

Wholly quantitative models can be impractical from a landslide perspective and less reliable than qualitative or semi-quantitative models due to the natural variability associated with landslides. The ability to collect sufficient and accurate information at the scale necessary to execute meaningful models can be impractical over large areas. Due to the large uncertainties and variabilities with many aspects of quantitative modeling, dependence on such a model for use in landslide management is not recommended at this time.

Prescriptiveness can also be conceived of as a sliding scale ranging from wholly non-prescriptive to wholly prescriptive. That is, ranging 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 a company agreed-upon approach. This ultimately increases efficiency and the likelihood of consistency of practice. The primary disadvantage of a wholly prescriptive system is that it either lacks flexibility to accommodate the natural variabilities associated with landslides or, in order to account for all possible permutations, it becomes highly convoluted, overly conservative, and/or difficult to execute.

As discussed previously, the particulars of a CDM system are determined by each operator. However, this guideline recommends a semi-prescriptive, semi-qualitative approach that is referred to as the "95-percent approach" for implementation of a CDM system. The 95-percent approach is a conceptual idea that in most cases (e.g., 95%) the vast majority of landslide/pipeline scenarios for a given operator 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

---

[16] An example of a mechanical model is one in which an annual probability of landslide occurrence is calculated for all slopes in proximity to a pipeline system based on the physical properties of the slopes (e.g., steepness, soil/rock type, groundwater depth) using a limit-equilibrium model or similar.

approach streamlines the process of decision-making 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 rate of movement of the landslide, distance from the pipeline, preexisting strain induced by the landslide, whether the landslide is active or inactive, and pipe characteristics). The characteristics of the landslide and the pipeline determine the response; thus, applicable landslide/pipeline characteristics should be included in the system.
- Hazard 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 rather than a POF, the process of decision-making is simplified and made more consistent.
- The buckets should be developed with a focus on those landslides and landslide/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 information is acquired that necessitates additional categories.

7.4 Implementation of Classification and Decision-Making

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

1. Characterization and FFS assessment of newly identified landslide hazards or possible landslide hazards. Here, the CDM system serves to
    - establish the level of information needed to make a decision, and
    - once enough information has been collected, make and implement that decision.
2. Ongoing monitoring of previously identified landslide hazards. Here, the CDM system serves to
    - determine if additional action is needed based on monitoring results, and
    - if additional action is needed, to establish the type of action(s) to take.

7.4.1 Classification and Decision-Making for Newly Identified Landslides or Possible Landslides

Under the phased approach to landslide identification and characterization (Section 5), a CDM system serves to determine how far to take the assessment before a decision is made. Once enough information has been collected, the CDM system serves to help make and implement a decision.

Because there are no regulatory requirements or universally accepted standards governing the level to which possible landslides should be evaluated, it is up to each operator to determine the requirements for assessment, which are reflected in their CDM system. The CDM system addresses three key points at each phase of the phased assessment process: 1) verification of the landslide; 2) clarification of the threat to the pipeline system; and 3) has sufficient information been collected to determine a response or does additional assessment need to be performed?

This process is shown in Figure 7-1.

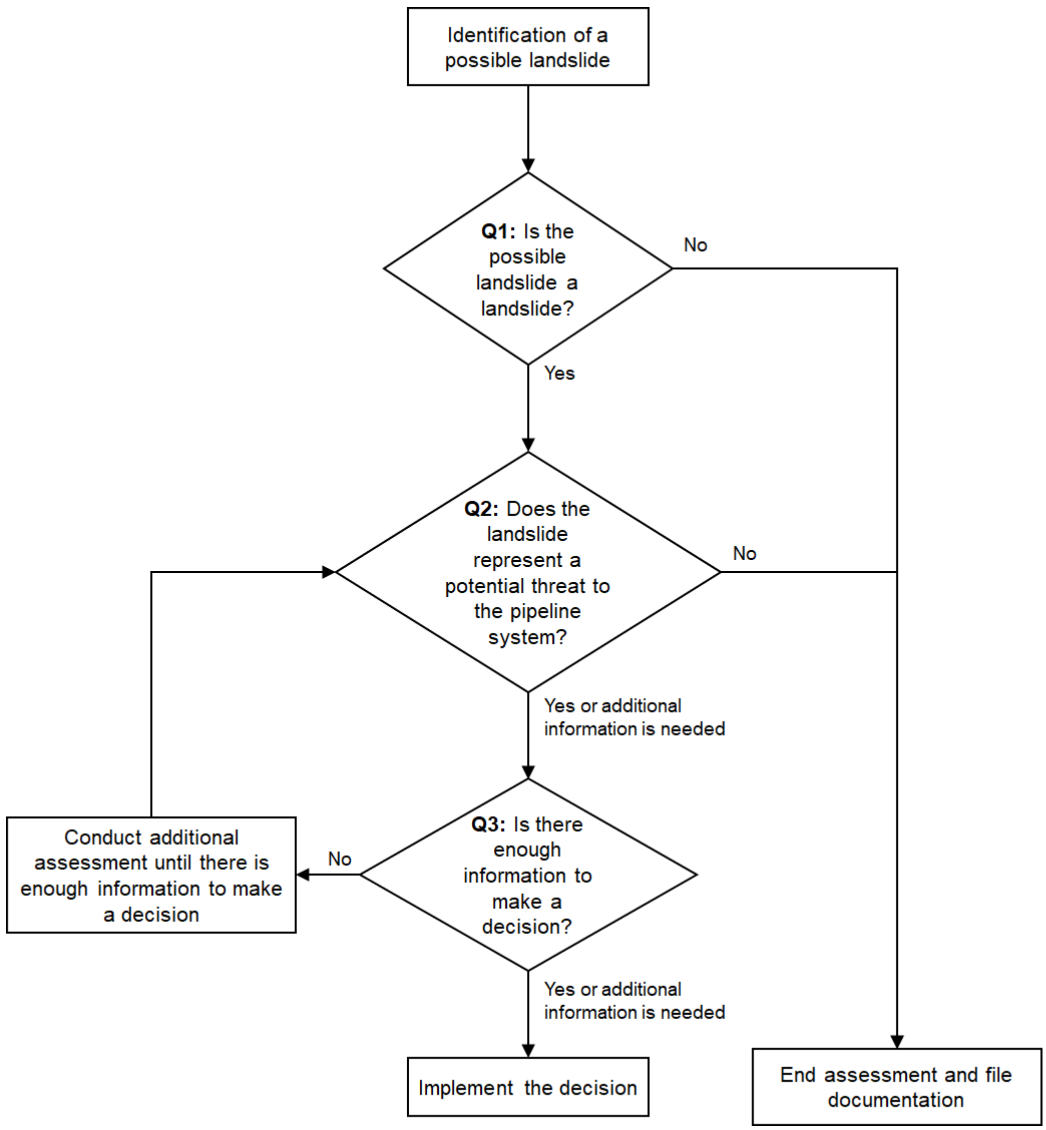

Figure 7-1. CDM flowchart for newly identified possible landslides

Once enough information is collected to determine a response, there are three broad categories of options that can be implemented: 1) risk acceptance, 2) monitoring, and 3) mitigation. Risk acceptance is an informed decision that landslide risk is low enough that no action is anticipated to be needed before the next periodic reassessment (i.e., proceed with neither mitigation nor monitoring at the time of the assessment because the potential risk is understood to be sufficiently low). Monitoring and mitigation are risk reduction strategies that reduce the likelihood of negative event occurrence and/or the consequence from such an event. Monitoring is usually a preferred risk reduction approach when the results of monitoring allow for sufficient time to reduce risk to an acceptable level in the event of landslide movement or occurrence, such as through situational mitigation or consequence reduction triggered by monitoring results. Preemptive mitigation is usually a preferred risk reduction approach when a monitoring based approach does not allow for sufficient time to implement measures to reduce risk to an acceptable level in the event of landslide movement or occurrence.[17]

Once enough information has been collected to determine a response, the decision-making process is essentially as follows (Figure 7-2):

- Step #1: Is the risk level from the landslide or landslide hazard area sufficiently high to warrant further action? If no, then implement risk acceptance. If yes, then proceed to Step #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.
- Step #3: Manage the landslide through preemptive mitigation.

Once a determination has been made to manage a landslide through monitoring or mitigation, then the CDM system either 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 semi-prescriptive elements for selecting monitoring approaches, while mitigation decisions be made on a case-by-case basis. Considerations for selecting monitoring and mitigation are addressed further in Sections 8 and 9. An example CDM system for a pipeline system in the Appalachian region of the United States is presented in Appendix B.

[17] Note that terms like “sufficient” and “acceptable” have deliberately been left undefined. 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 two years.

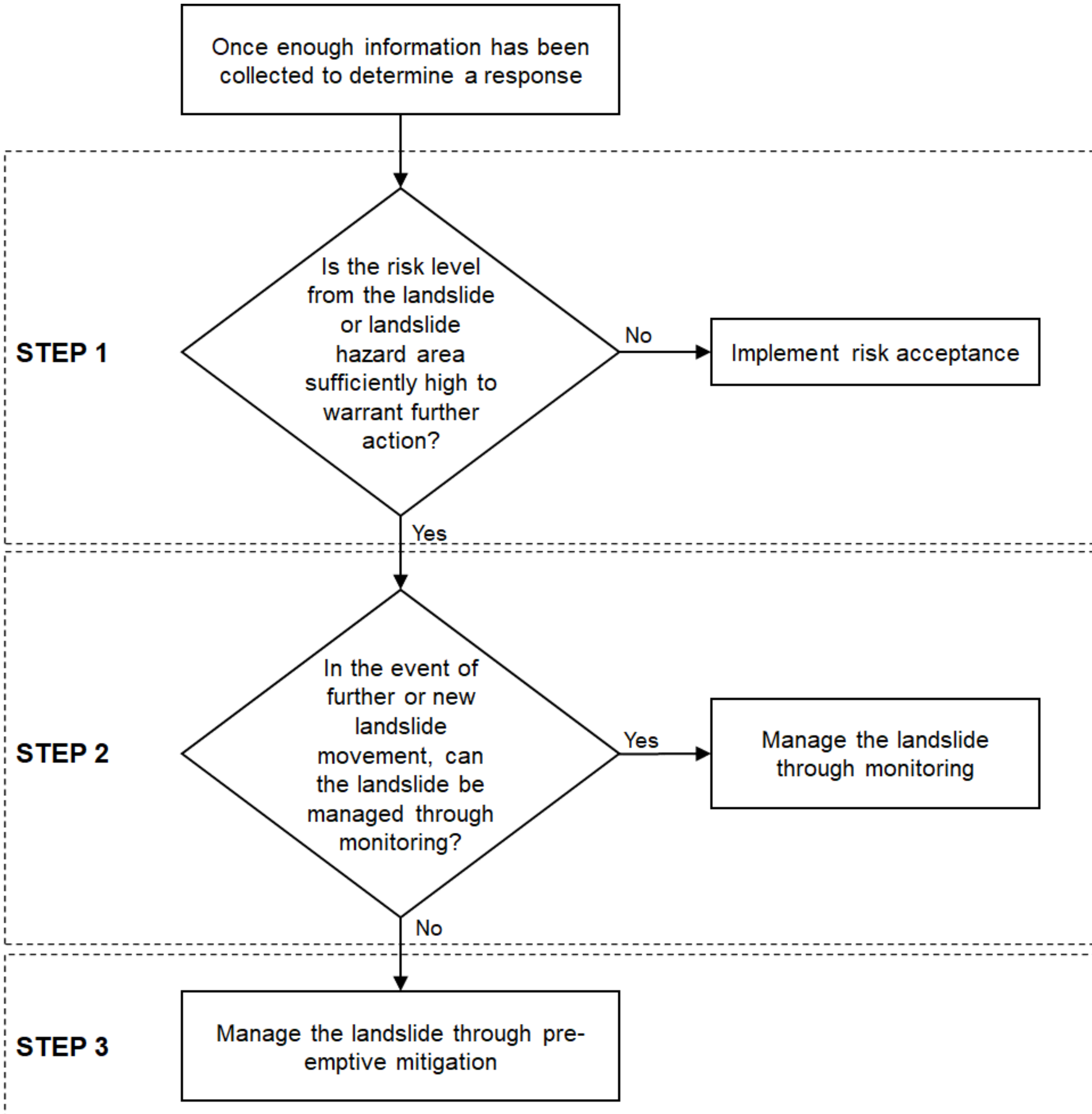

Figure 7-2. Decision-making process for implementing a landslide management response

7.4.2 Decision-Making for Ongoing Monitoring

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

- Evaluating (or reevaluating) a possible or known landslide site by an SME (such as through the Phase I or Phase II process discussed in Section 5)
- Conducting an FFS assessment (Section 6)
- Collecting or reviewing other monitoring data for comparison (if available)
- Increasing the frequency of monitoring

- Installing or implementing additional types of monitoring
- Implementing risk mitigation 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. As discussed further in Section 9, whenever possible, multiple monitoring methods should be cross-compared to formulate stronger and more accurate decision-making.

The general decision-making process for response to monitoring data is as follows (Figure 7-3):

- 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 risk-reduction measures and possibly mitigation. If no, proceed to Step #2. If uncertain, proceed to Step #4.
- Step #2: Do the results of the monitoring data indicate a higher level of threat than previous? If yes or uncertain, proceed to Step #3. If no, continue with monitoring as before.
- 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.
- Step #4: Conduct an additional evaluation and return to Step #1.

An example CDM approach for ongoing monitoring is provided in Appendix B.

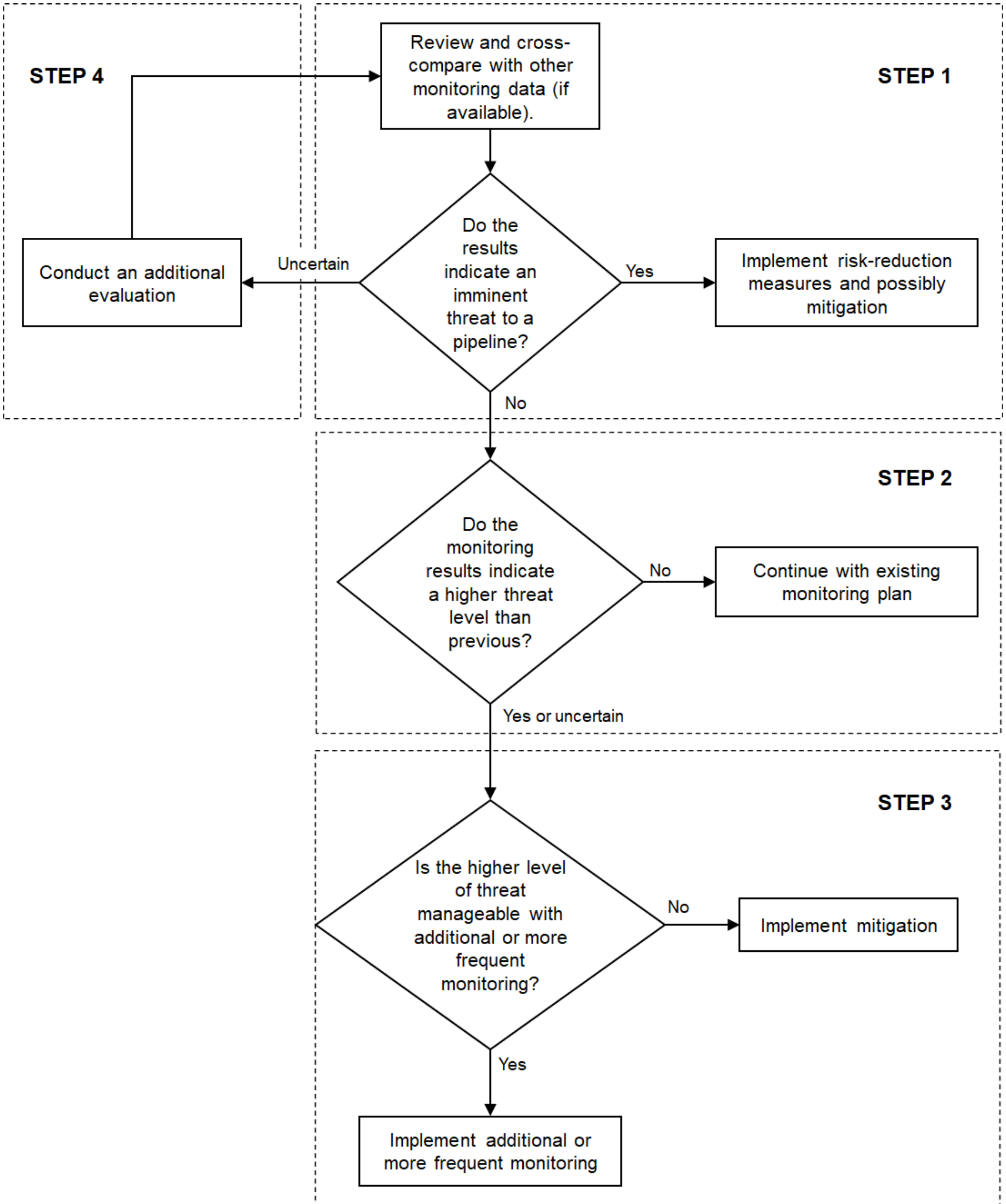

Figure 7-3 CDM flowchart for ongoing monitoring

7.5 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 landslides. 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 LOC event or other impact from a landslide
- Resource availability

The inputs to a CDM system can be used to prioritize action. For instance, in the example CDM system in Appendix B, the combination of landslide characteristics and strain demand vs. strain capacity are used to decide on an action; these can be also be used to assign a priority of response, where certain actions would be prioritized over other actions. By adding consequence as a third-axis to the decision-making matrix, sites with a certain set of characteristics in higher consequence areas could be prioritized over similar sites in lower consequence areas.

8 MITIGATION OF LANDSLIDE HAZARDS

Mitigation is a means to manage landslide risk through implementation of physical means to reduce likelihood of impact, including 1) avoid landslide hazards, 2) reduce the vulnerability of a receptor to the adverse effects of landslide movement (in this case, a pipeline), or 3) eliminate, stabilize, or reduce the likelihood of landslide occurrence. There are two main strategies for landslide risk control: proactive mitigation and monitoring. Proactive mitigation is often combined with monitoring. The discussion herein assumes that the operator has already proactively collected and analyzed data as described in Sections 5 and 6 and then applied a systematic process of Classification and Decision-Making (CDM) as described in Section 7.

This section is largely centered around mitigation for existing pipelines, not new construction, although many aspects of this discussion apply to new construction as well. The focus on existing pipelines vs. new construction is an important distinction because the feasibility and cost of some of these measures differ greatly between planned construction and existing pipelines; for example, avoiding a landslide hazard via rerouting is generally a relatively small cost before a pipeline has been built, but it can be a major expense for an existing pipeline.

This section presents a relatively brief overview of mitigation measures for landslides that may affect pipelines. Extensive reporting on potential geotechnical mitigation measures can be found in the 2009 PRCI guidelines on construction in areas prone to landslide and subsidence, the JIP of Wang et al. (2017), and the 2016 INGAA Foundation document on construction of pipelines in West Virginia (see Table 3-1 for summaries of these documents).

8.1 Consideration for Mitigation Selection

The decision on the type, location, and scale of mitigation 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- and long-term variability over the anticipated lifetime of the pipeline system
- Landslide characteristics (e.g., type, movement rate, footprint, landslide-pipeline interaction)
- Site objectives and goals (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
- Pipeline operating conditions (current and future)
- Pipeline characteristics (strain capacity)
- Pipeline strain conditions (strain demand)
- Budgetary constraints

Mitigation of landslide hazards through implementing targeted measures can be accomplished during or after the pipeline is constructed. It is likely that a combination of mitigation methods will be used to address any given site or groups of sites.

When selecting measures to mitigate landslides, the pipeline operator should consider the following:

- The landslide hazard should be sufficiently understood and characterized to make an appropriate mitigation selection (i.e., a geologic/landslide model should be created). Factors such as limits of the landslide, likely movement rate, depth of the landslide relative to the pipe, pipeline strain conditions, and pipeline characteristics should be understood.
- Constraints imposed by the geologic, topographic, and land use conditions at the landslide location should be incorporated into the selection of appropriate mitigation measures.
- Prior mitigation measures, such as during an emergency response or during a prior mitigation attempt, and the nature and success of the prior measures should be understood prior to selecting a mitigation option.
- The design and implementation of mitigation should protect the public, employees, contractors, the environment, adjacent infrastructure and property, and the pipeline company's assets both during and after implementation.
- The selected measure(s) should not worsen the landslide(s), their impact on pipeline(s), or areas outside of the ROW.
- The operator should determine whether permanent mitigation measures (i.e., those that require little or no long-term maintenance cost, but which might have higher up-front costs) are needed or whether temporary mitigation measures with ongoing monitoring and planned response are more appropriate. Permanent mitigation measures could have lower overall costs but have higher up-front costs, more significant planning, and time delays before implementation. Temporary mitigation measures, such as stress-relief excavations may be executed faster but may need to be repeated multiple times over the life of the pipeline or associated facility.
- For mitigation measures that do not completely eliminate or avoid landslide hazards, post-implementation monitoring should be conducted to confirm the efficacy of the mitigation and to identify if additional mitigation response is needed.

Commonly used approaches and measures that could be implemented to reduce landslide hazards can be generally organized into the following mitigation approaches described in Sections 8.2 through 8.4:

- Avoidance of the landslide hazard(s) through lateral or vertical rerouting
- Pipeline-focused mitigation measures to reduce the strain demand imposed on a pipeline by a landslide and/or to enhance the strain capacity of the pipeline
- Landslide-focused mitigation measures intended to eliminate, stabilize, slow, or reduce the likelihood of occurrence of a landslide

8.2 Avoidance Mitigation Measures

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

- Rerouting to avoid the hazard
- Relocating the pipe below the failure plane of the landslide (e.g., via deep burial or HDD)
- Relocating the pipe above ground (e.g., directly on the ground surface or on ground supports, or via a bridge/span)

Avoidance can result in complete elimination of the risk (such as routing from a landslide-prone area to a non-landslide-prone area); avoidance can also be used as a risk reduction measure (such as routing from a high-risk area to a lower-risk 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 phased 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 or below a landslide, it is critical that the current extent (i.e., aerial footprint and depth) of the targeted landslide is known and that the landslide has been characterized to the extent that future activity and possible expansion of the hazard can be understood and predicted.
- Deep burial through conventional trenching can carry considerable risk during construction because the deep trench might destabilize or worsen the landslide. In addition, deep burial limits future access to the pipe. This option should be done under the oversight and design of a geotechnical SME.

8.3 Pipeline- and Trench-Focused Mitigation Measures

Pipeline- and trench-focused mitigation measures reduce the potential strain demand transferred to the pipe by a landslide, increase the strain capacity of the pipe, or relieve stress already transferred to a pipeline by a landslide. Pipeline- and trench-focused mitigation measures are not generally targeted at affecting the landslide hazard[18] itself, but, in some circumstances, they can provide protection for the pipeline and assist in landslide stabilization. Additionally, pipeline- and trench-focused mitigation measures can be combined with landslide-focused mitigation measures. In the context of this section, pipeline- and trench-focused mitigation measures do not cover the avoidance, stabilization, or reduction of the likelihood of a landslide. Thus, pipeline- and trench-focused mitigation measures, especially if used alone, should be monitored to identify if additional mitigation is needed (discussed in Section 9).

8.3.1 Strain Demand Reduction

Strain demand reduction measures are mitigation measures that reduce the strain demand transferred to a pipeline from landslide movement. These measures include the following and have been modified from Wang et al. (2017):

- Modifying a pipeline alignment across the landslide area to reduce the strain demand induced by ground movement. In other words, orienting the pipe 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 and reducing bends within the landslide, or changing the orientation of the pipeline from perpendicular to the landslide movement to axial.
- Improving the geometry of the pipeline trench. A wider, lower angle trench configuration can reduce the strain demand induced by horizontal ground movement.
- Using shallower burial such that normal loads on the pipe from backfill constraints are reduced.
- Installing select backfill in the pipe trench (Figure 8-1). Select backfill refers to loosely placed, cohesionless sand or rounded gravel with a low fines content (<5% silt or clay). This type of backfill is commonly used when a landslide occurs in fine-grained soil or in rock. Select backfill can reduce the load transferred to a pipeline and can also improve subsurface trench drainage. In most cases, select backfill is separated from the native soils by a geotextile fabric. Installation of select backfill is commonly combined with a stress-relief excavation.
- Using low-friction pipe coating and geotextile wrap. This method reduces load transferred to a pipeline by wrapping the pipe in layers of geotextile or using low-friction coating. This method is discussed in C-Core et al. (2009) and Wang et al. (2017).

[18] Installation of select backfill can result in improved drainage characteristics resulting in reduced landslide likelihood or rate of movement and reduces the load transferred to a pipeline by a landslide.

Figure 8-1. Select backfill (clean sand) being placed on and around a pipeline in a landslide in western Washington. The vertical piping was for inspection and cleanout (D. West, 2002 photo).

8.3.2 Increase Strain Capacity

Measures to increase strain capacity are preemptive mitigation measures that increase the amount of strain that a pipeline can withstand before resulting in LOC. Since most landslide-induced ruptures occur as the result of tension at a girth weld[19] (rather than within the pipe body), these measures are generally oriented at increasing the TSC of girth welds. The following are measures to increase strain capacity:

- Replacing affected pipe segments with a purposely designed strain-resistant pipe segment using strain-based design principles (Wang et al. 2016b, Wang 2020).
- Applying Robust Allowable Stress Design (RASD) concepts. RASD differs from strain-based design in that pipe materials and welds are not prequalified and tested to meet strain performance, but they are selected to provide more robust performance than would be the case under conventional design (an example application is provided in Albrecht et al., 2020). RASD concepts include using lower grade and thicker walled pipe and higher strength welding consumables than would usually be used in areas not potentially subject to geohazards.

[19] In some cases, LOC also occurs as the result of compression-induced buckling, but this is much less common.

- Enhancing the strain capacity of girth welds using measures such as Type B sleeves, compression sleeves or composite wraps. These measures are also discussed in Section 10.5.3.

8.3.3 Stress-Relief Excavation

Stress-relief excavations[20] are probably the most commonly employed mitigation measure for pipelines affected by landslides. A stress-relief excavation by itself is usually considered a temporary mitigation measure because, while it can relieve accumulated elastic stress on a pipeline from a landslide, it does not avoid or stabilize a landslide and does not increase the resistance of the pipeline to future landslide movement. If a pipe is plastically deformed, residual strain will remain after excavation.

Where landslide movement that leads to the need for a stress-relief excavation occurs, unless measures are taken to slow or stop landslide movement, ground movement could continue and result in the need to conduct additional stress-relief excavations. However, for slow-moving landslides where strain accumulation in the pipe occurs over years or decades, stress-relief excavations can be an appropriate option as a primary mitigation measure.

Stress-relief excavations can often be combined with other mitigation measures to increase the time between excavations or to eliminate the need for repeat excavations. Commonly performed combinations with stress-relief excavations include placing select backfill in the pipeline trench following the excavation; improving drainage to the pipe trench; improving drainage to the landslide and contributing area to reduce landslide movement; and replacing the affected section of pipe with pipe of higher strain capacity. If other mitigation measures have been implemented on the slope or around the pipe in the past, considerations around how to minimize disturbance to existing measures should be made prior to starting the stress-relief excavation.

Stress-relief excavations are not an ideal mitigation option for all landslides. Typically, stress-relief excavations are appropriate for slow-moving landslides where stress-accumulation occurs over years or decades. Stress-relief excavations are not usually appropriate for landslides where pipe failure could occur in a single event, unless the stress-relief excavation is combined with measures to stabilize the landslide. Stress-relief excavations may also be impractical to implement where the pipe is deeply buried or where it is located on a very steep slope; both scenarios could lead to further slope destabilization during excavation or could pose unsafe working conditions.

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

- The strain state of the pipeline should be considered prior to performing the excavation. In particular, the potential for transferring or focusing strain (and thus to possibly cause conditions such as buckling) should be considered and accounted for during planning.
- When planning the excavation, the limits of the excavation should include the stressed area plus some additional area on both sides to allow for the pipe to fully rebound. If the stressed area is unknown or poorly constrained, the limits of excavation should typically be the area

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

of the pipe crossed by the landslide, including appropriate additional area 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 pipe will be exposed for long periods of time before reburial (months to years), the potential for coating deterioration should be considered and appropriately managed.
- If the pipe has accumulated stress, pipe rebound should occur. Project planning for the stress-relief excavation should include a mechanism 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 (Figure 8-2) in order to facilitate measuring pipe rebound. In this approach, the excavation encompasses the stressed area plus some distance (such as 40 feet) beyond the point at which minimal pipe 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 temporary or permanent strain gauges as a means to confirm that the excavation has relieved accumulated stress (Figure 8-3).
- The optimal starting point for the excavation depends on how the pipe 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 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. Particular care and caution should 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 may be necessary to install temporary shoring.
- The pipeline should generally be depressurized during stress-relief excavations. If it is necessary to maintain pressure in the pipeline, applicable regulations (such as CFR 195.424) and operator-specific health and safety requirements should be followed prior to and during the excavation.

Figure 8-2. Stress-relief excavation of a natural gas pipeline showing pipe rebound and survey lathes placed to provide a visual reference to measure this rebound

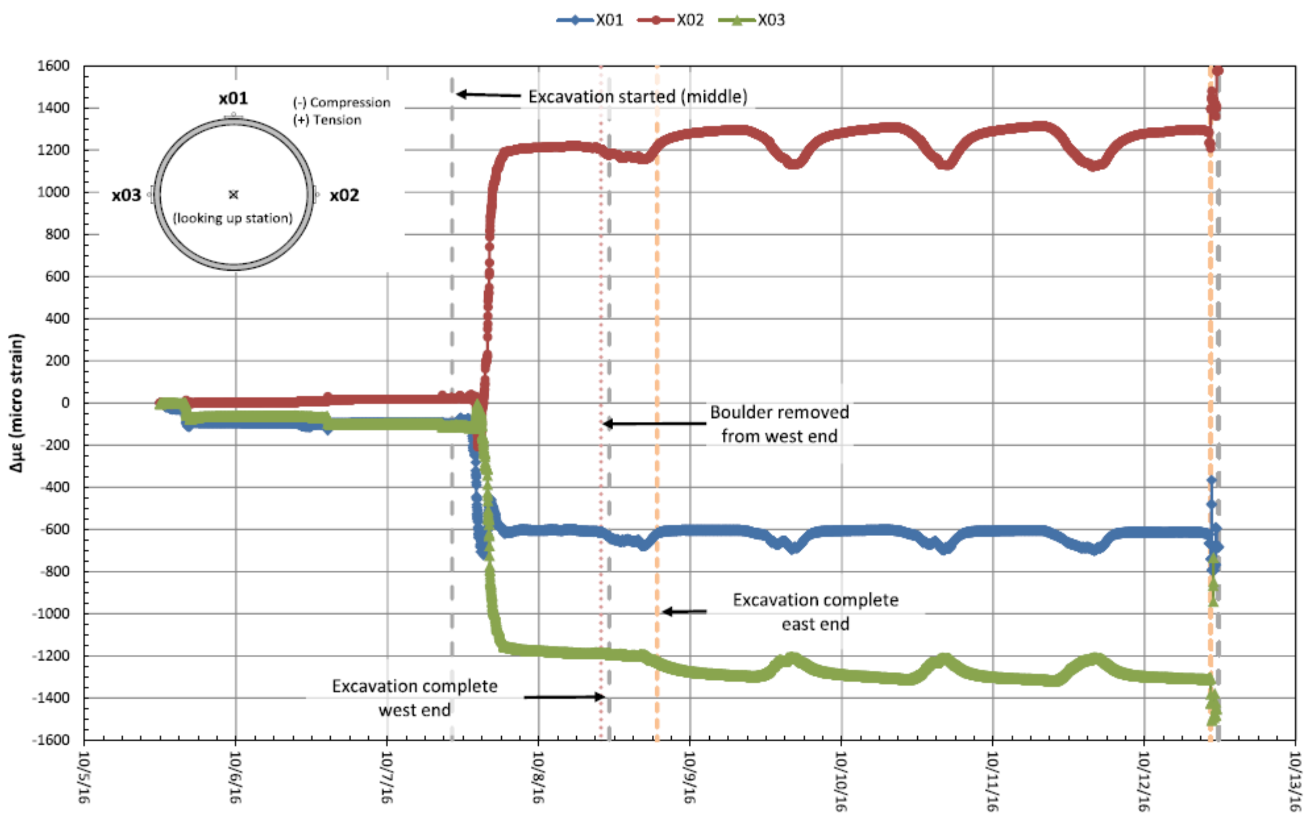

Figure 8-3. Example of using strain gauges to confirm that a stress-relief excavation has exposed enough pipe to relieve accumulated stress. In this example, strain gauges were installed before the beginning of the stress-relief excavation to provide a baseline. As shown, measured strain changed shortly after the beginning of the excavation, followed by the rate of strain change approaching zero once the section of pipe stressed by the landslide had been excavated. Based in part on these results, the excavation was then terminated. The oscillating patterns after the excavation was completed are caused by daily temperature changes on the exposed pipe.

8.4 Landslide-Focused Mitigation Measures

Landslide-focused 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 eliminate the landslide through earthworks
- 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 to slow movement to a manageable level by removing or reducing triggering mechanisms, such as by lowering the groundwater table and controlling surface water and toe erosion.

These measures, if performed successfully, either eliminate a landslide as a hazard or reduce the risk associated with a landslide to an acceptable level. These measures are also commonly referred to as “geotechnical mitigation” measures.

8.4.1 Selection of Landslide Mitigation Approach

Selecting an appropriate geotechnical mitigation approach 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, such as soil/rock types, movement rates, size, depth, and relationship to the area being protected. These characteristics should be well understood before implementing geotechnical mitigation. Incomplete characterization can render installed measures less effective than planned or not effective at all. Additionally, installing geotechnical mitigation measures with inadequate characterization can worsen site conditions, resulting in an increase in the overall landslide threat.
- The feasibility of successfully implementing geotechnical mitigation given the landslide characteristics. For instance, based on the landslide's size or type, it might be financially infeasible to stabilize the landslide or to reduce the likelihood of reoccurrence; in these circumstances, an alternative approach to mitigation, such as avoidance or pipe 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 geotechnical mitigation 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 location and geography where the mitigation is 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.

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

Operators may wish to identify certain preferred methods and create 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 built in to adapt to actual site conditions.

8.4.2 Landslide Elimination

Eliminating a landslide as a hazard is usually performed by either regrading a slope to a flatter angle or removing the unstable soil and replacing it with more stable soil. If performed correctly, the elimination of a landslide requires limited post-construction monitoring or maintenance (Wang et al. 2017, C-Core et al. 2009). This method generally 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 a new landslide could initiate during construction
- The financial cost associated with removing unstable soil and/or importing stable fill
- Any potential environmental restrictions

8.4.3 Landslide Stabilization

Stabilizing a landslide or isolating the ROW from a landslide can be achieved through mechanically reinforcing a slope, regrading the slope, constructing toe buttresses or berms, or by combining two or more of these measures. Figure 8-4 shows soil nails as an example of mechanical stabilization of a landslide combined with regrading. Other measures, such as controlling surface and groundwater flow or toe erosion, can also be considered to enhance the effectiveness of the landslide stabilization measures.

The following parameters should be considered when designing landslide stabilization measures:

- The landslide(s) or landslide-prone area should be well-characterized prior to selecting the mitigation approach and measures. Factors such as soil and rock type, groundwater conditions, depth, limits, movement rate, and other controlling factors should be well understood. To some degree, understanding these factors is important for all mitigation measures, but it is particularly true when attempting to stabilize all or part of a landslide. Additional investigation and evaluation may be needed before proceeding with design. Also, geotechnical information can be presented in contract documents and as the basis for contractor bids. Well-documented, comprehensive investigations reduce the potential for encountering unexpected site conditions and, thus, reduce the potential for unforeseen costs.
- 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, installing drainage if mitigation measures change or impede surface or groundwater flow).
- 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 may 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 may 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.
- 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- versus long-term solutions. The design lifetime affects the selection of materials and methods to account for threat factors that can persist and/or evolve through time.

Figure 8-4. Installation of soil nails combined with site regrading to stabilize a landslide downslope of a pipeline ROW

8.4.4 Reduction of Landslide Rate or Likelihood of Movement

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 or avoiding its rise. Elevated groundwater and saturation of soil that is usually unsaturated is generally considered to be one of the most common causes of landslide formation and movement. By lowering the piezometric surface, the effective stress acting on a potential slip surface increases, and, thus, the overall resistance of the soil mass to movement increases. Increasing the shear strength of the soil at the slip surface(s) will reduce the potential for landslide movement and/or reduce the rate of movement. Examples of methods to lower the piezometric surface or mitigate against its rise include sub-horizontal drains as well as drainage tunnels, wells, and trenches (e.g., French drains) (Holtz and Schuster 1996).

- 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 relatively 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 ultimately discharge diverted water so as to not 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 hydrogeologic, hydrologic, and climatic conditions (Holtz and Schuster 1996). 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, sub-horizontal drains might work well for soil that is predominantly composed of sand but might not work well for fine-grained soil dominated by clay and silt size particles (Pohll et al. 2013).

The measures described in this section typically result in less ground disturbance and are usually more cost-effective options than the mitigation options described in Sections 8.4.2 and 8.4.3. Nevertheless, there are considerable natural heterogeneities in surface and groundwater regimes that might not be fully addressed by these mitigation approaches; therefore, options such as lowering groundwater, controlling surface water, protecting toe areas from erosion, and similar might not result in completely stabilizing or eliminating the landslide hazard. These measures can be combined with additional mitigation measures to further reduce the potential for landslide movement.

8.4.5 Combined Geotechnical Mitigation Measures

The discussions in Sections 8.4.2, 8.4.3, and 8.4.4 have categorized various geotechnical mitigation approaches. It is quite common to combine multiple mitigation approaches, based on site-specific circumstances. For instance, a landslide mitigation project may involve regrading (Section 8.4.2), installing soil nails (Section 8.4.3), lowering the groundwater table through drainage wells, and armoring the landslide toe where it is crossed by a stream (Section 8.4.4). When multiple mitigation approaches are combined, each is chosen for a specific purpose; their mutual impacts and interrelationships with each other should be considered carefully in the planning and selection process.

8.4.6 Implementation of Geotechnical Mitigation Measures

Pipeline contractors might have the ability to implement some mitigation measures, but they might not have the capabilities to implement more difficult designs. Pipeline contractors typically provide services related to regrading, removing, and replacing soil as well as controlling surface water and toe erosion. Depending on the method(s) selected, the implementation may need to be performed by specialty geotechnical contractors with appropriate equipment, experience, on-site engineering inspections, and quality assurance.

8.5 Post-Mitigation Monitoring

In most cases, monitoring should be conducted after implementing mitigation measures. Monitoring is intended to confirm the efficacy of the mitigation and to 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 is situation dependent. Operators should implement an appropriate post-mitigation monitoring plan using the considerations and approaches discussed in Section 9.

9 MONITORING LANDSLIDE HAZARDS

Monitoring landslide hazards can be conducted by monitoring the landslide and the adjacent area, the pipeline, 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. Monitoring only the landslide may not provide insight into the type, location, and magnitude of strain induced by a landslide on the pipe, while monitoring only the pipe may overlook expanding or developing landslide movement that may adversely affect the pipe in the future. An integrated approach to monitoring both the landslide and the pipeline provides context for the monitoring results and provides for stronger, more reliable decision-making.

Landslide monitoring is used for four main purposes (from McKenzie-Johnson and West 2020):

1. To further characterize the landslide(s) and its relationship and threat to the pipeline
2. To act as a warning system to allow for preemptive intervention prior to exceedance of a pipeline's strain capacity or predetermined strain demand limit (SDL)
3. To confirm that previously completed mitigation or remediation measures are functioning as intended
4. To identify landslide movement caused by an extreme event, such as an earthquake or storm event

The following sections (Sections 9.1 through 9.4) discuss considerations for monitoring selection and the three main types of monitoring strategies that can be used to monitor landslide/pipeline interactions: regional-scale monitoring, landslide-focused monitoring, and pipeline-focused monitoring.

9.1 Considerations for Monitoring Method Selection

Selected monitoring methods should provide the types of data needed at the intervals needed in order to meet the objectives of the monitoring program. Major objectives of monitoring typically include some or all of the following:

- Detection or identification of new landslide hazards
- Further characterization of known landslides, including rates and timing of movement and depth(s) of slip surfaces
- Measurement or assessment of the effect(s) of a landslide on a pipeline
- Notification of landslide movement or impact to a pipeline
- Measurement of other information that may be useful for designing mitigation measures or characterizing landslide behavior, such as pore water pressure or precipitation
- Confirmation that the mitigation or remediation measures implemented at a landslide are performing as intended and expected

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:

- The monitoring objective(s) (as described above) should be defined prior to establishing a monitoring approach. By defining the objective(s) of monitoring, an appropriate monitoring approach can be implemented.
- 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 CDM system as discussed in Section 7. This will allow for consistent selection of monitoring types and appropriate prioritization of monitoring at 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 may occur, regional monitoring techniques (Section 9.2) are needed. If the intention is to monitor certain, discrete locations that have been previously identified, then specific landslide and/or pipe monitoring techniques are needed (Sections 9.3 and Section 9.4). In many cases, a single site may be monitored through multiple approaches.
- 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/depth (if known) and characteristics such as movement type (continuous versus episodic) and rate should be considered when developing a monitoring approach and design.
- The desired resolution of the monitoring data should be accounted for when selecting instrumentation, both in terms of the lower and upper limits that likely need to be detected as well as the frequency with which data will be collected. All instrumentation will have lower limits,[21] and some will have upper limits[22] as well; these limits should be understood and compared to the monitoring objectives and resolution needed when selecting instruments.
- 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 prior to the end of the intended monitoring duration; it may be prudent to use more robust equipment or to implement protective measures (e.g., placing bollards or fencing around instruments) in locations where installation is difficult or expensive to reduce costs associated with replacement.
- Site access constraints and topographical conditions will affect the types of instrumentation 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.

[21] Smallest unit that can be reliably measured.
[22] Largest unit that can be measured, past which point, the instrument is no longer effective or reliable.

For a remote site, the cost of manual monitoring, surveying, and maintenance can become significant. In this case, a monitoring system with capability of collecting data using a self-powered, automated data acquisition system (i.e., a remote monitoring unit) could be a feasible solution.

- The desired frequency of data interpretation and reporting should inform which 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 is not the same as the frequency of data reporting; both aspects should be considered when designing and implementing a monitoring system.

9.2 Regional Monitoring

Regional monitoring is monitoring of (usually) large areas of ground where no instruments are installed within or on the landslide or pipeline to conduct the monitoring. 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 future 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 information about the depth of the slip surface or direct measurement of impacts to pipelines (although they can be used to infer pipeline-related impacts). Frequency of data collection ranges from weeks (such as from aerial reconnaissance and InSAR) to months or years (such as from LiDAR and aerial photography collection). Regional monitoring methods are often combined with landslide- and pipeline-focused monitoring methods to provide context for the results of these other monitoring methods.

Types of regional monitoring include the following:

- **Aerial Patrol/Reconnaissance**: This includes regularly scheduled patrol of the ROW for pipeline operations (using trained observers) and regularly scheduled (e.g., annual) SME aerial reconnaissance. This also includes event-driven, operator aerial patrol and SME aerial reconnaissance following significant storm or intense rainfall events or seasons or following a significant earthquake. Although operator aerial patrol is often completed with a fixed-wing aircraft, a helicopter platform is preferred, particularly for SME reconnaissance, because its lower speed and ability to fly closer to the ground allow for more reliable detection of landslide features.
- **Ground Patrol/Reconnaissance**: Ground patrol includes regular examination of the ROW in landslide areas of concern by trained pipeline operator personnel and SMEs. Ground patrol is also conducted following significant meteorological or seismic events. Ground patrol is often combined with the other monitoring techniques described in this section to provide confirmation and site-specific information. 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., LiDAR or InSAR). Common remote sensing methods that have been used for regional monitoring of pipeline systems are described below.
  - LiDAR Change Detection Analysis
    - Repeated acquisition of LiDAR data over time and encompassing the same area can be used to identify new landslides as well as to monitor movement/expansion of known landslides. LiDAR Change Detection Analysis is a grid-to-grid comparison of successive LiDAR datasets that shows the apparent changes in elevation between the two datasets (Figure 9-1). A reasonable interval for repeated LiDAR data to be collected and analyzed will be based on density, type, and activity level of landslide hazards and should be reevaluated over time based on observed conditions. Specifications for LiDAR data collection are discussed in Section 5.1.2.

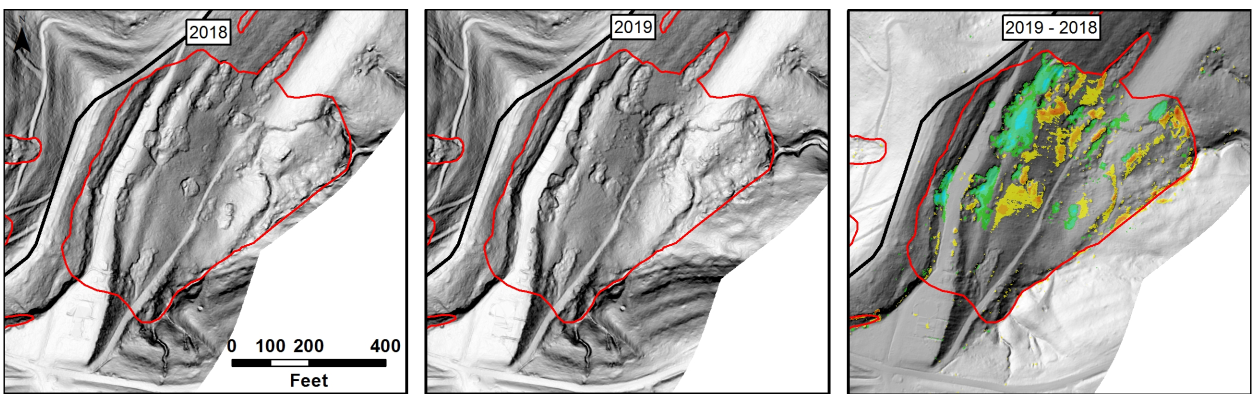

Figure 9-1. Example of LiDAR change detection analysis. Images show landslide with ground disturbance visible in 2018 LiDAR (left image), 2019 LiDAR (center image), and elevation change between 2019 and 2018, where green-blue spectrum represents decreases in ground elevations over this period and yellow-red spectrum represents increases in ground elevations over this period (right image).

  - Aerial Imagery
    - Repeated acquisition of aerial imagery (or use of public datasets) over time and encompassing the same area can be used to identify new landslides as well as to monitor movement and expansion of known landslides. In thickly vegetated areas, aerial imagery can have limited value as the sole monitoring technique, depending on the ground conditions when they are collected. Some landslide features could be too subtle to be recognized in aerial imagery alone. Aerial imagery can complement other monitoring techniques and provide additional context. Specifications for aerial imagery data collection are discussed in Section 5.1.2.
  - InSAR Monitoring

- Regional ground monitoring using satellite-based InSAR can be used to map and monitor centimeter- to millimeter-scale deformational changes (e.g., landslide movement) in the ground surface over large areas, without the need to physically access a site. While historical InSAR data can be used to identify areas of past landslide movement, ongoing InSAR data collection allows for monitoring of known landslides or potentially unstable slopes. Repeated data collection of the same location typically occurs at intervals ranging from 4 to 46 days, depending on the InSAR satellite platform being used (Moretto et al. 2017, Tre Altimira 2020).
- InSAR also has important limitations to consider as detailed in several references (Wang et al. 2017, Del Soldato et al. 2019, Moretto et al. 2017, McCormack et al. 2011, Hoser 2018) (as of the date of this document):
  - Depending on the InSAR type used, the cell size of InSAR data may be measured in meters to tens of meters. Because of these large cell sizes, it may be difficult for InSAR to resolve movement of relatively small landslides or small areas of larger landslides.
  - Most InSAR satellites cannot effectively monitor movement in areas with seasonal vegetation changes without installing reflective targets. The Japanese Space Agency's (JSA) Advanced Land Observing Satellite 2 (ALOS 2) uses L-band InSAR that can work in vegetated areas but has very limited commercial availability. Future satellite launches may overcome this limitation.
  - Relatively rapid movements of landslides with discrete boundaries between stable and unstable soil (such as translational landslides) can cause InSAR data to lose coherence and be unresolvable; thus, InSAR might have limited utility for landslides where the movement is expected to be rapid and varies substantially over short spatial intervals.
  - InSAR satellites have a polar-orbit (roughly north-south) and can have difficulty resolving ground movement in the same direction as the orbital direction. In other words, landslide movement in north-south directions might be difficult to monitor via InSAR.

Each regional monitoring method has advantages and disadvantages that should be accounted for during planning. To maximize advantages and minimize disadvantages of each, it is recommended that, to the extent feasible, multiple monitoring methods be used. For instance, a regional monitoring program that uses a mix of LiDAR, aerial patrol, and targeted ground patrol will generally provide better, more actionable information than a program that relies on just one of these methods. In this example, LiDAR provides a high-resolution, high-accuracy method for identifying new landslides and quantifying subtle movement, but there is a time lag associated with collecting, processing, and reviewing the data. Aerial patrol provides information on current ground conditions quickly but might miss more subtle areas of movement. Ground patrol provides site-specific information at sites identified through LiDAR data review and by aerial patrol to further characterize the threat to the pipeline but is time consuming to perform for multiple sites and might not be suitable for monitoring of large areas.

In addition to the general considerations for monitoring selection listed in Section 9.1., the following items should be considered when selecting regional monitoring methods:

- The type(s) of landslides being monitored. Landslides that are relatively slow moving with subtle geomorphic features are usually difficult to monitor visually through aerial patrol or ground patrol. In these instances, LiDAR data, high-resolution aerial imagery, and InSAR offer higher resolution data and increase the ability to resolve movement that might be not be apparent with visual inspection. In contrast, landslides that move rapidly, such as debris flows, are usually apparent using any regional monitoring method.
- The presence or absence of obscuring vegetation. Thick vegetative cover can obscure signs of landslide movement unless the movement is rapid or large enough to significantly disturb the vegetation. Thick vegetation also interferes with InSAR data collection.[23] High-resolution LiDAR data can typically be processed to remove vegetation and, thus, provides a good monitoring option in thickly vegetated areas, although optimum data collection is usually in leaf-off conditions. Conversely, in sparsely vegetated areas, visual monitoring and InSAR might provide a sufficient view of landslide movement and, thus, could be more feasible than using LiDAR data.
- The number of sites and extent of the area to be monitored. In large regions and regions with a high density of sites to be monitored, ground patrol might be inefficient and slow compared to other regional monitoring methods. Aerial patrol might be fast, but, given the speed at which an aircraft typically flies, it could be difficult to accurately monitor a large number of closely spaced sites. In extensive or high-density landslide areas, aerial imagery, LiDAR, or InSAR are generally preferable monitoring options. In contrast, in areas with few sites, aerial patrol and/or ground patrol might be more efficient options.
- The required timeline in which to identify locations of movement. The collection and review of LiDAR data (for vegetated areas) and repeat aerial imagery (for unvegetated areas) are, in most respects, the ideal and preferred methods for regional monitoring. However, both methods rely on data collection by aircraft followed by a period of data processing and then finally the review of the data to identify locations with movement. As such, the time between commissioning data collection and receiving results is measured at a minimum in weeks and usually in months, depending on the size of the monitoring area. InSAR data collection, processing, and review are typically faster than for LiDAR data and are usually measured in weeks.[24] When rapid results are needed, aerial and ground patrol provide near real-time turnaround between observation and identifying locations with movement.

9.3 Landslide Monitoring

In the context of this document, "landslide monitoring" refers to monitoring of a landslide or landslide-prone area by installing instrumentation. It is distinguished from regional monitoring discussed in Section 9.2 (no installed instruments) and pipeline monitoring discussed in Section 9.4 (instruments used to monitor the pipeline directly). Landslide monitoring instrumentation does not directly monitor effects on a pipeline but can be used to infer or model those effects.

[23] As of the time of publication. The launching of additional L-Band InSAR satellites, which has some ability to penetrate vegetation, may partially remove this as a consideration.
[24] Newer satellites scheduled for launch in the 2020s may make this reporting time as short as days.

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, such as monitoring stability of retaining walls, dams, mines, general construction sites, and other infrastructure type projects. Because of this broad usage, a variety of geotechnical instruments have been developed, many of which can be applied to monitoring landslides along pipelines.

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

- Rate and direction of landslide movement (to a high level of accuracy usually measured in fractions of an inch)
- Depth of landslide movement
- Changes to parameters that influence landslide behavior (e.g., pore water pressure)
- Warning of impending or accelerating movement

Geotechnical instrumentation is usually installed as a point monitoring system, where only the location where the instrument is installed is monitored. Accordingly, prior to installing the instruments, it is important that the area (landslide or landslide-prone area) has been well characterized through the phased assessment process (Section 5), such that the landslide boundaries and general characteristics have been defined. When installing instrumentation that measures the depth of movement, Phase III 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).

Geotechnical instruments typically have lifetimes of more than a decade if installed according to manufacturer instructions. Most failure of these instruments are related to the damage after being installed, such as vandalism, recreational or construction vehicles, animals, surge induced by lightning, or landslide movement beyond the intended limits of the instrument. Proper planning and design (e.g., installing fencing or bollards) can prevent most damages.

Table 9-1 provides a summary of commonly used geotechnical instruments for landslide and pipeline monitoring purposes. Table 9-1 is not intended to be an exhaustive list, but rather summarizes those instruments most commonly used, along with their relative advantages and disadvantages.

When selecting geotechnical instrumentation, it is important to consider the ultimate objectives of the monitoring, in accordance with Section 9.1. Considerations for specific landslide monitoring instruments are as follows:

- Manually measured survey monuments are the recommended approach where the objective is primarily to measure rate and direction of surface ground movement, the needed frequency of measurement is low (weeks to years between measurements), and the depth of the movement is relatively unimportant. The initial installation cost of survey monuments is low, making them easily replaceable in the event of damage, and there is no inherent maximum amount of movement that can be measured.[25]

- High-accuracy, self-locating survey monuments are able to self-locate (through an internal GPS or similar) and do not need to be manually measured. At the time of this document, these systems were in the early stages of commercial viability and are considered relatively expensive; however, for locations where the rate and direction of movement is needed and the frequency of reporting is high, self-locating survey monuments can be a feasible option. Similar to most new technology, they are expected to become more cost-competitive over time.
- Manually read inclinometers are the recommended approach when the objectives are to measure the rate, direction, and depth of movement and when a low-frequency of measurement and reporting is needed (weeks to years). Inclinometers can be expensive to install but are generally inexpensive to measure. They can also be installed at the same time and in the same hole as VW piezometers (discussed in the final bullet). A major limitation of inclinometers is that, in most cases, they cannot measure more than about 4 to 6 inches of movement before the amount of movement damages the inclinometers rendering them unusable.
- Automated inclinometers are the recommended approach when the objectives are to measure the rate, direction, and depth of movement and a high-frequency of measurement and reporting is needed (hours to days). The cost of installation is similar to that of the inclinometer, with additional cost associated with the data management system (either a data logger or a remote monitoring system). Similar to inclinometers, automated inclinometers can be easily co-located with VW piezometers. Unlike manual inclinometers, they can measure much larger movements, totaling feet.
- Time-domain reflectometry (TDR) systems are recommended when the primary objective of the monitoring is to identify movement and depth of movement and to provide an early warning system of movement. The major limitation of TDR-type systems is that while they can provide depth of movement with high accuracy, they are not reliable in identifying magnitude of movement with high accuracy. They are somewhat cheaper and easier to install than inclinometers and can tolerate much larger movements than inclinometers.
- Piezometers (VW or otherwise) are not recommended as a primary monitoring method. Piezometers 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 drawdown groundwater. However, since piezometers do not directly measure landslide movement, they should not be used in the place of other instruments when the goal of monitoring is to measure and quantify movement. VW piezometers co-located with inclinometer casing is a relatively small, incremental cost and should be considered when installing inclinometers.

---

[25] Although, practically speaking, large landslide movements (multiple meters or feet) can destroy the survey points, making them unusable.

Table 9-1. Commonly Used Geotechnical Monitoring Methods

Method	Advantages	Disadvantages	Monitoring Objective(s) and Needs
Survey Monuments	Provides rate and direction of ground movement Inexpensive to install	Does not provide depth of landslide slip surface Requires licensed surveyor and survey crew for repeat measurements Measurement conducted manually Data availability is limited to survey frequency	Rate and direction of movement Low frequency of measurement Depth not needed
Self-Locating Survey Monuments	Provides rate and direction of ground movement Inexpensive to monitor Near real-time with automated remote data collection	Does not provide depth of landslide Expensive to install Vulnerable to damage Requires maintenance of data acquisition system	Rate and direction of movement High frequency of measurement Depth not needed
Inclinometer–Manual	Provides high-accuracy, high-precision rate, direction, and depth of ground movement Minimal training requirements to conduct measurements Measurements inexpensive to collect Can be installed as part of Phase III investigations to reduce installation costs	Expensive to install Installation requires drill rig and proper site access Vulnerable to damage Measurement conducted manually Data availability is limited to survey frequency Usually becomes unusable after about 4 to 6 inches (or less) of ground movement, generally requiring replacement	Rate, direction, and depth of movement Low frequency of measurement
Automated Inclinometer – Shape Acceleration Array (SAA)	Provides high-accuracy, high-precision rate, direction, and depth of ground movement Inexpensive to monitor Near real time with automated remote data collection Monitors up to a few feet of ground movement	Expensive to install Requires drill rig and proper site access for installation. Vulnerable to damage Data acquisition system requires maintenance	Rate, direction, and depth of movement High frequency of measurement

Table 9-1. Commonly Used Geotechnical Monitoring Methods

Method	Advantages	Disadvantages	Monitoring Objective(s) and Needs
Time-Domain Reflectometry (TDR)	Provides direction and depth of ground movement Relative measurement of movement (not absolute) Inexpensive to monitor Near real time with automated remote data collection Monitors up to a few feet of movement.	Expensive to install Requires drill rig and proper site access for installation Vulnerable to damage Data acquisition system requires maintenance Does not provide absolute measurement of displacement	Direction and depth of movement High frequency of measurement
Vibrating Wire (VW) Piezometers	Provides information about groundwater level and/or pore water pressure Inexpensive to monitor Can be near real time with automated remote data collection Inexpensive to install when co-located on inclinometer casing	Does not provide rate, direction or depth of ground movement Expensive to install when stand-alone piezometer used (when not co-located on inclinometer) Requires drill rig and proper site access for installation (if stand-alone) Maintenance of data acquisition system (if remote data collection used) Vulnerable to damage	Pore water pressure and/or depth to groundwater table needed

9.4 Pipe Monitoring

Pipeline monitoring can be divided into two categories: strain gauges and ILI tools. There are other types of instruments that could be used to monitor the pipeline, such as FO cables or on-pipe survey monuments (see discussions in C-Core et al. [2009] or Wang et al. [2017] for more information). However, these are not discussed herein because they were not commonly used in North America at the time of this document.

Strain gauges and ILI tools provide related but separate information about whether a landslide is affecting the pipeline (landslide-induced strain) and, if so, by how much (i.e., strain demand). Strain gauges provide measurements at discrete locations and can report as often as available power allows. ILI tools provide information over entire pipe segments. The primary ILI technology used for landslide monitoring is IMU bending strain analysis (see Section 5.2), but this does not preclude the use of other ILI technologies, as appropriate.

Both have distinct advantages. Strain gauges can provide near-continuous, close to real-time reporting at known or suspected locations of pipe strain resulting from landslides, making them ideally suited for tracking trends over time and as an early warning system. ILI tools provide information over pipe segments and are useful for tracking and analyzing landslide effects on pipelines where multiple landslides are a concern. Both also have distinct disadvantages. Strain gauges measure only distinct locations and only measure changes in strain after their installation. ILI tool runs are relatively expensive, infrequently run (time between measurements is usually years), and cannot be used for all pipe segments. Like many other methods and technologies discussed herein, strain gauges and ILI tools have the most optimal results when used as complementary, integrated technologies. Strain gauges and ILI tools are discussed separately in Sections 9.4.1 and 9.4.2, but their use should be considered complementary.

9.4.1 Strain Gauges

Strain gauge installation and use are discussed and introduced in Section 6.5.2.2 (FFS assessment). In addition to their use in FFS assessments, strain gauges are also useful as a long-term monitoring method to evaluate if landslide movement is affecting a pipeline and, if so, the magnitude of that impact. As discussed in Section 6.5.2.2, for most applications, spot-weldable VW strain gauges are recommended for use in landslide monitoring.

When interpreting strain gauge readings, it is important to distinguish strain caused by temperature changes, operating pressure, and external force. Figure 9-2 through Figure 9-4 show examples of strain-induced by these three primary causes.

All types of strain gauges can be manually measured, recorded by on-site data logger (with periodic data downloads), or monitored by remote monitoring units that upload data to the cloud and from there to a webpage or supervisory control and data acquisition (SCADA) system. For most applications, remote monitoring units are recommended. The use of remote monitoring units can result in lower long-term costs than manually reading or downloading from data loggers, can provide continuous data tracking, and can be equipped with threshold notifications to provide short message service (i.e., text message) and email push-notifications to alert end-users when strain readings having exceeded predetermined levels. Advancements in solar panels, batteries, and cellular and satellite modems, have significantly reduced the cost of remote monitoring units and made them cost-effective for most uses.

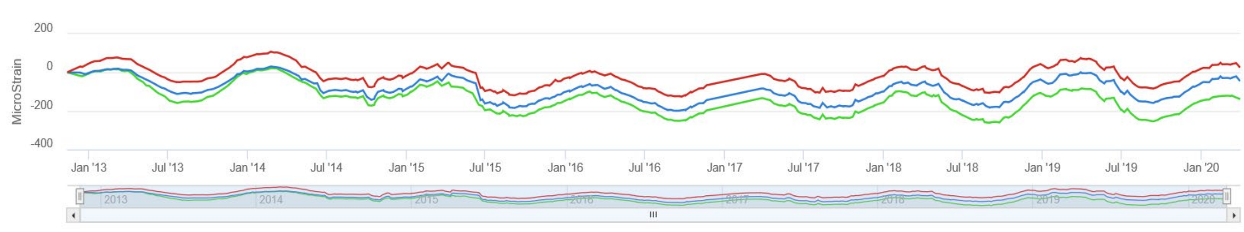

Figure 9-2. Strain gauge readings plot from late 2012 to early 2020 showing seasonal changes to pipe strain, likely resulting from ground temperature changes. All of the gauges show changes of roughly the same amount and in the same direction (positive is tension and negative is compression). In this example, the gauges experience maximum tension in spring and maximum compression in fall. The short, sharp jumps are related to operational changes.

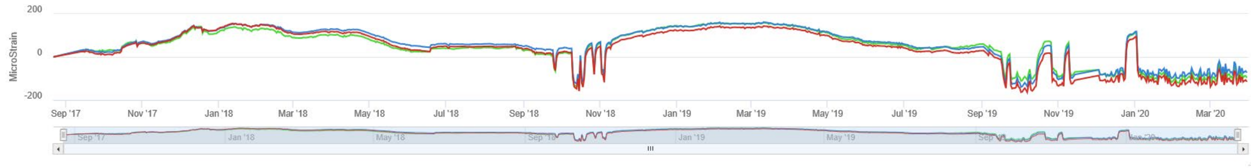

Figure 9-3. An example of strain changes resulting primarily from operational changes. Short, abrupt changes where all three gauges increase in tension or compression at the same time are characteristics of strain changes caused by operational changes.

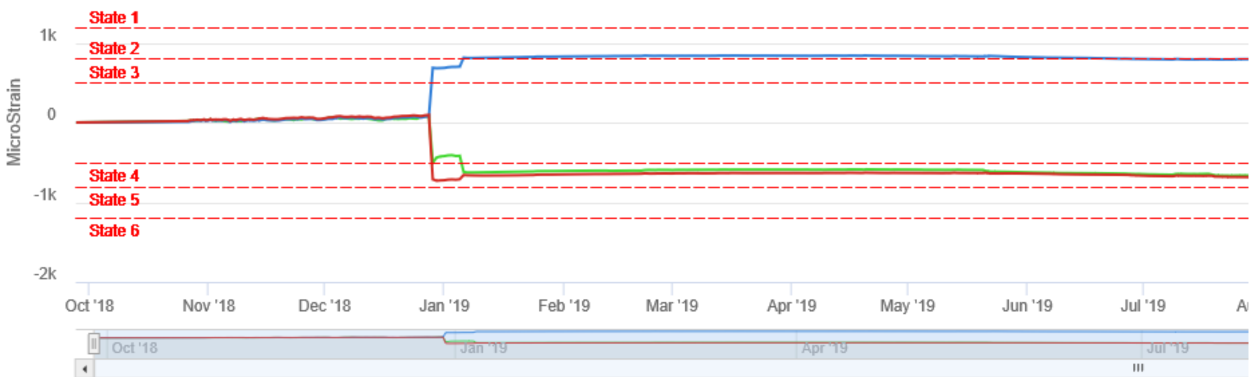

Figure 9-4. An example of strain changes associated with landslide movement. One strain gauge sharply increases in tension while the other two gauges increase sharply in compression. This pattern of change (one gauge increasing in compression or tension and the other two increasing in the opposite direction) is characteristic of strain induced by external force, in this case, a landslide (confirmed through field visit). The red lines show predetermined thresholds that when exceeded, will result in the remote monitoring system providing push notifications of the strain exceedance.

9.4.2 ILI IMU Bending Strain Data

Review of IMU bending strain data as a method for landslide identification and assessment was previously discussed in Section 5.2. IMU bending strain data can also be useful for landslide monitoring, both at a regional scale and at a site-specific scale. At a regional scale, IMU bending strain data can be used to identify landslides that have impacted a pipeline(s) since an initial landslide inventory was conducted. This identification of landslide impact can be used to identify newly formed landslides or to elevate or confirm assumed hazard levels for previously known landslides. At a site-specific scale, bending strain data can be examined in more detail to determine the extent, amount, and direction of pipe movement and the area and amount of accumulated strain as well as be used as an input into determining the overall FFS of the pipe.

Both single-run and run-to-run analyses can be valuable for monitoring. Single-run data provide measurements of the total magnitudes of the bending, and run-to-run data provide information on bending between runs (e.g., bending caused by the movement of active landslides). It may also be valuable to compare later runs back to the baseline run, instead of just comparing to the most recent run because small movements that may not be detected in run-to-run analyses could be detected in run-to-baseline analyses.

The use of IMU bending strain data as a landslide monitoring tool is most useful for pipe segments crossed by one or more landslides where those landslides have a relatively slow rate of movement (i.e., the rate of movement is slow enough that strain accumulation is measured in years and decades). Conversely, this tool has limited applicability for pipe segments not currently crossed by landslides or for locations where landslide movement is too rapid and subsequent pipe movement/impact is potentially too large relative to the monitoring frequency (e.g., pipe rupture could conceivably occur between monitoring events without sufficient warning; thus, other monitoring techniques would be more suitable).

10 LANDSLIDE EMERGENCY RESPONSE

10.1 Scope and Intent

The scope of this section covers the response after a landslide event along a pipeline ROW where the damage to the pipeline is uncertain. Each landslide event has its unique features. The impact on the integrity of a pipeline due to a landslide event depends on the characteristics of the pipeline and the local site conditions. The response plan presented here is meant to be versatile and provides operators with a logical set of steps to assess the affected pipeline's FFS, to identify what is needed to restore the ROW, and to help in developing a long-term plan to manage the specific ground movement hazard. Depending on the site-specific event, not all steps may be necessary, or some refinements might be needed.

10.2 Role of Emergency Response Plan

The vast majority of buried pipelines are not designed to accommodate significant localized landslides. When such a landslide event occurs along the ROW of a buried pipeline, it is imperative that the pipeline operator determine whether the landslide is a threat to pipeline integrity in order to protect those responding to the event, those living near the affected ROW, and the environment.

Operators are often faced with difficult decisions when a landslide event occurs. For instance, the impact on the subject pipeline may be uncertain even when there is clear evidence of a landslide. The tolerance of the pipeline to the stresses and strains imposed by the landslide can vary greatly. In addition, the level of stresses and strains imposed on the pipeline prior to the landslide event is often unknown.

Some of the critical decisions after an event include, but are not limited to, the following:

- Has the event affected the pipeline, the local ROW, or those living adjacent to the ROW?
- Should the line be shut down?
- If the line is to continue operation, is pressure reduction beneficial?
- Once the decision is made to shut down the pipeline and/or reduce the pressure, what additional work is needed to return the line to full-pressure service?

The central part of this section is an emergency response plan intended to guide the investigation and addresses the unique conditions associated with unforeseen landslide events. Much of the response was developed under a PRCI-sponsored project (Wang et al. 2019a, Wang et al. 2020b).

Since every landslide event is different and each pipeline has its unique set of circumstances, the response plan can only cover key elements that should be considered in performing assessments that support decision-making. It is not possible to have detailed plans for every possible scenario.

10.3 Overall Structure of a Response Plan

The most appropriate response plans depend on the pipeline characteristics and conditions and the characteristics of the ground movement event. Suitable response options are determined by the following:

- The pipeline(s) characteristics and conditions

- The ground movement characteristics and conditions
- Whether further movement is likely to occur
- If further movement is likely to occur, the likely rate of movement
- The amount of strain already imparted on the pipe by the ground movement if known (i.e., the strain demand)
- The amount of strain the pipe can experience before failing if known (i.e., the strain capacity)

The overall response plan is presented in three main stages.[26]

1. **Stage 1: Initial Response.** In most cases, this stage may take a few days to a few weeks. The most important goal of this stage is minimizing the risk of pipeline failure and the potentially negative impact on the surrounding properties and environment.
2. **Stage 2: Follow-On Assessment and Actions.** This stage may take weeks to months. The overall goal of this stage is returning the affected pipeline to full-pressure service. The necessary work to achieve this goal may be completed in this stage or may have to be done in Stage 3.
3. **Stage 3: Long-Term Management.** This stage focuses on long-term management of the geohazard and/or pipeline so that the risks associated with operating the line at the affected location are reduced to and then maintained at a tolerable level.

10.4 Stage 1: Initial Response

The most important goal of this stage is minimizing the risk of pipeline failure and the potentially negative impact on people, properties, and the environment. The key decisions are as follows:

- Should the affected pipeline(s) be shut down or pressure be reduced?
- Are there any undue risks to those living in close proximity?
- Should immediate actions be taken to stabilize the site to minimize the possible continued damage?
- Is there a need to install a bypass?

In Stage 1, the focus is on acquiring information about the event site and the affected pipeline and taking initial actions to ensure the safety of nearby lives and properties and maintain the integrity of the affected pipeline. It is anticipated that the duration of Stage 1 would range from several days to a few weeks depending on the logistics to access the site, severity of the event, and the availability of needed information and work team.

The key steps in Stage 1 are performing initial assessments of the site and pipeline conditions and making decisions in each of the following three interlinking tracks:

[26] In the final report of PRCI project SBD-1-2, the term "phase" is used in the place of "stage" in this section. The term "stage" is used in this section to avoid confusion with the phased approach in Section 5.

- Track 1 – focus is on immediate risk to nearby lives and properties and necessary actions if such risk exists.
- Track 2 – focus is on determining need for initial work to stabilize the event site.
- Track 3 – focus is on pipeline integrity and deciding whether change in operation is needed (i.e., shutdown, pressure reduction, full-pressure operation, or installation of a temporary bypass).

A few key issues in Stage 1 are further described below.

10.4.1 Safety of the Work Site

Once the decision is made about the need to perform work on the event site, it should be determined if the site is safe for work. The following factors should be considered in determining whether the site is safe for work:

- **Risk to personnel working at the site**. If the landslide is continuing and the movement rate is high or if instability could be triggered by natural events like rainfall, it could be unsafe or impossible for workers to implement site stabilization. It is also possible that the proposed measures, such as cutting into unstable slopes, could, depending on the situation, cause the instability to worsen and be counterproductive or represent a hazard to workers and the public.
- **Risk to cause more damage to the pipeline.** Using the above example, measures that cut into unstable slopes could destabilize site conditions, worsen the situation, and cause unexpected additional damage to the pipeline. For instance, additional movement imposed on the segment could cause LOC if the affected segment is close to its strain capacity due to the initial event.
- **Use of heavy equipment**. Immediate action on-site commonly requires heavy equipment, so the ability and safety for heavy equipment to access and work on the site should be assessed.
- **Evacuation plan.** There should be an evacuation plan that contains methods to monitor for unexpected movement and appropriate measures to take in the event of such movement to safely evacuate the response team.

10.4.2 Public Safety and Impact on Environment

Nearby lives, properties, and the environment could be adversely affected if there is a leak or rupture of the pipeline. The severity of possible impacts depends on the magnitude of the event (leak, rupture, fire, etc.), nature of the product, local topography, weather conditions, the presence of sensitive environmental areas (such as water bodies), the proximity of built structures and human-occupied areas to the event site, and secondary effects (such as shut down of nearby pipelines or travel ways).

Decisions about potential risks and acceptable risk level should be made by operators with knowledge of their pipelines, site conditions, surrounding communities, and company philosophies. If it is determined that there is imminent risk to nearby lives and properties, the nearby public should be notified and an evacuation plan implemented, if necessary, following standard company procedures. The perceived risk may change due to the continuing changes in site conditions and/or availability of additional information.

10.4.3 Initial Assessment

The following actions may be performed simultaneously or sequentially in any order that fits a particular situation:

- Identifying and assessing immediate risks to personnel, the local public, or adjacent properties
- Confirming that the apparent ground movement is real or, at least, cannot be definitively disproven
- Estimating the type, nature, extent, and magnitude/amount of ground movement across and/or adjacent to the pipe, once it is safe to do so
- Performing a preliminary visual assessment of potential impacts to the pipe from the ground movement and determining initial conclusions regarding whether the pipe has been adversely affected
- Assessing whether ground movement is continuing
- Assessing site security and ability to safely access the site
- Assessing the ability to safely access the site by heavy equipment
- Collecting and reviewing available pipeline, site records, and data

These action items are usually interconnected and sometimes do not have clear boundaries. The primary goal is to generate as much information as possible to facilitate the decisions in the three tracks identified in the beginning of Section 10.3.

The initial field assessment is typically qualitative and conducted as soon after the event as possible by staff responsible for pipeline integrity. Once site conditions are known, the geotechnical and integrity experts would engage with available design and geohazard experts to make the initial field assessment. The scope is recommended to cover the following items:

- Examining and/or updating the information acquired in site reconnaissance and survey, including the type, magnitude, and rate of landslide movement across and/or adjacent to the pipe and the location of the pipe (horizontal and vertical) relative to the landslide.
- Assessing the likelihood of further landslide movement. This process may involve the use of geotechnical models.
- Assessing the impact on pipeline integrity by the event or potential for further landslide movement. In principle, the integrity of the pipeline can be assessed by comparing strain demand with the strain demand limit (SDL). However, in most cases, such quantitative assessment cannot be completed within the short period of time needed for Stage 1. The initial field assessment is time sensitive because the pipeline operator must make decisions quickly—normally within a few hours or days to a few weeks after the event. Therefore, the initial integrity assessment is mostly based on the experience of integrity experts combined with the interpretation of currently available information.

10.4.4 Decision about Shutdown

If it is clear that the landslide has caused the pipeline to be displaced or there is an imminent possibility of further landslide movement that could displace the pipeline, then a decision must be made to either maintain current operations, shut down further operation, reduce pressure, or depressurize/purge the line. To make such a decision, the response team and available experts need to develop a package that summarizes their best judgment of the current situation based on the available information. Since each company has its own practices for making such a risk management decision and each specific event has unique characteristics, there is no simple answer of what to do that is broadly applicable.

Many factors can influence the decision. The order of importance depends on the specific situation. The following are factors for consideration to include:

- Potential consequences of a leak or rupture, including public safety, damage to adjacent properties, impact on adjacent pipelines, etc.
- Stability of the affected site (e.g., whether the landslide is still active and continuing to affect the pipeline or ROW)
- Regulatory requirements, including any required notifications
- The confidence level associated with the initial assessment
- Impact on customers if the pipeline is shut down

10.4.5 Decision about Pressure Reduction

Pressure reduction could be beneficial or detrimental depending on many factors, especially the loading conditions of the pipe after the landslide. For instance, if the pipe segment is under tension, a pressure reduction of sufficient magnitude is beneficial in avoiding a tensile rupture. If the pipe segment is under compression, a pressure reduction may increase the risk of compressive failure, such as buckling, because the stability of a pressurized pipe is higher than a depressurized one. In addition, a temperature increase, possibly exacerbated by a non-flow condition, in a pipe segment exposed due to landslide movement could cause additional compressive stress that could increase the potential for compressive failure.

Considering the varied pipeline conditions and event characteristics, there is no simple answer to whether a pressure reduction is beneficial or detrimental. The operators are recommended to rely on the initial field assessment to make a decision. The following sections provide general guidance regarding pressure reductions but should never supersede site-specific assessment.

10.4.5.1 Scenarios That Can Benefit from Pressure Reduction

A pressure reduction may be beneficial if the following conditions exist:

- There are concerns about seam weld integrity.
- It is desirable to increase the margin between TSC and strain demand where strain demand may be approaching the TSC. In scenarios where this is necessary as determined by an SME, it can be accomplished by decreasing the internal pressure of affected pipeline sections. The increase of TSC starts when the hoop stress is at approximately

0.5×SMYS. The TSC increases linearly until the pressure is dropped to zero. The TSC at zero pressure is approximately twice the TSC at hoop stress of 0.5×SMYS.

- Further landslide movement is not anticipated.
- Post-buckling leaks are judged to be not likely (even if a buckle were to form).

10.4.5.2 Scenarios Where a Pressure Reduction May Be Detrimental

A pressure reduction may be detrimental if the following conditions exist:

- An unsupported span is under load-controlled loading, and
    - a temperature increase in the pipe is likely, as it can cause a reduction of tensile stress or addition of compressive stress, and
    - an increase of the load on the free span is expected.
- An exposed pipe is subjected to compression, such as at the toe of a landslide. A temperature increase in the pipe is likely, causing additional compressive stress.
- The formation of a buckle may result in additional (collateral) loss of stability.

10.4.5.3 Additional Considerations about Pressure Reduction

The tolerance to the potential formation of a buckle due to pressure reduction may be considered in conjunction with an in-line inspection plan. The formation of a buckle may restrict tool passage. The minimum pressure or flow needed to run in-line tools may also be considered.

10.5 Stage 2: Follow-On Assessment and Actions

In some cases, such as a shallow landslide that only moved a few inches and is clearly above the pipeline, the landslide may be small enough to cause no damage to a pipeline. In such cases, further assessment will not be necessary. If such determination cannot be made with reasonable levels of confidence, further assessment should be performed. Stage 2 may take weeks to months to complete in most cases.[27]

The overall goal of this stage is returning the affected pipeline to full service. The necessary work to achieve this goal may be completed in this stage or may have to be done in Stage 3. The work in this stage may include the following:

- Further assessment of the site and the condition of the pipeline (i.e., integrity and safety).
- Performing site work to reduce or eliminate the possibility of further movement.
- Enhancing the strain capacity of the affected segment.
- Determining if more substantial work on the site and pipeline is needed in Stage 3, such as rerouting and HDD. If rerouting is considered as an option, the route(s) under consideration

[27] Stage 2 should be understood to constitute an intermediate phase between the initial rapid or emergency response and the implementation of a long-term management plan. Depending on the complexity of the site conditions and factors over which the pipeline operator may have limited control (such as regulatory requirements), Stage 2 could last longer (e.g., years).

should be assessed using the phased approach described in Section 5 to avoid potentially routing into a landslide-prone (or other geohazard-prone) area.

After the initial response in Stage 1, the focus of Stage 2 is on further assessing and stabilizing the situation to either return the pipeline to full-pressure service or to identify what is needed to get to that point. It is expected that more information may become available in this stage than in Stage 1.

The work in Stage 2 includes the following key steps:

1. Perform further site assessment to determine whether new or additional remediation of the site is needed during the Stage 2 timeline. This should be understood to be remediation that is implemented relatively quickly (i.e., within months or a few years after the initial event) and, depending on the nature of the remediation, may either be suitable as a long-term solution or may need to be supplemented with further action at a later date.
2. Consider if enhancement of the pipeline is a necessary and a viable option. If so, perform such enhancement.
3. Perform additional integrity assessment of the pipeline with the available and most relevant information about the site and pipeline conditions. For instance, if site remediation and pipeline enhancement are performed, the assessment should consider these "new" conditions.
4. Determine, based on the outcome of the integrity assessment and site conditions,
    a. if the state of the pipeline from Stage 1 should be altered to either allow full-pressure service or, if necessary, to be downgraded to lower-pressures service or shutdown; and
    b. if site remediation work in this stage can be considered permanently acceptable. If not, further work in Stage 3 might be necessary.

Key steps in Stage 2 are further described below.

10.5.1 Perform Further Site Assessment

In Stage 1, either no immediate action is taken on the event site or the site is addressed using options suitable for rapid response (e.g., temporary stabilization, temporary bypass, pressure reduction). With more available information than in Stage 1, further site assessment should be performed in Stage 2 to determine whether any further site remediation work is required.

Further site assessment may include the following:

- Determining whether the landslide is continuing to move based on newly available monitoring data
- Determining whether further landslide movement is possible or not, based on more sophisticated geotechnical models and/or SME opinion

10.5.2 Perform Additional Integrity Assessment

The line could be in full-pressure service, reduced-pressure service, or shutdown conditions when this action is taken. In this step, the integrity of the pipeline is assessed using SBA (Section 6). The possible outcomes of the assessment are as follows:

- Maintaining or returning the line to full-pressure service
- Maintaining, upgrading, or downgrading the line to reduced pressure service
- Shutting down the line
- Determining the need for long-term mitigation

10.5.3 Enhancement of Pipe Segment

A number of factors can influence whether an enhancement of the affected pipe segment should be pursued, including the following:

- Availability of enhancement options
- Cost and duration of performing the enhancement
- Relative cost and feasibility comparison with the option of reducing strain demand

The most widely used methods to enhance the strain capacity of pipelines include pipe replacement and installation of Type B sleeves. Other options include compression sleeves and composite wraps. These options should be properly engineered to provide enhanced strain capacity and avoid transferring points of low strain capacity from one location to another location. An ongoing PRCI project is examining various options for enhancing the strain capacity of pipeline girth welds (PRCI Project SBD-1-6).

In addition to the effectiveness of an enhancement option, the following factors should be considered:

- Safety of personnel and pipeline during installation
- Loading conditions, both hoop and axial directions, at the time of installation
- Long-term effectiveness of the enhancement under static loads and possibly cyclic loads when applicable
- Expected performance of enhancement options
    - Some enhancement options, such as Type B sleeves, are considered capable of maintaining containment in an event of leaks in the underlying carrier pipe. The effectiveness of such containment should be considered with an expectation that further straining after installation is possible.
    - Other enhancement options, such as compression sleeves and composite wraps, are not expected to maintain containment in an event of leaks in the underlying carrier pipe. Consequently, the enhancement should be designed to ensure there are no leaks in the carrier pipe if the segment is subjected to further straining after installation.

10.6 Stage 3: Long-Term Management

This stage is focused on long-term management of the landslide hazard and/or pipeline so that the risks associated with operating the line at the affected location are reduced to and then maintained at a tolerable level. In some cases, this could entail major one-time activities such as rerouting and HDD, strain relief excavation, or major site remediation that requires months of advance planning and may take months to complete once the work is started. Alternatively, or in addition, the solution might be the installation of on-site and/or pipeline instrumentation to provide information necessary to safely manage the landslide hazard over the pipeline's design life.

After Stages 1 and 2, the focus of Stage 3 is on steps operators may take to manage the long-term threats to a pipeline(s) from landslide movement, if not completely addressed in prior stages.

The work in Stage 3 may include the following key steps:

1. Develop plans for long-term management that address conditions making Stage 3 necessary.
2. Execute long-term management plans.

The long-term management plan may include the following:

- Avoiding the hazard (Section 8.2)
- Reducing strain demand on the pipeline
- Increasing strain capacity of the pipeline
- Installing monitoring devices and establishing future intervention criteria

Methods of reducing strain demand are covered in Section 8.3.1. Methods of increasing strain capacity are covered in Section 8.3.2. Developing a monitoring plan and installing monitoring devices are covered in Section 9. Along with the monitoring plan, future intervention thresholds may be established as an outcome of the pipeline integrity assessment in Section 6.

10.7 Planning for Emergency Response

Emergency response to an unanticipated event can be most effective if prior planning is done and information needed for making quick decisions is readily available. In addition to having a response plan as outlined in this section, site and pipe conditions are often needed to make appropriate decisions.

The information likely needed to execute an emergency response plan is given below. This list is not meant to be exhaustive or all-inclusive. An operator should understand the information likely needed to make quick decisions in the event of an unexpected landslide. There should be a plan and process to quickly retrieve such information when an emergency response plan is established.

10.7.1 Site Conditions

The following information on site conditions is valuable:

- Terrain conditions
- Access to the site

- Soil or rock type and characteristics of the landslide(s) and surrounding area
- Possible landslide characteristics (e.g., type of movement, movement rate, orientation of movement relative to the pipeline)

10.7.2 Pipe Conditions

The following information on the pipe at the site is useful:

- Pipe orientation and position relative to the landslide(s) or potential landslide(s) of concern
- Precise pipe location from construction or post-construction surveys
- Depth of cover
- General pipeline conditions (e.g., outside diameter, wall thickness, grade, type of pipe, year of construction, year of commissioning, maximum operating pressure or maximum allowable operating pressure)
- Original construction records of pipes and girth welds (e.g., pipe MTR, girth weld WPS, inspection criteria and records)
- ILI records and results, including anomalies, at the location of interest. For instance, records from geometry and IMU tools (buckles, dents, ovality, etc.), records from crack tools (seam weld, SCC); and records from girth weld anomaly tools (UT, electromagnetic acoustic transducer)
- Past history, including but not limited to
  - prior history of landslides and mitigation measures;
  - success of the prior mitigation measures;
  - prior incident reports; and
  - records of prior modifications, such as pipe replacement, installation of Type B sleeves, etc.

11 CONSIDERATIONS FOR LANDSLIDE DATA MANAGEMENT

A well-developed landslide hazard management program will likely result in generating ever-expanding and evolving sets of data, with collected information varying widely in source, type, 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 help minimize risk, prevent overreacting or underreacting to scenarios as they arise or evolve, and help with efficient and informed decision-making. Thus, data management is an essential process for the long-term management of landslide hazards. Data management is used to properly inventory potential landslide hazards (e.g., location, type, threat level) and to track and document changes through time (e.g., changing hazard conditions or site activities, such as assessments or remediation that may be completed through time). Because of the geographic nature and complexity of landslide hazard data, it is generally recommended that a GIS database be used for data management. In general, there are two broad types of data that need to be managed: spatial and nonspatial data. These two types of data and examples of each of them are as follows:

- Spatial Data – Data that inherently depend on a map location in space:
    - Pipeline centerline
    - The delineation (i.e., boundary or lateral limits) of a landslide
    - Monitoring instrument locations such as strain gauges, monitoring points, and slope inclinometers (SIs)
    - ILI IMU bending strain sites (i.e., distinct pipeline segments)
    - Implemented mitigation measures
- Nonspatial Data – Data that may be tied to a specific map location or landslide, but that are not spatial in nature:
    - Unique landslide ID number
    - Time-series data, such as strain gauge data or monitoring point data (e.g., SI, geodetic)
    - Landslide characteristics (e.g., depth of the landslide surface of rupture, movement rate, landslide type)
    - Pipe characteristics (e.g., age, diameter, depth)
    - Mitigation designs or as-builts
    - Site photographs, which are georeferenced

Spatial data should generally be managed in some form of a GIS platform where dimensional aspects of the data can be viewed and assessed. For example, a GIS database may hold the following data:

- Delineated landslide hazard boundaries (e.g., mapped landslide footprints that can be viewed on a two-dimensional map).

- Information associated with each hazard. These data would be embedded in a table(s) and tied to the spatial data. Such information may include the following:
  - Characteristics of the landslide (e.g., landslide type, movement rate, activity level, thickness)
  - Hazard classification or risk ranking
  - Status of each site (e.g., mitigation planned or completed; monitoring planned, ongoing, or completed)
  - Observations from multiple events (e.g., aerial reconnaissance, ground visits, monitoring events), which track the site history

Nonspatial data can be managed in a variety of platforms depending on the data type (e.g., tabular, charts, reports), the need for updates (e.g., one-time data collection versus ongoing, manually collected versus automated data collection), and accessibility requirements (e.g., single versus many users/viewers, desktop versus online platforms). Ideally, nonspatial data can be linked with spatial data.

A data management system can range from simple to complex and may evolve over time based on the types of data produced, the amount of data, the number and status of people (i.e., viewer versus data manager) who need to access the system, etc. In addition to organizing and storing spatial and nonspatial data, data management tools can also be developed to aid in landslide hazard management itself. Tools can be implemented to help with tasks such as scheduling, tracking action items and budgets, providing reminders for overdue items, generating summaries and reports for planning and decision-making activities, and providing alerts based on preset triggers (e.g., for monitoring instrument readings or rainfall).

12 TRAINING AND AWARENESS

Training and awareness of landslide hazards by the pipeline operator/contractor staff with field responsibilities (e.g., line and aerial patrol) can be an important component of landslide management. While a mature program should have ongoing monitoring of landslide-prone areas, there could be landslides that are not recognized by this monitoring or landslides that occur between monitoring intervals, which could result in data regarding the landslide not being available until well after occurrence. Having field staff trained to recognize a landslide event may help improve hazard identification and response times and potentially avoid serious consequences.

This guideline recommends that staff with regular field responsibilities in areas identified as potentially landslide prone receive regular (annual or biannual) training in landslide hazards. This training can be conducted by an internal SME or a qualified third party and should cover the following areas:

- Landslide basics (e.g., what constitutes a landslide)
- Geomorphic characteristics of a landslide (e.g., what types of features to look for and how to describe them)
- How and what to document (e.g., how to collect photos and notes on observations, GPS coordinates)
- Where the documentation should be sent (i.e., who should receive the report)

The intention of this training is not to make field staff into SMEs. The primary intention of the training should be focused on providing enough information to the individual or group designated by the operator with responsibility for landslide hazard management to evaluate whether further assessment is needed. Thus, the trained field staff should have a basic idea of what type of information is important to this individual/group and where to send the information. As a guideline, this training can generally be completed in classroom-based training in one-half day or less.

The expectation at the end of this training should be that field staff can identify obvious landslide events and features, document them with photographs and some basic notes, and report them to the proper group. It should not be expected that field staff identify and report subtle landslide changes that might only be apparent to an SME. The following are examples of items to document (in addition to photographs):

- Date of observation
- Person doing the observation
- GPS latitude and longitude coordinates of possible landslide
- Pipeline name and stationing/milepost (if known)
- City, county, state
- Length and width of possible landslide (rounded to nearest 5 feet)

- Position of pipeline relative to possible landslide (e.g., does it cross? If it does not cross, how many feet away, and uphill or downslope?)
- Depth of pipeline where crossed by or adjacent to the possible landslide (if known)
- Summary of observations

It is anticipated that in a mature landslide management program, most possible landslide sites reported by field staff are already known by the group tasked with landslide management. Thus, training field staff in proper documentation will help to quickly determine whether the site is already known and monitored or whether additional resources need to be expended (such as an SME evaluation). For those sites not previously known or when a known site has noticeably changed, good documentation will assist in rapidly determining whether emergency measures might be needed to respond to the situation as described in Section 10.

13 QUALITY ASSURANCE

Quality assurance in a landslide hazard management context is the process of verifying that the landslide hazard management processes are functioning as intended to identify and rectify omissions in the program that could result in adverse consequences. A quality assurance process should verify the following:

- The processes to identify and characterize landslides are appropriate for the areas traversed by the operator's pipeline network and are being conducted in accordance with the operator's requirements for identification and characterization (i.e., potentially damaging landslides are not being omitted or excluded from the identification, characterization, and monitoring processes).
- Areas of the operator's pipeline network, including newly acquired and newly built pipelines, are not excluded from the landslide management processes unless it can be demonstrated that there is no landslide-related risk.
- The decisions to manage landslide hazards are consistent with the operator's CDM system and are in-line with the operator's risk tolerance.
- Scheduled monitoring is being conducted at the intervals planned, and the results of this monitoring are being appropriately reviewed and analyzed.
- Scheduled mitigation is being conducted within the timelines planned; the mitigation types being selected are appropriate and have appropriate design; and the effectiveness of the mitigation is being verified after implementation.
- Data associated with the landslide management program are being appropriately stored and tracked.
- Internal and external technical staff have appropriate qualifications, experience, and licensure (as applicable).

The nature of a quality assurance program will vary by operator. Possible options for who should perform quality assurance audits could include the following:

- An internal group or department specifically tasked with conducting quality assurance audits of other groups
- A separate individual within the Integrity/Engineering department who is not directly involved with the landslide hazard management program
- A qualified third party with suitable experience in pipeline landslide hazard management who can be retained to conduct a periodic quality assurance audit

Whatever methods are used, it is not recommended for the individual or group that conducts quality assurance audits to be the same individual or group primarily responsible for landslide hazard management.

14 MANAGEMENT OF CHANGE AND CONTINUOUS IMPROVEMENT

For a landslide hazard management program to have long-term success, the program must be able to manage necessary changes and improvements. The following are areas where changes in landslide hazard management should be expected:

- **Changes to the regulatory environment**. At the time of publication of this guidance document, there are essentially no prescriptive requirements around landslide hazard management in North America. Operators should stay engaged with and track potential changes to regulatory requirements on landslide management if and when they develop.
- **Technological changes.** If this guideline were written 20 years ago (in the year 2000), the recommendations would look very different. For instance, LiDAR, a cornerstone and leading practice discussed in this guideline, was in its relative infancy at that point, being expensive, not widely available, and relatively low resolution. The maturation of LiDAR technology has had a transformative effect on the ability to identify, characterize, and monitor landslide hazards. Similarly, other technologies, such as InSAR, machine learning, drones, and upcoming ILI technologies, have the possibility of transforming the methods by which landslide hazards are managed. Operators should stay involved with and provide appropriate research funding to develop new technologies, which will make landslide hazard management more effective and practical in the coming decades.
- **Internal processes**. Similar to technological changes, 20 years ago relatively few pipeline operators had procedures and staff dedicated to landslide hazard management. At the time of this guideline, the practice of developing, maintaining, and implementing internal procedures to manage landslide hazards had become much more widespread. It should be expected that in coming years, landslide management processes will become more routine and standardized between and within pipeline operators. Teams tasked with landslide hazard management should periodically revisit their own procedures and processes and, to the extent possible, share information about processes between operators to improve the overall industry approach to landslide hazard management. Appropriate information sharing will also contribute to moving toward industry consensus on best management practices for landslide hazards.

15 BIBLIOGRAPHY

ALA. 2001. *Guideline for the Design of Buried Steel Pipe*. American Lifelines Alliance (ALA). Available at: https://www.americanlifelinesalliance.com/pdf/Update061305.pdf. July.

Albrecht R., J. Calame, M. Cook, I. Falcon, and P. Lee. 2020. "High-Pressure Natural Gas Pipeline in Geohazard Region of Papua New Guinea Sustains Mw7.5 Earthquake: Key Factors of Successful Outcome." Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9473, September 28–October 2, 2020, Calgary, Alberta, Canada. [Not published at time of report].

ASME. 1984. *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*. American Society of Civil Engineers, Committee on Gas and Liquid Fuel Lifelines, Technical Council on Lifeline Earthquake Engineering, American Society of Civil Engineers (ASCE), New York.

C-Core. 2003. *Extended Model for Pipe Soil Interaction*. Prepared for PRCI project PR-02-044-113, Catalog No. L51990. August.

C-Core. 2008. Pipeline Integrity for Ground Movement Hazards. Prepared for PRCI , Catalog No. L52291. December.

C-Core, D.G. Honegger Consulting, and SSD, Inc. 2009. *Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines Through Areas Prone to Landslide and Subsidence Hazards*. Prepared for PRCI, Catalog No. L52292. January.

Clague, J.J., and D. Stead. eds. 2012. *Landslide Types, Mechanisms, and Modeling*. Cambridge University Press. New York, New York, USA.

Crapps, J.M., X. Yue, R.A. Berlin, H.A. Suarez, P.A. Pribytkov, B.A. Vyvial, and J.S. Proegler. 2017. "Strain-Based Pipeline Repair via Type B Sleeve." Proceedings of the Twenty-Seventh International Ocean and Polar Engineering Conference, San Francisco, California.

Cruden, D., and D.F. VanDine. 2013. *Classification, Description, Causes and Indirect Effects; Canadian Technical Guidelines and Best Practices Related to Landslides; a national initiative for loss reduction.* Geological Survey of Canada Open File 7359.

Cruden, D.M. and D.J. Varnes. 1996. "Landslide Types and Processes." In *Landslide Investigation and Mitigation by Transportation Research Board* Special Report 247.

CSA. 2011. *Oil and Gas Pipeline Systems*. CAN/CSA Z662-11. Canadian Standard Association Group. Available at: https://www.scc.ca/en/standardsdb/standards/26057.

Del Soldato, M., L. Solari, F. Raspini, S. Bianchini, A. Ciampalini, R. Montalti, A. Ferretti, V. Pellegrineschi, and N. Casagli. 2019. "Monitoring Ground Instabilities Using SAR Satellite Data: A Practical Approach." ISPRS *Int. J. Geo-Inf*. Vol 8, No.307. doi:10.3390/ijgi8070307.

Dinovitzer, A. 2018. *Guidance on Predicting Pipeline Strains Induced by Slope Movement*. Prepared for PRCI by BMT, Catalog No. PR-214-154503. December.

Dorey, A.B, D.W. Murray, and J.J.R. Cheng. 2002. "Material Property Effects on Critical Buckling Strains in Energy Pipelines." Proceedings of the 4th International Pipeline Conference. Calgary, Alberta, Canada. September 29–October 3.

Dorey, A.B., D.W. Murray, and J.J.R. Cheng. 2006. "Critical Buckling Strain Equations for Energy Pipelines – A Parametric Study." *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 128, pp. 248–255.

Fredj, A., and A. Dinovitzer. 2012. "Simulation of the Response of Buried Pipelines to Slope Movement Using 3D Continuum Modeling." Proceedings of the 2012 9th International Pipeline Conference, IPC2012-90437, Calgary, Alberta, Canada. September 24–28.

Fredj, A., and A. Dinovitzer. 2014. "Pipeline Response to Slope Movement and Evaluation of Pipeline Strain Demand." Proceedings of the 2014 10th International Pipeline Conference, IPC2014-33611, Calgary, Alberta, Canada, September 29–October 3.

Golder. 2016. *Mitigation of Land Movement in Steep and Rugged Terrain for Pipeline Projects: Lessons Learned from Constructing Pipelines in West Virginia*., Golder Associates, Inc. prepared for the INGAA Foundation, Inc. Final Report No. 2015-03, Golder. April.

Gresnigt, A.M. 1986. "Plastic Design of Buried Steel Pipelines in Settlement Are-As." *HERON*, Vol. 31, No. 4, pp 1–113.

Gunawardana, S., and F. Rongere. 2019. *Use of Aerial LiDAR Data Collection for Geohazard Assessment*. Prepared for PRCI by Enview and PG&E, Catalog No. PR-680-183907. June.

Herr, K., and T. Atkinson. 2020. "Creation and Management of Landslide and Erosion Geohazards Inventory for Natural Gas Transmission Pipelines in California." In Salama et al. (eds.) *Pipeline Integrity Management Under Geohazard Conditions*: ASME Book No. 861998, p. 127–132.

Highland, L.M., and P. Bobrowsky. 2008. *The Landslide Handbook—A Guide to Understanding Landslides*. Reston, Virginia, U.S. Geological Survey Circular 1325.

Holtz, R.D., and R.L. Shuster. 1996. "Stabilization of Soil Slopes." In: *Landslides Investigation and Mitigation, Transportation Research Board Special Report 247*: A.K. Turner, and R.L. Schuster. (eds).

Honegger, D.G., and D. Nyman. 2004. *Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines*. Prepared for PRCI project PR-268-9823.

Honegger, D., and D. Nyman. 2017. *Pipeline Seismic Design and Assessment Guideline (2017 Revision).* Pipeline Research Council International. PRCI Contract PR-268-134501.

Honegger, D., D.K. Wijewickreme, and H. Karimian. 2008. *Assessment of Geosynthetic Fabrics to Reduce Soil Loads on Buried Pipelines – Phase I*. Pipeline Research Council International. PRCI L52325.

Hoser, T. 2018. *Analysing the Capabilities and Limitations of InSAR Using Sentinel-1 Data for Landslide Detection and Monitoring*.: Master of Science Thesis, Faculty of Mathematics and Natural Sciences, University of Bonn, Department of Geography. July.

Hungr, O., S. Leroueil, and L. Picarelli. 2014. "The Varnes Classification of Landslide Types, an Update." *Landslides* Vol. 11, No. 2, pp. 167–194.

Iverson, R.M., D.L. George, K. Allstadt, M.E. Reid, B.D. Collins, J.W. Vallance, S.P. Schilling, J.W. Godt, C.M. Cannon, C.S. Magirl, R.L. Baum, J.A. Coe, W.H. Schulz, and J.B. Bower. 2015. "Landslide Mobility and Hazards: Implications of the 2014 Oso Disaster." *Earth and Planetary Science Letters* Vol. 412, pp. 197–208.

Jia, D., Y-Y. Wang, and S. Rapp. 2020. "Material Properties and Flaw Characteristics of Vintage Girth Welds," Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9658, September 28–October 1, Calgary, Alberta, Canada.

Joehan, R.M., W.I.W.M. Marzuki, K. Ibrahim, Z. Bob, and R. Azam. 2020. "Dynamic Geohazard Management in Challenging Environment." In Salama et al. (eds.). *Pipeline Integrity Management Under Geohazard Conditions*: ASME Book No. 861998, pp. 139–144.

Kiefner, J.F., and M.J. Rosenfeld. 2012. *The Role of Pipeline Age in Pipeline Safety*. Prepared for the INGAA Foundation, Inc., INGAA Foundation Final Report No. 2012.04.

Kiefner, J.F., J.M. Tuten, and T.A. Wall. 1986. *Preventing Pipeline Failures in Areas of Soil Movement – Part 1, State of the Art – A Report of 1985 Activities*. Prepared for Pipeline Research Council International, Inc.

Kotian, K. and Y.-Y. Wang. 2016 "Mechanical Properties of Vintage Girth Welds." Proceedings of the 11th International Pipeline Conference, Paper No. IPC2016-64420, September 26–30, Calgary, Alberta, Canada.

Leis, B. 2009. "Vintage Pipelines." in PHMSA R&D Forum, June. Available at: https://primis.phmsa.dot.gov/rd/mtgs/062409/BrianLeis.pdf.

Liu, M., Y.-Y. Wang, Y. Song, D. Horsley, and S. Nanney. 2012a. "Multi-tier Tensile Strain Models for Strain-Based Design Part II – Development and Formulation of Tensile Strain Capacity Models." Proceedings of the 9th International Pipeline Conference, Calgary, Alberta, Canada, Paper No. IPC2012-90659. September 24–28.

Liu, M., Y.-Y. Wang, D. Horsley, and S. Nanney. 2012b. "Multi-tier Tensile Strain Design Models for Strain-Based Design Part III – Model Evaluation Against Experimental Data." Proceedings of the 2012 9th International Pipeline Conference. Paper No. IPC2012-90660. Calgary, Alberta, Canada. September 24–28.

Liu, M., Y.-Y. Wang, F. Zhang, and K. Kotian. 2013a. *Realistic Strain Capacity Models for Pipeline Construction and Maintenance.* Final report. Revision 1. United States Department of Transportation, Pipeline and Hazardous Materials Safety Administration, DTPH56-10-T-000016. December 9.

Liu, M., Y.-Y. Wang, F. Zhang, X. Wu, and S. Nanney. 2013b. "Refined Compressive Strain Capacity Models." Proceedings of the 6th Pipeline Technology Conference, Ostend, Belgium, October 7–9.

Liu, M., Y.-Y. Wang, M. Sen, and P. Song. 2016. "Integrity Assessment of Post-Peak-Moment Wrinkles." Proceedings of the 11th International Pipeline Conference, Paper No. IPC2016-64654, Calgary, Alberta, Canada. September 26–30.

Liu, B, Y.-Y. Wang, X. Chen, and D. Warman. 2020. "Effects of Biaxial Loading on the Tensile Strain Capacity of Girth Welds with Weld Strength Undermatching and HAZ Softening." Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9663, Calgary, Alberta, Canada. September 28–October 1.

McCormack, H., A. Thomas, and I. Solomon. 2011. *The Capabilities and Limitations of Satellite InSAR and Terrestrial Radar Interferometry:* Available at: http://www.dijkmonitoring.nl/_sitefiles/file/technologieen-en-toepassingen/Thomas%20et.%20al%20-%20The%20capabilities%20and%20limitations%20of%20satellite%20InSAR%20and%20terrestrial%20radar%20interferometry.pdf. Accessed April 10, 2020.

McKenzie-Johnson, A., and D. West. 2020. "Introduction to Section 3 – Geohazard Monitoring." In Salama et al. (eds.). *Pipeline Integrity Management Under Geohazard Conditions*: ASME Book No. 861998, pp. 103–104.

Moretto, S., F. Bozzano, C. Esposito, P. Mazzanti, and A. Rocca. 2017. "Assessment of Landslide Pre-Failure Monitoring and Forecasting Using Satellite SAR Interferometry." *Geosciences* Vol. 7, No. 36. doi:10.3390/geosciences7020036.

Muhlbauer, W.K. 2019. "Pipeline Risk Assessment – A New Era." In: *Pipeline Geohazards: Planning, Design, Construction and Operations.* Rizkalla, M., and R.S. Read, R.S (eds). American Society of Mechanical Engineers (ASME), New York, New York.

Nasrallah, J., B. Theriault, A. Kammereck, D. Yu, B. Liu, and Y.-Y. Wang. 2020. "Case Study of a Teamed Approach to Geohazard Identification, Characterization, and Mitigation." Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-14963, Calgary, Alberta, Canada. September 28–October 1.

Newton, S., A. Zahradka, G. Ferris, and M. Porter, M. 2020. "Use of a Geohazard Management Program to Reduce Pipeline Failure Rates." In Salama et al. (eds.) *Pipeline Integrity Management Under Geohazard Conditions*: ASME Book No. 861998, pp. 133–137.

PHMSA. 2019. Advisory ADB 2019-02: *Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards*. Pipeline and Hazardous Materials Safety Administration. Available at: https://www.federalregister.gov/documents/2019/05/02/2019-08984/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-earth-movement-and-other. May 2.

PHMSA. 2020. *Overview: Integrity Management*. Pipeline and Hazardous Materials Safety Administration. Available at: https://primis.phmsa.dot.gov/comm/IM.htm., accessed January 22, 2020.

Pohll, G.M., R.W.H. Carroll, D.M. Reeves, R. Parashar, B. Muhunthan, S. Thiyagarjah, T. Badger, S. Lowell, and K. Willoughby. 2013. *Design Guidelines for Horizontal Drains used for Slope Stabilization*. Washington State Department of Transportation Report No. WA-RD 787.1.

Popescu. R. 1999. *Finite Element Analysis of Pipe/Soil Interaction Phase I – Two- Dimensional Plane Strain Analysis*. Prepared for the Geological Survey of Canada, C-CORE Publication 99-C23. June.

Popsecu, R., P. Guo, and A. Nobahar. 2001. *3D Finite Element Analysis of Pipe/Soil Interaction.* Final report. Prepared for Geological Survey of Canada, Chevron Corp. and Petro Canada, C-CORE contract report 01-C08.

Rizkalla, M., and R. Read (eds.). 2019. *Pipeline Geohazards, Planning, Design, Construction and Operation*s.–American Society of Mechanical Engineers (ASME), New York, New York.

Rosen. 2019. *Integrity Management of Geohazards*. Webinar. July.

Salama, M.M., Y.-Y. Wang, D. West, A. McKenzie-Johnson, A.B. A-Rahman, G. Wu, J.P. Tronskar, J. Hart, and B.J. Leira (eds.). 2020. *Pipeline Integrity Management Under Geohazard Conditions*: ASME Book No. 861998.

Sancio, R., A. Rice, J. Audibert, D. Morgan, and J. Rattray. 2018. *Guidelines for Management of Geohazards Affecting the Engineering and Construction of New Oil and Natural Gas Pipelines.* PRCI, Chantilly, Virginia. Geosyntec Consultants, Inc.

Sancio, R., and D. Vance. 2020. "Example of a Semi-Quantitative Stream Crossing Hydrotechnical Hazard Assessment for a New Pipeline." In Salama et al. (eds.), *Pipeline Integrity Management Under Geohazard Conditions.* ASME Book No. 861998, p. 151–157.

SGA Webinar Series. 2015. *Determining Geohazard Threats to Buried Onshore Pipelines, Assessing Pipeline Response, Mitigation Alternatives, Monitoring*. SGA Webinar Series. February.

SkyGeo. 2020. *InSAR Technical Background*. Available at: https://skygeo.com/insar-technical-background/. Accessed April 6, 2020.

The Nature Conservancy. n.d. *Improving Steep-Slope Pipeline Construction to reduce Impacts to Natural Resources*. Operators and The Nature Conservancy.

Theriault, B., J.D. Hart, A. McKenzie-Johnson, and S. Paulsen. 2019. "Correlation of Single-Run ILI IMU Bending Strain Features to Geohazard Locations." Proceedings of the Conference on Asset Integrity Management-Pipeline Integrity Management Under Geohazard Conditions. Houston Texas. March 25–28.

Tre Altimira. 2020. SAR Imagery. Available at: https://site.tre-altamira.com/insar/. Accessed April 9, 2020.

Turner, A.K., and R.L. Schuster (eds). 1996. *Landslides, Investigation and Mitigation*. Turner and Schuster, eds. National Academy Press. Washington, D.C. TRB SR 247.

USGS. 2004. *Landslide Types and Processes*. United States Geological Survey Fact Sheet 2004-13723072. July.

Wang, Y.-Y. 2019a. *Guidance for Assessing Buried Pipelines after a Ground Movement Event.* Prepared for PRCI by CRES. Catalog No. PR-350-164501-R01.

Wang, Y.-Y. 2020. "Strain-Based Design and Assessment – Concepts and Gaps." Pipeline Integrity Management under Geohazard Conditions, Paper No. AIMPIMG2019-1067, M. Salama, Y.-Y. Wang, et al., eds, ISBN: 978-07918-6199-8, ASME, New York, New York.

Wang, J., B. Liu, Y.-Y. Wang. 2019. "Girth Weld ECA Software Version 1.0." Prepared for PRCI project API-3-1, PRCI contract PR-350-174508. March.

Wang, Y.-Y., and M. Liu. 2013. "Status and Applications of Tensile Strain Capacity Models." Proceedings of the 6th Pipeline Technology Conference, Ostend, Belgium, October 7–9.

Wang, Y.Y., M. Liu, Y. Song, M. Stephens, R. Petersen, and R. Gordon. 2011. *Second Generation Models for Strain-Based Design*. Prepared for US DOT PHMSA by PRCI and CRES with assistance from C-FER Technologies and Microalloying International. July 31. Available at: http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=201.

Wang, Y.-Y., D. Rudland, R. Denys, and D.J. Horsley. 2002. "A Preliminary Strain-Based Design Criterion for Pipeline Girth Welds," Proceedings of the International Pipeline Conference 2002, Calgary, Alberta, Canada. September 29–October 3.

Wang, Y.-Y., M. Liu, F. Zhang, D. Horsley, and S. Nanney. 2012a. "Multi-Tier Tensile Strain Models for Strain-Based Design Part 1– Fundamental Basis." Proceedings of the 9th International Pipeline Conference, Paper No. IPC2012-90690, Calgary, Alberta, Canada. September 24–28.

Wang, Y.-Y., M. Liu, and Y. Song. 2012b. "Tensile Strain Models for Strain-Based Design of Pipelines." Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering. Rio de Janeiro, Brazil. July 1–6.

Wang, Y.-Y., F. Zhang, M. Liu, W. Cho, and D. Seo. 2012c. "Tensile Strain Capacity of X80 and X100 Welds." Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, Rio de Janeiro, Brazil. July 1–6.

Wang, Y.-Y., D. Horsley, S. Mamdouh, and M. Sen. 2014. "General Framework for Strain-Based Design and Assessment of Pipelines." Proceedings of the 10th International Pipeline Conference. Paper No. IPC2014-33745. Calgary, Alberta, Canada. September 9–October 3.

Wang, Y.-Y., D. Horsley, and S. Rapp. 2016a. "Evolution of Linepipe Manufacturing and Its Implications on Weld Properties and Pipeline Service." Proceedings of the 11th International Pipeline Conference, Paper No. IPC2016-64632, Calgary, Alberta, Canada. September 26–30.

Wang, Y.-Y., D. West, D. Dewar, A. McKenzie-Johnson, and M. Sen, M. 2016b. "Integrity Management of Ground Movement Hazards," Proceedings of the 11th International Pipeline Conference, Paper No. IPC2016-64513, Calgary, Alberta, Canada. September 26–30.

Wang, Y-Y., B. Wang, K. Kotian, D. West, D. Dewar, W. Webster, S. Rapp, J. Hart, and A. McKenzie-Johnson. 2017. *Management of Ground Movement Hazards for Pipelines*: CRES Project No. CRES-2012-M03-01, Joint Industry Project (JIP) February 28.

Wang, Y.-Y., S. Rapp. D. Horsley, D. Warman, and J. Gianetto. 2018. "Attributes of Modern Linepipes and Their Implications on Girth Weld Strain Capacity." Proceedings of the 12th

International Pipeline Conference, Paper No. IPC2018-78809. Calgary, Alberta, Canada. September 24–30.

Wang, Y.-Y., D. Jia, S. Rapp, and D. Johnson. 2019. "Low Strain Capacity Girth Welds of Newly Constructed Pipelines and Mitigative Approaches." Proceedings of the 1st AIM-PIMG Conference, AIMPIMG-1064, Houston, Texas. March 25–28.

Wang, B., B. Liu, Y.-Y. Wang, and O. Huising. 2020a. "Estimation of Tensile Strain Capacity of Vintage Girth Welds." Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9664, Calgary, Alberta, Canada. September 28–October 1.

Wang, Y.-Y., D. Yu, and M. Cook. 2020b "Structured Response Plan after a Ground Movement Event." Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9717, Calgary, Alberta, Canada. September 28–October 1.

Yu, D., Y-Y. Wang, X. Chen, and B. Liu. 2020. "A Review of Pipe-Soil Interaction Models for Strain Demand Estimation." Proceedings of the 2020 13th International Pipeline Conference. Paper No. IPC2020 9678. Calgary, Alberta, Canada. September 28–October 2.

Appendix A
Examples of Applying FFS Assessment to Landslide Hazard Management

Appendix A: Examples of Applying FFS Assessment to Landslide Hazard Management

The examples provided here illustrate possible applications of fitness-for-service (FFS) assessment as a part of a landslide hazard management program. Understanding the hazards, the stress/strain imposed on a pipeline by such hazards, and the pipeline's tolerance to such stress/strain provides an opportunity to make the most effective mitigation decisions.

These examples are for illustrative purposes. They are not exhaustive or exclusive. Unless noted otherwise, the numerical values of the strain demand and strain capacity and other characteristics are slightly altered to protect the identity of the pipeline operators.

A.1 Integrated Approach to Landslide Hazard Management

The events described here occurred in 2019 in the eastern United States (Nasrallah et al. 2020). A geotechnical investigation suggested that a pipeline might have been impacted by previous and current landslides. The owner engaged a consultant to conduct an FFS assessment and to work with a geotechnical firm to develop necessary mitigation and monitoring measures. The FFS assessment was to estimate the strain demand imposed on the pipeline by the landslide, assess the strain capacity of the pipeline, and determine the current integrity status and tolerance to further ground movement.

In February 2019, when the current ground movement was identified, information on the landslide and the pipeline properties was limited and still being collected. With the limited information, including the span and maximum magnitude of the landslide, the consultant performed a preliminary assessment of the strain demand with simplified analytical models. Combined with strain capacity estimates from previous work for the same pipeline, the consultant concluded that the strain demand was lower than the lowest strain capacity of all girth welds in the affected segment by a comfortable margin. Consequently, immediate field work that might have involved strain/stress relief was deemed unnecessary, and the line was allowed to operate at its normal pressure. In addition, working on the saturated soil in early spring carried a risk of further destabilizing the ground and causing additional movement, especially considering the pipe at the location was under over 10 feet of cover and the pipeline was on a side slope.

In March and April 2019, detailed information became available, including the landslide characteristics from a field survey by the geotechnical firm and site-specific pipeline properties collected by the owner. Based on the updated information, the consultant performed a refined assessment to obtain the strain demand and site-specific strain capacity. Pipe-soil interaction modeling performed as a part of the assessment indicated a lower strain demand 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 pipe joints and girth welds, the case-specific strain capacity analysis focused on two manual tie-in girth welds, as other types of welds in the affected segment were expected to have a higher strain capacity than those two tie-in welds.

This new analysis produced a slightly higher strain capacity than the preliminary strain capacity estimates. The consultant concluded that strain/stress relief of the affected segment was unnecessary due to the large margin that existed between the strain capacity and the strain demand. Concurrently, site stabilization work involving the diversion of groundwater was conducted by the geotechnical firm. In addition, 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 geotechnical firm and the consultant worked together to develop bell-hole locations so that the same locations were used for the work on the groundwater management and strain gauge installation, thus minimizing the amount of excavation. The consultant provided intervention thresholds for possible mitigation actions should the strain measured by the strain gauges exceed these thresholds.

The integrated approach for hazard management and FFS assessment considerably reduced the amount of field work, while the line was kept in service with a reasonable assurance of integrity. The site work simultaneously addressed the immediate threat and provided a path forward for future evaluation through the use of strain gauge monitoring and intervention strain thresholds.

A.2 Low Strain Demand Justifying Continued Operation

A landslide displaced a medium diameter pipeline by 3 feet over 350 feet of span. A Level 1 strain demand analysis meant to produce upper bound value concluded that there was a strain demand of less than 0.2%. Analysis of the time of year the pipeline was installed determined the baseline strain from temperature differential was low. Since this strain demand level was below the lower bound strain capacity of the welds, the integrity of the affected segment was judged sound. An allowance of 1 foot of additional movement was given before mitigation action should be implemented. The line was put back to full pressure service while site monitoring was implemented. Frequent follow-up surveys of the line found no additional movement.

A.3 High Strain Demand and Even Higher Strain Capacity Justifying Continued Operation with a Planned Site Mitigation

A landslide displaced a small-diameter pipeline constructed of low-grade electric resistance welded (ERW) pipes by 6 feet over 130 feet of span. A Level 1 strain demand analysis meant to produce upper bound value estimated a strain demand in excess of 0.7%. The review of MTRs of the pipe and the welding procedure, including welding consumables, determined that weld strength overmatched the pipe strength by a 10% to 20% margin. The affected welds did not include tie-in welds. All of the welds had been inspected and accepted by workmanship flaw acceptance criteria during construction, and none had been repaired. The level of heat-affected zone (HAZ) softening was estimated to be moderate. It was judged unlikely that strain was localized in the weld region.

The strain capacity of the segment was estimated in excess of 1.0% as the welds were determined to be stronger than the pipe. The line was judged to be safe for operation. However, due to the high level of strain demand and likely low strain hardening characteristics of the ERW pipes, a planned mitigation of the site, including stress/strain relief, was recommended. Site monitoring was put in place until the planned mitigation could be completed.

A.4 Moderate Strain Demand on Low Strain Capacity Girth Welds Leading to Mitigation Work

A segment of a pipeline was suspected to have been affected by a landslide. The segment contained a field cold bend. Strain demand was analyzed using an inertial measurement unit (IMU) bending strain report. Based on this analysis, the total strain demand from the landslide was estimated at approximately 0.3%. The affected pipe segment was constructed with “super strong” X70 pipes with actual yield strength approaching 90 kilopound force per square inch (ksi). Girth welding was done with shielded metal arch welding (SMAW) processes using E6010/E8010 cellulosic consumables. The review of the chemical composition of the pipe determined that the pipe is susceptible to high levels of HAZ softening.

With the girth welds having weld strength undermatching and HAZ softening, the strain capacity of the welds was estimated at 0.3% to 0.4%. Welds having similar properties have failed at a strain demand at 0.35% to 0.40%. Because of this low strain capacity, mitigation of the site was recommended. A complete stabilization of the site was considered difficult because the surrounding soil was a part of a mining spoil. Possible options considered included rerouting the pipe around the slope, routing the pipeline beneath the landslide via horizontal directional drilling (HDD), or enhancing the strain capacity of the girth welds (using Type-B sleeves or pipe replacement).

Appendix B
Example Classification and Decision-Making (CDM) System

Appendix B: Example Approach for Classification and Decision-Making System (CDM)

This guideline does not prescribe or recommend a particular classification and decision-making (CDM) system, other than the conceptual recommendations for a 95-percent concept described previously in Section 7.3. In evaluating how an operator might implement its own CDM system for landslide hazard management, it is useful to consider an example of an actual system. The CDM system provided below is modified and simplified slightly from a system developed for a baseline inventory of landslide hazards in the western Appalachians.

Landslides are classified based on five attributes: proximity to pipeline centerline, activity, movement rate, depth of landslide relative to pipeline depth of cover, and strain previously induced on a pipeline. Strain capacity is based on prior testing where available, otherwise, strain capacity is estimated with a conservative assumption. Consequence is assumed to be fixed in this example, although this approach can be modified to include variable consequence inputs.

This CDM system provides an example of a qualitative, semi-prescriptive system where subject matter expert (SME) experience and knowledge are important but are not the basis for decision-making. An SME determines the attributes needed for classification but does not decide whether or not a landslide is a high or low threat and does not determine the response. The threat or risk is determined by a predetermined matrix.

This CDM system also provides an example of some of the key concepts discussed in this document: the 95-percent concept, the interrelationship between the phased assessment system, fitness-for-service (FFS) assessment, and classification, and how prescriptive systems codify company risk tolerance and resource availability.

B.1 Example CDM System Attributes

The attributes used for classification are as follows:

- Landslide Proximity to Pipeline (Figure B-1):
  - Landslide crosses the centerline (CC)
  - Right-of-way (ROW) crosscuts (e.g., post-dates) the landslide with no visual indications of post-construction landslide movement (RC)
  - Proximal (P): In this example, a landslide is within 50 feet of the centerline, but not crossing
  - Distal (D): In this example, a landslide more than 50 feet from the centerline
- Landslide Activity
  - Active (A): A landslide that
    - has fresh, sharp landslide features and exposed soil suggesting that it is currently moving or has moved recently within the past five years, or
    - has evidence of movement within the past five years, based on monitoring instrument measurements, direct observation, or inference.

- Inactive (I): A landslide that
  - has rounded, weathered-appearing landslide features with no exposed soil suggesting that it has not moved within the past five years, and the conditions that caused the previous movement(s) have not appreciably changed, and reactivation or further movement is a distinct possibility, or
  - is definitively known to not have moved within the past five years based on monitoring or other quantifiable data.

- Landslide Movement Rate[28]
  - Slow (S): A landslide in which the rate of movement is less than 2 feet per year.
  - Moderate (M): A landslide in which the rate of movement is between 2 and 20 feet per year.
  - Rapid (R): A landslide in which the rate of movement is greater than 20 feet per year.
- Landslide Depth[29]
  - Above the pipeline (A): A landslide where the basal slip surface is above a pipeline.
  - Below the pipeline (B): A landslide where the basal slip surface intersects or is below the pipeline.
- Pipe Strain[30]
  - None (S-0): No reported bending strain
  - Low (S-1): <0.15% bending strain[31]
  - Moderate (S-2): 0.15% to 0.2% bending strain
  - High (S-3): 0.2% to 50% of estimated strain capacity
  - Very High (S-4): >50% of estimated strain capacity

The CDM system assumes that a phased assessment approach has been performed and that enough information is available to determine an action. Other components of the CDM system (not provided here) provide the decision-making to determine whether to proceed from Phase I to Phase II and from Phase II to Phase III. Typically, subsurface investigations (Phase III) are only performed when there is significant ambiguity remaining after the performance of the phased investigations or subsurface information is needed for a mitigation decision.

As shown, the decision on what types of monitoring to be installed are generally prescriptive, while the need for and type(s) of mitigation are determined on a case-by-case basis. The locations for

---

[28] The delineations between movement rate approximately reflect landslides where strain accumulation is measured in years (slow), weeks or months (moderate), and minutes to days (rapid).

[29] Estimated during Phase II. Given that pipelines are generally relatively shallow, simple geometric relationships are usually sufficient to determine if a pipeline is above or below a landslide slip surface. If this relationship is ambiguous and it effects the response, the analysis may progress to Phase III.

[30] Usually derived from single-run inertial measurement unit (IMU) bending strain analysis

[31] Typical reporting limit for IMU bending strain is 0.125%; thus, this category reflects a low-level of bending strain.

monitoring instrumentation are determined by SMEs using guidelines but are not prescriptively predetermined.

Once enough information has been collected, each landslide (or unconfirmed landslide if there is remaining uncertainty) is classified according to the example matrix provided in Table B-1. The classification is based on a combination of the landslide characteristics (activity and movement rate), the relationship of the landslide to a pipeline(s) (position and depth[32]), the prior effects of the landslide on the pipeline (strain demand as measured by IMU bending strain), and the pipe characteristics (estimated strain capacity). Consequence is deliberately not included in this matrix because several historical landslide-caused pipeline ruptures of natural gas pipelines in this region resulted in property damage in areas that were "Class 1" locations and, thus, would have been modeled as low consequence. However, there is no reason that the matrix could not be modified to include consequence if desired.

[32] To simplify the example for the purposes of this guideline, the depth component has been dropped, assuming that all landslides are at or below pipe depth.

Table B-1. Example Landslide Classification and Decision Matrix[33]

Proximity	Activity	Movement	Strain				
			S-0	S-1	S-2	S-3	S-4
CC	A	M	R4	R4	R4	R5	R6
		S	R3	R3	R3	R4	R5
	I	M	R3	R3	R4	R4	R5
		S	R3	R3	R3	R4	R5
RC	A	M	R3	R3	R4	R5	R6
		S	R2	R2	R3	R4	R5
	I	M	R2	R2	R3	R4	R5
		S	R2	R2	R3	R4	R5
P	A	M	R3	N/A	N/A	N/A	N/A
		S	R2	N/A	N/A	N/A	N/A
	I	M	R2	N/A	N/A	N/A	N/A
		S	R2	N/A	N/A	N/A	N/A
D	N/A	N/A	R1	N/A	N/A	N/A	N/A

Risk:

	Very High
	High
	Med-High
	Medium
	Med-Low
	Low

[33] The "R" options are response options listed in Table B-2.

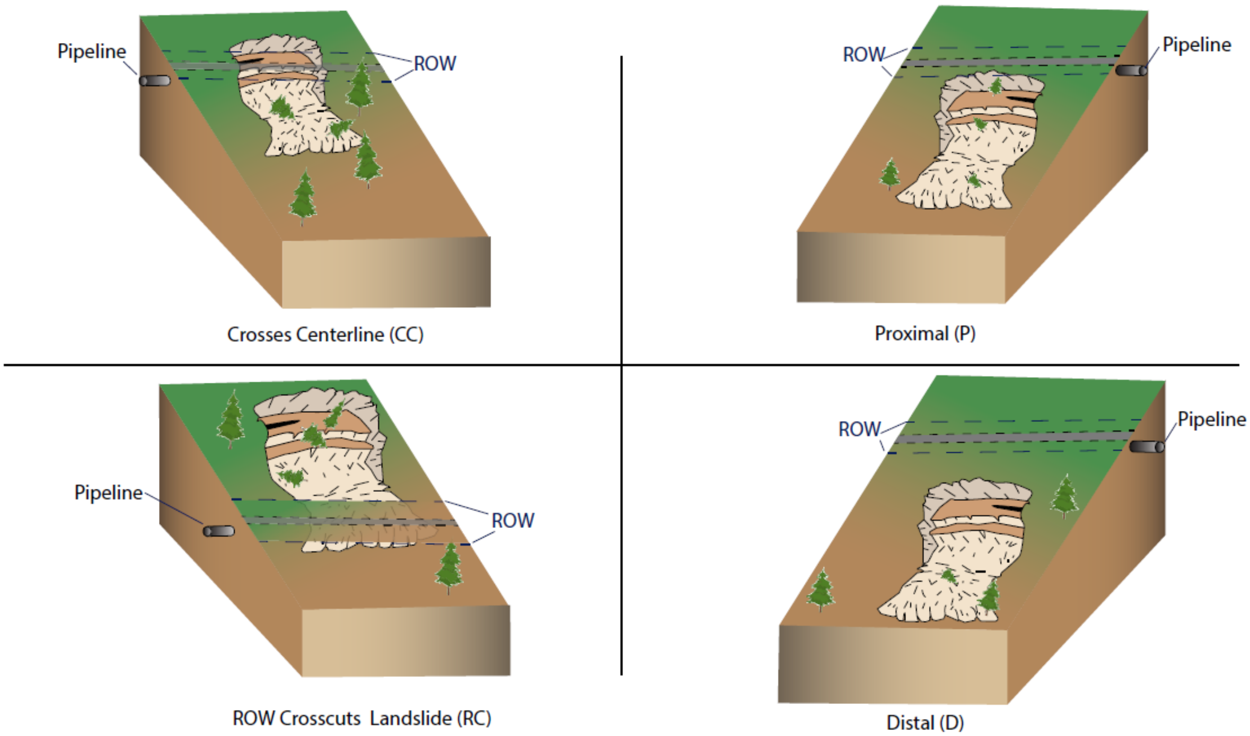

Figure B-1. Conceptual examples of the four different landslide proximity to pipeline scenarios

B.2 Example CDM Actions

Once the landslide or unconfirmed landslide has been classified, the action is then determined by applying the matrix in Table B-1. Under this system, there are six standard response options (Table B-2):

- R1: Risk Acceptance (no further action)
- R2: Regional monitoring (through repeat light detection and ranging [LiDAR], interferometric synthetic aperture radar [InSAR], repeat aerial photographs, or aerial reconnaissance).
- R3: Regional monitoring + install survey points (survey points monitored quarterly or annually).
- R4: Regional monitoring + survey points + strain gauges (strain gauges monitored daily using remote monitoring units).
- R5: Schedule mitigation within next year.
- R6: Immediate mitigation (as soon as possible).

Table B-2. Example CDM Actions

Response Option	Action					
	Risk Acceptance	Regional Monitoring	Survey Points	Strain Gauges	Scheduled Mitigation	Immediate Mitigation
R1						
R2						
R3						
R4						
R5						
R6						

These response actions are ordered in accordance with increasing apparent risk as established by the matrix, ranging from lowest risk (risk acceptance) to highest risk (mitigation as soon as possible).

B.3 Omissions from Example CDM System

In accordance with the 95-percent concept, the example CDM system has been designed to accommodate the landslide hazards most commonly encountered in the region for which it was prepared. Notably, it does not include such landslide phenomena as the following:

- Rockfall
- Debris flows
- Long run-out landslides
- Quick clay landslides
- Landslides in permafrost
- Landslides triggered by human activities (such as mining and timber harvest)

These phenomena are not included in the CDM system because in the region for which the CDM system was prepared (western Appalachia), such phenomena are relatively rare. If such phenomena were identified, they would be addressed on a case-by-case basis under this system. If one of these types of landslides was regularly encountered (for example, a new pipeline system is acquired with exposure to many debris flows), the CDM system could be modified to accommodate the new landslide type.

B.4 Sample Applications of Example CDM System for Unconfirmed Landslides

The following examples are fictional but are provided to demonstrate how the example CDM system is applied to unconfirmed landslides.

Case 1 – Distal (D) Unconfirmed Landslide

In this example a possible distal landslide is identified during a Phase I assessment. No evidence is observed of long run-out or other behavior that would modify the CDM system or dictate case-by-case decision-making. Because the possible landslide is distal, the other attributes (strain, movement rate, depth, etc.) are irrelevant, and the risk level is assigned as low. The action assigned for this possible landslide is "risk acceptance."

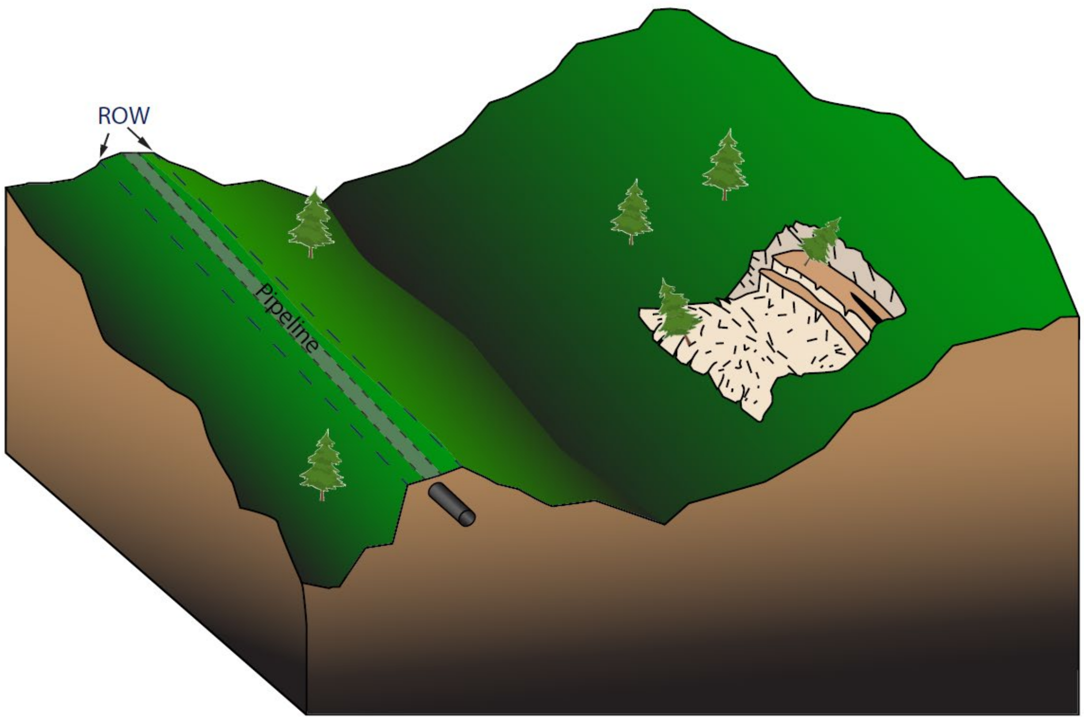

Figure B-2: Case 1 – Distal Unconfirmed Landslide

Case 2 – Proximal (P), Active (A), Slow (S)

In this example a possible landslide is identified in proximity to a pipeline during a Phase I assessment, and a Phase II assessment is scheduled to further assess the possible landslide. The follow-up Phase II confirms that the feature is a landslide and, based on fresh soil cracks and tilted trees, concludes that the landslide is active, with a slow rate of movement. Strain and depth are not relevant since the landslide does not cross the centerline. Based on these characteristics, a risk level of "medium-low" is assigned and monitoring of the landslide through regional monitoring (such as repeat LiDAR) is selected to monitor this landslide and the adjacent area.

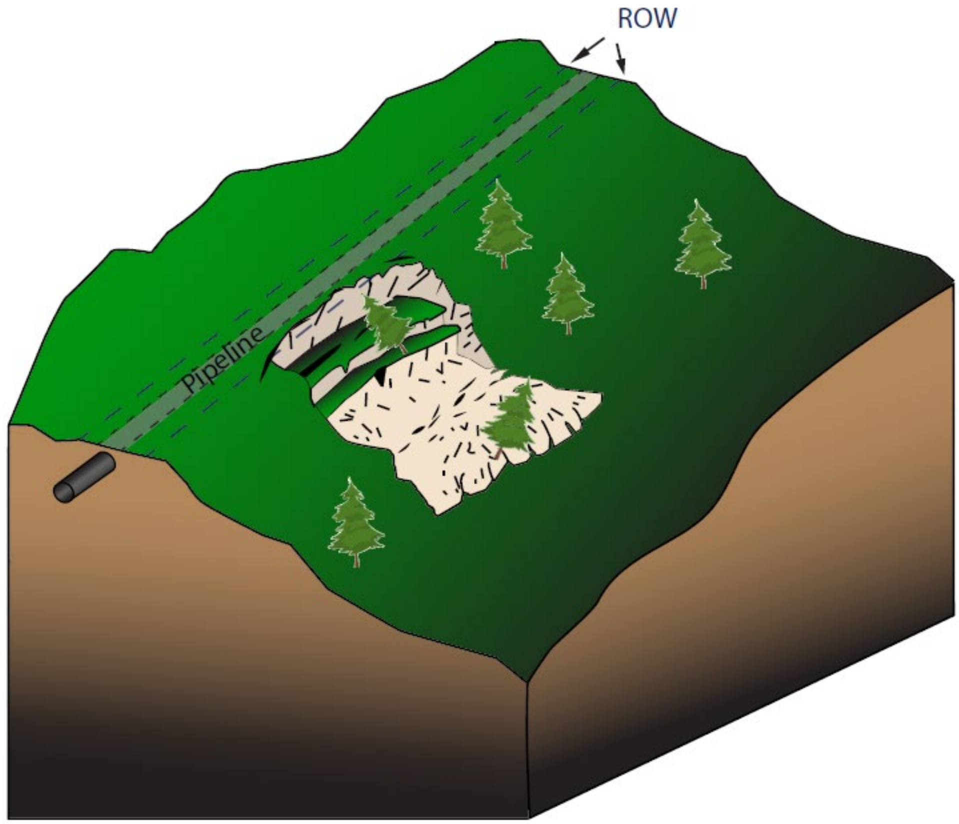

Figure B-3: Case 2 – Proximal, Active, Slow Landslide

Case 3 – Crosses Centerline (CC), Active (A), Moderate (M), Below the Pipeline (B), Moderate Strain (S-2)

In this example, a possible landslide is identified during a Phase I that appears to cross a pipeline centerline. The subsequent Phase II concludes that the landslide is active with a moderate rate of movement. A review of IMU bending strain finds a bending strain feature with a moderate level of strain coincident with the landslide and concludes that the strain was likely induced by the landslide.

Based on these characteristics, a risk level of "medium-high" is assigned, and the action selected is to monitor the landslide through a combination of regional monitoring (e.g., repeat LiDAR), survey points, and strain gauges. An action plan is created to implement mitigation in the event of further increases in strain.

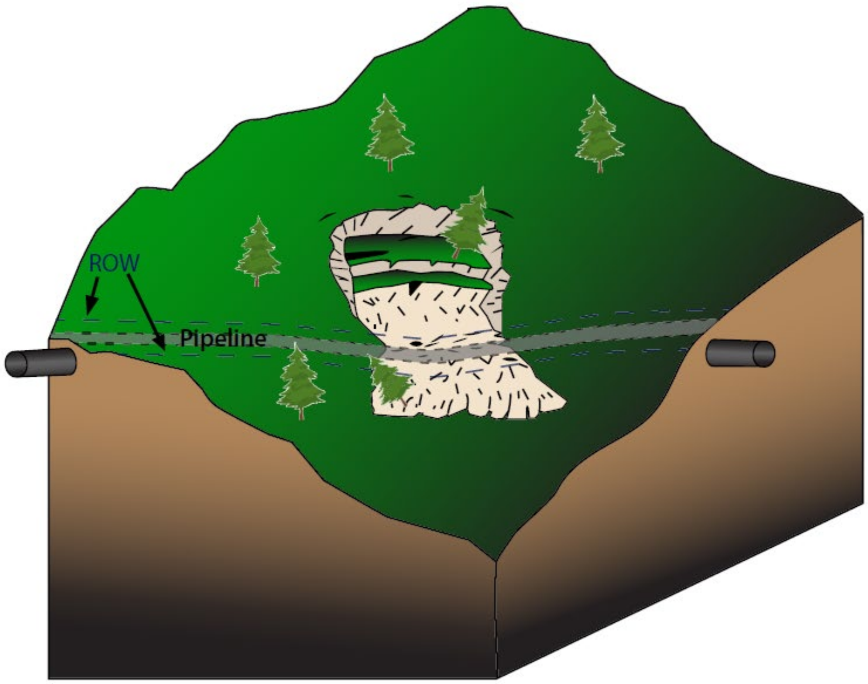

Figure B-4: Crosses Centerline, Active, Moderate, Below the Pipeline, Moderate Strain Landslide

Case 4 – Landslides Triggered by Active Coal Mining

In this example, the expansion of an open pit coal mine has triggered landslides in the vicinity of a pipeline. Because this is an unusual situation, the response and further actions are determined on a case-by-case basis.

B.5 Sample Applications of CDM System for Ongoing Monitoring

The following are fictional examples of application of a CDM system for ongoing monitoring provided for illustration purposes only. In these examples, landslides or landslide-prone areas have been identified and a monitoring program implemented as a risk reduction measure. The operator has established qualitative and quantitative thresholds for additional action based on the monitoring type.

Case 1 – New Unconfirmed Landslide Identified by LiDAR

In this example, repeat LiDAR is used as a regional monitoring method for a landslide-prone area of North Dakota. Between the baseline collection of LiDAR and the initial repeat, an unconfirmed landslide formed in proximity to the monitored pipeline. The operator had established a qualitative threshold that all new unconfirmed landslides that formed in proximity or over the monitored pipeline should be evaluated with a ground reconnaissance (Phase II). Following the Phase II, it is established that the feature is a landslide and may have the potential to retrogress and affect the pipeline. The operator decides in this instance that additional monitoring is needed and installs remotely monitored strain gauges to provide daily monitoring of the pipeline.

Case 2 – Bending Strain Identified by Repeat IMU Runs

In this example, an operator uses repeat IMU bending strain analyses to monitor a pipeline segment in a landslide-prone area. The most recent bending strain report indicates that a bending strain of approximately 70% of the operator-estimated strain capacity for the monitored segment has formed between the prior and current IMU runs. The operator had previously determined a quantitative threshold that any bending strain features greater than 50% of the established threshold should result in immediate depressurization of the affected segment, followed by an evaluation. Cross-comparison of the IMU bending strain results with the results of repeat LiDAR indicates that a landslide has occurred at the bending strain location. The pipeline is depressurized, and additional evaluation of the landslide is conducted. Following the evaluation, the operator decides to mitigate the landslide site.

Case 3 – Survey Points with Remotely Monitored Strain Gauges

In this final example, an operator identifies and characterizes a landslide site and determines that the appropriate course of action was to monitor using a combination of regional monitoring, survey points, and remotely monitored strain gauges. The latest round of survey point monitoring indicates that movement of up to 12 inches had occurred between the prior and current rounds of surveying. The operator had previously established a quantitative threshold that more than 6 inches of movement required additional assessment. The operator cross-compares the survey point results with the strain gauge results, which showed no change. To confirm that the landslide had not affected the pipeline, the operator schedules an evaluation. The evaluation concludes that landslide movement had occurred, but that it appeared to be above the pipe depth. Based on the results of the strain gauges and field evaluation, the operator decides to continue with the previously established monitoring program.