Experimental Validation of the Newmark Permanent Displacement Method Using Small-Scale 1g Shaking Table Test and GIS-Based Seismic Hazard Mapping of Slopes Near a Nuclear Power Plant

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1. Introduction

Earthquake-induced slope failures threaten infrastructure, causing damage and casualties. Near nuclear power plants, such failures pose safety risks and require quantitative seismic risk assessments. Current methods mostly use deterministic models, which lack the probabilistic insight needed for nuclear site safety. The Newmark permanent displacement method has been validated by comparing it with back-analyses of earthquake records and numerical models. However, these validations are limited: the first cannot accurately isolate errors due to estimated soil and ground motion properties, while the second relies on shared modeling assumptions, leading to circular validation. This research directly tests the Newmark method using small-scale 1g shaking table tests, compares multiple empirical equations, and examines how varying the critical acceleration definition impacts results. Building on these findings, it proposes a GIS-based seismic hazard mapping procedure for slopes near the Hanbit nuclear power plants

2. Methods and Results

This section describes the small-scale 1g shaking table tests, the Newmark permanent displacement estimation framework, and the method for constructing a GIS-based seismic hazard map for slopes near the Hanbit Nuclear Power Plant.

2.1 Newmark Permanent Displacement Method

The Newmark sliding-block method is a quasi-analytical approach for estimating the earthquake-induced permanent displacement of a slope; it idealizes the slope as a rigid block and assumes sliding occurs when ground acceleration exceeds a critical acceleration (A_c, g) [1]. The permanent displacement (D_n) is obtained by double-integrating, over time, the acceleration exceeding A_c, which is defined as follows.

$$FS = c / (\gamma \cdot t \cdot \sin\alpha) + \tan\varphi / \tan\alpha \quad (1)$$

$$A_c = (FS - 1) \cdot \sin\alpha \quad (2)$$

Here, FS is the factor of safety, c is the cohesion, γ is the unit weight, t is the slope thickness, φ is the internal friction angle, and α is the slope angle. This study quantified the effect of the critical acceleration definition on predictive performance by jointly applying a slope-angle-specific definition and a single criterion based on the upper bound of the test range. The benchmark empirical equations were the three models of Ambraseys and Menu (1988) [2], Jibson (2007) [3], and Saygili and Rathje (2008) [4]; a direct integration method, which double-integrates the measured acceleration directly, was applied in parallel as a physical benchmark for the empirical predictions.

2.2 Small-Scale 1g Shaking Table Test

Using a uniaxial shaking table (maximum 20 Hz) and an acrylic soil box, a total of 125 shaking table tests were performed—three repetitions each for 125 conditions combining five slope angles (20°, 30°, 40°, 50°, 60°), five real earthquake acceleration records, and five levels of peak ground acceleration (PGA). The specimen was a 1:1 mixture of sandy soil and natural soil, and model-prototype similitude was ensured using the Iai (1989) [5] similitude law (acceleration scale 1, length scale 1/33.3, displacement scale ×33.3, time scale ×5.77). The permanent displacement of the slope surface was measured in every trial.

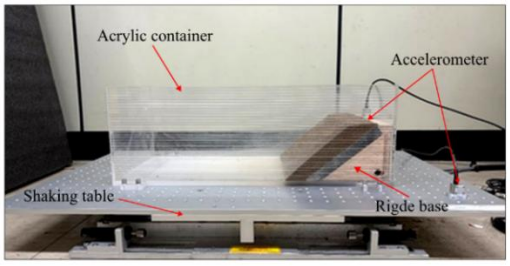


Fig. 1. Small-scale 1g shaking table test setup

In the validation for the 20° slope condition, the rank correlation coefficient (Spearman's ρ) between the measured and predicted permanent displacements

remained nearly unchanged across prediction methods. It ranged from 0.90 to 0.95: $\rho = 0.946$ for direct integration, and $\rho = 0.904$ for AM88, J07, and SR08 alike. The geometric-mean bias, in contrast, varied by nearly a factor of six depending on the prediction method, from 0.12 for direct integration to 0.72 for SR08. The squared correlation coefficient (r^2) varied correspondingly, from 0.76 for direct integration to 0.56 for SR08. Direct integration thus showed both the smallest bias and the highest r^2. This shows that the empirical equations generally follow the trend of experimental results and are not as precise predictors of absolute displacement magnitude; however, they can be effective indicators for relatively vulnerable zones.

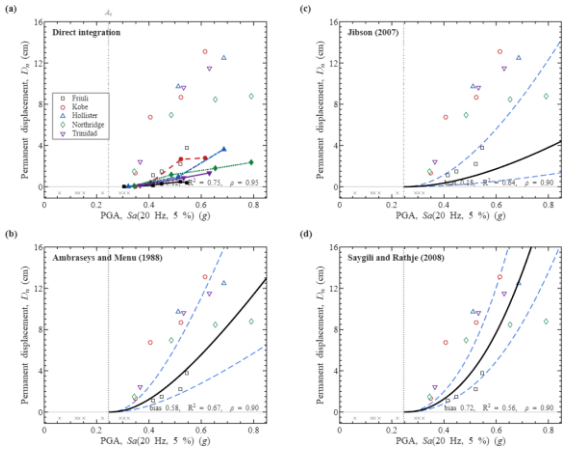


Fig. 2. Comparison of permanent displacement (D_n) prediction performance among the direct integration method and the empirical equations (AM88, J07, SR08) for a 20° slope angle

2.3 GIS-Based Seismic Slope Hazard Mapping (near Hanbit Nuclear Power Plant)

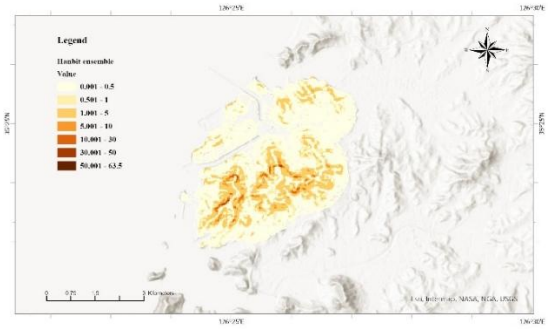


Fig. 3. GIS-based seismic hazard map of slopes near the Hanbit Nuclear Power Plant

Building on these results, the GIS-based seismic hazard map for slopes near the Hanbit Nuclear Power Plant was constructed as an equally weighted ensemble of the three validated empirical equations (AM88, J07, SR08) [6]. This equal weighting is justified by their statistically indistinguishable rank correlation ($\rho = 0.52$–0.60) across the full 125-case validation. This is the relevant criterion, since the mapped output is a relative displacement grade rather than an absolute value. For each DEM grid cell, the ensemble displacement is computed from the local slope angle. This displacement is then classified into a seven-level relative grade. The resulting map enables spatial identification of vulnerable zones that slope angle alone does not reveal (Fig. 3).

3. Conclusions

This study directly validated the Newmark permanent-displacement method through 125 small-scale 1g shaking-table tests, spanning five slope angles, five ground motions, and five PGA levels. The rank correlation coefficient was unaffected by the critical-acceleration definition or the scaling criterion. The bias, however, varied by more than a factor of three across the empirical equations. This confirms that the equations are effective for screening relative vulnerability, not for predicting absolute displacement magnitude. Based on this rank-order consistency, rather than the equations' differing absolute bias, an equally weighted ensemble of the three equations was adopted. This ensemble was used to construct a relative-grade-based GIS seismic hazard map for slopes near the Hanbit Nuclear Power Plant. The map can support seismic safety assessment and disaster-prevention planning for slopes near nuclear power plants.

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