

RISK-BASED SLOPE STABILITY CRITERIA AND INSTRUMENTATION AND MONITORING REQUIREMENTS

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Risk-based design utilizing probabilistic analysis and the observational method (instrumentation and monitoring) are commonly implemented to mitigate the inherent risks and limitations associated with the deterministic Factor of Safety (FS) approach and/or in the absence of a well-defined slope stability criteria and instrumentation and monitoring requirements. However, the acceptable probability of failure as well as the instrumentation requirements and monitoring frequency are subject to the risk tolerance of stakeholders (designers, regulators, reviewers, asset owners, contractors), and their understanding of probability of occurrence and the perceived consequences (experience). As such, the acceptance criteria and associated risk level are inherently inconsistent from one slope stability project to another. A slope stability probabilistic acceptance criteria and necessary associated monitoring requirements is proposed, which includes defining the risk level and managing risk tolerance by using a matrix of evaluation and definition of consequences. The authors hope this will promote a more concise and consistent approach to assessing project risks and establishing proper instrumentation and monitoring controls to meet the observational approach requirements. This should also help owners to establish a baseline for the management of their geotechnical assets.

Keywords: Risk-based, Probability of Failure, Instrumentation, Monitoring, Slope Stability, Risk Management

1. Introduction

Geotechnical practitioners are generally very familiar with using the Factor of Safety (FS) approach in the context of assessing the reliability of a natural or man-made slope and stabilization design. Through decades of research and well documented cases, this deterministic approach with either Limit Equilibrium Modeling (LEM) or Finite Element Modeling (FEM) for example, is particularly efficient when a well-constrained geological model can be obtained as well as accurate and representative shear strength parameters are defined. However, there are cases where FS methods have limited applicability:

- Uncertainties related to reliability of design or the variability/distribution of the soil properties cannot be accounted for in the FS. Two solutions may have equal and acceptable FS, but carry very different reliability and probability of failures.
- The absence of deformation in LEM implies that stress and strength are independent of deformation. This means that the FS provides an empirical basis for checking that deformations won't be excessive (CFEM 2023).
- In earthquake prone regions, deterministic analysis cannot incorporate the variability in seismic loading and soil response (dynamic analysis) (Boruah and Chakraborty, 2022).
- There are limitations in incorporating the geological model into the failure mode.
- For critical infrastructure with high consequences, deterministic approaches do not offer a more comprehensive risk assessment compared to probabilistic methods.

Probabilistic methods are often not well understood, with criteria often poorly presented within the context of risk management. As discussed by the CDA (2013), the unconditional probability of a fatality, is the product of the probability of the event, the probability of a failure during said event, and the probability of fatality occurring with failure. Frequently, when probability of failure is presented or discussed, it is not clear if this is in reference to the overall probability (of fatality, etc.), or the probability of failure during an unspecified event. This has led to a wide range of what is considered an acceptable probability of failure, and has also led to misunderstanding and misuse of probabilistic design approach and consequently, risk management and tolerance of geotechnical systems.

2. Observational method in slope problems

The observational method is often leveraged in situations where inputs are not or cannot be well defined, or there is a balance of managing assets, risk, and safety/access; this is done by implementing a geotechnical

instrumentation program, which can be associated with “ingredient” number seven of the method. However, there is no prescribed or systematic way to define what type of instrumentation or controls should be applied under various circumstances. Depending on where the slope is located, the engineer of record should decide based on judgment and knowledge of the site what controls are to be implemented.

2.1. Instrumentation

In order to assess whether the slope is performing within the predicted behavior, in-situ measurements are collected through a multitude of commercially available instruments. The choice of instruments should be dictated by the failure mechanism anticipated, and the uncertainty/sensitivity of the component. It is highly recommended that both investigative and predictive monitoring be conducted (Eberhardt 2012). For the purpose of providing an application guideline presented in Figure 1 below, typical monitoring instruments are classified as follow:

- Surface displacement, in-situ: GPS, GNSS, prisms, wire extensometers, crack meters, tiltmeters, settlement gauges
- Surface displacement, airborne or remote: iNSAR, LiDAR, photogrammetry, slope stability radar, laser scanner
- Subsurface displacements and deformations: ShapeAccel Arrays (SAA), cased inclinometers, extensometers
- Groundwater monitoring: Vibrating wire piezometers (VWP), standpipe, Casagrande
- Structural elements monitoring: Load cells, pressure cells, strain gauges
- Weather/earthquake monitoring: In-situ weather stations, local tidal stations, local precipitation stations, earthquake stations, seismographs, vibraphones

2.2. Automation and early warning system

Data collection of the majority of the instruments listed above can be automated and should be automated if an early warning system (EWS) is prescribed as part of the monitoring plan. An EWS is defined as: “the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss” (UNISDR 2009). If an EWS is prescribed in the slope monitoring plan, practitioners should ensure that the four following components have been included (Michoud et al.): (1) a slope stability back analysis to understand the failure mechanism and risks related to site activities in the vicinity of the previous slides, (2) installation of instrumentation to monitor movement and data interpretation through investigative and predictive monitoring, (3) definition of thresholds and implementation of an alert distribution system, and (4) roles and responsibilities definition and attribution of response actions for all stakeholders.

3. Risk Level Framework

The risk, or risk level of a design in its simplest form may be described as the product of the consequence of an event and the probability of the occurrence. Acceptable risk is subject to the risk tolerance of stakeholders (designers, regulators, reviewers, asset owners, contractors), and their understanding of probability of occurrence and the perceived consequences (experience). This consequently can lead to risk adverse decisions and inconsistencies, from different definitions of a severe consequence to perceived acceptable probability of a fatality. This discrepancy can be shown in an acceptable risk of a fatality of a highway constructed on a slope, being lower than that of the dam upstream in the same valley as may be the case following SMHI (2018) and CDA (2013). Obviously, in this scenario, the risk to the user of the highway is controlled by the dam design. In order to present well defined consequences, and acceptable probability of failure, the authors undertook a literature review and provide definition of consequences in order to present a universal matrix of evaluation and managing risk.

3.1. Consequence of failure

In order to provide a universal definition of consequences, a literature review was completed (SHMI, 2018; Silva et al., 2008; Kim & Mission, 2011; CDA, 2013; ICMM, 2020). The authors’ recommended definition of consequences is provided in Table 1.

Table 1. Description of Levels of Consequences

Level Of Consequence	Population Risk	Infrastructure And Economic	Environmental And Cultural
Insignificant to Minor	Non-life-threatening injury	Performance based failure impacting limited infrastructure or	Environmental impact is low and localised (i.e. limited to site or

	or short-term health	services requiring maintenance or minor repairs to minor localised failure of low economic loss. No impact on production activities	immediate vicinity) resulting in possible minor short-term loss, but no long-term loss. Low likelihood of heritage, community, or cultural impact.
Moderate to Significant	≤ 1	Loss of recreational facilities, closure of infrequently used routes, detours of collectors and arterial transportation routes, to partial closure of highways. Minor and temporary disruption to production activities.	No significant loss or deterioration of fish or wildlife habitat. Slow uncontrolled release of fluid producing off site pollution and requires cleanup. Restoration or compensation in kind highly possible. Disruption to regional heritage, community, or cultural assets.
Severe to Major	≤ 10	Loss of recreational facilities, closure of infrequently used routes, detours of collectors and arterial transportation routes, to partial closure of highways. Minor and temporary disruption to production activities.	No significant loss or deterioration of fish or wildlife habitat. Slow uncontrolled release of fluid producing off site pollution and requires cleanup. Restoration or compensation in kind highly possible. Disruption to regional heritage, community, or cultural assets.
Extreme to Catastrophic	≥ 100	Extreme losses affecting critical infrastructure or services (e.g. hospital, major storage facilities for dangerous substances). Loss of facilities, shutdown of operations and loss of public trust.	Significant loss or deterioration to major loss of critical fish or wildlife habitat or extensive loss beyond vicinity of site ($\geq 10 \text{ km}^2$) of important fish or wildlife habitat. Restoration or compensation in kind impossible. Significant national heritage or cultural assets destroyed.

3.2. Probability of failure

The acceptable probability of failure (probability of failure given an event), as determined by LEM software programs and corrected for the error within determination of the probability of failure (i.e. PF_{\max}) is provided in Figure 1. The acceptable probability of failure was determined through literature review, typical design conditions, consideration of the consequence of failure, and instrumentation and monitoring requirements (CFEM, 2023; WSDOT, 2013; SMHI, 2018; Silva et al., 2008; Kim & Mission, 2011; Fenton et al., 2008, CDA, 2013; ICMM, 2020). Note that the probability of failures presented in Figure 1 are based on typical design requirements, such as consideration of groundwater level/flood events. As such, the probabilities provided for permanent slopes, interim slopes, and temporary slopes are associated with designs considering events with probability of occurrence of 1/100, 1/25, and 1/5, respectively. These probabilities of occurrence are based on design requirements for permanent earth structures (1/100 event) and adjusted by the authors for the interim and temporary conditions (FHWA, 2009). Momentary slopes are anticipated to have minimal investigations completed and designed based on observed conditions and therefore, do not have an associated design event. The acceptable probability of failures presented in Figure 1 should be corrected based on project specific event occurrences.

4. Conclusion

The acceptable probability of failure as well as the instrumentation requirements and monitoring frequency are subject to the risk tolerance of stakeholders (designers, regulators, reviewers, asset owners, contractors), and their understanding of probability of occurrence and the perceived consequences (experience). As such, the acceptance criteria and associated risk level are inherently inconsistent from one slope stability project to another. A slope stability probabilistic acceptance criteria and necessary associated monitoring requirements has been proposed (Fig. 1), which includes defining the risk level and managing risk tolerance by using a matrix of evaluation and definition of consequences. The authors hope this will promote a more concise and consistent approach to assessing project risks and establishing proper instrumentation and monitoring controls to meet the observational approach requirements. This should also help owners to establish a baseline for the management of their geotechnical assets.

CONSEQUENCE		INSIGNIFICANT TO MINOR	MODERATE TO SIGNIFICANT	SEVERE TO MAJOR	EXTREME TO CATASTROPHIC
PERMANENT SLOPES DESIGN LIFE 75+ YEARS	PF _{max}	20%	10%	1%	0.1%
	Risk Management	Bi-annual visual inspections, Include in asset management program	Min. bi-annual visual inspections, min. 1 surface/subsurface displacement monitoring, 1 groundwater monitoring, 1 structural element (if present) monitoring Include in asset management program	Min. bi-annual visual inspections, min. 2 surface/subsurface displacement monitoring, or high redundancy in the number of instruments installed, 1 groundwater monitoring, 1 structural element (if present), include in asset management program	Consider modifying design to reduce to a "severe to major" category. Min. bi-annual visual inspections, min. 3 surface/subsurface displacement monitoring, or high redundancy in the number of instruments installed, 1 groundwater monitoring, 1 structural element (if present), early warning system, include in asset management program
	PF _{max} No Risk Management	10%	1%	0.1%	0.01%
INTERIM SLOPES DESIGN LIFE 1-10 YEARS	PF _{max}	30%	25%	3%	0.25%
	Risk Management	Same as permanent slopes	Same as permanent slopes, consider different frequencies of data collection during operational life		
	PF _{max} No Risk Management	3%	2.5%	0.25%	0.03%
TEMPORARY SLOPES DESIGN LIFE ≤ 1 YEAR	PF _{max}	30%	15%	5%	Generally Not Applicable
	Risk Management	At least weekly visual inspections, or at a frequency that is adjusted to the construction stages	Daily visual inspections during construction stage Min. 1 surface/subsurface displacement monitoring and min 1 groundwater monitoring, weather monitoring	Daily visual inspections during construction stage, min. 2 surface/subsurface monitoring, or high redundancy in the number of instruments installed, min. 1 groundwater monitoring, weather monitoring	
	PF _{max} No Risk Management	3%	2%	1%	
MOMENTARY SLOPES DESIGN LIFE ≤ 4 MONTHS (WITH SEASONAL CONSTRAINTS)	PF _{max}	40%	30%	20%	Generally Not Applicable
	Risk Management	Same as temporary slopes	Same as temporary slopes, consider different frequencies of data collection during construction		
	PF _{max} No Risk Management	LOCAL OCCUPATIONAL HEALTH AND SAFETY RULES AND REGULATIONS APPLY			

Fig. 1. Risk Management Framework for Slopes

References

- Boruah, P. P., & Chakraborty, A. (2022). Deterministic and Probabilistic Approach of Seismic Slope Stability Analysis – A State-of-The-Art Review. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 53(3), 31.
- Canadian Dam Association [CDA]. (2013). *Dam safety guidelines*. Canadian Dam Association.
- Canadian Geotechnical Society. (2023). *Canadian Foundation Engineering Manual (5th ed.)*. Canadian Geotechnical Society.
- Duncan, J. M., Wright, S. G., & Brandon, T. L. (2014). *Soil Strength and Slope Stability (2nd ed.)*. John Wiley & Sons.
- Eberhardt, E. (2012). Landslide monitoring: *The role of investigative monitoring to improve understanding and early warning of failure*. In Chen et al. (eds.), *Landslides: Types, Mechanisms and Modeling*. Cambridge University Press, Cambridge, pp. 222-234.
- Federal Highway Administration [FHWA]. (2009). *Mechanically stabilized earth (MSE) walls* (FHWA-NHI-10-024). U.S. Department of Transportation.
- International Council on Mining and Metals, United Nations Environment Programme, & Principles for Responsible Investment [ICMM]. (2020). *Global industry standard on tailings management*.
- Kim, H., & Mission, J. (2011). *Probabilistic evaluation of economical factor of safety for the geotechnical design of pile axial load capacity*. *KSCE Journal of Civil Engineering*, 15(7), 1167–1176. <https://doi.org/10.1007/s12205-011-0948-8>
- Lee, E. M., & Jones, D. K. C. (2021). *Landslide Risk Assessment (3rd ed.)*. Emerald Publishing Limited.
- Michoud, C., Bazin, S., Blikra, L., Derron, M., & Jaboyedoff, M. (2013). *Experiences from site-specific landslide early warning systems*. *Natural Hazards and Earth System Sciences*, 13, 2659–2673.
- Peck, R. B. (1969). *Advantages and limitations of the observational method in applied soil mechanics*. *Geotechnique*, 19(2), 171-187.
- Silva, F., Lambe, T. W., & Marr, W. A. (2008). *Probability and risk of slope failure*. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(12), 1691–1699. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2008\)134:12\(1691\)](https://doi.org/10.1061/(ASCE)1090-0241(2008)134:12(1691))
- Saskatchewan Ministry of Highways and Infrastructure [SMHI]. (2018). *Foundation investigation manual*. Government of Saskatchewan.
- Washington State Department of Transportation. (2013). *Geotechnical design manual M 46-03.08* (p. 7-1). Washington State Department of Transportation.
- United Nations International Strategy for Disaster Reduction (2009). *UNISDR terminology on disaster risk reduction*.