SLOPE STABILITY (LANDSLIDE) MANAGEMENT AND PIPELINES

Approaches, Strategies, and Techniques

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Topics Covered

- Why identify and mitigate landslide hazards? Importance of landslide hazard identification and mitigation
- Typical effects of active landslides on pipelines
- Elements of a landslide hazard assessment and management program
- Landslide hazard assessment program phased approach, and description of each phase
- Keys to hazard/threat identification
- Hazard mitigation options
- Hazard monitoring approaches, techniques and tools

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Importance of Landslide Hazard Identification and Mitigation

- A significant number of releases or ruptures can be from landslide processes/hazards acting on a pipeline.
- Identification, mapping and threat classification of landslide hazards along a pipeline system allows operators to understand the spatial distribution, nature, magnitude, extent and level of activity of the hazard.
- This information allows operators to formulate and implement informed landslide mitigation as well as develop informed risk management and operational decisions.
- Older pipeline systems have been exposed to the effects of landslide hazards for longer, particularly slow-moving landslides that are now just beginning to show effects on the pipes.
- Identification and mitigation of landslide hazards can reduce risks to pipeline integrity and maintain public safety.

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Typical Effects of Active Landslides on Pipelines

- Shearing along landslide limits (head scarp, lateral scarps, toe), and because of differential movement within the landslide body/mass
- Bending, stretching and compression due to movement within landslide mass and at the landslide limits
- Dents, scrapes and dings (i.e. mechanical damage) from slope/soil movement around the pipe

PNW Landslide and Pipeline Experience

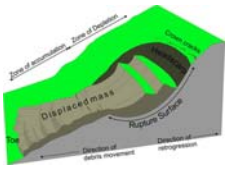
- Nature of landslide hazard experience:
  - Reactive and proactive
  - Regional and site-specific
  - Systematic hazard (threat) identification, characterization, evaluation, mitigation and monitoring
  - Existing pipelines and new pipelines
  - The experience has been evolutionary

What We've Learned

- There is a basic "life cycle" with landslides and pipelines
- It typically begins with landslide detection/identification, but can be entered at any point
- It is often iterative, and repeated if the landslide continues to be active, and/or changes behavior
- Pipeline operators need an assessment and management program to address and deal with landslide hazards along their systems

Elements of a Pipeline Landslide Hazards Assessment and Management Program

1. Objective is to be proactive and appropriately reactive
2. Systematic Process-based approach to identification and classification (hierarchy) of potential landslide hazards to develop inventory of threats that may affect the pipeline(s)
3. Landslide hazard/threat characterization, mitigation and monitoring
4. Scheduled and event-driven reconnaissance of ROW for adverse changes to landslide hazards that may affect the pipeline(s)
5. Emergency response to ruptures/releases
6. Action plans for developing landslide threats, or following natural events (storms, earthquakes)
7. Geologic hazard/threat identification/recognition training for pipeline field personnel



Approach to Pipeline Landslide Hazards Assessment Program

- Phased approach designed to go from regional-scale landslide hazard identification and screening to site-specific hazard characterization, mitigation and monitoring.
- Phase I
  - Primarily a desk-top screening tool to identify potential landslides of concern along a pipeline system. Based on a geomorphic assessment of remote sensing data, the location of each landslide is identified and mapped, and a preliminary qualitative landslide hazard threat level of "low," "moderate," or "high" is assigned from criteria developed for the Phase I process. The threat level is related to potential magnitude, location, likelihood, and severity of landslide impact to the system. The landslide hazard/threat inventory derives from this phase.
  - Augmented with an aerial reconnaissance (helicopter or fixed-wing) to provide up-to-date, real-time data. Data managed and deliverables in GIS format.
- Phase II
  - First site-specific , non-intrusive study that focuses on the specific landslides of concern identified during the Phase I study to confirm the preliminary landslide threat levels. Each landslide is investigated more fully to gain a better understanding of the location, nature, extent and potential affect on the pipeline.

Approach to Pipeline Landslide Hazards Assessment Program (cont.)

- Phase II (cont.)
  - Additional, more detailed desk-top studies are completed along with a field-based geomorphic and geologic reconnaissance of each landslide of interest. Conclusions and recommendations are developed regarding need for, and nature of specific landslide site mitigation and site monitoring. GIS used to manage data and as deliverable.
- Phase III
  - Focuses on the landslides of concern confirmed during the Phase II study to develop and implement mitigation design options. Also development and implementation of a site-specific monitoring plan that includes a response, or action plan.
  - Detailed site-specific surface and subsurface (intrusive) geologic and geotechnical investigations, and development of a site geologic (landslide) model are completed to support identification of mitigation options and development of a selected mitigation design(s). Site-specific studies also used to develop site monitoring plan(s).

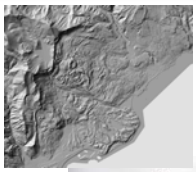
Keys to Landslide Hazard Identification

Basis for landslide hazard assessment for pipelines:

- A landslide hazard/threat is the result of an active geologic process.
- Active landslide processes are evident in observable changes to the Earth's surface; they affect the geomorphology.
- Active landslide processes/hazards are often re-activations at past locations. Thus, "active" processes to be considered may be hundreds to thousands of years old.
- Avoid "tunnel vision" along the ROW. The landslide hazard may originate off (below or above) the ROW.
- Landslide processes/hazards can be triggered or influenced by human activity. As development encroaches toward or adjacent to the ROW, landslides may be triggered or accelerated.

Primary Tools – Phase I Assessment

- Phase I (desk-top using available data)
  - Published topographic and geologic maps
  - Published DEM data
  - Published geologic hazard mapping
  - Published literature and data on geologic hazards
  - GIS geologic and geologic hazard mapping databases
  - Pipeline operator O&M experience history
  - Available remote-sensing data
    - Published LiDAR data
    - Stereoscopic alignment aerial photos (other sources)
    - Google Earth™ imagery
    - Satellite imagery
  - Aerial reconnaissance (helicopter or fixed-wing)

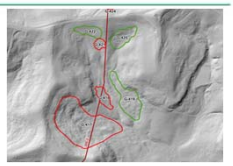


Primary Tools – Phase II Assessment

- Phase II (detailed desk-top and first site-specific field investigation)
  - Acquire detailed topographic and geologic mapping of site
  - Site-specific LiDAR data may be collected
    - DEM
    - "Hillshades"
  - Non-intrusive field geomorphic and geologic mapping of the landslide
    - to establish type of landslide, age, and lateral and vertical extent with respect to pipeline
    - uses precise pipeline locating to compare pipe to landslide
  - Formulate preliminary geologic model of the landslide
  - Recommendations for Phase III

Primary Tools – Phase III Assessment

- Phase III (detailed site-specific investigations and analyses to develop mitigation designs and support implementation)
- Ground Surface Characterization
  - Detailed topographic mapping (LiDAR, conventional)
  - Detailed geomorphic and geologic mapping to locate landslide scarps, cracks, springs, seeps
  - Detailed pipeline location survey
  - Detailed mapping of surficial and bedrock geology
- Subsurface Investigation
  - Test pits and boreholes
  - Inclinometers and piezometers
  - Geophysics
- Site geologic (landslide) model
- Slope stability analyses
- Mitigation design(s) and monitoring plan(s)



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Possible Landslide Mitigation Options/Alternatives

- No action, with emergency response, as needed
- Remediate (eliminate) the landslide effects through engineered solutions:
  - Avoidance (e.g., re-route, HDD, deep burial, above-ground)
  - Stabilization (control surface and groundwater, remove driving forces, increase resisting forces, improve slope geometry)
- Stay in place and mitigate (reduce /delay) the landslide effects through stress relief excavation and engineered solutions (drainage and deformation improvements) in the pipe trench and on the slope
  - Performance monitoring of landslide and pipe
  - Periodic, as needed, stress relief of pipeline and repair of mitigation measures to maintain integrity
- Favorable pipe trench orientation/geometry and select backfill
- All require an understanding of the nature, magnitude and rate of landslide movement; i.e., the geologic model

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Landslide Characterization – Development of a Geologic Model

- Data Needs for Model Development:
  - Landslide nature, type, failure mechanism
  - Landslide extent (laterally, vertically, geometry and position w/respect to pipeline)
  - Magnitude, age and rate of landslide movement
  - Surface and subsurface geologic conditions of landslide and local geologic environment
  - Hydrologic conditions (surface and groundwater)
- Data needs and model development require the implementation of detailed surface and subsurface geologic, geotechnical and hydrogeologic investigations, and data analysis and evaluation

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Landslide Hazard Monitoring – Development of a Program

- A landslide monitoring program is site-specific, and case-by-case.
- What are the monitoring objectives; performance of mitigation measures or additional landslide characterization?
- Does the landslide cross the pipeline, or is it adjacent?
- Is the landslide currently active, or dormant?
- What are the amounts and rates of landslide movement/affect?
- Nature and state of adjacent land development?
- What monitoring techniques best fit the landslide type, the site, monitoring objectives and budget?
- What is the frequency of monitoring data collection; is it manual or automated?
- How are the monitoring data being managed, analyzed, evaluated and reported?
- Is there an emergency response plan and additional mitigation plan?

Possible Landslide Monitoring Strategies and Techniques

- Monitor the Landslide/Ground Surface
  - Visual (visual changes to landslide surface geomorphic features)
  - Geodetic surface displacement survey array (change to x, y, z; GPS or ground-based; magnitude and rate)
  - Repeated LiDAR surveying; DEM comparison
  - InSAR (magnitude, rate and direction of movement)
  - Subsurface displacement (inclinometer/extensometer; location, magnitude and rate of displacement of failure surface)
  - Groundwater (piezometer; magnitude and timing of groundwater fluctuation)
- Monitor the pipe (strains on the pipe, or pipe movement)
  - Strain gauges
  - Inline tools (IMU)

Landslide Monitoring Approaches

- Integrated use of both slope (landslide) and pipe monitoring is recommended to get the best picture of what is happening, and it allows for a more focused and appropriate mitigation/remediation action if needed
- Slope (landslide) monitoring tells where the landslide is moving relative to the pipeline, and can tell the amount and rate of movement, but it does not necessarily tell whether the pipe is being affected
- Pipe monitoring instruments show the effects (response) of slope (landslide) movement on the pipe, but may not be situated to record all the landslide movement that may be affecting the pipe (excepting inline tools)

Possible Elements of a Landslide Monitoring Plan

- Identify monitoring types/methods being employed
- Instrumentation details and baseline data
- Monitoring frequency
  - Scheduled
  - Event-driven
- Reporting, and review schedule and distribution
- Emergency response plan
  - Highlight types of mitigation that could be employed, triggers levels in the monitoring data, and conditions that would dictate the method(s) used
  - Site access details for emergency response
  - Materials and equipment availability
  - Shutoff criteria
  - Emergency supply
  - Public safety and evacuation plan

Concluding Remarks

- Landslide hazards and pipelines make for a complex issue.
- The landslides are concentrated, generally where the landslide processes are most active.
- The current landslide threats to a pipeline are where landslide processes tend to have occurred in the past, and the evidence is in the surface morphology.
- Approaches to dealing with landslide hazards for pipelines have many common themes, but seem to be unique to the particular pipeline operator, the nature, age and history of the pipelines themselves and the geologic environment within which they are located, or traverse.
- Keeping on top of landslide hazards and threats takes commitment.

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Questions?

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