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Research Article

Seismic hazard and risk analyses of historical masonry structures in Kocaeli, Türkiye

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ABSTRACT

Protection of masonry structures is among the most important building groups around the world. Generally constructed of heavy materials such as stone and brick, these structures are highly seismically vulnerable. In large earthquakes, masonry structures that have not received adequate engineering services are usually heavily damaged or destroyed. To prevent damage to these structures, seismic hazard and risk analyses must first be conducted correctly. This study investigates the seismic hazards and risk distributions of historical masonry structures in Kocaeli, Türkiye. As a preliminary step, information and document collection studies on historical masonry structures were conducted in Kocaeli, Türkiye. Then, a detailed building inventory data set was prepared. Following that, a probabilistic seismic hazard assessment for the investigation area was conducted considering the different attenuation relationships. In the seismic hazard analyses, the hazard maps, hazard curves and response spectra were prepared based on the inventory data set at select reference points. After that, the seismic risk analyses were conducted to determine the structure distribution based on damage levels for the structures in the data set considering different fragility curves. Accordingly, historical masonry structures in Kocaeli province close to the North Anatolian Fault (NAF) Line have high hazard curves and spectrum values, whereas structures on the Black Sea coast have low values. According to the hazard maps obtained as a result of the analyses, Kartepe, Darica, Gölcük, and Başiskele districts have a high estimated hazard distribution, while Kandira has a lower estimated hazard distribution. Further, when the risk assessment is carried out by looking at the distribution of building groups based on damage levels, it was determined that towers, aqueducts, residential structures, and dome structures are the highest priority risk structures, respectively.

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1. Introduction

Historical masonry buildings are universal values that carry the traces of past civilizations to the present, thanks to their architecture, construction techniques, construction dates, types of use and building materials. When the destructive earthquakes occurring around the world have been examined, it is understood that historical masonry structures have been damaged to a great extent by the earthquakes (VGM 2017.) However their performance under horizontal dynamic loads such as earthquakes is often poor, which makes reliable seismic performance evaluation and strengthening needs critical (Akın and Alagöz 2024). Accordingly, the preservation of cultural heritage has become increasingly important in the face of conflicts and natural disasters that threaten

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historical sites worldwide (Arzomand et al. 2024). In addition, the structural performance of materials used in historical buildings may deteriorate over time due to natural events or human induced interventions, which can further increase their vulnerability under seismic actions (Zardari et al. 2024).

In order to protect historical masonry structures from earthquake hazards and ensure their safe transfer to future generations, it is important to understand their structural behavior and conduct hazard and risk analyses. It is very important to predict earthquake losses, to take the necessary precautions before the earthquake and to determine the seismic risk levels of masonry structures in order to minimize earthquake damage. Thus, hazard and risk assessment studies estimate damages and identify possible risks before an earthquake occurs. Hazard analysis today is based on both deterministic and probabilistic methods. Risk analysis studies can provide damage and loss estimations in addition to hazard curves and hazard maps. Earthquake risk management includes preventing the effects of earthquakes and reducing their damages, realizing the necessary planning and coordination to be prepared for earthquakes, intervention and recovery activities after the earthquake (Oktay et al. 2020). When the studies in the literature are examined, there are risk analyses based on different building groups, especially historical buildings and masonry structures, together with regional or more comprehensive hazard analyses carried out throughout the world. For example, Biglari et al. (2022) conducted a numerical evaluation of the seismic vulnerability of historical buildings in Kermanshah city, which is known as the center of prehistoric and historical cultures in the Zagros seismotectonic region of Iran, using numerical modeling. The study has indicated the seismic vulnerability of the examined mosques and the need to provide parameters such as slab type and aggregate configuration in order to evaluate Iranian historical buildings more effectively. Fazzi et al. (2021) proposed a methodology for seismic vulnerability assessment of a series of historic churches characterized by a specific building typology. This methodology allows the coordination and interprets seemingly distant data on the seismic behavior of historic buildings, obtained by different research scales and analysis tools. Within the scope of the study, a multi-disciplinary evaluation covering historical, environmental, geometric, technological and mechanical issues was conducted for a number of basilica churches affected by the 2009 L'Aquila earthquake in the central region of Italy to reveal the weaknesses related to the associated building typology. Zulfikar et al. (2021) conducted an earthquake hazard analysis for a typical power generation facility in the Marmara region, Türkiye. With the study, loss curves have been obtained in order to determine the risks that the relevant facility will be exposed to as a result of a possible earthquake ground motion that may occur in the Marmara region and to develop the activities that can be done to reduce these risks.

Pirchio et al. (2021) emphasized the importance of cultural heritage, they proposed a method to determine the seismic risk assessment for a historic masonry church in a fast, measurable and comprehensive approach. Within the scope of the study, 72 existing reinforced masonry medieval churches across Italy were examined in the field. For each risk component (hazard, vulnerability, exposure and consequence), 13 different indices were developed. Ademović et al. (2021) prepared old-generation probabilistic seismic hazard maps for Bosnia and Herzegovina. In the study, in which areal and linear faults were taken into account, an earthquake catalog was prepared with the filtering of fore and aftershocks and two seismotectonic models were created. The greatest ground acceleration parameter was taken as a basis while creating the hazard maps. Hoveidae et al. (2021) investigated the earthquake damage of the historical Arge-Tabriz structure using ground motion records simulated specific to the region where the structure is located. Within the scope of the study, it was aimed to estimate the damage level of the Arge-Tabriz monument against a possible earthquake. In order to evaluate the seismic damage of the Arge-Tabriz structure, possible earthquake scenarios of different magnitudes were simulated. Gundogdu Gok (2020) conducted a probabilistic earthquake hazard analysis based on the Monte Carlo method by using the 1999 Kocaeli Earthquake. In the study, the open-source OpenQuake program was used for analysis and the earthquake hazard of the Eastern Marmara Region was determined. Govsulu (2020) conducted a seismic hazard analysis for the region located in a circle with a radius of 150 km, centered on the Urla-Çeşme-Karaburun districts of İzmir province, Türkiye. Different new generation attenuation relationships were used in the study, in which the CRISIS 2015 software was used within the scope of the analysis. Within the scope of the analysis, seismic hazard maps and acceleration spectrum curves were obtained. Hofer et al. (2018) carried out a damage survey on a large church stock in Central Italy, which was affected by the Amatrice earthquake on August 24, 2016. Within the scope of the study, damage assessments were made for 196 churches in the relevant region. In this study, which aims to determine the damage mechanisms, empirical fragility functions were derived for certain structural types. Lourenço et al. (2013) developed a method that provides lower bound formulas for different simplified geometric indices and simplifies the seismic evaluation of large-span masonry structures applied to a data set of 44 monuments in Italy, Portugal and Spain. Cuadra et al. (2008) performed a seismic risk analysis of the cultural structures in Machu Picchu. In the study, the dynamic properties of Inca stone structures were investigated, and this approach was proposed to assess seismic vulnerability.

When the studies in the literature are examined, it is seen that seismic hazard and risk studies related to structural groups such as reinforced concrete and steel are mostly carried out. On the other hand, studies in the literature for structures that are more difficult to evaluate according to inventory information, construction years, construction techniques and usage purposes compared to new-generation building groups such as masonry structures are in the minority. However, studies have shown that the fragility curves suitable for these structures are also insufficient, and it is thought that this is an important issue that needs to be developed in terms of the correct evaluation of these building groups. In this study, masonry structures registered as buildings within the scope of immovable cultural assets were evaluated. It is thought that the study will make an important contribution to the literature, as the study area, Kocaeli, is located on the Alpine-Himalayan fold belt, one of the most important active earthquake zones in the world, and hosts many historically qualified structures.

2. Building Inventory Data Set

As stated earlier, there are two basic approaches for performing seismic hazard analyzes: deterministic and probabilistic. In this study, a probabilistic approach was used within the scope of hazard analysis. Compared to the deterministic approach, the probabilistic approach is preferred, considering that it can provide more effective results because it assumes many scenarios, considers all magnitudes associated with all seismic sources and considers all possible distances between the source and the site. Within the scope of the analysis, firstly, the investigation area (Fig. 1) was divided into grids in the QGIS program to determine the study area, and the locations of the structures in the region were also added to the grids (Fig. 2).

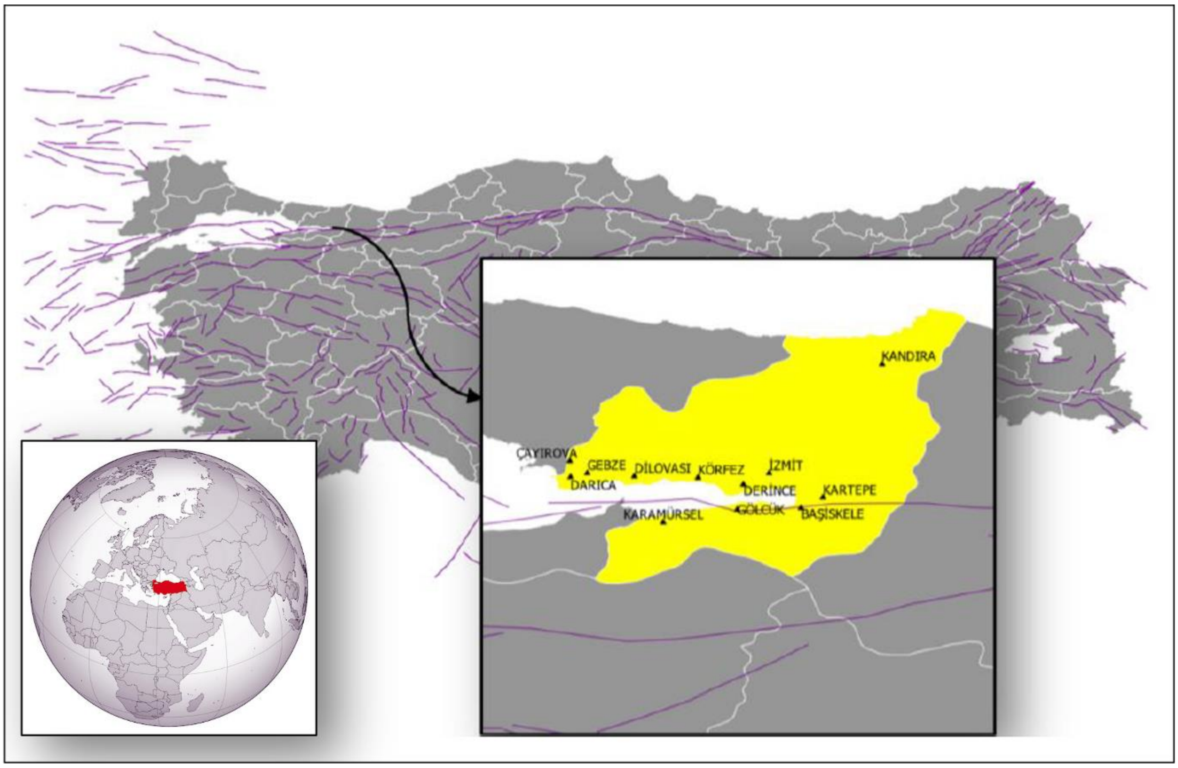

Fig. 1. The Investigation area and fault sources from the SHARE Project.

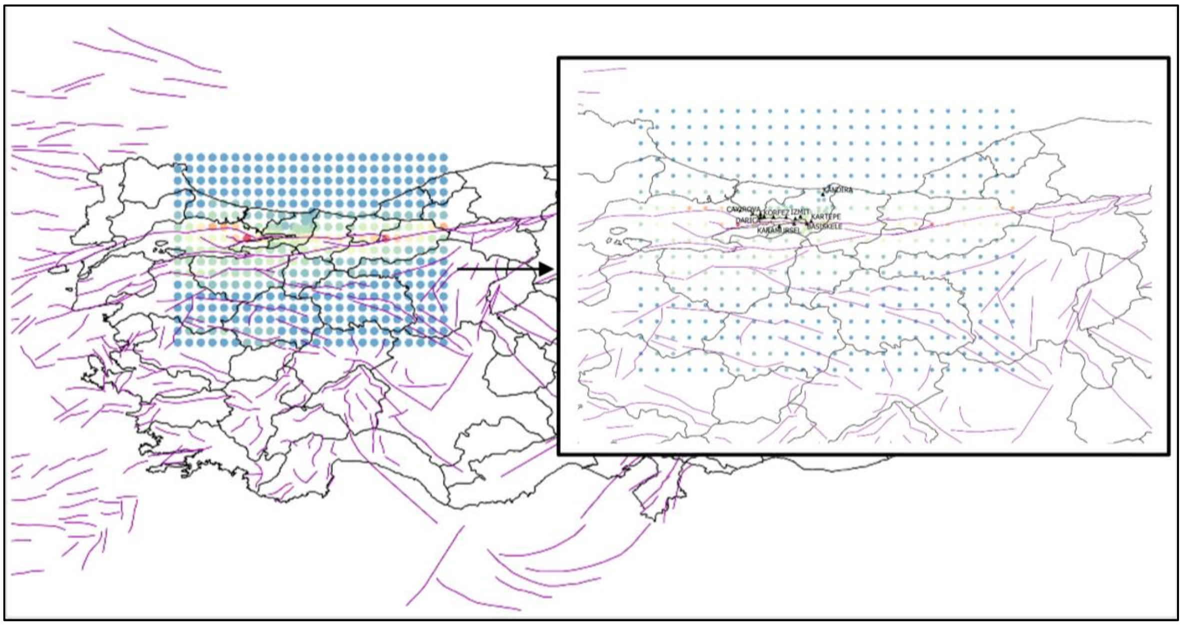

Fig. 2. The investigation area divided into grids.

Within the scope of the study, firstly, information and document collection studies were carried out on the masonry structures in Kocaeli province and detailed building inventory data was prepared considering each district of Kocaeli. In the study, only registered historical masonry structures were taken into account and Kocaeli Cultural Inventory Book Aksoy (2011) was used as a source for the identification of the historical masonry structures. This inventory data contains parameters such as stories, construction materials and quality of construction as well as structural types and occupancy types. An example of the inventory data was given in Table 1.

Table 1. Detailed building inventory data form.

IDENTIFICATION					
Property Name (If any): İzmit Clock Tower					
Address or Street Location: Kemalpaşa District of İzmit					
City: Kocaeli					
			District: İzmit		
Owner: Kocaeli Metropolitan Municipality			**Address**:		
Original use: Clock Tower			**Current use**: Clock Tower		
Architect/Builder (if known): Architect Vedat			**Date of construction (if known)**: 1901		
DESCRIPTION Materials – please check those materials that are visible					
Exterior Walls:	☐ wood	☐ wood	☐ vertical boards	☐ plywood	
	☒ clipboard	☐ shingle	☐ poured	☐ concrete	
	☐ stone	☐ brick	☐ concrete	☐ block	
Roof:	☐ shingle	☐ rool	☐ wood	☒ metal	☐ slate
Foundation:	☒ stone	☐ brick	☐ poured concrete	☐ concrete block	
Other materials and their location: There are marble columns on the sides of the 1st floor					
Alterations, if known:				**Date**:	
Condition:	☐ excellent	☒ good	☐ fair	☐ deteriorated	
PHOTOS			**MAPS**		
					

In addition to the inventory classification, a typological categorization was introduced based on architectural function, material usage, and geometric features such as arches and domes (Fig. 3). This classification was supported by expert evaluations from structural engineers experienced in historical architecture. Reference was also made to typologies defined in international seismic risk literature to ensure consistency with widely adopted structural taxonomies. Therefore, first of all, registered historical masonry buildings were separated according to districts and it was determined which buildings were located in which district (Figs. 4 and 5). Then, buildings were classified into eight structural classes according to their structural types and intended uses after determining the registered structures (Table 2).

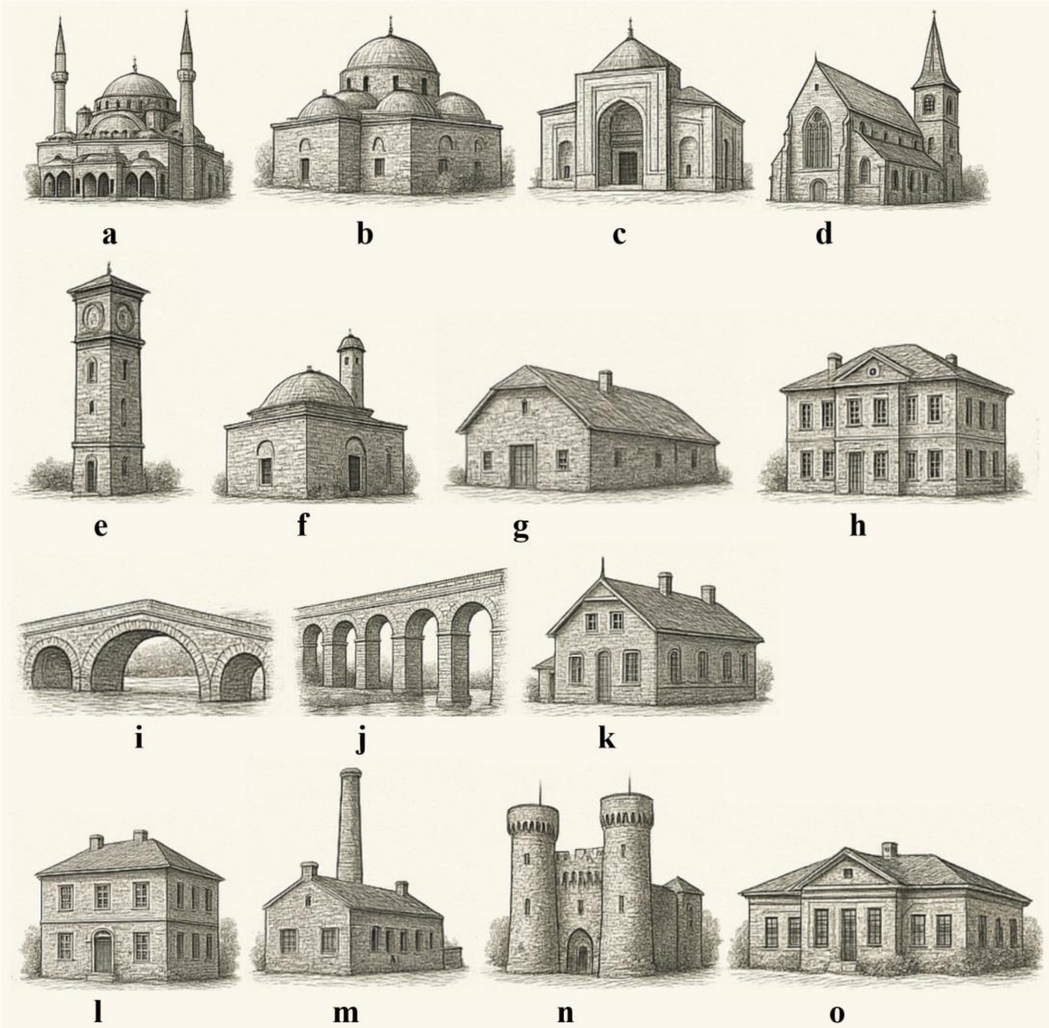

Fig. 3. The classification of the masonry structures: (a) Mosques; (b) Masjids; (c) Madrasahs; (d) Churches; (e) Clock towers; (f) Baths; (g) Barns; (h) Administrative structures; (i) Bridges; (j) Aqueducts; (k) Train stations; (l) Schools; (m) Factories; (n) Castles; (o) Townhouse (AI-generated).

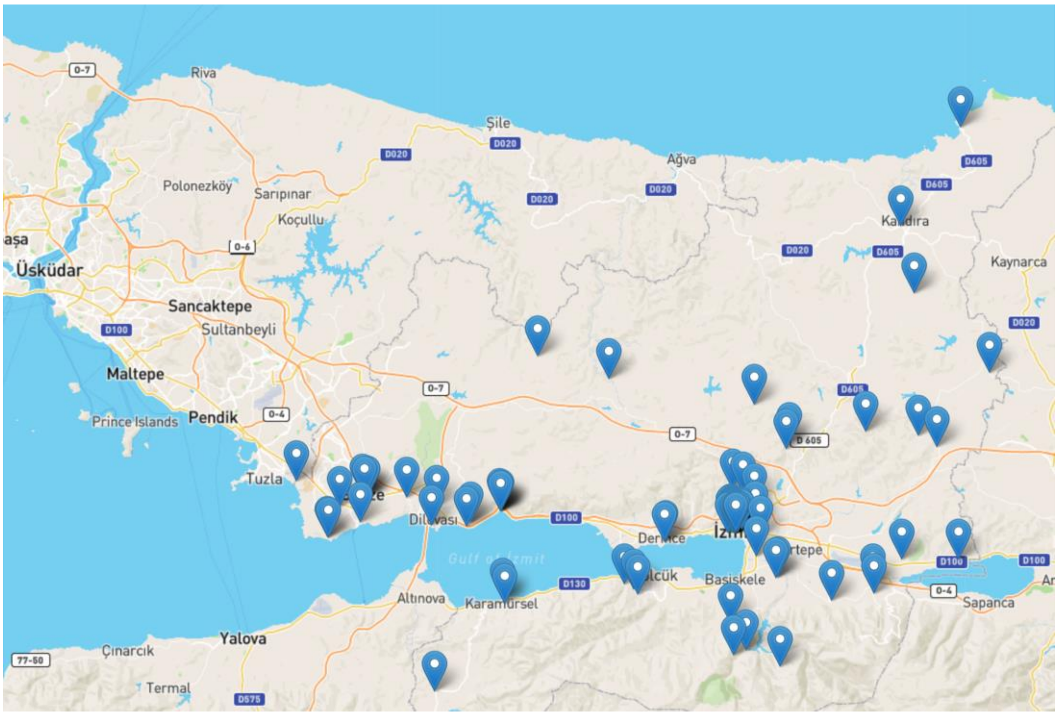

Fig. 4. The historical masonry structures in the investigation area.

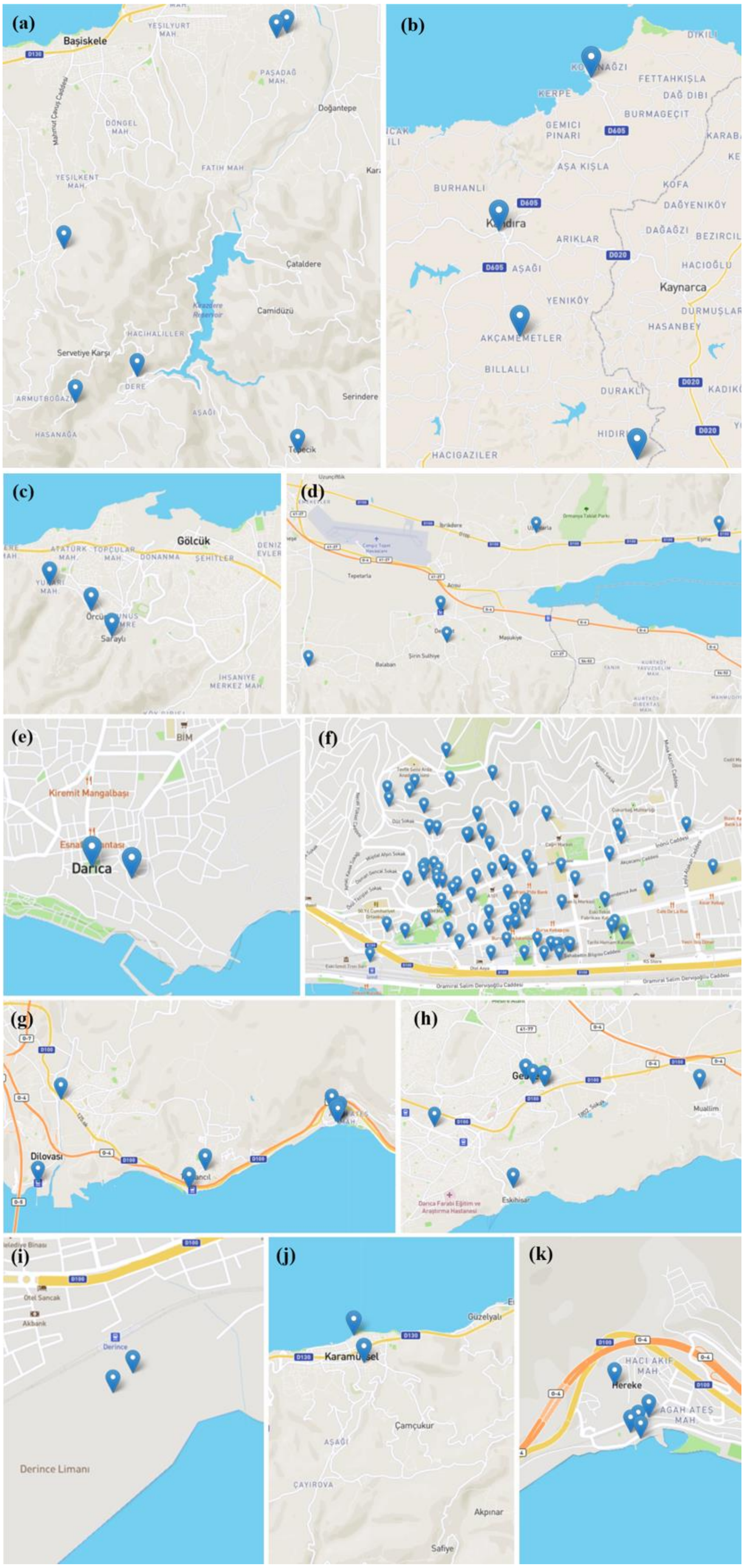

Fig. 5. Distribution of the historical masonry structures by districts; (a) Başiskele; (b) Kandıra; (c) Gölcük; (d) Kartepe; (e) Darıca; (f) İzmit; (g) Dilovası; (h) Gebze; (i) Derince; (j) Karamürsel; (k) Körfez.

Table 2. The distribution of the buildings.

		İzmit	Kartepe	Başiskele	Gölcük	Karamürsel	Derince	Körfez	Dilovası	Gebze	Darıca	Kandıra	Total
Religious Buildings	Mosques	12	3	2	2	1	–	1	1	3	–	4	29
	Masjids	5	–	–	–	–	–	–	–	–	–	–	5
	Madrasahs	–	–	–	–	–	–	–	–	–	–	–	0
	Churches	2	–	–	–	–	–	–	–	–	1	–	3
Social and Cultural Structures	Clock Towers	1	–	–	–	–	–	–	–	–	–	–	1
	Baths	6	–	–	1	–	–	–	–	2	–	–	9
	Barns	–	–	1	–	–	–	–	–	–	–	–	1
	Administrative Structures	–	–	–	–	1	–	–	–	–	–	–	1
Transportation Structures	Bridges	1	–	2	–	1	–	1	1	1	–	–	7
	Aqueducts	5	–	–	–	–	–	–	–	–	–	–	5
	Train Stations	1	1	–	–	–	1	1	2	1	–	–	7
Educational Structures	Schools	6	–	1	–	–	–	–	–	–	–	–	7
Industrial Structures	Factories	4	–	1	–	–	1	2	–	2	–	–	10
Defense Structures	Castles	2	–	–	–	–	–	–	–	–	1	–	3
Mansions	Townhouse	9	1	–	–	–	–	1	–	–	–	–	11
Other Residences		39	–	–	–	–	–	–	–	–	–	–	39
	Total	93	5	7	3	3	2	6	4	9	2	4	138

3. Seismic Hazard Analysis

The time, location, magnitude, and other characteristics of future earthquakes in seismically active regions cannot be predicted in advance. One of the most challenging aspects of earthquake engineering is to estimate the maximum effects of earthquakes that may occur in a given time period on construction sites, especially for parameters related to ground motion. As ground motion parameters, acceleration, velocity, displacement, and spectral acceleration, which reflect the characteristics of ground vibrations in the studied region, are expressed. A probabilistic and statistical approach is required to determine the parameters to be considered in designing earthquake-resistant structures due to the variability and uncertainty associated with earthquakes in terms of time, location, and intensity (Yücemen 2011). A seismic hazard analysis determines the ground shaking hazard in a particular area numerically. There are two types of seismic hazards analysis: the deterministic method, where the assumption of a special scenario earthquake is assumed, and the probabilistic method, which takes into account the uncertainties associated with earthquake magnitude, location, and time (Kramer 1996).

During earthquake-resistant building design, it is important to simulate the ground motions caused by the decisive earthquake so that the design can be adapted to reality as much as possible. Because earthquake motions based on the design are defined by ground motion characteristics, it is necessary to develop methods for calculating ground motion parameters. Attenuation relations are used to calculate ground motion parameters by expressing them in terms of the most strongly affecting magnitudes. Based on conditions such as magnitude, fault mechanism, propagation direction, and local ground effects, attenuation relationships predict strong ground motion parameters.

In the developed attenuation relations, spectral accelerations are defined depending on the moment magnitude of the earthquake, distance, earthquake mechanism and local soil conditions. Care should be taken to use the same earthquake magnitude scale in attenuation relationships, in compiling the magnitude-frequency data, and in determining the maximum magnitude. The distance parameter used for attenuation relations can be expressed as the distance from the focal center, the epicenter, the energy discharge center, the fault surface and the fault extension. Attenuation relations usually describe ground motion parameters as a function of magnitude, distance, and in some cases, other variables. The reduction relationship is expressed by the function $Y=f(M, R, Pi)$. In the function, Y is the desired ground motion parameter, M is the magnitude of the earthquake, R is the distance between the source and the project site, and Pi is used to characterize the earthquake source, wave propagation or local ground conditions. Attenuation relationships are developed by regression analysis methods using the data of recorded strong ground motions. This data set changes as more ground motions occur over time. The attenuation relationships in the literature are generally updated every 3 to 5 years or after major earthquakes occur in locations with a good measuring grid (Kramer 1996).

Seismic hazard analyses were conducted using an open-source program, OpenQuake. A total of eleven attenuation relations, which were suitable for the investigation area, were considered along with seismic characteristics and ground conditions (Table 3). After that, the seismic hazard analysis of the investigation area was conducted based on each attenuation relation. In comparison with the TEC (2018), Campbell and Bozorgnia (2014) was determined to have the most favorable attenuation relation for the investigation area. The results obtained for the three critical reference locations (İzmit, Kartepe, Kandıra) against the earthquake ground motion level of DD-2 (10% probability of exceeding in 50 years, recurrence period of 475 years) are listed below (Figs. 6-8).

After the determination of the most appropriate attenuation relationship, seismic hazard analyzes were carried out considering the 50 years in the analysis. The analysis was carried out assuming bedrock ground ($(Vs)_{30}$ = 760 m/sec). Within the scope of the seismic hazard analyses, hazard curves corresponding to PGA (with/without $(Vs)_{30}$) and the spectral periods for 11 selected reference locations (İzmit, Kartepe, Başiskele, Gölcük, Karamürsel, Derince, Körfez, Dilovası, Gebze, Darıca, Kandıra) were prepared (Figs. 9, 10, 13, and 15). The PGA, $Sa(0.2)$ and $Sa(1.0)$ spectral periods corresponding to DD-2 earthquake ground motion levels were prepared as colored maps (Figs. 11, 12, 14, and 16). In addition, the response spectrums obtained for DD-2 earthquake ground motion levels at the reference locations were prepared in the seismic hazard analyses for reference points (Figs. 17–27).

Table 3. The attenuation relationships used in the study.

Attenuation Relationships in the Study	OpenQuake Hazard Library Name
AS08: Abrahamson and Silva (2008)	AbrahamsonSilva2008
BA08: Boore and Atkinson (2008)	BooreAtkinson2008
CB08: Campbell and Bozorgnia (2008)	CampbellBozorgnia2008
CY08: Chiou and Youngs (2008)	ChiouYoungs2008
ASK14: Abrahamson et al. (2014)	AbrahamsonEtAl2014
BSSA14: Boore et al. (2014)	BooreEtAl2014
CB14: Campbell and Bozorgnia (2014)	CampbellBozorgnia2014
CY14: Chiou and Youngs (2014)	ChiouYoungs2014
ASB14: Akkar et al. (2014)	AkkarEtAlRepi2014
AC10: Akkar and Cagnan (2010)	AkkarCagnan2010
Z06: Zhao et al. (2006)	ZhaoEtAl2006Asc

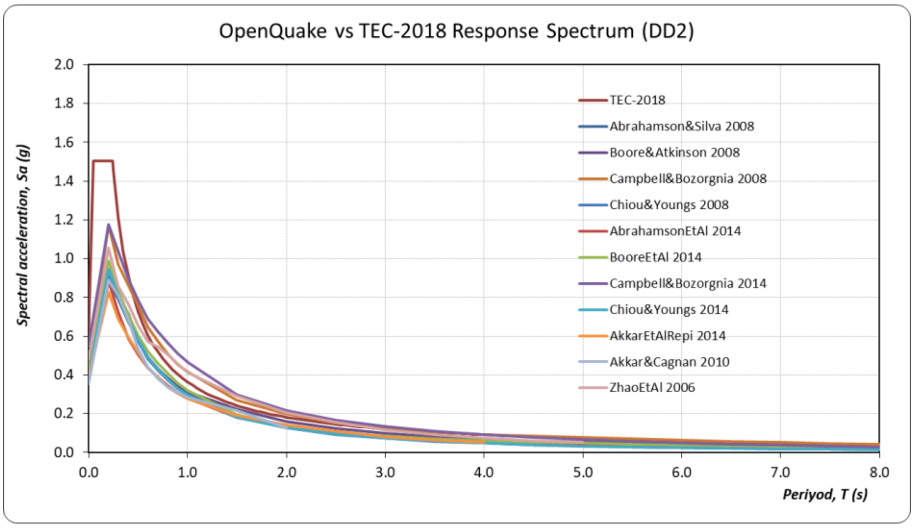

Fig. 6. Comparison of the results obtained from OpenQuake with the TEC-2018 spectrum using the relevant attenuation relations for the DD-2 earthquake ground motion level at the İzmit district.

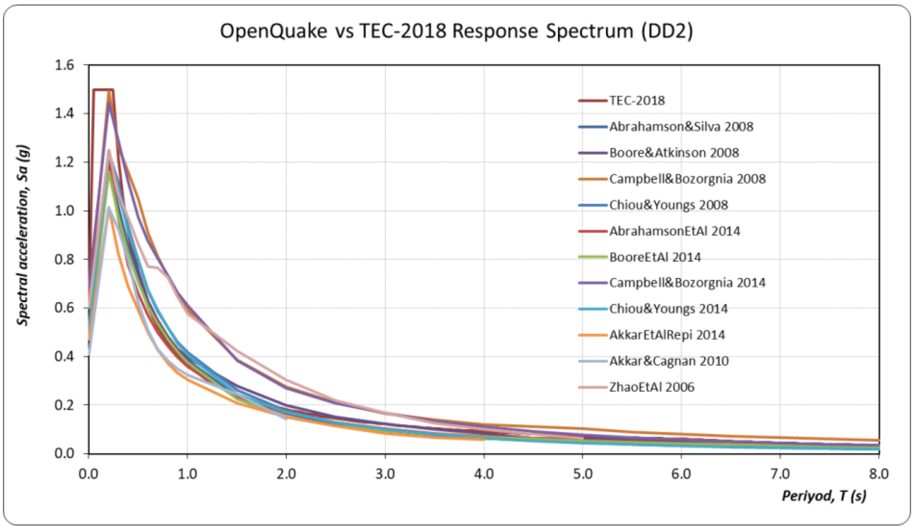

Fig. 7. Comparison of the results obtained from OpenQuake with the TEC-2018 spectrum using the relevant attenuation relations for the DD-2 earthquake ground motion level at the Kartepe district.

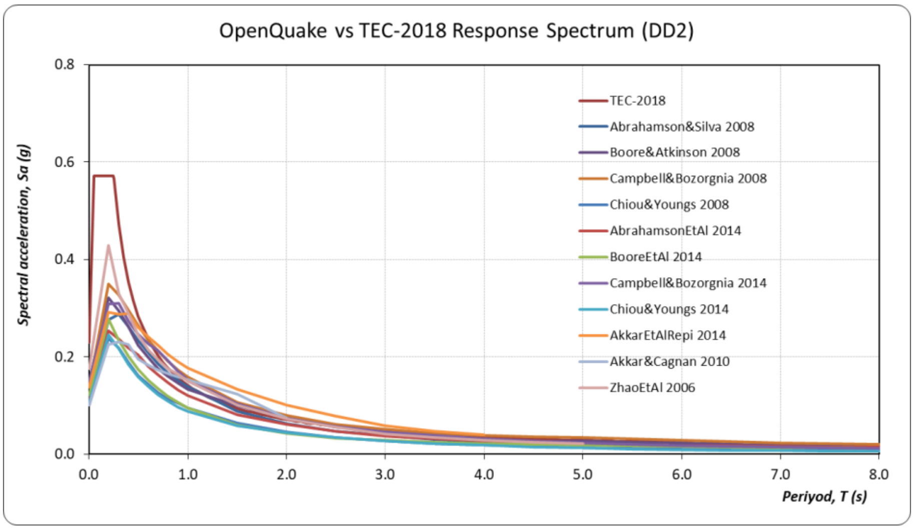

Fig. 8. Comparison of the results obtained from OpenQuake with the TEC-2018 spectrum using the relevant attenuation relations for the DD-2 earthquake ground motion level at the Kandıra district.

4. Seismic Risk Analyses

If the losses that may occur as a result of earthquakes can be reliably estimated, more rational decisions can be made for disaster preparedness, response and mitigation, and efficient use of the country's resources in line with development goals can be achieved. Seismic risk assessment studies provide important information about what needs to be done before and after an earthquake. From raising public awareness to conducting exercises, planners use the estimation of losses that may occur from earthquakes to prepare for disasters. Contributes to the development of national building design and reinforcement regulations, earthquake insurance and reinsurance models, cost-benefit analyses, and risk reduction plans (Çetin and Erberik 2017).

Using earthquake hazard and data related to the region together, earthquake risk analysis evaluates probabilities considering the earthquake risk, earthquake hazard, land use, demographic structure and economic structure. The outputs of the earthquake risk analysis include the estimations of the material losses that will occur in case of damage to the structures such as roads, industrial facilities, bridges, and dams, especially the loss of life caused by the earthquake (Tutar et al. 2017).

During the seismic risk analyses, the fragility curves used for the examined building group are important in terms of performing the analysis correctly. Fragility functions (curves) expressed as analytical functions are widely used to evaluate seismic risk or to make loss estimations. The fragility functions define the exceedance probabilities for different damage limit situations (Destroyed-Heavy-Medium-Low-Damaged) at a given ground shaking level (Çetin and Erberik 2017). The fragility curves used for loss and damage estimations in seismic risk assessments are created for building types with similar characteristics in a particular country or region. Due to the difficulties in creating fragility curves that take into account regional characteristics, existing fragility curves, which are mostly obtained as a result of international studies, are used to make damage and loss estimations (Çetin and Erberik 2017).

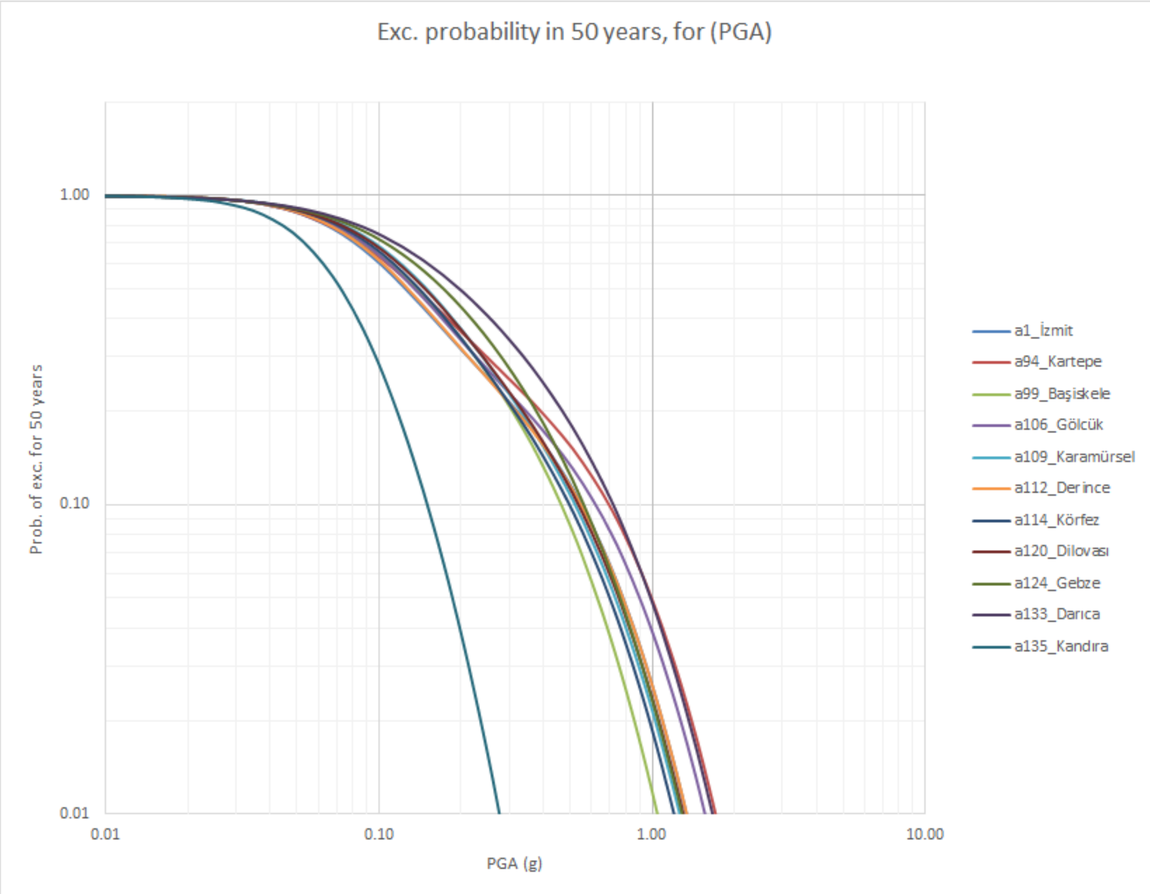

Fig. 9. Hazard curves obtained for PGA(g) at selected locations with $(Vs)_{30}$.

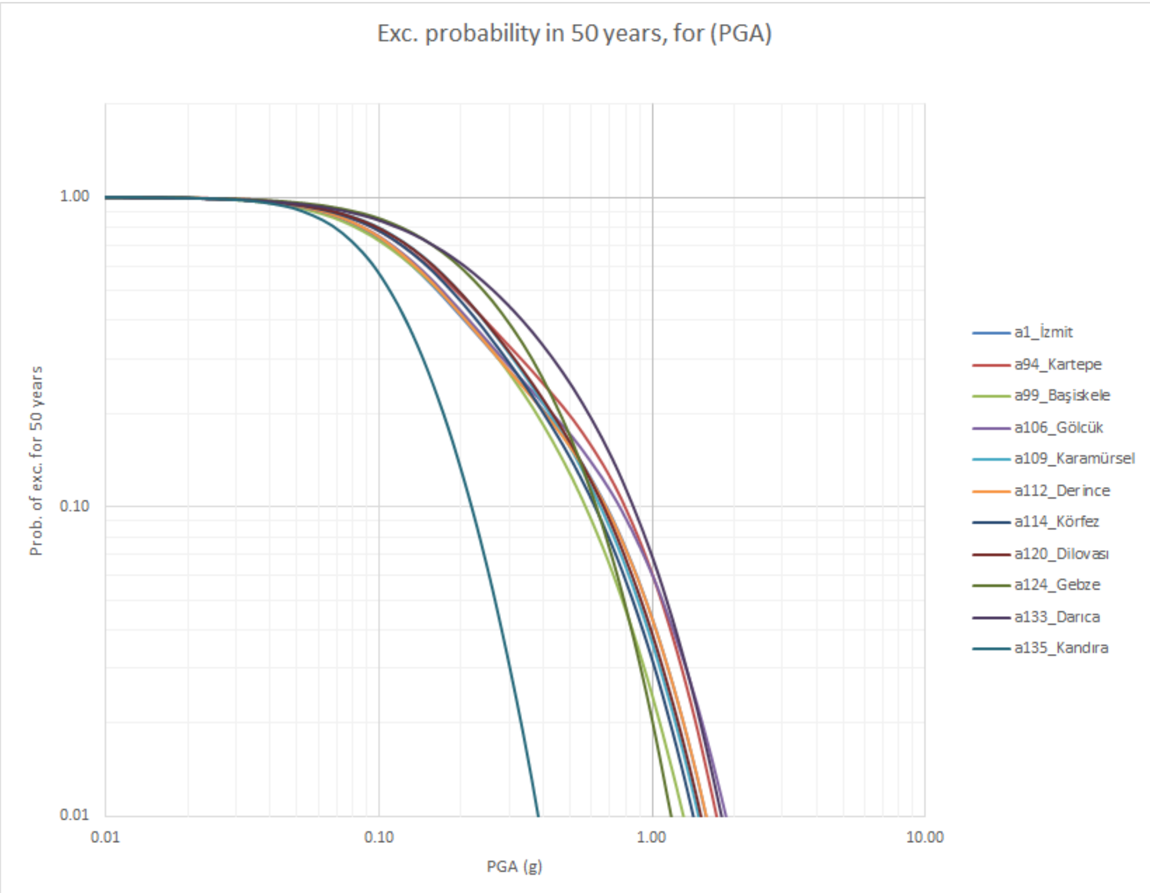

Fig. 10. Hazard curves obtained for PGA(g) at selected locations without with $(Vs)_{30}$.

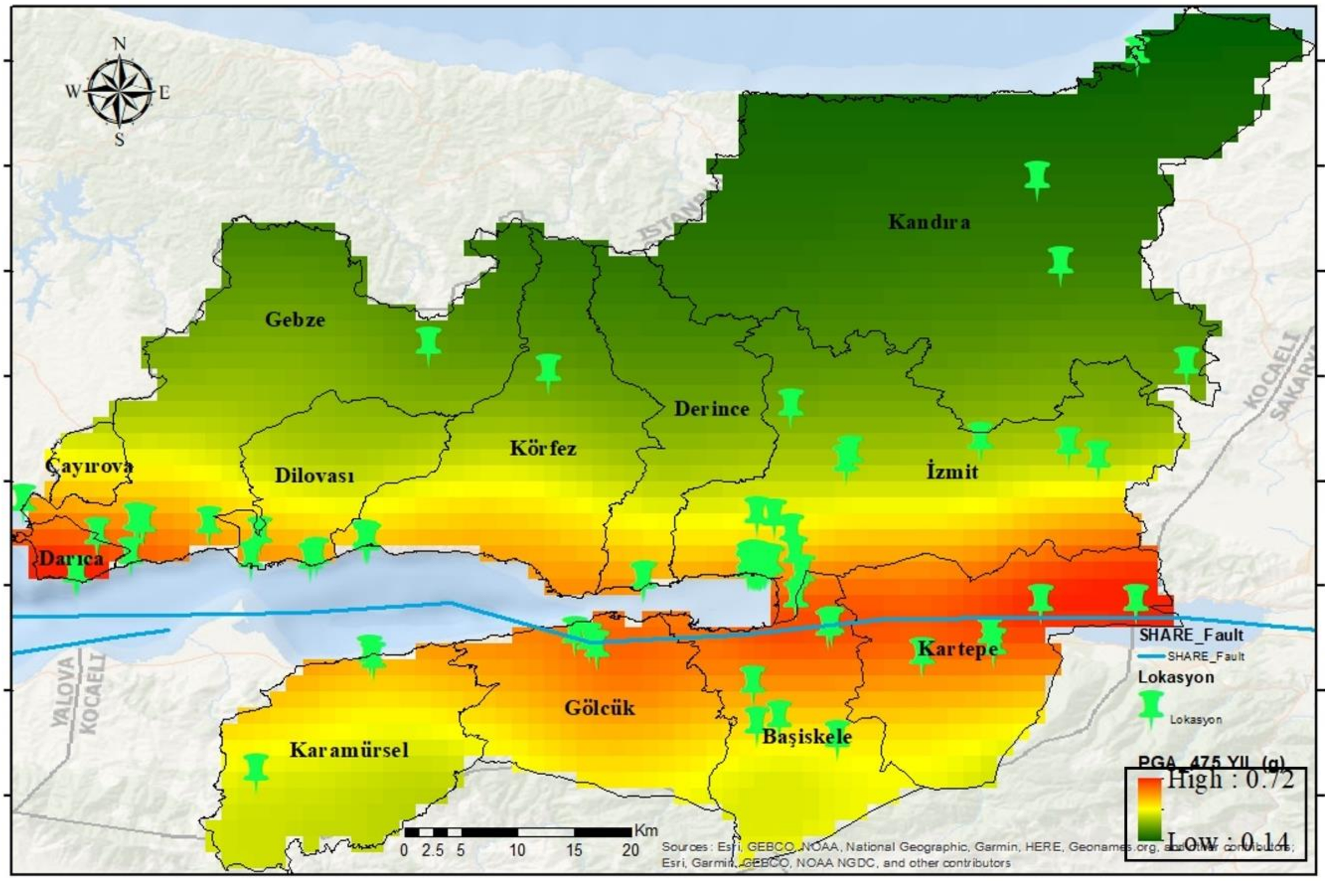

Fig. 11. PGA(g) level distribution for DD-2 earthquake ground motion level without $(Vs)_{30}$.

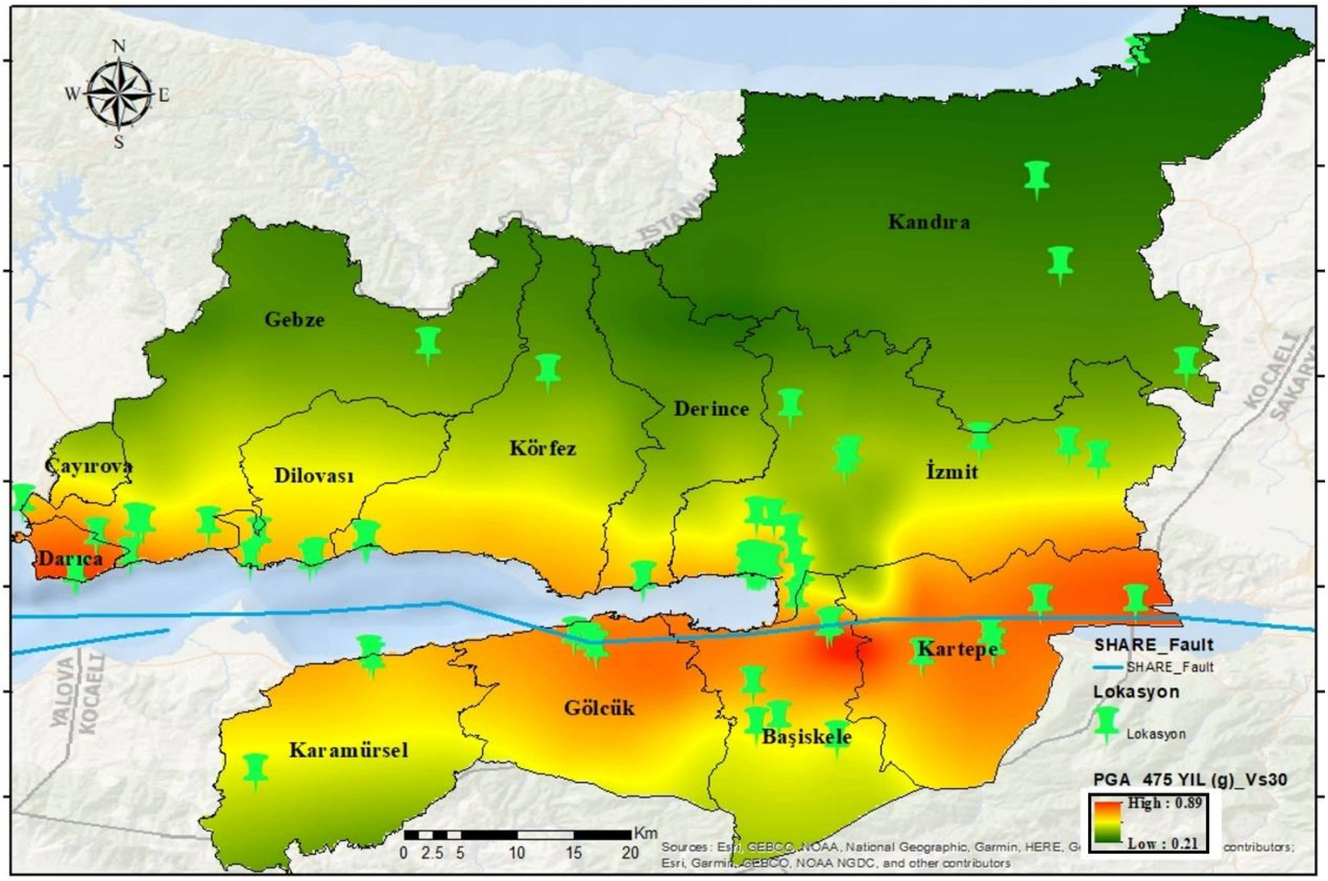

Fig. 12. PGA(g) level distribution for DD-2 earthquake ground motion level with $(Vs)_{30}$.

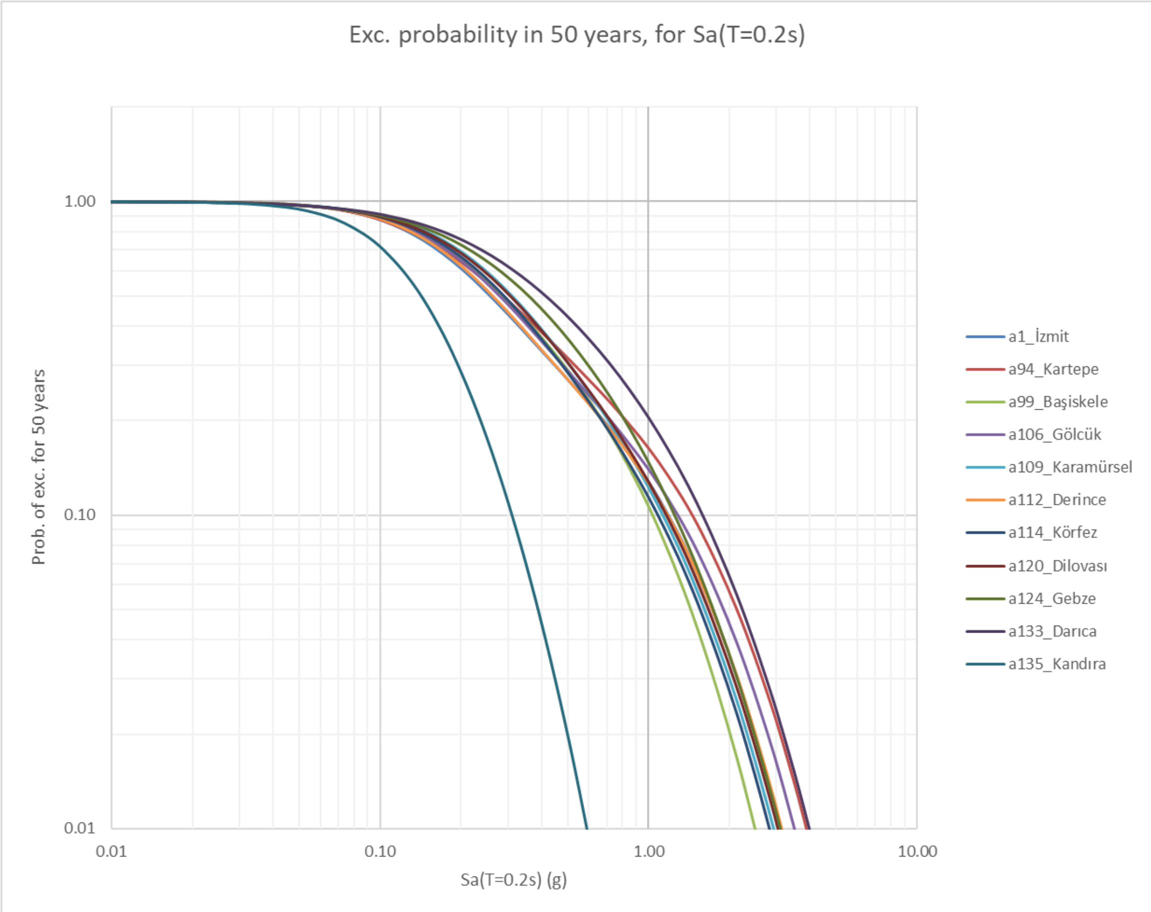

Fig. 13. Hazard curves obtained for $Sa(0.2)(g)$ at selected locations with $(Vs)_{30}$.

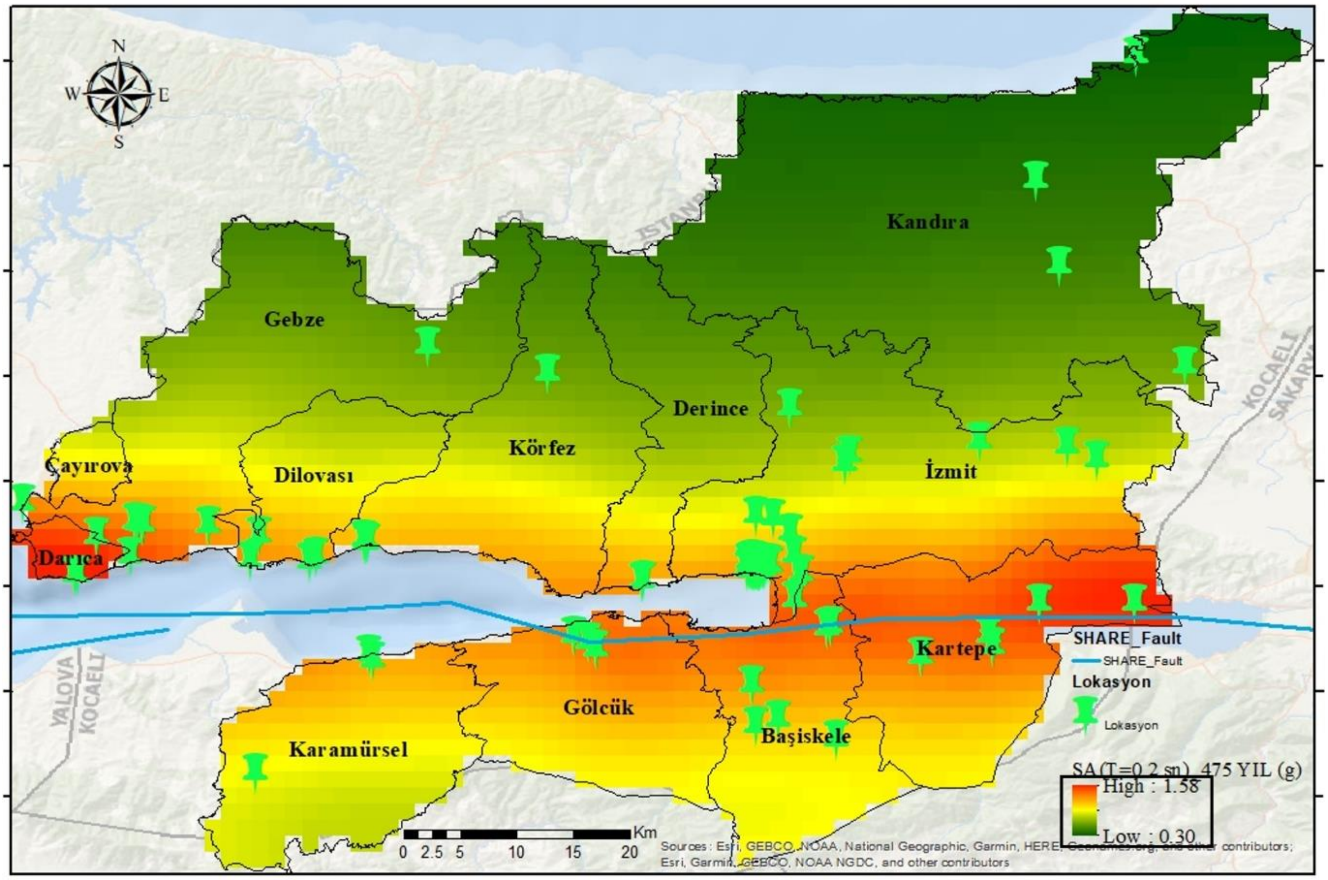

Fig. 14. $Sa(0.2)(g)$ level distribution for DD-2 earthquake ground motion level without $(Vs)_{30}$.

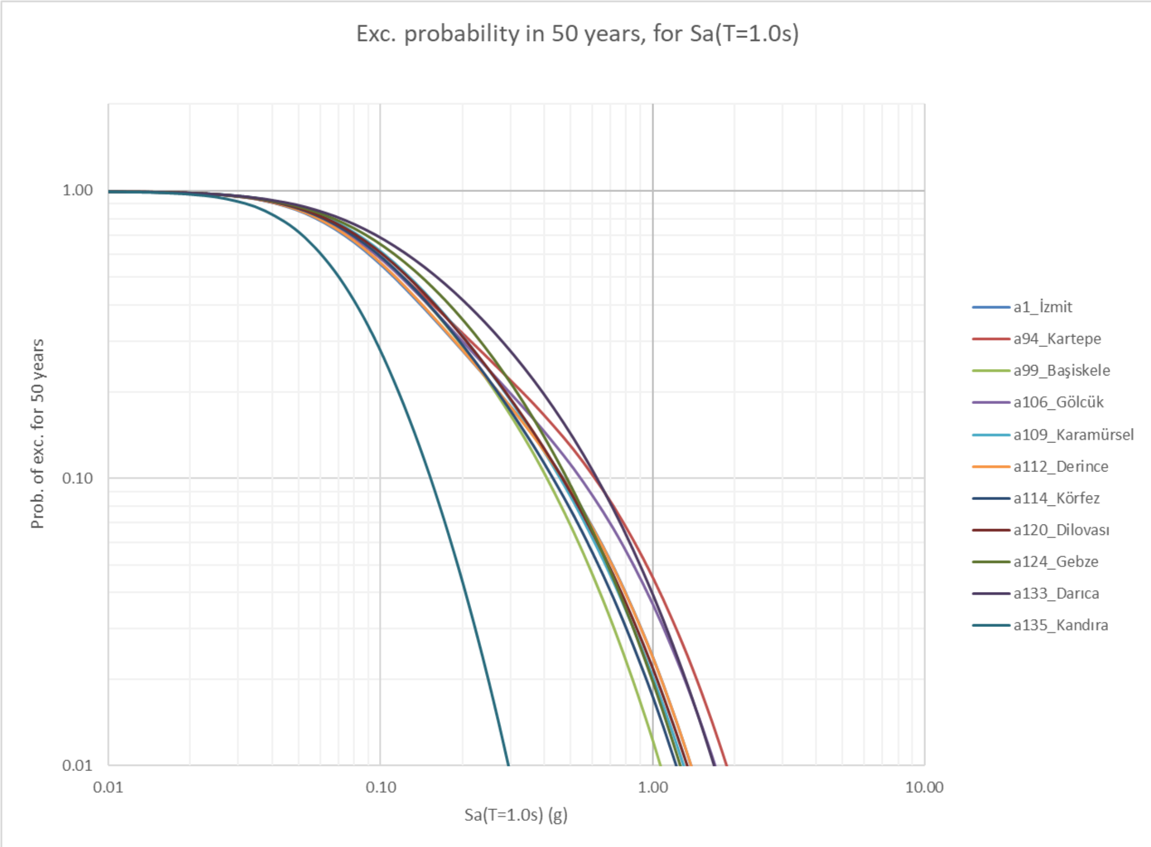

Fig. 15. $Sa(1.0)$(g) level distribution for DD-2 earthquake ground motion level without $(Vs)_{30}$.

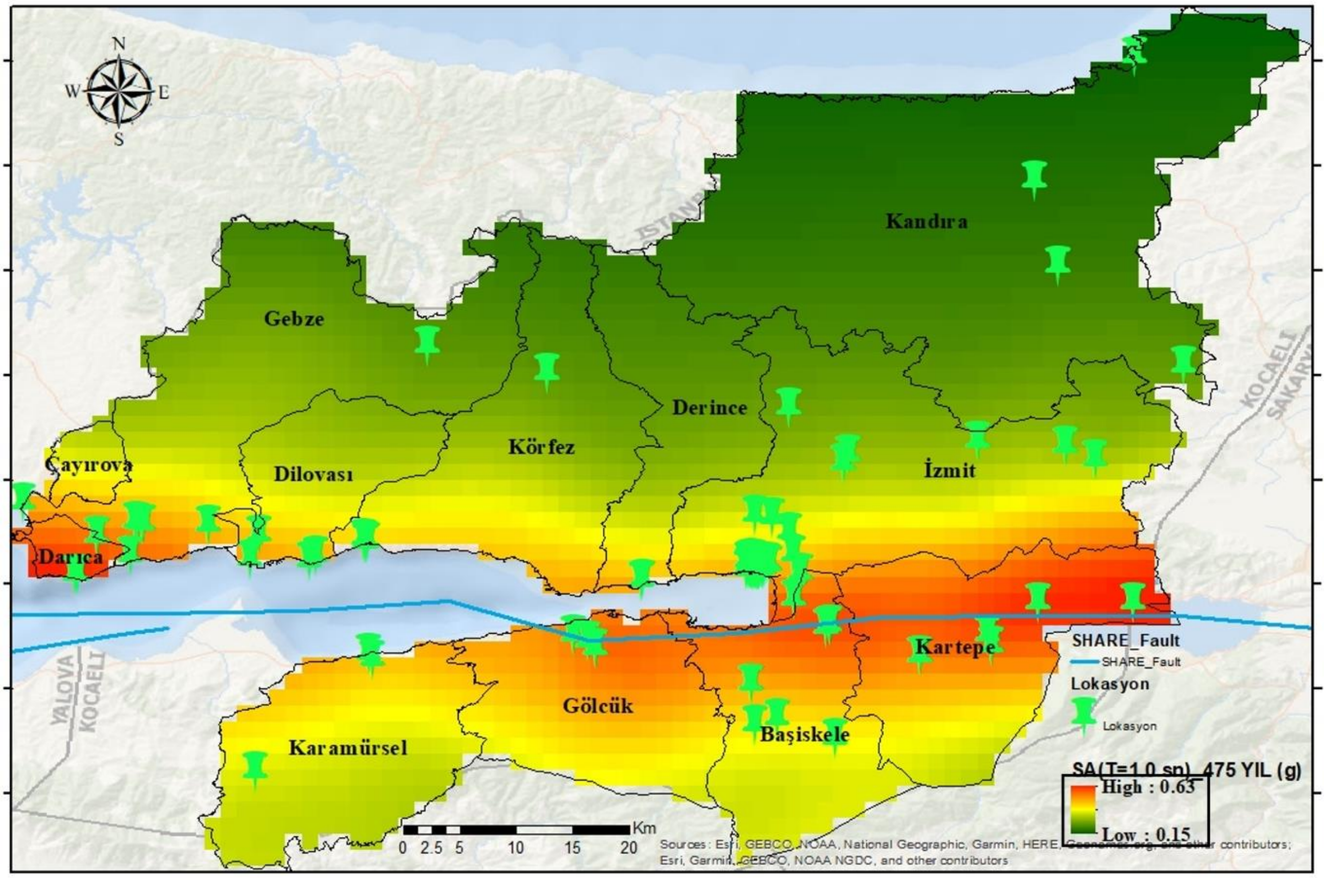

Fig. 16. $Sa(1.0)$(g) level distribution for DD-2 earthquake ground motion level without $(Vs)_{30}$.

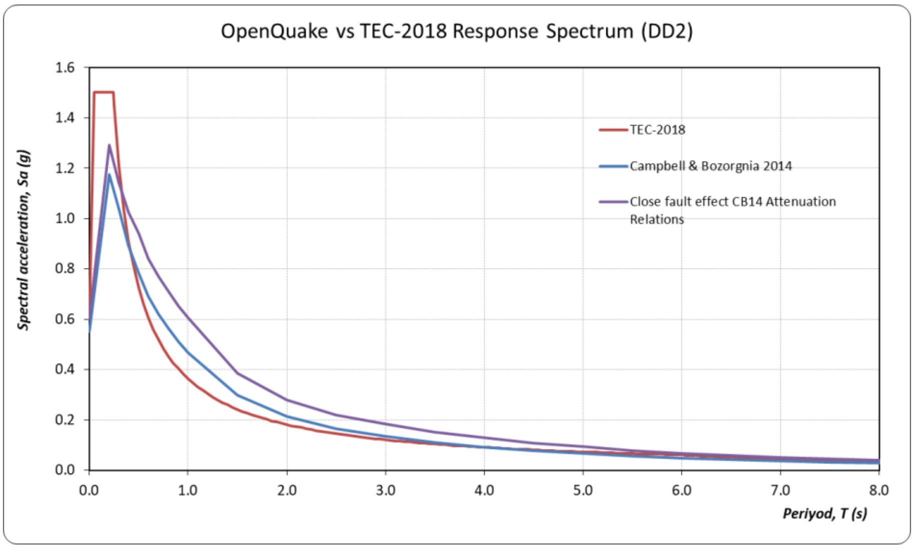

Fig. 17. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at İzmit location.

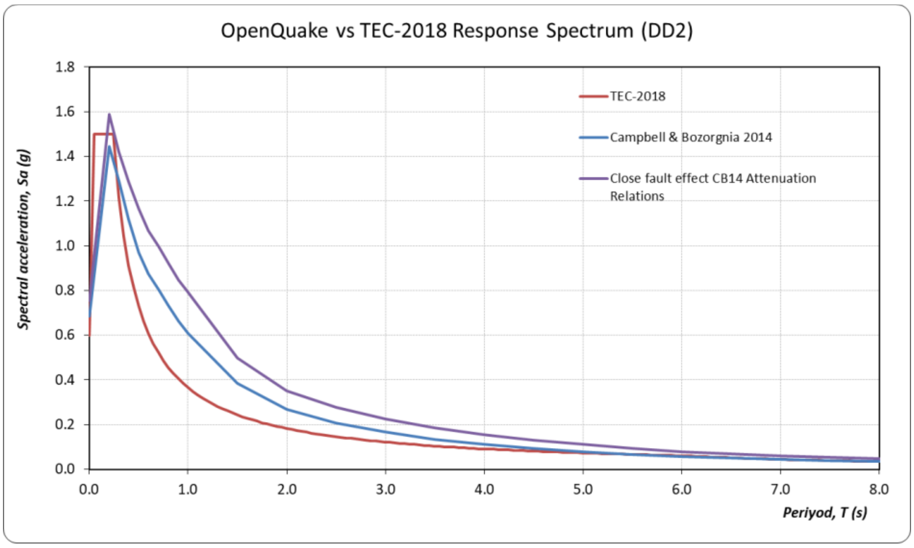

Fig. 18. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Kartepe location.

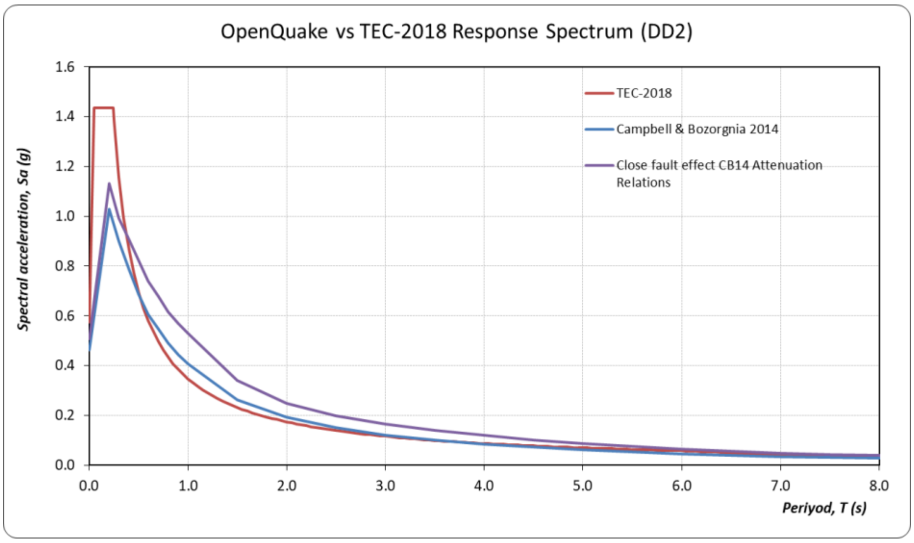

Fig. 19. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Başiskele location.

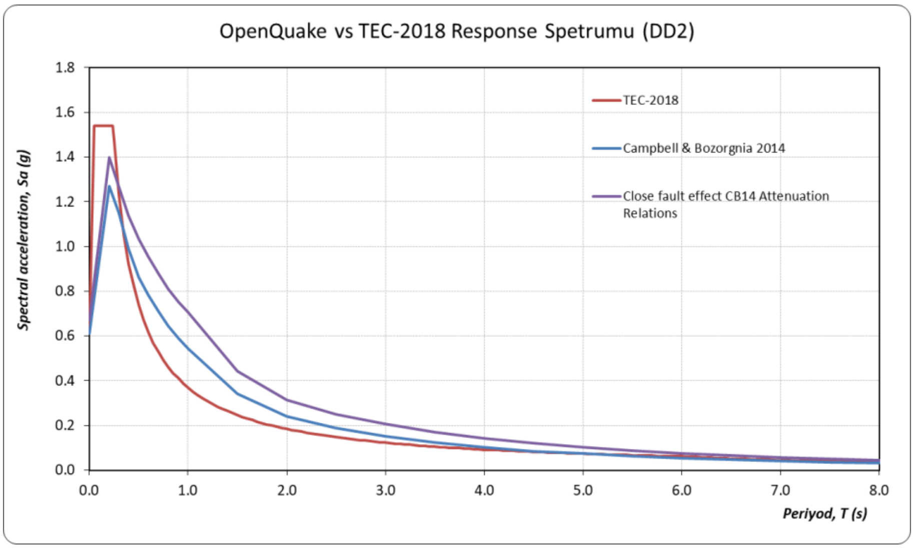

Fig. 20. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Gölcük location.

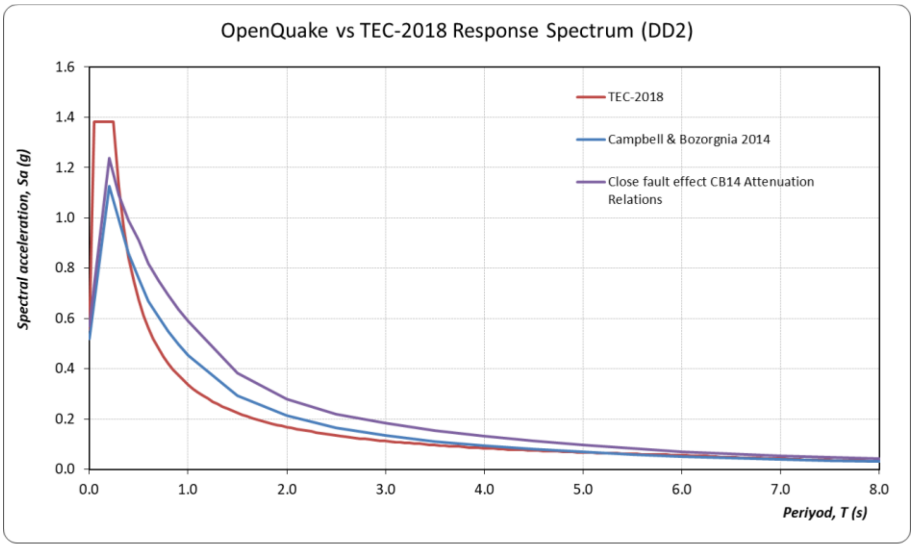

Fig. 21. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Karamürsel location.

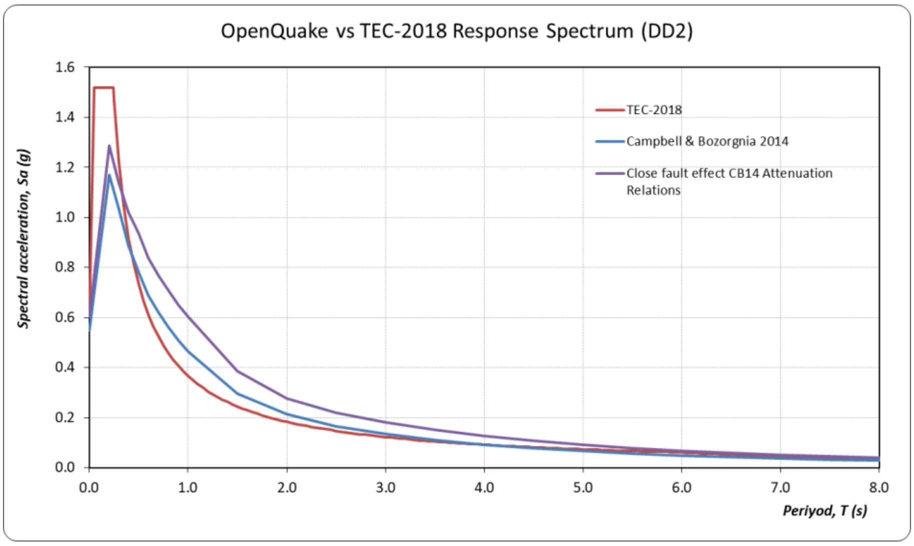

Fig. 22. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Derince location.

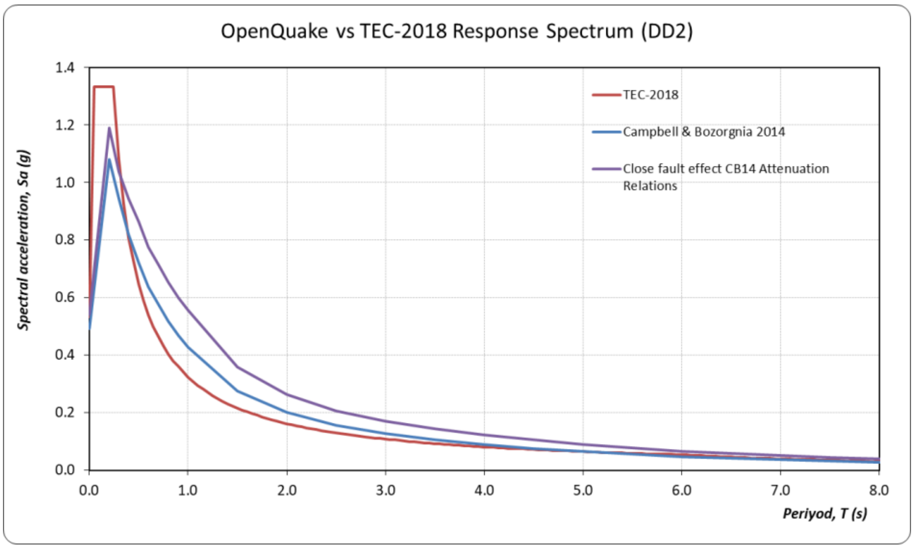

Fig. 23. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Körfez location.

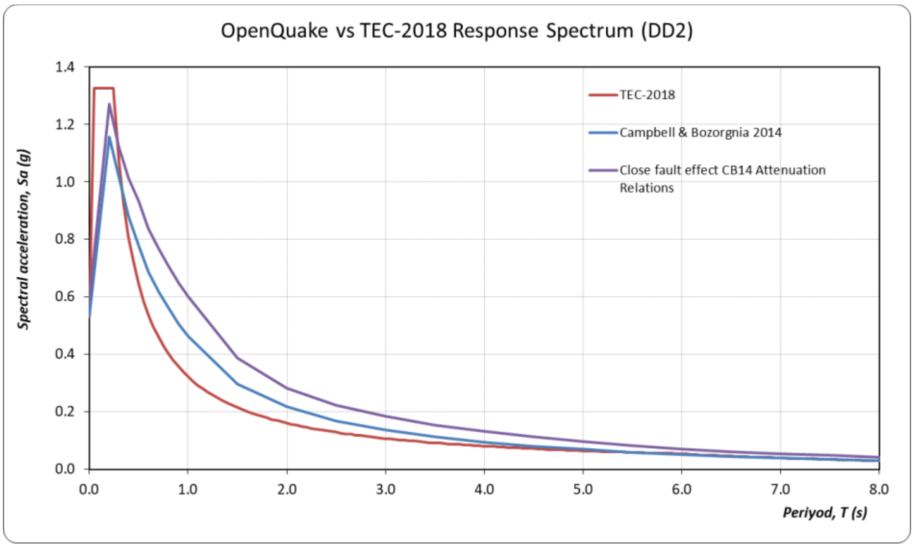

Fig. 24. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Dilovası location.

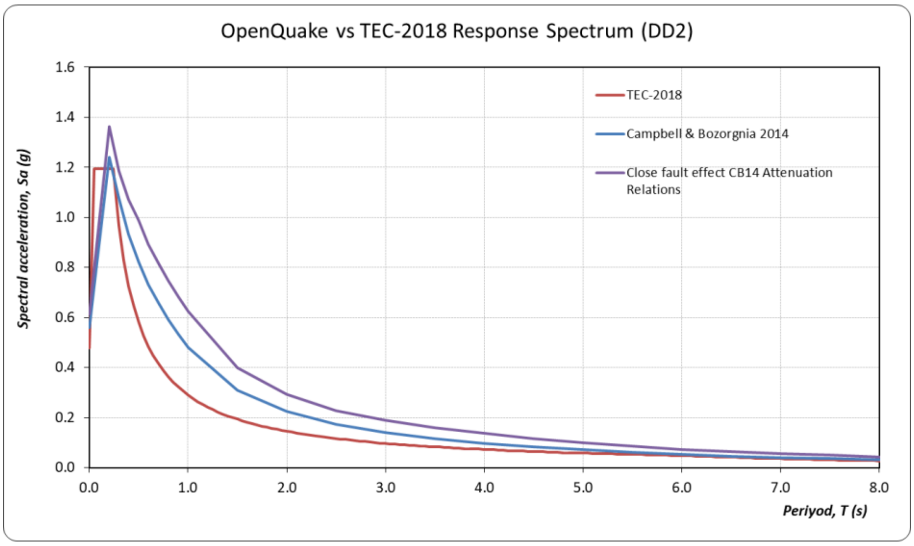

Fig. 26. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Gebze location.

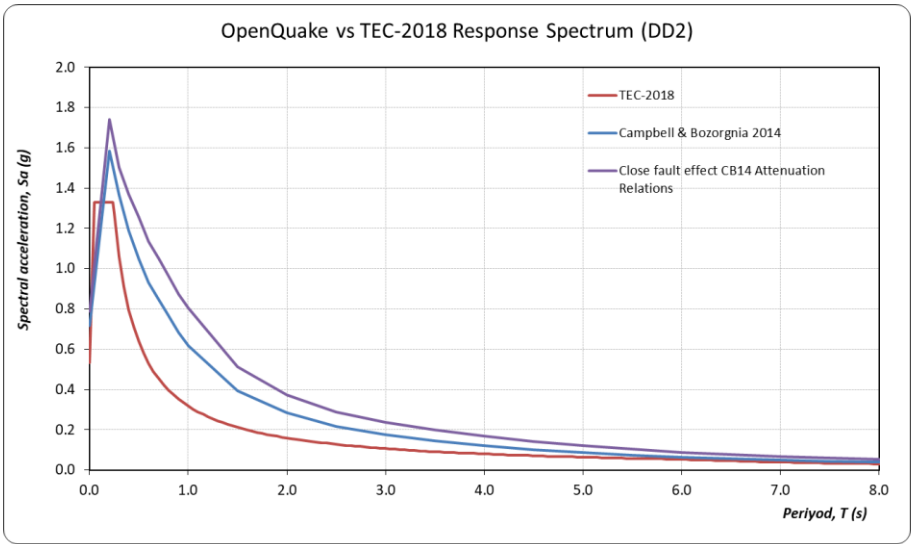

Fig. 26. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Darıca location.

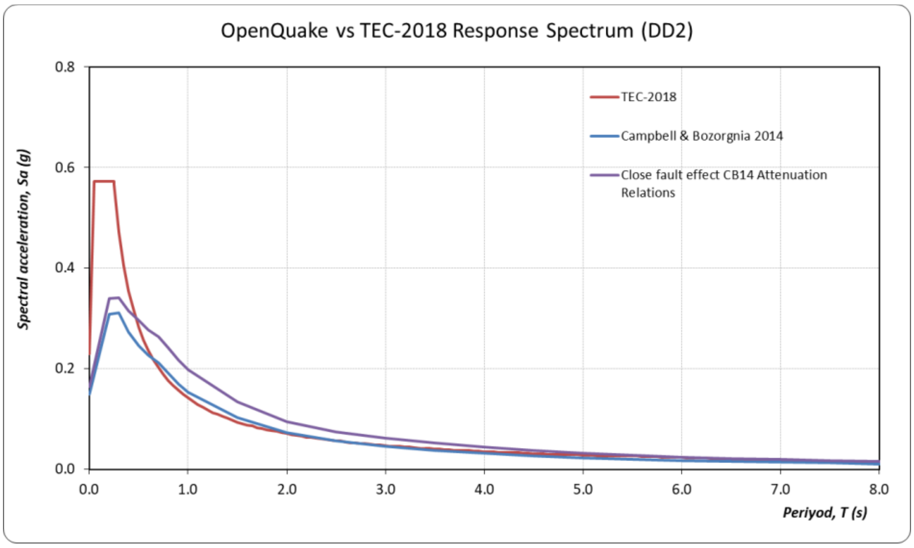

Fig. 27. Comparison of TEC-2018 spectrum with Campbell and Bozorgnia (2014) attenuation relationship and near-fault effect spectra obtained from OpenQuake for DD-2 earthquake ground motion level at Kandıra location.

In this study, there are 138 structures evaluated in this study, and these structures are categorized according to their types. Appropriate fragility curves for this building group, which consists entirely of masonry structures, have been investigated considering geographical applicability and structural features. Fragility curves determined according to the structures after the OpenQuake program library and literature research are given in Table 4.

Seismic risk estimations inherently involve various sources of uncertainty, particularly when applied to historical masonry structures with limited empirical data. In this study, two major sources of uncertainty were identified: (1) the use of international fragility curves, and (2) potential limitations within the building inventory data.

Due to the lack of region-specific empirical damage data for Turkish historical masonry buildings, fragility curves developed in different geographical and construction contexts were utilized. While these curves represent best available proxies, they may not fully capture the unique structural characteristics, material behavior, and construction practices of local heritage structures. As such, their application introduces uncertainty into the predicted damage distributions and associated risk levels.

When the results are examined, it is predicted that most of the structures will be damaged. At the same time, it was predicted that relatively few buildings would suffer mild to moderate damage and, as expected, a smaller number of building groups would suffer severe damage. Due to the relatively small number of structures examined in terms of a risk study, it is more meaningful to make the risk assessment proportionally within the scope of this study. In this context, when the building groups are interpreted by evaluating their ratio to all buildings, it has been determined that the risk values are tower-type structures, aqueduct-bridges, residential-type structures and domed structures, respectively, from high to low. At this point, the reason why domed structures are in the last place among the examined building types is thought to be due to the selection of the ones that can be used most closely, since the appropriate fragility curves for some different structures included in this study (such as mosques, some masjids) cannot be found in the literature. It should be noted that the assumptions made due to the limited number of the analyzed building stock, the relatively small number of some building groups compared to the others, the distribution of the structures and their distance from the fault sources, and the lack of sufficient number of fragility curves specific to different structures in the literature affect the results.

Table 4. Fragility curves used in the study.

Building Type	Number of Floors	Reference	Taxonomy	Number of Buildings
Building (Housing, Mansion, etc.)	1	Erberik (2008)	MUR+CBH+MOL/LWAL/HEX:1/IRIR+IRPP: TOR+IRPS:IRN (GEM)	7
Building (Housing, Mansion, etc.)	2	Erberik (2008)	MUR+CBH+MOL/LWAL/HEX:2/IRIR+IRPP: TOR+IRPS:IRN (GEM)	55
Building (Housing, Mansion, etc.)	3	Erberik (2008)	MUR+CBH+MOL/LWAL/HEX:3/IRIR+IRPP: TOR+IRPS:IRN (GEM)	18
Building (Housing, Mansion, etc.)	4	Erberik (2008)	MUR+CBH+MOL/LWAL/HEX:4/IRIR+IRPP: TOR+IRPS:IRN (GEM)	3
Domed Structures (Mosque, Church, Some Masjids and Baths)	-	Hofer et al. (2018)	M99/LWAL/RSH7	42
Aqueduct and Bridges	-	Tecchio et al. (2016)	M99/COM+COM6/RSH7	12
Clock Tower	-	Durgut et al. (2021)	M99/LWAL/COM/PLFSQ	1

Table 5. Distribution of damage levels by building types.

Building Type	No Damage	Slight-Moderate	Extreme-Compete	Number of Buildings
Building Structures	49.531	10.898	22.570	83
Domed Structures	32.461	3.899	5.640	42
Aqueduct and Bridges	6.816	1.870	3.314	12
Clock Tower	0.090	0.232	0.680	1
Total	88.899	16.899	32.204	138

While seismic risk assessment provides a quantitative basis for identifying structurally vulnerable buildings, effective conservation planning must also consider the cultural and historical significance of these assets. Structures such as towers and aqueducts, although assessed as high-risk in terms of seismic vulnerability, may vary in their heritage value depending on historical context, architectural uniqueness, and community relevance. Therefore, conservation prioritization should be based on a balanced approach that combines structural fragility with cultural importance. This dual-criteria framework can help authorities ensure that limited restoration and retrofitting resources are directed not only toward the most physically endangered structures, but also those with the highest historical and symbolic value to society.

5. Conclusions

Türkiye is prone to earthquakes due to its location, so it is considered necessary to conduct regional or comprehensive hazard and risk analyses for a broad range of building types to determine which buildings are at risk. In this context, fragility curves, which are critical data in risk analysis, are not found in sufficient numbers, especially in Türkiye, which hosts a wide range of building types. Consequently, it would be beneficial to develop structure-specific fragility curves to improve the efficiency of risk analysis.

In this part of the study, the results of seismic hazard and risk analyzes were examined and the results were discussed. Based on the hazard curves generated by OpenQuake hazard analysis, the following conclusions can be drawn. The majority of the 11 reference locations in the investigation area are located near faults. From these locations, it is seen that the values in locations such as Darıca, Gölcük, Kartepe, which are relatively close to the faults, give higher values compared to other points. However, the values obtained in Kandıra district, which is farther from the faults compared to other regions, were lower.

In the three different hazard curves obtained against the spectral periods of PGA, $Sa(0.2)$ and $Sa(1.0)$, the values of Kandıra district yielded lower results compared to other locations. DD-2 earthquake ground motion level from these three different graphs indicate that the hazard values of Kandıra district vary between 0.15-0.30 (g), while in other locations, it was between 0.40-1.00 (g) and in the curves obtained for $Sa(0.2)$. It was observed that these values reached 1.50 (g) levels at points such as Darıca and Kartepe, which were relatively close to the faults.

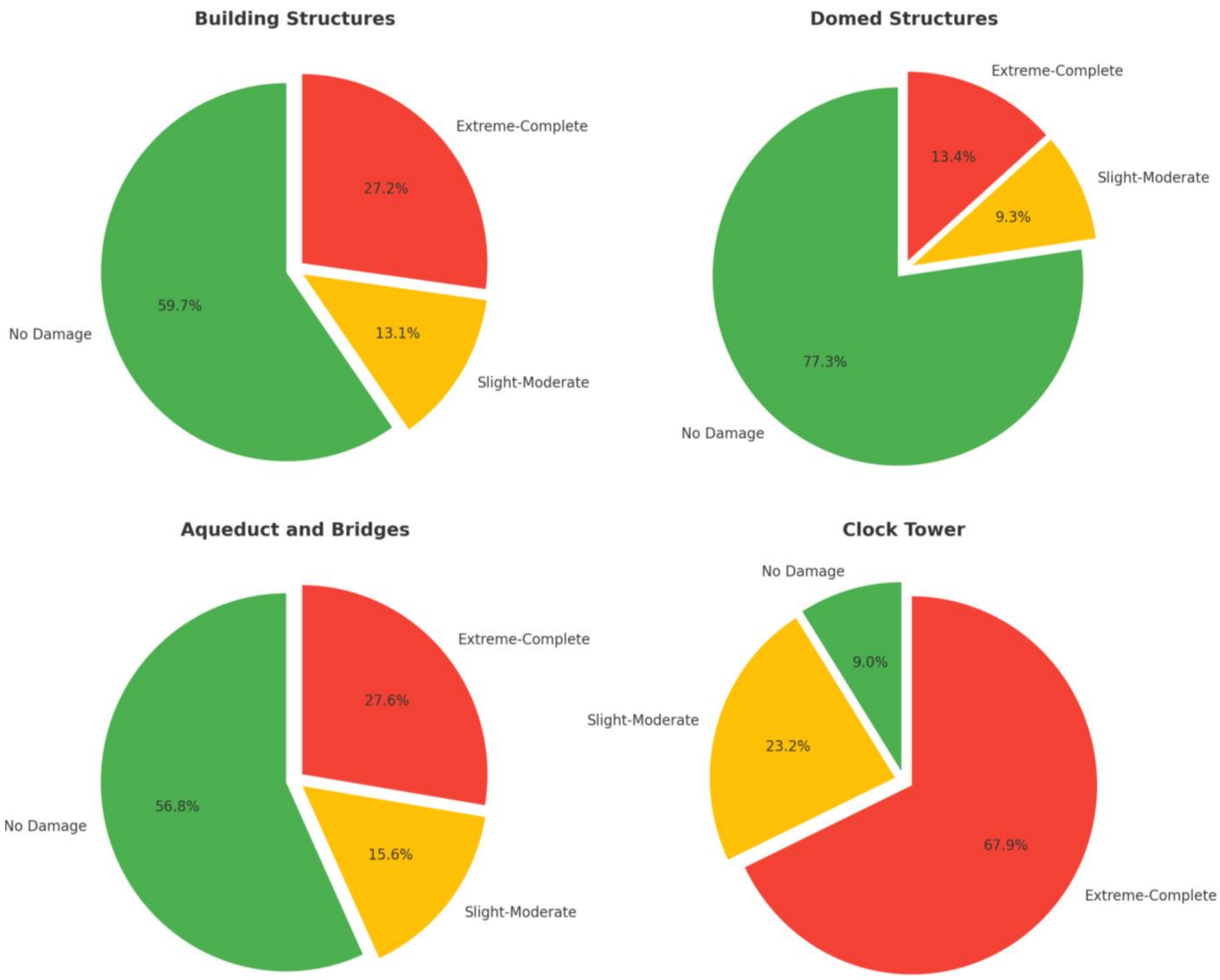

Fig. 28. Distribution percentage of damage levels by building groups.

When looking at the general earthquake hazard maps obtained in response to the DD-2 earthquake ground motion level and PGA, $Sa(0.2)$ and $Sa(1.0)$ spectral periods, a certain level of detection is detected in the middle section covering the northern parts of Karamürsel, Gölcük, Başiskele districts from the southern part of Kandıra district. The intensity distributions obtained increased on a point basis depending on their proximity to the fault but remained in an average range. In addition, decreases in values are observed in the northern parts of Kandıra district and in the southern borders of Karamürsel and Başiskele districts, which are far from the faults compared to other locations. It is possible to interpret the maps in detail as follows.

When the results obtained for the PGA were examined, the values obtained for the DD-2 earthquake ground motion level were in the range of 0.28-0.76 (g), while this value increases to 0.88 (g) in locations close to the fault and decreases to 0.16 (g) in the northern borders of Kandıra district and the southern end of the investigation area. When the results obtained for $Sa(0.2)$ are examined, the values obtained for the DD-2 earthquake ground motion level are in the range of 0.62-1.46 (g), while this value is at the level of 0.35 (g) in the northern borders of Kandıra district and the southern end of the target area. When the results obtained for $Sa(1.0)$ are examined, the values obtained for the DD-2 earthquake ground motion level are in the range of 0.26-0.68 (g), while this value increases to 0.68-0.79 (g) levels in locations close to the fault, and decreases to 0.15 (g) in the northern borders of Kandıra district and the southern parts of the target area.

Risk studies of different building groups, regional and more comprehensive hazard studies, and hazard analyses using deterministic approaches have been published in the literature. Nevertheless, this study is at a critical point in terms of earthquake activity, as explained in the previous sections. The probabilistic approach covers evaluating a wide range of parameters within the possibilities rather than the deterministic approach. Therefore, it is considered to be a study that includes many features, including the necessity of protection. It presents information about the material used, the building type, and the period when it was built, among others.

Although domed structures were ranked as having the lowest seismic risk among the structural typologies analyzed, this result should be interpreted with caution. The absence of typology-specific fragility curves for domed heritage structures, such as mosques and some churches, likely results in an underestimation of their actual vulnerability. This limitation stems from the necessity to adopt proxy fragility curves that may not adequately reflect the dynamic behavior of such geometrically complex and historically unique structures. Therefore, the risk categorization presented in this study does not fully capture the seismic fragility of domed buildings and highlights the need for future empirical calibration based on field testing and structural monitoring.

In future studies, the development of fragility curves specifically calibrated for Turkish historical masonry structures is strongly recommended. These curves should be based on empirical damage data and structural monitoring from local case studies to more accurately reflect the behavior of region-specific building typologies under seismic loading. Additionally, integrating seismic risk outputs into regional early warning systems and conservation prioritization frameworks can significantly enhance proactive risk mitigation for cultural heritage assets. Such integration would allow authorities to make data-driven decisions for emergency preparedness, resource allocation, and long-term resilience planning. Moreover, on-site dynamic testing and modal analyses of representative structures are suggested to support numerical model calibration and further reduce uncertainties in both hazard and risk assessments.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, ChatGPT-5 (OpenAI) was used exclusively for image creation, language editing and stylistic refinement. The authors take full responsibility for the content, interpretation, and conclusions of the published article.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

References

Abrahamson N, Silva W (2008). Summary of the Abrahamson & Silva Nga Ground-motion relations. *Earthquake Spectra*, 24, 67–97.

Abrahamson NA, Silva WJ, Kamai R (2014). Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra*, 30, 1025–1055.

Ademović N, Demir V, Cvijić-Amulić S, Málek J, Prachař I, Vackář J (2021). Compilation of the seismic hazard maps in Bosnia and Herzegovina. *Soil Dynamics and Earthquake Engineering*, 141.

Akın S, Alagöz A (2024). Structural behavior of historical Obruk Inn under different earthquakes. *Challenge Journal of Structural Mechanics*, 10(1), 21-33.

Akkar S, Cagnan Z (2010). A local ground-motion predictive model for Turkey, and its comparison with other regional and global ground-motion models. *Bulletin of the Seismological Society of America*, 100, 2978–2995.

Akkar S, Sandıkkaya MA, Bommer JJ (2013). Empirical ground-motion models for point and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of Earthquake Engineering*, 12, 359–387.

Aksoy T (2011). Kocaeli Cultural Inventory. Kocaeli Metropolitan Municipality Department of Culture and Social Affairs Culture Publishing, Kocaeli, Türkiye.

Arzomand K, Rustell M, Kalganova T (2024). From ruins to reconstruction: Harnessing text-to-image AI for restoring historical architectures. *Challenge Journal of Structural Mechanics*, 10(2), 69-85.

Biglari M, Formisano A, Davino A (2022). Seismic vulnerability assessment and fragility analysis of Iranian historical mosques in Kermanshah City. *Journal of Building Engineering*, 45.

Boore DM, Atkinson GM (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01*s*and 10.0*s*. *Earthquake Spectra*, 24, 99–138.

Boore DM, Stewart JP, Seyhan E, Atkinson GM (2014). NGA-WEST2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. *Earthquake Spectra*, 30, 1057–1085.

Campbell KW, Bozorgnia Y (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra*, 24, 139–171.

Campbell KW, Bozorgnia Y (2014). Nga-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. *Earthquake Spectra*. 30, 1087–1115.

Çetin C, Erberik MA (2017). Kırılganlık eğrileri kullanılarak elde edilen tahmini hasar dağılımının hasar tespit verileriyle karşılaştırılması. *Fourth International Conference on Earthquake Engineering and Seismology*, Eskişehir, Türkiye. (in Turkish)

Chiou BSJ, Youngs RR (2008). An NGA model for the average horizontal component of peak ground motion and Response Spectra. *Earthquake Spectra*, 24(1), 173–215.

Chiou BSJ, Youngs RR (2014). Update of the Chiou and Youngs Nga model for the average horizontal component of peak ground motion and Response Spectra. *Earthquake Spectra*, 30, 1117–1153.

Cuadra C, Karkee MB, Tokeshi K (2008). Earthquake risk to Inca's historical constructions in Machupicchu. *Advances in Engineering Software*, 39, 336–345.

Durgut E, Kuran F, Ispir M, Demir C, Turan ÖT, İlki A (2021). Bursa ilindeki tarihi minarelerin kırılganlık eğrilerinin elde edilmesi. *Bursa Historical Mosque Minarets Earthquake Behavior Workshop*, İstanbul, Türkiye. (in Turkish)

Erberik MA (2008). Generation of fragility curves for Turkish masonry buildings considering in-plane failure modes. *Earthquake Engineering & Structural Dynamics*, 37, 387–405.

Fazzi E, Galassi S, Misseri G, Rovero L (2021). Seismic vulnerability assessment of the Benedictine basilica typology in Central Italy. *Journal of Building Engineering*, 43.

Gövsulu G (2020). CRISIS (2015) Programı Kullanılarak İzmir İli Urla-Çeşme-Karaburun Çevresi Sismik Tehlike Analizi. *M.Sc. thesis*, Dokuz Eylül University, İzmir, Türkiye. (in Turkish)

Gündoğdu Gök M (2020). Monte Carlo Yöntemi İle Kocaeli İli ve Çevresi İçin Olasılıksal Deprem Tehlike Analizi. *M.Sc. thesis*, Gebze Technical University, Kocaeli, Türkiye. (in Turkish)

Hofer L, Zampieri P, Zanini MA, Faleschini F, Pellegrino C (2018). Seismic damage survey and empirical fragility curves for churches after the August 24, 2016 Central Italy earthquake. *Soil Dynamics and Earthquake Engineering*, 111, 98–109.

Hoveidae N, Fathi A, Karimzadeh S (2021). Seismic damage assessment of a historic masonry building under simulated scenario earthquakes: A case study for Arge-Tabriz. *Soil Dynamics and Earthquake Engineering*, 147, 106732.

Kramer S (1996). Geotechnical Earthquake Engineering. First ed. Prentice Hall, New Jersey, USA.

Lourenço PB, Oliveira DV, Leite JC, Ingham JM, Modena C, da Porto F (2013). Simplified indexes for the seismic assessment of masonry buildings: International database and validation. *Engineering Failure Analysis*, 34, 585–605.

Merdan Tutar Z, Zülfikar AC, Demircioğlu MB, Kariptaş Ç (2017). 1999 Kocaeli Depremi'nin Deprem Tehlikesi ve Riski Açısından Kocaeli İlindeki Etkisi. *Fourth International Conference on Earthquake Engineering and Seismology*, Eskişehir, Türkiye. (in Turkish)

Oktay S, Taş N, Taş M (2020). Kültürel Miras Alanlarının Korunması ve Afet Yönetimi İlişkisi. *Resilience*, 2, 305-321. (in Turkish)

Pirchio D, Walsh KQ, Kerr E, Giongo I, Giaretton M, Weldon BD (2021). Seismic risk assessment and intervention prioritization for Italian medieval churches. *Journal of Building Engineering*, 43, 103061.

TEC (2018). Turkish Earthquake Code. Republic of Türkiye Ministry of Interior, Disaster and Emergency Management Authority (AFAD), Ankara, Türkiye.

Tecchio G, Donà M, da Porto F (2016). Seismic fragility curves of as-built single-span Masonry Arch Bridges, *Bulletin of Earthquake Engineering*, 14, 3099–3124.

VGM (2017). Guide to the International Symposium of Earthquake Risk Management of Historical Structures. https://www.vgm.gov.tr/organizasyonlar/tarihi-yapilarda-deprem-risklerinin-yonetimi-uluslararasi-sempozyumu/kilavuz/ [accessed 02 February 2022].

Yücemen M (2011). Olasılıksal sismik tehlike analizi: Genel bakış ve istatiksel modellemede dikkat edilmesi gerekli hususlar. *1st Turkey Earthquake Engineering and Seismology Conference*, Ankara, Türkiye. (in Turkish)

Zardari S, Kutlu İ, Nayeb A (2024). Investigation of structural performances of historical building elements made with local materials using the finite element method. *Challenge Journal of Concrete Research Letters*, 15(3), 101-111.

Zhao JX (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, 96, 898–913.

Zülfikar AC, Okuyan Akcan S, Yeşilyurt A, Eröz M, Cimilli T (2021). Kritik enerji tesislerinin deprem risk değerlendirmesinde farklı hasargörebilirlik fonksiyonlarının incelenmesi. *Çukurova University Faculty of Engineering Journal*, 36(4), 1019-1032. (in Turkish)