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Kaynak Parametrelerindeki Değişkenliğin RVT Tabanlı Zemin Tepkisi Analizine Etkisi: Türkiye Ege Bölgesi Örneği

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Öz

Bu çalışmada, kaynak parametrelerindeki değişkenliğin özellikle gerilme düşümü (stress drop) ve anelastik azalım zemin tepkisi analizine etkisi, Rastgele Titreşim Teorisi (Random Vibration Theory, RVT) yöntemi kullanılarak araştırılmıştır. Analizler, Türkiye'nin Ege Bölgesi'nde yer alan temsili bir saha için, literatürde bildirilen dört farklı kaynak parametresi seti ile gerçekleştirilmiştir. Zemin profillerindeki belirsizliği temsil etmek amacıyla tek bir rastgeleleştirilmiş Vs profili seti kullanılmış, bu profiller tüm senaryolar için sabit tutulmuştur. Kaynak parametrelerine bağlı epistemik belirsizlik (τ_{kaynak}) yaklaşık 0.04 saniye civarında en yüksek değere ulaşmakta olup, bu durum yüksek frekanslı saha tepkisinin gerilme düşümü ve sönümleme parametrelerine duyarlılığını göstermektedir. Çalışma, Ege Bölgesi için kaynak parametrelerinden kaynaklanan epistemik belirsizliğin bölgesel olarak kalibre edilmiş bir nicelendirmesini sunmaktadır. Elde edilen bulgular, deprem tehlike analizlerinde kaynakla ilişkili belirsizliklerin dikkate alınmasının gerekliliğini vurgulamaktadır. Daha önceki RVT tabanlı çalışmaların çoğundan farklı olarak, bu çalışma gerilme düşümü ve sönümlemenin saha büyütmesi üzerindeki etkisini açık biçimde ayırıp nicel olarak ortaya koymakta ve epistemik belirsizliğe yeni bir katkı kaynağına işaret etmektedir. Gelecekteki çalışmalar, kaynak parametrelerinin Monte Carlo simülasyonunu içerecek şekilde genişletilerek olasılıksal sismik tehlike analizi (PSHA) uygulamalarına destek sağlamalıdır.

Anahtar kelimeler: Zemin tepki analizi, Kaynak parametreleri, Epistemik belirsizlik, Rastgele titreşim teorisi, Gerilme düşüşü, Anelastik azalma

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Effect of Source Parameter Variability on RVT-Based Site Response Analysis: A Case Study for the Aegean Region of Türkiye

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Abstract

This study investigates the influence of source parameter variability specifically stress drop and anelastic attenuation on site response analysis using the Random Vibration Theory (RVT) framework. Site amplifications were computed for a representative site in the Aegean region of Türkiye using four different source parameter sets based on regional literature. A single set of randomized Vs profiles was used to account for subsurface variability, while varying source models enabled the evaluation of epistemic uncertainty in site amplification. The epistemic uncertainty associated with source parameters, expressed as τ_{source}, peaks at approximately 0.04 **s**, reflecting the sensitivity of high-frequency site response to stress drop and attenuation. The study provides a regionally calibrated quantification of source-parameter-driven epistemic uncertainty for the Aegean region. The findings emphasize the need to account for source-related uncertainty in seismic hazard assessment. Unlike most previous RVT-based studies, this work explicitly isolates and quantifies the effect of stress drop and attenuation on site amplification, highlighting a novel contributor to epistemic uncertainty. Future work should incorporate Monte Carlo simulation of source parameters to support PSHA applications.

Keywords: Site response analysis, Source parameters, Epistemic uncertainty, Random vibration theory, Stress drop, Anelastic attenuation

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1. Introduction

Site response analysis plays a critical role in seismic hazard assessment and ground motion modeling, particularly in regions characterized by complex subsurface conditions. However, uncertainties in input parameters—including soil profiles, damping, and seismic source characteristics—can significantly affect predicted ground motions. Among these, the influence of source parameters, such as stress drop and anelastic attenuation, on site response remains a significant contributor to epistemic uncertainty yet, it is often underrepresented in logic tree frameworks [1-3].

Recent studies have emphasized the importance of characterizing both aleatory and epistemic components of site response variability. Rodriguez-Marek et al. [4] and Assimaki et al. [5] demonstrated that uncertainties in input motion and subsurface modeling can significantly affect predicted surface ground motions, especially through nonlinear response. These studies explored how the interaction between soil nonlinearity and input motion characteristics can lead to amplified variability in spectral ordinates. Additionally, [6] reviewed multiple sources of uncertainty in seismic ground response analysis, including soil property variability, damping assumptions, and input motion selection. However, these prior studies do not explicitly quantify the contribution of source parameters—such as stress drop or attenuation—to the overall uncertainty in site response. The present study addresses this gap by directly analyzing the sensitivity of site amplification to different source parameter combinations and estimating their contribution to epistemic uncertainty in the context of RVT-based analysis.

In recent years, several studies have revisited the treatment of epistemic uncertainty in site and source modeling within probabilistic seismic hazard frameworks. Rodriguez-Marek et al. [4] emphasized the need to explicitly capture epistemic components of site response through non-ergodic ground motion models, while Assimaki et al. [5] quantified the propagation of modeling uncertainties in nonlinear site response analyses. Similarly, Foti et al. [6] and Stewart et al. [3] discussed how epistemic variability can arise from differences in model assumptions, input motion characterization, and regional source properties. More recent efforts, such as those by Akıncı et al. [10] and Sandıkkaya et al. [8], have incorporated regional source parameter variability—such as stress drop, geometrical spreading, and attenuation—into simulation-based ground motion models for Türkiye, highlighting its importance in capturing realistic spectral variability. Despite these advances, the direct influence of source parameters on site amplification within an RVT-based framework remains largely unexplored, forming the main focus of the present study.

In this study, the influence of source parameter variation on site response is investigated using the Random Vibration Theory (RVT) framework implemented in Strata [7]. Rather than performing stochastic simulations, parameter values are selected based on region-specific literature for the Aegean region of Türkiye, particularly those compiled by Sandıkkaya et al. [8]. Stress drop and attenuation parameters are perturbed incrementally to evaluate their effect on site amplification, and later refined using representative stress drop and anelastic attenuation (Q) models for the region [9-11]. To represent subsurface uncertainty, the analysis incorporates randomized Vs profiles, following the statistical modeling frameworks Toro [12] and Al Atil et al. [13]. Randomization allows the analysis to account for natural geological variability and measurement uncertainty, which can otherwise bias predictions if a single deterministic profile is used [14-15]. Simulated Vs profiles for the Aegean basin are used to explore how site response behaves across different spectral periods under varied source conditions.

The results highlight the period-dependent sensitivity of site amplification to source parameters and quantify the epistemic uncertainty introduced by source variability, particularly in short-period ranges. While this study does not perform Monte Carlo simulation of source parameters, it establishes a methodology that can later be extended for use in PSHA logic trees, where branch weighting can reflect regional variability in stress drop and attenuation.

This framework contributes to a better understanding of source-driven uncertainty in site response. While previous studies have emphasized soil and input motion variability, the present study is novel in directly quantifying how source parameter variability (stress drop and attenuation) propagates into site amplification uncertainty within an RVT framework. This distinction is particularly relevant for western Türkiye, where tectonic diversity and sedimentary complexity demand more regionally tailored ground motion modeling.

2. Method

2.1. Overview

This study investigates the influence of source parameter variability on site amplification using a frequency-domain site response framework based on Random Vibration Theory (RVT). All simulations are performed using the open-source software Strata [7], which implements the RVT method for calculating one-dimensional equivalent linear site response (EQL). The goal is to quantify how changes in stress drop and anelastic attenuation affect the surface spectral acceleration when propagated through stratified soil columns representative of the Aegean region.

2.2. Source model and input motion

Input motion spectra are defined using the stochastic point-source model, which remains a widely used framework for modeling crustal earthquake sources. In this model, the Fourier amplitude spectrum of the ground motion is shaped by key source parameters such as the stress drop, attenuation, crustal amplification, and other factors. In this study, no Monte Carlo simulation is applied to source parameters. Instead, representative values are taken directly from the literature, focusing on region-specific studies compiled by Sandıkkaya et al. [8]. These include previous estimates of stress drop (Δσ) for the Aegean and Marmara regions derived from both ground motion modeling and empirical waveform studies [16-18].

- Δσ=80 bars for the 2020 Samos earthquake [10]
- Δσ=100 bars as a regional average [9]
- Δσ=190–250 bars for events such as the 2011 Simav and 2017 Karaburun earthquakes [18]
- Δσ=350 bars in a magnitude-dependent model for İzmir [11]

The RVT-based input motions in this study are generated using the ω^{-2} point-source model, which is suitable for representing the average spectral characteristics of moderate-to-large crustal earthquakes. While this formulation is most accurate for moderate magnitudes, it was intentionally retained for the present analysis to enable a controlled investigation of source parameter sensitivity (Δσ and Q) under a consistent theoretical framework. The selected magnitude ($M_w = 7.0$) represents a strong regional event for the Aegean zone and was used to examine how larger input amplitudes influence nonlinear response and site amplification trends. The results are therefore interpreted in a relative sense, highlighting the effects of varying source parameters, rather than as absolute predictions of a specific finite-fault rupture.

To explore the sensitivity of surface response to source variability, stress drop values were perturbed in increments of 10 bars. This increment was selected because it is small relative to the full variability range reported for western Türkiye (≈80–350 bars) yet large enough to produce noticeable spectral differences. Thus, it provides a practical balance between resolution and computational efficiency.

2.3. Attenuation models

The anelastic attenuation models $Q(f)$used in this study were selected from regional literature and represent the frequency-dependent path effects for crustal earthquakes in western Türkiye. The models vary between moderately and weakly attenuating conditions and are expressed in the general form $Q(f) = af^b$, where a and b are empirically derived coefficients. In the present analysis, a ranges from 170 to 190 and b from 0.45 to 0.64, consistent with the values proposed by Akıncı et al. [9], Kurtulmuş and Akyol [19], and Sandıkkaya et al. [8] for the Aegean region. These models are described in Table 1 and were verified to ensure internal consistency in notation and physical interpretation.

To explore regional variability, the anelastic attenuation function $Q(f)$ was further evaluated using empirical models proposed for both the Aegean and Marmara regions. According to [8], the Aegean region is characterized by higher Q values than Marmara, indicating lower attenuation. The models considered for the Aegean include: $Q(f)=190f^{0.64}$ [19] and $Q(f)=180f^{0.55}$ [9]. For contrast, typical Marmara models such as: $Q(f)=81f^{0.90}$ [17], $Q(f)=17f^{0.80}$ [20] and $Q(f)=180f^{0.45}$ [16] were not used in the main analysis but are referenced for regional context. Each Q(f) model was paired with different stress drop values in the input spectra to evaluate their combined effect on predicted amplification.

The two adopted attenuation models, $Q(f) = 180f^{0.55}$[9] and $Q(f) = 190f^{0.64}$[19], represent frequency-dependent behavior typical of the Aegean region. The latter has a higher intercept and stronger frequency dependence, resulting in greater attenuation at low frequencies and weaker attenuation at higher frequencies relative to the former. This distinction provides a useful contrast for assessing how different attenuation characteristics influence the site amplification.

2.4. Vs and damping randomization

To incorporate epistemic uncertainty in the subsurface characterization, randomized Vs and damping profiles were used in the analysis. The randomization process follows the procedure outlined by [7], which provides statistical models for shear wave velocity and damping variation that are appropriate for 1D site response analysis.

The Vs profile is randomized by assigning a log-normal distribution to the shear wave velocity of each layer, with a coefficient of variation (COV) typically ranging from 0.2 to 0.4 depending on material type. Perturbations are applied while maintaining the layer thickness and stratigraphic sequence, as this better reflects field conditions observed in geotechnical investigations. For damping, the same framework is used to define frequency-independent small-strain damping values. These randomized damping profiles are used as input in the RVT procedure, consistent with the linear analysis framework implemented in Strata.

This randomization scheme produces a statistically valid ensemble of Vs profiles that reflects both measurement uncertainty and natural variability in site conditions. In this study, the Vs profile was randomized once, independently of the source parameters. The same ensemble of velocity profiles was then used for all input motion scenarios (e.g., different combinations of stress drop and Q models), allowing a consistent evaluation of the effects of source variability on site amplification. This approach isolates the influence of source parameters while still accounting for subsurface uncertainty. The randomized ensemble and the median profile are shown in Figure 1.

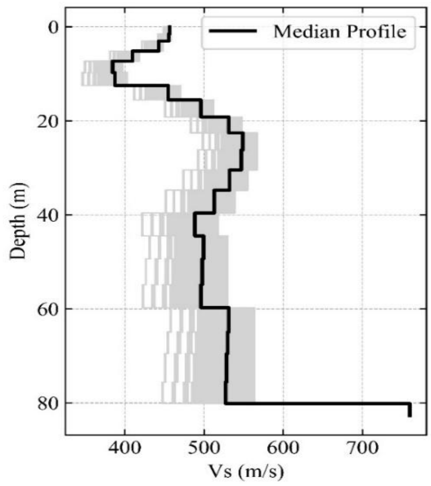

Figure 1. Randomized shear wave velocity (Vs) profiles used in the site response analysis. Grey lines represent 100 realizations generated based on statistical variability. The thick black line shows the median Vs profile used for reference

2.5. Site characterization and source scenarios

The analysis was conducted using a representative shear wave velocity (Vs) profile for the Aegean region of Türkiye, where complex tectonics and thick sedimentary basins strongly influence site amplification. The selected profile reflects basin-edge stratigraphy, which is common in areas of the region where strong impedance contrasts exist between shallow alluvium and deeper bedrock layers. This profile was randomized using the procedure described in Section 2.4 to account for subsurface variability.

The input motions used in the RVT-based site response simulations correspond to a moment magnitude M_w = 7.0 earthquake at an epicentral distance of 30 km, representative of strong crustal events that may impact western Türkiye. The scenario is anchored to station 3524 (Karşıyaka-İzmir), a recording site. This station was selected because it is representative of stiff-soil sites in the Aegean region and provides a suitable test case for evaluating EQL assumptions. One of the objectives is to assess whether shear strain levels remain within acceptable thresholds for EQL assumptions-particularly that strain levels do not exceed 0.1%, as will be discussed in later sections. The site corresponds to a limestone rock formation, and the analysis employed the EPRI [21] generic rock amplification curve to represent reference rock site conditions in the RVT framework.

To evaluate the influence of source characteristics on site response, four distinct source parameter sets (S1–S4) were defined using combinations of stress drop and anelastic attenuation values compiled from regional studies. These models are summarized in Table 1 and were chosen to span a realistic range of source behavior observed in the Aegean region [8-10,19].

Table 1. Scenarios and model parameters used in this study

Source	Q Model	Stress Drop (bar)
S1	$190f^{0.64}$	80
S2	$180f^{0.55}$	80
S3	$190f^{0.64}$	100
S4	$180f^{0.55}$	100

3. Results

3.1. Strain profiles and validity of eql assumption

Before analyzing the effect of source characteristics, shear strain profiles were examined to verify the applicability of the EQL method under the selected ground motion scenario. Figure 2 shows the maximum strain distribution with depth for different stress drop and Q models. For all cases, the strain levels remain below 0.03%, with most profiles peaking at or below 0.01%, which supports the use of the EQL framework in this study. The selected site (station 3524) lies on relatively stiff soil, which further reduces the potential for nonlinear response for the imposed input motions.

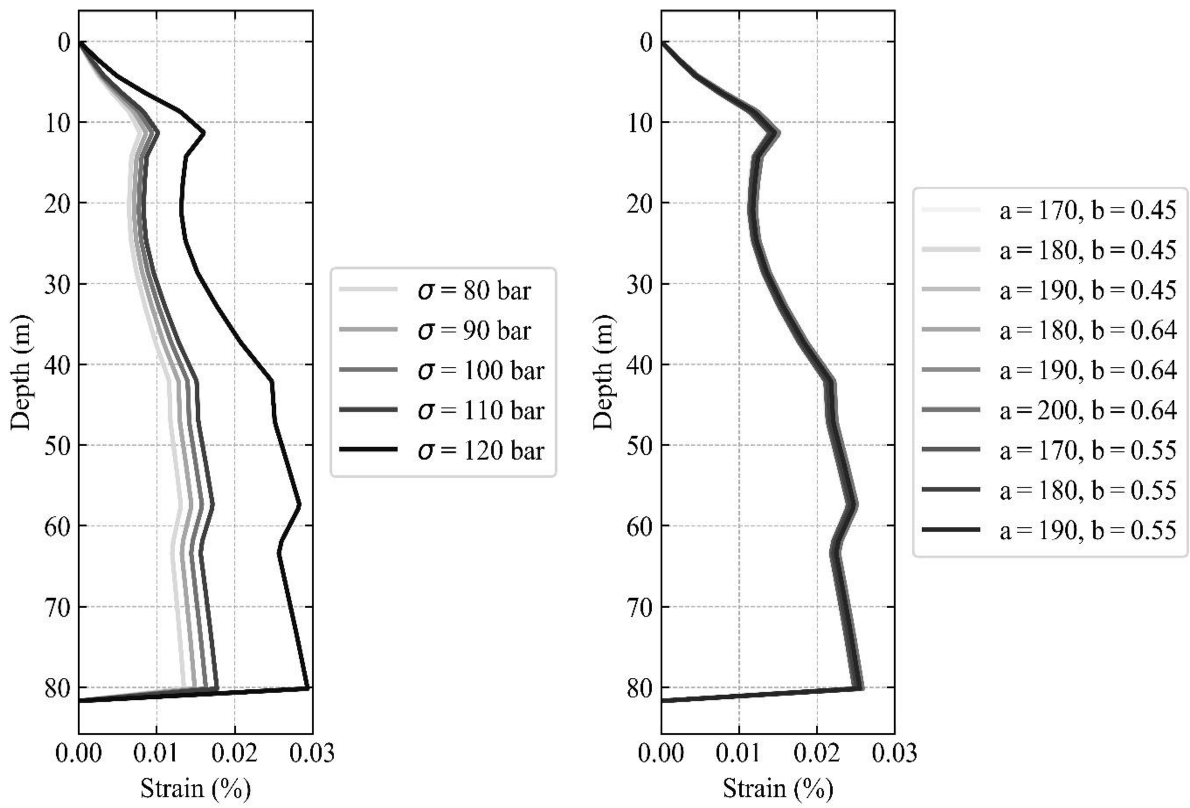

Figure 2. Maximum shear strain distribution with depth for varying stress-drop values (left) and Q models (right). For the stress-drop variation, the Q model parameters are fixed at $a = 180$ and $b = 0.45$. For the Q variation, the stress drop is set to 100 bar. All profiles remain below 0.03%, confirming the validity of the equivalent-linear (EQL) analysis

3.2. Effect of stress drop and anelastic attenuation on amplification

The sensitivity of the site amplification to stress drop and anelastic attenuation (Q) is shown in Figure 3. Increasing the stress drop from 80 to 120 bars results in higher amplitude input motions, which in turn induce stronger nonlinear behavior in the soil profile. This leads to reduced amplification at short periods (< 0.2 s) due to increased damping and shear modulus degradation. Conversely, lower stress drop levels are associated with smaller input amplitudes, resulting in a more linear site response and thus higher amplification at short periods.

Variations in the Q model also influence spectral shape, particularly for periods below 0.1 s. Figure 3 (bottom panel) shows how higher Q (i.e., less attenuation) leads to higher short-period amplification, while stronger attenuation (lower Q) yields smoother, damped amplification curves. These findings highlight the period-dependent sensitivity of amplification to source parameters.

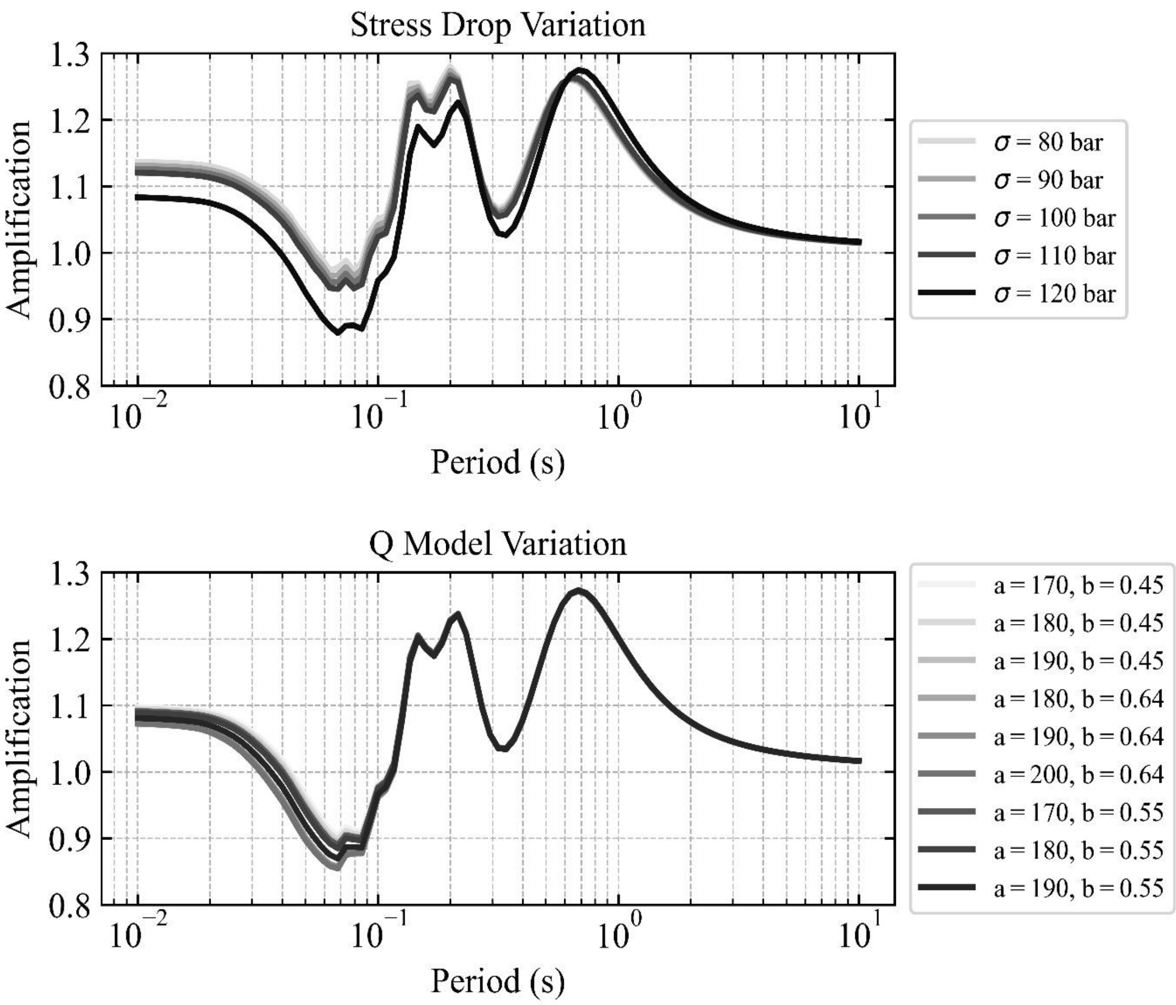

Figure 3. Site amplifications for varying stress drop (top) and Q models (bottom). Grey scale indicates increasing parameter values). For the stress-drop variation, the Q model parameters are fixed at $a = 180$ and $b = 0.45$. For the Q variation, the stress drop is set to 100 bar

3.3. Combined source effects in the aegean region

To evaluate the practical implications of source parameter variability, four representative source scenarios (S1–S4) were simulated for an $M_w = 7.0$ earthquake at an epicentral distance of 30 km. These scenarios reflect realistic combinations of stress drop and anelastic attenuation drawn from previous studies of crustal events in western Türkiye, particularly the Aegean region, as detailed in Sections 2.2 and 2.3. The selected values span the typical range observed in empirical and simulation-based models for the region and are summarized in Table 1. Figure 4 shows the resulting site amplifications, with grey lines indicating individual realizations from randomized Vs profiles and colored lines representing the median response for each scenario.

S1 and S2 use a lower stress drop (σ = 80 bars) with different Q models, while S3 and S4 increase stress drop to 100 bars. Results indicate that higher stress drop produces lower short-period amplification due to increased nonlinearity. Changes in Q primarily influence the overall amplitude across the spectrum rather than shifting specific peak frequencies. Scenario S2 (red), which combines lower stress drop with weaker attenuation, results in the highest short-period amplification, particularly below 0.2 s, due to the predominantly linear soil response. In contrast, scenarios S3 and S4 with higher stress drop exhibit reduced short-period amplification driven by increased input motion amplitude and corresponding nonlinear effects. The differences among the scenarios diminish at longer periods (>0.5 s), where site response becomes less sensitive to both source characteristics and soil nonlinearity.

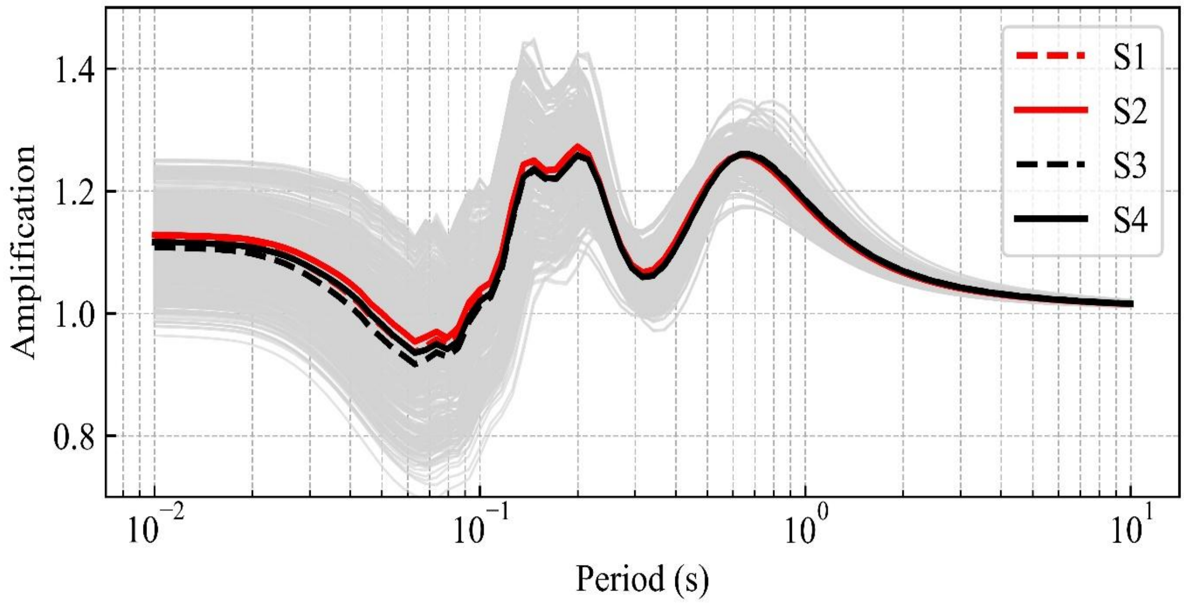

Figure 4. Site amplification for four source scenarios (S1–S4). Grey lines show 100 Vs realizations; colored lines represent median curves. Red indicates low σ/high Q (S2), and dashed lines correspond to site 3524

3.4. Quantifying epistemic uncertainty from source parameters

The final analysis focuses on quantifying the epistemic uncertainty in site response due to source parameter variability. Figure 5 presents the period-dependent standard deviation computed from the logarithmic difference between the four scenario means. The results show a clear peak around 0.03–0.04 s, where uncertainty reaches its maximum (≈0.04). This range represents the high-frequency part of the motion spectrum, where the variability is primarily governed by source radiation and attenuation characteristics, rather than soil nonlinearity. The influence of stress drop and Q is most pronounced at these short periods, where high-frequency content dominates. Beyond 0.09 s, the uncertainty declines rapidly, suggesting that long-period site amplification is less sensitive to source variability.

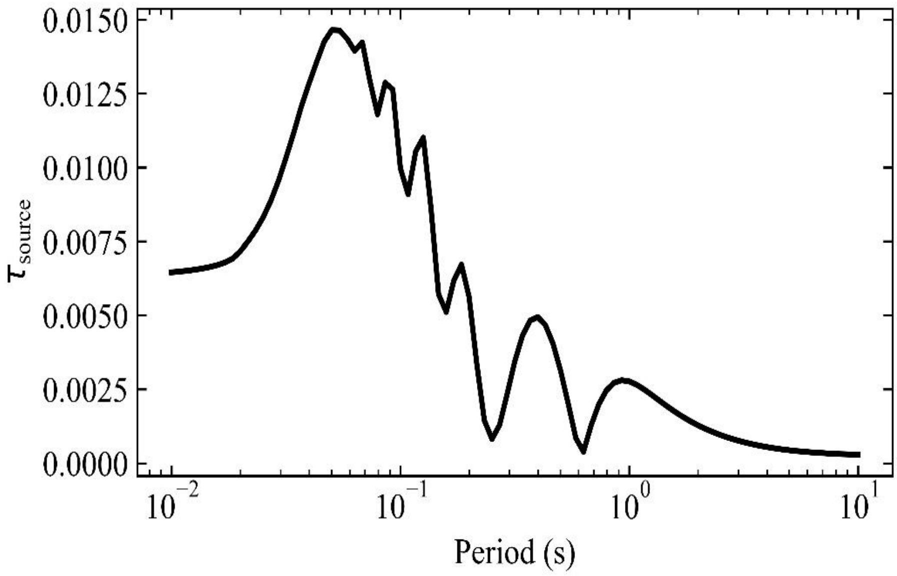

Figure 5. Epistemic uncertainty in site amplification due to source parameter variation, expressed as the standard deviation across the four source scenarios. Uncertainty is largest near 0.2 s and minimal at long periods

4. Discussion

This study demonstrates that variability in source parameters particularly stress drop and anelastic attenuation (Q) can significantly influence the site amplification, especially at short periods (< 0.3 s). Using four representative source parameter sets drawn from the literature, the analysis quantifies how these variations impact the predicted amplification and the associated epistemic uncertainty in site response.
The results confirm that even modest changes in source parameters (e.g., ±20 bars in stress drop) can shift spectral amplification curves. These findings reinforce the need to represent source variability in site response analysis—not only as a modeling detail, but as a key driver of uncertainty.

In this study, the epistemic uncertainty was estimated from just two discrete branches for each parameter (i.e., low and high stress drop; low and high Q). While sufficient to demonstrate sensitivity trends, this simplification likely underrepresents the full extent of source variability. Stress drop and Q distributions are continuous, and their interaction with other parameters (e.g., geometrical spreading, kappa etc.) adds further complexity. It is acknowledged that the present analysis considers only four discrete source parameter scenarios (S1–S4). While this approach captures the representative range of stress drop and attenuation models reported for the Aegean region, it likely underestimates the full spectrum of possible source variability. The epistemic uncertainty values derived here should therefore be viewed as lower-bound estimates. Future work will expand the analysis to incorporate a larger number of source realizations through Monte Carlo simulations or logic-tree sampling of stress drop, geometrical spreading, and attenuation parameters to obtain a more comprehensive quantification of source-related uncertainty for PSHA applications. This approach would allow for a more comprehensive quantification of uncertainty across the period range and help define branch weights in logic-tree-based seismic hazard models. Additionally, this method could be extended to other site conditions or regional tectonic environments.

5. Conclusions

This study investigated the influence of source parameter variability specifically stress drop and anelastic attenuation on site amplification using the RVT-based equivalent-linear site response framework. The results show that both parameters significantly affect short-period amplification, with increasing stress drop leading to higher input motion amplitudes and enhanced nonlinear behavior, thereby reducing surface amplification. Randomized Vs profiles, applied consistently across all source scenarios, enabled an independent assessment of source effects while accounting for subsurface uncertainty.

- Stress drop significantly affects short-period amplification, with peak variability observed between 0.02–0.1 seconds.
- Randomized Vs profiles, held constant across all input scenarios, allowed the effects of source parameter variations to be evaluated independently of site condition variability.
- The epistemic uncertainty introduced by stress drop and Q variation reached a maximum of approximately 0.015 in log units near 0.2 s and diminished toward longer periods. This magnitude of uncertainty, while modest, is comparable to other secondary sources of variability considered in hazard models.
- The quantified epistemic uncertainty τ_{source} reached approximately 0.015 in log units, peaking around 0.04 s, highlighting the short-period sensitivity of site amplification to source variability. The study's novelty lies in explicitly evaluating source-parameter-driven epistemic uncertainty within an RVT framework for the Aegean region—a topic that has been largely overlooked in previous literature.
- The selected site (station 3524) showed strain levels below 0.03%, validating the use of EQL analysis for this scenario.
- The omission of finite-fault and directivity effects is acknowledged as a limitation, and their inclusion is recommended for future extensions of this work.

Although only four source combinations were analyzed here, the framework provides a foundation for integrating source-driven uncertainty into site-specific and regional hazard assessments. Future work should incorporate Monte Carlo simulations of source parameters to better capture the underlying distributions and propagate them through PSHA logic trees.

6. Author Contribution Statement

The author confirms sole responsibility for the following: conceptualization, methodology, formal analysis, software development, visualization, writing-original draft preparation, writing-review and editing.

7. Ethics Committee Approval and Conflict of Interest

"Ethics committee permission is not required for the prepared article" "
There is no conflict of interest with any person/institution in the prepared article."

8. Ethical Statement Regarding the Use of Artificial Intelligence

No artificial intelligence-based tools or applications were used in the preparation of this study. The entire content of the study was produced by the author in accordance with scientific research methods and academic ethical principles.

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