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Fragility curves as a basis for dynamic early warning thresholds for geotechnical structures

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Abstract

Levees, embankments, and slopes face environmental hazards whose frequency and intensity are increasing due to climate change. Failure risk of geotechnical structures is inadequately captured by fixed threshold early warning systems. Fragility curves express failure probability as a function of hazard intensity, offering a more rigorous, updatable alternative. This paper reviews main methods for developing fragility curves and presents framework with the integrated real-time sensor network and dynamic early warning systems.

Key words: fragility curves, geotechnical structures, early warning systems, probabilistic analysis, Bayesian updating

Krivulje ranjivosti kao osnova za dinamičke pragove ranog upozoravanja za geotehničke objekte

Sažetak

Nasipi i pokosi izloženi su okolišnim hazardima čija učestalost i intenzitet rastu zbog klimatskih promjena. Rizik otkazivanja geotehničkih objekata nije adekvatno obuhvaćen sustavima ranog upozoravanja s fiksnim pragovima. Krivulje ranjivosti izražavaju vjerojatnost otkazivanja kao funkciju intenziteta hazarda, nudeći pouzdaniju i lakše ažurabilnu alternativu. Ovaj rad daje pregled glavnih metoda razvoja krivulja ranjivosti i istražuje kako se mogu kombinirati s praćenjem senzorima u stvarnom vremenu za razvoj sustava ranog upozoravanja koji reagiraju na stvarno stanje geotehničkog objekta.

Ključne riječi: krivulje ranjivosti, geotehnički objekti, sustavi ranog upozoravanja, probabilistička analiza, Bayesovo ažuriranje

1 Introduction

Due to climate change, the frequency and intensity of extreme hydro-meteorological hazards is increasing [1]. Geotechnical structures such as levees, embankments, natural and engineered slopes are exposed to such hazards and their failure during extreme weather events can cause devastating human and economic losses. Despite this, probabilistic methods for assessing their failure risk remain less developed than for other infrastructure classes [2], and Early Warning Systems (EWS) for such structures still mostly rely on fixed, empirically derived thresholds that do not incorporate uncertainty in their hazard forecasts. For example, the same observed precipitation can imply very different failure probabilities depending on antecedent saturation, material variability, and event duration, something a fixed threshold cannot capture [3].
Fragility curves provide a way to clearly account for all these dependencies, by expressing the conditional probability of reaching or exceeding a defined limit state as a function of hazard intensity [4]. When combined with real-time sensor monitoring, they provide a continuously updatable estimate of failure probability rather than a static threshold, which is a concept that drives the discussion in this paper. This paper explores the methods behind developing fragility curves for geotechnical structures and discusses their potential role in developing more physically grounded, condition-aware EWS frameworks.

2 Fragility curves – State of the art

2.1 Fragility curves concept

Fragility curves describe vulnerability by expressing the probability of reaching or exceeding a defined limit state as a function of hazard intensity [5-7]. Unlike a deterministic factor of safety, which condenses response to a single value, fragility curves capture increase of failure probability across the range of hazard intensity, portraying variability in structural properties and loading conditions [6]. The limit state can be defined as geomechanical properties such as factor of safety, internal erosion, crest settlement, or as consequences such as overtopping, breach probability or service interruption [4,6-8]. A complete fragility model is made up of a family of fragility curves, one for each relevant limit state, ranging from serviceability exceedance to structural failure, as seen in Figure 1 [4,8].
The selection of hazard intensity measure is critical and depends on the governing hazard. For example, for flood protection structure instability it could be water level or flood duration [5]. For rainfall induced instability it could be accumulated precipitation or storm intensity [6,8]. The applicability of the resulting

fragility curves relies on the ease of definition of the chosen hazard intensity measure and on how broadly the derived functions can be applied across different sites and scenarios [7].

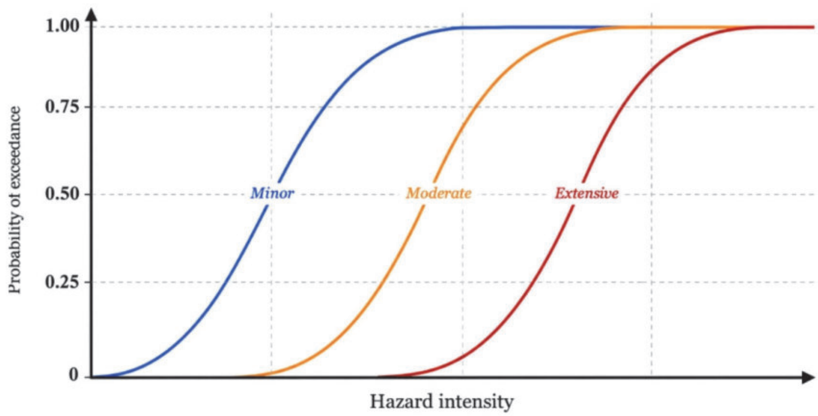

Figure 1. Schematic fragility curves for 3 limit states as a function of hazard intensity [adapted from 6]

2.2 Determination methodologies for fragility curves

Several methodological approaches are documented in the literature, broadly classified as empirical, analytical and hybrid. The empirical approach is derived from observed damage data, following past hazard events, while analytical approach utilises numerical models [2,7]. While conceptually direct, empirical approach has limited applicability for geotechnical structures, since fragility curves for them are rarely informed by field data, which would take into consideration state of the structure. Analytical approaches have therefore become the predominant method in this domain [6].

Analytical fragility curves are developed by feeding uncertain input parameters through computational models of structural response [6,7]. The most commonly used method is Monte Carlo Simulation, where uncertain input parameters are sampled from their predefined probability distributions, and stability analysis is performed for each run of the simulation. This is repeated for different levels of hazards, and the results form a fragility curve. [6] Important first step for reliable analytical models is statistical characterization of soil parameter uncertainty, which covers inherent variability, measurement error and transformation uncertainty [9]. Running large-scale simulations has also been shown to be more accurate than using specific distributional assumptions, which is demonstrated in [10], showing that common assumptions can lead to significant errors in both fragility curves and life cycle loss estimates.

Hybrid methods combine analytical model outputs with field observations through Bayesian updating, a probabilistic framework that works by starting with an initial estimate, then improving it every time new data is collected. Each updated estimate then becomes the new staring point, so the method improves as more data becomes available. Trinidad González et al., 2023 [11] applied this approach to clay railway earthwork cut slopes, demonstrating that the probability of failure can be assessed even where historical data is limited. This method is relevant for Early Warning System (EWS) application. Where sensors continuously collect real-time data, such as in active monitoring systems for infrastructure, Bayesian updating can be used to constantly improve failure probability estimates as conditions evolve.

A useful real-world example is provided in Gupta et al., 2025 [12], where EWS framework for unsaturated highway slope in Western Himalayas is developed. Piezometers and volumetric water content sensors fed a calibrated seepage model and slope stability analysis, and a machine learning algorithm trained on months of sensor data was used to predict the factor of safety from sensor readings in near-real time. Warnings were issued when the predicted factor of safety fell below defined threshold. This study demonstrated that sensor-driven stability assessment is practically achievable, and it gives a good indication of the infrastructure needed to implement a fully dynamic, fragility-based EWS in practice.

3 Fragility curves and early warning system

3.1 Current EWS Practice and its limitations

Conventional geotechnical EWS work by setting pre-defined threshold values applied to monitored parameters. When a threshold is exceeded, an alert is issued. While it is commonly used in practice [3] it has a fundamental limitation as it ignores uncertainty. In Guzzetti et al., 2020 [3], a systematic review of 26 landslide EWS found that none of them accounted for uncertainty in their hazard forecasts. Thresholds are calibrated using representative conditions and do not adapt to actual, evolving state of a structure exposed to hazard event.

Another problem is that structures gradually deteriorate over time, due to continuous exposure to loads. Briggs et al., 2023 [13] reviewed evidence for this process for clay earthwork slopes under repeated seasonal weather cycles. It shows that seasonal pore pressure cycles drive irreversible displacements. Climate change is expected to increase the magnitude of seasonal pore water pressure cycles, reducing the remaining time to failure for slopes that have already experienced substantial deterioration. A warning threshold calibrated at or near the time of construction cannot account for such cumulative, long-term degradation.

Nocentini et al., 2024 [14] optimised rainfall thresholds for an operational EWS in the Liguria region of Italy and found that standard intensity-duration thresholds produced more than double the false alarms compared to correct alarms in most alert zone. The false alarm rate was only brought down to acceptable level by adding a third factor, accounting for how much rain had fallen in the area prior to current event.
The lack of uncertainty quantification and probabilistic framing is a weakness that keeps appearing across many EWS. The underlying issue is that fixed thresholds cannot fully account for evolving multi-variable nature of geotechnical failure conditions.

3.2 Sensor-based monitoring framework for EWS

Fragility curves are a natural addition to sensor-based monitoring. Instead of a fixed threshold value, the operator is provided with a continuously computable estimate of failure probability, based on currently observed hazard intensity. Threshold levels can then be expressed as probability ranges, making the system sensitive to the actual structural state rather than a pre-calibrated number. As sensor data accumulates through multiple hazard events, it can in principle be used to update the fragility model through Bayesian updating, so that the fragility curves themselves evolve with the structure's condition. Conceptual framework is shown in Figure 2.

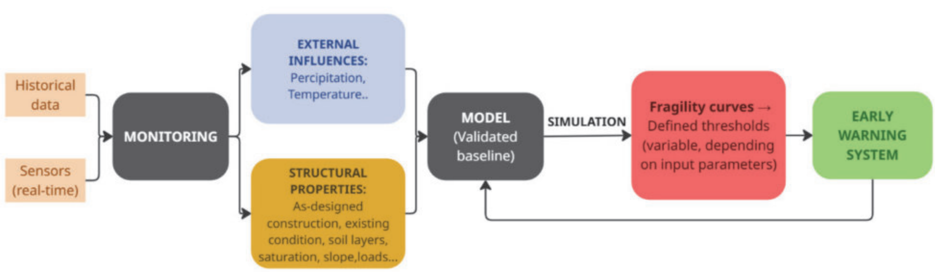

Figure 2. Conceptual framework for a sensor-informed, fragility-based dynamic EWS for geotechnical structures

Future research will apply this framework to geotechnical structures in the City of Dubrovnik, Croatia, within the context of the Horizon Europe AI-Warn project [15]. The Dubrovnik area, with its steep urbanized hilly terrain, has repeatedly experienced rainfall induced slope instabilities and retaining wall failures, making it a well justified case study location. Historical geotechnical data and a real-time sensor network which will be deployed within AI-Warn project will provide the monitoring inputs. Monte Carlo simulation combined with slope stability analysis will be used to develop families of fragility curves for extreme precipitation scenarios, parameterised by antecedent soil saturation and structural geometry. These fragility curves will form the foundation for dynamic warning thresholds integrated into the early warning system of City of Dubrovnik.

4 Conclusions

This paper has reviewed the methods behind developing fragility curves for geotechnical structures and examined their potential role in Early Warning Systems. Fragility curves are a reliable probability-based tool for expressing how vulnerable the structure is at different hazard levels. Of the three main ways to define them, Monte Carlo Simulation is the most flexible and widely applied. Hybrid approaches combine analytical models with real world data through Bayesian updating offer further improvements as monitoring data accumulates.

Conventional EWS rely on fixed threshold that don't incorporate uncertainty. This is problematic because of the gradual long term structural deterioration after exposure to hazards.

Fragility curves offer a natural probabilistic complement to sensor-based monitoring. They provide a continuously computable estimate of failure probability that can be updated via Bayesian inference as sensor data accumulates, with the threshold values adapting to the evolving state of the structure. Combining fragility curves with real time sensor data in geotechnical EWS is still actively developing area. The three key components – probabilistic stability analysis, sensor-based monitoring and data assimilation have each been developed and used in their own fields. However, bringing them all together into a coherent operational framework for geotechnical infrastructure needs to be further explored. The ongoing research will address this gap through a Dubrovnik case study, developing fragility curve families for rainfall-induced slope instabilities using sensor monitoring data from the Horizon Europe AI-Warn project and implementing them as adaptive warning thresholds.

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