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Considerations for an Integrated System Incorporating Predictive Models for Geohazard Management

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Outline

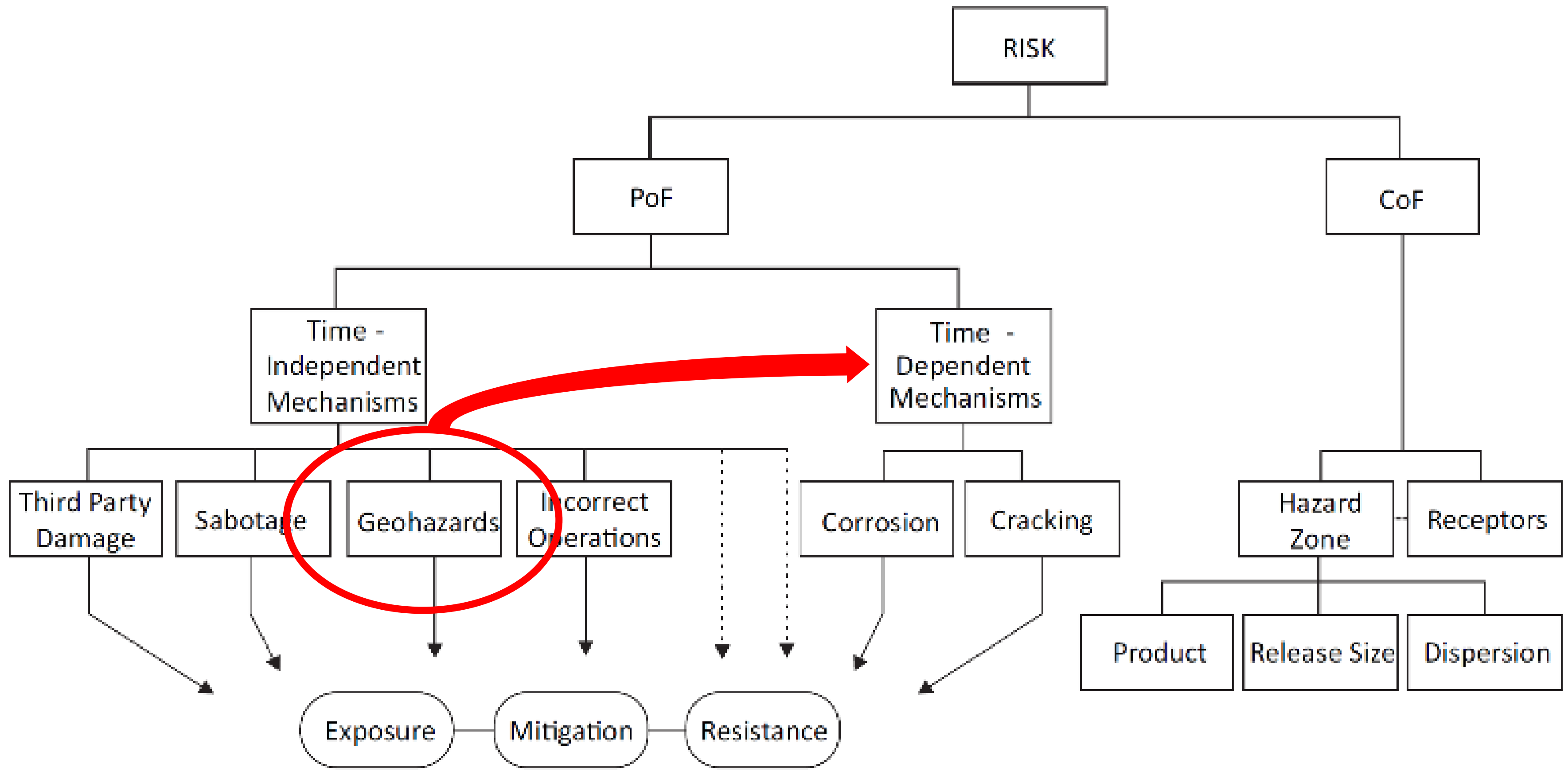
- Introduction
- Evolution of risk and geohazard assessment
- Slope stability and deformation models
- Monitoring
- Recent advances
- Key considerations
- Conclusions

Introduction

- Geohazards are a significant threat to pipeline systems, particularly in mountainous terrain with severe climatic and seismic conditions
- Several generations of geohazard assessment approaches and models have been adopted by different pipeline operators
- Quantitative predictive models for credible geohazard mechanisms are essential components of a risk management strategy
- Important aspects of pipeline geohazard assessment and key considerations for an integrated system incorporating predictive models for geohazard management are covered in the paper


Risk and geohazard assessment evolution

Pipeline Risk Assessment Evolution



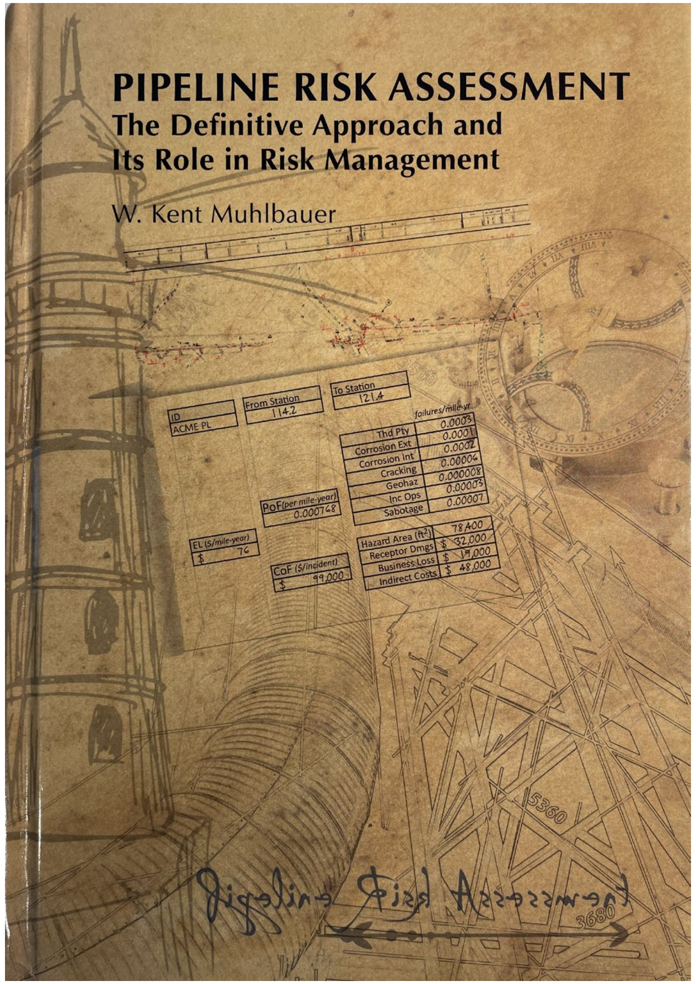
Muhlbauer 2015

Quantitative Risk Assessment

"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, numerical risk estimates in the form of consequence per length per time are essential. Anything less is an unnecessary compromise…

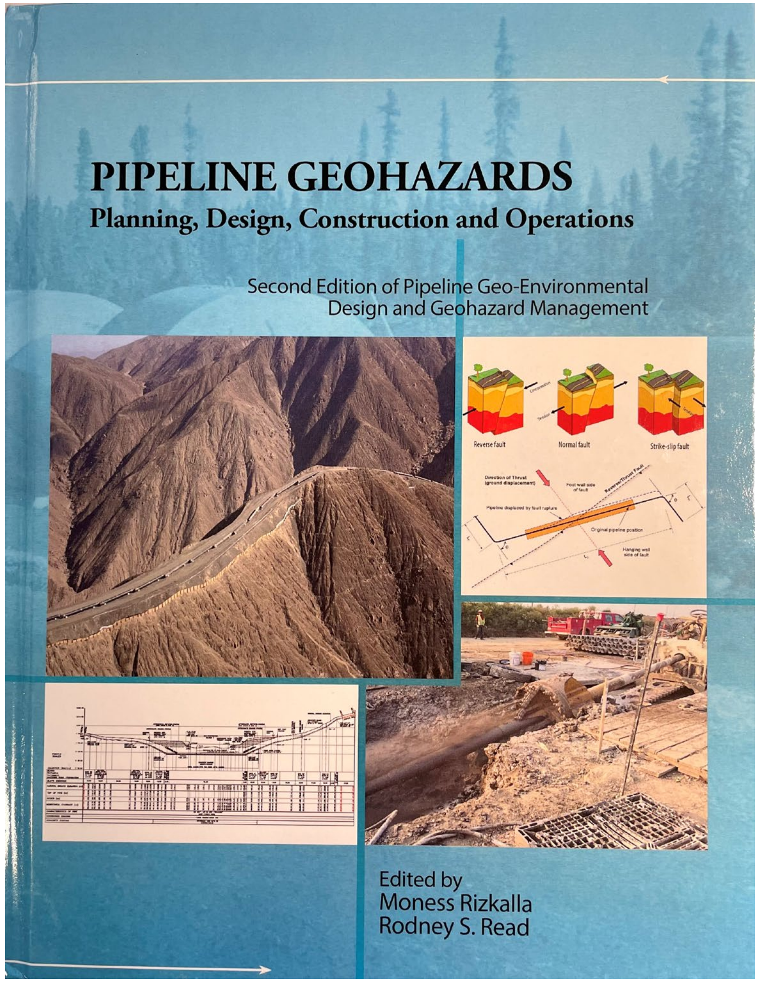
We should take an engineering- and physics-based approach rather than rely on questionable or inadequate statistical data."

- Muhlbauer 2015



Geohazard Assessment Evolution

- Progressive shift in geohazard assessment from qualitative observation-based approaches to quantitative approaches that blend observations, data and modeling to estimate "absolute" failure probabilities
- Evolution described in a series of technical papers at international conferences (Rio Pipeline, IPG, IPC) and two ASME books (2008, 2019)



Quantitative Geohazard Assessment

- Susceptibility – product of geohazard probability of occurrence and vulnerability; annual probability of loss-of-containment per site
- Partitioned approach

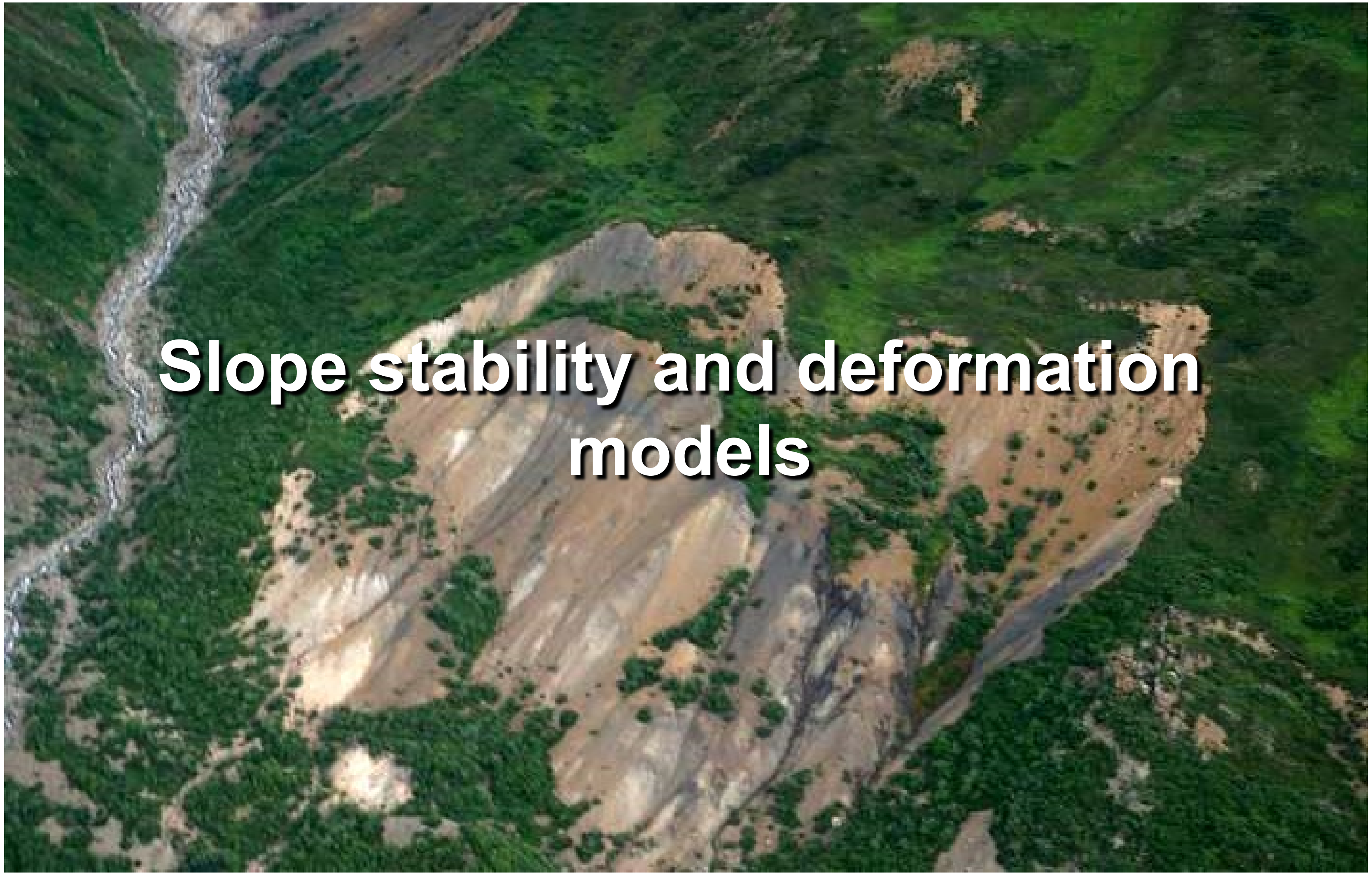
$$\mathbf{S_i = I_i \cdot F_i \cdot V_i \cdot M_i}$$

I = Initiation feasibility

F = Frequency of occurrence of a geohazard

V = Vulnerability of the pipeline (including spatial and temporal conditional probabilities)

M = Mitigation factor



Slope stability and deformation models

A Note on Models

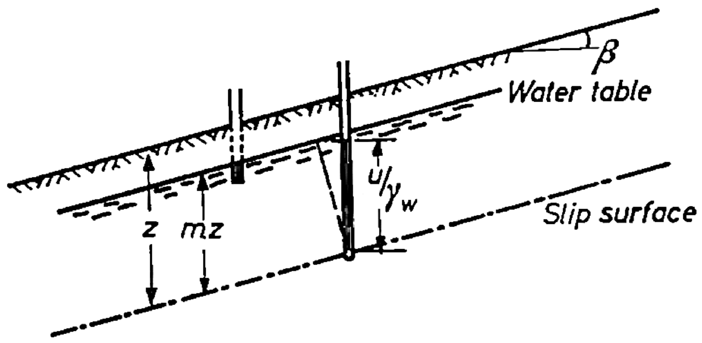
- Mechanistic models are mathematical abstractions of physical phenomena or processes
- Seldom an exact representation of a given phenomenon or process, especially if it is complex
- Model error is an important consideration, and must be recognized in geohazard assessment

“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.”

- Box 1976; Box & Draper 1987

Mechanistic Stability Models

- Physics-based models of planar failure



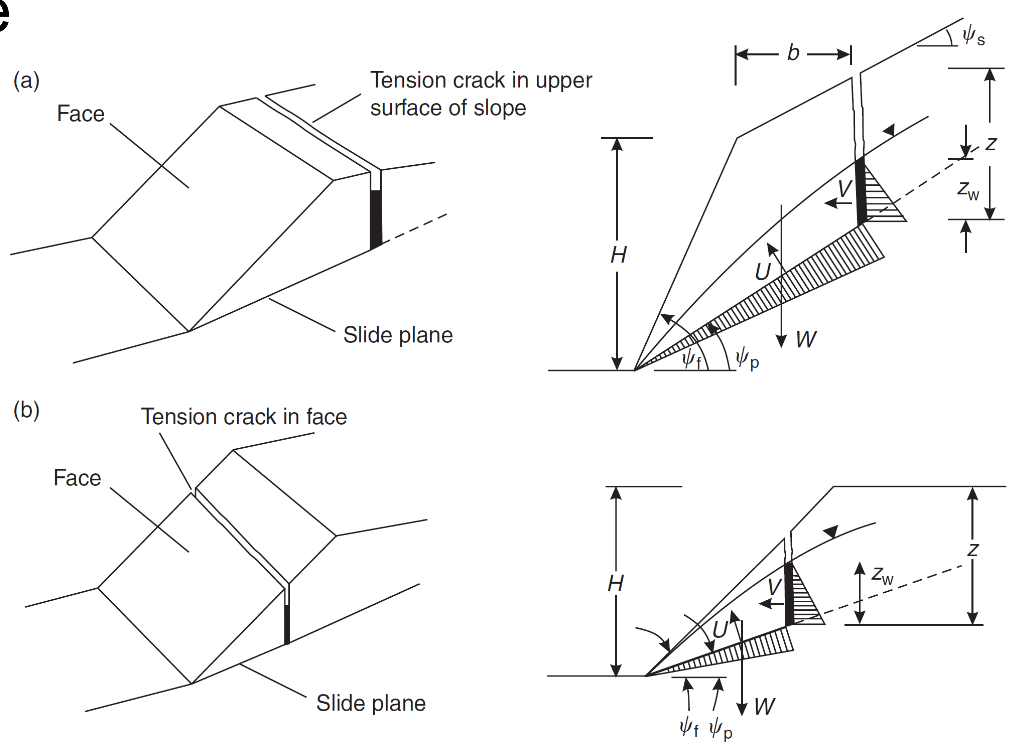
For limiting equilibrium

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

If $c' = 0$:

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

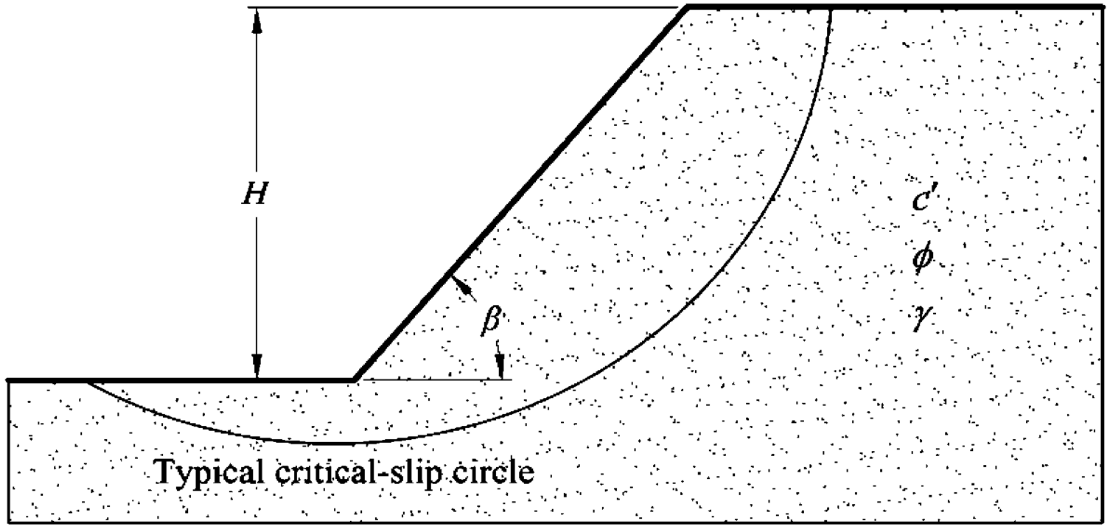
Translational slip (Skempton and De Lory 1957)



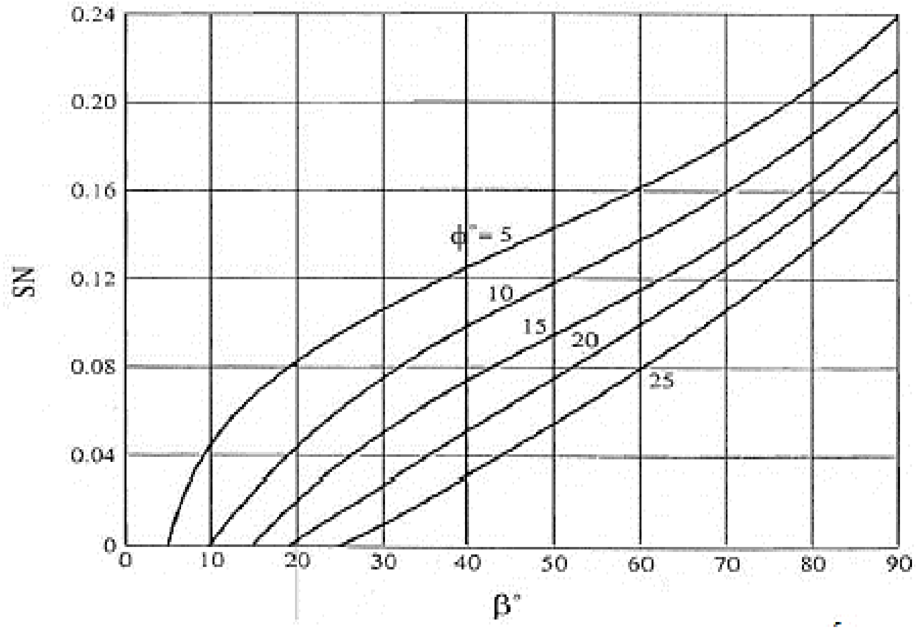
Plane failure with tension crack (Wyllie 2018)

Mechanistic Stability Models

- Physics-based model of rotational failure using method of slices



Rotational failure of a simple uniform slope (Janbu 1959)



Stability chart for simple uniform slopes subject to rotational failure (Taylor 1937)

Surrogate Stability Models

- Empirical relation based on slope stability parametric analysis

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

$a = 5.94466 \times 10^{-5}$

$b = -0.00807 + 3.41 \times 10^{-5}\beta - \lambda\pi/180$

$c = 0.042186 + 0.004905\beta - 6.44 \times 10^{-5}\beta^2 + 4.07 \times 10^{-7}\beta^3$

$\lambda = \frac{c'}{\gamma H \tan(\phi)}$

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

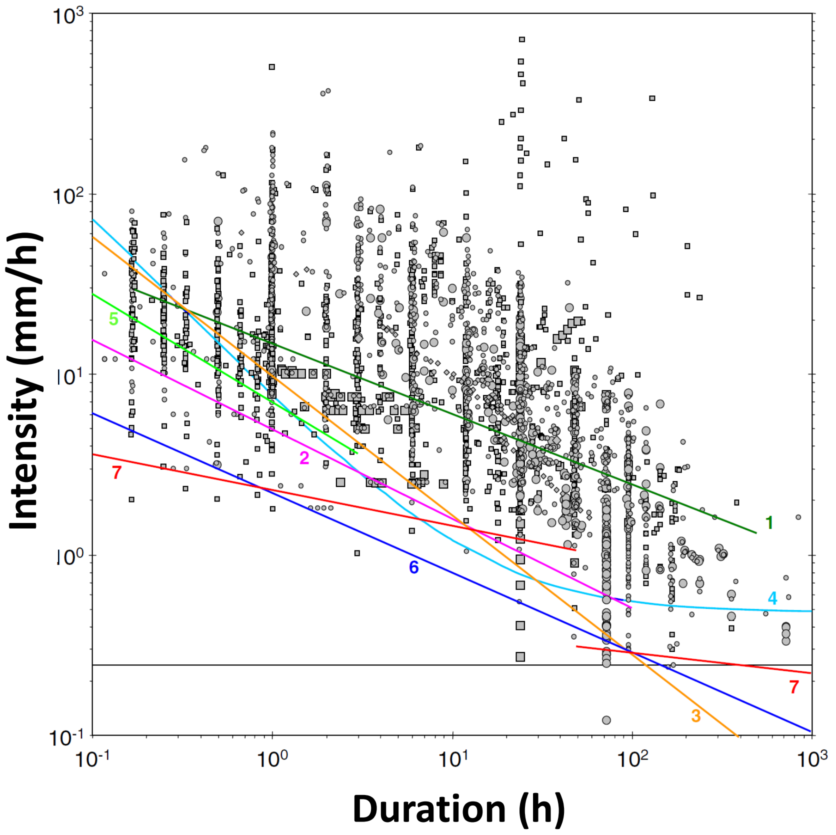
$SN = c'/\gamma HF$ = stability number

$\phi_m = (\tan\phi)/F$ = mobilized friction angle (degrees)

Rotational failure of a simple uniform slope (Easa and Vatankhah 2011)

Surrogate Stability Models

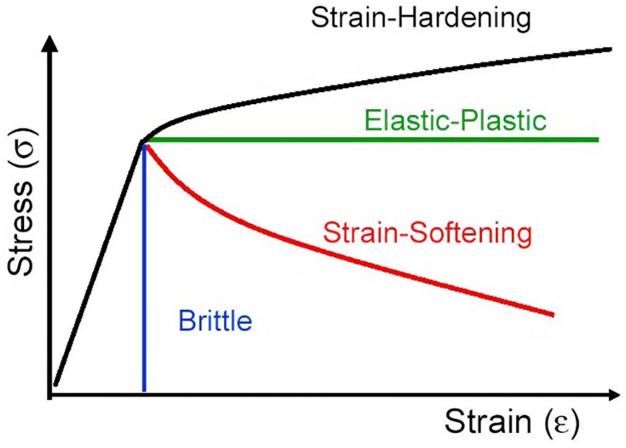
- Integrated slope stability models linking rainfall to change in groundwater table through flow accumulation model and rainfall infiltration model
- Empirical models linking rainfall parameters to onset of shallow slope instability
- Significant effects of climate and geologic variability require subject matter expert (SME) engagement

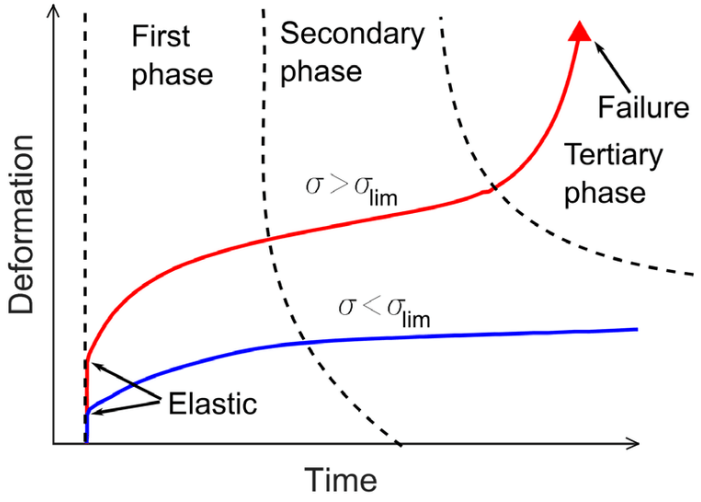


Global rainfall intensity-duration thresholds for shallow slope instability (Guzzetti et al. 2008)

Deformation Models

- Deformation is a function of constitutive model for the earth material (soil, rock); affects pre- and post-peak strain
- Materials subject to time-dependent creep deformation under constant load may experience creep rupture (tertiary creep)
- Change in bulk and shear modulus due to change in moisture content may cause episodic deformation (i.e., displacement)
- Newmark model for seismic deformation

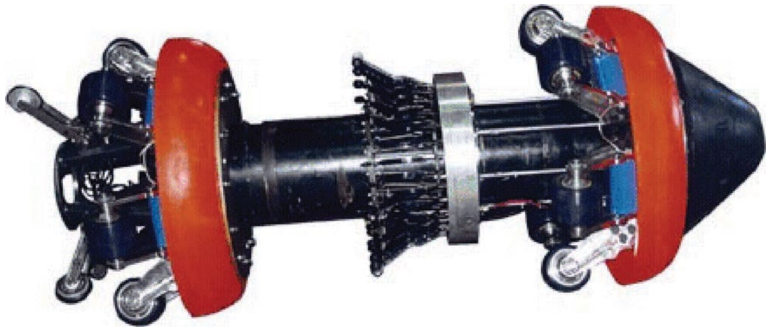


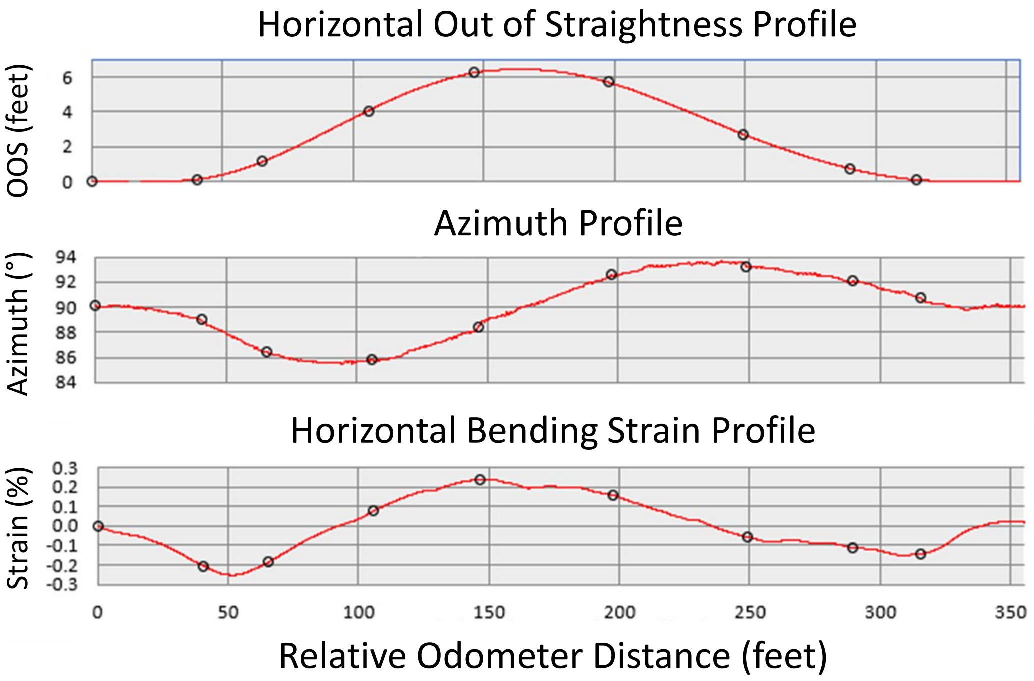



Monitoring
OPTIMA

Monitoring Approach

- Ground deformation monitoring with pipeline IMU/ILI and remote methods (differential LiDAR, InSAR) and installed instrumentation
- Most monitoring systems are intermittent with a delay between readings plus time for data processing
- Near real-time monitoring is an ideal standard to relate changes in driving forces (e.g., precipitation) to slope deformation response





Monitoring Example

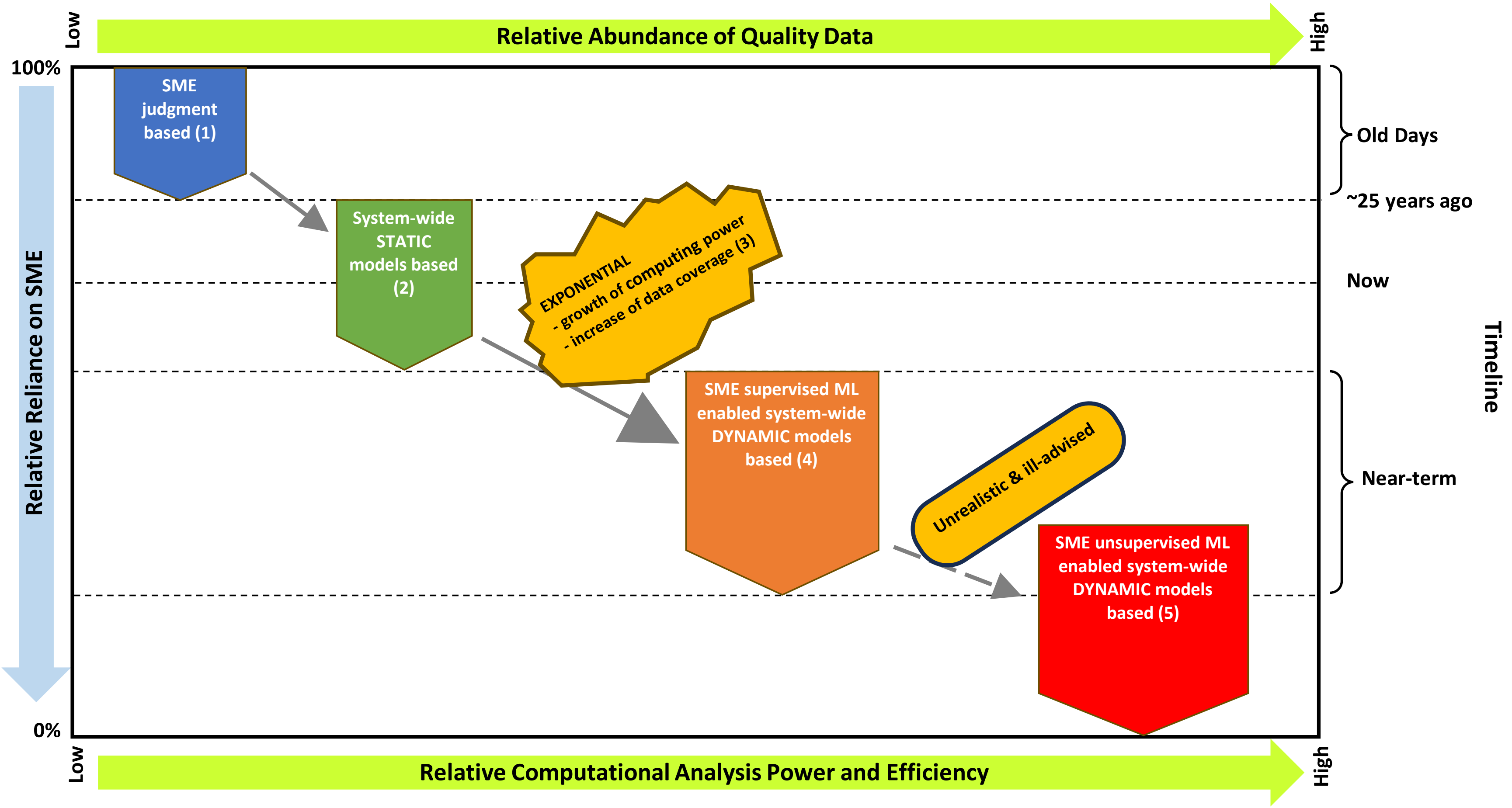
- 2016 loss-of-containment incident at NPS 16 pipeline crossing of North Saskatchewan River in Canada
- Pipeline buckled at a mid-slope overbend due to ground movement from a large ancient landslide complex
- Implemented real-time geotechnical instrumentation (inclinometers, piezometers), high fidelity distributed fiber optic sensing (HDS), repeat IMU/ILI, repeat LiDAR and site-specific weather monitoring
- Early-warning system with alarm thresholds developed to proactively shut-in pipeline; system operated successfully during period leading to pipeline replacement


Recent advances

Recent Advances - AI and ML

- 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
- Is elimination of the geotechnical SME from the process of predicting geohazard occurrence and progression possible/advisable given AI and ML advances ("SME unsupervised" perspective) or will expert judgment always be needed to guide/evaluate predictions using AI and ML ("SME supervised" perspective)?

Advances in Geohazard Management



(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)

Key considerations and conclusions

Considerations - Development

- Geologic model – baseline; upgrade to improve predictions
- Causation vs. correlation – physics-based models; guides management
- Static vs. dynamic variables – geohazard mechanism; time variability
- Application of AI and ML – SME supervised or unsupervised; implications
- Data – essential datasets; availability; cost; quality/reliability (pedigree, vintage, scale, etc.); legacy dataset reconciliation and integration; QA/QC
- Monitoring – reading frequency/resampling; processing time; QA/QC
- Warning system integration – alarm thresholds; warning criteria; calibration
- Barriers to collaborative R&D – intellectual property, non-disclosure, etc.

Considerations - Implementation

- Deliverables – desired end product (in-house, third party, commercial)?
- Leverage – blank slate or build on existing assets (GIS database, etc.)?
- Timeline – schedule, staging, interim products, prototype testing?
- Team – single vendor, collaboration, expert group; coordination?
- Commissioning – commissioning process, acceptance criteria, synthetic calibration data?
- Stakeholder engagement – assurances, external peer review, engagement process and schedule?
- Maintenance – future upgrades, continuous improvement?

Conclusions

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

Questions?