egusphere-2026-638

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 1# Comments

I am happy to recommend accept after Minor Revision as it clearly needs a revision on Abstract, Results & Analyses and Conclusions sections how about clear Discussions? in order to streamline the message right.

Response:

Following this suggestion, we have thoroughly revised the Abstract, Results & Analyses, and Conclusions sections. The main focus of these revisions is to ensure that these sections present more clearly the novelty, research content, research value, and limitations of our study. These revisions help streamline the core message and strengthen the logical flow of the manuscript. Should there be any further concerns, we would greatly appreciate your comments.

Reviewer 2# 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 revised the manuscript as suggested, in lines 33–34. Detailed explanations are as follows:

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.*" The corresponding references are also included.

- **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 accordingly in lines 60–68. The specific details are as follows:

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 cumulative absolute velocity (CAV) as the intensity measure for MAS ground motions and, based on the PDEM, establishes a reliability analysis framework for the permanent displacement of soil slopes. The proposed method is capable of accounting for the influence of aftershocks, which can provide a reference for stability evaluation and disaster prevention of soil slopes subjected to MAS.

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

Response:

The phrase "*Seismic in Section 3*" has been replaced with "*The MAS dataset in this research*" as per the reviewer's suggestion, in line 105.

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:

We have supplemented and revised the manuscript in lines 161–170 according to the above comments. Detailed explanations are as follows:

(1) The detailed selection criteria for the 96 MAS records were supplemented:

a) The mainshock and aftershock belong to the same seismic event, the aftershock being the largest-magnitude event within 12 months of the mainshock;

b) Both have a moment magnitude ≥ 5.0 and PGA ≥ 0.05 g;

c) The two records are taken from the same component of the same station;

d) The station has an average shear-wave velocity of 100 ≤ V_S30 ≤ 700 m/s;

e) Its rupture distance does not exceed 80 km.

(2) In the selection criteria, the earthquake depth has been quantitatively defined, and the corresponding references (Bray & Macedo, 2019; Yeznabad et al., 2022) have been included. These revisions respond to the reviewer's comment on clarifying the limitation of shallow crustal earthquakes.

(3) 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.

(4) 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.

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:

In response to the reviewer's comment, meanwhile, referring to previous studies, 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.

To validate the rationality of the results obtained by the proposed method, while ensuring consistency with the conditions used in previous research, three threshold values (0 m, 0.5 m, and 1.0 m) were adopted in this study.

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 accordance with the above comments, we have added supplementary clarifications in lines 110–118. Specific details are provided below:

(1) Within the framework of reliability analysis, it is essential to identify a ground-motion parameter that exhibits the strongest correlation with slope displacement responses for MAS events. 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. The correlation

coefficients for six specific relationships were explored:

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

②ρ_2, the correlation coefficient between the mainshock parameters and D_{ma};

③ρ_3, the correlation coefficient between the aftershock parameters and D_a;

④ρ_4, the correlation coefficient between the aftershock parameters and D_{ma};

⑤ρ_5, the correlation coefficient between MAS parameters and D_{ma};

⑥ρ_6, the correlation coefficient between the ratio of MAS parameters and δ_D.

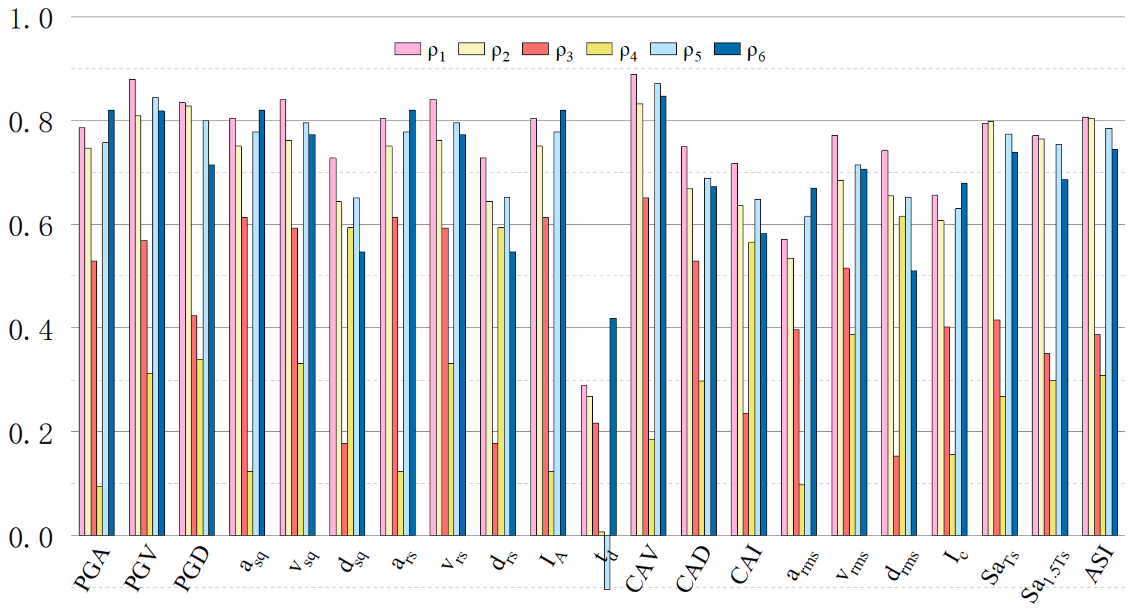

Fig. 1. Correlation coefficient values of the 21 ground motion parameters corresponding to ρ_1~ρ_6

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, with a correlation coefficient of 0.767 and 0.844, respectively. CAV is a time-domain integral parameter defined as $\text{CAV} = \int_0^{T_d} |\dot{u}_g(t)|\ dt$. 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.

(2) The comparison between our results and PGA is motivated by two considerations: first, PGA is a widely used indicator in existing reliability analyses and correlates relatively well with slope displacement; second, other ground-motion parameters (e.g., frequency content and duration)

exhibit weaker correlations with slope displacement. Consequently, a comparison with PGA serves as a reasonable benchmark to effectively illustrate the advantages and shortcomings of the proposed approach.

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:

We have explicitly discussed this limitation in lines 209–216 according to the reviewer's comments and the references provided by the reviewer. Details are as follows:

In agreement with the reviewer's comment, the correlation analysis (Fig. 1) demonstrates that other ground-motion parameters, such as frequency and duration, indeed play an important role in slope displacement responses. Among the 21 ground-motion parameters of the MAS, CAV exhibits the highest sensitivity and also captures the aftershock effects well. However, this correlation is only relatively high, and therefore the dispersion of displacement responses at various CAV levels is reasonable, which also indicates that this parameter has certain limitations. Similar results have also been reported in other studies (Rathje and Saygili, 2008; 2009; Yeznabad et al.,2022; Wang et al., 2023). Given the current lack of a single comprehensive ground-motion parameter that can effectively predict slope displacement responses, the PDEM framework propagates this inherent variability into the reliability estimate, thus rendering a probabilistic treatment indispensable. Building on previous studies, the present work introduces a reliability probabilistic analysis method that integrates the PDEM.

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:

We have provided explanations and clarifications in the conclusions section according to the reviewer's comments. Details are as follows:

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 emphasized, however, that the primary objective of this study is to develop a generalizable methodological framework. This is intended to fill the current research gap in reliability analysis methods for slope displacement that fully account for aftershock effects. We sincerely acknowledge that key factors—such as slope angle, soil layering, spatial variability of soil properties, and different tectonic settings—can significantly influence the seismic response of slopes. These limitations have been explicitly acknowledged in the revised manuscript, 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. This is intended to fill the current research gap in reliability analysis methods for slope displacement that fully account for aftershock effects.

(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:

We have already added relevant explanations in lines 110-118、209-216 of the revised manuscript. Details are as follows:

Within the framework of reliability analysis based on PDEM, it is essential to identify a ground-motion parameter that exhibits the strongest correlation with slope displacement responses for MAS. As detailed in our responses to Comments 4 and 5, 21 ground-motion parameters were analyzed. These include spectral parameters such as Sa_{Ts}, $Sa_{1.5Ts}$, ASI, among others. The results indicate that CAV exhibits the relatively highest correlation with slope displacement responses. Meanwhile, as can also be observed from Fig. 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.

Given the current lack of a single comprehensive ground-motion parameter that can effectively predict slope displacement responses, the PDEM framework propagates this inherent variability into the reliability estimate, thus rendering a probabilistic treatment indispensable. Building on previous studies, the present study introduces a reliability probabilistic analysis method that integrates the PDEM. However, conducting this study requires selecting the parameter with the highest correlation as the controlling indicator.

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. If such a parameter existed, there would in fact be no need to employ reliability methods to characterize the response. This will constitute a key research priority in the future. We sincerely thank the reviewer once again for the valuable comments and suggestions.

In addition to the above revisions made in response to the reviewers' comments, we have also polished the language of the entire manuscript.