# Landslide Susceptibility Maps for Pipeline Geohazard Assessments

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## Abstract

Landslides are present in every state of the United States and every province of Canada, and the extensive network of transmission, distribution, and gathering pipelines is vulnerable to impacts from landslides, including pipeline rupture. Based on statistics from the Pipeline and Hazardous Materials Safety Administration (PHMSA), landslides are one of the most expensive causes of pipeline rupture, resulting in more onshore pipeline ruptures than all other natural force incidents combined. For these reasons, the management of landslide hazards has been the subject of considerable focus, such as PHMSA advisories ADB-2019-02 and ADB-2022-01 and the recently released API RP 1187. The traditional framework to address landslide hazards, as summarized in API RP 1187, starts with a system-wide desktop screening of geohazards (Level 1) and ends with site-specific detailed investigations (Level 3).

To enhance the desktop Level 1 Assessment process, Geosyntec has developed three novel methods to produce landslide susceptibility maps and inform decision-makers about the exposure to this geohazard for several North American pipeline operators. These landslide susceptibility methods not only map existing landslide hazards, as is traditionally performed at Level 1 as described in API RP 1187, but they also predict areas where future landslide activity is more likely to occur in response to forcing events, such as significant precipitation (e.g., rainfall or snowmelt) or topographic change (e.g., from naturally occurring erosion or construction). These methods use various combinations of high-resolution light detection and ranging (lidar), soils, geologic mapping produced by public agencies, and subject matter expert (SME) input. This paper discusses these three methods, which, combined to date, have been implemented along more than 18,000 miles of pipelines in the United States and Canada. Additionally, this paper discusses how the resultant landslide susceptibility maps are and can be used to design or refine pipeline management practices, such as pipeline integrity assessment, budgeting, risk modelling, and construction planning.

## Introduction

A landslide is the downslope mass movement of soil or rock. Landslides are often caused by other geological hazards, such as earthquakes or seasonal rainfall, and the damage they cause can sometimes exceed that of the original triggering event. Understanding the exposure to potential damage produced by landslides has been a substantial concern for stakeholders responsible for the performance and integrity of existing and new infrastructure. The extensive network of buried pipelines in North America is vulnerable to landslides, as many transmission and distribution lines traverse several landslide-prone areas, and their burial depth can often be shallower than the typical depth of a landslide. Landslides are considered one of the costliest pipeline rupture causes and the predominant type of natural hazard that results in significant incidents. Knowing this, pipeline regulatory agencies such as the Pipeline and Hazardous Materials Safety Administration (PHMSA) have published advisories for pipeline operators to identify and monitor geohazards (PHMSA 2019 and 2022). To address this recommendation, organizations such as the Interstate Natural Gas

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Association of America (INGAA) Foundation and the American Petroleum Institute (API) have published recommended practices for pipeline integrity management of landslide hazards (INGAA 2023 and API RP 1187, respectively). These practices involve an approach that starts with a system-wide desktop screening of geohazards (Level 1) that results in a Geographical Information System (GIS) database containing an inventory of landslides typically (and not exclusively) within 100 feet of existent pipelines or proposed centerlines.

As part of the desktop Level 1 assessment, Geosyntec has developed three innovative methods for generating landslide susceptibility maps to inform decision-makers about exposure to this geohazard. This paper presents these methods and explores their applications as practical tools for improving pipeline management practices.

## Landslide Susceptibility Maps

As with all maps, landslide susceptibility maps provide a simplified depiction of spatial relationships and features, enabling users to interpret and interact with complex spatial information effectively. Numerous methods for landslide susceptibility mapping are documented in geological literature, ranging in complexity from simple, subject matter expert (SME)-driven maps to sophisticated models developed using machine learning algorithms and spatial statistics.

These maps are often created by integrating two primary sets of variables within a GIS environment: the morphological characteristics of the terrain and the geological conditions. Morphological characteristics are assessed using topographic maps or remote sensing data, such as aerial imagery and digital elevation models (DEMs) derived from light detection and ranging (lidar). Landslide inventories, a key outcome of geomorphological assessments, serve as critical input parameters for developing landslide susceptibility maps.

Geological conditions, on the other hand, can be derived from publicly available sources, such as geological maps, surficial geological units, or soil unit datasets. While these datasets are generally accessible with varying geographical coverage and resolution, maximizing input data's spatial resolution and consistency is crucial for creating meaningful landslide susceptibility maps tailored to pipeline applications.

Additional variables, such as vegetation and land cover, along with triggering factors like seismicity and precipitation, are frequently incorporated into robust landslide susceptibility maps, particularly those developed at regional or national scales (e.g., the Landslide Hazard Assessment for Situational Awareness [LHASA] model developed by the National Aeronautics and Space Administration [NASA Goddard Space Flight Center 2021]).

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In practice, proprietary lidar data collected for pipeline operators are often preferred over publicly available data. Proprietary lidar typically offers higher-resolution and more recent information, making it better suited for detailed and accurate assessments along specific areas of interest.

This paper discusses three approaches to develop landslide susceptibility maps, which are described as follows:

- SME-Driven Approach
- Soil/Geology-Based Approach
- Lidar-Driven Approach

## SME-Driven Approach

This method assumes that landslides occur primarily on slopes and within geological units exhibiting prior signs of instability. By mapping potential landslides, adjacent areas with similar geological characteristics can be identified as susceptible to future landslide formation. When reviewed by suitably experienced geologists or geological engineers (i.e., SMEs), the primary information sources for developing these maps include landslide inventories, hillshade, contours, and slope layers derived from high-resolution DEMs.

The SMEs performing the review differentiate between natural ground conditions and artificial features created by human terrain modifications, such as smoothed rights-of-way (ROWs). The natural human ability to detect differences and identify patterns, combined with expertise in landslide morphology, enables SMEs to classify terrain into areas with varying susceptibility to landslides.

In principle, the SME-driven map approach employs the same methods historically used to create geological maps (e.g., drawing boundaries between rock units), most of which remain valuable resources still in use. For example, the SME-driven map illustrated in Figure 1 was classified using the following categories:

- **Mapped Landslide:** Areas within the boundaries of the landslide inventory.
- **Proximal to Landslide:** Areas located within 20 feet of a mapped landslide.
- **Susceptible:** Slopes with characteristics such as geology, steepness, and terrain texture that imply an increased likelihood of landslide activity. Susceptible areas typically include rugged hillsides, benched morphologies, concave slopes, or evidence of landslides within the same slope or geological unit.
- **Less Susceptible:** Areas where landslides are less likely to develop, such as relatively flat alluvial valleys, smooth textures within the same slope or geological unit, or stable ridges underlain by more competent bedrock.

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Geomorphological analysis of the texture of the terrain was evaluated using the lateral extent of a geological unit inside and outside the area of interest. For instance, Figure 1 illustrates a potential landslide complex located more than 100 feet outside the area of interest, where the pipeline and ROW traverse a smooth, convex, west-dipping slope. Within the area of interest, the extension of the geological unit displaying landslide morphology was classified as Susceptible.

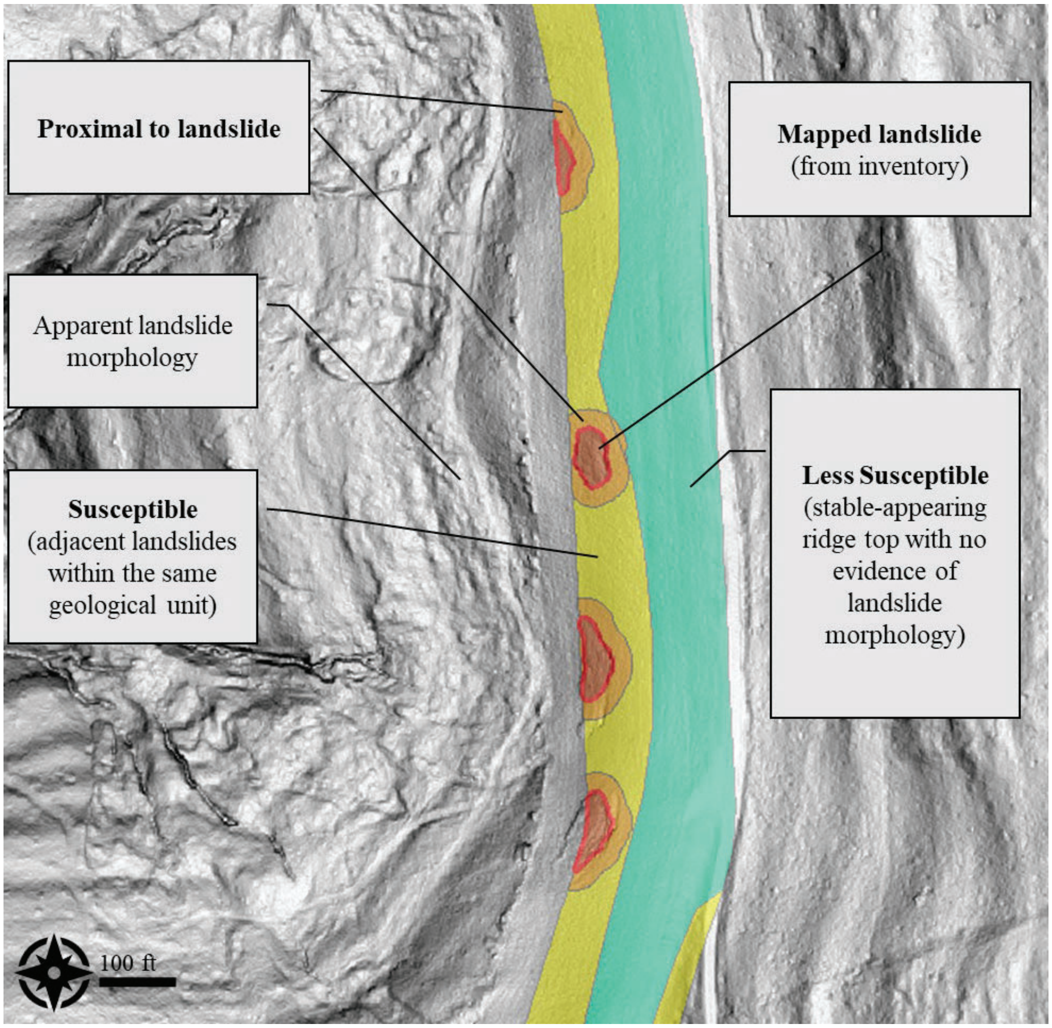

**Figure 1**. Example of SME-driven Landslide Susceptibility map along 100 feet of a pipeline. Basemap: Slope with inverted grayscale.

As a rough, screening-level approach, this landslide susceptibility mapping method provides an adequate depiction of conditions observed along the ROW and offers valuable insight into the general conditions surrounding buried pipelines. Since the method heavily relies on interpretation, results may vary among SMEs. However, when analyses are performed by experienced professionals following established geological standards, these differences are unlikely to produce significantly divergent maps.

### Soil/Geology-Based Approach

Similar to the SME-driven map, this method is based on the premise that landslides tend to occur in soil or rock units with a history of producing landslides. However, this method differs in that it uses publicly available sources to understand existing surficial geological or soil units rather than interpreting their lateral extent from the DEM datasets. These geological and soil maps are often a synthesis of field mapping and remote sensing analysis conducted by public agencies and are frequently used by geoscientists.

For pipelines in the United States, this method leverages publicly available surficial soil mapping developed by the United States Department of Agriculture Natural Resources Conservation Service (NRCS) and original mapping from lidar. The benefits of using NRCS soils are as follows:

- NRCS soil mapping covers most of the continental United States and is available as vector (digital shapes) in GIS format.
- NRCS soil mapping incorporates information such as slope angle, soil type, and other characteristics (such as typical soil strength) into their soil unit descriptions. By combining slope angle, soil type, and other related soil properties, many factors that control landslide susceptibility are included directly in the soil mapping.
- The original mapping scale was generally at either 1:12,000 or 1:24,000, which is more suitable for pipeline landslide susceptibility mapping than most geologic mapping, typically available at 1:100,000 or smaller scales.
- The NRCS soil mapping is representative of near-surface soil characteristics and is more likely to reflect the ground conditions at the shallow depths of buried pipelines than most geologic maps.

For pipelines in Canada, the method can leverage soil surveys from the Canadian Soil Information Service National Soil Database (at scales as fine as 1:20,000) and surficial geologic maps produced by provincial agencies (at scales of up to 1:1,000,000).

Creating the Soil/Geology-Based Map involves overlaying the landslide inventory against the soil or geological units. When both datasets are combined, it is possible to quantify the area of the landslides within each soil unit they intersect. This calculation excludes the fractions of the landslides that solely depict zones of accumulation at the toe of the landslides since they do not represent soils experiencing ground failure; ergo, they do not contribute to the landslide susceptibility of the slope. Once the cumulative area of landslides within each soil unit is known, a percentage of landslide coverage (LS) is calculated based on the total area of each soil unit within the study area (e.g., the soil unit A has 5% of its area covered by mapped landslides, or $LS_A = 5\%$).

This approach is an adaptation of the method used by the Oregon Department of Geology and Mineral Industries (DOGAMI) to map landslide susceptibility statewide. The DOGAMI method combines this map (derived from geologic maps at a lower resolution) with a map of landslide density to provide susceptibility classes (Burns and Madin 2009). On the other hand, Geosyntec's

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Soil/Geology-Based Map solely uses the LS variable to define thresholds for landslide susceptibility. Pipeline operators can set LS thresholds to match their level of risk tolerance based on their intended usage for the landslide susceptibility mapping. As an example, Figure 2 provides the results of a Soil/Geology-Based Approach using the following thresholds:

| | |
|---|---|
| LS < 2% | Low Susceptibility |
| 2% ≤ LS< 10% | Moderate Susceptibility |
| 10% ≤ LS< 100% | High Susceptibility |
| LS = 100% | Existent |

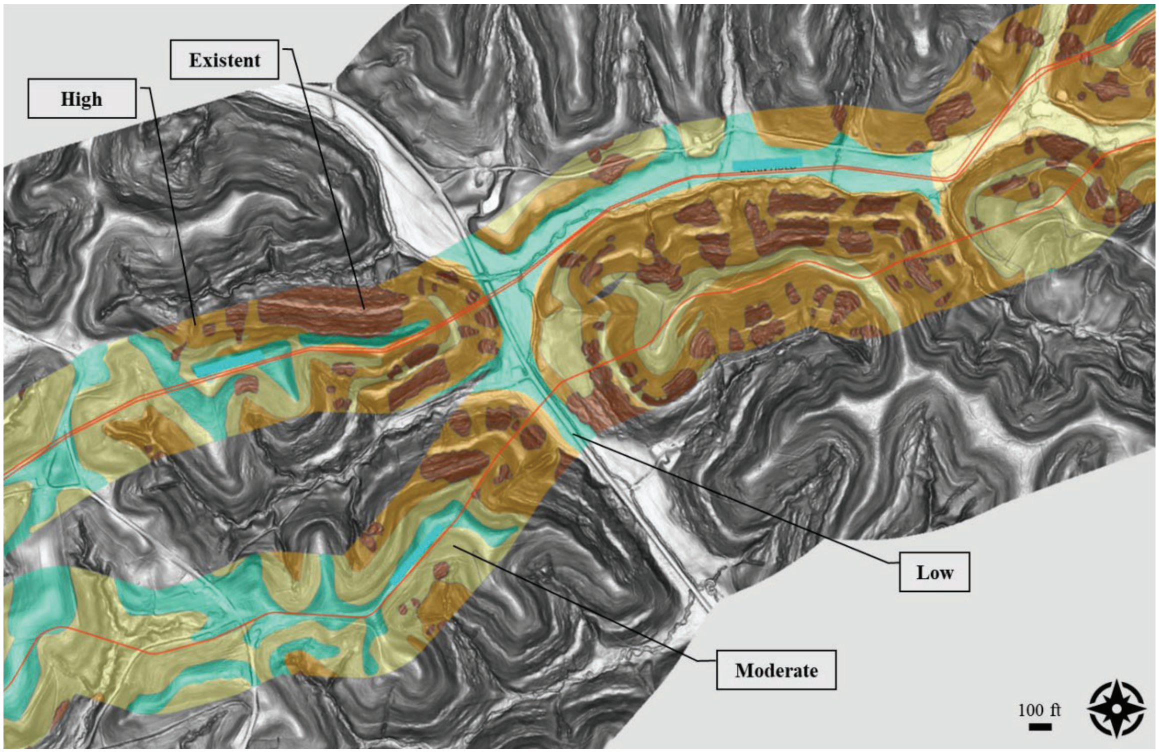

**Figure 2**. Example of Landslide Susceptibility Map based on Soil/Geology-based approach. Basemap: Slope with inverted grayscale.

The area depicted in Figure 2 was delineated using soil boundaries derived from the NRCS. These units demonstrate a strong correlation with the morphology observed in the slope basemap, closely aligning with the contours of ridges and valleys. In this region, the Soil/Geology-Based Approach effectively captured the lithological variations, highlighting the more competent ridges and the lower geological units prone to landslides. However, the alignment between the high-resolution DEM and the soil/geology layer may become less precise as the scale of the publicly available map decreases. To address this limitation, mappers can refine the shapes of the soil or geological boundaries to better align with the morphology observed in the DEM datasets prior to running the landslide susceptibility model.

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## Lidar-Driven Approach

This method is based on an automated landslide pattern recognition of the terrain using high-resolution DEM and landslide inventories. The principle of this Lidar-Driven Approach consists of sampling within mapped landslides and conducting spatial statistics to identify areas with similar characteristics along the area of interest. One notable example of this approach is the United States Geological Survey (USGS) Landslide Inventory and Susceptibility Map (2024), which uses linear and non-linear regression models of slope and relief (elevation change) to define thresholds based on their resulting cumulative density functions.

The approach described in this paper consists of a combination of slope percentage ($S = 100 * rise/run$) and terrain roughness ($R = [mean\,elevation - min.\,elevation]/[max.\,elevation - min.\,elevation]$). For each pixel within the area of interest, an index $I$ is calculated as $I = S * R$. This simplified approach yields the lowest values for flat and smooth terrain and the highest values for steep and rugged terrain. $I$ values are sampled from the landslide inventory to create a probability density function and to define thresholds of landslide susceptibility using the mean and standard deviation (SD) as illustrated in Figure 3. This classification is then applied for all pixels of the DEM.

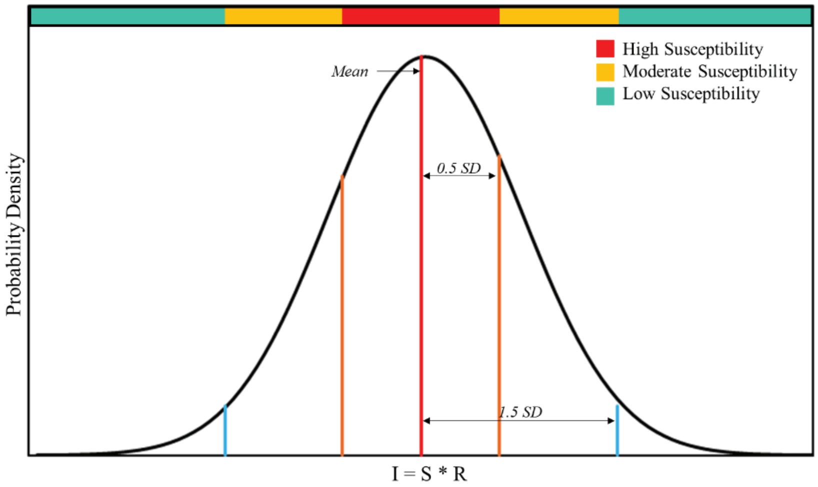

**Figure 3**. Definition of thresholds for landslide susceptibility using the Lidar-Based Approach.

Certain considerations were made during the implementation of this approach, with the most significant being the need to run the model for distinct areas sharing similar geological and geomorphological characteristics. It became evident that adjustments were necessary as the area of interest encompassed three markedly different geological settings: (1) lowlands composed of fluvial valleys and floodplains, (2) hillsides characterized by narrow ridges and stable slopes, and (3) other hillsides showing broad, rounded ridges densely covered with landslides. Such geological contrasts are often tied to the lithological properties of the bedrock, particularly when near the surface. For example, hard limestones tend to support more stable, steep slopes than do softer shales. Recognizing

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that these differences influence slope and roughness across varying geomorphological units, the model was executed separately for each area.

Another consideration consisted of conducting a spatial statistical analysis to minimize individual outliers (e.g., a lone pixel of low susceptibility surrounded by pixels of high susceptibility). This can be achieved by calculating a semivariogram to assess the distance at which the lateral correlation of the *I* values remains significant. For instance, semivariogram tests conducted for the example shown in Figure 4 showed that a positive spatial correlation was maintained within a range of approximately 10 feet. The *I* values were then resampled using a bilinear interpolation: the value of a new pixel was calculated by taking a weighted average of the surrounding pixels within a 10-foot radius.

The primary drawback of this method is its lack of geological context, which can be addressed by delineating distinct geomorphological units and running the model separately. Additionally, the resulting map cannot differentiate between landslide morphology and erosional features, often leading to gullies being misclassified as highly prone to landslides. However, the main advantage of this method lies in its relative simplicity while still yielding meaningful results. The map in Figure 4 illustrates this by showing the lowest risk in valleys, ridges, and benches, while areas with moderate to high risk are concentrated on hillsides containing landslides.

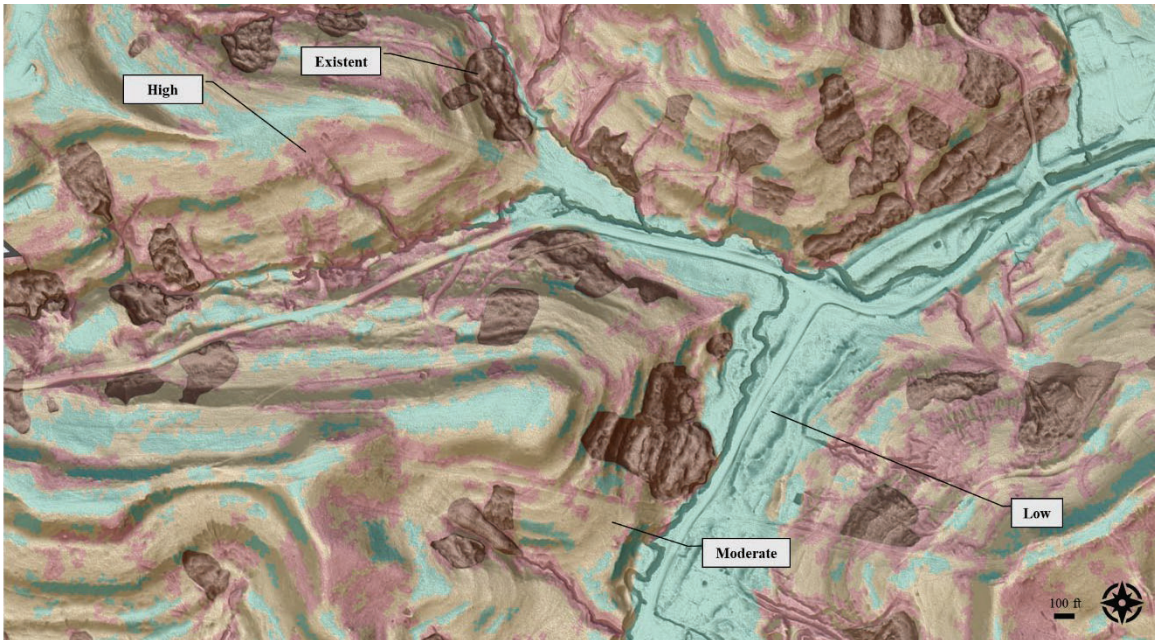

**Figure 4**. Example of Landslide Susceptibility Map based on Lidar-Based Approach. Basemap: Slope with inverted grayscale.

## Applications for Pipeline Management

In the author's experience, landslide susceptibility mapping is used by pipeline operators in the following ways:

- Awareness of areas potentially susceptible to landslide occurrence as an input to planning for construction projects, such as loop lines, valve stations, replacements, or other work involving significant ground disturbance. This helps in selecting safer and more stable routes, minimizing future geohazard exposure. The results of landslide susceptibility mapping are loaded into the operator's internal GIS viewer and can be accessed by the operator's project managers and other personnel involved in project planning. For projects that are planned for areas with heightened landslide susceptibility, additional preventative and mitigative measures can be implemented by the project teams to reduce the potential for triggering or worsening landslide movement.

- Planning, budgeting, and execution of landslide monitoring. Landslide susceptibility mapping, by identifying areas that are likely susceptible to landslide formation outside of existing landslides, can be used to delineate areas of heightened large-area monitoring, such as targeted, repeat lidar collection or reoccurring inertial measurement unit (IMU) bending strain analysis, in order to monitor not only known landslides but also areas where new landslides may form.

- As an input to risk models. Varela et al. (2022) discuss how, using a Soil/Geology-Based Approach combined with landslide-specific data calibrated with prior pipeline failure locations, an order of magnitude probability of failure (POF) resulting from landslides can be derived for pipeline systems. This model (or similar ones also derived from landslide susceptibility mapping) can be used to separate decision-making and risk analysis for pipeline integrity management programs.

- Regulatory compliance. Landslide susceptibility maps can help operators demonstrate due diligence and compliance with regulations that require the identification and management of geohazards affecting pipeline safety. These maps can also be used to communicate risks and mitigation strategies to stakeholders, including regulatory agencies and landowners, thereby fostering transparency and trust.

## Conclusions

Landslide susceptibility maps can be valuable tools in managing the significant risks posed by landslides to North America's vast pipeline network. These maps enable pipeline operators to address the growing demands for improved geohazard management, as underscored by regulatory agencies and industry standards like API RP 1187. By integrating lidar, advanced GIS analysis, and expert input, the methods discussed in this paper represent substantial progress in identifying and mitigating landslide-related risks along pipeline corridors.

The three approaches detailed—SME-Driven, Soil/Geology-Based, and Lidar-Driven—offer distinct advantages and limitations, making them adaptable to diverse operational needs. These methods provide pipeline operators with comprehensive tools to detect, monitor, and predict landslide hazards, improving their ability to plan and manage assets in challenging terrains.

Landslide susceptibility maps can be implemented far beyond risk identification. They support a range of pipeline management activities, including route planning, construction, landslide monitoring, and integrity risk assessment. By proactively addressing areas of heightened susceptibility, operators can reduce the likelihood of triggering new landslides during construction or maintenance, ensuring safer and more sustainable pipeline operations. Furthermore, the integration of these maps into risk models enables data-driven decision-making, enhancing resource allocation for pipeline integrity and compliance with regulatory requirements.

## References

API. 2024. *Pipeline Integrity Management of Landslide Hazards.* API Recommended Practice 1187. First edition. American Petroleum Institute. August 27.

Burns, W. J., and I. P. Madin. 2009. “Landslide Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (lidar) Imagery.” Oregon Department of Geology and Mineral Industries Special Paper 42.

INGAA Foundation. 2023. *Recommended Practice for Pipeline Integrity Management of Landslide Hazards*. Version 1. April.

NASA Goddard Space Flight Center. 2021. Landslide Hazard Assessment for Situational Awareness (LHASA) Model 2.0. Available at: https://gpm.nasa.gov/landslides/projects.html

PHMSA. 2019. “Advisory Bulletin ADB-2019-02, Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards.” Pipeline and Hazardous Materials Safety Administration. Federal Register. 84(85):18919. May 2.

PHMSA. 2022. “Advisory Bulletin ADB-2022-01, Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards.” Pipeline and Hazardous Materials Safety Administration. Federal Register 87:33576–33579. June 2.

United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). Soil Survey Geographic (SSURGO) Database. Available online at: https://websoilsurvey.nrcs.usda.gov/app/

USGS. 2024. U.S. Landslide Inventory and Susceptibility Map. United States Geological Survey. Available at: https://www.usgs.gov/tools/us-landslide-inventory-and-susceptibility-map.

Varela, P., S. Cheng, R. Sancio, D. Cook, A. Mckenzie-Johnson, and S. Koduru. 2022. “A new GIS-Based Method to Estimate Annual Probability of Pipeline Failure Resulting from Landslides Based on Actual Failure Locations.” Proceedings of the ASME 2022 13th International Pipeline Conference. IPC2022-86749. September 26–30.

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