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Multi-Hazard Slope Safety Assessment near Nuclear Power Plants: Influence of Seismic Activity and Soil Saturation

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1. Introduction

Landslides represent a major hazard near nuclear power plants (NPPs), particularly due to the heightened risk associated with earthquake-induced slope failures. In recent years, intensified climate variability has underscored the necessity for robust methodologies capable of evaluating landslide susceptibility under diverse precipitation conditions. While existing research commonly employs various methods to estimate slope displacement, these approaches often fall short in precisely identifying the most vulnerable areas under extreme seismic and rainfall scenarios. To bridge this critical gap, this study examines slope stability through worst-case scenarios, specifically analyzing beyond-design-basis earthquakes (BDBE) characterized by a return period of 100,000 years. Moreover, the research investigates the influence of soil moisture variability, from completely dried to fully saturated conditions, to accurately identify zones with maximum vulnerability.

2. Methods and Results

Identifying slope failure susceptibility near NPPs using GIS and simplified Newmark slope permanent displacement methods involves the following steps:

2.1 Study Area:

The nuclear facilities we studied are situated at 35.2°N latitude and 129.18°E longitude (Fig. 3). Their high elevation and proximity to seismic activity zones increase their risk exposure to earthquakes, thus raising significant safety concerns.

2.2 Proposed methodology

Slope failure susceptibility near NPPs is assessed by considering critical soil parameters, including cohesion (c), friction angle (φ), slope angle (α), soil unit weight (γ), and saturation ratio (m). This analysis specifically examines the influence of these parameters on slope stability under seismic conditions, with a particular focus on the effects of soil saturation and Peak Ground Acceleration (PGA). Initially, the parameters are identified within the study area. Given the uncertainty in soil saturation, two scenarios are considered: Case 1 - dried condition (m = 0) and Case 2 - fully saturated condition (m = 1), with the factor of safety (FS) and critical acceleration calculated for each. Then, the seismic assessment considers both design-basis and beyond-design-basis earthquakes across multiple return periods, utilizing the maximum return period to evaluate extreme conditions. Using empirical models proposed by Jibson (2007) [1], Ambraseys & Menu (1988) [2], and Saygili & Rathje (2008) [3], slope permanent displacements (D_n) are computed across the study area through GIS-based mapping.

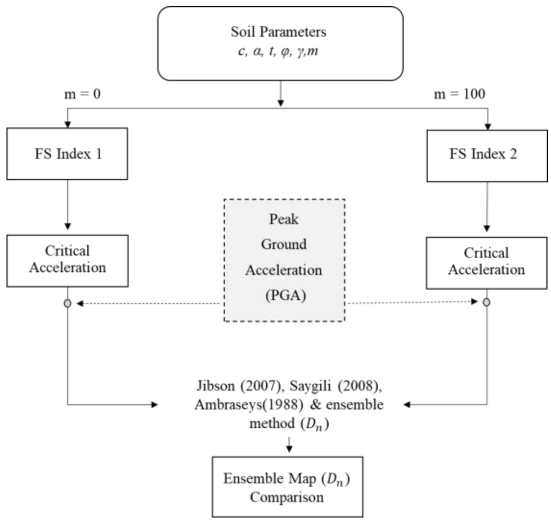

Fig. 1. Workflow illustrating the process for creating a landslide susceptibility comparison map.

To minimize the limitations inherent to simplified methods, an ensemble method was implemented in this study (Fig. 1). The ensemble approach provides robust findings, revealing variations in displacement values that help quantify the risk differences effectively.

2.3 Factor of Safety

The factor of safety is calculated using Equation 1 to determine vulnerable areas.

$$FS = \frac{c}{\gamma \cdot t \cdot Sin\alpha} + \frac{Tan\phi}{Tan\alpha} - \frac{\gamma_w \times m \times Tan\phi}{\gamma \times Tan\alpha} \qquad (1)$$

Here, c represents effective cohesion; φ is the effective friction angle; α is the slope angle; γ is the unit weight of the soil; t is the slope-normal thickness of the failure surface; m is the percentage of the failure thickness that is saturated; γ_w is the unit weight of water. Under dried conditions, the saturation ratio (m) is set to 0, whereas in fully saturated conditions, it is assigned a value of 1. The FS is calculated using the following soil parameters: cohesion (c) = 25.2 kPa, friction angle (φ) = 33.484°, soil unit weight (γ) = 19.5 kN/m³, and the slope angle (α) and slope-normal thickness (t) obtained from raster data computations.

Fig. 2 presents the computed FS for both Cases, indicating an FS value of 1.76 under dried condition and 1.44 under fully saturated condition.

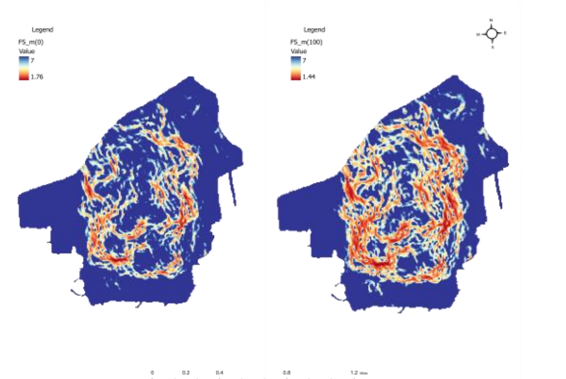

Fig. 2. Factor of safety index map when m = 0 and m = 1.

Using the computed FS, the critical acceleration (A_c) is determined using Equation 2.

$$A_c = (FS - 1) \times \sin\alpha \qquad (2)$$

Then, PGA values for different return periods (Table I) are compared, with PGA = 0.7g considered. Equations from the mentioned references are employed to estimate slope displacements.

Table I: Different Return Periods PGA values.

Return Period	Min (g)	Max (g)	Mean (g)
1,000 years	0.128	0.132	0.13
2,400 years	0.178	0.182	0.18
4,800 years	0.228	0.233	0.23
10,000 years	0.296	0.304	0.30
100,000 years	0.692	0.710	0.70

2.4 Ensemble Slope Permanent Displacement

This study assesses the extent of slope displacement under seismic event using the simplified Newmark displacement models proposed by [1-3]. Under identical conditions in Case 1, the slope permanent displacement values computed using Jibson, Ambraseys, and Saygili's models are 45 cm, 90 cm, and 116 cm, respectively. In Case 2, these values increase to 78 cm, 142 cm, and 137 cm, respectively.

In the proposed ensemble method, the scenario with minimal soil saturation (m = 0) suggests a displacement of approximately 84 cm. This value represents the displacement under dried conditions, which, while significant, remains somewhat constrained due to the absence of lubrication typically provided by moisture. In contrast, fully saturated conditions (m = 1) result in a displacement of approximately 119 cm (Fig. 3). This increase underscores the effect of water saturation on soil stability, significantly reducing the slope's resistance to seismic forces and amplifying displacement.

Fig. 3. Slope Permanent Displacement Comparison for Minimum and Maximum Soil Saturation Ratios.

3. Conclusions

This study evaluates the impact of seismic activity and heavy precipitation on slope stability near nuclear power plants, emphasizing the role of soil saturation in displacement variations. The analysis reveals that in dried conditions (m = 0), slope permanent displacement measures 84 cm, whereas under fully saturated conditions combined with a 100,000-year return period seismic event, permanent displacement increases to 119 cm. Notably, the difference in soil saturation alone contributes to a 30% rise in maximum displacement. These findings show the necessary need to strengthen safety measures against multi-hazard scenarios.

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