Evaluation of Seismic Slope Fragility near Nuclear Power Plants and GIS-Based Mapping via Small-Scale 1g Shaking Table Tests and Newmark Method

Kyeongjae Park [a], Chaeyeon Go [a], Shinyoung Kwag [a*], Seunghyun Eem [b], Daegi Hahm [c]
[a] *Department of Civil and Environmental Engineering, Hanbat National University, Daejeon, Republic of Korea*
[b] *Department of Convergence & Fusion System Engineering, Kyungpook National University, 80, Daehak-ro, Buk-gu, Daegu, 41566*
[c] *Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong Gu, Daejeon, Republic of Korea*
[*] *Corresponding author: skwag@hanbat.ac.kr*

Keywords : Slope, Seismic response, Seismic fragility, Newmark permanent displacement analysis, Small-scale shaking table test, GIS-based fragility map

1. Introduction

Seismic-induced slope failures can disrupt critical infrastructure and cause significant social and economic losses. In critical facilities such as nuclear power plants (NPPs), adjacent slope failures can compromise safety and cause casualties; thus, codes and standards require a quantitative risk assessment. However, conventional evaluations rely primarily on numerical or deterministic methods, which limit the risk analysis required for NPPs. Therefore, in this study, seismic slope model tests were conducted on a small-scale 1g shaking table, and the results were analyzed using the Newmark permanent displacement method. GIS-based topographic and geotechnical analyses were performed for the Hanbit NPP site. In addition, a machine learning–based HCLPF (High Confidence Level of Probability of Failure) prediction application was developed for the slope fragility analysis required for the NPP risk assessment. This approach enables efficient evaluation of the seismic fragility of slopes surrounding the NPP.

2. Methods and Results

This section presents the experimental setup and analytical procedures used in this study, including shaking table tests, the Newmark method, and HCLPF-based seismic fragility evaluation.

2.1 Newmark Permanent Displacement Method

The Newmark sliding block method is a semi-analytical approach for estimating earthquake-induced permanent slope displacement [1]. The slope is modeled as a rigid block that slides when ground acceleration exceeds the critical acceleration (a_c). Permanent displacement (D_n) is calculated by integrating the acceleration exceeding a_c over time [2]. The a_c can be expressed as:

$$a_c = (FS\text{-}1)\cdot g\cdot \sin(\alpha) \qquad (1)$$

The critical acceleration is derived from the static factor of safety (FS), gravitational acceleration (g), and slope angle (α). For the slope HCLPF calculation, this study follows the seismic slope fragility method developed in the previous study [3]. D_n was estimated using the Newmark method based on the experimental results. The estimated D_n was used to define the limit state for seismic performance evaluation and served as a key input parameter for HCLPF evaluation.

$$HCLPF = A_m\cdot \exp[-1.645(\beta_R+\beta_U)] \qquad (2)$$

Specifically, seismic fragility analyses were initially performed across various slope conditions. The resulting seismic fragility curves were then derived, and HCLPF values were computed using Equation (2). Here, A_m indicates the median seismic capacity, and β_R and β_U denote the logarithmic standard deviations quantifying aleatory and epistemic uncertainty, respectively.

2.2 Small-Scale 1g Shaking Table Test

To obtain fundamental data for evaluating the seismic fragility of slopes, small-scale model tests were conducted on a 1g shaking table. The initial condition was set to a completely dry state (saturation ratio, m=0), and the soil was uniformly prepared with a constant unit weight. Water content was selected as a key variable, and additional conditions of 2.5% and 5% were prepared to reflect the effect of increasing moisture. The corresponding increase in apparent cohesion with higher water content was incorporated into the experimental setup. To ensure reproducibility, the total soil mass was calculated from identical volume and unit weight, and compaction was repeated to maintain consistent conditions across all tests.

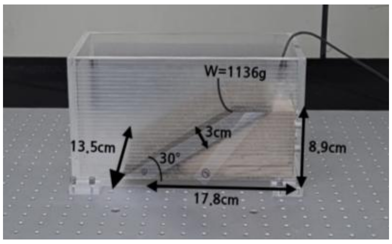
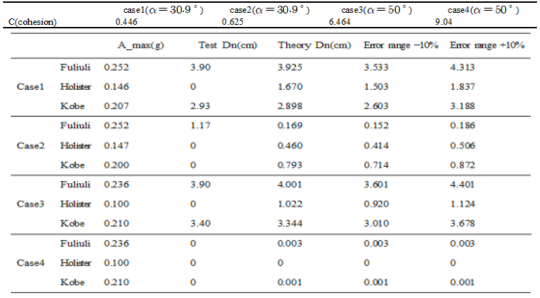


Fig. 1. Small-scale 1g shaking table test setup and target slope

A scaled model test was conducted to simulate seismic ground behavior using similitude laws. The prototype length of 1 m was reduced to 3 cm (scale factor 3/100). Under 1g conditions with identical materials, $\lambda\rho = 1$, $\lambda\sigma = 3/100$, $\lambda t = \sqrt{\lambda L}$, and $\lambda a = 1$. A transparent acrylic soil box (width: 11.3 cm, height: 8.9 cm, length: 17.8 cm) enabled visual observation of slope deformation. Two slope angles, 30.9° and 50°, were tested. Three real earthquake acceleration records with distinct frequency characteristics and durations were applied to analyze the resulting permanent displacements of the slope. Table I compares shaking table test results with predictions from the Newmark method.

Table I: Comparison of shaking table test results and Newmark permanent displacement(D_n) predictions



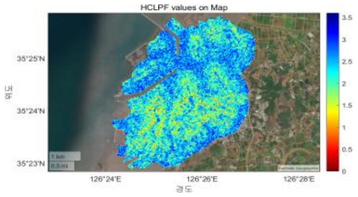
	case1($\alpha=30.9°$)	case2($\alpha=30.9°$)	case3($\alpha=50°$)	case4($\alpha=50°$)
C(cohesion)	0.446	0.625	6.464	9.04

		A_max(g)	Test Dn(cm)	Theory Dn(cm)	Error range −10%	Error range +10%
Case1	Fuliuli	0.252	3.90	3.925	3.533	4.313
	Holister	0.146	0	1.670	1.503	1.837
	Kobe	0.207	2.93	2.898	2.603	3.188
Case2	Fuliuli	0.252	1.17	0.169	0.152	0.186
	Holister	0.147	0	0.460	0.414	0.506
	Kobe	0.200	0	0.793	0.714	0.872
Case3	Fuliuli	0.236	3.90	4.001	3.601	4.401
	Holister	0.100	0	1.022	0.920	1.124
	Kobe	0.210	3.40	3.344	3.010	3.678
Case4	Fuliuli	0.236	0	0.003	0.003	0.003
	Holister	0.100	0	0	0	0
	Kobe	0.210	0	0.001	0.001	0.001

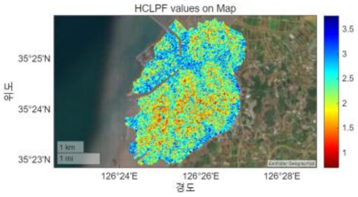
2.3 Development of the HCLPF Application

An application was developed to estimate the HCLPF for slopes using GIS data and machine learning (ML) models trained on a previously generated seismic fragility dataset across various slope conditions. The calculated HCLPF values were visualized on color-coded hazard maps to enable intuitive identification of high- and low-risk zones, even for non-expert users.

The following input parameters were used for the dataset: Cohesion(c): 0.1–10 kPa; Friction angle(α): 30°; Slope angle: pixel-wise values obtained from Arc GIS Pro; Soil unit weight: 16 kN/m³; Slope thickness: pixel-wise values obtained from ArcGIS Pro; Saturation ratio(m): 0.



(a)



(b)

Fig. 2. Comparison of actual and predicted HCLPF map. (a) Actual HCLPF map. (b) Predicted HCLPF map (GPR model).

To identify the most suitable model for HCLPF prediction, representative regression-based ML algorithms—multiple linear regression (MLR), support vector machine (SVM), and Gaussian process regression (GPR)—were implemented. The predictive performance of each model was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE), enabling an objective comparison of model accuracy and generalization (see Table II).

Table II: Performance comparison of ML models

	MLR	**SVM**	**GPR**
R^2	-4.907	0.703	0.964
RMSE	1.188	0.266	0.222
MAE	0.964	0.092	0.071

3. Conclusions

Small-scale 1g shaking table tests and the Newmark displacement method were used to analyze acceleration and permanent displacement across various slope angles. The results confirmed that the Newmark method effectively evaluates the relative stability of slopes during earthquakes. Accordingly, based on this method, ArcGIS Pro–based spatial data, and an HCLPF estimation procedure, the seismic fragility of slopes in the study area was quantified at the pixel level. The ML–predicted HCLPF map showed good agreement with the actual calculated results, validating the reliability of the proposed GIS–ML application. Thus, the MATLAB-based HCLPF application reduced computational time, demonstrating its efficiency as an evaluation tool. Overall, this study can effectively support probabilistic seismic slope safety assessment and disaster management.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2022–00144328). Also, this work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS), granted financial resources from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (RS-2024-00404119).

REFERENCES

[1] Jibson, R. W., Harp, E. L., and Michael, J. A. A method for producing digital probabilistic seismic landslide hazard maps. Engineering Geology, 58, 271–289, 2000.

[2] Jibson, R. W, Regression models for estimating coseismic landslide displacement. Engineering Geology. 91(2–4), 209–218, 2007.

[3] Mostafizur, R. M., Go, C., Kwag, S., Eem, S., and Hahm, D., On a cost-effective integrated framework of earthquake-induced fragility assessment and GIS mapping concerning slopes near nuclear facilities. Nuclear Engineering and Technology, 103807, 2025.