

Article

Seismic Soil Amplification in a Thick Alluvial Basin: One-Dimensional Site Response Analysis for Afyonkarahisar, Türkiye

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Abstract

Recent destructive earthquakes have clearly demonstrated that damage distribution in many cities developed on thick alluvial deposits is strongly controlled by local soil amplification and site response effects. Soil conditions therefore play a critical role in determining the characteristics of ground motion and the seismic performance of structures during earthquakes. This study presents the first microzonation-oriented site response assessment for the rapidly urbanizing city of Afyonkarahisar, which is characterized by thick alluvial deposits and a shallow groundwater table. A database consisting of 124 boreholes was compiled to characterize the subsurface stratigraphy of the study area. Shear-wave velocity profiles were verified using both SPT-based correlations and MASW measurements to ensure reliable input parameters for dynamic analyses. One-dimensional equivalent linear and nonlinear site response analyses were performed using the DeepSoil program, employing eleven earthquake ground motion records scaled according to the Turkish Building Earthquake Code. The results indicate that for Earthquake Level-1 (EL-1; 2% probability of exceedance in 50 years) ground motions, nonlinear analyses produce lower amplification factors (1.00–1.62), whereas equivalent linear analyses tend to predict higher amplification values, reaching up to 4.52, owing to their simplified treatment of soil nonlinearity. Under Earthquake Level-2 (EL-2; 10% probability of exceedance in 50 years) motions, both methods yield comparable amplification values ranging from 1.18 to 1.72. GIS-based amplification maps reveal significant spatial variability within the study area and identify zones where local soil conditions may substantially increase seismic demand. The findings suggest that nonlinear site response analysis is more appropriate for representing soil behavior under strong ground motions (EL-1), while both approaches provide comparable results for moderate ground motions (EL-2). Comparisons with Eurocode 8 and NEHRP site classifications further confirm the broader applicability of the results. Overall, this study provides a practical framework for reliable site response assessment that supports earthquake-resistant design and microzonation studies in seismically active regions characterized by complex alluvial environments.

Keywords: seismic soil amplification; site response analysis; nonlinear analysis; equivalent linear analysis; alluvial basin; GIS-based microzonation



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1. Introduction

Strong ground motions can lead to catastrophic events depending on local soil and geotechnical characteristics. Local geological and geotechnical conditions significantly influence the amplitude, frequency content, and duration of seismic waves; variations in soil deposits can either strengthen or weaken ground shaking. While the characteristics of the earthquake source and faulting mechanisms are critical, geological formation and local site conditions are generally the dominant factors controlling the seismic response [1–3]. The extent of structural damage during earthquakes is primarily determined by three parameters: (i) earthquake source characteristics, (ii) local soil conditions, and (iii) super-structure characteristics. The interaction between these factors alters the surface ground motion characteristics, leading to spatial variability in damage distribution. Therefore, earthquake-resistant building design must simultaneously consider resource characteristics, local site conditions, and structural characteristics [2,4–8].

In recent years, interdisciplinary collaborations among geotechnical, geological, and structural engineers have improved our understanding of earthquake–soil–structure interactions. These studies highlight the importance of estimating earthquake ground motion parameters and analyzing soil behavior accordingly to minimize human and economic losses. Modeling earthquake motion along with site-specific soil response has proven crucial in designing resilient structures [9,10]. Among site effects, soil amplification is one of the most critical seismic hazards. Seismic waves generated in the bedrock are altered by the mechanical properties of the overlying soil layers, causing increased shaking intensity at the surface. Initially small accelerations in the bedrock can increase several times under unfavorable soil conditions, leading to serious structural damage [11]. The 1999 Adapazarı earthquake in Türkiye provided striking evidence of this phenomenon; here, alluvial soil deposits significantly intensified the ground shaking and caused liquefaction in saturated grain soils, leading to tilting and settlement in otherwise sound structures [12,13]. Recent major earthquakes in Turkey have also once again highlighted the decisive role of local soil conditions in earthquake damage. In particular, studies conducted after the Mw 7.7 Pazarcık and Mw 7.6 Elbistan earthquakes on 6 February 2023 have shown that ground amplification, basin effects, and high ground accelerations play a significant role in the concentration of damage in areas located on thick alluvial units and soft soils [14–16]. Furthermore, studies based on field observations and dynamic analyses have revealed that local soil conditions can significantly amplify ground motion, and this is consistent with the damage observed, especially in medium- and high-rise buildings [17,18]. Similarly, geotechnical and structural assessments conducted after the earthquake also show that the distribution of damage is closely related to local soil conditions [19]. These findings reveal that site-specific site response analyses are critical for accurate assessment of earthquake hazard in developed settlement areas on alluvial soils [20].

Therefore, the extent of earthquake-induced damage is a combined function of seismic activity, structural properties, and soil conditions [21]. Site-specific analyses are generally performed to determine soil response spectra and evaluate ground motion changes. Soil response depends on the material properties of the bedrock, geometry, and dynamic properties of soil layers [22]. Liquefaction and soil amplification are direct consequences of soil–wave interactions caused by the propagation of seismic waves from the bedrock to the ground surface [23]. The most commonly used approach in evaluating such changes is one-dimensional (1D) dynamic site response analysis, where seismic wave propagation from horizontal soil layers is modeled with shear-wave transfer functions [24,25]. Despite being simplified, one-dimensional analyses have proven to provide conservative and reliable predictions for engineering applications, and many designs based on such analyses have demonstrated satisfactory performance in past earthquakes [2,17,26–35].

However, shallow sediments with low bearing capacity often exhibit destructive ground behavior when subjected to dynamic loading [36]. Therefore, microzonation studies integrating geological, geotechnical, and seismic data play a critical role in settlement planning and disaster mitigation efforts [37]. Geographic Information Systems (GIS) have become an important tool for storing, analyzing, and visualizing the results of such studies. Recent field response surveys worldwide confirm the necessity of one-dimensional (1D) analyses to capture the impact of local ground behavior [20,38–44]. Therefore, microzonation studies, supported by site-specific site response analyses, are of great importance for accurate assessment of seismic hazard and ensuring safe engineering design, especially in urban areas with thick alluvial units. Afyonkarahisar, located in western Türkiye, is one such region where settlements are predominantly covered by alluvial deposits carried by the Akarçay River over centuries. Historical evidence, including the 1999 Kocaeli earthquake, has revealed that similar soils are highly susceptible to amplification and liquefaction, causing significant building damage [45]. The soil profile of Afyonkarahisar typically consists of silty clay and sandy soils with shallow groundwater levels, creating unfavorable conditions for seismic loading [46]. Many studies have confirmed that such alluvial deposits can significantly alter incoming seismic waves, further justifying the need for detailed dynamic characterization of this region [47–52].

To address this research gap, the present study aims to evaluate the ground amplification characteristics of the Afyonkarahisar city center using both equivalent linear and nonlinear one-dimensional ground response analyses. This study involved selecting representative bedrock movements, scaling 11 earthquake records determined in accordance with international building codes for the Earthquake Level-1 and Earthquake Level-2 design levels defined in the Turkish Building Earthquake Code [53], generating general shear-wave velocity profiles using existing field and laboratory data, and performing equivalent linear and nonlinear ground response analyses using DeepSoil software. The originality of this study lies in it representing the first systematic evaluation of the ground amplification potential of the Afyonkarahisar city center using a comprehensive geotechnical database and multiple analytical approaches. Furthermore, the obtained results were integrated with Geographic Information System (GIS)-based amplification maps generated using ArcGIS 10.7.1 (Esri, Redlands, CA, USA) to reveal the spatial variability in local soil conditions and their influence on seismic behavior. This approach is expected to make significant contributions not only to Afyonkarahisar but also to seismic microzonation studies and earthquake-resistant urban planning strategies to be carried out in alluvial basins with similar geological characteristics.

2. Seismotectonic and Geological Setting

Afyonkarahisar and its surroundings are located within the borders of the Aegean Region, at the intersection of Central Anatolia and the Aegean. Tectonically, the province has been subjected to the extensional seismic regime of the Aegean Region, and numerous earthquakes have occurred in different periods [54]. The updated Active Fault Map of Turkey (2011) indicates that several active fault segments exist within the system extending from Simav to Sultandağı, which significantly affect the young grabens and associated basins (Figure 1). The Afyon–Akşehir Fault System (AAFS) extends approximately 400 km, from Sındırgı in the west to Ilgın in the east. The northwestern part of the AAFS consists of seven right-lateral strike-slip fault segments, while the southeastern part is characterized by an active depression zone trending NW–SE, with an average segment length of 30 km and a total length of about 130 km [55–58].

laboratory tests, including natural water content determination, Atterberg limits, grain-size distribution (sieve analysis), and uniaxial compression tests.

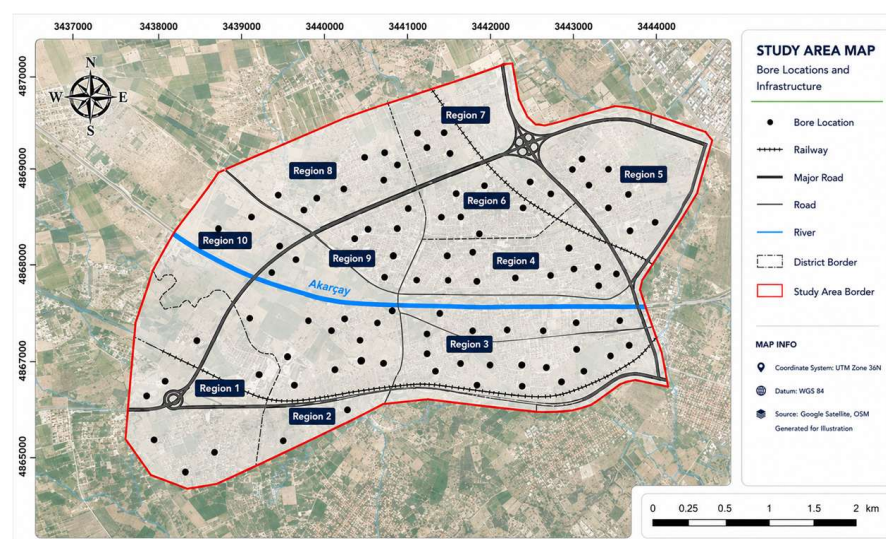


Figure 2. Inspection area and general distribution of drilling points.

Based on the laboratory results, soil layers were classified according to the Unified Soil Classification System (USCS), and a depth-dependent geological profile of the study area was established. The stratigraphic sequence generally consists of high-plasticity clays (CH) and low-plasticity clays (CL) within the 0–7.5 m depth range, silty sands (SM) and clayey sands (SC) between 7.5 and 18 m, and again high- and low-plasticity clays (CH–CL) between 18 and 20 m depth (Table 1).

Table 1. Idealized soil profile of the study area.

Depth (m)	Soil Class	SPT Values (N ₃₀)	Vs (m/sec) İyisan, 1996 [66]	MASW (m/sec)	% Difference
1.50–1.95	CH-CL	14	201	200	−0.5
3.00–3.45	CL-CH	14	201	203	1.0
4.50–4.95	CL-CH	14	201	206	2.49
6.00–6.45	CL-CH	15	208	212	1.92
7.50–7.95	SM	17	222	225	1.35
9.00–9.45	SM-SC	17	222	229	3.15
10.50–10.95	SM-SC	20	242	245	1.24
12.00–12.45	SM-SC	21	248	254	2.42
13.50–13.95	SM	22	254	259	1.97
15.00–15.45	SM	21	248	260	4.84
16.50–16.95	SM	22	254	259	1.97
18.00–18.45	CL-CH	16	215	228	6.05
19.50–19.95	CL-CH	13	193	208	7.77

To verify the reliability of correlation-based shear-wave velocity (Vs) estimates, geophysical investigation data were incorporated into the study. In addition to the empirical Vs values derived from SPT-N correlations [66], Multichannel Analysis of Surface Wave (MASW) measurements conducted by private companies in the Afyonkarahisar region were used for validation purposes. Table 1 presents the comparison between the two datasets, indicating differences typically ranging between 2 and 15 m/s. This close agreement demonstrates that the correlation-based Vs estimates are consistent with the field measurements, thereby increasing the reliability of the dynamic soil profiles used in the analyses.

To verify the reliability of the correlation-based shear-wave velocity (V_s) estimates, geophysical investigation data were incorporated into the study. Rather than relying solely on the MASW measurements, the empirical V_s values derived from the SPT-N correlation proposed by Iyisan [66] and the MASW-derived V_s values were jointly evaluated and calibrated to establish representative shear-wave velocity profiles. The MASW surveys were conducted at each investigation location as part of the original site investigation program by a professional geotechnical and geophysical survey company, and the comparison presented in Table 1 was performed using corresponding depths where both SPT and MASW data were available. The close agreement between these two independent datasets provided additional confidence in the calibrated shear-wave velocity profiles adopted for the site response analyses.

The integration of both geotechnical and geophysical datasets provides a more comprehensive representation of subsurface conditions, reduces uncertainty, and enhances the overall reliability of the site response analyses. The water content of the collected samples ranges between 6.58% and 40.43%, while the natural unit weights vary between 15.27 and 19.93 kN/m³. A summary of the field and laboratory test results is presented in Table 2.

Table 2. General test results of laboratory experiments.

Soil Layers (m)		0–7.50	7.50–18.00	18.00–19.95
General Soil Class		CH-CL	SM-SC	CH-CL
Fine-grained rate (%)	Min.	61.36	4.95	70.66
	Max.	97.96	31.15	85.52
	Mean	79.89	19.53	78.93
Coarse-grained rate (%)	Min.	13.78	58.42	11.78
	Max.	26.86	95.81	33.36
	Mean	20.11	80.66	21.07
Liquid limit (LL, %)	Min.	26.00	0.00	30.60
	Max.	69.70	36.47	72.50
	Mean	48.60	11.92	51.20
Plastic limit (PL, %)	Min.	12.00	0.00	13.60
	Max.	34.60	23.70	31.70
	Mean	23.30	7.64	22.60
Water content (w, %)	Min.	6.58	19.60	23.90
	Max.	20.40	40.43	34.20
	Mean	14.80	30.20	26.37
Unit weight (kN/m ³)	Min.	15.27	16.89	15.73
	Max.	17.75	18.56	19.93
	Mean	16.50	17.69	18.13

In addition, data obtained from five deep groundwater boreholes drilled by the State Hydraulic Works (SHW) were also included in the evaluation. These boreholes show that the first approximately 100 m of the subsurface consists mainly of sand, sandy–silty clay, and clayey sediments. Below this level, at a depth of approximately 251 m, more stable rock units such as trachyandesite are reached. These findings reveal the presence of a thick alluvial sediment sequence in the study area and that the bedrock level is located quite deep.

4. One-Dimensional Site Response Analysis

DeepSoil, developed and continuously updated by the University of Illinois Urbana-Champaign, is one of the widely used one-dimensional (1D) soil response analysis tools

in geotechnical earthquake engineering [67]. The program simulates seismic wave transmission from the bedrock to the surface using wave propagation models based on the assumption that the soil profile consists of infinite horizontal layers exhibiting viscoelastic behavior. While this approach does not fully represent the complexity of real soil conditions, it is widely preferred in engineering applications due to its practicality and reliability. DeepSoil converts input base motions into the frequency domain using the Fast Fourier Transform (FFT) algorithm, propagating these motions along the soil column to calculate the soil response at the surface.

The main reason for choosing DeepSoil software in this study is its capability to perform both equivalent linear and nonlinear site response analyses within the same computational framework. The combined use of these approaches enables a comprehensive assessment of strain-dependent soil stiffness degradation and damping evolution. As suggested by Ding et al. [68], considering both methods together helps reduce uncertainties in site response analyses and provides a more robust evaluation of local site effects.

One-dimensional field response analyses yield particularly effective results in cases where the soil profile is horizontally layered and lateral variability is limited. Since alluvial basins are often characterized by such layered soil structures, 1D field response analyses are widely used due to their computational efficiency and proven reliability in engineering applications. Therefore, a one-dimensional field response approach was adopted in this study to evaluate the dynamic behavior of thick alluvial deposits located in the city center of Afyonkarahisar.

Nonlinear analysis requires more advanced soil behavior modeling compared to the equivalent linear approach. In this method, shear modulus and damping values are updated iteratively depending on the shear stress level for each soil layer. Although modeling the dynamic behavior of soils is challenging because of the complex interactions among soil particles and their strain-dependent response, nonlinear analysis explicitly accounts for stiffness degradation and damping evolution with increasing shear strain. Therefore, the variation in ground motion along the soil column may differ between equivalent linear and nonlinear analyses, and both approaches have their own assumptions, advantages, and limitations.

Although the SHW deep boreholes indicated that the geological bedrock was located at approximately 251 m depth, the numerical soil profiles were developed using the available site-specific geotechnical and geophysical data. The upper 20 m of each profile was established through joint evaluation and calibration of SPT-N values and measured shear-wave velocity (V_s) data. Between 20 and 30 m depth, where detailed SPT data were unavailable, the soil profile was completed using the available V_s measurements. Below 30 m, the underlying material was modeled as an elastic half-space. The site response analyses were performed in DeepSoil using Outcrop Motion as the input motion and a Compliant (Elastic) Base boundary condition. Consequently, the numerical model boundary represents an engineering elastic half-space rather than the actual geological bedrock encountered at approximately 251 m depth.

Accordingly, the numerical model was developed to evaluate the near-surface site response based on the available engineering-scale geotechnical and geophysical data, rather than to simulate the dynamic response of the entire sedimentary basin. Therefore, the use of an elastic half-space does not imply the presence of a rigid boundary at 30 m depth but represents the standard boundary condition adopted for one-dimensional site response analyses.

Following the determination of soil index properties and soil classifications, one-dimensional dynamic site response analyses were performed using DeepSoil for representative soil profiles developed from the available geotechnical and geophysical data. In such

analyses, it is crucial to accurately define not only the index properties of the soils but also the dynamic behavior parameters. Therefore, modulus reduction and damping curves were used to represent soil stiffness and damping properties at different shear stress levels. In this study, the Darendeli [69] model, widely accepted for various soil types and based on extensive databases, was preferred, and the relevant modulus reduction and damping curves were used in the analyses (Figure 3).

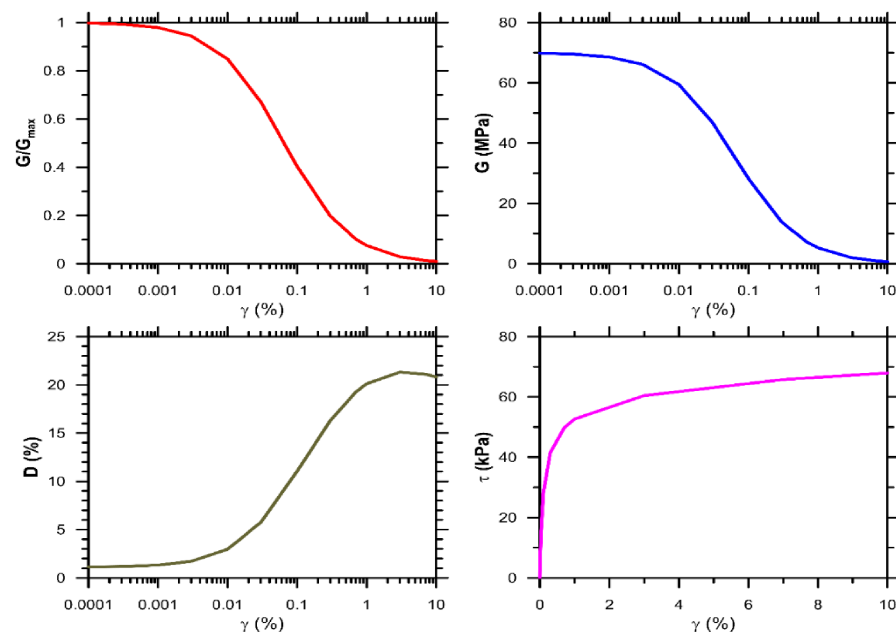


Figure 3. The modulus reduction and damping rate curves generated by Darendeli equation.

The Darendeli, 2001 [69], model was selected because it provides a generalized framework applicable to a wide range of soil types and incorporates the effects of plasticity index (PI), effective confining stress, overconsolidation ratio (OCR), and loading frequency on modulus reduction and damping behavior. These parameters are particularly important for representing the heterogeneous alluvial deposits encountered in the study area, which consist of high-plasticity clays (CH), low-plasticity clays (CL), and silty sands (SM). Alternative empirical models, such as those proposed by Seed and Idriss and Vucetic and Dobry, were evaluated during methodology selection. However, the Seed and Idriss relationships were primarily developed for sandy soils and do not explicitly incorporate effective confining stress, while the Vucetic and Dobry model mainly relates soil behavior to plasticity index without explicitly accounting for stress-dependent effects. Consequently, the Darendeli model was considered to provide a more consistent representation of the strain-dependent behavior of the different soil units encountered throughout the study area. Although site-specific dynamic laboratory tests such as resonant column or cyclic triaxial testing would provide more representative modulus reduction and damping curves, such data were not available within the scope of this regional-scale microzonation study. Therefore, the widely validated Darendeli, 2001 [69], model was adopted as the most appropriate generalized constitutive relationship for the analyses.

Soil behavior analysis was performed by creating damping rate curves and modulus reduction rate curves for clays and sands. In the dynamic analysis, the layers were made using the soil class, the unit volume weight values of the specific layer along with the average shear-wave velocity. For the study area soils, sensitivity tests were conducted by varying shear-wave velocity estimates derived from Iyisan, 1996 [66], which was preferred

for determining the shear-wave velocity from the SPT-N values at each drilling point (Equation (1)).

$$V_s = 51.5N^{0.516} \quad (1)$$

V_s : Shear-wave velocity (m/s). N : SPT blow count.

To assess the accuracy of the estimated V_s values, a subset of boreholes was cross-validated with geophysical measurements. The mean shear-wave velocity (V_{s30}) over the top 30 m is a fundamental indicator widely used in determining soil classes and defining seismic design parameters. In Turkey, the V_{s30} parameter was officially included in the soil classification system with the Turkish Building Earthquake Code [53], which came into force in 2018.

Figure 4 shows the soil classes defined based on V_{s30} values, consisting of six different range categories. In this classification, ZA represents the hard rock environment, while ZE represents the softest soil conditions. According to the data presented in Table 3, the layer-specific shear-wave velocity (V_s) values within the study area generally range between approximately 180 and 360 m/s, reflecting the variability in the near-surface soil layers. However, the local soil classification was determined based on the calculated V_{s30} values rather than the individual layer-specific V_s values. Based on the calculated V_{s30} values, the study area comprises both ZD and ZE local soil classes according to TBEC-2018, with ZD representing the predominant site class. This spatial variation reflects the heterogeneity of the alluvial deposits across the study area.

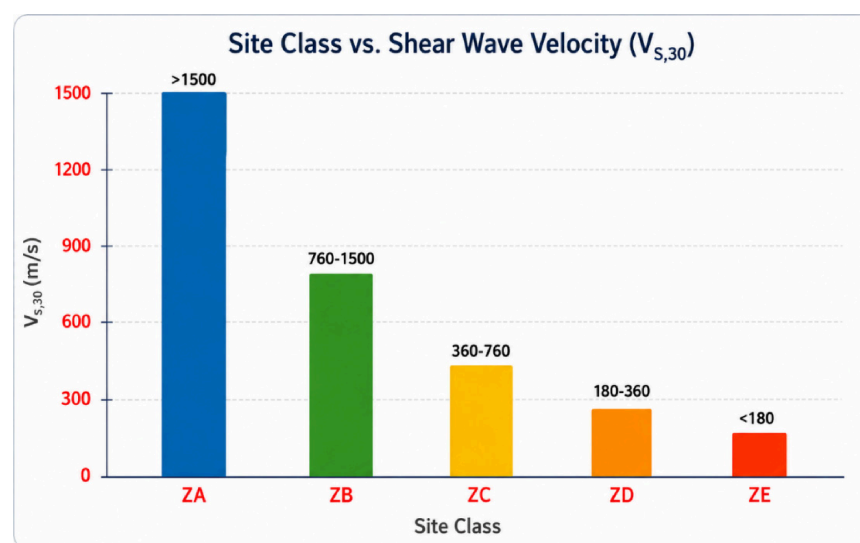


Figure 4. Seismic site classes in 2018 TBEC.

Table 3. Acceleration values of the study area according to the earthquake ground motion level.

Earthquake Ground Motion Level	Acceleration Values (g)
EL-1 (return period—2475 years)	0.64
EL-2 (return period—475 years)	0.33

To accurately assess the impact of a potential earthquake on the existing building stock, both earthquake source characteristics and surface soil behavior must be considered. For this purpose, the soil stratigraphy of the study area was determined in detail, and dynamic soil behavior analyses were performed using selected real earthquake records compatible with seismic hazard analysis.

The Turkish Building Earthquake Code [53] defines four earthquake ground motion levels corresponding to different probability levels. These levels are Earthquake Level-1

(EL-1), Earthquake Level-2 (EL-2), Earthquake Level-3 (EL-3), and Earthquake Level-4 (EL-4), respectively, corresponding to recurrence periods of approximately 2475, 475, 72, and 43 years. In this study, soil response analyses were performed for EL-1 and EL-2 ground motion levels, which are the most commonly used earthquake levels in engineering design. The peak ground acceleration (PGA) values determined for the study area within the scope of Turkish Building Earthquake Code (TBEC) are presented in Table 3.

The Akşehir–Simav Fault System (ASFS) and earthquakes occurring along the northeast–southwest trending faults in the region indicate that Afyonkarahisar and its surroundings are located within a highly active tectonic system in terms of seismic hazard. The Akşehir–Simav Fault System, approximately 113 km long, stretches between Çukurören in the northwest and Çobanlar in the southeast, and consists of normal, oblique, and strike-slip fault segments. Considering this tectonic structure, 11 different earthquake records conforming to regulatory criteria were selected for use in field response analyses, taking into account fault type, epicenter distance, and peak ground acceleration (PGA) values at the bedrock level. The characteristics of these earthquake records used in the analyses are presented in Table 4.

Table 4. Earthquake records used in analysis [70,71].

Eq. No	Earthquake Name	Station	Depth (km)	PGA (g)	Magnitude (M_W)
E1	19 August 1976 Denizli	2001	20	0.35	5.0
E2	13 March 1992 Erzincan	2402	23	0.41	6.6
E3	17 January 1995 Kobe	Kobe JMA	17.6	0.69	6.9
E4	1 October 1995 Afyon/Dinar	0302	5	0.28	6.1
E5	27 June 1998 Adana	0105	23	0.22	6.2
E6	17 August 1999 Kocaeli	4106	15.9	0.21	7.4
E7	21 September 1999 Chi Chi	TCU	8	0.18	7.3
E8	12 November 1999 Düzce	8101	11	0.41	7.2
E9	1 May 2003 Bingöl	1201	6	0.55	6.1
E10	23 October 2011 Van	6503	19.02	0.18	6.7
E11	20 March 2019 Denizli	2017	10.76	0.36	5.5

The selected earthquake records were scaled using a uniform amplitude (PGA) scaling procedure to represent the designed earthquake levels defined in the Turkish Building Earthquake Code (TBEC-2018). For each earthquake record, a single scaling factor was calculated as the ratio of the target PGA to the original PGA of the recorded motion. The entire acceleration time history was then multiplied by this constant factor to obtain the required input motion. Unlike spectrum-matching procedures, no modification of the frequency content, phase characteristics, or duration of the original records was performed.

This approach was intentionally adopted to preserve the recorded seismic characteristics and to avoid introducing artificial changes that could influence the nonlinear soil response. Since the objective of this study was to compare equivalent linear and nonlinear site response analyses using representative real earthquake motions, maintaining the original spectral characteristics of the records was considered more appropriate than enforcing spectral compatibility through frequency-domain modification. As an example of scaled ground motions, records made compatible with a 0.33 g PGA value for EL-2 are shown in Figure 5.

The selection of earthquake records is a critical step in ensuring the reliability of site response analyses. In this study, a total of eleven ground motion records were selected, considering criteria such as earthquake magnitude, epicenter distance, faulting mechanism, and compatibility with local geological conditions. The records were selected based on multiple seismological and engineering criteria rather than earthquake magnitude alone, ensuring that they adequately represented the expected regional ground motion charac-

teristics. Furthermore, the spectral content of the selected records was compared with the target design spectrum defined in TBEC-2018 to ensure that they represented the expected potential seismic scenarios in the Afyonkarahisar region.

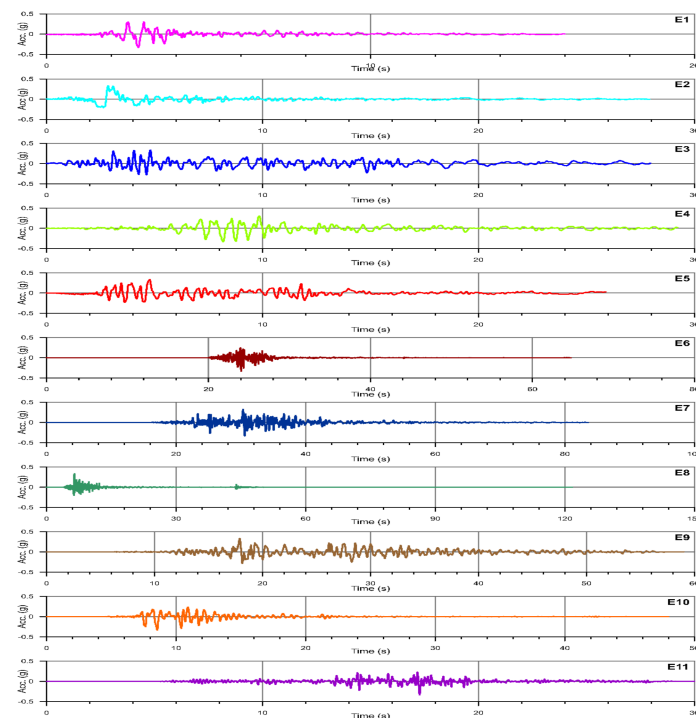


Figure 5. The scaled versions of base motions for EL-2 level with a PGA of 0.33 g.

Summary information demonstrating the compatibility of the selected ground motions with the TBEC-2018 design spectrum is presented in Table 4. This approach ensures that the analyses are based on earthquake records reflecting both regional seismotectonic conditions and international seismic hazard assessment principles.

For each earthquake record, the amplification factor (AF) was calculated as the ratio of the peak ground acceleration (PGA) computed at the ground surface to the PGA of the corresponding input motion applied at the model base. The mean amplification factor for each soil profile was then calculated as the arithmetic average of the amplification factors obtained from the eleven selected earthquake records. This averaging procedure was applied consistently to both the equivalent linear and nonlinear analyses to reduce record-to-record variability and to obtain representative amplification values for each soil profile.

For each earthquake record, the amplification factor (AF) was calculated as the ratio of the peak ground acceleration (PGA) at the ground surface to the PGA of the corresponding input motion applied at the model base:

$$AF = \frac{PGA_{surface}}{PGA_{input}}$$

where

AF : Amplification factor for the i th earthquake record;

$PGA_{surface}$: Peak ground acceleration at the ground surface;

PGA_{input} : Peak ground acceleration of the corresponding input motion at the model base.

The representative amplification factor for each soil profile was then calculated as the arithmetic mean of the amplification factors obtained from the 11 earthquake records:

$$AF = \frac{1}{N} \sum_{i=1}^N AF$$

where

AF : Mean amplification factor for the soil profile;

$N = 11$: Number of earthquake records used in the analyses.

This averaging procedure was applied consistently to both the equivalent linear and nonlinear analyses.

In this study, scaled acceleration records for EL-1 and EL-2 ground motion levels were determined and used in ground amplification analyses. Site-specific surface ground motion parameters were calculated using one-dimensional equivalent linear and nonlinear site response analyses with DeepSoil 7.0 software for representative soil profiles. The maximum amplification factors obtained for different ground motion levels are spatially represented using a GIS-based mapping method. To illustrate the analysis process, the results of nonlinear and equivalent linear ground amplification analyses performed for the soil profile of the borehole designated as BH62 are presented. The surface response spectrum of the nonlinear analysis of the BH62 soil profile is shown in Figure 6. According to the nonlinear analysis results, the ground motion varied between 0.17 and 0.30 g up to 0.02 s and reached a maximum value of 1.28 g at 0.68 s. It was observed that the earthquake effect was particularly concentrated in the period of 0.02–0.68 s. The highest acceleration value in the nonlinear analysis results was obtained for the Adana–Ceyhan (1998) earthquake record.

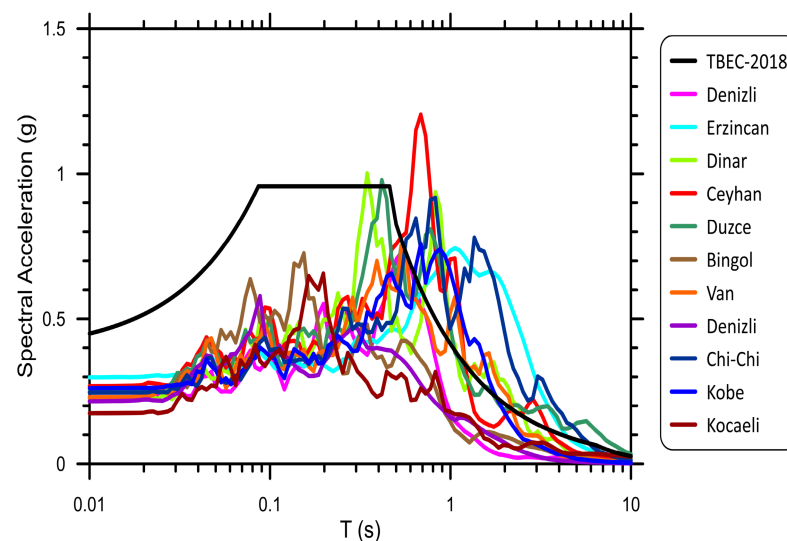


Figure 6. Ground response spectrum based on nonlinear soil amplification analysis of sample soil profile BH62.

The surface response spectrum of the equivalent linear ground amplification analysis performed for the BH62 borehole is presented in Figure 7. According to the equivalent linear analysis results, it was determined that the ground motion showed a linear increase in the range of 0.18–0.35 g until 0.05 s, after which the earthquake effect increased, reaching a maximum spectral acceleration value of 1.41 g in a period of 0.64 s. The analysis results show that the earthquake effect is concentrated especially in the period range of 0.05–0.64 s. The highest acceleration value obtained in the equivalent linear analysis method was observed for the Adana–Ceyhan (1998) earthquake record.

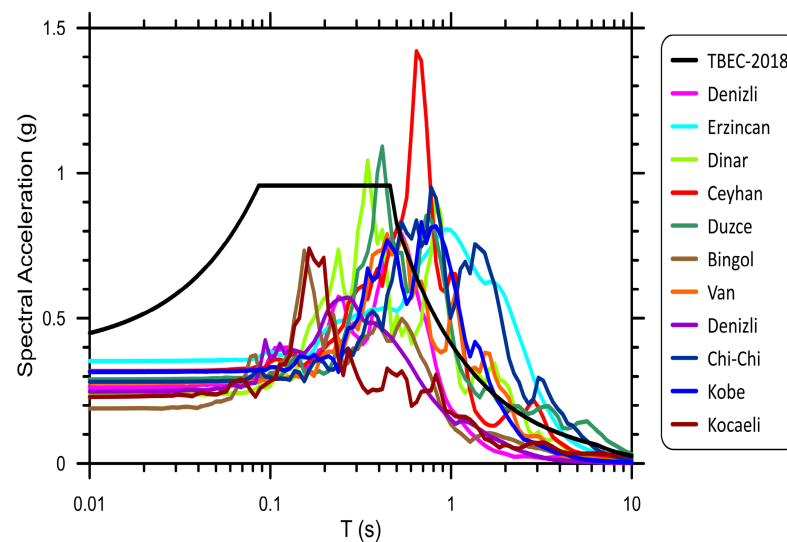


Figure 7. Equivalent linear soil amplification analysis of sample soil profile BH62.

5. Findings and Discussion

In engineering applications, the response spectrum is a fundamental parameter reflecting the dynamic properties of the soil during an earthquake and playing a critical role in the design of structures. When evaluating the response spectra, it is observed that in nonlinear analysis, the maximum spectral acceleration reaches approximately 1.28 g at a period of 0.68 s, while in the equivalent linear analysis method, the maximum value is 1.41 g at a period of 0.64 s. Although soil behavior generally shows similar trends in higher period ranges, it has been determined that the maximum spectral acceleration values occur at different periods. This situation can have significant engineering implications, particularly regarding the resonance behavior of medium- and high-rise structures.

To evaluate the international applicability of the results, the soil amplification analyses obtained under TBEC-2018 were compared with Eurocode 8 [72] and NEHRP [73] regulations. This comparison is based on matching TBEC hazard levels with their international equivalents. Accordingly, EL-1 (2%/50% year) corresponds to the Maximum Considered Earthquake (MCE) level in NEHRP, while EL-2 (10%/50% year) corresponds to the designed earthquake level defined in Eurocode 8. The representative layer-specific shear-wave velocities (V_s) of the investigated soil profiles generally range between approximately 200 and 260 m/s. Based on the calculated V_{s30} values, the study area includes sites corresponding predominantly to site classes D and E according to Eurocode 8 (EC8) and NEHRP, and ZD and ZE according to TBEC-2018, reflecting the spatial variability in local soil conditions. This comparison allows for a direct comparison of surface PGA values and amplification factors with international regulations.

Soil amplification is an important engineering phenomenon, and the analysis results were evaluated in this context. Amplification factors were calculated by ratioing the surface spectral behavior to the ground motion spectral behavior, and the average of the maximum values for different analyses was taken. The obtained amplification values were presented as 1/1000 scale maps using Geographic Information Systems for one-dimensional equivalent linear and nonlinear analysis methods.

Since the study area is characterized by a high concentration of residential and multi-story buildings, local ground amplification represents a critical factor that can directly influence the seismic performance of these structures. The results of the ground motion level-based analyses performed using the nonlinear (EL-1) and equivalent linear (EL-1) approaches are presented in Figures 8 and 9. According to the nonlinear analysis results,

the lowest amplification ratio within the study area was identified in Region 1 with a value of 1.00, while the highest amplification ratio was observed in Region 5 with a value of 1.62 (Figure 8).

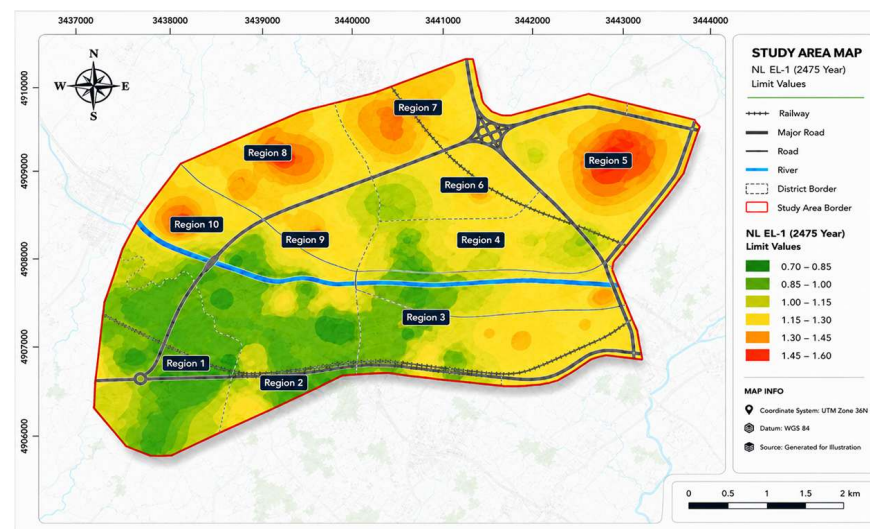


Figure 8. Nonlinear (EL-1) soil amplification analysis results.

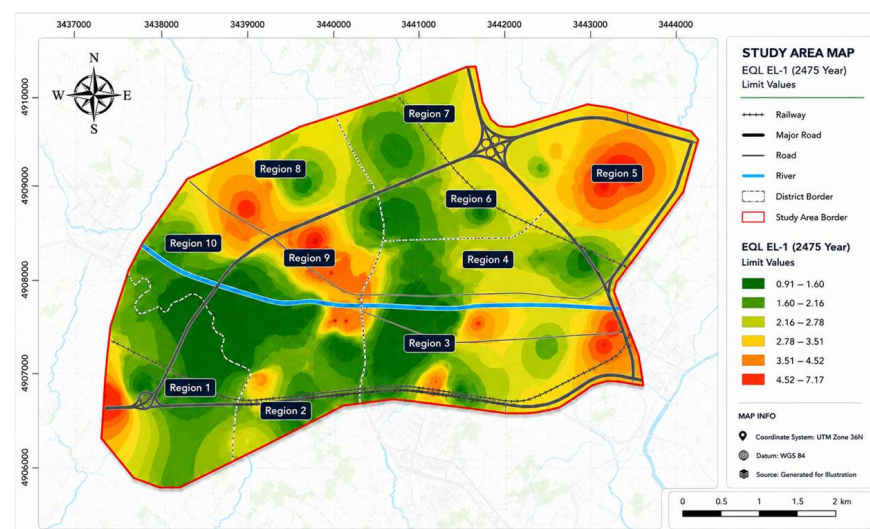


Figure 9. Equivalent linear (EL-1) soil amplification analysis results.

According to the equivalent linear analysis results, the lowest amplification ratio was identified in Regions 1, 2, and 6 with a value of 1.89, while the highest amplification ratio was observed in Region 9 with a value of 4.52 (Figure 9). These results indicate that the equivalent linear approach tends to estimate ground amplification more effectively, particularly under high strain conditions.

Considering the entire study area, amplification factors ranging from 1.00 to 1.62 were obtained from the nonlinear analyses for EL-1 ground motions, representing large earthquakes with a low probability of occurrence. In contrast, the equivalent linear analyses produced amplification values ranging from 1.89 to 4.52, indicating a tendency to predict higher amplification levels under strong ground motions. This difference reflects the different assumptions and the treatment of strain-dependent soil behavior adopted by the two analysis approaches. Consequently, relying solely on the equivalent linear method for EL-1 earthquakes may lead to conservative estimates of seismic site amplification and, therefore, more conservative superstructure design.

Figure 10 shows that, according to the nonlinear analysis results, the amplification values for EL-2 in the study area range between 1.25 and 1.55. The lowest amplification value was determined for Regions 1, 2, 4, and 6, while the highest amplification value of 1.55 was obtained in Region 5. These results reveal that ground amplification under the EL-2 ground motion level exhibits limited but significant spatial variability within the study area.

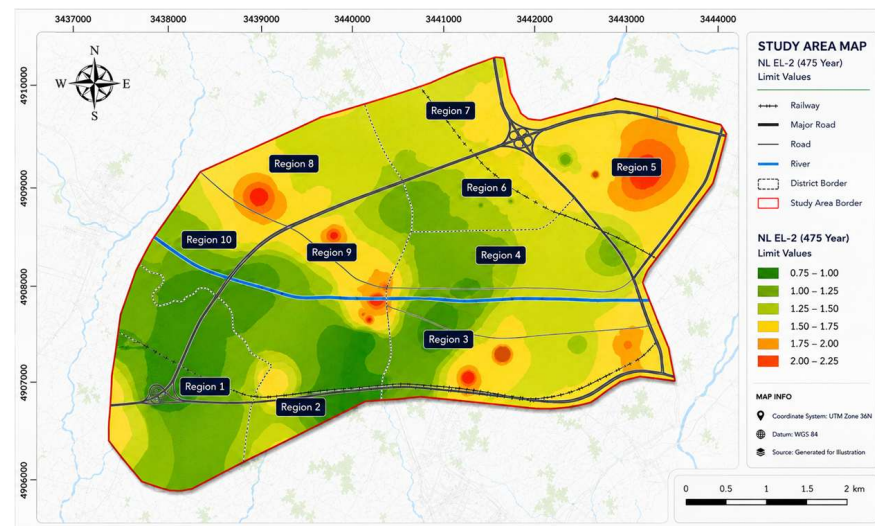


Figure 10. Nonlinear (EL-2) soil amplification analysis results.

Examining the equivalent linear analysis results presented in Figure 11, it is observed that the amplification values range between 1.18 and 1.72. The lowest amplification value was determined in Region 6, and the highest amplification value was determined in Region 9. These results show that the equivalent linear method can produce higher amplification values in some regions compared to nonlinear analyses.

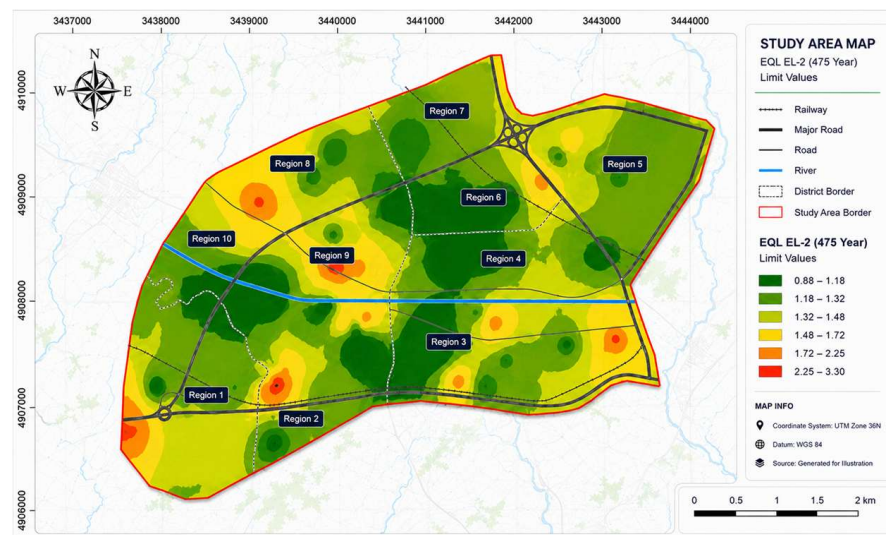


Figure 11. Equivalent linear (EL-2) soil amplification analysis results.

Overall, it is observed that the amplification values obtained for EL-2 are in similar ranges in both analysis methods. According to the nonlinear analysis results, the amplification values vary between 1.25 and 1.55, while according to the equivalent linear analysis results, these values are determined to be in the range of 1.18–1.72. This indicates that, considering the entire study area, the ground amplification for the earthquake scenarios

used in the design is estimated to be at a similar level with both methods. Therefore, using either the nonlinear or equivalent linear analysis approach in superstructure designs for the EL-2 ground motion level can provide reliable results from an engineering perspective.

The spatial variability observed in the GIS-based amplification maps is closely related to the geotechnical characteristics of the study area. The SPT-based soil profiles were calibrated using MASW-derived shear-wave velocity (V_s) measurements (Table 1), providing a reliable representation of the near-surface stiffness conditions. In general, areas characterized by relatively lower shear-wave velocities exhibited higher amplification levels, whereas areas with comparatively higher shear-wave velocities tended to show lower amplification. However, the observed amplification patterns cannot be explained solely by V_{s30} . Local amplification is also influenced by the thickness of the alluvial deposits, impedance contrasts between adjacent soil layers, and local stratigraphic conditions. Therefore, the spatial distribution of the amplification factors reflects the combined influence of shear-wave velocity and local geological conditions within the Afyonkarahisar basin.

To evaluate the relationship between equivalent linear (EQL) and nonlinear (NL) analysis approaches and the predictability of these models in field response estimations, the results obtained from both methods were compared. In this context, peak spectral acceleration (PSA) values obtained at specific periods, which are important in determining the design spectrum, were examined. Figures 12 and 13 show a comparison of PSA values obtained from EQL and NL analyses for selected periods.

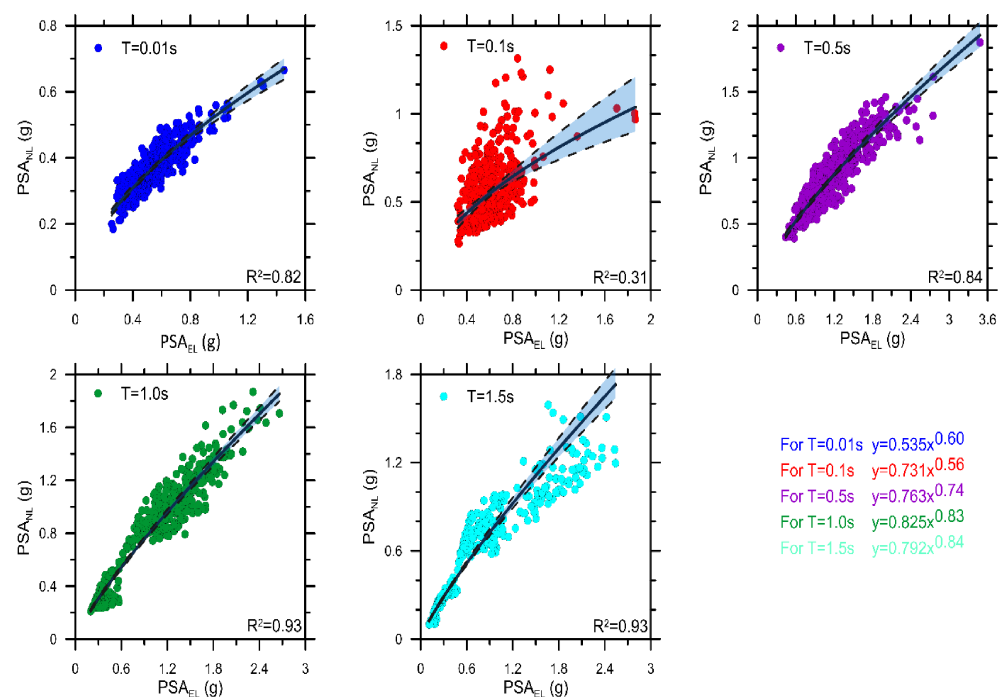


Figure 12. Spectral comparison of equivalent linear (EQL) and nonlinear models for EL-1.

Five different period values were selected due to their importance in creating the design spectrum. Figure 12 presents a graphical comparison between the peak spectral accelerations obtained from the equivalent linear (EQL) and nonlinear (NL) analyses for selected structural periods. The fitted regression lines are only intended to illustrate the overall relationship between the two analysis approaches and should not be interpreted as statistical prediction models. The shaded regions represent the 95% confidence interval of the fitted regression line and are included solely to provide a visual indication of the dispersion of the relationship. The results indicate that the agreement between the two methods generally improves with increasing period, whereas larger differences are

observed at shorter periods, particularly around $T = 0.1$ s, where nonlinear soil behavior has a greater influence on the computed response.

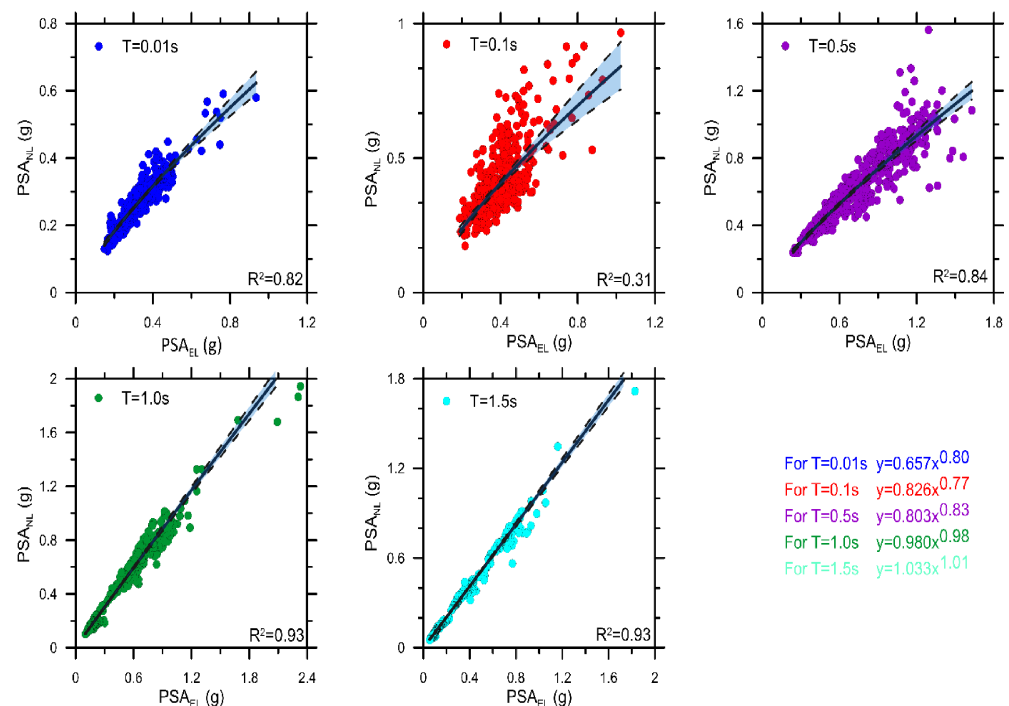


Figure 13. Spectral comparison of equivalent linear (EQL) and nonlinear models (NL) for EL-2.

Figure 13 shows the corresponding comparison for EL-2. In general, the agreement between the equivalent linear and nonlinear analyses is closer than that observed for EL-1. Differences between the two approaches remain more pronounced in the short-period range, while the results converge progressively toward longer periods. These observations are intended as an engineering comparison of the two analysis approaches rather than a statistical assessment of model performance. The regression lines shown in Figures 12 and 13 are provided only to facilitate visual comparison between the equivalent linear and nonlinear analysis results. They are not intended for statistical inference or predictive modeling.

Overall, it appears that the nonlinear field response is more variable, particularly in shorter periods, while in longer periods, the equivalent linear (EQL) and nonlinear (NL) analysis results are closer to each other. These observations indicate that nonlinear effects tend to be more pronounced in the short-period range, whereas the responses obtained from the equivalent linear and nonlinear analyses become increasingly similar at longer periods.

6. Conclusions

This study presents the first microzonation-focused site response assessment for Afyonkarahisar, a city built on thick alluvial units and under pressure from rapid urbanization. Equivalent linear and nonlinear one-dimensional site response analyses were performed using the DeepSoil program with data from a total of 124 boreholes, and eleven earthquake records representing EL-1 and EL-2 seismic hazard levels under the Turkish Building Earthquake Code were used.

Comparison of shear-wave velocities obtained from SPT-based correlations and MASW measurements revealed an average difference of approximately 6 m/s (2.7%) and a standard deviation of ± 4.4 m/s (2.2%). This low difference indicates a high degree of agreement between empirical correlations and site measurements, confirming the reliability of the soil profiles used in the analyses.

The site response analyses revealed significant differences between the equivalent linear and nonlinear methods. For EL-1, amplification factors obtained from the nonlinear analyses ranged from 1.00 to 1.62, whereas those obtained from the equivalent linear analyses ranged from 1.89 to 4.52. The equivalent linear analyses generally yielded higher amplification levels under strong ground motions. In contrast, the nonlinear analyses explicitly accounted for strain-dependent stiffness degradation and damping evolution, resulting in lower predicted amplification levels at large shear strains.

For EL-2, the difference between the two methods was found to be significantly reduced. Amplification factors were calculated in the range of 1.25–1.55 in nonlinear analyses and 1.18–1.72 in equivalent linear analyses. This shows that both methods can provide similar results in terms of engineering design due to the limited soil deformations in moderate ground motions.

GIS-based amplification maps revealed significant spatial variability in site response across the study area. In particular, higher amplification factors were identified in specific zones, highlighting priority areas for earthquake risk reduction and seismic microzonation. These findings demonstrate the strong influence of local soil conditions on seismic ground motion and emphasize the importance of incorporating site-specific effects into seismic hazard assessments.

From an engineering perspective, the proposed GIS-based amplification maps may serve as a practical tool for site-specific seismic design and seismic microzonation studies. The results demonstrate that amplification can vary considerably even within the same code-defined site class, indicating that site-specific ground response analyses may be beneficial, particularly for important structures and critical infrastructure. The presented maps are intended to complement, rather than replace, the site classification procedures specified in TBEC-2018 by providing a higher spatial resolution assessment of local amplification characteristics.

Spectral acceleration results also varied depending on the analysis methods. In the nonlinear analysis, the maximum spectral acceleration was obtained as 1.28 g in a period of 0.68 s, while in the equivalent linear analysis, this value was calculated as 1.41 g in a period of 0.64 s. These differences in period and amplitude can have significant engineering consequences, especially in terms of the occurrence of resonance effects in medium- and high-rise structures.

The findings indicate that nonlinear site response analyses generally predict lower amplification levels under strong ground motions, whereas the equivalent linear method tends to produce more conservative estimates. Furthermore, the results are generally consistent with Eurocode 8 and NEHRP soil classifications. The findings of this study provide useful insights not only for Afyonkarahisar but also for other alluvial basins with similar geological and geotechnical characteristics.

Indeed, the 2023 Kahramanmaraş earthquake sequence clearly demonstrated the decisive role of local soil conditions on earthquake damage. Post-earthquake studies show that ground amplification, basin effects, and high ground accelerations play a significant role in the concentration of damage, especially in areas located on thick alluvial units and soft soils [14–16]. Furthermore, studies based on field observations and dynamic analyses have shown that local soil conditions can significantly amplify ground motion, and this is consistent with the damage observed, particularly in medium- and high-rise buildings [17,18]. Similarly, geotechnical and structural assessments carried out after earthquakes also show that the distribution of damage is closely related to local soil conditions [19]. These findings demonstrate that site-specific site response analyses are critically important for accurate assessment of earthquake hazards in settlements developed on alluvial soils [20].

Overall, this study demonstrates that integrating site response analyses with GIS-based spatial assessments more clearly reveals the impact of local soil conditions on seismic behavior. The results show that site-specific nonlinear site response analyses in developed urban areas on thick alluvial soils are critical for accurate earthquake hazard assessment and ensuring safe engineering design. Furthermore, it is considered that the effective use of microzonation studies in urban planning and earthquake risk reduction strategies will provide an important decision support framework for local governments and design engineers.

Limitations

Although this study provides important findings through a microzonation-focused site response assessment for the Afyonkarahisar settlement area, several limitations should be acknowledged. First, the analyses were performed using one-dimensional (1D) site response analyses, which assume vertical wave propagation only. Therefore, two-dimensional and three-dimensional wave propagation effects associated with basin geometry, including basin effects, wave focusing, and edge effects, which may occur in thick alluvial basins, were not considered within the scope of this study.

The nonlinear analyses were performed using the generalized modulus reduction and damping relationships proposed by Darendeli, 2001 [69]. Although these relationships have been extensively validated for a wide range of soil types, future studies incorporating site-specific resonant column or cyclic triaxial testing would further reduce uncertainty in the predicted nonlinear soil response.

Accordingly, the presented results should be interpreted as near-surface site response characteristics based on the available engineering-scale subsurface data, rather than as a simulation of the full deep-basin response.

Shear-wave velocity profiles were developed using SPT-based empirical correlations and MASW measurements. Although a high level of agreement was observed between these two approaches, subsurface heterogeneity, stratigraphic discontinuities, and local soil variability may not have been fully represented across the entire study area. Particularly in large alluvial basins, small-scale lithological variations should be considered, as they may significantly influence dynamic soil behavior.

In addition, while local soil amplification and dynamic soil behavior were evaluated in this study, liquefaction potential, liquefaction-induced excess pore pressure generation, soil-structure interaction (SSI), and the influence of structural response on seismic performance were not included within the analysis framework. Therefore, the obtained results should be interpreted primarily in terms of local ground behavior rather than direct structural damage prediction. Future studies should consider coupled analyses integrating liquefaction triggering and site response modeling to provide a more comprehensive assessment of seismic site effects in liquefaction-prone areas, as demonstrated by recent studies on seismic resilience assessment (Shen et al., 2026) [74].

The analyses are based on one-dimensional site response modeling, and two- or three-dimensional effects associated with basin geometry were not considered. In addition, uncertainties related to the scaling of the selected earthquake records may influence the results. Future research should focus on two- and three-dimensional numerical modeling, detailed investigation of basin effects, integration of liquefaction analyses, probabilistic seismic hazard assessment, and the development of machine learning-based approaches for shear-wave velocity prediction. The combined application of these approaches with seismic microzonation and urban seismic risk assessment is expected to provide more comprehensive and reliable evaluations of local site effects.

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