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Reliability Analysis Method for Soil Slopes Permanent Displacement under Mainshock-Aftershock Sequences

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Abstract

After a primary seismic event, subsequent aftershocks frequently induce progressive damage to slopes. Evaluating the response of slopes to mainshock-aftershock sequence (MAS) from a probabilistic perspective is crucial for disaster prevention and mitigation. Current research primarily focuses on single mainshock events, with limited consideration of the aftershock effects. Our study addresses the MAS events. Firstly, the random input field of the MAS is constructed through the collaboration of theoretical models and real data. Then, considering the peak characteristics, cumulative characteristics and spectral characteristics of the MAS, the numerical simulation method is used to explore the control parameters for the soil slope response. Ultimately, leveraging the probability density evolution method (PDEM), we introduce a reliability assessment framework for soil slope behavior under MAS loading. Compared with the existing approaches, the new method fully accounts for aftershock characteristics and assesses the degree of slope permanent displacement response with greater precision. These results offer substantial practical utility for engineering applications and serve as guidance for slope stability assessment and disaster mitigation strategies.

Keywords: mainshock-aftershock sequences, probability density evolution method, seismic response, soil slope, permanent displacement reliability

1 Introduction

Strong seismic events generally trigger subsequent smaller earthquakes. The impact of aftershocks on slopes cannot be ignored, as they may trigger more severe incremental damage effects (Yin et al, 2023). As safety requirements for engineering structures continue to escalate, slope stability under MAS has attracted considerable interest from researchers and practitioners alike. Li et al. (2009, 2017) pioneered and refined the PDEM framework for examining stochastic dynamic systems, establishing novel methodologies for nonlinear stochastic dynamic analysis and reliability evaluation of large-scale complex engineering structures. This framework demonstrates particular effectiveness when applied to slope stochastic dynamic investigations. Expanding upon this foundation, Pang et al. (2021, 2024) introduced an enhanced generalized-PDEM approach for examining reliability in complex slope configurations. Their methodology encompasses multiple

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slope parameters alongside ground motion uncertainties. Additionally, accounting for the spatial variation in soil strength properties, a reliability assessment methodology integrating the Newmark method and PDEM is developed to evaluate the effects of aftershocks and spatial heterogeneity on slope dynamic reliability. (Zhou et al., 2023; Wang et al., 2023; Xu et al., 2025). Contemporary investigations predominantly utilize peak ground acceleration (PGA) as the primary intensity metric. Nevertheless, within MAS contexts, maximum PGA typically manifests during the mainshock phase. Consequently, intensity parameters derived solely from peak values inadequately characterize the comprehensive ground motion attributes of MAS. (Ruiz-Garcia and Negrete-Manriquez 2011; Amiri et al., 2022).

In terms of characterizing the ground motion random field of the MAS, the Monte Carlo method is a classic and effective means (Hu et al., 2018; Nithin et al., 2020; Kim and Sitar, 2013). However, it also has problems such as a large number of samples and incomplete probability information of the sample set (Jiang et al., 2021). Since the MAS time histories obtained via the random function - dimension reduction simulation technique carries associated probabilities and establish a complete probabilistic set, they can be coupled with PDEM to perform sophisticated dynamic response and reliability analyses for complex engineering structures under MAS excitation. (Liu et al., 2017; Liu et al., 2019; Liu et al., 2022).

Considering the peak value, cumulative and spectral characteristics of MAS, a slope reliability analysis method is proposed, adeptly accounting for the characteristics of the aftershock. The findings offer a reference for stability evaluation and disaster prevention of soil slopes under MAS ground motions.

2 Methods

2.1 Model

This investigation employs a binary structural slope configuration to examine slope under the MAS. Fig. 1 shows the double-layer slope model established by referring to Wang et al. (2022). The dimensions of the model are 150 m in length and 30 m in height. Grid dimensions ΔL range from 0.5 m to 1.8 m, with a finer resolution of approximately 0.5 m in the potential sliding zone. The soil material is clay sourced from the southwestern region of China (Yang et al., 2022; Ma et al., 2023; Zhang et al., 2024), and its properties are detailed in Table 1.

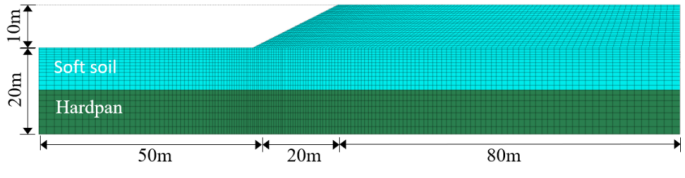

Fig. 1. Geometric dimensions and mesh division of the slope model

Table 1 Parameters of the slope

Soil layer	Density / (kg·m^{-3})	Bulk modulus /MPa	Shear modulus /MPa	Cohesion /kPa	Internal friction angle /(°)	Shear strength /kPa
Soft soil	1900	70	37	34	24	4.2
Hardpan	2000	875	560	120	42	120

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This investigation utilizes the finite-difference platform FLAC3D, with soil mechanical behavior characterized through a Mohr-Coulomb constitutive formulation incorporating tensile-cutoff provisions. Local damping is adopted in this study. Its implementation is given by Ep. (1) (Li et al., 2006). Given that this computational strategy eliminates the requirement for global matrix construction, substantial reductions in time step magnitudes become achievable. Such computational architecture enhances processing efficiency without compromising solution fidelity, rendering this methodology particularly appropriate for investigating nonlinear dynamic phenomena. (Hu et al., 2017; Puthanpurayil et al., 2018; Yan et al., 2011).

$$\xi = \pi D_s \tag{1}$$

Within Equation (1), the coefficient ξ quantifies localized damping intensity, Ds designates the critical damping fraction, while π maintains its conventional value of 3.14.

This investigation adopts a 5% critical damping fraction to replicate energy dissipation characteristics during seismic wave transmission through soil media (Qu et al., 2015), yielding a local damping coefficient of 0.157 according to Ep. (1).

2.2 Reliability analysis method of slope under MAS

Leveraging fundamental probability conservation principles, we may derive generalized density evolution equations applicable to stochastic dynamic system investigations. Integration with virtual stochastic process methodologies facilitates probabilistic modeling of stochastic datasets. Furthermore, based on the PDEM, the reliability analysis of the permanent displacement of the slope under the MAS action is realized (Li et al., 2008; Liu et al., 2017; Jiang et al., 2021). The main steps are as follows:

(1) The measured data of the MAS were statistically analyzed to obtain the frequency-domain energy distribution function curves of each ground motion. Employing optimal square approximation criteria, we determine the parameter vector λ defining each evolving power spectral density function. The seismic in Section 3 can be regarded as a zero-mean non-stationary ground motion process generated by the evolving power spectral density function model. The discrete representative points of each ground motion are expressed as $\theta_q = (\theta_{1,q}, \theta_{2,q}, \ldots, \theta_{s,q}, q = 1, 2, \ldots, 96)$, the discrete representative points assigned to probability for Eq. (2) :

$$P_q = \int_{V_q} p\theta\,(\theta) d\theta \tag{2}$$

(2) Previous research by our group demonstrated that among the 21 parameters evaluated across three categories—namely, peak types (PGA, PGV, PGD), spectral characteristics (Sa_{Ts}, $Sa_{1.5Ts}$, ASI), and cumulative types (a_{sq}, v_{sq}, d_{sq}, a_{rs}, v_{rs}, d_{rs}, I_A, CAV, CAD, CAI, a_{rms}, v_{rms}, d_{rms}, I_c, t_d)—CAV exhibited the highest correlation with the slope displacement response and more effectively captured the characteristics of aftershocks(Zhang et al., 2024) , as shown in Fig. 2. Consequently, CAV was selected as the indicator for evaluating slope response under MAS.

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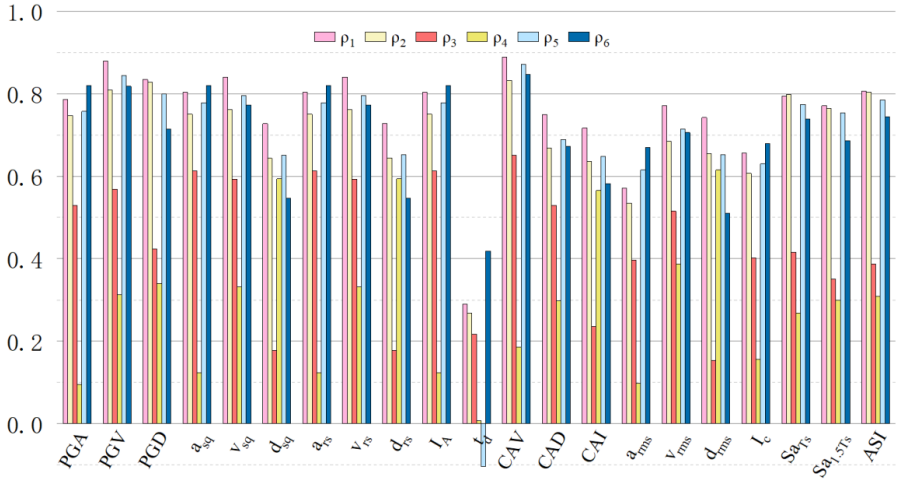

Fig. 2. Correlation coefficient of the 21 ground motion parameters (Zhang et al., 2024)

Based on trial calculations, 96 sets of MAS were scaled to three CAV levels: 12 m/s, 28 m/s, and 40 m/s. Using the FLAC3D, the slope response under MAS, denoted as $\dot{X}_j(\Theta_q, t)$; j=1, 2, …, 96.

(3) Based on the above two steps to get assigned to probability P_q and slope of the response results $\dot{X}_j(\Theta_q, t)$ probability density evolution Eq. (3):

$$\frac{\partial p_{X\Theta}(x,\theta,t)}{\partial t} + \sum_{j=1}^{m} \dot{X}_j(\Theta_q, t) \frac{\partial p_{X\Theta}(x,\theta,t)}{\partial x} = 0,\ \text{q =1, 2, 3, ……, 96} \quad (3)$$

Within this formulation, X designates system response quantities, Θ encompasses the ensemble of random variables exclusive of initial conditions. $\Theta = (X_0, \dot{\Theta})$ represents the vector comprising all stochastic variables within the system; $X = H(\Theta, t)$ indicates the physical response of X; $p_{X\Theta}(x, \theta, t)$ signifies the joint probability density function (PDF) for X and Θ.

When $t = t_0$, the following initial condition is as shown in Eq. (4):

$$p_{X\Theta}(x, \theta, t)|_{t=t_0} = \delta(x - x_0)\, P_\Theta(\theta) \quad (4)$$

In this expression, δ denotes the Dirac delta function, while x_0 corresponds to the X value $t = t_0$. The PDF of X at any given time can be derived by accumulating all discrete numerical solutions, as expressed in Eq. (5):

$$p_X(x, t) = \int p_{X\Theta}(x, \theta, t) d\theta \quad (5)$$

Probability density evolution equations necessitate numerical solution methodologies. Direct analytical solution derivation for Eq. (5). presents considerable mathematical complexity. Conventional practice employs finite difference approximations for solution advancement.

$$\frac{\partial p(z,t)}{\partial t} + a(t) \frac{\partial p(z,t)}{\partial z} = 0 \quad (6)$$

First-order Taylor series expansion of Eq. (6), yields approximate differential expressions:

$$\left[\frac{\partial p}{\partial t}\right]_j (k) = \frac{p_j^{(k+1)} - p_j^{(k)}}{\Delta t} \quad (7)$$

For spatial coordinate z, analogous treatment produces:

$$\left[\frac{\partial p}{\partial z}\right]_j (k) = \frac{p_j^{(k+1)} - p_j^{(k)}}{\Delta z} \quad (8)$$

Substitute Eps. (7) and (8) into Ep. (6):

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$$p_j^{(k+1)} = p_j^{(k)} - \lambda a^{(k)}\left[p_j^{(k)} - p_{j-1}^{(k)}\right] \text{ or } p_j^{(k+1)} = \left(1 - \lambda a^{(k)}\right)p_j^{(k)} + \lambda a^{(k)} p_{j-1}^{(k)} \quad (9)$$

Eq. (9) is the one-sided difference scheme. Substitute $\dot{X}_j(\Theta_q, t)$ obtained from ② into Eq. (3), and solve the partial differential equation using the L-W or TVD format of the finite difference method.

(4) The PDF of slope displacement response $p\_X(x,t)$ is obtained numerically through cumulative summation of the joint PDF $p\_X\Theta(x,\theta,t);\ q = 1, 2, \ldots, 96$. Subsequently, both PDF and cumulative distribution function (CDF) graphs for slope displacement are developed. The statistical characteristics of slope displacement datasets are visualized via these PDF and CDF graphs to determine slope reliability.

3 Stochastic simulations of MAS

Empirical MAS recordings furnish superior fidelity representations of structural damage phenomenology and cumulative degradation mechanisms (Yang et al., 2022). This study uses diverse real seismic data to avoid bias from specific seismic motion types. Through iterative parameter identification employing evolutionary power spectrum density modeling paradigms, this study synthesizes theoretical frameworks with data-driven methodologies to construct stochastic seismic input characterizations. This offers a stochastic loading source for studying how MAS affect slope reliability.

This investigation selected 96 authentic mainshock-aftershock pairs from the Pacific Earthquake Engineering Research Center strong-motion repository. Each MAS assembly adopted a "mainshock + 20-second temporal gap + aftershock" configuration to preserve comprehensive non-stationary sequence characteristics (Wang et al., 2023). Fig. 3 displays a typical mainshock–aftershock acceleration record from the Whittier Narrows event, with the mainshock and aftershock numbered 589 and 707, respectively, in the NGA-West2 database.

For the mainshock-aftershock sequential ground motion assemblies constructed above, frequency-domain energy distribution investigations proceed utilizing evolutionary power spectrum modeling of fully non-stationary ground motion processes (Priestley, 1965; Liu et al., 2017). The best square approximation criterion and the least square method are adopted to fit the energy distribution curve in the frequency domain. The parameter vector λ is further obtained through inversion and regression. In the process, considering the site damping ratio ξ_f excellence, site soil circular frequency ω_f and the influence of a frequency modulation function parameter. The identification results are shown in Fig. 4, and the data results are presented in Table 2. In the constructed earthquake, it can be regarded as a zero-mean real non-stationary ground motion process generated by the evolving power spectral density function model.

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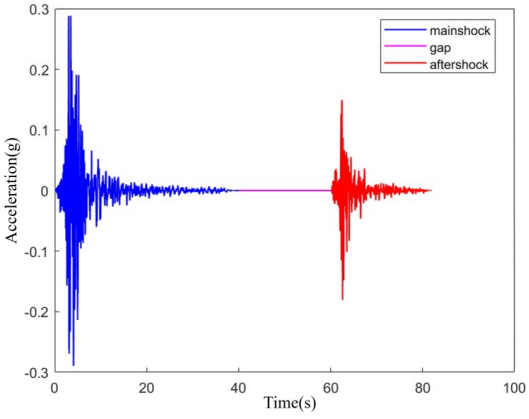
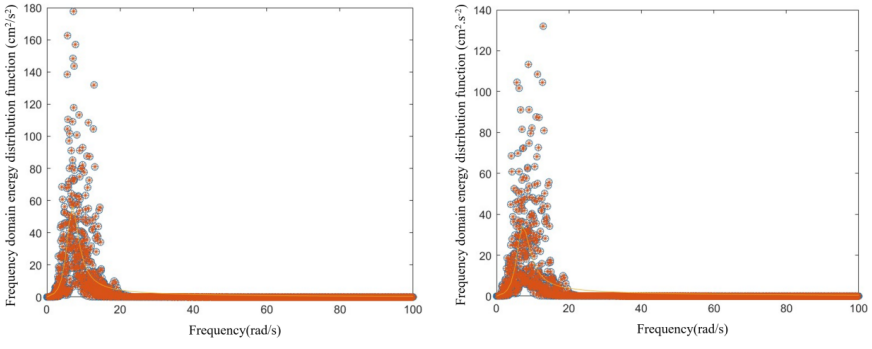


Fig. 3. Typical acceleration time history of a MAS



（a）the fitting results of the mainshock　　（b）The fitting results of the aftershock

Fig. 4. The identification effect of the parameter vector λ

Table 2 Identification results of MAS

Earthquake type	Damping ratio	Superior circular frequency	Time−frequency modulation function
mainshock	0.32	14.09	0.64
aftershock	0.37	14.64	0.71

4 Results and analysis

To assess slope reliability based on permanent displacement outcomes, defining critical stability states proves necessary. Jibson and Michael (2009) classified slope displacement into four ranges for seismic landslide risk evaluation: displacements of 0-1cm indicate low risk, 1-5cm suggest medium risk, 5-15cm represent high risk, and those exceeding 15cm denote very high risk. For permanent displacement, Yener (1988) suggests that the control standard for seismic sliding deformation is 1m. In this study, combined with the actual engineering requirements, three slope displacement thresholds of 0.05m, 0.5m and 1.0m were selected, corresponding to three failure degrees of low, medium and high respectively, to systematically evaluate the reliability of slope displacement under the MAS action.

Fig. 5 shows the distribution of the slope permanent displacement under the MAS. The

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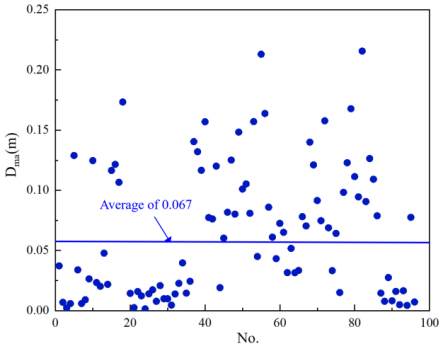
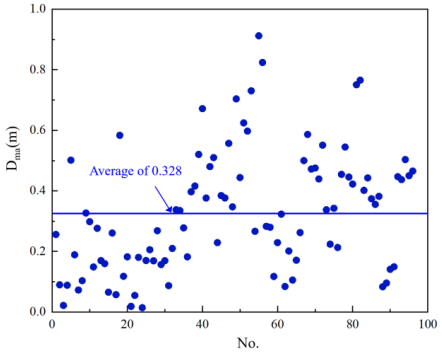
distribution has a large degree of dispersion, and with the increase of ground motion intensity, the displacement response of the slope also increases. When the CAV of the MAS was 12m/s, 28m/s and 40m/s respectively, the permanent displacements of the slope were 0.067m, 0.328m and 0.633m respectively, which were like the slope displacement results when the PGA of the MAS was 0.4g, 0.5g and 0.6g in reference (Wang et al., 2023). The difference is that the discreteness degree of the permanent displacement of the slope obtained in this study becomes smaller. With the increase of the CAV, the slope displacement response results are increasingly concentrated around the average value. This tendency substantiates CAV superiority relative to PGA as the characterization parameter for MAS when investigating slope displacement reliability.

Fig. 6 delineates PDF and CDF curves characterizing slope displacement. PDF curves reveal the clustering patterns and variation extents within displacement datasets, thus presenting the distributional features of slope movement data in a visual manner. The CDF curve determines the cumulative probability of displacement and is used to evaluate the reliability of the permanent displacement of the slope. The PDF for slope displacement shown in Fig. 5 display bimodal or multimodal patterns, making it difficult to describe them using standard distributions like normal or lognormal models. Under the MAS action of different intensities, the displacements of slopes have diverse distribution patterns, and their probabilities are also not the same. When the CAV is 12 m/s, the fluctuation span of slope displacement response ranges from 0-0.25m. Under a low failure degree with a displacement threshold of 0.05 m, the reliability of the slope is 48.5%. With the growth of CAV, the variation range of slope displacement response under the MAS keeps expanding, while the concentrated area of permanent displacement becomes wider. When the CAV is 28 m/s, the fluctuation span of slope displacement response extends from 0 m to 1 m, mainly concentrated between 0 m - 0.5 m. Under the medium failure degree with the displacement threshold of 0.5 m, the reliability of the slope is 82.0%. When the CAV is 40 m/s, the fluctuation span of slope displacement response spans from 0 m to 2 m, mainly concentrated between 0 m -1 m. Under the high failure degree with a displacement threshold of 1m, the slope's reliability reaches 91.7%.



(a) displacement distribution map when CAV = 12 m/s



(b) Displacement distribution map when CAV = 28 m/s

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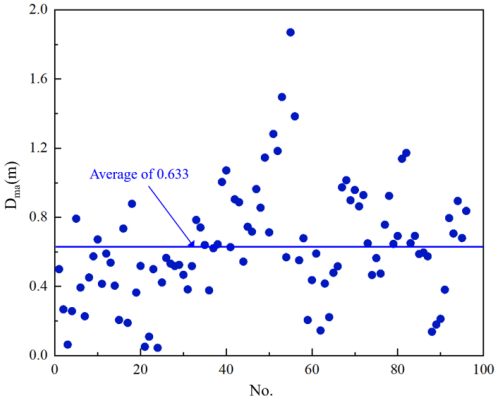
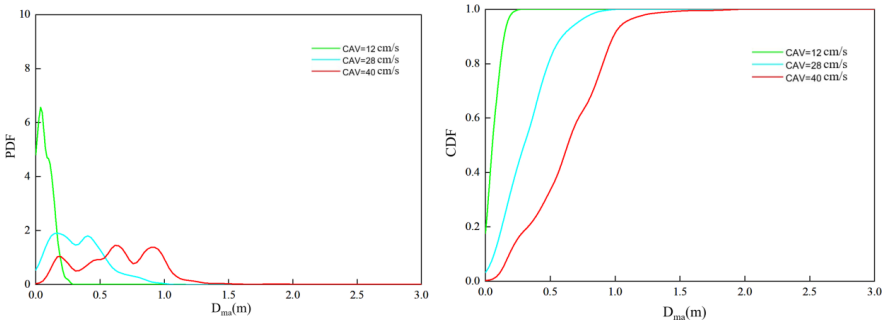


(c) displacement distribution map when CAV = 40 m/s

Fig. 5. displacement response distribution of slopes under mas



(b) PDF (b) CDF

Fig. 6. Statistical analysis of slope displacement response probability under mas action

This investigation's outcomes undergo comparative evaluation against conventional slope displacement reliability analysis results, which customarily employ PGA as the seismic ground motion parameter (Wang et al., 2023), as depicted in Fig. 7-9. Fig. 7 demonstrates that the use of CAV as the seismic ground - motion parameter in this study leads to a more concentrated distribution of slope displacement. The range of displacement is reduced by 37.5% to 50%, the probability of outliers is lower, and the assessment of slope displacement response is more precise. Fig. 8 and Fig. 9 indicate that at the low damage threshold of 0.05 m, the slope reliability is 39.2% when using PGA as the index, while it rises to 48.5% when using CAV as the index, showing an increase of 9.3%. At the moderate damage threshold of 0.5 m, the slope reliability is 76.7% for PGA and 82.0% for CAV, with an increase of 5.3%. At the high damage threshold of 1 m, the slope reliability is 77.2% for PGA and 91.7% for CAV, with an increase of 14.5%. These results demonstrate that using CAV as the seismic intensity control parameter for sequence-type ground motions can more effectively evaluate slope reliability。

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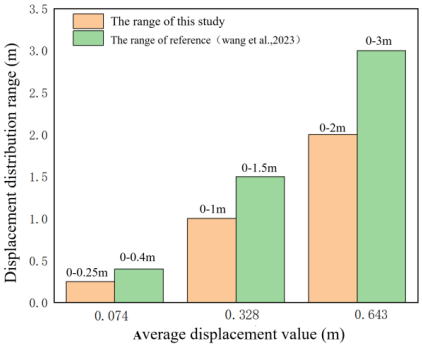

Fig. 7. Comparison of slope displacement response distribution

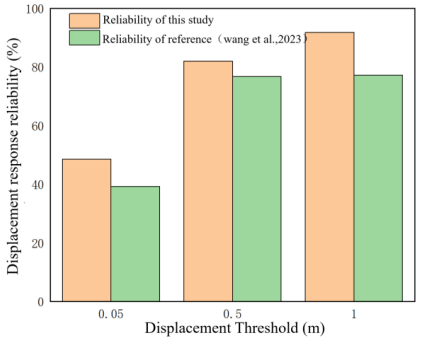

Fig. 8. Comparison of slope displacement reliability

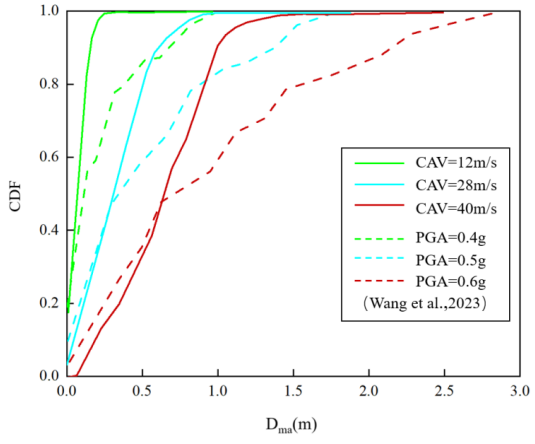

Fig. 9. Compared with the reliability results of slope displacement response in reference

5 Conclusions

By studying the intensity-controlling parameters of the MAS in soil slope responses and based on PDEM, an assessment methodology addressing slope reliability under MAS excitations is presented herein. Benchmarking against conventional techniques reveals the following insights:

(1) Among 21 distinct MAS parameter types, CAV demonstrates superior capability in capturing MAS characteristics and comprehensively representing MAS cumulative effects. Therefore, CAV can be used as the optimal parameter to assess the response of soil slopes under the MAS action.

(2) Based on the dynamic calculation results, as CAV increases from 12 m/s to 40 m/s, the slope displacement response gradually increases, while the displacement results still exhibit a degree of scatter. Consequently, employing probabilistic analysis methodologies becomes essential when evaluating soil slope stability under MAS loading.

(3) By incorporating MAS characteristics and utilizing PDEM, a methodology for computing slope displacement response reliability under MAS has been established. This method fully reflects the characteristics of aftershocks and can more accurately evaluate the response degree of slopes under MAS action, which has both theoretical significance and practical engineering value.

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It is worth pointing out that this study focuses on clayey soil slopes in the southwestern region of China, with an emphasis on the feasibility of the reliability analysis method for soil slope response under MAS action. The study does not consider the variability of soil parameters. Considering the variability of soil parameters will be of great significance to practical engineering applications.

Code and data availability. The MAS goundmotions in this study was based on the NGA-West2 strong-motion database from the Pacific Earthquake Engineering Research Center.

Author contributions. JZ and CZ designed the research and optimized the overall structure of this paper. TW and CZ completed most of the main work, including the programming, debugging of parameters, and final drafting of the article. SC and ZD contributed some important algorithm ideas and completed the work of the comparison part. JZ and CZ provided the original algorithm ideas and framework for this study and provides valuable suggestions for program optimization and parameter adjustment.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Review statement.

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