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CONSIDERATIONS FOR AN INTEGRATED SYSTEM INCORPORATING PREDICTIVE MODELS FOR GEOHAZARD MANAGEMENT

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ABSTRACT

Geohazards are a significant threat to pipeline systems. In recent years, pipeline geohazard management has evolved toward a quantitative definition of threat severity (Rizkalla and Read, eds., 2019). The quantitative geohazard assessment framework is robust but flexible to accommodate models and engineering judgment required to inform estimations within the framework. For preliminary system-wide screening, threat severity (or susceptibility) estimates are often based on expert judgment, sometimes with limited information as a basis. This necessitates adoption of reasonable conservatism and recognition that accuracy of susceptibility estimates for geohazards is at best order-of-magnitude at the screening stage. As a project or pipeline system matures, site-specific analysis based on detailed characterization and monitoring data should replace preliminary screening results. To achieve this functional upgrade, predictive models that inform susceptibility estimates are required. These mechanistic models and the data acquisition and processing systems to feed them must be adaptive to account for inherent complexities of in situ conditions, and ideally must operate in near-real time to function effectively as predictive tools. Understanding the essential variables associated with these models is a first step in developing an integrated system that can ultimately incorporate artificial intelligence and machine learning coupled with "big data" to develop an early warning system.

Keywords: Predictive models, geohazard management

1. INTRODUCTION

Geohazards are a significant threat to pipeline systems, particularly those operating in challenging mountainous terrain with severe climatic and seismic conditions. Major pipeline operators in such settings have invested significantly in approaches to identify, characterize, and evaluate the threat severity posed to pipeline infrastructure by geohazards [1]. Nonetheless, geohazard events resulting in loss of containment from operating pipelines continue to occur and impact pipeline operations.

Several generations of geohazard assessment approaches and associated models have been proposed and adopted by different pipeline operators. These approaches include qualitative, semi-quantitative and quantitative assessment frameworks, which have been used in different settings with varying degrees of success to identify and characterize significant geohazard sites. However, in general, predictive capabilities of these approaches are limited.

Quantitative predictive models for credible geohazard mechanisms are essential components of an integrated system for geohazard management within an overall risk management strategy. This paper reviews important aspects of pipeline geohazard assessment and discusses key considerations related to an integrated system that incorporates quantitative predictive models for geohazard management.

2. GEOHAZARD ASSESSMENT METHODS

Several approaches for geohazard assessment have been generally accepted by regulatory agencies in Canada and elsewhere, including qualitative risk matrix approaches, semi-quantitative index-based approaches, and quantitative approaches. However, in order to incorporate the results of geohazard assessment into overall risk assessment of all threat categories affecting a pipeline, pipeline susceptibility to a geohazard event must be expressed in "absolute" terms (e.g., annual probability of failure per site or per unit length). "Absolute" in this context should not be misunderstood as a measure of precision, but is simply the form of the hazard or risk expression metric. It is important to recognize that estimates expressed in "absolute" terms have associated uncertainty that must also be expressed along with the assessment results [1].

2.1 Pipeline Risk Assessment Evolution

The evolution of pipeline risk assessment toward a quantitative "absolute" estimate of risk is described in the book "Pipeline Risk Assessment – the Definitive Approach and its Role in Risk Management" [2]. The author advocates abandoning all scoring (point assignment) systems outlined in predecessor publications, adopting the probability of failure triad (exposure, mitigation and resistance), incorporating OR and AND logic to combine hazard probabilities, using both measurements and estimates to replicate a Subject Matter Expert's (SME's) decision processes, and calculating hazard zones to drive consequence of failure estimates. The refined framework for modeling pipeline risk is shown in Figure 1.

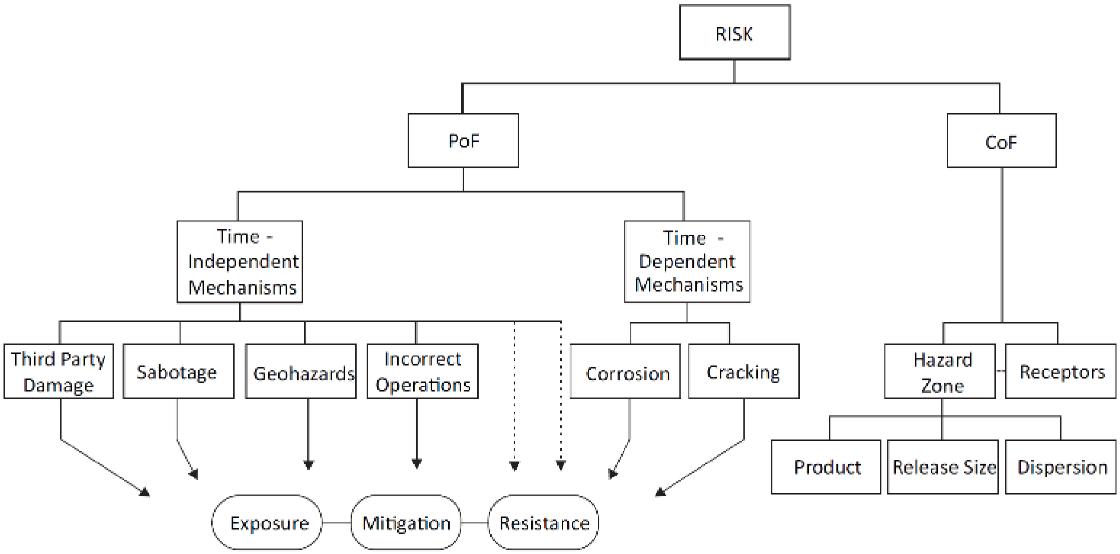


FIGURE 1: FRAMEWORK FOR MODELING PIPELINE RISK FROM ALL THREAT CATEGORIES [2]

This approach deviates from two previous risk assessment methodology categories: 1) scoring systems designed for simple ranking of pipeline segments, and 2) statistics-based quantitative risk assessments (QRAs) used in more robust applications for site-specific situations. Approaches of the first type were deemed to be limited in their ability to accurately measure risk and to meet Integrity Management Program (IMP) regulatory requirements, and those of the second type were deemed to be costly and generally ill-suited for system-wide assessment of long linear pipeline assets. The use of weighting factors in scoring systems was also shown to obscure real risks and to interfere with risk management, and it was recommended that their use be discontinued:

> *"Terminology has been getting in the way of understanding in the field of risk assessment… for true understanding of risk and for the vast majority of regulatory, legal, and technical uses of pipeline risk assessments, ["absolute"] numerical risk estimates in the form of consequence per length per time are essential. Anything less is an unnecessary compromise… We should take an engineering- and physics-based approach rather than rely on questionable or inadequate statistical data."* [2]

This refined approach to pipeline risk assessment considers probability broadly as a "degree of belief," and estimates "absolute" annual failure probabilities per length directly based on available information coupled with SME judgment and observations. The estimated failure probabilities have associated uncertainty but provide an unambiguous basis for decision-making without obscuring risk results with unnecessary complexity associated with scoring systems.

A key concept in this reframing of risk assessment is the adoption of engineering- or physics-based models of relevant phenomena affecting pipeline integrity. The underlying premise is that the best way to predict future events is to understand and adequately model the mechanisms that lead to events. This viewpoint is aligned with the evolution of geohazard assessment addressed in the next section.

2.2 Geohazard Assessment Evolution

Geohazard assessment has seen a progressive shift from qualitative observation-based approaches to quantitative approaches that blend observations, data and modeling to estimate "absolute" failure probabilities.

The geohazard assessment methodology [3, 4] used for several recent major pipeline projects is based on the approach originally accepted as fit-for-purpose in the National Energy Board (NEB) Reason for Decision regarding the Mackenzie Gas Project in Canada [5]. This originally semi-quantitative index-based methodology described in the 2008 ASME book "Pipeline Geo-Environmental Design and Geohazard Management" [4] has been progressively refined to produce estimates of pipeline susceptibility in quantitative terms, and to address various aspects of geohazard assessment. A detailed description of the refined quantitative methodology is included in the 2019 ASME book "Pipeline Geohazards: Planning, Design, Construction and Operations" [6].

In addition, several conference papers at the International Pipeline Conference (IPC) and the International Pipeline Geotechnical Conference (IPG) have been published to address specific aspects related to this evolution.

The important role of engineering judgment by Subject Matter Experts (SMEs) in conducting geohazard assessment is emphasized in a paper "Bridging the gap between qualitative, semi-quantitative and quantitative risk assessment of pipeline geohazards – the role of engineering judgment" [7]. While this essential role continues to evolve, the role of the SME in light of rapid technological developments in artificial intelligence (AI) and machine learning (ML) is at the heart of recent technical discussions and workshops, such as the Banff Pipeline Workshop in April 2023 [8].

A common misconception of the use of a quantitative geohazard assessment approach that produces "absolute" estimates of pipeline susceptibility is the appearance of precision in the estimated result. The paper "Framing uncertainty in pipeline geohazard assessment for integrity management and iterative risk assessment" [1] describes the essential nature of estimating and reporting uncertainty alongside quantitative numeric results from geohazard assessment. The paper also highlights various aspects of the geohazard management activities associated with the Camisea pipeline system in Perú, and the advancements toward a quantitative geohazard management strategy.

The context of a geohazard assessment is important to understand prior to planning an assessment strategy. While most literature on pipeline geohazard assessment is focused on pipeline integrity during pipeline operations, specifically the probability of loss of containment from the pipeline, another important context is geohazard management during construction, with an emphasis on construction safety and temporary mitigation measures to address potential geohazard threats. The paper "Pipeline geohazard assessment - Bridging the gap between integrity management and construction safety contexts" [9] provides commentary on reinterpreting system-wide geohazard assessment results from a pipeline integrity context for new pipelines as a starting point for determining construction safety mitigation requirements.

Finally, the linkage between geohazard assessment and quantitative risk assessment (QRA) of all threat categories is explored in the paper "Pipeline geohazard target susceptibility threshold – a reliability-based rationalization" [10]. The principles of reliability-based design and assessment of onshore pipelines described in Annex O of the Canadian Standard CAN/CSA-Z662-19 [11] are used as a basis for establishing and iteratively checking target susceptibility thresholds for geohazard assessment. The paper also explains the process to relate per site susceptibility values to reliability-based allowable probability of failure (PoF) values for a specified sliding evaluation length compatible with assessment of other threat categories. This approach has been used in several new pipeline projects, demonstrating the compatibility of quantitative geohazard assessment results as input to QRA software such as PIRAMID® or other similar software products.

The governing equation to estimate pipeline susceptibility associated with an individual geohazard mechanism *i* at a given segment of the pipeline is as follows:

$$S_i = I_i \cdot F_i \cdot V_i \cdot M_i \tag{1}$$

where

S_i	Pipeline susceptibility (or annual PoF) due to occurrence of the geohazard,
I_i	Initiation feasibility of the geohazard representing the degree of certainty that a geohazard occurrence at a specific location is feasible or infeasible,
F_i	Frequency of occurrence of the geohazard representing the number of events per year based on an estimated recurrence interval of geohazard triggers (e.g., rainfall, seismicity) or progressive development of a critical state (e.g., progressive toe erosion, episodic movement),
V_i	Vulnerability of the pipeline to an occurrence of the geohazard representing the expected degree of damage, or conditional probability of exceeding a prescribed limit state, from the pipeline being subjected to the geohazard (accounting for spatial and temporal conditional probabilities of soil-pipe interaction), and
M_i	Mitigation factor representing the ameliorating effects of mitigation measures installed during construction and, if necessary, during operation of the pipeline to reduce impact of the geohazard.

At an identified geohazard location, the first three assessment parameters are each assigned conditional probability values between 0 and 1 based on observational evidence from terrain analysis, and engineering calculations incorporating estimated material properties and route conditions, including topography and possible triggering mechanisms. The resulting value of pipeline susceptibility is considered to be an order of magnitude estimate of PoF (or FLoC) prior to mitigation (i.e., pre-mitigation susceptibility). The mitigation factor required to reduce the estimated pipeline susceptibility to an acceptable level is used to inform selection of mitigation.

The collection of conference papers described above does not delve deeply into the models and algorithms used to populate the various parameters in the quantitative geohazard governing equation, leaving the selection of appropriate models and algorithms to the practitioner based on the specific requirements of a project, and information available. Chapter 13 of the 2019 ASME book "Pipeline Geohazards: Planning, Design, Construction and Operations" [12] offers summaries of published algorithms for each of 36 geohazard mechanisms ranging from landslides to karst collapse. Many of these are closed-form solutions that can be easily implemented in a GIS environment. The following section offers more insight into different types of models.

3. SLOPE STABILITY AND DEFORMATION MODELS

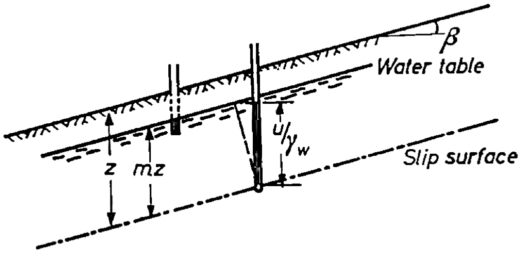
While landslides and slope stability issues represent only one of several categories of geohazards, there have been considerable developments on this topic. Therefore, examples of models provided in this section focus on slope stability and deformation, but the principles are transferable to models of other geohazard mechanisms.

3.1 Mechanistic Stability Models

Mechanistic models are mathematical abstractions of physical phenomena or processes and are seldom an exact representation of a given phenomenon or process, especially if it is complex. Consequently, model error is an important consideration, and must be recognized in geohazard assessment:

> *"Essentially, all models are wrong, but some are useful… the scientist cannot obtain a 'correct' one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena."* [13, 14]

Mechanistic models are differentiated from purely empirical relations (or weights-of-evidence models) by the underlying objective of replicating a process through physics-based principles. Figure 2 shows a classic example of the closed-form solution for the factor of safety of a plane translational slip with slope parallel seepage [15], which can be derived from first principles considering the slope angle, *in situ* and saturated unit weight of the soil, unit weight of water, depth of groundwater table, depth of sliding plane, and effective strength parameters for the soil (cohesion c' and friction angle ϕ').



For limiting equilibrium

$$\gamma z \sin\beta \cos\beta = c' + (\gamma - m\gamma_w) z \cos^2\beta \tan\phi' \qquad (2)$$

If $c' = 0$:

$$\tan\beta = \frac{\gamma - m\gamma_w}{\gamma} \tan\phi'$$

FIGURE 2: MECHANISTIC MODEL OF TRANSLATIONAL SLIP WITH SLOPE PARALLEL SEEPAGE [15]

This relatively simple mechanistic model is a reasonable representation of long, uniform slopes with soil materials that tend to slide parallel to the slope due to natural layering, weathering profile (e.g., residual soils), or other structural controls. Variations of this model have been developed to account for such conditions as seepage that is not parallel to the slope [15], three-dimensional edge effects [17], and pseudo-static loading from earthquakes [18]. These models are all framed around limit equilibrium analysis of shear strength versus shear stress to determine a factor of safety against initiation of slope instability, in this case slope-parallel translational slip.

Using the model in Figure 2 as an example, the model parameters can be classified as either static (e.g., slope angle, saturated unit weight of soil, unit weight of water, depth of sliding plane) or dynamic (depth of groundwater table, effective cohesion and friction angle). The effective cohesion and friction angle are each a function of normal stress if the soil material exhibits a non-linear Mohr-Coulomb failure envelope under drained conditions, or can be considered constant ("static") if the envelope is linear. Normal stress is a function of the depth to groundwater table and the depth of the failure plane. Therefore, some parameters are independent, and others are not. A physics-based model correctly captures the relations between parameters and recognizes the interdependency of some parameters.

Another example of a physics-based model of slope stability is for plane failure of a rock slope involving a tension crack and a sliding plane inclined less steeply than the slope face angle [19]. The model geometry is illustrated in Figure 3. There are two scenarios considered: (a) the tension crack occurs in the upper surface of the slope, and (b) the tension crack occurs in the slope face. The geometry of a plane failure and the groundwater conditions can be completely defined by four dimensions (H, b, z and z_W) and by three angles (ψ_f, ψ_p and ψ_s). These simple models, together with the groundwater conditions, seismic ground motion concepts and mitigation options allow stability calculations to be carried out for a wide variety of conditions.

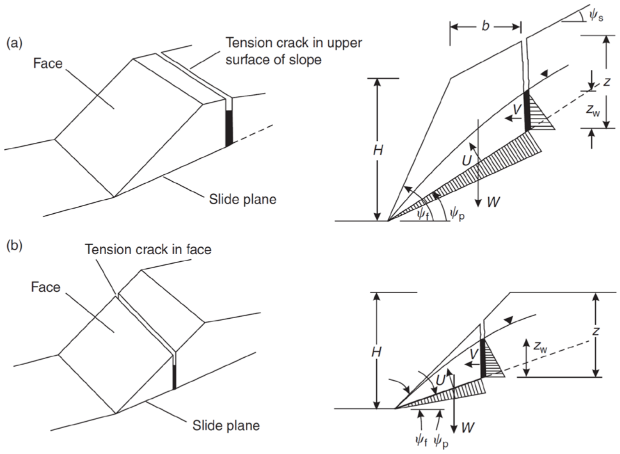


FIGURE 3: MECHANISTIC MODEL OF PLANE FAILURE WITH TENSION CRACK [19]

The equation for factor of safety is the ratio of resisting force to driving force, given as follows:

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi}{W\sin\psi_p + V\cos\psi_p} \qquad (3)$$

$$A = (H + b\tan\psi_s - z)\operatorname{cosec}\psi_p$$
$$U = 0.5\,\gamma_W z_W (H + b\tan\psi_s - z)\operatorname{cosec}\psi_p$$
$$V = 0.5\,\gamma_W z_W^2$$

For scenario (a)

$$W = \gamma_r\left[\left(1 - \cot\psi_f \tan\psi_p\right)\left(bH + 0.5\,H^2 \cot\psi_f\right) + 0.5b^2\left(\tan\psi_s - \tan\psi_p\right)\right] \tag{4}$$

and for scenario (b)

$$W = 0.5\,\gamma_r H^2 \left[\left(1 - \frac{z}{H}\right)^2 \cot\psi_p \left(\cot\psi_p \tan\psi_f - 1\right)\right] \tag{5}$$

where
c = cohesion (kPa)
ϕ = internal friction angle (degrees)
γ_r = unit weight of rock (kN/m^3)
γ_w = unit weight of water (kN/m^3)
A = area of sliding plane (m^2/m)
H = slope height (m)
z = tension crack depth (m)
z_W = depth of water in tension crack (m)
ψ_s = upper slope surface angle (degrees)
ψ_f = slope face angle (degrees)
ψ_p = sliding plane angle (degrees)
U = water forces acting on sliding plane (kN/m)
V = water forces acting in tension crack (kN/m)
W = weight of sliding block (kN/m)

3.2 Surrogate Stability Models

Alternative empirical models for slope stability have been proposed whereby important parameters associated with slope stability are identified and assigned weighting factors to represent their relative significance. Weighting factors are sometimes determined through multi-linear regression assuming all variables are independent. While this approach is used for the prediction of liquefaction-induced lateral spread displacement [20], this assumption may be incongruent with physics-based models relating important parameters for slope stability analysis.

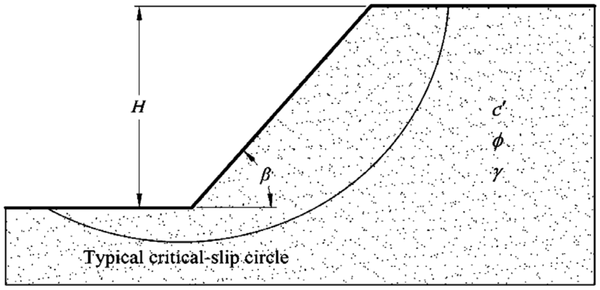


FIGURE 4: IDEALIZED MODEL OF ROTATIONAL FAILURE OF A SIMPLE UNIFORM SLOPE [21]

Other more complex relations can be determined through multi-variate analysis, ideally producing a function that reasonably approximates the results from a physics-based model within a given range of the underlying variables. An example of this type of analysis is a best-fit explicit equation for safety factor of simple uniform slopes subject to rotational failure [21] (Figure 4) based on stability charts (Figure 5) from Taylor [22].

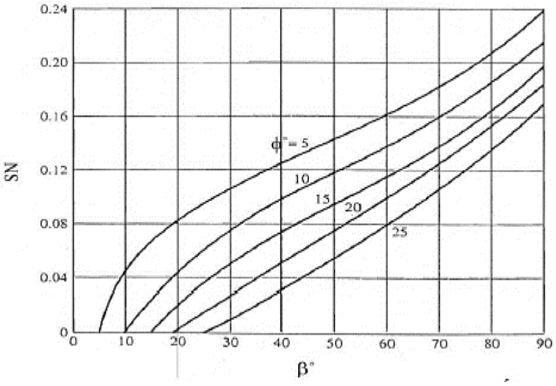


FIGURE 5: STABILITY CHART FOR SIMPLE UNIFORM SLOPES SUBJECT TO ROTATIONAL FAILURE [22]

The resulting empirical equation is given as follows:

$$F = \frac{\tan\phi}{\tan\left(\dfrac{-b - \left(b^2 - 4ac\right)^{1/2}}{2a}\right)} \tag{6}$$

where
$a = 5.94466 \times 10^{-5}$
$b = -0.00807 + 3.41 \times 10^{-5}\beta - \lambda\pi/180$
$c = 0.042186 + 0.004905\beta - 6.44 \times 10^{-5}\beta^2 + 4.07 \times 10^{-7}\beta^3$
$\lambda = \dfrac{c'}{\gamma H \tan(\phi)}$
c' = soil cohesion (kPa)
ϕ = internal friction angle (degrees)
γ = unit weight of soil (kN/m^3)
H = slope height (m)
F = safety factor with respect to shear strength
$SN = c'/\gamma HF$ = stability number
$\phi_m = (\tan\phi)/F$ = mobilized friction angle (degrees)

The proposed equation (Eq. 6) is applicable to the case of homogeneous slopes without seepage as well as the special cases involving complete submergence, complete sudden drawdown, steady seepage, and zero boundary neutral force. Validation of the proposed equation was performed by comparing its results with those of existing graphical and analytical methods for rotational failure, including those of Taylor [22] and Janbu [23]. The results show that the proposed equation is accurate within the range of mobilized friction angle, stability number, and slope angle considered. A more accurate formulation for mobilized friction angle, which reduces model error, is also included in the paper [21].

Simple limit equilibrium models have been incorporated into numerical simulations of study areas [24, 25] using a 3D bare-earth Digital Elevation Model (DEM) to represent ground surface topography, and linking rainfall to a change in groundwater table through a flow accumulation model, accounting for natural basins and gullies. A more realistic rainfall infiltration model (e.g., Horton) is contingent on a number of factors including degree of saturation of the soil, hydraulic conductivity of the soil and its variability with depth or soil conditions [26]. In this integrated system of models, the effects of rainfall intensity can be evaluated in terms of change in factor of safety. Predictions of slope instability were compared to observations of instability, with reasonable correlation, indicating some degree of model error associated with one or more of the integrated models. Nonetheless the relations between parameters in the models were considered. The deficiency in the model performance in this case was possibly due to a higher degree of complexity or variability in materials and material properties, or oversimplification of the relation or time-dependency of change in groundwater table with rainfall intensity. Variability in rainfall intensity over time within the study area was also a possible contributor to model error.

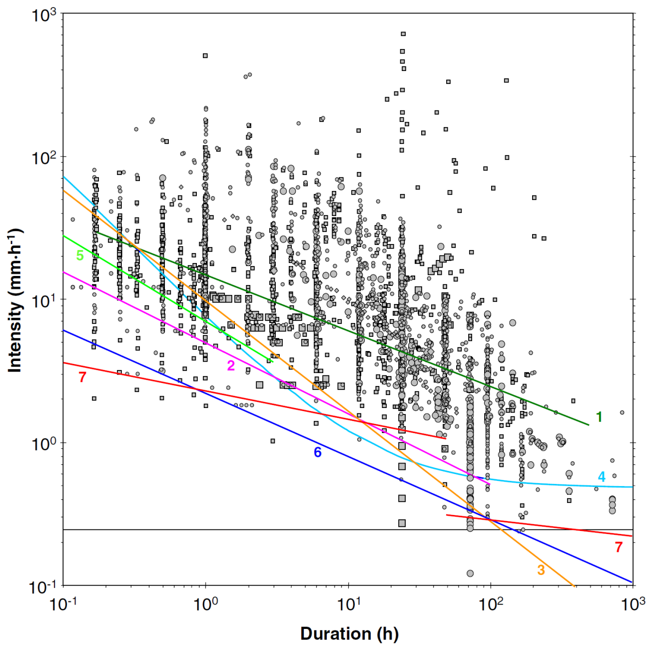


FIGURE 6: GLOBAL RAINFALL INTENSITY-DURATION THRESHOLDS FOR SHALLOW SLOPE INSTABILITY [27]

Empirical models have been developed to link rainfall inputs to the onset of slope instability. Guzzetti et al. [27] lists several relations that consider various precipitation attributes for a given area, including intensity, duration and antecedent rainfall total over different time periods (Figure 6). Findings suggest that for areas of similar topography and geological conditions, such models may be useful as inputs to early warning systems, but their utility is limited by the fact that the specific geologic attributes of an area are not considered directly. Consequently, the predictive system relies on historical observations of previous instability events to correlate the various rainfall parameters considered. Significant changes in geology or topography along a linear infrastructure route would require a geotechnical SME to parse the route into areas with similar surface and subsurface conditions, then use information from those parsed areas in combination with climatic data to calibrate such a model. In areas with limited historical slope instability events, reliable calibration of a model might be challenging.

3.3 Deformation Models

Mechanistic and surrogate models in the literature tend to focus on factor of safety estimates, with the onset of slope instability coincident with a factor of safety of unity. Factor of safety is based on the ratio between shear strength and shear stress of the soil or rock material comprising a slope. The underlying constitutive model in these analyses is implicitly an elasto-plastic stress-strain response, with the pre-peak portion of the stress-strain curve typically defined by Young's modulus and Poisson's ratio, or equivalent elastic moduli (e.g., bulk and shear modulus). The post-peak response may be considered perfectly plastic, brittle plastic, strain-softening, or strain hardening depending on the materials involved. The amount of plastic deformation depends on the nature of this post-peak response. For materials with strength made up of cohesion and frictional resistance, the sudden loss of cohesion may result in a residual strength that is insufficient to retain the failed material at its original slope angle, resulting in very large deformation or long-runout landslide events. Predicting post-peak deformation is challenging without sufficient material characterization and spatial delineation of geologic conditions in a geologic model.

Another type of material response that generates displacement is creep. In some models, creep rate is proportional to the magnitude of differential stress (or shear stress) that a material experiences. A material may undergo primary creep, reach a relatively stable secondary creep stage, and ultimately reach a tertiary creep stage that accelerates to creep rupture at some critical strain. This type of behaviour may be sensitive to moisture content of the soil, with a threshold moisture content required to initiate the creep process. Creep tests can be conducted to determine the creep characteristics of a material and the relation between creep rate and moisture content, clay content, or other material constituent.

Even without shear stress dependent creep, changes in moisture content may result in changes in bulk and shear modulus of a material, resulting in intermittent or episodic downslope movement as the slope material experiences wetting and drying cycles that change the moisture content of the soil. This behaviour can be modeled once the soil material characteristics are understood.

Seismically-induced deformation can be estimated using pseudo-static models that relate the ground acceleration caused by an earthquake to the static factor of safety of a slope with known material properties and groundwater table. The work by Jibson et al. [28] provides an example of estimating Newmark displacement associated with a design seismic event determined through geologic and seismic characterization of a site. The underlying model for Newmark analysis is a sliding block on an inclined plane subjected to horizontal and vertical acceleration generated by a seismic event. The model is simplistic, but widely used to estimate slope displacement. The displacement estimates in conjunction with information on the area of slope movement in relation to a pipeline allows direct estimates of pipe strain related to ground movement.

4. MONITORING

Slope displacement or deformation is unquestionably as significant as the point of onset of instability. For this reason, ground deformation monitoring using inertial mapping unit/in-line inspection (IMU/ILI) of the pipeline in combination with remote methods (differential LiDAR, InSAR) or installed instrumentation (slope inclinometers, fibre optics, survey pins, robotic optical survey systems, crack deformation gauges, tiltmeters, GPS sensors) have been used. With some exceptions, most monitoring systems are intermittent with a delay between readings and processing time required. Near real-time monitoring is the ideal standard to relate changes in driving forces, such as precipitation measured by a dedicated weather station, to changes in slope deformation response directly. This allows development of a cause-effect relationship that can be used in a predictive sense as a system matures.

The Turtle Mountain Monitoring Project (TMMP) is an example of a near real-time integrated monitoring system tied to an early warning system and emergency response protocols [29]. The project was initiated in 2003 at the site of the 1903 Frank Slide in southern Alberta, Canada. The 1903 event, a rock avalanche, involved 30 million cubic metres of rock debris that took 90 seconds to reach its final destination in the valley bottom, killing over 70 people in the process. The prominent south peak of Turtle Mountain was later identified as a possible source for a second rock avalanche with an estimated volume of about 8 million cubic metres. In 2003, the valley bottom in the shadow of Turtle Mountain contained residences, utilities, a highway, and a railway mainline along the Crowsnest River.

The TMMP monitoring system comprised a robotic optical survey system with reflector targets, permanent GPS sensors, extensometers and crack gauges across major fissures at the top of the mountain, tiltmeters, permanent photogrammetric targets, a microseismic monitoring network, a thermistor string to check for alpine permafrost, stream outflow gauges at a spring at the toe of the mountain, and a dedicated weather station to monitor rainfall, temperature, wind speed and other climatic parameters. The philosophy of this integrated monitoring network was to detect indicators of rock mass instability and the climatic and seismic conditions driving the rock mass response. Monitoring data were recorded hourly and transmitted by radio to a central database housed at the Frank Slide Interpretive Centre in the valley bottom. Alarm thresholds were established for each of the instruments and warning logic was developed based on the suite of instruments. The warning system was then set to communicate with the local Emergency Response Plan for the area. The project cost $1.1 million and was operated by the Government of Alberta for several years, until the system was replaced with a ground-based InSAR system in 2009, and another in 2014.

Another example of an integrated monitoring system is the one installed in response to a 2016 loss-of-containment incident on Husky Midstream's NPS 16 pipeline on the south slope of the North Saskatchewan River, Canada. The pipeline buckled at a mid-slope overbend as a result of ground movement associated with a large ancient landslide complex. In conjunction with pipeline replacement at the site, a robust state-of-the-art instrumentation monitoring program was implemented by Husky Midstream, which included real-time geotechnical instrumentation, high fidelity distributed fiber optic sensing (HDS), repeat ILI and weather data monitoring to identify, evaluate and monitor areas of ground and pipeline movement so that potential impacts to the pipeline could be mitigated [30]. An early-warning system that included alarm thresholds was also developed to identify when to proactively shut-in the pipeline.

The HDS monitoring comprised strain, acoustic and temperature sensing that revealed an excellent correlation to the geotechnical, ILI and weather station monitoring data on the actively moving landslide complex. The HDS monitoring showed increased strain magnitudes following a significant rainfall event that correlated to an acceleration in survey monument and slope inclinometer movement, and was also correlated to ILI locations of bending strain. Accumulated strain magnitudes also correlated to LiDAR change detection results and visual observations of the ground surface. Acoustic and strain accumulation was also correlated to construction activity on the right-of-way.

While the installation of sophisticated integrated monitoring systems such as the TMMP or Husky examples is not feasible everywhere along linear pipeline systems, the examples illustrate the utility of an integrated system of data collection and analysis to produce actionable results in near-real time. These types of systems may be suited for site-specific application in identified critical areas. For general overland segments of pipeline, repeat IMU/ILI surveys (Figure 7), repeat LiDAR, InSAR, repeat photogrammetry, and climatic and seismic monitoring, along with new technologies such as high-fidelity fiber optic sensing installed as a continuous linear sensor along the pipeline provide a means of collecting corroborating datasets, albeit with disparate data collection schedules. Supplemental observations from ground patrols also inform the assessment of local stability and ground movement. Such systems are used for the Camisea pipline in Perú [1].

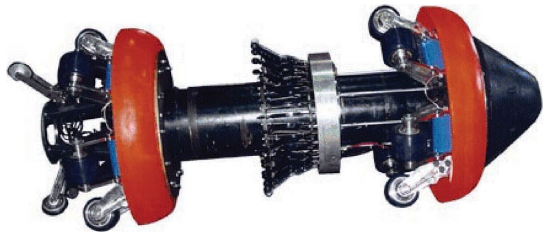


FIGURE 7: INERTIAL MAPPING UNIT (IMU) TOOL [4]

5. RECENT ADVANCES

Artificial intelligence (AI) and machine learning (ML) coupled with "big data" holds the promise of progressive improvement in models and predictive capabilities. "Big data" refers to the growing collection of readily-available data compiled by various vendors, government agencies and others, some free of charge and other for purchase.

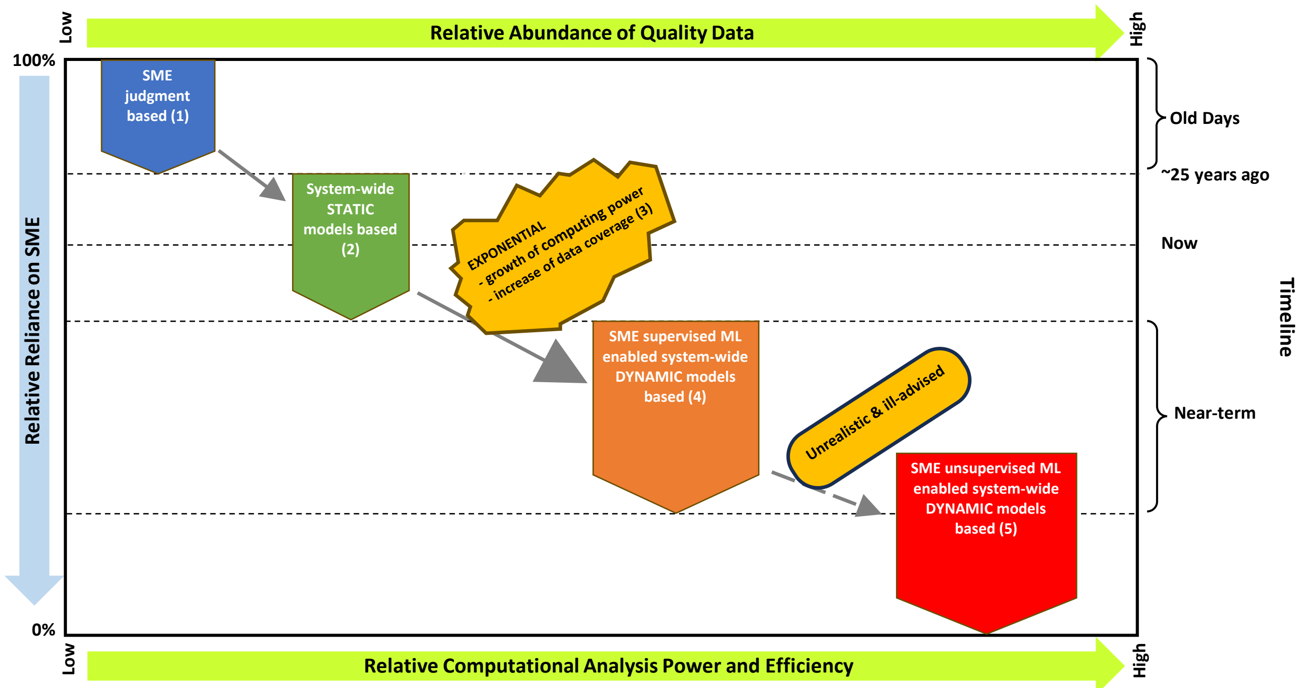
One utopian idea that has gained some traction recently is the elimination of the geotechnical SME from the process of predicting geohazard occurrence and progression, instead relying on AI and ML to determine mathematical functions that adequately describe the range of observations and data points for an area as a means of predicting future geohazard events and their impact on infrastructure. This "SME unsupervised" viewpoint relies entirely on AI and ML to develop working models. The issue with this viewpoint is no fundamental underlying mechanistic model against which to check reasonableness of predictions that fall outside of the range of the calibration dataset. If for example the relation of pore pressure to factor of safety is not framed in a physically-correct relation, predictions of effects of pore pressure outside of the range of the calibration dataset might be wildly erroneous. A geotechnical SME is therefore a critical element in the evolving use of new technology, a "SME supervised" viewpoint, that provides a basis for identifying unrealistic predictions or trends, diagnosing the cause, and improving the models used for prediction.

Figure 8 illustrates the evolution of the role of geotechnical SME in relation to the advances in availability of quality data and computing power. The transition from a central role in identifying geohazards and assessing threat severity with little or no computer support to a current state of significantly improved access to data, computing power, monitoring technology, and support from software applications is a major step toward near real-time assessment of geohazard threats to linear infrastructure. The development of predictive models within an integrated assessment system is central to further advances toward increased use of AI and ML to support geotechnical SME judgment.

6. KEY CONSIDERATIONS

Key considerations in the advancement of predictive models and integrated geohazard management systems are:

- Geologic model – a baseline geologic model of the pipeline route and a process to upgrade the model as new information is acquired is an essential component of an integrated system, with the model maturing with time to improve predictions of geohazard occurrence and behaviour
- Causation vs correlation – physics-based models are intended to directly relate cause and effect, linking driving force to changes in key dynamic parameters such as pore pressure or groundwater table depth. Empirical models may be used to correlate conditions to outcomes but may blur the relation between cause and effect.
- Static vs dynamic variables – defining the key variables that describe a geohazard mechanism, and understanding which variables are "static" (i.e., constant for the sake of predictions) and which are "dynamic" (i.e., change with time) is essential to identify data inputs, possible sources of information and monitoring requirements.
- SME supervised vs unsupervised application of AI and ML – the adoption of "SME supervised" use of AI and ML is a prudent step toward a more powerful and efficient integrated system of predictive models, whereas "SME unsupervised" use of this technology increases the likelihood of unrealistic predictions, false alarms, and reduced availability of qualified geotechnical SMEs over the course of time if geotechnical SMEs are removed as gatekeepers of inputs and outputs from predictive models.
- Data – data availability and cost have improved dramatically in recent years, but the quality and reliability of data must be evaluated for use by a qualified geotechnical SME, considering such aspects as pedigree, vintage, scale, reliability of third-party interpretation, algorithms used to generate interpreted datasets (e.g., landslide susceptibility maps), and intended use of the original interpreted data products.
- Dataset refresh rate/interval and processing time – different sources of "dynamic" data have different refresh or resampling rates and processing time, making the goal of near real-time predictions challenging over a long, linear infrastructure route.
- Data reconciliation and integration – data mining, checking and conversion protocols along with suitable metadata (e.g., map projection, datum, etc.) are required to ensure the quality and compatibility of information acquired from legacy studies, public sources and data vendors.
- Analysis process and duration – the effort and duration required to process information from various sources and check results directly impacts the duration between data acquisition and prediction outcomes; efficient QA/QC checks are essential to ensure quality and minimize delay in predictions, and the ensuing issuance of warnings and emergency response if required.
- Warning system integration – once critical sites have been identified and instrumented, establishing alarm thresholds and warning criteria based on alarms is a progressive refinement process to reduce false alarms and to avoid missed alarms (i.e., minimizing false negatives and false positives).
- Barriers to collaborative research and development – a dedicated team of experts from various agencies and companies is one approach to research and development of predictive models and integrated systems for geohazard management, but issues such as



Notes:
(1) SME judgment applied to SME-identified sites
(2) Computational data-intensive GIS-enabled applications of closed-form solutions of geotechnical and pipeline response models
(3) Growth in computing power to train ML-algorithms and increasing data coverage and supporting analytical and integrating tools provide options for increased near real-time mapping
(4) Computational extension of static models with near real-time dynamic inputs of triggering mechanism and pipeline response spatial data
(5) SME unsupervised ML-enabled models potentially reduce reliability of predicted responses (i.e., increase in false positive and false negative outcomes)

FIGURE 8: PROGRESSION OF PIPELINE GEOHAZARD MANAGEMENT ASSESSMENT METHODOLOGIES [31]

intellectual property, non-disclosure, and non-competition clauses in contracts must be navigated to fully leverage the mutual benefit arising from well-crafted models and systems.

Once a decision is made to develop an integrated system of predictive models, additional considerations include:

- Deliverable – What is the desired end product - in-house, third party or commercial?
- Leverage – Does the development process involve integrating an existing GIS database and tools, and optimizing existing field and monitoring activities, or starting from a blank slate?
- Timeline – What is the development schedule? Is it a staged development process? Are there interim products and target dates? Is prototype testing planned? Are there key deadlines?
- Team – Will the development be undertaken by a single vendor, a collaboration of internal/external personnel, or an expert group collaboration? How will this be coordinated?
- Commissioning – What is the process to validate any development (e.g., prototype testing)? What are the acceptance criteria? How will synthetic data be generated to calibrate models?
- Stakeholder engagement – What assurances are required by stakeholders? Is there a requirement for external peer review? What is the plan for presentations and meetings to engage stakeholders? What is the process for stakeholder endorsement?

7. CONCLUSION

Pipeline integrity management continues to adapt and improve with the adoption of new technologies. The use of predictive models is becoming an essential part of an integrated system for geohazard management. The examples provided in this paper have focused on slope-related hazards, but the principles espoused are applicable to other geohazard mechanisms such as debris flow, ground subsidence, karst collapse, and other geohazard phenomena.

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