

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

Response to Reviewer Comments

First, we would like to express our sincere gratitude to the reviewer for the detailed, in-depth, and constructive comments. The authors have revised the manuscript accordingly. A point-by-point response is provided below.

Reviewer Comments

The manuscript presents a framework for evaluating slope permanent displacement under mainshock–aftershock sequences (MAS) using PDEM and CAV as the controlling intensity measure. The topic is relevant and the proposed framework is promising. However, several important technical and clarity issues need to be addressed before the manuscript can be considered for publication.

1. Clarity and Presentation

- **Line 31:** The statement “*more severe damage*” is vague and requires clarification. The authors should specify the reference condition and support the claim with appropriate quantitative evidence or citations.

Response:

We have replaced the vague expression “more severe damage” with a more specific and evidence-based statement: “Actual seismic damage observations indicate that aftershocks often serve as the final trigger for overall failure of slopes.” This revision is supported by documented field investigations of earthquake-induced landslides, where aftershocks were observed to cause the culminating failure of slopes already weakened by the mainshock.

Specifically, we have added the following references to support the threshold selection:

[1] Xu Q, Huang R Q. Preliminary study on dynamic characteristics of large-scale landslide hazards induced by the 5.12 Wenchuan earthquake[J]. *Journal of Engineering Geology*, 2008, 16(06): 721-729.

[2] Yin Y P. Research on geological hazards induced by the Wenchuan M8.0 earthquake[J]. *Journal of Engineering Geology*, 2008(04): 433-444.

- **Lines 50, 53, 57–60:** The writing quality requires improvement. In particular, Lines

57–60 should clearly define the **research gap, motivation, and main objectives** of the study. This section currently does not adequately frame the contribution.

Response:

We have rewritten this section to clearly articulate the following:

Research gaps: (1) Current reliability analysis methods for seismic slopes are mostly designed for single-mainshock scenarios and cannot adequately perform reliability assessment under MAS. (2) Existing studies on sequential ground motions predominantly use PGA as the intensity measure, which cannot capture the cumulative damage effect contributed by aftershocks.

Motivation and objectives: This study adopts CAV as the intensity measure for mainshock–aftershock sequence-type ground motions and, based on the Probability Density Evolution Method (PDEM), establishes a reliability analysis method for permanent displacement of soil slopes under MAS ground motions. The findings offer a reference for stability evaluation and disaster prevention of soil slopes under MAS ground motions.

- **Line 97:** The phrase “*Seismic in Section 3*” is unclear and should be rewritten to explicitly describe the seismic input or dataset.

Response:

The original text “The MAS described in Section 3” has been replaced with “The MAS dataset in this research” for clarity and precision.

2 Ground Motion Selection and Scaling

- **Line 151:** The manuscript does not sufficiently justify the selection of the 96 MAS records. The authors should provide:
 - selection criteria (magnitude, distance, mechanism, site conditions)
 - statistical representativeness of the dataset
 - scaling methodology and its compliance with established practices
 - relevant ground motion characteristics (PGA, PGV, duration, frequency content)

As the dataset is derived from NGA-West2, it represents shallow crustal earthquakes only, which limits the generality of the conclusions. The sensitivity of the results to the selected

dataset should be discussed or mentioned. Example relevant references for comparison and checking's are:

- Bray & Macedo (2019) – seismic slope displacement under crustal earthquakes
- Yeznabad et al. (2022, *Soil Dynamics and Earthquake Engineering*) – probabilistic slope displacement assessment

Response:

Thanks for this thorough and constructive comment. The detailed selection criteria for the 96 MAS records were supplemented:

- (1) The mainshock and aftershock belong to the same seismic event, the aftershock being the largest-magnitude event within 12 months of the mainshock;
- (2) Both have a moment magnitude ≥ 5.0 and $\text{PGA} \geq 0.05 \text{ g}$;
- (3) The two records are taken from the same component of the same station;
- (4) The station has an average shear-wave velocity of $100 \leq V_{S30} \leq 700 \text{ m/s}$;
- (5) Its rupture distance does not exceed 80 km.

We used real earthquake records in this study, preserving the natural amplitude and frequency characteristics of the ground motions. This approach avoids introducing biases associated with amplitude scaling.

We also calculated the parameters of these ground-motion sequences, including PGA, PGV, duration, frequency content, and others. The statistical results are shown in the attached Excel file.

On the Representativeness of Ground Motions from the NGA-West2 Database, we have added a discussion acknowledging that the NGA-West2 database is limited to shallow crustal earthquakes, which may affect the generality of the conclusions for subduction or intraslab events. This limitation is now explicitly discussed in the revised Discussion section, with references to Bray & Macedo (2019) and Yeznabad et al. (2022).

3 Displacement Thresholds

Line 173: The use of Jibson (2009) requires clarification. This framework is based on Newmark-type analysis and is typically used for regional hazard mapping. In engineering practice ~15 cm displacement is widely used to indicate high hazard, ~25 cm is also commonly adopted. The thresholds of 0.5 m and 1 m represent very large displacements,

generally associated with severe damage or failure

The authors should justify their chosen displacement thresholds within an engineering context.

Response:

We thank the reviewer for this valuable comment. In the study, for reliability analysis, as stated in the manuscript, “*three slope displacement thresholds of 0.05 m, 0.5 m and 1.0 m were selected, corresponding to three failure degrees of low, medium and high respectively*”. In response to the reviewer’s comment, we have revised the thresholds to 0 m, 0.25 m, and 0.50 m for evaluating slope reliability, representing low, medium, and high failure degrees, respectively.

4 Evaluation of Intensity Measures

- **Line 188:** The conclusion that CAV is superior to PGA requires stronger quantitative support (e.g., correlation values, reduction in dispersion, improvement in reliability).

Although 21 intensity measures were initially evaluated, the final comparison is limited to **CAV versus PGA**. Important intensity measures such as: PGV, spectral acceleration, duration-related measures are not included in the final analysis. The values should be added or the rationale for excluding these measures should be clearly explained.

Response:

In our previous studies, we have investigated the correlation between ground motion parameters of mainshock–aftershock sequences and slope responses, and the results are shown in Figures 1 (Zhang C D, et al., 2024).

[3] Zhang, C., Zhang, J., Chen, S., et al., 2024. Response characteristics of soil slope under mainshock–aftershock sequences–type ground motions: Incremental damage effect, polarity effect, and correlation. *Soil Dynamics and Earthquake Engineering*. 187, 108940

To comprehensively elucidate the response patterns of slopes under the influence of MAS characterized by various attributes, we selected 21 ground motion parameters with three different types: peak-type (PGA, PGV, PGD), cumulative-type (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), and spectral characteristics-type (Sa_{Ts} , $Sa_{1.5Ts}$, ASI), as the objects, and the correlation between 21 MAS parameters and slope response were analyzed.

To study the correlation between the MAS parameters and the slope displacement, the correlation coefficients for six specific relationships were explored:

- ① ρ_1 , the correlation coefficient between the mainshock parameters and D_m ;

- ② ρ_2 , the correlation coefficient between the mainshock parameters and D_{ma} ;
- ③ ρ_3 , the correlation coefficient between the aftershock parameters and D_a ;
- ④ ρ_4 , the correlation coefficient between the aftershock parameters and D_{ma} ;
- ⑤ ρ_5 , the correlation coefficient between MAS parameters and D_{ma} ;
- ⑥ ρ_6 , the correlation coefficient between the ratio of MAS parameters and δ_D .

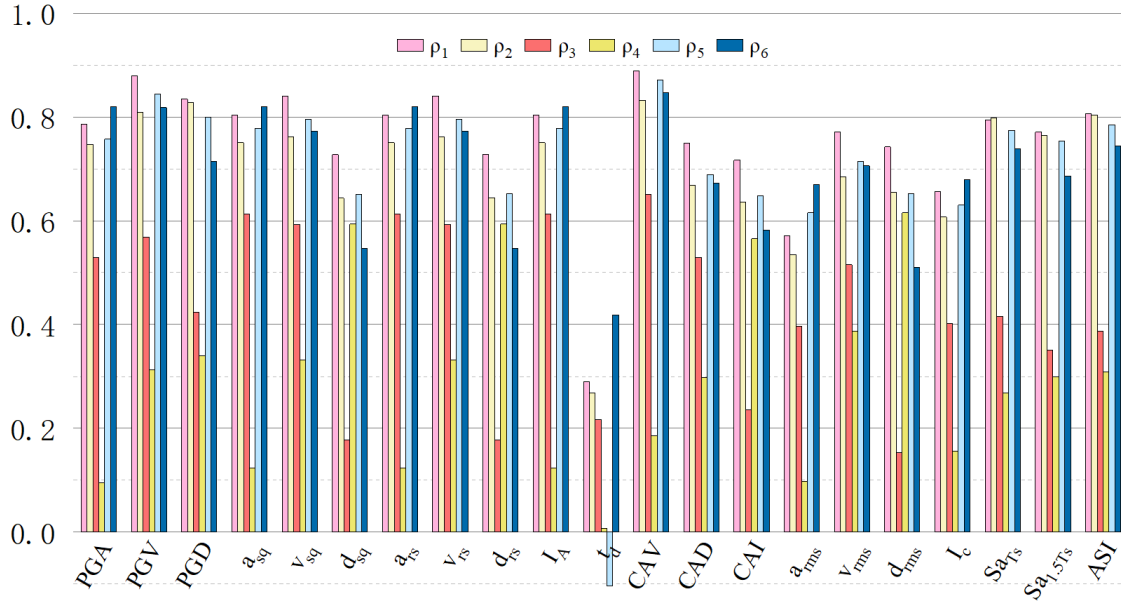


Fig. 1. Correlation coefficient values of the 21 ground motion parameters corresponding to $\rho_1 \sim \rho_6$

The results show that CAV exhibits the highest correlation with slope response, with a correlation coefficient of 0.872. Meanwhile, as noted by the reviewer, peak parameters such as PGA and PGV also show relatively high correlations. CAV is a time-domain integral parameter defined as $CAV = \int_0^{T_d} |\dot{u}_g(t)| dt$. It can measure the cumulative energy and duration effects of ground motion. For studying the excitation of slopes subjected to MAS, CAV contains more information than peak-based parameters. More importantly, it can capture the influence of aftershocks, because peak parameters are often dominated by the mainshock. Therefore, CAV is selected as the intensity measure in this study.

5 Scatter in Displacement Results (Key Concern)

- **Figure 5:** The displacement results show a large spread for each CAV level, ranging from negligible values to very large displacements.

This raises a critical issue:

If displacement varies significantly at a fixed CAV level, how robust is CAV as a predictive

parameter?

This behavior suggests that additional factors—such as frequency content, duration distribution, and dynamic interaction effects—play an important role in slope response.

This observation is consistent with:

- Rathje & Saygili (2008, 2010), which demonstrate the importance of both scalar and spectral ground motion characteristics
- Yeznabad et al. (Earthquake Spectra), which highlight the role of frequency compatibility in displacement prediction

The manuscript should explicitly discuss this limitation.

Response:

As mentioned above, based on the correlation analysis results, among the 21 ground-motion parameters of the MAS, CAV exhibits the highest sensitivity and also captures the aftershock effects well. Compared with the peak parameters (e.g., PGA and PGV) commonly used in existing studies, CAV shows higher correlation and better reflects the sequential characteristics of MAS events. However, this correlation is only relatively high, and therefore the dispersion of displacement responses at various CAV levels seems to be acceptable, which also indicates that this parameter has certain limitations. As the reviewer pointed out, other ground-motion parameters such as frequency content also affect slope displacement responses. It is precisely based on the above considerations that this study attempts to introduce a reliability method to characterise the response of slopes subjected to MAS.

The above discussion will be incorporated into the relevant sections of the manuscript in accordance with the reviewer's suggestion. In addition, we are also exploring whether a single index that comprehensively accounts for intensity, duration, and frequency content can be established to more fully represent seismic effects in engineering practice, and this would be a highly meaningful research direction. We sincerely thank the reviewer again for the valuable comments.

6 Model Assumptions and Limitations

The study considers:

- a single slope geometry
- a single soil stratigraphy

Thus, key parameters such as slope angle, layering, and soil variability are not investigated. These factors are known to significantly influence slope response.

In addition: Only crustal ground motions are considered, No assessment is made for subduction or intraslab events, which exhibit different characteristics

These limitations should be clearly acknowledged and supported with appropriate references.

Response:

A loess slope in southwestern China was selected as the representative numerical model to illustrate the proposed methodology. The soil parameters investigated in this study are specific to soils found in southwest China. This region is characterized by two factors: first, there are more mountainous areas, a large number of slopes and a large population; Second, it is located at the junction of the Eurasian plate and the Indian Ocean plate, where earthquakes occur frequently. For instance, the devastating landslides triggered by the 2008 Wenchuan Ms8.0 earthquake resulted in significant casualties and economic losses. Therefore, this study holds considerable importance for disaster prevention, mitigation, and relief efforts in southwest China.

It also should be emphasised, however, that the primary objective of this study is to develop a generalisable methodological framework. We sincerely acknowledge that key factors—such as slope angle, soil layering, spatial variability of soil properties, and different tectonic settings (e.g., subduction and intraslab events)—can significantly influence the seismic response of slopes. These limitations have been explicitly acknowledged in the revised discussion section, with appropriate references added to support the discussion.

That said, we would like to highlight that:

(1) The principal contribution of this work lies in the methodological framework, specifically the integration of CAV as the intensity measure for MAS with the probability density evolution method (PDEM) for efficient reliability analysis.

(2) Parametric sensitivity analyses investigating the effects of slope geometry, stratigraphy, soil variability, and the extension to subduction-zone ground motions represent important future research directions, which we have now clearly outlined in the revised manuscript.

We greatly appreciate the reviewer's constructive comments, which have helped us better define the scope and contributions of our study.

7 Frequency Content and CAV Applicability

CAV is a cumulative intensity measure but does not explicitly capture frequency-dependent response. The manuscript does not evaluate the sensitivity of results to frequency content or site conditions.

Previous studies (Rathje & Saygili, 2008; Yeznabad et al. SDEE 2021 and 2022) demonstrate that frequency content plays a critical role in seismic slope displacement.

The authors should either: provide supporting justification for using CAV as a standalone parameter, or clearly acknowledge

Response:

As detailed in our responses to Comments 4 and 5, 21 ground-motion parameters were analyzed. These include spectral parameters such as SaTs, Sa1.5Ts, ASI, among others. The results indicate that CAV exhibits the relatively highest correlation with slope displacement responses. Meanwhile, as can also be observed from Figure 1, spectral parameters also show relatively high correlations, which further demonstrates that frequency content plays a critical role in seismic slope displacement. Based on the above analysis, we selected CAV, which shows relatively higher correlation, as the intensity measure in this study. At the same time, in view of the complexity and randomness of MAS, a reliability method is introduced in this study to characterise the displacement response of slopes subjected to MAS.

Furthermore, it would be of great significance for engineering seismic design to develop a control parameter that integrates ground-motion intensity, duration, and frequency content. This will constitute a key research priority in the future. We sincerely thank the reviewer once again for the valuable comments and suggestions.