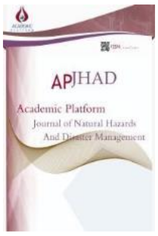

Research Article
Academic Platform Journal of Natural Hazards and Disaster Management
4(1), 1-11, 2023 DOI: 10.52114/apjhad.1211625

Comparative Probabilistic Seismic Hazard Analysis for Sakarya

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Received: / Accepted: 29-November-2022 / 24-January-2023

Abstract

Sakarya province can be significantly affected by earthquakes on the North Anatolian Fault. Earthquake hazard includes some uncertainties. Earthquake catalog data is needed for probabilistic earthquake hazard calculations. In addition to current catalog information, existing attenuation relationships, including earthquake characteristics for the region, should be developed or their suitability checked. For this purpose, an earthquake hazard analysis was carried out for the Serdivan, Erenler, Adapazarı, and Arifiye districts of Sakarya by using the Earthquake Model of the Middle East Region (EMME) data catalog, which was carried out on a global scale and using the Abrahamson Silva Kamai 2014 (ASK14) model from the Next Generation Attenuation (NGA)-West2 equations. CRISIS software was used for analysis. As a result of the study, changes were observed in different exceedance rates and different site classes.

Keywords: Probabilistic earthquake hazard analysis, Sakarya, CRISIS, TBEC 2018

1. Introduction

Sakarya province was greatly affected by the 1999 Kocaeli and Düzce earthquakes, and as a result, significant losses were experienced. Due to its location, it has a tectonic origin basic structure with fertile alluvium on the North Anatolian Fault Line [1]. After 1900, earthquakes started to be recorded instrumentally in Türkiye. In earthquake studies for Türkiye, the first unofficial seismic zone map was published by Sieberg (1932) [2]. After the 1939 Erzincan Earthquake and the 1944 Bolu Gerede Earthquake, the first official seismic zone map for Türkiye was published in 1945. In 1963, isothermal intensity maps, tectonic maps, literature studies, and macro seismic intensity were taken into account and were renewed. In 1992, an earthquake zone map that considered probabilistic calculations was developed for peak ground acceleration with recurrence periods of 100, 225, 475, and 1000 years [3].

Probabilistic methods started to be used in earthquake hazard calculations, and the Turkish Building Earthquake Code 2018 (TBEC 2018) took its place [4]. In the TBEC 2018, earthquake levels are given according to the probability of exceeding them in 50 years. The largest earthquake ground motion level (DD-1) represents an earthquake with a 2% probability of being exceeded in 50 years, and the design basis earthquake level (DD-2) represents an earthquake with a 10% probability of being exceeded in 50 years. Exceeding probabilities are calculated using distribution approaches such as Poisson and Gumbel [5], [6].

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Projects such as National earthquake research program (UDAP) (2012-2023) [2], Provincial Level Disaster Risk Reduction Plan (İRAP)[7], AFAD Rapid Earthquake Damage and Loss Estimation (AFAD-RED)[8], and Earthquake Loss Estimation Routine (ELER)[9] are existing projects and software that contribute to Türkiye for earthquake hazard and risk studies.

Some researchers have applied various scenarios of earthquakes while others have used research methods. Scenario earthquake takes into account a single earthquake, while probabilistic extension considers all earthquakes occurring in the region. For this reason, it has been a preferred solution method in recent years. Various purposes are used to avoid making probabilistic recommendations. While earthquakes are described as a random events, the knowledge-based models of these events are characterized by epistemic uncertainty [10].

Many probabilistic seismic hazard analysis studies are conducted in Türkiye [11]–[14]. The most recent study found in the literature for the Marmara region was made for Kocaeli and its surroundings and included a part of Sakarya [3].

Global Earthquake Model (GEM1) [15], Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain (SYNER-G) [16], Seismic Hazard Harmonization in Europe (SHARE) and Earthquake Model of the Middle (EMME) [17] large-scale projects such as East Region [18] have contributed to the determination of earthquake hazard and risk on a global scale.

EMME is a Middle East region project that aims to assess the earthquake hazard and the associated risk in terms of structural damage, loss of life, and economic losses. The EMME Earthquake catalog consists of 6102 records covering 1899-2000 BC and the instrumental period catalog data from 1900-2010. Ground Motion Prediction Equations (GMPEs) and logic tree applications in seismogenic source modeling were applied in the project.

The NGA-West2 ground motion database contains extensive ground motion datasets from active shallow crustal earthquakes worldwide [19]. Earthquakes created by Türkiye's Northeast Anatolian fault are also active shallow crustal earthquakes [2]. For this reason, it is aimed to better predict the NGA-West2 equations with an extensive data set by adapting them to Türkiye. Earthquake activity is described as a random process. Therefore, the last earthquake catalog data is needed. Ground motion prediction equations created with current data reveal the current earthquake hazard. Therefore, this study, it is aimed to create the last earthquake hazard maps of the research site by making calculations with the ASK14 model, which has not been used in the calculations of Türkiye earthquake hazard maps.

2. Materials and Method

Earthquake hazard maps for Adapazarı, Serdivan, Arifiye, and Erenler districts of Sakarya were produced at the local scale, aiming to narrow the analysis framework and obtain more reliable results. For this reason, earthquake hazard maps were obtained using CRISIS software [21], which is used in academic and commercial projects. While performing hazard calculations in CRISIS software, coordinate files should be prepared to obtain the region's polygon file to be studied and calculate the spectral acceleration values. After the necessary data entry is made to determine the source information, the a and b values obtained using the Gutenberg Richter relations, the minimum and maximum earthquake magnitudes should be defined. The source area and line or point can be determined as a source. Generally, great earthquakes are defined as line sources, and other earthquakes are defined as area sources. Appropriate a and b values for Türkiye are taken from the EMME project data. For this study, the sources of the Northeast

Anatolian Fault covering the province of Sakarya were considered [22], [23]. Unlike the EMME project, the ASK14 [10] model developed in 2014 was used as a ground motion prediction model.

2.1. Theory

Probabilistic Seismic Hazard Analysis is an analysis method in which the seismic source characteristics and the distance of the source to the site, earthquake recurrence, attenuation relations, and the probability of exceeding the ground acceleration in a specific region are calculated by taking into account the uncertainties (Figure 1).

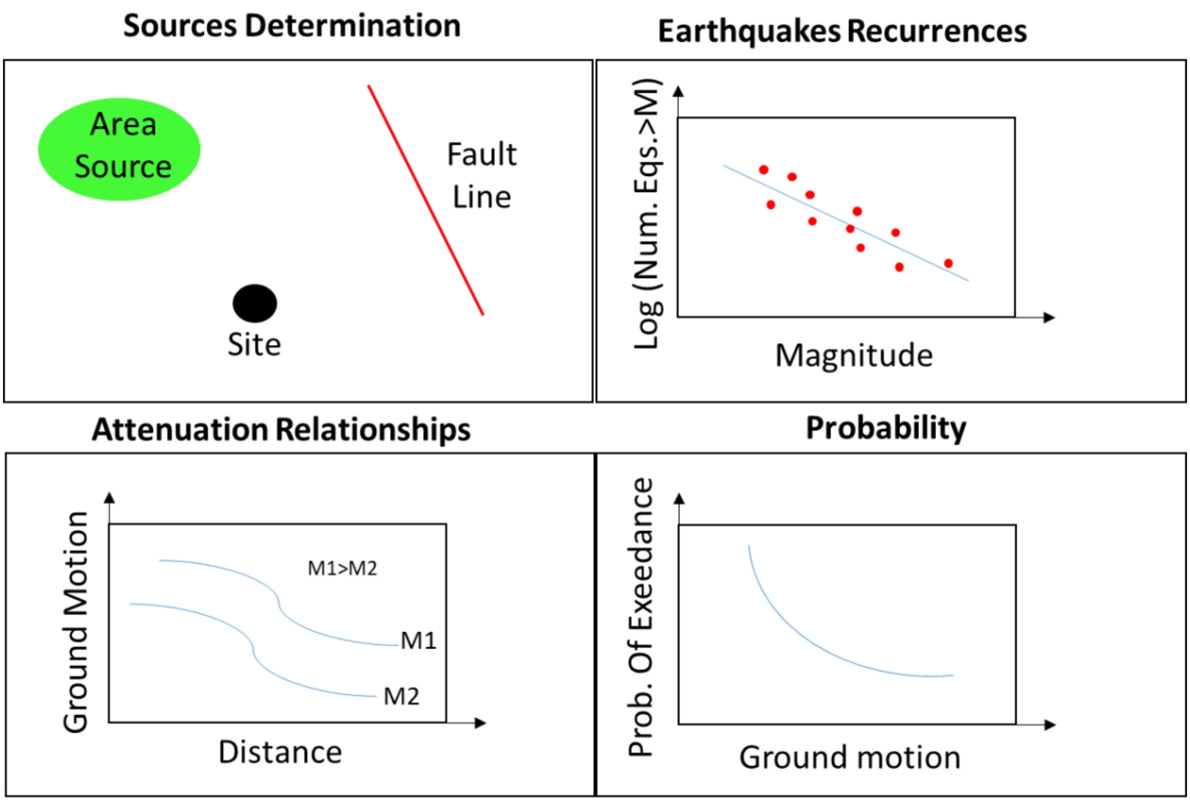


Figure 1. Probabilistic Seismic Hazard Analysis Steps [5]

2.2. Determination of earthquake recurrence and probability

The Poisson probability model is widely used in earthquake hazard studies. According to the Poisson model (Eq.1), each event occurs independently of the other. Thus, the probability of two seismic events occurring at the same place and time approaches zero. Thus, earthquakes are separated from aftershocks and foreshocks, and uncertainties are eliminated. In Equation 2, λ is the average occurrence rate of an event. In Equation 3, the magnitude-frequency relationship, proposed by Gutenberg and Richter (1954), expresses the average occurrence rate of an event as logarithmic is presented. The "a" values are related to the size of the selected region and the time interval studied and the "b" values are related to the tectonic structure of the region in this equation [5].

$$P(N>1)=1-e^{\lambda t} \quad (1)$$

$$\lambda = -\frac{ln\,(1-P)}{t} \qquad (2)$$

$$Log\,\lambda(M) = a - bM \qquad (3)$$

2.3. Selecting ground motion prediction equations

Due to the tectonic structure of Türkiye, ground motion prediction equation models created for active shallow crustal, subduction zone, and subducting intraplate earthquakes are the most appropriate choice. Although many Attenuation relationship models are developed for Türkiye, the estimation equations developed within the scope of NGA West1 [24], and NGA West2 [19] can be preferred for Türkiye as they contain more data than others. In this study, a seismic hazard calculation was made using CRISIS software for the ASK14 model, which covers the most data, and is compared with the data obtained from Earthquake Hazard Maps for Türkiye. ASK14 model relation is given in equation 4.

$$lnS_a(g)=f1(M,R_{rup})+F_{RV}f7(M)+F_Nf8(M)+F_{AS}f11(C_Rjb)+f5(S_a1100,V_s30)+F_{HW}f4(R_{jb}, R_{rup},R_x,W,Dip,Z_{TOR},M)+f6(Z_{TOR})+f10(Z1.0,V_s(30))+R_{eg}(V_s(30),R_{rup}) \qquad (4)$$

*M: Moment magnitude
*C_{RJB}: Centroid RJB
*Z_{TOR}: Depth-to-top of rupture (km)
*$V_s(30)$: Time-averaged shear-wave velocity over the top 30 meters of the subsurface
*Z1: Depth to V_S=1.0 km/sec at the site (m)
*F_{RV}: Flag for reverse faulting earthquakes
*F_N: Flag for normal faulting earthquakes
*F_{AS}: Flag for aftershocks
*F_{hw}: Hanging Wall
*R_{JB}: Joyner-Boore distance (km)
*R_x: Horizontal distance (km) from the top edge of rupture
*R_{y0}: Horizontal distance off the end of the rupture measured parallel to strike
*W: Down-dip rupture width (km)
*Dip: Dip rakes

In order to determine whether the ASK14 model, one of the ground motion prediction equations, is compatible with the region, the peak ground accelerations of the 7.6 magnitudes 17.08.1999 Kocaeli and 7.2 magnitudes 12.11.1999 Düzce earthquakes data from Türkiye Acceleration Database and Analysis System (TADAS) were compared with the ASK14 model (Figure 2).

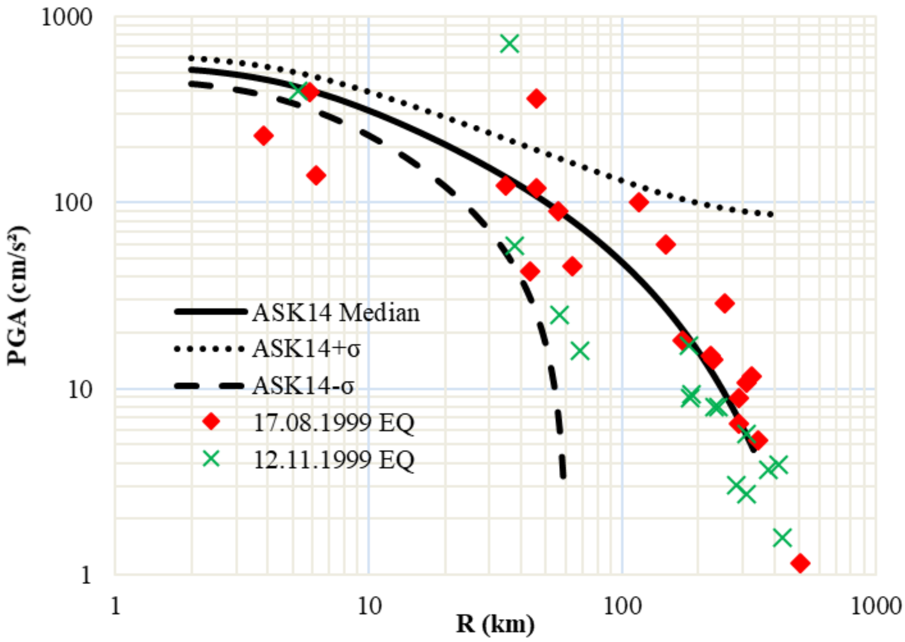
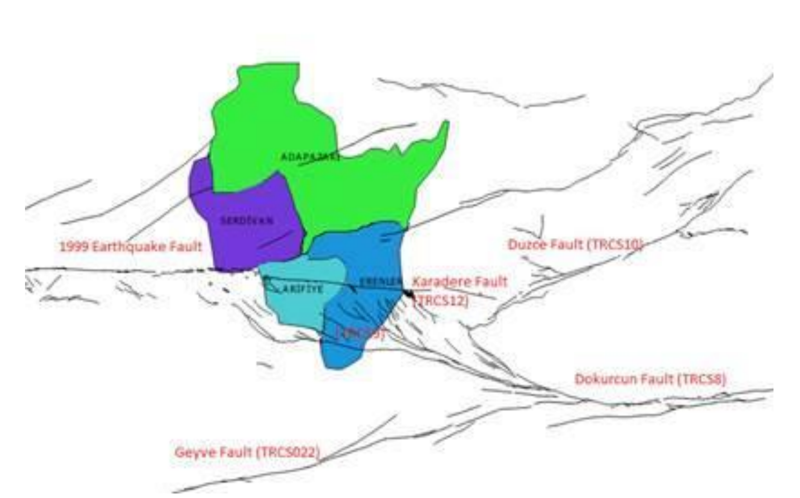


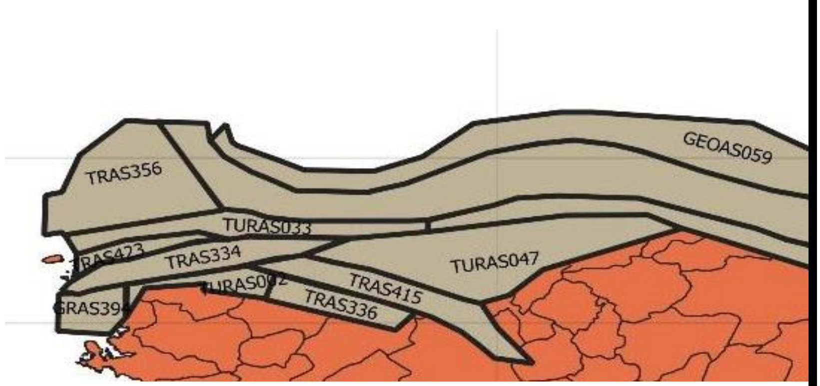
Figure 2. Comparison of Kocaeli and Düzce earthquakes with ASK 14 GMPE model

3. Research Site and Seismic Source Model

Within the scope of the numerical study, the earthquake hazards for the 475 and 2475-year recurrence periods for the coordinates taken from each district for Sakarya province were calculated using CRISIS software. Coordinate information from the site and districts is given in Figure 2a. The source features used in the analysis were transferred to CRISIS using the EMME14 model data. The region's area and line source characteristics were determined, and their visuals were presented. Karedere, Dokurcun, Düzce, and Geyve Faults in the Sakarya province are earthquake surface ruptures and active faults forming surface faulting between 1900 and the present (Figure 3).



(a) Line sources



(b) Area sources

Adapazarı: 30.402231, 40.775276
Erenler: 30.398179, 40.75460
Serdivan: 30.363258, 40.7546
Arifiye: 30.362514, 40.714283

Figure 3. The research site and seismic sources

4. Results

The average Vs30 value was calculated as 203 m/s from the obtained geotechnical reports in the Adapazarı, Serdivan, Erenler, and Arifiye districts. Considering the effects of the ground is essential since it is below the reference ground condition. For this reason, the earthquake hazard maps obtained for earthquake levels with 10% and 2% probability of exceedance in 50 years (Recurrence period 475 years and 2475 years) as a result of the analyzes made for Vs30 =760 m/s and Vs30=203 m/s It has been given in Figure 4-5.

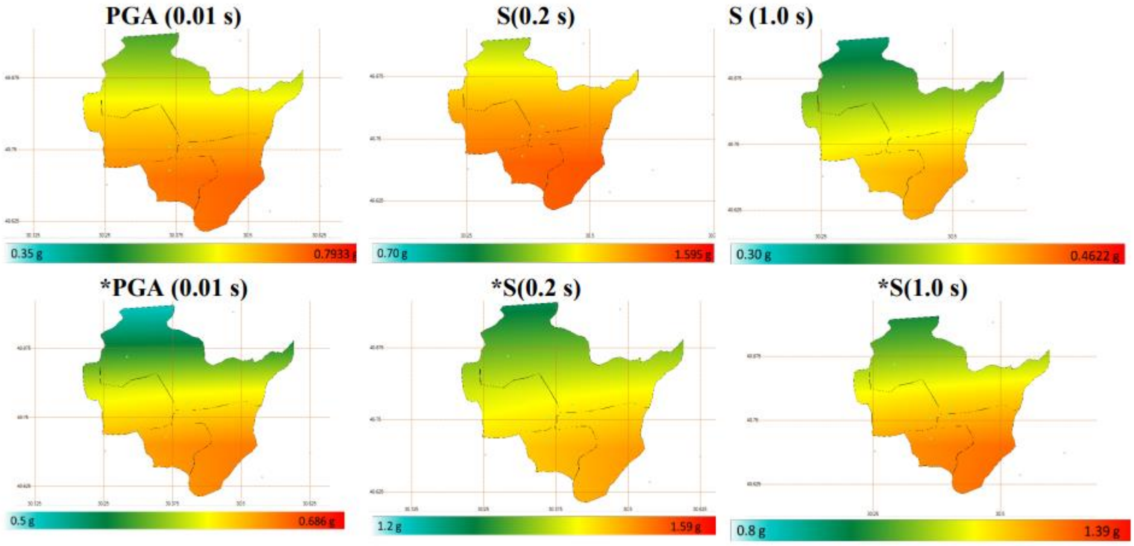


Figure 4. ASK14 hazard maps for a recurrence period 475 years (Vs30=760m/s and * Vs30=203 m/s)

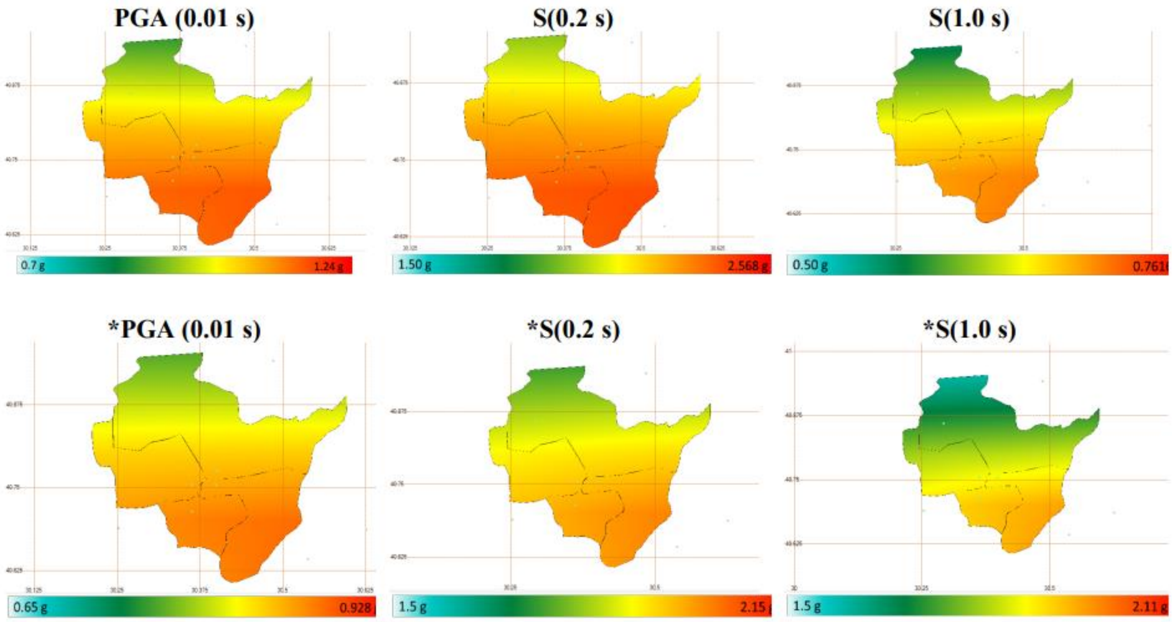
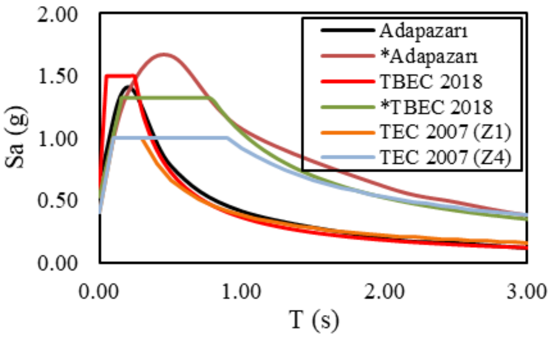
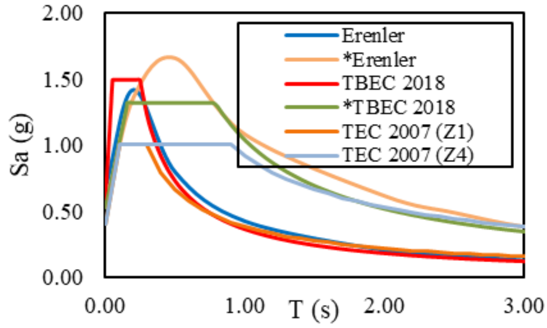


Figure 5. ASK14 hazard maps for recurrence period 2475 years (Vs30=760m/s and * Vs30=203 m/s)

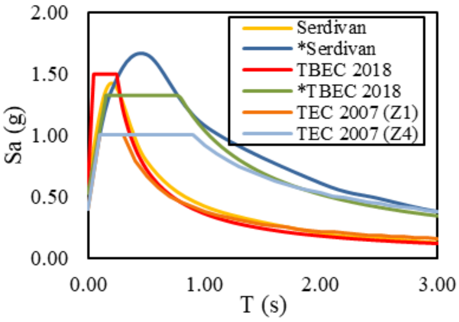
As seen in the hazard maps, there is a significant increase in peak ground acceleration for long periods. ASK14 ground motion prediction equation model and TBEC 2018 and TEC 2007 were compared in Figure 6 and Figure 7.



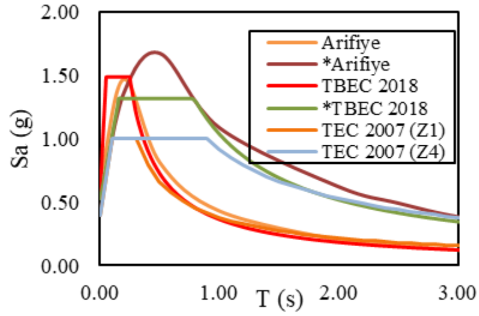
a) Adapazarı



b) Erenler

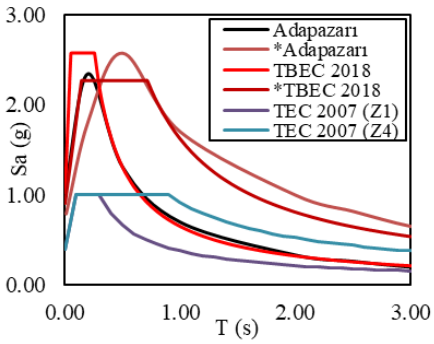


c) Serdivan

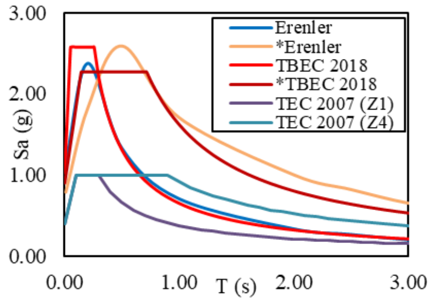


d) Arifiye

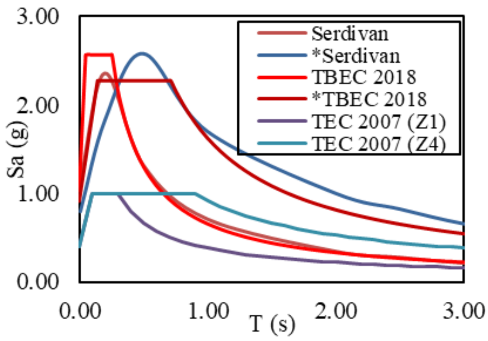
Figure 6. Comparison of spectrum curves for a recurrence period of 475 years



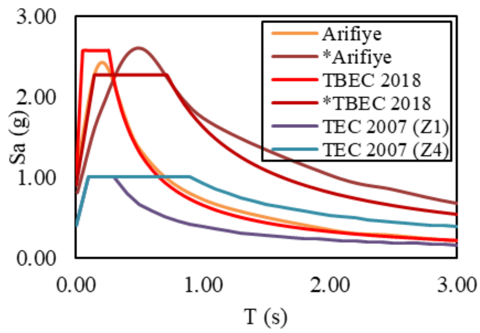
a) Adapazarı



b)Erenler



c) Serdivan



d)Arifiye

Figure 7. Comparison of spectrum curves for a recurrence period of 2475 years

When comparing the DD-2 design basis earthquake defined in TBEC 2018 for Vs30=760 m/s and the DD-1 The largest earthquake ground motion level, it is seen that the ASK14 analysis results overlap in the long-period region. In the short period region, TBEC 2018 is on the safer side (Figure 5a). However, there will be a high difference between the maximum acceleration values to be read in the 0-0.2 s range. For Vs30=203 m/s, while the ASK14 model remains on the safe side in the long period region, there will be a high difference between the maximum acceleration values to be read in the 0-0.35 s range in Figure 6b. When the study results are compared with the literature data, it is observed that the results are close to each other for the peak ground acceleration. However, there is a difference in the results for the short and long-period regions (Table 1).

Table 1. Comparison of results with literature

	PGA (g)		**Sa (0.2 s) (g)**		**Sa (1.0 s) (g)**	
	%2	%10	%2	%10	%2	%10
ADAPAZARI	1.14	0.708	2.34	1.41	0.701	0.415
***ADAPAZARI**	0.792	0.554	1.81	1.36	1.70	1.07
ERENLER	1.15	0.716	2.37	1.42	0.710	0.421
***ERENLER**	0.796	0.557	1.82	1.36	1.71	1.08
SERDIVAN	1.14	0.715	2.36	1.42	0.706	0.420
***SERDIVAN**	0.794	0.556	1.82	1.36	1.70	1.08
ARIFIYE	1.17	0.735	2.42	1.47	0.714	0.434
***ARIFIYE**	0.802	0.564	1.84	1.37	1.73	1.09
TBEC 2018 (ZB)	1.028	0.597	2.571	1.473	0.653	0.363
***TBEC 2018 (ZD)**	0.907	0.5278	2.2675	1.32	1.6205	1.037
HARMAN,2016	0.95	0.68	2.49	1.73	0.93	0.63
GÖK,2020 (EMME14)	1.12	0.939	2.52	2.22	0.78	0.584
	PGA (g)		**Sa (0.2 s) (g)**		**Sa (1.0 s) (g)**	
GÖK,2020 (ASK14)**	0.5		1.21		0.3	
GÖK,2020 (BS14)**	0.474		1.10		0.386	
GÖK,2020 (CY14)**	0.54		1.30		0.447	
GÖK,2020 (IDRISS14)**	0.71		1.26		0.29	
TEC 2007 (Z1)	0.4		1		0.382	
TEC 2007 (Z4)	0.4		1		0.919	

***VS30=203 M/S**
****SCENARIO EARTHQUAKE**

As a result of the study, it is seen that the TBDY 2018 data for the reference soil condition is safe for design earthquake according to the ASK14 model, but in soft soils, the ASK14 model is safe when the earthquake recurrence period is 475 years, and there is variability according to the spectrum curve period in the case of 2475 years. This study, contrary to logic tree applications in the literature, was used the ASK14 model for seismic hazard analyses. As a result of the analysis, when the estimated accelerations between the districts were compared, it was seen that the Erenler had the highest acceleration values.

4. Discussion

As a result of the study, to accurately predict the response of Sakarya province to earthquake effects, ground velocities should be determined correctly, and site-specific earthquake hazard analyses should be performed. It is seen that there is a possibility of a security vulnerability in TBEC 2018, especially in calculations where the shear wave velocity is low. Concomitantly, the more stiff soil sites where TBEC 2018 is safe may affect design costs. For this reason, increasing the analytical frameworks and carrying out cost-benefit analyses is essential by considering the new generation attenuation relations in the evaluations.

Author Contributions

Elif TOPLU and Osman KIRTEL contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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