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Evaluation of Rainfall–Earthquake Induced Landslide Hazard Using Generative AI and Monte Carlo Simulation

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ABSTRACT: In recent years, the combined effects of rainfall and seismic activity have emerged as critical factors influencing the stability of geotechnical structures. However, their interactive impact remains inadequately explored. This study proposes an innovative framework that integrates Generative AI and Monte Carlo simulation to evaluate geological hazards under complex conditions. Generative AI is employed to model the nonlinear relationships between rainfall, seismic activity, and geotechnical characteristics. It generates synthetic scenarios and identifies patterns of vulnerability to geological hazards. Monte Carlo simulation complements this by simulating diverse rainfall and seismic scenarios to evaluate their impact on slope stability and soil integrity, providing a probabilistic quantification of geological risks. The proposed framework was applied to the coastal region of West Sumatra, Indonesia, where a magnitude 7.6 earthquake struck on September 30, 2009, in conjunction with record-breaking rainfall. This compound disaster triggered widespread slope failures in mountainous terrain, resulting in hundreds of casualties and entire villages buried under massive debris. The study area represents a typical case of multi-hazard interaction, with extreme precipitation and seismic shaking co-occurring in a geologically vulnerable region. Application of the framework to this event demonstrated its enhanced accuracy and reliability in predicting geological hazard probabilities compared to traditional methods. The findings underscore the importance of addressing multi-hazard interactions in geological hazard assessments and offer actionable insights for disaster risk management and infrastructure resilience planning. By providing a robust and scalable approach to geohazard risk evaluation in the face of increasing environmental uncertainties, this study advances the field and lays the groundwork for more comprehensive risk assessment methodologies.

KEYWORDS: Generative AI, Monte Carlo Simulation, Rainfall and Earthquake, Spatial probability, Landslide

1 INTRODUCTION

Due to recent climate change, the frequency of compound geohazards involving both rainfall and earthquake events has increased, significantly impacting the stability of geotechnical structures (Crosta and Frattini, 2003). In mountainous regions, the combined effects of intense rainfall and seismic shaking can trigger large-scale slope failures. However, the interaction between these two factors and their joint influence on slope stability remains insufficiently explored.

A representative case occurred in 2009 in West Sumatra, Indonesia, where a magnitude 7.6 earthquake coincided with record-breaking rainfall. This compound event resulted in widespread slope failures and severe casualties, clearly illustrating the limitations of conventional single-hazard assessments in capturing the complexity of such scenarios (Nguyen et al., 2020).

Existing geohazard assessments are typically based on deterministic infinite slope models, treating rainfall and earthquakes as independent triggers. These methods do not account for the simultaneous effects of rainfall-induced pore water pressure increases and earthquake-induced excess pore pressure, leading to potential underestimation of actual hazard levels (Jibson, 1993; Meehan and Vahedifard, 2013).

To overcome these limitations, this study proposes a novel framework for evaluating geohazard stability induced by combined rainfall and earthquake events. The framework integrates Generative Artificial Intelligence and Monte Carlo simulation. Generative AI is used to model nonlinear relationships among rainfall, seismic input, and geotechnical properties, generating diverse and realistic multi-hazard scenarios (Song et al., 2025). Monte Carlo simulation then quantifies the probabilistic slope stability and geotechnical integrity under these scenarios.

The proposed framework was applied to the 2009 Sumatra compound disaster and demonstrated improved predictive accuracy and applicability compared to conventional assessment methods (Nguyen et al., 2025).

2 METHODOLOGY

The overall methodological framework for evaluating slope failure risk under compound hazard conditions is illustrated in Figure 1. The approach consists of three main phases corresponding to the triggering mechanisms: rainfall-only, earthquake-only, and combined rainfall–earthquake scenarios.

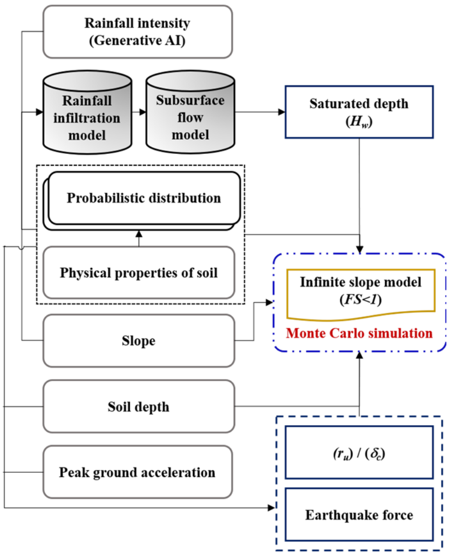

Figure 1. Methodology

Step 1: Rainfall scenario modeling:

Historical rainfall records during the observed slope failure period are collected and used to build a rainfall database for the study area. A rainfall infiltration analysis is conducted using a hydrological–geotechnical coupled model to evaluate the pore water pressure response within the slope (Iida, 1984). The factor of safety under rainfall-only conditions is computed to assess slope stability degradation due to infiltration (Crosta and Frattini, 2003).

Step 2: Earthquake scenario modeling:

Seismic records during the observed failure period are collected from ground motion monitoring networks or seismic stations. These include actual ground acceleration time histories (e.g., PGA, PGV), which are used directly as input in dynamic slope stability analyses. Depending on data availability, either pseudo-static analysis using measured PGA or full dynamic analysis incorporating real acceleration time histories is performed to evaluate the factor of safety under earthquake-only conditions (Jibson, 1993; Jibson et al., 2000; Meehan and Vahedifard, 2013).

Step 3: Combined hazard scenario modeling:

For the compound hazard assessment, rainfall infiltration and seismic shaking are considered simultaneously. The excess pore water pressure generated by the combined effect of rainwater infiltration and seismic acceleration is estimated using a coupled hydro-mechanical slope stability model (Nguyen et al., 2024). This model incorporates both hydrological loading and seismic acceleration to compute the factor of safety under combined conditions (Song et al., 2023).

Step 4: Quantitative validation:

The resulting slope stability assessments from each scenario are quantitatively compared with observed failure cases using similarity metrics or performance indices. This step validates the effectiveness of the proposed framework and its capability to capture compound hazard behavior (Nguyen et al., 2025).

2.1 *Selection of study area*

On September 30, 2009, the western coastal region of Sumatra, Indonesia, experienced a magnitude 7.6 earthquake accompanied by record-breaking rainfall. This compound event triggered extensive slope failures in the mountainous terrain, resulting in hundreds of casualties and the burial of several villages under massive debris. Given the severity and complexity of this disaster, the affected area was selected as the case study site for developing and validating an AI-based slope stability assessment framework under compound hazard conditions. Figure 2 presents a photographic and spatial overview of the study area, including the location and extent of the geotechnical failures induced by the compound event.

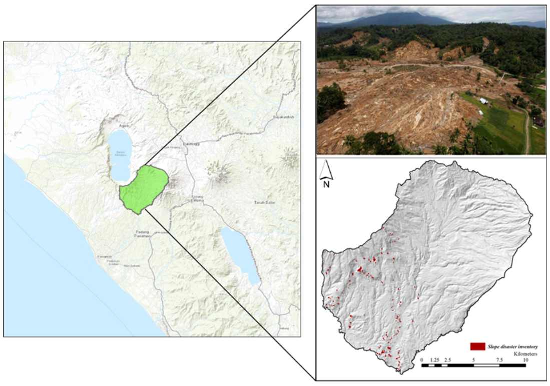

Figure 2. Study area

2.2 *Generation of realistic rainfall scenarios using generative AI model (Study area)*

To explore a wide range of possible rainfall inputs, Generative Artificial Intelligence (Generative AI) was used to generate multiple synthetic 48-hour rainfall scenarios based on a representative seed event. These scenarios maintain realistic intensity patterns while introducing probabilistic variations.

Figure 3 presents a heat map of the seed scenario, while Figure 4 illustrates the full envelope of the AI-generated scenarios, including the minimum, maximum, mean, and observed rainfall series. These synthetic scenarios provide a robust basis for assessing slope stability under compound rainfall–earthquake conditions.

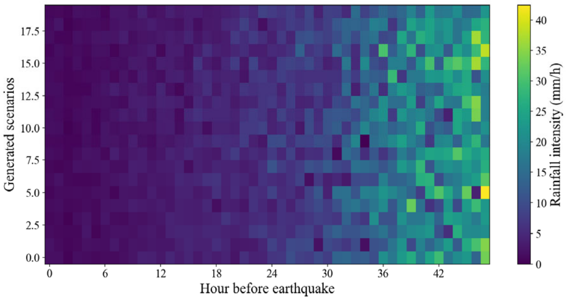

Figure 3. Seed rainfall scenario (48-hour heat map)

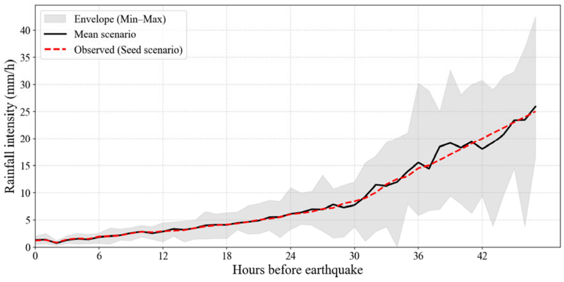

Figure 4. Envelope of AI-generated rainfall scenarios

2.3 *Geotechnical and seismic parameter database construction*

Figure 5 presents the spatial distribution of key input parameters, including slope, soil depth, and seismic loading, which form the basis of the slope stability analysis in this study.

A high-resolution Digital Elevation Model (DEM) with a 10 × 10 m grid was utilized to derive key terrain attributes, including elevation, slope, curvature, and slope length. Using standard terrain analysis techniques, slope gradients and soil depth were calculated to characterize the geomorphological conditions of the study area. For the seismic input, the Peak Ground Acceleration (PGA) recorded during the 2009 West Sumatra earthquake was employed. The corresponding cyclic shear stress within the slope was estimated using the empirical relationship proposed by Seed and Idriss (1971), which relates PGA to the equivalent uniform shear stress generated during seismic loading.

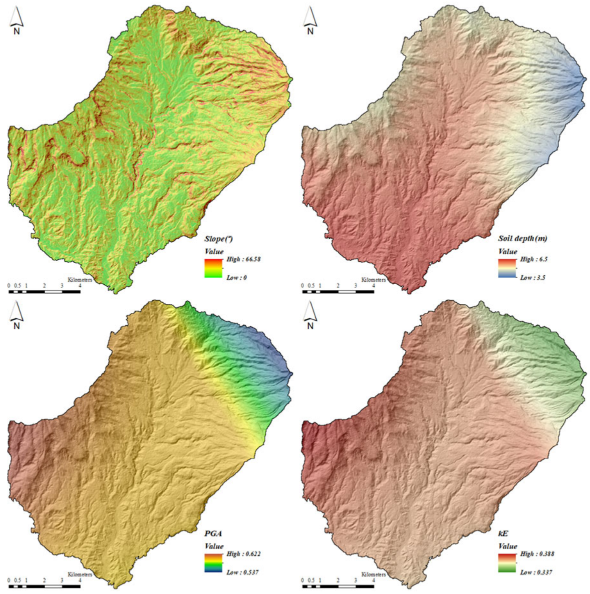

Figure 5. Spatial distribution of slope, soil depth, and seismic loading

Geotechnical properties were compiled from official geotechnical investigation reports and relevant literature. The parameters included unit weight, cohesion, internal friction angle, saturated hydraulic conductivity, unsaturated hydraulic conductivity, saturated water content, initial water content, plasticity index, over consolidation ratio, and maximum shear modulus. These values, summarized in Table 1, were used as input parameters for coupled hydro-mechanical slope stability modeling under combined rainfall and seismic conditions.

These geotechnical parameters, combined with the seismic and rainfall inputs, were applied to simulate the hydrological and mechanical interactions within the slope. The numerical modeling captured the variations in moisture content, reduction in matric suction, degradation of shear strength, and redistribution of stress throughout the slope profile. This comprehensive approach provides a realistic and quantitative evaluation of slope stability under concurrent rainfall and seismic loading, ensuring that the simulation reflects the actual mechanical behavior of the site-specific soil conditions.

Table 1. This is a table caption.

Properties	value
γ(kN/m^3)	*18*
c (kPa)	*18.2*
Friction angle (º)	*35*
k_s *(mh^{-1})*	*0.075*
q_s	*0.67*
q_i	*0.5*
PI (%)	*18*
OCR	*1*
G_{max} *(kPa)*	*35,000*

2.4 *Monte Carlo Simulation for Probabilistic Stability Assessment*

To probabilistically evaluate slope stability under uncertain geotechnical and seismic conditions, a Monte Carlo Simulation (MCS) was implemented using the input parameters derived from the preceding analyses. This probabilistic approach enables the quantification of variability and uncertainty inherent in natural slopes, which are often influenced by heterogeneous subsurface conditions, spatially varying material properties, and temporal changes in external loading.

A large number of slope stability realizations were generated by randomly sampling key input variables including slope angle, soil unit weight, internal friction angle, cohesion, and seismic acceleration based on their respective probability distributions. These distributions were defined according to available geotechnical data, field measurements, and empirical correlations, typically assuming normal or log-normal behavior depending on the physical nature of each parameter. In particular, cohesion and friction angle were treated as correlated variables to reflect realistic soil behavior and minimize overestimation of uncertainty.

For each Monte Carlo iteration, a Factor of Safety (FoS) was computed through limit equilibrium analysis, yielding a large ensemble of FoS values that collectively represent the stochastic behavior of the slope system. The results were aggregated to construct the probability density function (PDF) of the FoS, from which the probability of failure (Pf) was estimated as the proportion of realizations with FoS values below the critical stability threshold of 1.0. This probabilistic representation allows for explicit quantification of failure likelihood while accounting for uncertainty propagation through the slope stability model.

As illustrated in Figure 6, the histogram and fitted PDF clearly exhibit the stochastic dispersion of FoS values, emphasizing the influence of parameter variability on stability outcomes. The shaded region to the left of the critical threshold (FoS = 1.0) delineates the computed probability of failure, providing a direct measure of the slope's reliability under the combined effects of rainfall infiltration and seismic excitation.

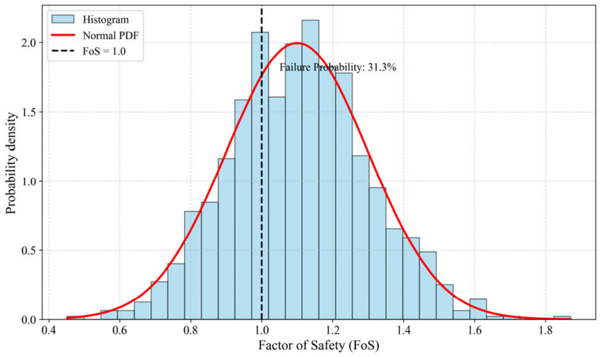

Figure 6. FoS distribution and failure probability from Monte Carlo Simulation

Beyond estimating Pf, the MCS framework also facilitates sensitivity evaluation, identifying the parameters that contribute most significantly to uncertainty in stability outcomes. This information can guide targeted site investigations or parameter refinement in future studies. Overall, the probabilistic Monte Carlo approach enhances the robustness of slope stability assessment by integrating uncertainty quantification with geotechnical realism, thereby offering a more comprehensive understanding of potential failure behavior under multi-hazard conditions.

3 RESULT

As a first step, a rainfall infiltration analysis was conducted for the study area to evaluate slope stability under rainfall-only conditions. Using hydrological–geotechnical coupling, the variation of pore water pressure due to rainfall was quantified and integrated into limit equilibrium analysis to derive the FoS, as illustrated in Figure 7.

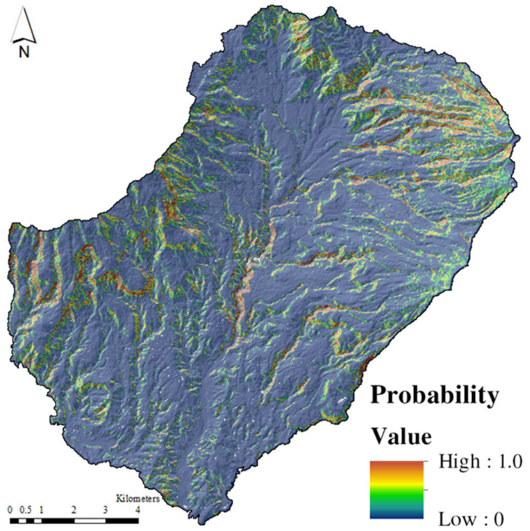

Figure 7. Spatial probability of landslides under rainfall-only condition

Subsequently, as shown in Figure 8, seismic records corresponding to the slope failure period were collected and processed to construct a ground motion database. These records were used to assess slope stability under earthquake-only conditions through both pseudo-static and dynamic analyses.

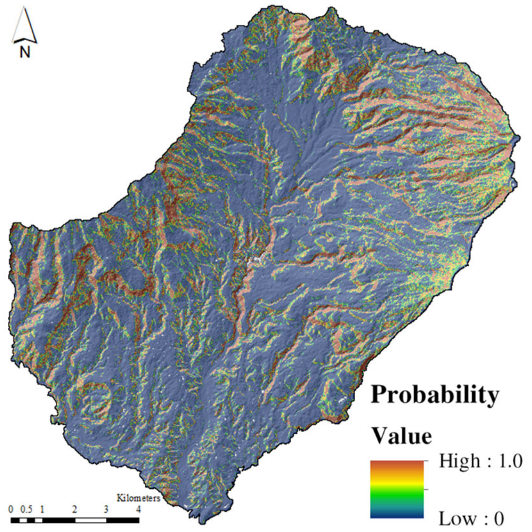

Figure 8. Spatial probability of landslides under earthquake-only condition

Finally, for the combined hazard scenario, rainfall-induced infiltration and seismic shaking were considered simultaneously. The excess pore water pressure generated by the interaction of rainfall and seismic loading, particularly through maximum ground acceleration, was estimated. This coupled effect was incorporated into the slope stability model to compute the FoS under compound loading conditions, as demonstrated in Figure 9.

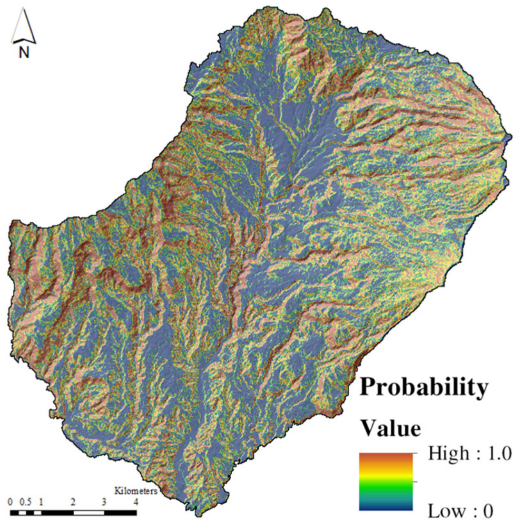

Figure 9. Spatial probability of rainfall–earthquake-induced landslides

Figure 10 illustrates the receiver operating characteristic (ROC) curves corresponding to the three hazard scenarios: rainfall-only, earthquake-only, and combined rainfall–earthquake conditions. The area under the curve (AUC) for each model provides a quantitative measure of its predictive accuracy in discriminating between stable and unstable slopes.

For the rainfall-only scenario, the AUC was calculated to be 0.622, suggesting a relatively low discriminative capability when precipitation is considered as the sole triggering factor. This limited performance is likely due to the short-term variability of rainfall intensity and the complex infiltration processes that influence pore water pressure distribution within the slope.

When only seismic loading was considered, the AUC increased to 0.679, indicating a moderate improvement in model performance. This enhancement can be attributed to the more direct influence of ground acceleration on the mobilized shear stress and instantaneous reduction in shear strength. However, the prediction accuracy under the earthquake-only scenario remains constrained, as it does not account for the hydrological preconditioning that often precedes slope failures during seismic events.

The combined rainfall–earthquake model achieved the highest AUC value of 0.741, clearly outperforming the single-hazard models. This improvement demonstrates the critical importance of considering the coupled effects of rainfall infiltration and seismic acceleration, as their interaction significantly amplifies slope instability potential. Rainfall infiltration increases pore water pressure and decreases matric suction, thereby reducing effective stress and weakening the slope prior to seismic shaking. Consequently, when an earthquake occurs under these hydrologically weakened conditions, the likelihood of slope failure substantially increases.

Overall, the ROC analysis confirms that the proposed multi-hazard modeling framework provides a more robust and realistic representation of failure mechanisms under compound triggering conditions. The enhanced predictive accuracy of the combined model underscores its potential applicability in early warning systems and regional-scale hazard assessments, offering improved reliability for decision-making in landslide-prone areas.

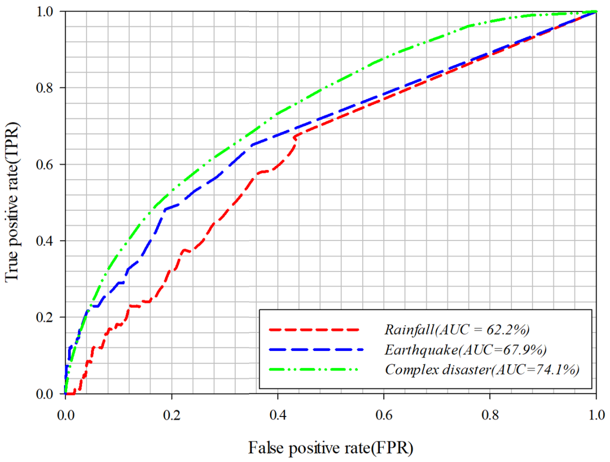

Figure 10. ROC curves under rainfall-only, earthquake-only, and rainfall–earthquake-induced scenarios

Figure 11 presents the quantitative performance indices of slope stability predictions under three distinct hazard scenarios: rainfall-only, earthquake-only, and combined rainfall–earthquake conditions. To provide a comprehensive evaluation beyond conventional binary classification, three statistical metrics were employed: the Success Index (SI), Error Index (EI), and Net Success Index (NSI). These indices collectively offer a balanced assessment of predictive accuracy and misclassification behavior, enabling a more refined interpretation of model reliability.

Under the rainfall-only scenario, the Success Index was calculated to be 33.21%, indicating a limited capacity to accurately predict failure locations when rainfall acts as the sole triggering factor. The corresponding Error Index was 2.61%, resulting in a Net Success Index of 30.60%. This modest performance suggests that rainfall-induced failures are governed by complex subsurface hydrological processes—such as infiltration heterogeneity, preferential flow, and transient pore pressure development—that cannot be fully captured by rainfall intensity alone. Consequently, the predictive capability of the rainfall-only model remains constrained.

For the earthquake-only scenario, the model performance improved notably, achieving a Success Index of 59.63% and an Error Index of 11.34%, which together yield a Net Success Index of 48.29%. The enhancement reflects the relatively direct relationship between seismic loading and the mechanical response of the slope, as ground acceleration instantly affects shear stress mobilization and deformation potential. However, the increased Error Index indicates that some false positives and negatives remain, likely due to the spatial variability of ground motion amplification and the simplifying assumptions inherent in uniform seismic input modeling.

The combined rainfall–earthquake scenario exhibited a marked improvement over the single-hazard cases, demonstrating the synergistic effects of coupled hydrological and seismic triggers. The Success Index reached 78.93%, with a marginal increase in the Error Index to 13.31%, leading to the highest Net Success Index of 65.62%. This significant enhancement underscores the necessity of jointly modeling rainfall and earthquake interactions. Rainfall infiltration reduces matric suction and increases pore water pressure, thereby preconditioning slopes to failure. When seismic loading subsequently occurs, the already weakened soil mass becomes far more susceptible to instability.

Overall, these findings confirm that the proposed Generative AI and Monte Carlo-based framework provides a robust and physically consistent representation of multi-hazard slope behavior. By incorporating stochastic uncertainty and capturing nonlinear hydro-mechanical interactions, the framework significantly improves predictive accuracy compared to traditional deterministic models. This capability is particularly valuable for regional-scale hazard assessment and early warning systems, where understanding the interplay between rainfall and seismic triggers is essential for reducing disaster risk and enhancing slope management strategies in geohazard-prone regions.

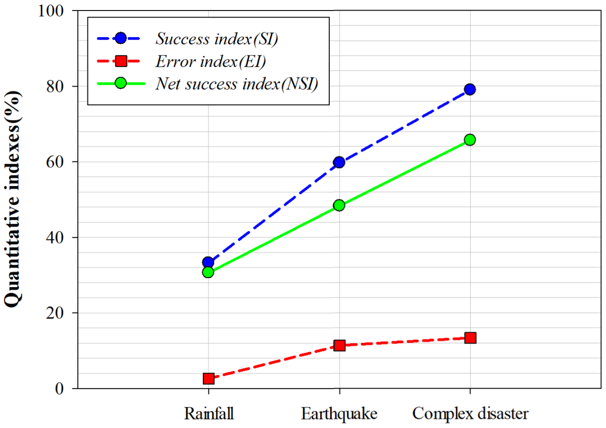

Figure 11. Evaluation of slope failure prediction accuracy by hazard type.

4 CONCLUSION

This study established a comprehensive and data-driven framework for evaluating slope failure risk under compound rainfall–earthquake hazard conditions. By integrating AI, MCS, and coupled hydro-mechanical modeling, the proposed methodology offers a physically consistent and probabilistically robust means of quantifying slope stability under multi-hazard environments.

The framework successfully captured the interaction between hydrological and seismic processes by simulating rainfall infiltration, pore pressure variation, and seismic-induced shear stress mobilization in a unified modeling system. The use of AI to generate synthetic rainfall scenarios effectively expanded the range of hydrological inputs, while MCS allowed for probabilistic quantification of uncertainty in geotechnical and seismic parameters. Application of the framework to the 2009 West Sumatra event reproduced the spatial distribution of observed slope failures, confirming its validity and practicality for real-world hazard assessment.

From a quantitative perspective, the results demonstrated that the rainfall-only and earthquake-only scenarios possess limited predictive capability, whereas the combined rainfall–earthquake model provides the most accurate and realistic predictions. Specifically, the combined model achieved the highest AUC (0.741) and NSI (65.62%), outperforming the rainfall-only (AUC = 0.622; NSI = 30.60%) and earthquake-only (AUC = 0.679; NSI = 48.29%) scenarios. These findings highlight the significant amplifying effect of rainfall infiltration on seismic-induced instability and underscore the necessity of jointly modeling compound hazards.

Overall, the results confirm that the proposed framework offers a substantial advancement in multi-hazard landslide prediction. By linking hydrological preconditioning with seismic response through a probabilistic lens, it enhances both predictive accuracy and interpretability. Future studies should focus on extending this approach to three-dimensional simulations, incorporating unsaturated soil behavior, and integrating real-time monitoring data to improve early warning capabilities.

In conclusion, the proposed AI- and MCS-based multi-hazard framework provides a scientifically rigorous, scalable, and practical tool for understanding and mitigating slope instability in regions simultaneously affected by rainfall and seismic activity. This approach represents a step forward toward next-generation geohazard forecasting systems that can support more resilient and sustainable land management practices.

5 ACKNOWLEDGEMENTS

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