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Mediterranean coastal bridges' vulnerability to combined earthquake-tsunami actions: fragility assessment

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Abstract

During natural disasters, such as earthquakes followed by tsunami events, bridges represent critical infrastructures whose failure can severely hinder emergency response and recovery efforts. Coastal regions are among the most susceptible to facing these unfortunate occurrences and it is also well established that even Mediterranean areas have experienced significant events of combined earthquake-tsunami actions. The 1908 Messina tsunami, triggered by a powerful earthquake, devastated southern Italy, causing many facilities and leaving a lasting memory to the Mediterranean regions' inhabitants. The focus of this research is to provide insights useful for more resilient infrastructure design standards for multi-hazard scenarios and effective mitigation measures. A probabilistic multi-hazard fragility assessment framework is presented to evaluate the structural vulnerability of bridges subjected to sequential earthquake and tsunami loads, since a significant increase in vulnerability occurs when seismic damage precedes tsunami loading, underscoring the need for integrated design and assessment strategies. The proposed methodology employs Monte Carlo simulations to account for uncertainties in tsunami forces and structural configurations, providing a statistically robust tool for vulnerability assessment. Representative bridge typologies from Mediterranean coastal zones are analyzed through a two-step process: nonlinear time-history analyses simulate seismic action, then force-controlled pushover analyses model tsunami impact. The simulation results have been examined to identify the most appropriate analytical lognormal-distributions capable of accurately representing structural fragility. A comprehensive comparison between the numerical results and the derived fragility functions has been conducted, confirming the robustness and precision of the proposed methodology.

Keywords: multi-hazard; tsunami vulnerability; bridges; Monte Carlo simulation; combined actions.

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1. Introduction

In recent decades, the vulnerability of coastal regions' built environment to seismic and tsunami events has garnered increasing attention due to the severe impacts of recent disasters [Oddo and Cavaleri (2025)]. Coastal areas, particularly those in the Mediterranean area, have historically been exposed to multi-hazard scenarios, where earthquakes often act as triggers for tsunamis (even if they can be caused by various natural hazards [Reid and Mooney (2023)]), as tragically demonstrated by the 1908 Messina event. This sequence of natural events not only increases the likelihood of damage but also highlights greater structural vulnerability, as prior seismic damage can significantly reduce the capacity of a structure to withstand subsequent tsunami forces.

An increasing number of studies have focused on the effects of tsunami loading on structures and infrastructure [Karafagka et al. (2018), Rahman and Billah (2023)], using numerical [Cavaleri et al. (2020)] but also experimental approaches [Seiffert et al. (2014), Hayatdavoodi et al. (2014)]. To this aim, fragility curves have been used for vulnerability assessment and risk mitigation [Suppasri et al. (2016), Horspool et al. (2014), Macabuag and Rossetto (2014)], but only a few advanced tsunami fragility analyses could account for the effects of prior seismic action. For example, Karafagka et al. (2018) focused on representative types of seaport structures in Greece, for which analytical tsunami fragility functions have been developed using nonlinear static tsunami analyses. While Petrone et al. (2017) concentrated on Reinforced Concrete (RC) structures for constructing tsunami fragility curves by the use of various analytical methods, including both nonlinear static and nonlinear dynamic analyses. But, since tsunami is often triggered by earthquake, the field literature has recently been filled with studies focused on assessing the tsunami fragility of structures and infrastructure under sequential earthquake-tsunami loading [Park et al. (2012), Petrone et al. (2020)]. Despite the growing interest within the scientific community in tsunami risk assessment - especially concerning critical infrastructure such as bridges - a comprehensive predictive framework is still lacking. Such a framework would enable the development of probabilistic damage models applicable to various structural typologies and tsunami scenarios, while accounting for the impact of preceding seismic damage. Although the development of seismic fragility curves is well established, tsunami fragility modeling remains an evolving field, still facing significant gaps and challenges.

In this field, the presented research aims to develop and discuss an advanced approach to investigate the vulnerability of bridges under sequential earthquake-tsunami events, to address a significant gap in the scientific literature, which often overlooks the interdependence between prior seismic damage and subsequent vulnerability to tsunami-induced forces. The proposed methodology is based on Monte Carlo simulations and allows for the integration of uncertainties related to tsunami loading and structural configurations. The analysis process involves a two-stage assessment: first, a nonlinear Time-History Analysis (THA) for seismic action, followed by a force-controlled Push-Over Analysis (POA) for tsunami loading. This sequential approach is crucial to realistically capture damage accumulation and structural capacity degradation. The study focuses on common bridge types in the Mediterranean coastal area.

The results provide valuable insights for refining multi-hazard assessments, highlighting the significant impact of earthquake-induced damage on tsunami vulnerability. A novel type of fragility curve is introduced for earthquake-tsunami interaction, accounting for the probability of collapse due to seismic action prior to tsunami impact. Moreover, analyses show that increasing seismic intensity reduces the inundation depth required for structural collapse. The consistency and effectiveness of the proposed methodology for constructing analytical fragility curves - well-fitted to lognormal distributions - are confirmed through comparative analyses. These findings provide meaningful contributions to advancing design approaches and emergency preparedness strategies.

2. Proposed framework for bridges' multi-hazard fragility

The proposed framework for the probabilistic assessment of bridge fragility under multi-hazard scenarios is specifically set for sequential earthquake-tsunami events. The probabilistic approach used is based on Monte Carlo simulations and allows for the integration of inherent uncertainties related to tsunami loading and structural configurations, providing a realistic assessment of bridge vulnerability. The entire multi-hazard framework has been implemented in Python using the OpenSeesPy library for structural analysis, optimizing computational efficiency and ensuring the integrity of the process. The analysis process is structured into two sequential phases: nonlinear THA for seismic action (it simulates the impact of an earthquake on the bridge model), then force-controlled POA for tsunami loading (it evaluates the performance of the damaged model under various tsunami loading conditions). These phases are preceded by the structural modeling: bridges are modeled as individual two-column bent, to represent the most common typologies in Mediterranean coastal areas.

2.1. Bridge Modelling

The procedure starts with the generation of twenty bridge models with randomly assigned geometric properties (Fig. 1), including pier height (h_p), circular column diameter (D), span length (L), deck width (B), and deck thickness (t), using uniform distributions within defined ranges, as exposed in Table 1.

Table 1. Geometric characteristics distributions for the random bridge's modelling.

	Random Variable	Range [m]
Bridge geometric characteristics	h_p	5 – 8
	D	0.8 – 1.5
	L	12 – 24
	B	6 – 10
	t	1.0 – 1.5

Each column is modeled as a nonlinear fiber-based beam-column element, with mass (m) concentrated at the top node, fixed bases and top left free to translate and rotate. Columns are connected by an infinitely rigid elastic beam column. Non linearities have been assigned to the section by assuming 'Steel02' uniaxial material for the steel fiber, and 'Concrete02' uniaxial material for confined and unconfined concrete, as shown in Table 2.

Table 2. Mechanical parameters of the material used in the modelling.

Steel 02		Concrete 02				
f_y	391 [MPa]	f_{pc}	Confined	39 [MPa]	Unconfined	30 [MPa]
E_0	210 [GPa]	f_{pcu}		7.8 [MPa]		6 [MPa]
b	0.01	f_t		5 [MPa]		4 [MPa]
R_0	15	E_{ts}		31 [GPa]		27 [GPa]
cR_1	0.925	ε_{c0}		0.0025		0.002
cR_2	0.15	ε_u		0.025		0.0035
		λ		0.1		0.1

2.2. Seismic analysis

The model randomly generated undergoes a THA, spectrum-compatible accelerograms are used, characterized by Peak Ground Acceleration (PGA) values (0.15g, 0.25g, and 0.50g), representative of the seismic conditions typical of Mediterranean regions, applied in the transverse direction of the bridge. The objective is to evaluate the severity of induced damage. At the end of this phase, if the model collapses during the THA the procedure proceeds with the generation of a new random model, skipping the tsunami phase, otherwise, if the model withstands the earthquake, the post-earthquake damage state is retained as the initial condition for the subsequent phase, that is the force-controlled POA for tsunami loading. This step is important to account for the possible initial damage of the bridge due to dynamic loading, which can cause a reduction of the structural capacity of the bridge before the tsunami forces act on its elements.

2.3. Tsunami loading analysis

This second phase is the one related to the tsunami forces, for simplification in this preliminary analysis, only hydrodynamic forces (F_d) are considered, calculated according to FEMA P-646 (2012) recommendations. Other tsunami-induced forces (e.g., impulsive forces, debris impact) are neglected. The hydrodynamic force is computed as:

$$F_d = \frac{1}{2}\rho D C_D \left(h v^2\right) \tag{1}$$

where ρ is the fluid density including the sediments (1100 kg/m^3), D is the column diameter, C_D is the drag coefficient (assumed to be 1.1), h is the inundation depth, and v is the flow velocity. Uncertainties in tsunami loading are introduced by generating random flow velocity (v) values (100 random velocity values are generated by selecting within a range defined by the Froude number (Fr), assumed between 0.7 (v_{min}) and 2.0 (v_{max})), for each inundation depth, which range is from 0.5 m up to 9.0 m, with 0.50 m increments.

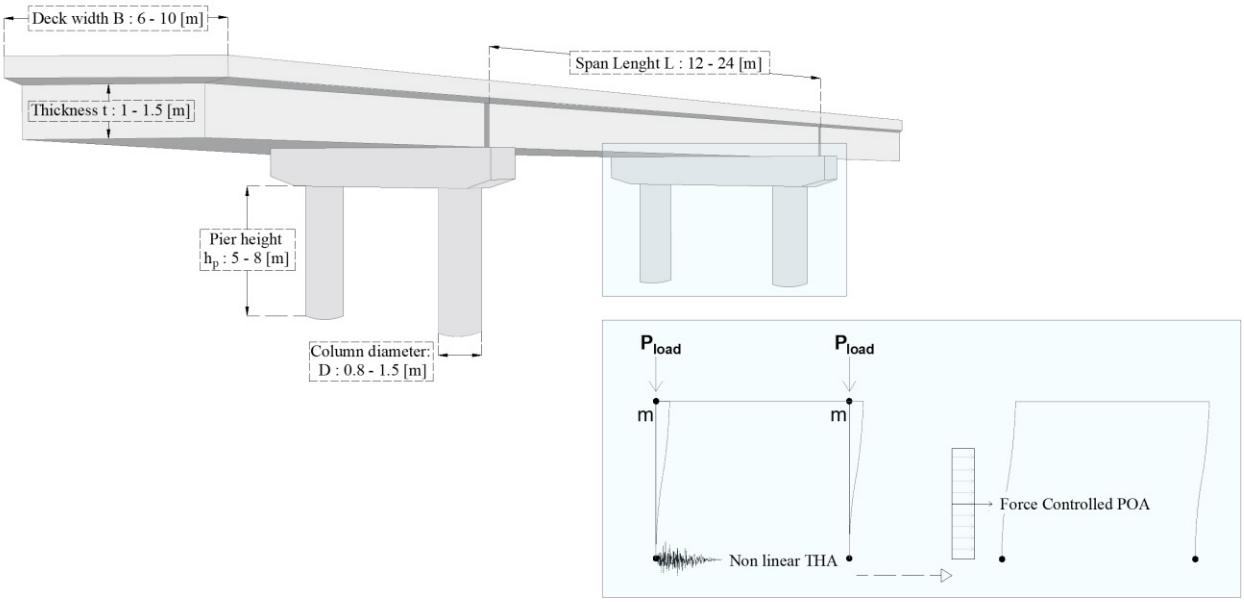


Fig. 1. Layout of the bridge model with random geometric characteristics and configuration of the bridge bent subjected to nonlinear THA and, once damaged, to a force controlled POA

2.4. Definition of collapse and derivation of multi-hazard fragility curves

Tsunami fragility is assessed by considering collapse as the limit damage state. Whenever the POA indicates structural failure, the corresponding inundation depth (h) leading to collapse is recorded. Data collected from Monte Carlo simulations are post-processed to obtain numerical fragility points and compute statistical parameters: namely, the mean (μ) and the standard deviation (β) of the logarithms of the inundation depths that caused collapse. Analytical fragility curves are then plotted assuming a lognormal distribution. An innovative aspect of this framework is the modification of the lognormal probability density function and cumulative distribution function to account for the percentage of models that collapsed solely due to seismic action, through a horizontal shift of the function as explained in the next section.

3. Collapse conditional probability density distribution

The derivation of the probability of collapse at various inundation depths, namely the collapse conditional probability density function (PDF), for combined earthquake–tsunami fragility plays a critical role in assessing structural vulnerability.

The process, based on Monte Carlo simulations, involves a sequential analysis: initially, a nonlinear THA is performed to simulate seismic action, then for those models that do not collapse due to the earthquake, a subsequent POA is conducted to evaluate the response under tsunami loading. During the POA phase, the inundation depth (h) that leads to structural collapse is recorded in a count vector.

Assuming a lognormal distribution for fragility, the mean (μ) and standard deviation (β) of the logarithms of the inundation depths causing collapse are computed. It is important to note that these parameters are calculated considering only the cases where the structure does not collapse due to prior seismic action.

The lognormal probability density function (f (x)) is defined using the formula:

$$f(x)=\frac{1}{\left(x+\bar{h}\right)\beta\sqrt{2\pi}}\exp\left(-\frac{\left(\ln\left(x+\bar{h}\right)-\mu\right)^{2}}{2\beta^{2}}\right) \tag{2}$$

Where x represents a new random variable, namely a new intensity measure, which, when added to $\bar{h}$, returns exactly the inundation depth:

$$h=x+\bar{h} \tag{3}$$

This fictitious probability density function is derived from the standard one, f (h), valid for values in the range 0.5 m - 9.0 m, by applying a horizontal shift equal to $\bar{h}$, in such a way that the area under the moved curve lying on the negative x-axis up to the 0.5 m value, h_0, corresponds exactly to the percentage of structures (k) collapsed solely due to seismic action, as in Fig. 2.

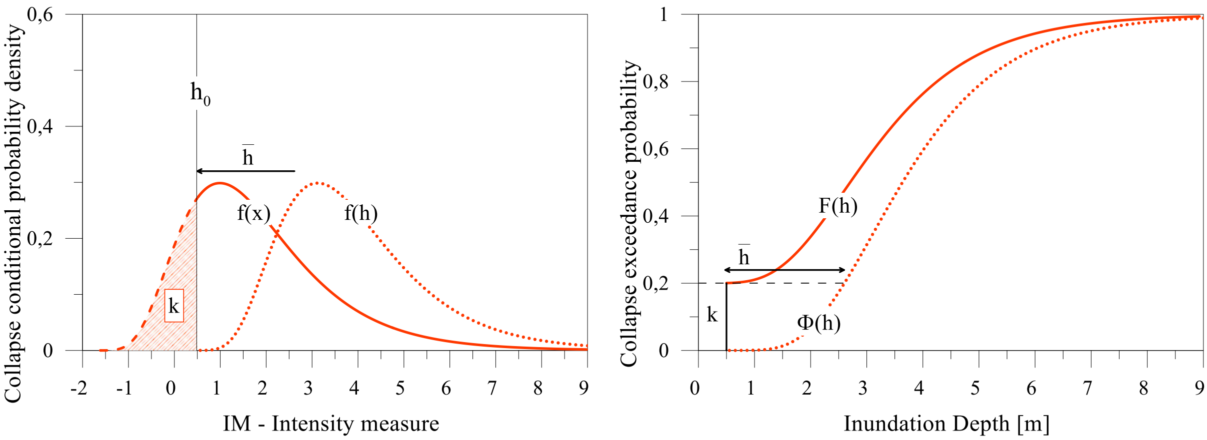


Fig. 2. (a) Standard and shifted collapse conditional probability density distribution; (b) Standard and modified fragility curve

To know the value of the shift should involve solving the following integral equation, that links the cumulative distribution function of the standard normal distribution, Φ(h), to k:

$$\Phi\left(\bar{h}+h_0\right)-\underbrace{\Phi\left(h_0\right)}_{0}=\int_{h_0}^{\bar{h}+h_0} f\left(h\right)dh=k \tag{4}$$

But this means that $\bar{h}$ can be easily found starting from the inverse of $\Phi\,(\bar{h}+h_0)$, $\Phi^{-1}(k)$, that is:

$$\Phi^{-1}(k)=\exp\left[\mu+\beta\sqrt{2}\left(\mathrm{erf}^{-1}(2k-1)\right)\right]=\bar{h}+h_0 \tag{5}$$

In order to clarify and for better comprehension, it's essential to define the modified cumulative distribution function F(h) that takes into account the percentage of models that collapse due to the earthquake:

$$F(h)=k+(1-k)\Phi(h) \tag{6}$$

This modified fragility curve, having k as the starting value, is related to the peculiar fictitious conditional density function described above, defined for a new random variable, x, dependent on the inundation depth, that helps in representing the probability of collapse due to the earthquake. This approach enables the generation of unconventional fragility curves that provide insights into both the probability of collapse due to seismic action and the influence of pre-existing seismic damage on tsunami vulnerability.

4. Results and comparison

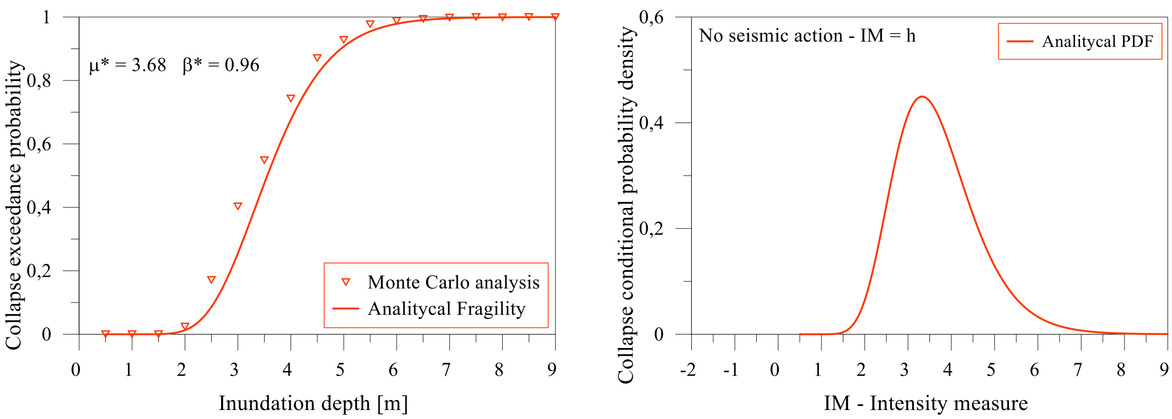
Statistical parameters of mean (μ) and standard deviation (β) of the logarithms of the inundation depths causing collapse and the percentage of collapses due to seismic action (k) have been used to derive the analytical collapse conditional probability density functions and fragility curves (Fig. 3), only the latter have been compared with the results obtained from the Monte Carlo simulations since PDFs are obtained backward after the fragilities are derived from Monte Carlo analyses. These analytical fragility curves are defined assuming a lognormal distribution, which has proven to be a reliable representation of the probability of collapse under tsunami loading.

In the following graphs standard collapse conditional probability density functions, f (h), and fragility curves, Φ(h), are also inserted to underline how the modified ones (by k in the case of fragility and by $\bar{h}$ in the case of probability) are capable to account for the percentage of collapses induced solely by seismic action.

The comparisons, performed for bridge pier models subjected to varying levels of seismic intensity (no earthquake, and with PGA = 0.15g, 0.25g, and 0.50g), confirmed the robustness and accuracy of the proposed methodology. The trend of the numerical fragility points closely aligns with the cumulative distribution functions of the lognormal model.

A distinctive feature of these fragility curves is the presence of a horizontal plateau at low inundation depths, representing the probability of collapse induced solely by seismic action before the tsunami effects manifest. As expected, the height of this plateau increases with the intensity of the earthquake: k = 0.15, namely 15% of collapses, occurred due to seismic action alone at a PGA of 0.15g, while k becomes 35% at a PGA of 0.50g.

This trend highlights the impact of seismic pre-damage on structural vulnerability: as the intensity of ground motion increases, structural components experience greater stiffness degradation and loss of load-bearing capacity. Consequently, the inundation depth required to trigger tsunami-induced collapse decreases with higher PGA levels.



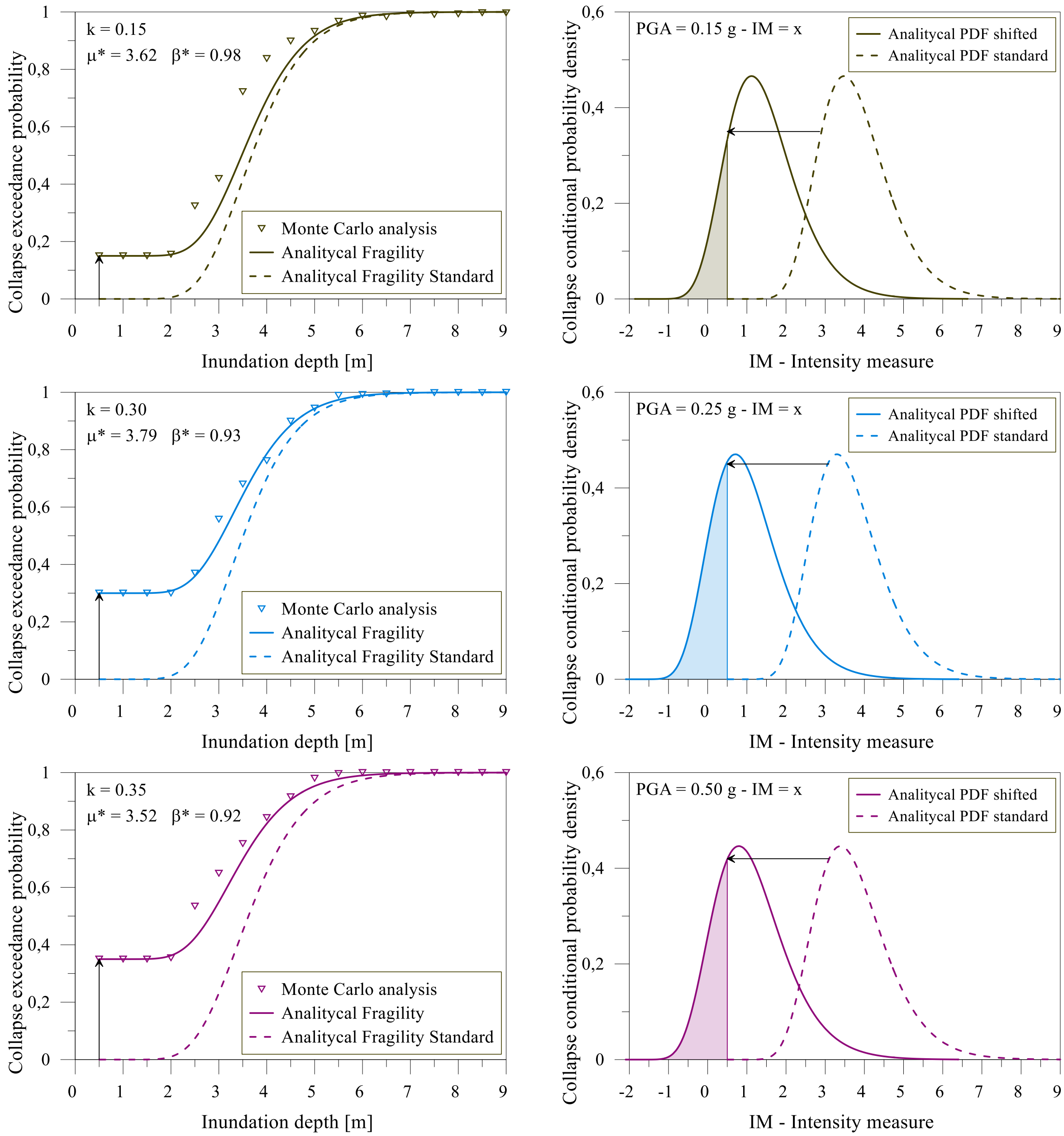


Fig. 3. Multi-hazard fragility curves and probability density functions in case of no seismic action, earthquake with a PGA equal to 0.15 g, earthquake with a PGA equal to 0.25 g, earthquake with a PGA equal to 0.50 g.

This result underscores the compounded effects of sequential hazards and reinforces the importance of accounting for earthquake-induced damage in tsunami fragility assessments to avoid significant underestimation of structural vulnerability in combined earthquake-tsunami scenarios. The analytical fragility curves visually demonstrate how increasing seismic intensity reduces the inundation depth required for structural collapse, emphasizing the need for an integrated approach to design and assessment strategies.

5. Conclusions

This research addresses the critical issue of the vulnerability of Mediterranean coastal bridges under combined multi-hazard scenarios, specifically sequential earthquake and tsunami actions. The primary objective was to provide valuable insights for the development of more resilient infrastructure design standards and effective mitigation strategies. The study highlights a significant gap in existing literature, which often overlooks the interdependence between prior seismic damage and the subsequent vulnerability to tsunami-induced forces. In response, a probabilistic framework for multi-hazard fragility assessment was proposed, employing Monte Carlo simulations to account for uncertainties in tsunami loading and structural configurations. It is based on a two-stage process: Nonlinear Time-History Analysis (THA) to simulate seismic action, Force-controlled Pushover Analysis (POA) to model the impact of tsunami loading on structures potentially pre-damaged by the earthquake.

Key findings include:

- A significant increase in vulnerability occurs when seismic damage precedes tsunami loading, underscoring the need for integrated design and assessment strategies.
- A novel type of fragility curve is introduced for earthquake-tsunami interaction, accounting for the probability of collapse due to seismic action prior to tsunami impact.
- Analyses demonstrated that increasing seismic intensity reduces the inundation depth required for structural collapse. This is reflected in the presence of a horizontal plateau in the fragility curves at low inundation depths, representing the probability of collapse induced solely by seismic action before tsunami effects occur.

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