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INTEGRATING MULTI-HAZARD IMPACTS: A SEQUENTIAL ASSESSMENT OF VOLCANIC ASHFALL AND EARTHQUAKE EFFECTS ON BUILDING VULNERABILITY

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Abstract

The increasing frequency and impact of natural hazard events worldwide, despite significant mitigation efforts, highlight the need for a paradigm shift in vulnerability assessment methods. A reliable approach must account for the effects of sequential events, whether dependently or independently related, as evaluating such events separately and summing their impacts can lead to inaccurate assessments. This study focuses on the impact of ashfall from volcanic eruptions, which increases axial loads on structural elements, altering lateral strength and dynamic properties of buildings due to the added seismic mass.
In cases of significant overloads, such as those near a volcano's central vent or during heavy rainfall, roof failure may occur, causing building interruptions and posing risks to occupants. The study introduces a mechanical method to quantify these effects by updating fragility curves to reflect the sequence of ashfall-induced overloads followed by seismic events. This methodology directly incorporates changes in structural lateral strength and dynamic properties, along with the probability of horizontal slab failure. The resulting fragility curves provide damage assessments across various grades, offering a realistic scenario given the likelihood of earthquake sequences during volcanic eruptions. This approach emphasizes the importance of accounting for multi-hazard interactions to enhance vulnerability assessments and disaster preparedness.

Keywords: Vulnerability assessment methods, Multi-hazard interactions, Ashfall overloads, Seismic events, simplified mechanical method

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1 INTRODUCTION

The increasing frequency and impact of natural hazards worldwide, despite significant mitigation efforts, underscore the need for a paradigm shift in vulnerability assessment methodologies. Traditional approaches that evaluate hazards independently and aggregate their impacts can lead to inaccurate risk estimations, failing to capture the complex interactions between sequential events.

Early seismic vulnerability frameworks, such as those developed in Japan and the U.S. during the 1970s, evolved in Europe through methodologies like GNDT [1], Risk-UE [2], and Vulneralp [3]. Recently, the Italian Department of Civil Protection (DPC, Dipartimento della Protezione Civile) issued a framework for National Risk Assessment [4,5]. All the approaches therein developed have been used within an expert elicitation approach for comparative fragility analysis [6], by using 10 typological classes (for both unreinforced masonry – URM - and Reinforced Concrete – RC - buildings) representative of Italian building assets. For the latter fragility curves are taken from the studies of [7,8,9]. In contrast, volcanic risk models, focusing on roof collapse due to tephra accumulation [10,11,12,13], emerged later, driven by the infrequency of large eruptions affecting urban centers.

Historically, risk assessments were compartmentalized, with hazards evaluated using isolated protocols and metrics [14]. This fragmentation limited cross-risk comparability, emphasizing the need for a unified multi-hazard framework grounded in consistent methodologies. Additionally, critical advancements acknowledge that one hazard can intensify vulnerability to another. For instance, volcanic ash loads exacerbate seismic vulnerability [11,12,13]. These time-dependent interactions demand dynamic models that address both abrupt and gradual asset deterioration.

To tackle these complexities, probabilistic methods have been pioneered in projects like Na.R.As. (2004-2006) [15], ARMONIA (2004–2007) [16], and MATRIX (2010–2013) [17].

This study focuses on ashfall from volcanic eruptions, which introduces significant axial loads on buildings, altering their lateral strength and dynamic properties due to the added seismic mass. In extreme cases—such as prolonged ash accumulation near a volcano's central vent or in combination with heavy rainfall—roof failure may occur, disrupting building functionality and posing serious risks to occupants. Furthermore, given the strong correlation between volcanic activity and seismic events, assessing the combined effects of these hazards is crucial for improving risk evaluation and mitigation strategies.

To address this challenge, the study proposes a mechanical-based methodology that updates fragility curves to account for sequential ashfall-induced overloads followed by seismic events. This approach directly integrates structural modification effects, including variation in lateral strength and modifications in dynamic behavior, as well as the probability of horizontal slab failure. The resulting fragility curves provide realistic damage assessments across various grades, reflecting the likelihood of multi-hazard sequences during volcanic activity. Thus, the proposed approach enhances disaster preparedness by offering a more reliable and physically grounded framework for evaluating the risks associated with complex hazard scenarios, ultimately supporting more effective mitigation and resilience strategies.

2 DERIVATION OF BASELINE SEISMIC FRAGILITY CURVES VIA POST METHOD

This section presents the procedure used to derive seismic fragility curves via the simplified mechanical method, POST. These fragility curves are then utilized as baseline in subsequent sections to assess variations caused by the added mass of ash load.

2.1 Briefly description of simplified mechanical method POST

The POST (PushOver on Shear Type models) method is a simplified mechanical approach for seismic vulnerability assessment of Reinforced Concrete (RC) buildings [18,19,20,21]. It evaluates the non-linear static response of RC buildings by assuming a shear-type behavior, which simplifies the structural analysis. The method considers the influence of infill panels on both the structural response and the assessment of building damage, with damage states defined according to the European Macroseismic Scale (EMS-98) [22].

The key steps in the POST method include:

- Building Model Definition: The model is based on global dimensions, number of storeys, and age of construction. It uses a simulated design procedure to estimate element dimensions and reinforcements based on historical design codes and seismic classifications.
- Seismic Capacity Assessment: The non-linear static response is evaluated through a pushover analysis, assuming a shear-type model. The method considers the tri-linear behavior of RC columns and the in-plane response of infill panels. The capacity curve of the equivalent Single-Degree-of-Freedom (SDoF) system is derived, and seismic capacity is evaluated in terms of spectral intensity measures at different damage states (DSs).
- Fragility Curve Derivation: Fragility curves are derived using a Monte Carlo simulation approach, accounting for uncertainties in geometry, material properties, capacity models, and seismic ground motion. The method translates qualitative EMS-98 damage descriptions into mechanical displacement thresholds for both RC columns and infill panels.

The POST method has been validated using a large database of RC buildings affected by the 2009 L'Aquila earthquake, showing good agreement between predicted and observed damage scenarios. It is particularly useful for large-scale seismic vulnerability assessments, providing a balance between simplicity and accuracy. For further details, the reader may refer to [18,19,20,21] where detailed theoretical developments and validation example are provided.

2.2 Archetype building definition

The archetype buildings in this study were chosen based on a statistical analysis of the geometric characteristics of the national building inventory. According to census data (ISTAT 2001), 85% of reinforced concrete (RC) buildings have up to three stories. Specifically, 18% are single-story buildings, while 48%, 19%, and 7% have two, three, and four stories, respectively. Additionally, 8% of RC buildings have five or more stories.

By examining the ratio of the total number of apartments to the number of buildings, the average number of apartments per building was determined for different story counts. As expected, the number of apartments increases with the number of stories. This growth is more than proportional, as it is influenced by two factors: the increase in plan surface area and the rise in the number of apartments per storey as the total number of stories increases.

Furthermore, by analyzing ISTAT data and the historical evolution of seismic classification in Italy, it can be inferred that approximately two-thirds of the entire RC building inventory was designed to resist only gravity loads, without accounting for the effects of lateral loads that simulate seismic actions. Consequently, the simulated design phase in this study is carried out by considering only gravity loads, based on technical codes and construction practices in place before 1970. The dimensions of the columns are designed based on the loads acting on an effective area surrounding them, with the longitudinal reinforcement proportionally determined according to the code requirements in force at the time. The floor plans of the archetype buildings considered in this study are illustrated in Figure 1.

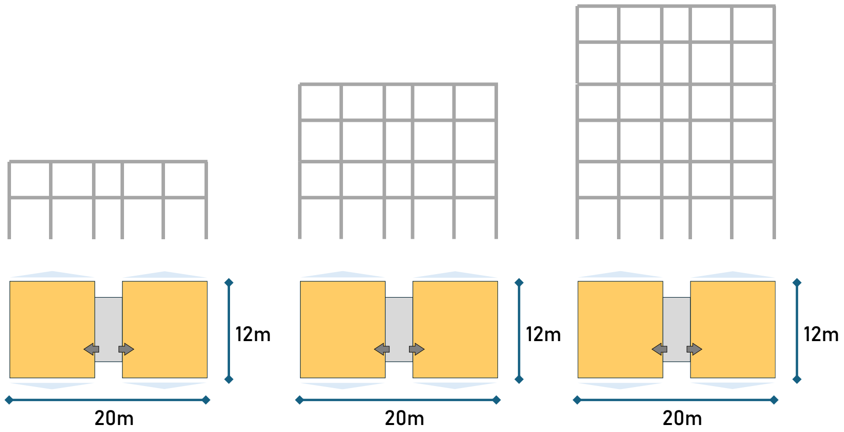


Figure 1: Archetypes buildings used in this study.

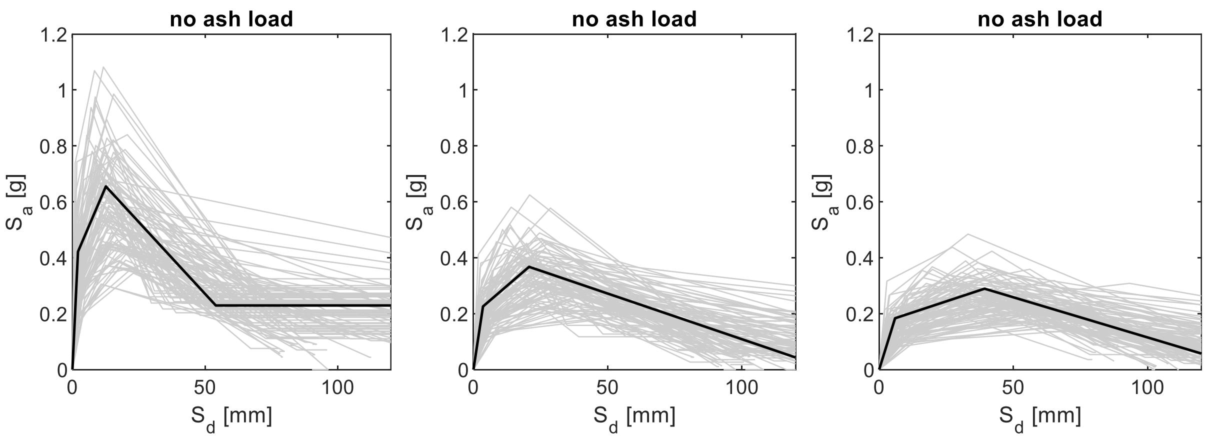
2.3 Non linear response and fragility curves derivation

The mechanical model of the archetype buildings is developed using a non-linear model for both RC columns and external infill panels. Specifically, the model for RC columns is based on [23], while the model for infill panels follows [24].

The pushover curve is derived using a MATLAB code that implements a closed-form procedure based on the shear-type assumption. This procedure allows for the determination of the base shear–roof displacement relationship once a force distribution is defined.

In Figure 2a, the interstorey displacement distribution at the peak step of the pushover curve for the two-storey building archetype is shown, consistent with the shear-type model assumption. The grey lines represent the variations due to different sources of uncertainties discussed in Section 2.1, while the black line represents the median model.

Figure 2b displays the median capacity curve (black line) for the two-storey building archetype, along with the uncertainty bounds (grey lines) derived from considering various sources of uncertainties. The capacity curve is obtained by approximating the building's behavior as a Single-Degree-of-Freedom (SDoF) system at the first vibration mode. This involves dividing the base shear by the effective mass of the SDoF and the modal participation factor of the 1st mode, and the roof displacement by the modal participation factor of the 1st mode.



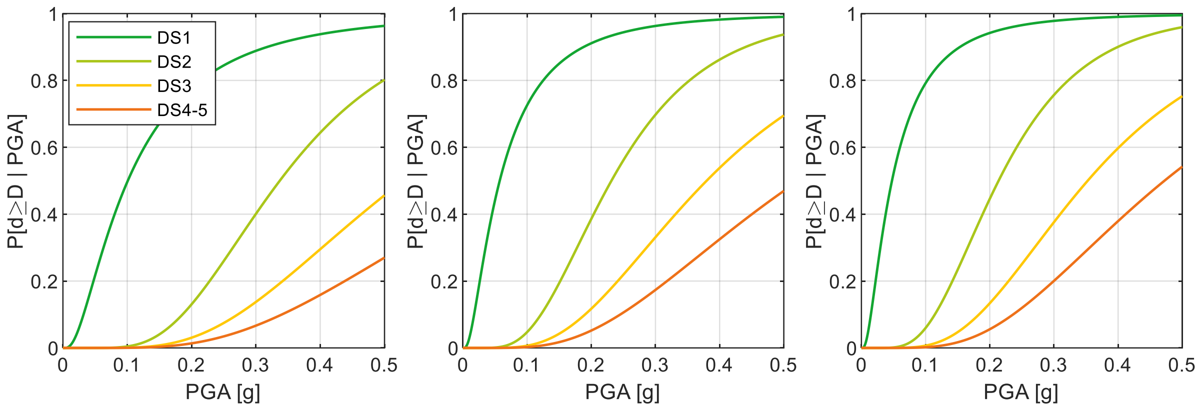


Figure 2: Capacity curves for the virtual population of two- four- and six-storey building archetypes considering all uncertainties (grey) and the median model (black) and ensuing fragility curves.

The seismic capacity is defined in terms of the damage classification outlined in the EMS-98. Displacement thresholds corresponding to the five damage levels for RC columns and infill panels are used to determine the overall damage to the building, following a damage classification scheme detailed in [21].
The introduction of the source of uncertainties outlined in section 2.1 within a MonteCarlo simulation technique allows define a probabilistic distribution of seismic capacity at different damage levels, represented in figure 2c as fragility curves for the two-storey building archetype. The fragility curves obtained for the three archetype buildings are utilized as baseline in subsequent sections to assess variations caused by the added mass of ash load.

3 DYNAMIC VULNERABILITY UPDATING

This section examines the variations in building response and fragility curve estimations caused by the added mass at the roof level, such as that resulting from ash load following a volcanic eruption.
It is evident that the addition of mass at the roof level influences the dynamic parameters of the building or its simplified model, i.e., the Single-Degree-of-Freedom (SDoF) system. Specifically, the added mass leads to changes in both the effective mass of the SDoF and the modal participation factor of the 1st mode. The added mass has a dual effect on the modal participation factor: it alters the shape of 1st vibration mode and increases the effective mass of the SDoF, both of which are considered in its definition. Overall, these effects result in a reduction in the modal participation factor of the 1st mode due to the added mass at the roof level.
Additionally, the addition of a mass at the roof level affects the axial load on structural elements. Assuming this load acts solely on the RC columns, it influences both the resistance and capacity values in the non-linear model of the columns. This occurs while the cross-sectional area and reinforcement area of the columns remain unchanged, as they were determined in absence of the added mass during the design and construction phases of the building.

Figure 3 demonstrates the impact of adding an increasing mass at the roof level on the capacity curve and displacement capacity. Overall, a reduction in all ordinate values is observed due to the increase in the effective mass, despite the decrease in the modal participation factor of the 1st mode. Regarding the displacement capacity for the first three damage levels (slight, light, and moderate damage), an increasing trend is noted, attributed to the change in the shape of the 1st vibration mode, which results in an elongation of the effective period. However, for the most severe damage level, the increase in axial load leads to a rise in displacement capacity, consistent with the model proposed by [23].

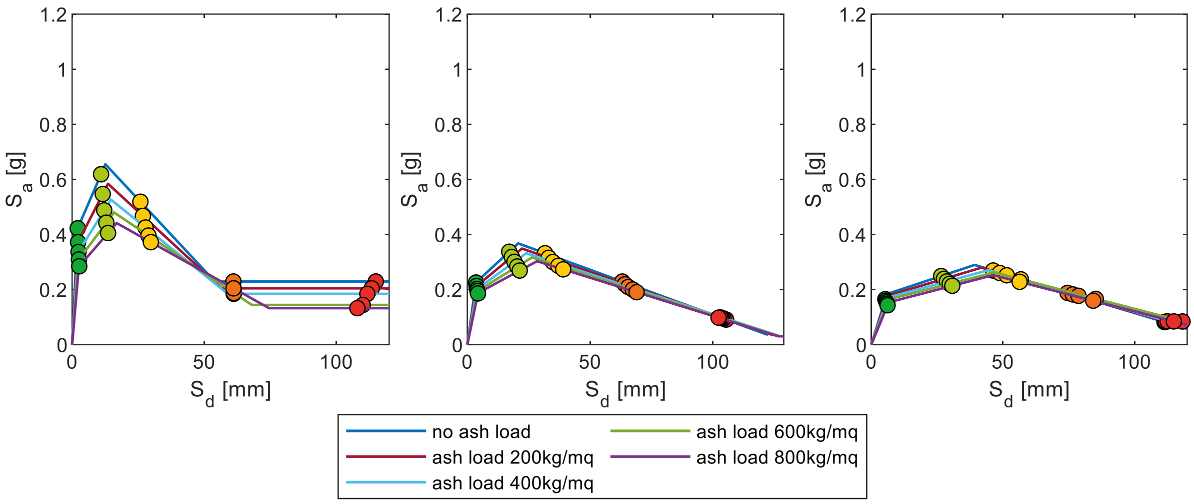


Figure 3: Variation in capacity curves and displacement capacity due to added roof mass for the median model of the virtual population of two- four- and six-storey building archetypes

Finally, Figure 4 shows the variation in the probability of collapse as a function of two intensity measures: peak ground acceleration (PGA) and ash load. When the ash load is zero, the probability of collapse corresponds to the fragility curve derived in Section 2.3. As the ash load increases, the resulting changes in the building's dynamic parameters and structural behavior—due to modifications in the capacity curve and displacement capacity—lead to a rise in the probability of collapse.

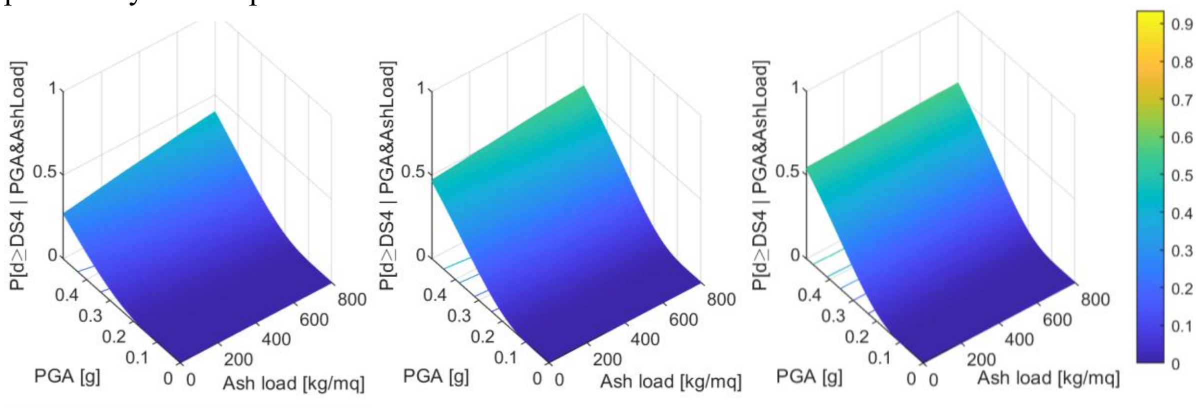


Figure 4: Variation in exceeding probabilities of DS4 due to the added roof mass for the two- four- and six-storeys building archetypes.

3.1 Variation in collapse fragility curves considering the probability of failure of RC slabs

All the computations in the previous section do not account for the possibility that the slab, as a structural element, could fail under ash load due to exceeding its design strength. To incorporate this effect, the probability of slab failure can be explicitly considered and combined with the results obtained above.

The ashfall vulnerability functions used in this study are derived from [12], which were developed through numerical simulations of roof behavior at the collapse limit state for various flat structure types (see Figure 5). By adjusting assumptions regarding constraint conditions and material strength, lower and upper load limits were established for each roof type, specifically for a single-span slab with a width of 5 meters. These theoretical curves are then validated with

loading tests conducted on a sample of real roofs up to the collapse limit, showing good agreement.
It has to be noted, that this vulnerability function aligns well with those derived in the study by [25].

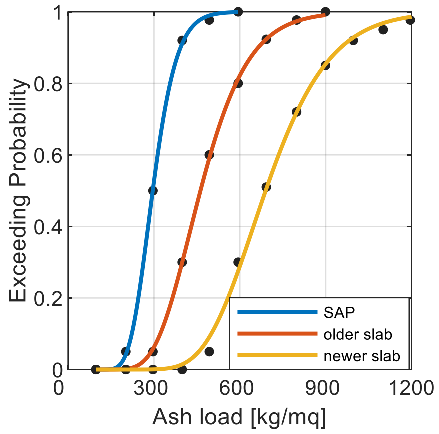


Figure 5: ashfall vulnerability functions for RC slab typologies modified from Zuccaro et al., 2008

In the case of a system exposed to two hazards (such as earthquakes and ash loads, as considered in this study), the overall fragility formulation should be expressed in terms of the two demands [17]. Specifically, when the vulnerabilities to the hazards are completely independent, as in this case, the multi-hazard vulnerability factor can be calculated as:

$$(1 - P_f) = (1 - P_{f1})(1 - P_{f2}) \rightarrow P_f = P_{f1} + P_{f2}(1 - P_{f1}) \tag{1}$$

where P_{f1} and P_{f2} are the probability of failure due to ash loads and earthquakes, respectively. Therefore, the 3D fragility function presented in Figure 4, which accounts for the two hazards (earthquakes and ash loads) but not considering the possibility of slab failure under ash load, is updated in Figure 6 to explicitly include this effect.
It is important to note that explicitly incorporating the failure of the slab results in a significant increase in the overall fragility formulation, as shown in Figure 6.

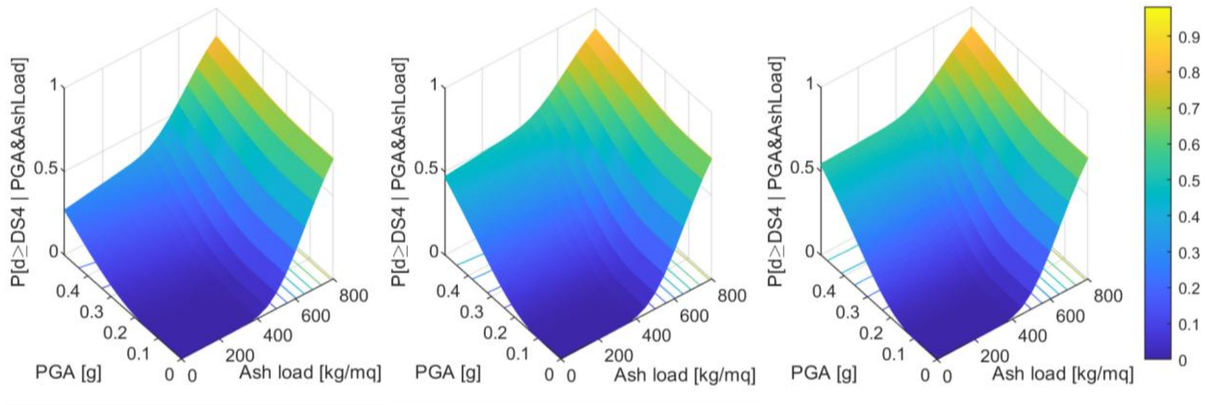


Figure 6: Variation in exceeding probabilities of DS4 due to the added roof mass for the two- four- and six-storeys building archetypes, incorporating roof slab collapse probability (newer slab).

4 CONCLUSION

This study addresses the growing need for advanced vulnerability assessment methodologies in the face of increasing natural hazards, particularly the cascading effects of multi-hazard scenarios such as volcanic ashfall and seismic events.
The non-linear response of existing RC archetype buildings is evaluated using the simplified mechanical method POST, which explicitly accounts for the influence of infill panels in determining building lateral resistance and damage estimation, following the EMS-98 classification. The POST method automates the building model definition, pushover analysis, seismic capacity assessment, and fragility curve derivation, incorporating uncertainties in geometry, materials, and ground motion through Monte Carlo simulations. These fragility curves are then utilized as baseline with reference to multi-hazard scenarios such as volcanic ashfall and seismic events.
This study demonstrates that the addition of ash load at the roof level significantly alters the dynamic properties of buildings, including changes in the effective mass and modal participation factor of the Single-Degree-of-Freedom (SDoF) system. Secondly, ash loads increases the axial load on structural elements, particularly RC columns, influencing their resistance and capacity in the non-linear model. These effects are clearly shown in the increase of the probability of collapse with increasing ash load, as demonstrated by the updated fragility curves that account for both ashfall and seismic demands.
Additionally, the explicit consideration of the failure probability of slab due to ash load significantly increases the overall fragility formulation. This highlights the importance of accounting for the failure of horizontal structural elements in multi-hazard vulnerability assessments.
Traditional approaches that evaluate hazards independently often fail to capture the complex interactions between sequential events, leading to inaccurate risk estimations. By focusing on the combined effects of ashfall and earthquakes, this research provides a more comprehensive framework for assessing structural vulnerability and resilience. The proposed methodology provides a more realistic and physically grounded framework for assessing structural vulnerability. The 3D fragility functions, updated to include slab failure, offer a robust tool for evaluating the combined risks of these hazards.

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