Pipeline Geohazards: Planning, Design, Construction and Operations

Second Edition of Pipeline Geo-Environmental Design and Geohazard Management

Edited by
Moness Rizkalla
Rodney S. Read
PIPELINE GEOHAZARDS

Planning, Design, Construction and Operations

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ASME
SETTING THE STANDARD
# Table of Contents

IN MEMORIAM MICHAEL C. METZ (1943–2017)

1  INTRODUCTION  
*Moness Rizkalla and Rodney S. Read*

1.1  Introductory Remarks  
1.1.1  Setting the Context  
1.1.2  Structure of the Book  

Reference

2  TERRAIN ANALYSIS FOR PIPELINE CORRIDOR SELECTION  
*Lynden A. Penner, Jason I. Cosford, and Troy A.M. Zimmer*

2.1  Introduction

2.2  Terrain Mapping and Geohazard Assessment  
2.2.1  Terrain Analysis Tools  
2.2.2  Air Photo Interpretation  
2.2.3  Satellite Imagery  
2.2.4  Digital Surface Modeling  
2.2.5  Existing Maps and Reports  
2.2.6  GIS and Geospatial Data Visualization

2.3  Terrain Features Evaluated for Geohazard Mapping and Assessment  
2.3.1  Surficial Materials and Geotechnical Properties  
2.3.2  Topography  
2.3.3  Drainage  
2.3.4  Groundwater Conditions  
2.3.5  Geohazards  
2.3.6  Cultural and Environmental Constraints

2.4  Applications of Terrain Analysis to Pipeline Routing, Construction, and Operation  
2.4.1  Scales of Terrain Analysis – From the Desktop to the Field  
2.4.2  Corridor and Route Selection Process  
2.4.3  Design and Construction  
2.4.4  Operation

2.5  Assessing Geohazards in Different Regions  
2.5.1  Glaciated Terrain  
2.5.2  Fluvial Terrain  
2.5.3  Permafrost Terrain  
2.5.4  Peatlands and Organic Terrain  
2.5.5  Coastal Terrain  
2.5.6  Karst Terrain
2.5.7 Mountain Terrain
2.5.8 Volcanic Terrain
2.5.9 Desert Terrain

2.6 Summary

Acknowledgments

References

Additional Reading

3 DATA GENERATION, INTEGRATION, MANAGEMENT, AND VISUALIZATION

Matt Tindall, Moness Rizkalla, and Rodney S. Read

3.1 Introduction

3.1.1 Geological Model
3.1.2 Master Database

3.2 Geographic Information Systems (GIS) Platforms

3.2.1 ArcGIS (ESRI)
3.2.2 ArcGIS PRO
3.2.3 QGIS (Open Source)
3.2.4 MapINFO Professional (Pitney Bowes)
3.2.5 Global Mapper (Blue Marble Geographics)
3.2.6 Google Earth Pro

3.3 Data

3.3.1 Vector Data
3.3.2 Raster Data
3.3.3 Spatial Reference System
3.3.4 Linear Referencing
3.3.5 Scale
3.3.6 Resolution
3.3.7 Accuracy
3.3.8 Temporality

3.4 Data Formats

3.4.1 Hard Copy Data
3.4.2 Digital Hard Copy Data
3.4.3 Native Files
3.4.4 Web Services (WMS & WFS)

3.5 Data Sources

3.5.1 Government Agencies
3.5.2 Commercial Data Vendors
3.5.3 Online Data Communities and Repositories

3.6 Digital Elevation Models (DEM)

3.6.1 Light Detection and Ranging (LiDAR) Data
3.6.2 DEM Derived Datasets
3.6.3 No-Cost DEM Products
3.7 Digital Imagery
- 3.7.1 Orthoimagery
- 3.7.2 Stereo Imagery
- 3.7.3 Multispectral and Hyperspectral Imagery
- 3.7.4 No-Cost Digital Imagery Products

3.8 Field Data

3.9 Operational Pipeline Data
- 3.9.1 Construction Records
- 3.9.2 Inspection, Maintenance, and Repair Records
- 3.9.3 Pipeline Inline Inspection (ILI) Data

3.10 Visualization Techniques
- 3.10.1 Plan View
- 3.10.2 Profile View
- 3.10.3 Three-Dimensional Presentation
- 3.10.4 Emerging Technologies

3.11 Concluding Remarks

References

4 GEOTECHNICAL ENGINEERING AND PIPELINE CONSTRUCTION INTERFACE CONSIDERATIONS
Rodney S. Read, Tim Bossenberry, Ray Boivin, Michael Wagner, and Moness Rizkalla

4.1 Introduction

4.2 Pipeline Project Structure
- 4.2.1 Phased Project Development Cycle
- 4.2.2 Early Contractor Involvement
- 4.2.3 Cost and Schedule Implications
- 4.2.4 Form of Contract Considerations

4.3 Respective Roles of Engineering and Construction
- 4.3.1 Engineering Team
- 4.3.2 Construction Team
- 4.3.3 Other Teams
- 4.3.4 Complementary Roles

4.4 Interface Dynamics
- 4.4.1 Project Setting
- 4.4.2 Route Selection
- 4.4.3 Construction Right-of-Way Components
- 4.4.4 Right-of-Way Configurations
- 4.4.5 Lateral Slopes
- 4.4.6 Longitudinal Slopes
- 4.4.7 Ridges
- 4.4.8 Valleys
- 4.4.9 Drainage, Erosion and Sediment Control
- 4.4.10 Geotechnical Control Measures
5 TRENCHED AND ELEVATED RIVER CROSSINGS
Wim M. Veldman

5.1 Introduction
5.1.1 General
5.1.2 Use of this Chapter
5.1.3 Organization

5.2 Design – Trenched Crossings
5.2.1 General
5.2.2 Quantitative Analysis Versus Qualitative Assessments
5.2.3 Integration with Other Disciplines
5.2.4 River Classification System
5.2.5 Overview of the Design Steps
5.2.6 Data Needs
5.2.7 Design Flood Criteria
5.2.8 Design Methodologies

5.3 Design – Elevated Crossings
5.3.1 Reasons for Its Use
5.3.2 Design Requirements
5.3.3 Examples

5.4 Construction - Trenched Crossings
5.4.1 Overview
5.4.2 Examples

5.5 Operational Monitoring
5.5.1 Objectives
5.5.2 Components of Integrity Management Program
5.5.3 Outline of a Monitoring Program
5.5.4 Knowing What to Look For
5.5.5 Response to Major Floods
5.5.6 Follow Up Mitigative Works
5.5.7 Monitoring Documentation
5.5.8 Lessons Learned from Arctic River Crossings

Acknowledgment

References
6 TRENCHLESS TECHNIQUES FOR PIPELINE INSTALLATION

Erez Allouche, Carrie Murray, Rodney S. Read, Shawn Gaunt, and Moness Rizkalla

6.1 Introduction

6.2 Geotechnical Considerations
   6.2.1 Geotechnical Investigation
   6.2.2 Key Geotechnical Issues

6.3 Horizontal Directional Drilling

6.4 Horizontal Boring Techniques
   6.4.1 Auger Boring
   6.4.2 Pilot Tube Guided Auger Boring

6.5 Pipe Jacking Techniques
   6.5.1 Open Face Shields
   6.5.2 Microtunneling
   6.5.3 Direct Pipe®
   6.5.4 Easy Pipe™

6.6 Percussion Techniques
   6.6.1 Pipe Ramming
   6.6.2 Horizontal Pipe Driving

6.7 Conventional Tunneling
   6.7.1 Tunnel Boring Machines (TBMs)
   6.7.2 Hand Tunneling
   6.7.3 Drill-and-Blast Tunneling
   6.7.4 Mechanical Rock Excavation

6.8 Discussion

6.9 Concluding Remarks

Acknowledgments

References

Additional Reading

7 HORIZONTAL DIRECTIONAL DRILLING

Jeff Puckett and Jeff Scholl

7.1 Introduction

7.2 The HDD Process
   7.2.1 Pilot Hole
   7.2.2 Prereaming
   7.2.3 Pullback
7.3 Site Investigation
   7.3.1 Surface Survey
   7.3.2 Subsurface Survey

7.4 Drilled Path Design
   7.4.1 Entry and Exit Points
   7.4.2 Entry and Exit Angles
   7.4.3 P.I. Elevation
   7.4.4 Radius of Curvature

7.5 Workspace Requirements
   7.5.1 Rig Side
   7.5.2 Pipe Side

7.6 Drilling Fluids
   7.6.1 Drilling Fluid Flow Schematic
   7.6.2 Functions of Drilling Fluid
   7.6.3 Composition of HDD Drilling Fluid
   7.6.4 Material Descriptions
   7.6.5 Inadvertent Returns
   7.6.6 Hydrofracture Evaluation
   7.6.7 Drilling Fluid and Spoil Disposal

7.7 Pipe Specification
   7.7.1 Installation Loads
   7.7.2 Installation Stresses
   7.7.3 Operating Loads
   7.7.4 Operating Stresses
   7.7.5 Pulling Load Calculation
   7.7.6 External Coating

7.8 Contractual Considerations
   7.8.1 Lump Sum Contracts
   7.8.2 Specifications and Drawings
   7.8.3 Daywork Contracts

7.9 Construction Monitoring
   7.9.1 Directional Performance
   7.9.2 Drilling Fluid
   7.9.3 Additional Concerns

References

8 BUOYANCY CONTROL AT WATER CROSSINGS AND OVERLOAD
   Ray Boivin

8.1 Introduction

8.2 Pipeline Codes

8.3 Buoyancy Design Philosophy
8.4 Buoyancy Control Options
8.4.1 Concrete Weights
8.4.2 Concrete Weight Dimensions
8.4.3 Concrete Reinforcement
8.4.4 Soil Weights
8.4.5 Anchors
8.4.6 Buoyancy Control Applications Summary

8.5 Buoyancy Design Forces
8.5.1 Buoyancy Calculation Input Values
8.5.2 Mineral Soil Density
8.5.3 Organic Soil Density
8.5.4 Backfill Shear Resistance
8.5.5 Density Values for Water and Other Items
8.5.6 Safety Factor
8.5.7 Soil Liquefaction
8.5.8 Pipe Stress
8.5.9 Operational Temperature

8.6 Buoyancy Control Spacing and Locations
8.6.1 Concrete Weighting Spacing
8.6.2 Soil Weighting
8.6.3 Anchor Weighting Spacing
8.6.4 Concrete and Anchor Spacing Comparison
8.6.5 Buoyancy Control Item Locations Work Process

Acknowledgments

References

Definitions and Abbreviations

9 EROSION AND SEDIMENT CONTROL OF PIPELINE RIGHT-OF-WAYS
James M. Oswell

9.1 Introduction

9.2 Need for Erosion Control and Sediment Containment

9.3 Factors Influencing Overland Erosion
9.3.1 Climate
9.3.2 Soil Properties
9.3.3 Topography
9.3.4 Ground Cover

9.4 Erosion Potential Evaluation

9.5 Pipeline Specific Erosion and Sediment Control Strategy
10 | Pipeline Geohazards: Planning, Design, Construction and Operations

9.6 Surface Erosion Control Measures and Techniques
9.6.1 Strategies for Preventing or Reducing the Opportunity for Erosion
9.6.2 Erosion Control and Sediment Management Measures and Techniques
9.6.3 Tool Box Approach to Erosion Control and Sediment Containment

9.7 Selected Erosion Control and Sediment Containment Measures for Pipeline Projects
9.7.1 Silt Fences
9.7.2 Diversion Berms/Slope Breakers
9.7.3 Wattles, Bio-Rolls, and Related Barriers
9.7.4 Revegetation
9.7.5 Surface Blankets, Mulching and Soil Covers
9.7.6 Interception Ditches and Check Dams
9.7.7 Ditch Plugs/Trench Breakers

9.8 Sediment Containment

9.9 Inspection and Contingency Measures

9.10 Summary of General Erosion Control and Sediment Containment Selection Guidelines

References

10 GEOTECHNICAL ASPECTS OF PIPELINES IN PERMAFROST
James M. Oswell

10.1 Introduction
10.1.1 Oil and Gas Pipelines
10.1.2 Geotechnical Design Process

10.2 Brief Introduction to Permafrost
10.2.1 Permafrost Definition and Distribution
10.2.2 Properties of Permafrost

10.3 Site Investigations
10.3.1 Field Drilling, Testing and Sampling
10.3.2 Geophysical Investigations

10.4 Geothermal Modeling
10.4.1 Geothermal Model Configurations
10.4.2 Geothermal Parameters
10.4.3 Geothermal Effects on a Pipeline Right-of-Way

10.5 Thaw Settlement and Frost Heave
10.5.1 Introduction
10.5.2 Thaw Settlement
10.5.3 Frost Heave
10.5.4 Mitigation for Thaw Settlement and Frost Heave Conditions

10.6 Limit State Design
10.7 Slopes Design
  10.7.1 Slope Design Process
  10.7.2 Characterization of Failure Modes
  10.7.3 Static Slope Stability Assessment and Design
  10.7.4 Thawing Slope Instability Mitigation

10.8 Construction Issues
  10.8.1 Ditching
  10.8.2 Buoyancy and Uplift of Pipelines in Thawing Permafrost
  10.8.3 Impact of Ice-Rich Permafrost on Backfill
  10.8.4 Restraint from Delta-T Effects
  10.8.5 Horizontal Directional Drilling in Permafrost

10.9 Monitoring and Mitigation

10.10 Concluding Remarks

References

Additional Reading

11 ASSESSMENT AND MITIGATION OF SEISMIC GEOHAZARDS FOR PIPELINES
Doug Nyman and George Bouckovalas

11.1 Introduction

11.2 Fault Rupture Displacement
  11.2.1 Pipeline Crossings of Active Tectonic Faults
  11.2.2 Fault Identification and Characterization
  11.2.3 Fault Crossing Design

11.3 Liquefaction
  11.3.1 Liquefaction Hazards
  11.3.2 Preliminary Screening of Potential Liquefaction Hazards
  11.3.3 Site-Specific Subsurface Investigation
  11.3.4 Mitigation of Potential Lateral Spread Hazard at Watercourse Crossings
  11.3.5 Mitigation Strategy for Buoyant Rise of Pipeline in Floodplains

11.4 Seismic Wave Propagation
  11.4.1 Idealization of Wave Propagation
  11.4.2 Past Performance of Pipelines Subjected to Wave Propagation
  11.4.3 Wave Propagation Strains in Straight Pipelines
  11.4.4 Computation of Stresses in Pipe Bends

11.5 Finite Element Analysis Methodology for PGD
  11.5.1 FEA Design Validation Process
  11.5.2 Finite Element Model Characteristics
  11.5.3 Soil-Pipeline Interaction
11.5.4 Stress-Strain Curve
11.5.5 Extent of Pipeline Model

11.6 Pipe Strain Limits for Seismic PGD Design
11.6.1 Tensile Strain Limits
11.6.2 Compressive Strain Limits

11.7 Pipe Selection and Welding
11.7.1 Pipe Selection for High-Strain Design
11.7.2 Welding and Weld Inspection

11.8 Seismic Geohazard Monitoring
11.8.1 Ground Motion Monitoring Network
11.8.2 Post-Earthquake Reconnaissance of Liquefaction
11.8.3 Fault Monitoring

11.9 Project Management for Effective Mitigation of Seismic Geohazards
11.9.1 Project Execution
11.9.2 Mitigation of Seismic-Induced PGD
11.9.3 Lessons Learned

Acknowledgement

References

12 GEOHAZARD ASSESSMENT AND MANAGEMENT - Overview
Moness Rizkalla, Rodney S. Read, and Gregg O’Neil

12.1 A Topic of Continuingly Increasing Importance

12.2 Mapping Contents of the Inter-Related Chapters 13, 14 and 15

12.3 Key Philosophical Starting Points

12.4 Fitness for Service

12.5 Key Topics in Related Chapters

Acknowledgments

References

Additional Reading

13 GEOHAZARD ASSESSMENT AND MANAGEMENT - Geohazard, Weather and External Force Mechanisms
Rodney S. Read, Moness Rizkalla, and Gregg O’Neil

13.1 Introduction

13.2 Regulatory Framework
13.3 Credible Geohazards
  13.3.1 Geohazard Assessment Philosophy
  13.3.2 Geohazard Triggers
  13.3.3 Note on Literature Review

13.4 Slope Instability Hazards
  13.4.1 Landslide
  13.4.2 Debris Flow
  13.4.3 Creep and Earthflow
  13.4.4 Rock Fall
  13.4.5 Rock Avalanche
  13.4.6 Snow Avalanche

13.5 Seismic/Tectonic Hazards
  13.5.1 Fault Displacement
  13.5.2 Soil Liquefaction
  13.5.3 Seismic Wave Propagation

13.6 Hydrotechnical Hazards
  13.6.1 Flooding
  13.6.2 Vertical Scour or Accretion
  13.6.3 Lateral Scour or Accretion
  13.6.4 Avulsion
  13.6.5 Buoyancy
  13.6.6 Rapid Lake Drainage (Outburst Flooding)
  13.6.7 Coastal Inundation (Tsunami)

13.7 Overland Erosion and Related Hazards
  13.7.1 Water Erosion
  13.7.2 Wind Erosion and Dune Migration

13.8 Ground Subsidence Hazards
  13.8.1 Soil Settlement
  13.8.2 Underground Cavity Deformation
  13.8.3 Sensitive Soil Collapse

13.9 Exposed Rock, Geochemical and Related Hazards
  13.9.1 Rock Indentation
  13.9.2 Acid Rock Drainage
  13.9.3 Saline Ground Corrosion

13.10 Permafrost and Thermal Hazards
  13.10.1 Frost Heave
  13.10.2 Thaw Settlement
  13.10.3 Thermokarsting of Massive Ice
13.10.4 Upheaval Displacement
13.10.5 Thaw-Induced Flow Mass Movement

13.11 Volcanic Hazards
13.11.1 Lahar
13.11.2 Ash Fall
13.11.3 Pyroclastic Flow
13.11.4 Lava Flow
13.11.5 Lava Tube Collapse

13.12 Discussion

13.13 Concluding Remarks

Acknowledgments

References

Additional Reading (Not Cited)

14 GEOHAZARD ASSESSMENT AND MANAGEMENT - Assessment Principles and Techniques
Moness Rizkalla, Rodney S. Read, and Gregg O’Neil

14.1 Introduction

14.2 Risk Assessment
14.2.1 Key Concepts
14.2.2 A Range of Typical Approaches
14.2.3 Advances in Pipeline Risk Assessment

14.3 Pipeline Geohazard Assessment
14.3.1 Role of Geohazard Assessment
14.3.2 Geohazard Assessment Concepts
14.3.3 Methodology Development Overview
14.3.4 Geohazard Assessment Framework
14.3.5 Reconciliation with Pipeline Risk Assessment
14.3.6 Uncertainty in Geohazard Assessment

14.4 Pipe-Soil Interaction Modeling
14.4.1 Interaction Factors
14.4.2 Practical Pipe-Soil Interaction Considerations

14.5 Operational Considerations
14.5.1 Pipeline Separation
14.5.2 Surface Loading on Buried Pipelines
14.5.3 Evaluating Blasting Effects on Buried Pipelines

14.6 Overarching Design Topics
14.6.1 Invited Technical Briefs
14.6.2 Test-of-Reasonableness Process

14.7 Concluding Remarks
Acknowledgments

References

Additional Reading

Selected References Related to PIPLIN

Annex A Supporting Tables

15 GEOHAZARD ASSESSMENT AND MANAGEMENT - Monitoring and Mitigation
Gregg O’Neil, Moness Rizkalla, and Rodney S. Read

15.1 Introduction
15.1.1 Summary of Credible Geohazards
15.1.2 Approach to Current Chapter

15.2 Geohazard Management Decision Process

15.3 Monitoring the Geohazards
15.3.1 Geohazard Monitoring Methods
15.3.2 Pipeline Monitoring Methods

15.4 Identification and Monitoring of Common Geohazards
15.4.1 Slope Instability
15.4.2 Tectonics/Seismicity
15.4.3 Hydrotechnical Geohazards
15.4.4 Erosion

15.5 Monitoring the Pipe to Detect Geohazard Impact
15.5.1 In-Line Inspection Methods
15.5.2 ILI for Geohazard Effects
15.5.3 Summary of Monitoring Options

15.6 Mitigation of Geohazards
15.6.1 Mitigation of the Geohazard
15.6.2 Pipeline Mitigation
15.6.3 Summary of Mitigation Options

15.7 2016 ASME Global Pipeline Award

References

16 INVITED PERSPECTIVES

16.1 Cost-Effective Risk Reduction Approach (CERRA): Pipeline Geohazard Case Study
Rafael G. Mora

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Liangliang Li and Lai Wei
16.3 Geotechnical Challenges for Onshore Pipelines
  Michael Sweeney

16.4 Managing Pipeline Geotechnical Issues from a Regulatory Perspective
  Alan Murray

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  W. Kent Muhlbauer

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  Jeffrey R. Keaton

16.7 Risk Assessment of Geohazards in Practice
  Noel Boylan and Suzanne Lacasse

BIBLIOGRAPHY

INDEX

AUTHOR BIOGRAPHIES

CO-EDITOR CLOSING THOUGHTS
IN MEMORIAM
MICHAEL C. METZ
1943–2017
The year 2017 brought the loss of a widely respected, career-long Arctic engineering geologist. Michael C. Metz passed away suddenly at his home in southern Utah on March 27, 2017. Mike was an engineer’s geologist equally comfortable in engineering, geology, paleo-seismology, and pipeline and facilities construction. He was responsible for innovations and their implementation in the management of route data collection and manipulation, air-photo and LiDAR interpretation, and their applications to landform identification and route design. He had a prominent role in applying the “Alaska Methodology” (Kreig and Metz, 2004) to the construction of the Trans Alaska Pipeline System (TAPS) as a member of the senior project management team as well as many subsequent projects.

After attaining his Bachelor of Science degree at Kansas State and his Master of Science degree in Geology at Washington State University, Mike’s professional career began with Atlantic-Richfield Oil Company (ARCO) at the Hanford Department of Energy Nuclear Research Facility, where he focused on the evaluation and coordination of applied technology and development projects for hazardous waste management. He went on to manage U.S. uranium exploration activities east of the Rocky Mountains for Anaconda Copper, a division of ARCO, discovering one of the largest uranium deposits in Wyoming.

In 1974, at the age of 31, ARCO assigned him to Alaska as part of the senior management team to conduct project criteria development, project description, design, and construction support for TAPS, including the marine terminal site at Valdez, where he had a $1M/day discretionary decision limit. Early in the project he realized the need for a comprehensive design and implementation plan for engineering geology field-data acquisition programs, including geologic mapping, drilling, sampling, laboratory analyses, and air-photo interpretation.

What came to be known as the “Alaska Methodology” was developed for the selection and early evaluation of pipeline alignments, potential facilities sites, and transportation routes. That methodology used terrain-unit analysis to predict subsurface engineering properties based on a database of landform vertical properties and soil characteristics developed from data in more than 8,900 borehole logs and 43,000 sample analyses. As new information was incorporated, mapping and databases were updated, facilitating more accurate and reliable route selection and minimizing effects of potential geohazards along the alignment.

The “Alaska Methodology” survived a legal challenge once construction was completed with Mike participating as an expert witness (Metz, 1983) and proved a sound basis for construction of TAPS, now celebrating 40 years of successful operation, even withstanding a 7.9-magnitude earthquake in 2002, which was triggered by displacements along the Denali Fault directly through one of TAPS special-design sections.
During the next 40 years of his career Mike applied this methodology, working with more than 25 employers and clients on 23 of the world’s largest projects, improving it as more information and technology became available. Through his foresight he designed and implemented the first GIS system for TAPS, retrieving data relegated to the trash bin after construction was completed. He continued refining this system, adding LiDAR as it became a viable tool during the many iterations of Alaska’s attempt to bring natural gas from the North Slope petroleum province to market along two major route alignments. He also participated in the development of Alpine pipeline and facilities in the Colville River delta, North Slope, Alaska, with site selection and soils investigation for the first drilled pipeline crossing of the Colville River through permafrost.

Mike exported his expertise to four projects in Russia and Canada, participating in Exxon Ventures (CIS), Conoco Arctic Inc., and the Polar Lights Pipeline Project in the Timan Pechora Basin, and worked with WorleyParsons Calgary on route selection for the Mackenzie Gas Project, looking at design verification, thaw settlement, geohazards, cross-country pipeline design, and route and soils characterization. He also participated in many other projects in Alaska, including the Kuparuk oil pipeline, the Trans Alaska Gas System, contributed to the EIS for the Pogo Mine near Delta, Alaska, and route selection, evaluation, and conceptual design for a proposed ore-concentrate slurry pipeline and railroad right of way from the Ambler Mining District to Kotzebue in western Alaska. These experiences allowed Mike to use and improve his methodology, focusing on increasing project integrity through the development of geologic models for route selection and pipeline design and its application to construction and pipeline engineering and cost estimating.

Mike was an expert in cold regions design and development for oil and gas pipelines and facilities. His expertise extended from initial route and feasibility studies, through design and construction, to facilities startup, operations and maintenance. His background incorporated many areas of innovation, including engineering terrain-unit analysis methodologies, patented technology for gas compression heating of pipelines in cold regions, evaluation of the use of insulation and geofabrics to reduce fill requirements for embankments on permafrost, and development of methods for construction access in remote cold regions.

He was a former member of the United States Committee on Permafrost, Polar Research Board, and of the US Permafrost Delegation to People’s Republic of China that inspected Chinese facilities and exchanged cold region design and construction technology. In addition, he assisted US/Russian Arctic information exchange as a consultant to the Gore-Chernomyrdin Commission.

Mike’s passing came less than a year into a well-deserved semi-retirement, during which he stood ready to help with any question or problem posed by his many career-long colleagues. Mike loved a challenge, but more than anything he was a master communicator and mediator. He enjoyed leading yearly field trips from Prudhoe Bay down the various pipeline routes he designed, noting where the “farthest north spruce tree” stood, or the “farthest north ant hill” resided and the names of grizzly bears whose ranges the routes crossed. He loved mentoring and coaching young engineers and took on a particularly bright group of them at WorleyParsons, furthering innovations in data manipulation and analysis while teaching them the basics of Arctic engineering geology.

Mike Metz was a teacher and an innovator. Henry Brooks Adams said, “A teacher affects eternity; he can never tell where his influence stops.” This is true of Mike’s teaching legacy. Those who worked with him and learned from him now span three generations of engineers, geologists,
and geophysicists. And those professionals are using what they learned from Mike to influence new generations of engineers, geologists, and geophysicists around the globe.

From the perspective of engineers working with Mike in diverse team environments, his ability to relate engineering requirements to geologists and geophysicists in understandable ways ultimately made it possible for his engineering colleagues to obtain the geological and geophysical information necessary to plan, design, build, and maintain large infrastructure projects in a multitude of environments in several countries. He made it possible for those engineering colleagues to better understand the complexities of landform properties captured in the Engineering Terrain Unit Analysis databases that he and his co-workers designed and created. The critical nature of this methodology to professional engineers charged with the safe and effective design, construction and maintenance of very large, complex and extraordinarily expensive projects was invaluable.

Mike found pathways to manage, in quantifiable terms, complex geological information so that engineers could reliably use that information. The scale of the data was immense – literally hundreds of millions of data points each with a string of properties, coordinates and identifiers in a three-dimensional landform world. All of it had to be input by hand. All the data was important to understanding the geological environment through which and over which billions of barrels of hot oil and trillions of cubic feet of cold gas would have to flow safely, reliably, and consistently. And it all worked, and it all worked well.

The success of the Trans-Alaska Pipeline, the largest civil engineering project of its time, stands as an early testament to the value and accuracy of the geological and geophysical data that Mike and his teams were able to compile and make practical sense of. Other projects followed, and the engineers of these many projects owe a great deal of their success to the ethical, practical, precise work of Mike Metz the teacher and innovator.

Mike’s innovation and remarkable career epitomize many aspects of this book – the importance of engineering geology and geologic models, use of LiDAR and increasingly sophisticated platforms for data analysis and manipulation, understanding the limitations and uncertainties associated with geology and permafrost, managing interfaces between different disciplines, and preparing the next generation of innovative thinkers and practitioners. His insightful grasp of complex problems and amicable personality and style in dealing with technical and non-technical folks alike is a model that is worth noting and emulating.

He was engaging and perceptive as well as respectful and patient while always expecting the best work of his colleagues, as he did of himself. His roots as a country boy from Kansas preceded his love for the challenges, wilderness, wildlife, and stark beauty of the Arctic that engaged his professional life and where his ashes will be spread. He and his ever-present pipe will be greatly missed.

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Tim Bossenberry
Introduction

This chapter focuses on:

1. What is the context for this book?
2. How is this book structured and organized?
3. How does the content compare to the first edition?
CHAPTER OVERVIEW


CHAPTER LAYOUT AT A GLANCE:

1.1 INTRODUCTORY REMARKS
This section provides a brief overview including the context and structure of the book.
1.1 INTRODUCTORY REMARKS

Similarly to its first edition, this book undertakes to treat onshore pipeline geohazards from a pipeline context in contrast to the classic treatment found extensively in geotechnical literature.

1.1.1 Setting the Context

Since the publication of the first edition of this book in 2008, numerous major pipeline projects have been proposed and advanced through various phases of project planning, design, and regulatory reviews and approvals. Some of these projects have been constructed and have since been commissioned and are in operations. A subset of these projects navigated through rugged and geohazard-intensive terrain as well as steadily rising stakeholder scrutiny and expectations. In undertaking these projects, the pipeline industry has responded with continuous improvements in the planning, design, construction, and operations of both proposed and existing pipelines.

As part of the industry’s overall continuous improvement, the past 10 years since the publication of the first edition of this book witnessed a resetting of the state of practice in the area of pipeline geohazard management across the planning, design, construction and operations stages of a pipeline’s life cycle. The experiences acquired in tackling challenging project environments as well as a wide range of advances in enabling technologies have underpinned the new state of practice that has emerged.

As a result of these developments, it is considered both timely and necessary to compile an expanded and updated treatment of a fuller range of pipeline geohazard management aspects to serve the global community of pipeline practitioners. A subset of those geotechnical background as well as their colleagues in the multi-disciplinary teams that deal practically with these issues. The "gray tsunami" describing the industry’s changing age profile with recent and pending retirements of many experienced practitioners lent to the timeliness of compiling an expanded and updated second edition of the book.

More specifically, the co-editors undertook to:

- Address several key topics that were not included in the first edition of this book.
- Invite the participation of a broader group of contributors.
- Adopt a more inviting and easier to navigate layout.

This book’s co-editors intended to strike a balance between providing overviews of certain topics and somewhat more detailed treatment of other topics. That balance is intended to provide a working knowledge of the current state of practice for a range of readers to better define the main issues related to pipeline geohazard management during planning, design, construction, and integrity management planning during operations.

To meet its objective, recognized experts were invited to contribute entire chapters, short Invited Technical Briefs or longer Invited Perspectives in their areas of specialization. Where suitable, some chapters include many photographs and figures of practical applications from projects around the world. Additionally, some authors elected to include supplemental references both for completeness and as recognition of the considerable work by others.

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1.1.2 Structure of the Book

The global community of pipeline geohazard management practitioners lost a respected colleague and thought leader in the passing of Mike Metz on March 27, 2017. Mike was a friend and mentor to many and he personified a commitment to continuous improvement and professional excellence in all aspects of pipeline geohazard management. In commemoration of this loss, readers will find the book starting with an In Memoriam to Mike Metz.

Following the present Introduction chapter, the expanded scope of the book is presented in 15 chapters numbered 2 to 16, before concluding with a bibliography, and a compilation of brief biographic summaries of the chapter authors. The biographic summaries of the contributors of Invited Technical Briefs embedded in some chapters and the Invited Perspectives presented in Chapter 16 are included in the respective chapters.

An interpretation of the geotechnical and topographic setting for proposed or operating pipelines serves as the foundation of planning, design, construction, and geohazard integrity management during operations. Accordingly, two chapters are presented at the start of the book titled:

- Chapter 2: Terrain Analysis for Pipeline Corridor Selection
- Chapter 3: Data Generation, Integration, Management, and Visualization

During the corridor selection stage of pipeline development, a balance is required in addressing engineering, biophysical and socioeconomic factors as noted in Chapter 2. The integration of multi-disciplinary data sets identifies boundaries for routing to address a pipelineponent’s range of responsibilities with respect to land owners, land users, the environment, and wildlife. The extensive use of remote sensing products including maps, satellite imagery and aerial photography is a hallmark of this stage of a project’s development. Enabled with the now ubiquitous application of Geographic Information Systems (GIS) in synthesizing various data sets into geological models to support decision making and communication, practitioners will find an...
overview of the very dynamic space of data set generation, integration, management, and visualization in Chapter 3. The state of practice and emerging technologies are presented in what is intended to serve as a connection between geotechnical and pipeline engineers and geomatics specialists.

Among the new topics in the expanded second edition of the book, a discussion is presented of the geotechnical aspects of pipeline construction in Chapter 4 titled “Geotechnical Engineering and Pipeline Construction Interface Considerations”. In recognizing that the geotechnical-construction interface goes beyond the mitigation of geohazards, this chapter identifies key interface points between geotechnical engineering and construction specialists, and highlights the areas where geological models and geotechnical principals can be leveraged to support construction execution planning and generate realistic estimates of geotechnical quantities.

Chapter 5 titled “Trenched and Elevated River Crossings” builds upon and expands on the recognized valuable reference on that topic presented in the first edition of the book. The chapter offers an overview of design considerations including design examples and lessons learned. Most importantly, guidance is provided in terms of what is critical and what is less critical in terms of design inputs. A discussion of water crossing construction methods is provided, differentiating between what needs “hard” versus “flexible” specifications. Practical recommendations are provided on monitoring practices during operations, mindful of what is suited and what is not suited for prediction.

The importance of the now prevalent trenchless techniques for pipeline construction is recognized by the treatment of the topic in two chapters titled:

- Chapter 6: Trenchless Techniques for Pipeline Installation
- Chapter 7: Horizontal Directional Drilling

The newly introduced Chapter 6 provides an overview of the range of trenchless techniques for pipeline installation including common methods used for road and railway crossings and more involved methods such as the microtunneling class of technology, and introduces Chapter 7 for an in-depth discussion of Horizontal Directional Drilling (HDD). Trenchless methodology selection guidelines are presented, identifying the benefits and risks of the different options. Building on the first edition’s treatment of the topic, an expanded and updated discussion of HDD is presented in Chapter 7. Following a description of the installation process, key engineering design, execution planning, and installation considerations are addressed.

The discussion of several geohazard mechanisms in so far as they apply to pipeline design, construction, and integrity management during operations are presented in turn in four chapters titled:

- Chapter 8: Buoyancy Control at Water Crossings and Overland
- Chapter 9: Erosion and Sediment Control of Pipeline Right-of-Ways
- Chapter 10: Geotechnical Aspects of Pipelines in Permafrost
- Chapter 11: Assessment and Mitigation of Seismic Geohazards for Pipelines

Building on the discussion presented in the first edition of this book, an updated treatment of buoyancy control is presented herein. This edition’s new erosion and sediment control chapter considers the types of erosion processes, the factors controlling the initiation of erosion, and the common best practices for mitigating this hazard. This edition’s new chapter on geotechnical aspects of pipelines in permafrost differentiates between pipelines in permafrost and temperate terrain, the special properties of permafrost that affect pipeline design, construction, and operations before delving into the unique permafrost-related geohazards of thaw settlement, frost heave, and thaw instability of slopes. This edition’s new chapter on the assessment and mitigation of seismic geohazards for pipelines begins with an overview of the assessment methods of seismic hazard mechanisms before describing the state of the art in the design, installation, and operational monitoring, as well as the associated lessons learned.

A set of four closely related chapters delves into the broad area of pipeline geohazard assessment and management considerably expanding on the treatment of the same topic presented in the first edition of the book. The chapters are titled:

- Chapter 12: Geohazard Assessment and Management: Overview
- Chapter 13: Geohazard Assessment and Management: Geohazards, Weather, and External Force Mechanisms
- Chapter 14: Geohazard Assessment and Management: Assessment Principles and Techniques
- Chapter 15: Geohazard Assessment and Management: Monitoring and Mitigation

Presented at the beginning of Chapter 12 is a statistical context of the magnitude of pipeline geohazards globally. Following a tabular mapping of the closely inter-related three subsequent chapters, key philosophical starting points which guide the approaches presented in these three chapters are discussed. An emphasis on pipeline-centric fitness for service is advocated. By necessity, an intentional filter
is applied to refocus the description of geohazards from the classic geotechnical and geomorphological perspectives to the impact of these geohazards on pipelines. Described in Chapter 13 are the effects of a range of globally encountered geohazards on pipelines. Presented in Chapter 14 is an overview of the analytical procedures and methodologies in current use to undertake rigorous geohazard assessments in support of design or integrity assessment planning during operations. Highlighted within this chapter are specialized multi-disciplinary analytical considerations. A survey of pipeline geohazard monitoring and mitigation technologies is presented in Chapter 15. In-depth treatment for specific technologies and notable case studies is included.

Finally, several distinguished industry colleagues graciously contributed seven essays on subjects of their choice related to the book’s overarching subject matter. These essays have been compiled in Chapter 16 titled “Invited Perspectives” and offer valuable insights on trends of interest to the global community of pipeline geohazard practitioners.

The benefit of capturing the wealth of peer-reviewed technical articles related to the book’s scope has not been overlooked. Related articles published in all of the proceedings to date of both the ASME International Pipeline Conference (IPC) and the ASME International Pipeline Geotechnical Conference (IPG) together with papers published in the proceedings of the seminal GeoPipe 2004 Conference have been compiled in a bibliography presented in the book, with articles cross-referenced to individual chapters in the book.

This book is intended to serve as a reference to the global community of colleagues, practitioners and stakeholders who are active or interested in dealing with pipeline geohazards. It is the co-editors’ hope that the book serves as a basis for constructive discussion and as a foundation for continuous improvement and advancement of the state of practice.

REFERENCE

CHAPTER SUMMARY

This chapter sets the stage for the reader of this second edition book and provides the reader with insights into its overarching themes and organization.

KEY POINTS AT A GLANCE:

- Significant advances in the state of practice in geohazard management have occurred since the publication of the first edition of this book in 2008.

- This book is intentionally focused on conveying lessons learned from experienced practitioners rather than step-by-step instructions, and provides a framework for rational thinking in relation to various aspects of pipeline planning, design, construction, and operations.

- The lessons learned are meant to impart knowledge and to encourage thoughtful consideration in decisions facing practitioners, managers, regulators, and the public with respect to pipeline geohazards.
2

TERRAIN ANALYSIS FOR PIPELINE CORRIDOR SELECTION

THIS CHAPTER FOCUSES ON:

1. What tools and techniques are used in terrain analysis for pipeline corridor selection?

2. What terrain features must be evaluated for characterization and assessment of pipeline routes?

3. How is terrain analysis applied to the pipeline corridor selection process?
CHAPTER OVERVIEW

This chapter focuses on the science and technology of terrain analysis and how terrain mapping is an important component in the selection of routing corridors and final alignments for pipelines. It introduces the reader to the definition of terrain analysis and its role in both pipeline corridor selection and geohazard assessment, as well as the various tools and data sources used in desktop terrain analysis studies. The various types of terrain features that must be evaluated during pipeline terrain analysis studies and other key considerations in the application of terrain analysis to pipeline are also discussed. Nine of the global terrain types that may be encountered during pipeline routing are summarized in detail.

CHAPTER LAYOUT AT A GLANCE:

2.1 INTRODUCTION
This section introduces readers to the definition of terrain analysis and its role in both pipeline corridor selection and geohazard assessment.

2.2 TERRAIN MAPPING AND GEOHAZARD ASSESSMENT
This section describes the general principles and data tools used in terrain mapping and geohazard assessment, including air photo and satellite image interpretation, digital surface modeling, integration of existing terrain data into a geographic information system (GIS), and the use of 3D visualization in the interpretation and mapping process.

2.3 TERRAIN FEATURES EVALUATED FOR GEOHAZARD MAPPING AND ASSESSMENT
This section discusses the main features of terrain that must be considered when carrying out terrain analysis and geohazard mapping for pipelines, including surface materials and their geotechnical properties, topography, drainage, groundwater, known geohazards, and cultural and environment constraints.

2.4 APPLICATIONS OF TERRAIN ANALYSIS TO PIPELINE ROUTING, CONSTRUCTION, AND OPERATION
This section discusses the application of terrain analysis and its role in the corridor and route selection process, design, construction, and operational phases of a pipeline. The importance of understanding scale in terrain analysis studies is also discussed.

2.5 ASSESSING GEOHAZARDS IN DIFFERENT REGIONS
This section summarizes nine of the most common terrain types that may be encountered during terrain analysis for pipeline corridor and route selection, design, construction and operation, including glaciated terrains, fluvial terrain, permafrost, peatlands and organic terrains, coastal terrain, karst terrain, mountains, volcanic terrain, and deserts.

2.6 SUMMARY
This section provides brief concluding remarks emphasizing the key messages.

A list of references and suggested further reading is provided for the reader at the end of the chapter. Green highlight boxes are used in this chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters or additional reading.
CHAPTER SUMMARY

This chapter describes how terrain analysis is an essential and cost-effective means to identify and evaluate alternative pipeline routes, avoid geohazards or other problem areas, and generate geotechnical data and maps to support the successful design, construction, and operation of oil and gas pipelines.

KEY POINTS AT A GLANCE:

- Among the techniques used in geohazard assessments of pipelines is terrain analysis, which involves the study of surficial characteristics and the interpretation of landforms.

- The “tools” (data types) used by the terrain analyst include aerial photography, satellite imagery, digital surface modeling, existing maps and field report, and 3D data visualization in a GIS.

- Pipeline terrain studies generally begin with high-level assessments using regional-scale imagery and geospatial datasets, then progress to more detailed (low-level) studies using higher-resolution data.

- Desktop studies should be accompanied by field reconnaissance and the collection of geotechnical, geological, and environmental data to support detailed design, risk assessment, and mitigation studies.

- Terrain analysts should be familiar with the types of terrain that may occur in their study area and their associated geohazards. This includes geohazards in glaciated, fluvial, permafrost, peatlands, coastal, karst, mountain, volcanic, and desert terrains.
3 Data Generation, Integration, Management and Visualization

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This chapter focuses on:

1. Introduction to Geographic Information Systems (GIS) software and the concept of the geological model.
2. How to populate the geological model through data mining, data acquisition, and data generation.
3. Data processing, presentation, and visualization.
CHAPTER OVERVIEW

THE CHAPTER LAYOUT IS AS FOLLOWS:

3.1 INTRODUCTION
This section introduces the concept of the geological model and covers the importance of the master database.

3.2 GEOGRAPHIC INFORMATION SYSTEMS (GIS) PLATFORMS
This section presents the most common GIS software packages.

3.3 DATA
This section clarifies the differences between raster and vector data and explains referencing systems, including projections, datums, and the two common types of linear referencing systems, continuous chaining and stationing. Additionally, this chapter covers the qualities that determine a dataset suitability for use: scale, resolution, accuracy, and temporality.

3.4 DATA FORMATS
This section describes the common formats that data will be found in when populating the geological model: hard copy, digital hard copy, native files, and web services.

3.5 DATA SOURCES
This section covers the three most common sources of spatial data: Government agencies, commercial data vendors, and online communities and repositories.

3.6 DIGITAL ELEVATION MODELS (DEM)
This section explains what a DEM is, why it is so important in the geological model and what are some of the common freely available DEMs. It describes what additional datasets can be created by processing a DEM: hillshades, slope rasters, aspect rasters, and contours. Furthermore, derived datasets that support a hydrological analysis are covered: hydrologically correct DEMs, flow direction rasters, and flow accumulation rasters.

3.7 DIGITAL IMAGERY
This section describes the three common types of digital imagery: orthoimagery, stereo imagery, and multispectral and hyperspectral imagery. Additionally, it covers what freely available imagery is offered and where it can be found.

3.8 FIELD DATA
This section covers how field work fits into the geological model and highlights its importance.

3.9 OPERATIONAL PIPELINE DATA
This section explains why construction records, in-line inspection data and inspection, maintenance, and repair records are all useful datasets to include in the geological model.

3.10 VISUALIZATION TECHNIQUES
This chapter covers the three common methods to present the data found in the geological model plan view, profile view and three-dimensional techniques. Additionally, a couple of potentially disruptive visualization technologies are discussed: virtual reality and augmented reality.

3.11 CONCLUSIONS
The chapter’s major themes and concepts are discussed in this section.
CHAPTER SUMMARY

This chapter provides an overview of available GIS tools and information, describes a general approach of building a geological model, and discusses what types of data sets are needed and how one goes about acquiring them. Various ways to present and visualize the geological model are also presented.

KEY POINTS AT A GLANCE:

- The geological model is used as an analog for, and represents the real-world conditions of, an area of study.
- The geological model can be initially populated with freely available datasets.
- Understanding both the spatial reference systems and linear referencing systems of all datasets is crucial.
- Digital elevation models (DEMs) form the foundation of the geological model and can be processed into several important datasets.
- Commonly available geomatics software can make field data collection more efficient and accurate.
- Visualizing the geological model can be accomplished using both 2D and 3D techniques.
4

GEOTECHNICAL ENGINEERING AND PIPELINE CONSTRUCTION INTERFACE CONSIDERATIONS

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THIS CHAPTER FOCUSES ON:

1. What are key interfaces between geotechnical engineering and construction specialists?
2. What are the benefits and means of early engagement of pipeline construction advisors?
3. What are the respective roles in relation to pipeline execution planning activities?
CHAPTER OVERVIEW

This chapter focuses on the importance of establishing well-defined functional interfaces between pipeline geotechnical and construction specialists. It identifies impediments to, and benefits of, early engagement of pipeline construction advisors in the work of the pipeline engineering design team in critical project execution planning activities. These activities involve topics such as route selection (both pipeline and access alignments), right-of-way design, and engineering mitigation design details as they relate to anticipated geotechnical and geohazard conditions. A case history is used to highlight some of these points and the importance of the geotechnical/construction interface.

CHAPTER LAYOUT AT A GLANCE:

4.1 INTRODUCTION
This section provides a brief description of large-diameter pipeline projects, including the overall objectives of such projects, and the importance of understanding pipeline route conditions from a geotechnical and a construction perspective.

4.2 PIPELINE PROJECT STRUCTURE
This section describes the various project stages and phases of a typical large-diameter pipeline project, cost and schedule implications, benefits of early engagement of a construction contractor, and various contracting strategies to balance project definition with overall expenditure leading to a Final Investment Decision (FID).

4.3 RESPECTIVE ROLES OF ENGINEERING AND CONSTRUCTION
This section describes the respective roles of the various teams involved in a pipeline project, including engineering, construction, and others. Complementary roles are described in the context of understanding geotechnical conditions along the route, and are illustrated with examples of geotechnical excavation quantities estimation and geohazard management.

4.4 INTERFACE DYNAMICS
This section describes examples of the types of situations where cooperation between geotechnical and construction personnel is beneficial in any given project setting, focusing on route selection and delineation of construction right-of-way components and right-of-way configurations. Design considerations for lateral and longitudinal slopes, ridges, and valleys illustrate the need for geotechnical input to the construction team. Examples of standard drainage, erosion and sediment control measures, and geotechnical control measures, implemented during construction are included, along with commentary on a geotechnical verification program, regulatory interactions and other considerations.

4.5 CASE HISTORY
This section provides a case history from a project in Mexico to illustrate the functional interfaces between the construction and geotechnical teams in undertaking a major project in a challenging setting, and to emphasize some key aspects introduced in previous sections.

4.6 DISCUSSION
This section reiterates and discusses several of the main points from the previous sections, with some lessons learned from major projects interwoven in the narrative to provide an experienced perspective on the relationship between the construction and geotechnical teams.

4.7 CONCLUDING REMARKS
This section provides brief concluding remarks emphasizing key messages.

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional reading.
**CHAPTER SUMMARY**

This chapter describes many aspects of a large-diameter pipeline project, including project structure, contracting strategy and typical construction activities. The importance of early engagement of construction contractors, and in establishing and maintaining well-defined functional interfaces between geotechnical engineering and construction specialists, is emphasized through practical examples and illustrative scenarios faced in challenging project settings. The benefits of collaboration in critical project execution planning activities such as route selection (both pipeline and access alignments), right-of-way design, and environmental mitigation design are demonstrated in a brief case history. The key points of this chapter are summarized below.

**KEY POINTS AT A GLANCE:**

- Early engagement of construction specialists, and intentional interaction between the construction team and the geotechnical team, is a benefit in developing and executing a construction execution plan, and reducing project risk for major pipeline projects.

- Pipeline project structure and contracting strategy are key determining factors in the feasibility of meaningful interaction and interface between geotechnical engineers and construction specialists.

- Major transmission pipeline projects are multi-disciplinary and require careful coordination between discipline teams to ensure efficient resource management, informed decisions, and effective communication across technical disciplines, with owners and with external parties.

- Pipeline construction involves many interrelated activities that are affected by route conditions and degree of knowledge about subsurface conditions, which in turn affect routing decisions, construction execution, schedule, and cost of a pipeline project.

- Understanding respective roles and responsibilities – in particular, who should lead certain activities – is an important lesson learned from major pipeline projects.
# TRENCHED AND ELEVATED RIVER CROSSINGS

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<table>
<thead>
<tr>
<th>Design</th>
<th>Construction</th>
<th>Operational Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is and what is not important in design?</td>
<td>2. What should be “hard” spec’d versus - should be left flexible?</td>
<td>3. What river changes can you predict and when and how should you react?</td>
</tr>
</tbody>
</table>

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CHAPTER OVERVIEW

CHAPTER LAYOUT AT A GLANCE:

5.1 INTRODUCTION
The scope, uses, and organization of the Chapter are outlined in this section.

5.2 DESIGN - TRENCHED CROSSINGS
The data needs, design steps, design criteria, and computational methodologies are outlined. The relative importance of various design components, especially general versus local scour, are stressed. The importance of qualitative assessments, in addition to quantitative analysis, is noted. For projects in data scarce areas, the value of knowledge from residents and local experts is stressed. Design examples are presented.

5.3 DESIGN - ELEVATED CROSSINGS
The rationale for this mode and examples of elevated crossing types are presented. The relative importance of various design components differ from those of trenched crossings.

5.4 CONSTRUCTION
Construction methodologies for trenched crossings using the open cut or flow isolation method are outlined and illustrated. Proven water and sediment management/treatment techniques are highlighted along with typical specifications. Recognize the need to provide flexibility re: the usage of various options while meeting the regulatory requirements.

5.5 OPERATIONAL MONITORING
An Integrity Management Program requires a sound understanding of what to look for in the field, a crossing database that is periodically updated and an effective response plan during and following a major flood event. Hydrotechnical hazards are illustrated along with examples of mitigative works. The need for works during operations is not an indication of an original design deficiency.
### CHAPTER SUMMARY

#### KEY POINTS AT A GLANCE:

- **Sound and practical river crossing designs require multi-disciplinary input and recognition by the hydrotechnical engineer of what is key to ensuring the integrity of the crossing.**

- **Incorporating local knowledge from long term residents and experts is paramount especially for pipeline projects in data scarce regions.**

- **Challenge conventional design wisdom. For example, routing a pipeline mid-stream may, under certain climatic river, topographic and environmental conditions, be the optimum solution.**

- **For construction, schedule and adapt techniques to local conditions and environmental requirements while providing a degree of flexibility to the contractor.**

- **Knowing what to look for and what is and is not predictable are keys to a sound operational integrity management program.**
6

TRENCHLESS TECHNIQUES FOR PIPELINE INSTALLATION

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THIS CHAPTER FOCUSES ON:

1. What are trenchless techniques for pipeline installation?
2. What are key considerations in selecting a trenchless option?
3. What are the benefits and risks of different techniques?
CHAPTER OVERVIEW

This chapter focuses on trenchless techniques for pipeline installation. The intent is to introduce a range of trenchless techniques that have been used, or are being developed, for pipeline crossings of waterbodies, roads, railways, third-party pipelines, wetlands, and other features or locations where standard trenching for buried pipeline installation is either prohibited, undesirable, or not feasible. Given the number of trenchless techniques and variants thereof, the depth of treatment in this chapter for each technique is relatively light, serving more as an overview and introduction than a comprehensive description of the detailed technical aspects of each technique. The over-arching geotechnical considerations for selecting a trenchless technique are explored, and the individual sections provide additional description of each technique and its capabilities. Chapter 7 of this book covers Horizontal Directional Drilling in more detail.

CHAPTER LAYOUT AT A GLANCE:

6.1 INTRODUCTION
This section provides a brief description of trenchless techniques for pipeline installation and the overall objectives and limitations of the chapter.

6.2 GEOTECHNICAL CONSIDERATIONS
This section describes the role of geotechnical investigation in selecting a trenchless technique for pipeline installation, and provides a table of key geotechnical considerations upon which to base a selection decision.

6.3 HORIZONTAL DIRECTIONAL DRILLING
This section provides a brief description of horizontal directional drilling, including some background on the development of the technique and its current use in the industry. A subsequent chapter in the book provides additional technical details on this commonly-used trenchless technique (see Chapter 7).

6.4 HORIZONTAL BORING TECHNIQUES
This section provides a brief description of horizontal boring techniques, including auger boring and pilot tube guided auger boring and their associated capabilities.

6.5 PIPE JACKING TECHNIQUES
This section provides a brief description of pipe jacking techniques, including open face shields, slurry and earth pressure balance microtunneling (EPBM). This section also covers the emerging DirectPipe® and Easy Pipe™ technologies.

6.6 PERCUSSION TECHNIQUES
This section provides a brief description of percussion techniques, including pipe ramming and horizontal pipe driving and their associated capabilities.

6.7 CONVENTIONAL TUNNELING
This section provides a brief description of more conventional tunneling techniques using tunnel boring machines (TBMs), drill-and-blast, and other mechanical excavation methods for utility tunnels and other larger openings.

6.8 DISCUSSION
This section discusses the current state of development and application of these various techniques, and some of the issues hindering broader application of some techniques.

6.9 CONCLUDING REMARKS
This section provides concluding remarks related to the selection and application of trenchless techniques.

The chapter ends with acknowledgements and a list of references. Throughout the chapter, green highlight boxes are used to emphasize key concepts or lessons learned, and to suggest links to other chapters in the book and additional reading.
CHAPTER SUMMARY

This chapter describes trenchless techniques for pipeline crossings of waterbodies, roads, railways, third-party pipelines, wetlands, and other obstacles where standard trenching for buried pipeline installation is either prohibited, undesirable, or not feasible. Techniques discussed include horizontal directional drilling, horizontal boring techniques, pipe jacking techniques, percussion techniques, and conventional tunneling techniques. The main geotechnical considerations for selecting a trenchless technique are summarized along with other considerations for successful completion of trenchless projects.

KEY POINTS AT A GLANCE:

- Subsurface ground conditions are a primary consideration in selecting and planning the execution of a trenchless installation of a large-diameter pipeline.

- The risks and benefits of selecting an uncased versus a cased trenchless method must be weighed as part of the selection process in relation to anticipated hazards and ground conditions.

- Several trenchless techniques can accommodate boulders up to about one third of the diameter of the bore, but packing density and other factors related to bouldery soils should also be considered.

- Microtunneling involving shafts has the benefit of a smaller footprint suitable for more constrained locations and higher thrust capacity than some other methods, but may be more costly than competing feasible surface-based methods.

- Hybrid trenchless techniques that combine the benefits of surface-based methods, such as horizontal directional drilling, and microtunneling are advancing the state of practice and capabilities of trenchless techniques.

- Future developments of these techniques and hybridization are expected to further improve the technology.
THIS CHAPTER FOCUSES ON:

1. **What are the considerations involved in the design of an HDD pipeline installation?**

2. **What are the workspace requirements and potential environmental impacts of HDD?**

3. **How are HDD installation and operating stresses analyzed?**
CHAPTER OVERVIEW

This chapter describes the fundamentals involved in designing, contracting, and monitoring the construction of pipelines installed by horizontal directional drilling (HDD). The HDD process represents a significant improvement over traditional cut and cover methods for installing pipelines beneath obstacles that warrant specialized construction attention. In order for these advantages to be realized, design engineers should have a working knowledge of the HDD process as well as a thorough understanding of design considerations and HDD industry standards.

### CHAPTER LAYOUT AT A GLANCE:

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>INTRODUCTION</td>
</tr>
<tr>
<td>7.2</td>
<td>THE HDD PROCESS</td>
</tr>
<tr>
<td>7.3</td>
<td>SITE INVESTIGATION</td>
</tr>
<tr>
<td>7.4</td>
<td>DRILLED PATH DESIGN</td>
</tr>
<tr>
<td>7.5</td>
<td>WORKSPACE REQUIREMENTS</td>
</tr>
<tr>
<td>7.6</td>
<td>DRILLING FLUIDS</td>
</tr>
<tr>
<td>7.7</td>
<td>PIPE SPECIFICATION</td>
</tr>
<tr>
<td>7.8</td>
<td>CONTRACTUAL CONSIDERATIONS</td>
</tr>
<tr>
<td>7.9</td>
<td>CONSTRUCTION MONITORING</td>
</tr>
</tbody>
</table>
**CHAPTER SUMMARY**

This chapter describes the fundamentals involved in designing an HDD pipeline installation as well as contractual and construction monitoring considerations. The topics that are covered include site investigation, drilled path design, temporary workspace requirements, drilling fluids, pipe specification, contractual considerations, and construction monitoring.

### KEY POINTS AT A GLANCE:

- **Engineers should have a working knowledge of the HDD process in order to produce designs that can be efficiently executed by HDD contractors.**

- **The practical limit of an HDD pilot hole using the drilled intersect technique is currently around 13,000 feet.**

- **A site investigation for an HDD installation should include both surface and subsurface surveys.**

- **The location and configuration of the drilled path can generally be defined by the entry and exit points, the entry and exit angles, the P.I. elevation, and the radius of curvature. These parameters, or their limiting values, should be specified on the plan & profile drawing.**

- **Tie-in welds during pullback increase the risk of the pipe becoming stuck.**

- **Drilling fluid is used in all phases of the HDD process. An awareness of the function and composition of drilling fluids is imperative in producing a permittable and constructible design.**

- **Once discharged downhole, drilling fluid will flow in the path of least resistance. The risk of lost circulation and inadvertent drilling fluid returns cannot be eliminated.**

- **Inadvertent drilling fluid returns can occur for a variety of reasons other than hydrofracture.**

- **Loads and stresses imposed during the HDD installation process should be analyzed in combination with operating stresses to insure that acceptable limits are not exceeded.**

- **Steel pipe to be installed by HDD should typically have a diameter to wall thickness ratio of 60 or less.**

- **Pulling loads are affected by numerous variables that can’t easily be accounted for in a theoretical calculation method. Engineering judgment derived from experience in HDD construction is essential.**

- **Contract documents for an HDD installation should be structured to clearly present technical, commercial, and legal requirements.**

- **The primary objectives of an HDD inspector are to assist in the interpretation of the contract documents and to document conformance, or non-conformance, by the HDD contractor.**
8

BUOYANCY CONTROL AT WATER CROSSINGS AND OVERLAND

THIS CHAPTER FOCUSES ON:

1. Pipeline buoyancy control philosophy.
2. Pipeline buoyancy control methods.
3. Pipeline buoyancy control design.
CHAPTER OVERVIEW

This chapter focuses on design and construction information related to providing buoyancy control for overland pipelines. It describes various buoyancy design criteria as well as typical, or industry standard, design values. A design process is presented along with representative calculations. Also presented are many of the available pipeline buoyancy control methods and their advantages and disadvantages. The methods include those that are more the typical industry methods, as well as other less well known and infrequently used methods. Also presented are guidelines on pre-construction assessments for determining the number and location of buoyancy control measures that may be required during pipeline construction.

CHAPTER LAYOUT AT A GLANCE:

8.1 INTRODUCTION
This section introduces the topic of pipeline buoyancy.

8.2 PIPELINE CODES
This section presents applicable pipeline codes related to proper burial depth.

8.3 BUOYANCY DESIGN PHILOSOPHY
The section presents a brief overview of where pipeline buoyancy control may be required and the level of effort that may be expended to determine where those types of areas may be located along a proposed pipeline route.

8.4 BUOYANCY CONTROL OPTIONS
This section is the major portion of this chapter. The various types of available buoyancy control are presented along with a discussion of each type of buoyancy control. Photographs or schematics of each type of buoyancy control are presented. Also, the uses, advantages and disadvantages are presented.

8.5 BUOYANCY DESIGN FORCES
This section addresses the temporary workspace that is required to accommodate HDD operations. Typical rig side and pipe side equipment layouts are also provided.

8.6 BUOYANCY CONTROL SPACING AND LOCATIONS
This section provides formulae for calculating buoyancy control spacing and example buoyancy control calculations are presented for soil weights, concrete weights, and anchors. The section concludes with the ranges of desktop and field investigations that may be conducted to assess a pipeline project’s buoyancy control requirements depending on the project’s complexity.

The chapter ends with a brief summary.
CHAPTER SUMMARY

This chapter presents design and construction information on providing buoyancy control for overland pipelines. Pipelines are subject to natural positive buoyancy when placed below the water table. The magnitude of the buoyant effect is proportional to the pipeline diameter. The need to mitigate the pipe buoyancy depends on many factors. These include the pipeline material, the pipe diameter and its wall thickness, the pipe product, the installation timing, the pipeline burial depth and the density and type of the trench backfill material. Even pipelines carrying a heavy product may require the use of buoyancy control measures as they may be subject to excessive buoyancy forces in the period between pipe installation and full operation or during maintenance. Consideration also has to be given to pipeline abandonment if the pipeline will not be removed, which is the current case for most abandoned pipelines. All factors should be taken into account when determining the optimum type and frequency of buoyancy control measures.

This chapter describes various buoyancy design criteria as well as typical, or industry standard, design values. A design process is presented along with representative calculations. It also presents many of the various pipeline buoyancy control methods available to designers and contractors. The methods include those that are more the typical industry standards, as well as other less well known methods. The latter methods, although less well known, are acceptable buoyancy control measures and may be preferred under certain circumstances.

Thermal expansion forces and overbend stability, although important considerations in keeping a buried pipe below the ground surface, are not part of this chapter. The various buoyancy control options described in this chapter can, however, also be utilized to mitigate high thermal expansion forces or overbend instability.

KEY POINTS AT A GLANCE:

- There are multiple buoyancy design issues and philosophy approaches that could be used. Designers should assess which approach will provide a safe and economic design for the particular project under assessment.

- There are multiple buoyancy control methods that are available for use on pipelines. The various options and their advantages and disadvantages should be assessed before choosing a particular type for a particular project. Several methods may be required and suited for different areas of a long pipeline.

- Designers should note the various buoyancy design forces that are relevant to their project and that should be considered in assessing net uplift loads and downward forces. Not all forces need to be used but the designer should note the reasoning for using or not using a particular force as well as its associated value as this will affect the frequency or configuration of specific buoyancy control measures.

- There are various levels of effort that can be applied to assessing where buoyancy control measures may be needed for a specific project. That level of effort should be commensurate with the potential cost and schedule impacts when considering the preferred buoyancy control method that is to be used and where it is needed, so as to provide a robust and economical design.
This chapter focuses on:

1. What are the types of overland erosion and why is erosion and sediment control important?
2. What are the primary factors that control erosion initiation?
3. What are the common best practices for controlling erosion and providing sediment containment on pipeline right-of-ways?
CHAPTER OVERVIEW

This chapter addresses erosion control and sediment containment along pipeline right-of-ways and associated areas, such as access roads, shoo-flies, and lay-down and stockpile sites. There are several types of erosion and many factors that control erosion initiation. An understanding of these issues will assist pipeline designers, inspectors, and construction personnel select the most appropriate erosion control measure.

The chapter ends with a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional reading.
CHAPTER SUMMARY

This chapter describes erosion control and sediment containment along pipeline right-of-ways and associated areas. The need for erosion control and sediment containment stems from the regulatory mandated requirement to protect water courses, wetlands, and water bodies from uncontrolled sediment laden runoff. The health of terrestrial vegetation, aquatic plants and animals is directly linked to the quality of the surface water that flows over ground, and the water entering aquatic habitats.

KEY POINTS AT A GLANCE:

- Erosion control and sediment containment are necessary to protect surface water systems.
- Project specific erosion control and sediment containment plans are required by many regulatory agencies, such as the U.S. Federal Energy Regulatory Commission.
- Erosion from pipeline construction activities can be controlled and prevented from entering surface water systems if the appropriate controls and mitigations are applied.
- Application of appropriate and sufficient erosion control measures prior to the initiation of erosion is necessary to minimize erosion.
- A toolbox approach to erosion control and sediment containment is more desirable than prescriptive approaches as it is adaptive to material supplies and field conditions.
- Many erosion control techniques are available. Revegetation should be considered the most desirable measure as it is natural, cost-effective, and permanent.
10

**GEOTECHNICAL ASPECTS OF PIPELINES IN PERMAFROST**

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**THIS CHAPTER FOCUSES ON:**

1. How pipelines behave in permafrost terrain requires additional geotechnical input compared to pipelines in temperate terrain.

2. Describes the properties and character of permafrost, including its geothermal behavior and strength properties.

3. Thaw settlement, frost heave and stability of thawing slopes are important design issues.
CHAPTER OVERVIEW

This chapter focuses on the geotechnical issues associated with the design, construction and operation of pipelines in permafrost terrain. From a geotechnical perspective, pipelines in permafrost face many additional design and operational challenges than do pipelines in non-permafrost terrain.

CHAPTER LAYOUT AT A GLANCE:

10.1 INTRODUCTION
The introduction discusses the characteristics of pipelines in permafrost, with the key differences relating to the temperature regime of the pipelines and the surrounding ground. As a result of the permafrost, geotechnical input to pipelines in permafrost terrain is usually much greater than for temperate pipelines.

10.2 BRIEF INTRODUCTION TO PERMAFROST
This section describes terrain features of permafrost. This includes the characteristics and properties of permafrost, ground temperatures and special conditions, such as salinity that affect the behavior of permafrost. The time and temperature dependence on the strength of frozen soils is also discussed.

10.3 SITE INVESTIGATIONS
Site investigation methods are discussed as they relate to permafrost terrain. Accurate characterization of the properties of the permafrost is necessary for the safe and reliable design of pipelines in permafrost.

10.4 GEOTHERMAL MODELING
Geothermal modeling is a unique aspect of the design of pipelines in permafrost. These models are used to estimate the effects of ground disturbance, pipeline operation and climate warming on the geothermal regime of the ground. These numerical tools help the designers identify issues that require design mitigation.

10.5 THAW SETTLEMENT AND FROST HEAVE
This section addresses the development and impact of thaw settlement and frost heave. Both phenomena can result in pipeline strains and integrity issues for both the pipeline and right-of-way.

10.6 LIMIT STATES DESIGN
This section provides a discussion of the role of limit state design for pipelines in permafrost. This approach allows the pipeline to strain beyond the yield point of the pipeline steel and accumulate plastic strain. Such an approach may be useful for addressing secondary pipeline movements such as thaw settlement and frost heave.

10.7 SLOPES DESIGN
Pipeline construction and operation can induce thawing of permafrost slopes. Rapid thawing generates pore water pressures that reduces the strength of the soils and promotes instability and slope failure. Stability analysis methods are discussed that determine the factor of safety for thawing slopes. Mitigation strategies are discussed.

10.8 CONSTRUCTION ISSUES
This section addresses issues such as ditching productivity, buoyancy, and ice rich backfill, and others.

10.9 MONITORING AND MITIGATION
Monitoring the pipeline to assess the interaction with the permafrost environment is discussed. Mitigations need to be applied to address any thaw settlement and frost heave, and the instability of thawing ice-rich slopes.

10.10 CONCLUDING REMARKS
Final concluding remarks are provided, recognizing the unique nature of permafrost terrain and the continual development of innovations to improve constructability and integrity.

The chapter ends with a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional reading.
CHAPTER SUMMARY

This chapter describes the geotechnical aspects (from a North American perspective) important to the design and construction of pipelines in permafrost terrain.

**KEY POINTS AT A GLANCE:**

- The geotechnical input to a pipeline project in permafrost terrain is greater than for non-permafrost pipeline projects.

- Investigations and characterization of the pipeline route to identify permafrost and geothermal properties is important to the successful design and operation of the pipeline. Key properties include: soil texture, ice content, ground temperature, and frost heave potential.

- Degradation of the permafrost may result simply from right-of-way preparation. Operation of the pipeline, whether warm or cold, may have only a small localized effect on the geothermal regime.

- The key geotechnical issues for pipelines in permafrost include:
  - Potential for frost heave and thaw settlement depending on the operating temperature of the pipeline and the thermal state of the soils.
  - Slope instability induced by melting of ice-rich permafrost. Analyses are needed to assess the rate of thawing and generation of excess pore water pressures that may destabilize the slope during operations.
  - Trenching in permafrost is often controlled by the soil texture and ice content of the soils.

- Mitigation strategies to address impacts or effects of permafrost degradation that may negatively impact the long-term integrity of the pipeline should be identified early in the design phase.
11

Assessment and Mitigation of Seismic Geohazards for Pipelines

THIS CHAPTER FOCUSES ON:

1. Elements of an engineering process to mitigate seismic geohazard effects on welded steel pipelines.

2. Nuances of pipeline seismic engineering not commonly recognized by owners and engineering practitioners.

3. Key ingredients of project management necessary for the successful implementation of seismic hazard mitigation.
CHAPTER OVERVIEW

This chapter presents methodology for the design mitigation of pipeline seismic geohazards for welded steel natural gas and liquid hydrocarbon pipelines. The scope encompasses fault rupture displacement, liquefaction-induced ground displacement, and seismic wave propagation. The methodology is supplemented with a discussion of finite element analysis methods, general recommendations for strain limits, and associated requirements for pipe selection and welding. Options for earthquake monitoring and post-earthquake field reconnaissance are discussed as a means of facilitating earthquake preparedness. The chapter concludes with a commentary on effective project management for seismic geohazards and lessons learned from past projects.

CHAPTER LAYOUT AT A GLANCE:

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>INTRODUCTION</td>
<td>This section provides a summary of seismic geohazards that can damage large-diameter pipelines and an introductory statement on strategies for mitigation.</td>
</tr>
<tr>
<td>11.2</td>
<td>FAULT RUPTURE DISPLACEMENT</td>
<td>This section describes the approach and methodology for the design of pipeline crossings of active tectonic faults and the requirements for field investigation in advance of design.</td>
</tr>
<tr>
<td>11.3</td>
<td>LIQUEFACTION</td>
<td>This section describes the review of pipeline routes for potential liquefaction hazards, the engineering design mitigation of liquefaction-induced ground displacement effects, including lateral spread and buoyant rise.</td>
</tr>
<tr>
<td>11.4</td>
<td>SEISMIC WAVE PROPAGATION</td>
<td>This section describes a practical approach to the evaluation of seismic wave propagation effects on buried welded steel pipelines.</td>
</tr>
<tr>
<td>11.5</td>
<td>FINITE ELEMENT ANALYSIS METHODOLOGY FOR PGD</td>
<td>The section summarizes the methodology for finite element analysis of ground displacement effects on buried pipelines accounting for nonlinear soil restraint, inelastic pipe behavior, and large-displacement effects.</td>
</tr>
<tr>
<td>11.6</td>
<td>PIPE STRAIN LIMITS FOR SEISMIC PGD DESIGN</td>
<td>This section presents pipe strain limits for use in the analysis of welded steel pipelines subjected to plastic deformation under displacement-controlled loading and the underlying requirements for weld performance.</td>
</tr>
<tr>
<td>11.7</td>
<td>PIPE SELECTION AND WELDING</td>
<td>This section summarizes general requirements for welding and weld inspection to assure weld overmatching of high pipe strain expected for seismic-induced permanent ground displacement.</td>
</tr>
<tr>
<td>11.8</td>
<td>SEISMIC GEOHAZARD MONITORING</td>
<td>This section provides a summary of options for seismic ground motion monitoring, assessment of fault rupture displacements and post-earthquake liquefaction reconnaissance.</td>
</tr>
<tr>
<td>11.9</td>
<td>PROJECT MANAGEMENT FOR EFFECTIVE MITIGATION OF SEISMIC GEOHAZARDS</td>
<td>This section provides a commentary on effective project management for mitigation of seismic geohazards on pipeline projects and a general summary of seismic lessons learned on past projects.</td>
</tr>
</tbody>
</table>

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key points of the discussion.
CHAPTER SUMMARY

This chapter presents a summary of best international practice for the mitigation of pipeline seismic geohazards for welded steel natural gas and liquid hydrocarbon pipelines according to the collective viewpoints of the authors. The chapter scope encompasses fault rupture displacement, liquefaction-induced ground displacement, and seismic wave propagation. Also included in the chapter is a description of finite element analysis methods, establishment of strain limits for high-deformation performance of pipelines, and associated requirements for pipe selection and welding. Throughout the discussion, key issues are identified and reviewed in detail pursuant to the authors’ experience and judgment. Options for automated earthquake monitoring are summarized followed by recommendations for post-earthquake survey monitoring of potential fault displacement and reconnaissance of potential liquefaction hazard areas. The chapter concludes with a commentary on effective project management for seismic geohazards and a summary of seismic geohazard-related issues that have commonly confronted major pipeline projects and recommendations for avoidance. The key points of this chapter are summarized below.

KEY POINTS AT A GLANCE:

- The engineering analysis of pipe-soil interaction is paramount to the mitigation of seismic PGD hazard effects on pipelines. It requires the utilization of numerical procedures that can account for inelastic pipeline behavior, nonlinear boundary conditions for the pipeline due to its embedment in the surrounding soil medium, and large-displacement effects on pipeline stiffness.

- Pipeline routing should anticipate the need to cross active tectonic faults with alignments that minimize induced strain.

- The design of a fault crossing is a matter of determining a pipeline angle of intersection, pipe wall thickness, and burial configuration that will limit longitudinal strain in the pipeline to project-specified limits while remaining feasible to construct. The crossings of reverse or thrust faults are the most difficult of all fault types because the pipeline will be loaded by direct (axial) compression.

- Geologic investigations of pipeline fault crossings should delineate location, orientation, slip characteristics, and zone of disturbance of the fault, and estimate the amount and type of potential displacement that may occur.

- Fundamental to pipeline routing is the need to minimize the crossings of potential liquefaction hazard zones (PLHZs) and, where necessary to cross, that cost-effective fit-for-purpose mitigation measures are undertaken.

- The options for mitigation of lateral spread at watercourse crossings are to minimize the length of deep burial by providing high-strain performance of the pipe over the length of the crossing or extend the length of deep burial beneath the lateral spread zone to avoid large ground displacement, thereby maintaining pipe stress below yield, or some combination thereof.

- Liquefaction-induced buoyancy can be efficiently mitigated by determining a depth of burial that will assure a pseudo-static factor of safety of 1.1 to 1.2 and will limit uplift displacement to an amount resulting in acceptable post-event residual depth of soil cover for the pipeline.

- To achieve high-strain performance in permanent ground displacement (PGD) areas, the girth welds connecting pipe joints must have adequate tensile strength to overmatch the longitudinal tensile stress in the joined pipe. Strain limits, fracture mechanics and welding procedures should be addressed during FEED or early in the EPC stage.
**KEY POINTS AT A GLANCE:**

- Strong ground shaking poses only a minimal hazard to modern, well-constructed, buried welded steel pipelines due to their longitudinal and flexural capacity to accommodate the ground oscillation effects caused by the propagation of seismic waves through rock or soil.

- Pipe strain due to seismic wave propagation can be evaluated according to linear elastic stress behavior for compliance with pipeline code provisions for restrained pipelines.

- Strain acceptance criteria for pipeline PGD design are closely tied to the specification of pipe, welding procedures, pipe fabrication, quality control, and assurance of overmatching strength of girth welds. Appropriate steps should be taken in the development of welding specifications and weld inspection requirements to assure that high-strain performance requirements are met; otherwise, pipeline PGD design should be based on sensibly elastic tensile and compressive strain limits.

- When a stress-strain curve has been altered by strain aging to contain a Lüder’s plateau, strain localization occurs at strain levels within the plateau and continues until the strains increase beyond the limiting strain of the plateau.

- The primary objective of seismic monitoring is to detect events of possible engineering significance to the pipeline and expedite post-earthquake response as a means of minimizing the consequences of potential damage.

- Significant problems arise in the mitigation of seismic geohazards, not so much from the technical aspects of the work, but from its multidisciplinary nature and the need to dovetail this work with the project planning, technical and regulatory activities constituting any pipeline project.

- Reluctance to commission adequate investigations of seismic geohazards and associated engineering of critical issues during FEED can result in reroutes, schedule impact, design errors and omissions, and claims during the EPC stage.

- The root cause of a majority of seismic hazard mitigation issues that arise on pipeline projects can be traced to a general reluctance to undertake geologic investigations of adequate scope early in the FEED stage so that a perceptive and optimal route for the pipeline can be established.
12 GEOHAZARD ASSESSMENT AND MANAGEMENT

Overview

This chapter focuses on:

1. Why is this an increasingly important topic?
2. How are inter-related chapters organized?
3. What are key philosophical points?
CHAPTER OVERVIEW

This brief chapter is intended to:

1. Provide context for the continuingly increasing importance of the topics in the three chapters that follow, addressing in turn the range of credible pipeline geohazards (Chapter 13), assessment principles (Chapter 14) and the range of practical monitoring and mitigation options (Chapter 15).
2. Present a mapping of the inter-related subtopics of geohazard assessment and management across the three chapters the inter-related chapters
3. Highlight several philosophical points that underpin the details presented in the following chapters
4. Offer a fitness-for-purpose focused Invited Technical Brief by a well-respected major operating company’s pipeline geohazards management subject matter expert.

CHAPTER LAYOUT AT A GLANCE:

12.1 A TOPIC OF CONTINUINGLY INCREASING IMPORTANCE
This section discusses drivers for continuing advancement of geohazard assessment and management, and provides statistics of pipeline failure frequencies associated with geohazards.

12.2 MAPPING CONTENTS OF THE INTER-RELATED CHAPTERS 13, 14 AND 15
This section provides a concordance between the various chapters in the book and the main topics.

12.3 KEY PHILOSOPHICAL STARTING POINTS
This section describes several key philosophical points that underpin the subsequent chapters.

12.4 FITNESS FOR SERVICE
This section emphasizes key points raise in the Invited Technical Brief.

12.5 KEY TOPICS IN RELATED CHAPTERS
This section provides a summary of key topics covered in the three subsequent chapters to help establish a general context for readers.

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional related reading.
CHAPTER SUMMARY

This chapter provides an introduction to geohazard assessment and management and an overview of the topics covered in subsequent inter-related Chapters 13, 14, and 15. An Invited Technical Brief provides a focus on fitness-for-service evaluation as a primary objective of pipeline geohazard assessment and management.

KEY POINTS AT A GLANCE:

- **Pipeline geohazard assessment and management continues to be a topic of increasing importance and active development globally**

- **There are several sources of reported statistics of geohazard-induced pipeline failure. These datasets are instructive, however caution is required in reviewing and applying the reported data**

- **Chapters 13, 14 and 15 offer an inter-related treatment of pipeline geohazard assessment and management**

- **In the context of pipeline geohazard assessment and management, a pipeline-centric fitness for service focus must necessarily extend beyond strictly geotechnical and geomorphological treatment of geohazards**
13

**GEOHAZARD ASSESSMENT AND MANAGEMENT**

Geohazard, Weather and External Force Mechanisms

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**THIS CHAPTER FOCUSES ON:**

1. What is the regulatory context for geohazard assessment?
2. What constitutes a credible geohazard mechanism in relation to pipelines?
3. How to evaluate and rationalize geohazard susceptibility in a consistent and systematic way?

---

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CHAPTER OVERVIEW

This chapter is the second of four on the topic of geohazard assessment and management, focusing on geohazard, weather and force mechanisms. The regulatory framework for geohazard assessment is introduced based primarily on US standard B31.8S and Canadian standard CSA Z662 as background for what constitutes a geohazard mechanism. The distinction between a hazardous geological/geotechnical condition, a geohazard trigger, and a geohazard event or process is described, and an overall philosophy for characterizing geohazards in a way that is compatible with the geohazard assessment methodology outlined in Chapter 14, and mitigation options outlined in Chapter 15, is introduced.

### CHAPTER LAYOUT AT A GLANCE:

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.1</td>
<td>INTRODUCTION</td>
<td>This section defines geohazards in a pipeline context and frames the content of the chapter.</td>
</tr>
<tr>
<td>13.2</td>
<td>REGULATORY FRAMEWORK</td>
<td>This section describes the regulatory framework for geohazard assessment using select Canadian and US standards and guidelines.</td>
</tr>
<tr>
<td>13.3</td>
<td>CREDIBLE GEOHAZARDS</td>
<td>This section presents a suite of credible geohazards and their potential effects on pipelines.</td>
</tr>
<tr>
<td>13.4</td>
<td>SLOPE INSTABILITY HA ZARDS</td>
<td>This section describes landslide, debris flow, creep, earthflow, rock fall, rock avalanche and snow avalanche mechanisms.</td>
</tr>
<tr>
<td>13.5</td>
<td>SEISMIC/TECTONIC HA ZARDS</td>
<td>This section describes active fault displacement, liquefaction, and seismic wave propagation mechanisms.</td>
</tr>
<tr>
<td>13.6</td>
<td>HYDROTECHNICAL HA ZARDS</td>
<td>This section describes flooding, vertical scour, lateral scour (channel migration), avulsion, buoyancy, rapid lake drainage (outburst flooding), and coastal inundation (tsunami) mechanisms.</td>
</tr>
<tr>
<td>13.7</td>
<td>OVERLAND EROSION AND RELATED HA ZARDS</td>
<td>This section describes overland water erosion, wind erosion and dune migration mechanisms.</td>
</tr>
<tr>
<td>13.8</td>
<td>GROUND SUBSIDENCE HA ZARDS</td>
<td>This section describes soil settlement, underground cavity deformation (karst collapse and mining-induced subsidence), and sensitive soil collapse mechanisms.</td>
</tr>
<tr>
<td>13.9</td>
<td>EXPOSED ROCK, GEOCHEMICAL AND RELATED HA ZARDS</td>
<td>This section describes rock indentation, acid rock drainage, and saline ground corrosion mechanisms.</td>
</tr>
<tr>
<td>13.10</td>
<td>PERMAFROST AND THERMAL HA ZARDS</td>
<td>This section describes frost heave, thaw settlement, thermokarsting of massive ice, upheaval displacement, and thaw-induced flow mass movement mechanisms.</td>
</tr>
<tr>
<td>13.11</td>
<td>VOLCANIC HA ZARDS</td>
<td>This section describes lahar, ash fall, pyroclastic flow, lava flow and lava tube collapse mechanisms.</td>
</tr>
<tr>
<td>13.12</td>
<td>DISCUSSION</td>
<td>This section discusses the implications of establishing credible geohazards for a project, and important considerations in assessing individual geohazard mechanisms and triggers.</td>
</tr>
<tr>
<td>13.13</td>
<td>CONCLUDING REMARKS</td>
<td>This section provides brief concluding remarks emphasizing key messages.</td>
</tr>
</tbody>
</table>

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional reading.
CHAPTER SUMMARY

This chapter provides an overview of the regulatory framework for pipelines and how it relates to geohazard, weather and force mechanisms. Despite falling in the time-independent defect type category in ASME B31.8S, many geohazard mechanisms are time-dependent or progressive in nature and are amenable to monitoring and intervention. A philosophy to systematically rationalize estimates of geohazard initiation, frequency, and vulnerability for individual geohazard mechanisms is introduced. This philosophy is elaborated on in Chapters 14 and 15.

KEY POINTS AT A GLANCE:

- The regulatory framework for pipelines provides a general, largely flexible (non-binding) basis for identifying geohazard, weather and external force mechanisms, but considers these as time-independent threats.

- Distinction between geohazard mechanisms, triggers and features/conditions is important; a mechanistic perspective is necessary to relate physical parameters to stability, pipeline impacts and effects of mitigation.

- The number and relative importance of credible geohazard mechanisms is project-specific and depends on physiographic setting, potential triggers, and other factors.

- A philosophy of systematic rationalization of the various components associated with a geohazard occurrence and its impacts on pipeline infrastructure is essential for consistent, transparent evaluation of susceptibility and communication of uncertainty.

- The approach described to characterize individual geohazards is intended to be illustrative, not prescriptive, to allow flexibility in selecting and applying published analytical solutions and analysis approaches.

- The number of publications on various geohazard topics is significant and growing; periodic review of the state-of-the-art in relation to assessment of geohazard mechanisms is recommended.
THIS CHAPTER FOCUSES ON:

1. *What is involved in conducting geohazard assessment for new and existing pipelines?*

2. *What are pipe-soil interactions and their implications for geohazard management?*

3. *What are some key related operational and overarching design considerations?*
CHAPTER OVERVIEW

This chapter is the third of four on the topic of geohazard assessment and management, focusing on assessment principles and techniques. The evolution of a geohazard assessment methodology and its relation to pipeline risk assessment is described, along with a process to estimate individual and combined geohazard susceptibility and select mitigation options. Pipe-soil interactions, operational considerations and overarching design topics related to geohazard assessment and management are also discussed.

CHAPTER LAYOUT AT A GLANCE:

<table>
<thead>
<tr>
<th>14.1</th>
<th>INTRODUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section provides a brief description of the chapter contents, purpose and scope.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.2</th>
<th>RISK ASSESSMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section describes key concepts, typical approaches, and advances in pipeline risk assessment.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.3</th>
<th>PIPELINE GEOHAZARD ASSESSMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section describes the role of geohazard assessment, geohazard assessment concepts, methodology development overview, a geohazard assessment framework, geohazard mitigation, probability of occurrence estimation, vulnerability estimation, reconciliation with pipeline risk assessment, and uncertainty in geohazard assessment.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.4</th>
<th>PIPE-SOIL INTERACTION MODELING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section describes pipe-soil interaction factors and a suite of practical considerations for pipe-soil interaction modeling including oblique interactions, pipeline ditch and backfill effects, and influence of landslide transition zones.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.5</th>
<th>OPERATIONAL CONSIDERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section describes several operational considerations including pipeline separation, surface loading, and adjacent blasting.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.6</th>
<th>OVERARCHING DESIGN TOPICS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section discusses overarching design topics including pipeline structural and metallurgical response, limit states and reliability based design, and a test-of-reasonableness process.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14.7</th>
<th>CONCLUDING REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This section provides brief concluding remarks emphasizing key messages.</td>
</tr>
</tbody>
</table>

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional related reading.
CHAPTER SUMMARY

This chapter is the third of four on the topic of geohazard assessment and management. The focus of this Chapter is on assessment principles and techniques, describing the evolution of a geohazard assessment methodology and its congruent relation to pipeline risk assessment. The role of uncertainty in geohazard assessment figures prominently in the discussion, along with the importance of considering both individual and combined geohazard susceptibility to account for cospatial geohazard interactions, and associated mitigations. Pipe-soil interactions, operational considerations and overarching design topics related to geohazard assessment and management emphasize the multi-disciplinary nature of geohazard assessment for site-specific design.

KEY POINTS AT A GLANCE:

- Approaches for pipeline geohazard assessment are trending towards producing quantitative estimated of annual probability of failure (loss of containment of a pipeline)
- Current industry-recognized approaches to pipeline risk assessment incorporate logic that is congruent with geohazard assessment methodologies currently in use
- Screening level geohazard assessment is useful to develop individual and combined geohazard susceptibility profiles and identify critical geohazard locations for more detailed evaluation
- Sophisticated multi-disciplinary tools and techniques are available to assess pipe-soil interactions and to aid in selection and design of appropriate mitigation measures
- Recognition, quantification and communication of uncertainty in data and analysis results is integral to a complete geohazard assessment
15

**GEOHAZARD ASSESSMENT AND MANAGEMENT**
Monitoring and Mitigation

**THIS CHAPTER FOCUSES ON:**

1. How are geohazards managed within the framework of a larger integrity management plan?
2. What are the options available to monitor and mitigate the common pipeline geohazard categories?
3. What are actual examples of key monitoring and mitigations strategies?
CHAPTER OVERVIEW

This chapter is the fourth of four on the topic of geohazard assessment and management, focusing on geohazard management and decision-making, as well as the options currently available for monitoring and mitigating the major geohazard groups. This chapter draws heavily on the previous three chapters on the larger topic: Chapter 12 Overview; Chapter 13 Geohazard, Weather and Outside Force Mechanisms; and Chapter 14 Assessment Principles and Techniques.

<table>
<thead>
<tr>
<th>CHAPTER LAYOUT AT A GLANCE:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>15.1</strong> INTRODUCTION</td>
</tr>
<tr>
<td>This section reviews the list of credible geohazards, presents the definitions of monitoring and mitigation and describes the approach to geohazard monitoring and mitigation.</td>
</tr>
<tr>
<td><strong>15.2</strong> GEOHAZARD MANAGEMENT DECISION PROCESS</td>
</tr>
<tr>
<td>This section describes how geohazards are managed, and key decisions made, in an Integrity Management Plan.</td>
</tr>
<tr>
<td><strong>15.3</strong> MONITORING THE GEOHAZARDS</td>
</tr>
<tr>
<td>This section provides an overview of the monitoring options for common pipeline geohazards, from the perspective of monitoring either or both the geohazard and the pipeline for both cause and effect.</td>
</tr>
<tr>
<td><strong>15.4</strong> IDENTIFICATION AND MONITORING OF COMMON GEOHAZARDS</td>
</tr>
<tr>
<td>This section presents in-depth discussion of the current alternatives for identifying and monitoring the common pipeline geohazards. The common geohazards categories are: Slope Instability; Seismic/Tectonics; Hydrotechnical; and Erosion. The discussion provides recommendations for monitoring options for each of the 18 individual geohazard mechanisms in the four common geohazard categories.</td>
</tr>
<tr>
<td><strong>15.5</strong> MONITORING THE PIPE TO DETECT GEOHAZARD IMPACT</td>
</tr>
<tr>
<td>This section extends the geohazard monitoring discussion to include methods to monitor the pipeline to detect and monitor the effects of geohazards.</td>
</tr>
<tr>
<td><strong>15.6</strong> MITIGATION OF GEOHAZARDS</td>
</tr>
<tr>
<td>Focusing again on the four common geohazard categories, this section describes current methods to mitigate the effects of pipeline geohazards. The section is divided into two parts, the first describing the options available to mitigate the geohazard and the second describing the options available for pipeline mitigation. The section concludes with a summary of mitigation options for all 38 geohazards.</td>
</tr>
<tr>
<td><strong>15.7</strong> 2016 ASME PIPELINE AWARD</td>
</tr>
<tr>
<td>The final section presents a summary of the monitoring and mitigation of a challenging Enbridge geohazard management project.</td>
</tr>
</tbody>
</table>

The chapter ends with acknowledgements and a list of references. Green highlight boxes are used in the chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters and additional related reading.
CHAPTER SUMMARY

This chapter presents an overview of practical and proven monitoring and mitigation techniques that may be applied as part of pipeline geohazard management programs. Retaining continuity in terms of how geohazards may be grouped and considered, this chapter completes the series of four closely-related chapters that include Chapters 12, 13, 14 and 15. A disciplined structure is adopted that differentiates between addressing the causes (the geohazards) and the effects (the pipeline and right-of-way response). Together with including comprehensive menus of options, a selection of key topics are addressed in considerable depth. The experiences shared in the chapter are drawn from a global vantage point and include three invited technical briefs from esteemed colleagues.

KEY POINTS AT A GLANCE:

- **A pipeline-centric geohazard management decision process focused on fitness for service is presented, complemented by an overview of environmental mitigation options**

- **A monitoring technology survey is presented before exploring two key technologies, namely inertial in-line inspection (ILI) and fiber optic technology based monitoring. A hypothetical case is presented to demonstrate the practical challenges of reconciling monitoring data.**

- **A mitigation technology survey is presented before delving into two key aspects, namely debris flow mitigation and pipeline strain relief**

- **The importance of the chapter’s topic to the pipeline industry was clearly recognized by the awarding of the 2016 ASME Global Pipeline Award to Enbridge Inc. for an exemplary deployment of numerous geohazard monitoring and mitigation technologies. An invited technical brief describing the award winning case study is presented at the end of the chapter**
16

INVITED PERSPECTIVES

THIS CHAPTER FocusES ON:

1. What are emerging trends in the pipeline world?
2. What are the challenges facing the industry?
3. How do we advance the state-of-the-art?
# Chapter Overview

This chapter includes a number of essays providing invited perspectives from recognized thought leaders in the international pipeline industry. These essays are intended to be thought provoking and impart some element of wisdom from seasoned practitioners.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.1</td>
<td>Cost-effective Risk Reduction Approach (CERRA): Pipeline Geohazard Case Study</td>
<td>Rafael G. Mora (Pipeline Integrity, Calgary, Alberta, Canada)</td>
</tr>
<tr>
<td>16.2</td>
<td>Development of an International Standard for Geohazard Assessment and Management of Onshore Pipelines</td>
<td>Liangliang Li and Lai Wei (PetroChina Pipeline Company, Liangfang, China)</td>
</tr>
<tr>
<td>16.3</td>
<td>Geotechnical Challenges for Onshore Pipelines</td>
<td>Michael Sweeney (formerly BP Upstream Technical Authority Geotechnics, <a href="mailto:mike14@btinternet.com">mike14@btinternet.com</a>)</td>
</tr>
<tr>
<td>16.4</td>
<td>Managing Pipeline Geotechnical Issues from a Regulatory Perspective</td>
<td>Dr. Alan Murray (Calgary, Alberta, Canada)</td>
</tr>
<tr>
<td>16.5</td>
<td>Pipeline Risk Assessment - A New Era</td>
<td>W. Kent Muhlbauer (WKM Consultancy LLC, Houston, Texas, USA)</td>
</tr>
<tr>
<td>16.6</td>
<td>Practical Examples of Value-Added Engineering Geological Models for Pipeline Projects</td>
<td>Dr. Jeffrey R. Keaton (Wood Ptc, Los Angeles, CA, USA)</td>
</tr>
<tr>
<td>16.7</td>
<td>Risk Assessment of Geohazards in Practice</td>
<td>Dr. Noel Boylan and Dr. Suzanne Lacasse (Norwegian Geotechnical Institute, Perth, Australia/Oslo, Norway)</td>
</tr>
</tbody>
</table>
BIBLIOGRAPHY
Related Publications from Key Pipeline Conferences

THIS BIBLIOGRAPHY INCLUDES:

1. ASME International Pipeline Conference papers
2. ASME International Pipeline Geotechnical Conference papers
3. GeoPipe 2004 Conference papers
BIBLIOGRAPHY OVERVIEW

This bibliography includes relevant papers from key pipeline conferences including:

1. International Pipeline Conference (biennial conference 1996-2016).
3. Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines Conference (GeoPipe 2004)

Publication references are presented in the format listed online, along with an assigned topic and a related Chapter in this book (in red text). Some publications may apply to more than one topic or Chapter.

Proceedings from the specialty conference GeoPipe 2004 are referenced as follows:

Several chapters include valued invited contributions of brief essays on specialized topics

<table>
<thead>
<tr>
<th>INVITED TECHNICAL BRIEF</th>
<th>IN CHAPTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of Terrain Mapping to Pipeline Routing and Design</td>
<td>3</td>
</tr>
<tr>
<td>Robin McKillop</td>
<td></td>
</tr>
<tr>
<td>Field Data Collection</td>
<td>3</td>
</tr>
<tr>
<td>Yan Wong</td>
<td></td>
</tr>
<tr>
<td>Geohazard Fitness for Service Determinations</td>
<td>12</td>
</tr>
<tr>
<td>Doug Dewar</td>
<td></td>
</tr>
<tr>
<td>Debris Flow Hazards and Pipelines</td>
<td>13</td>
</tr>
<tr>
<td>Matthias Jakob</td>
<td></td>
</tr>
<tr>
<td>Glaciomarine Soils</td>
<td>13</td>
</tr>
<tr>
<td>John Clague</td>
<td></td>
</tr>
<tr>
<td>Pipeline Structural &amp; Metallurgical Response</td>
<td>14</td>
</tr>
<tr>
<td>Marc Spencer</td>
<td></td>
</tr>
<tr>
<td>Reliability Based Limit States Design and Assessment for Geotechnical Loads</td>
<td>14</td>
</tr>
<tr>
<td>Maher Nessim</td>
<td></td>
</tr>
<tr>
<td>Monitoring Pipelines Using Inertial Survey ILI Tools</td>
<td>15</td>
</tr>
<tr>
<td>Jim Hart</td>
<td></td>
</tr>
<tr>
<td>Pipeline Mitigation – Strain Relief</td>
<td>15</td>
</tr>
<tr>
<td>Practical Lessons Learned from a Pipeline Strain Relief</td>
<td></td>
</tr>
<tr>
<td>Phil Kormann</td>
<td></td>
</tr>
<tr>
<td>2016 ASME Global Pipeline Award</td>
<td>15</td>
</tr>
<tr>
<td>Geohazard and Pipeline Monitoring</td>
<td></td>
</tr>
<tr>
<td>Nader Yoosef-Ghodsi, Millan Sen and John Richmond</td>
<td></td>
</tr>
<tr>
<td>Enbridge Pipelines Inc.</td>
<td></td>
</tr>
</tbody>
</table>
Pipeline Geohazards: Planning, Design, Construction and Operations

Second Edition of Pipeline Geo-Environmental Design and Geohazard Management

Edited by Moness Rizkalla and Rodney S. Read

This second edition of the 2008 ASME publication on the same topic is an expanded and updated treatment of a broader range of pipeline geohazard management aspects to serve the global community of pipeliners—both those of a geotechnical background as well as their colleagues in the multi-disciplinary teams that deal practically with these issues. The book strikes a balance between providing overviews of certain topics and somewhat more detailed treatments of other topics. Recognized experts were invited to contribute entire chapters, short Invited Technical Briefs or longer Invited Perspectives in their areas of specialization.

This book’s comprehensive treatment of pipeline geohazards includes:

- Terrain analysis for corridor selection using data generation, integration and visualization techniques
- Geotechnical engineering and pipeline construction interface considerations
- Trenched and elevated river crossings
- Trenchless techniques for pipeline construction
- Practical overview for addressing several critical pipeline geohazard mechanisms, namely: buoyancy control; erosion and sediment control; pipelines in permafrost and the assessment and mitigation of seismic geohazards
- State-of-practice overview of quantitative geohazard assessment, monitoring and mitigation of various mechanisms
- Bibliography of related publications from prominent pipeline conferences