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Fragility Assessment of Slope Stability for Producing Probabilistic Seismic Landslide Hazard Maps Using Nonlinear Incremental Dynamic Analysis

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1. Introduction

Landslides triggered by earthquakes have demonstrated their devastating potential to damage essential infrastructure during previous seismic events. Evaluating the capacity of slopes to withstand varying degrees of ground shaking in anticipation of future earthquakes remains a critical concern. The fragility curve method, coupled with the nonlinear incremental dynamic analysis (IDA) approach, stands out as a well-established strategy in the field of earthquake engineering, making it an ideal choice for addressing this issue (Baker 2015). This preference is attributed to key considerations such as the selection of seismic records, waveform scaling, and nonlinear simulation.

In this study, we conducted a fragility assessment of classic coseismic landslides during the 1994 Northridge earthquake (Jibson et al. 2000) using the nonlinear incremental dynamic analysis method. Regional slope models, incorporating variations in slope heights and angles, were subjected to the influence of globally representative records from past earthquakes. The resultant probabilistic fragility curves offer valuable insights into predicting slope failure ratios across diverse intensity levels of future earthquakes. The method not only demonstrates theoretical reliability but also holds clear physical sssignificance, rendering it applicable to the production of probabilistic seismic landslide hazard maps.

2. Methodology

The study area, occupying an 856×856 square meter space, is positioned adjacent to a highway, with a notable concentration of landslides (Fig. 1).

The distributions of regional slope height and angle were extracted through slope-unit division using a digital elevation model (DEM). By employing bivariate sampling procedures, we constructed 50 finite element models of slope samples with a classic soil-bedrock structure. Nonlinear dynamic simulations of Mohr-Coulomb material (Huang et al. 2024) were subsequently conducted to obtain residual displacements, utilizing 28 representative ground motions from the global PEER NGA-West2 Database scaled to five cumulative square acceleration (CSA) levels (Fig. 2). Parameters are from Jibson et al. (2000).

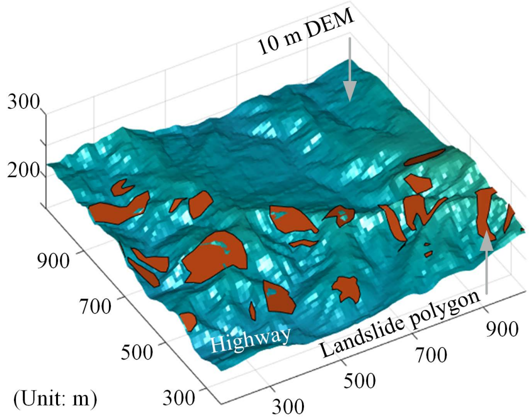

Fig. 1 Study area DEM and landslide polygons.

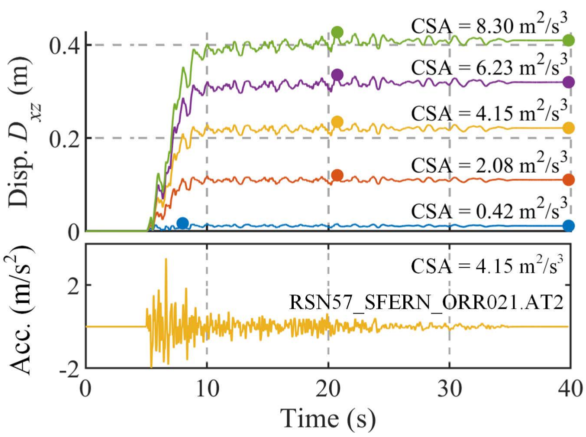

Fig. 2 Displacement histories of 120m_29° slope.

3. Results

The simulation results formed diverse IDA curves, considering variations in slope height, slope angle, CSA level, and seismic records (Figs. 3 and 4). Generally, with the increase in CSA values, the slope residual displacement tends to rise. Slope collapse threshold is set to the displacement over 0.3 m to calculate the theoretical slope collapse ratios at different CSA levels. Subsequently, fragility curves for each slope model were estimated using the Maximum Likelihood method, as outlined in Baker (2015). The resulting fragility curves demonstrate the robust calculation of the proposed workflow (Fig. 5). In comparison to the observed collapse ratio of 0.69 at a CSA value of 28.12 m^2/s^3, the predicted collapse probability reaches 0.76. A comprehensive discussion on slope sampling, displacement threshold, seismic intensity measure, seismic intensity level, and the selection of representative records is needed for future studies.

Acknowledgments

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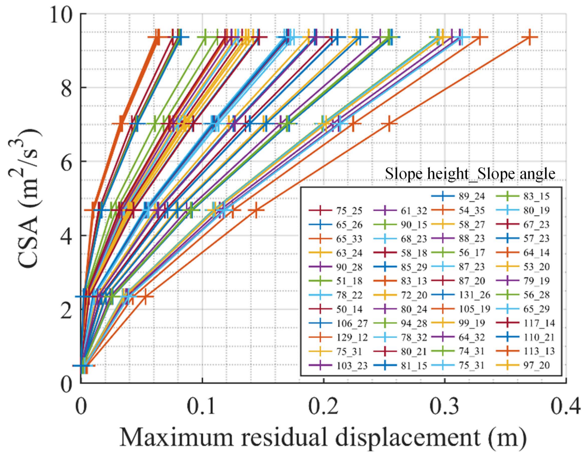

Fig. 3 IDA curves of 50 slope samples with the variations of slope height and angle under the action of the scaled RSN57_SFERN_ORR021.AT2 records.

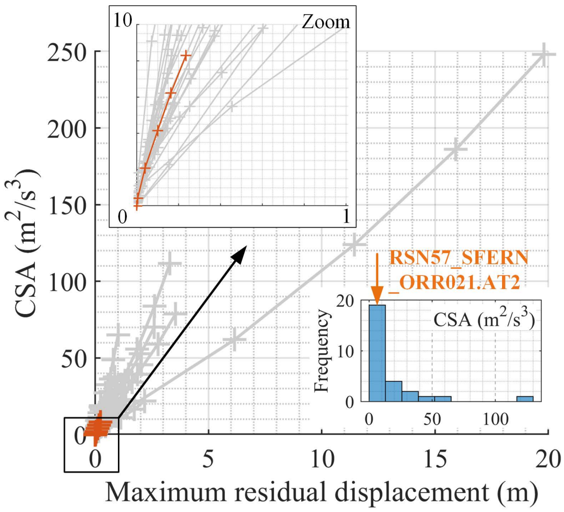

Fig. 4 IDA curves of 54m_35° slope using 28 records (CSA histogram attached) scaled at five CSA levels.

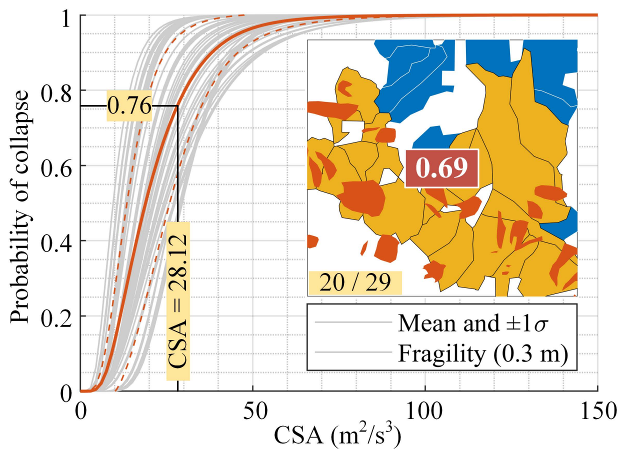

Fig. 5 The probabilistic fragility curve generated in this study and the corresponding observed damage ratio derived from 20 failed slope units (yellow) that covered by landslide polygons (red).