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SEISMIC PERFORMANCE OF THE KAHRAMANMARAŞ EARTHQUAKES: GROUND MOTION PREDICTION MODELS AND THE ROLE OF VERTICAL COMPONENTS

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ABSTRACT

On February 6, 2023, two very large earthquakes occurred in Türkiye. These earthquakes occurred on the Eastern Anatolian Fault, one of the most active fault zones in Türkiye. After two earthquakes occurred 9 hours apart, with Pazarcık (7.7 Mw) and Elbistan (7.6 Mw) epicenters, 11 cities of the country were directly affected by the earthquake. In addition to a significant number of casualties, structural damage caused by the earthquake occurred. Ground motion prediction equations (GMPEs), in short, are used to estimate the impact/value that the acceleration/velocity/spectral parameters etc. of a wave moving from an earthquake source can create in a study area. With the help of these attenuation relations, various earthquake parameters can be estimated depending on distance. In this study, the peak ground acceleration (PGA) values obtained from the stations taking measurements during the Kahramanmaraş earthquakes were examined using 6 different attenuation relations valid for Türkiye. In the study, data from 105 different stations measured during the Kahramanmaraş earthquake were used. In addition, the vertical earthquake effect caused by the earthquake was evaluated in terms of Turkish seismic code conditions. Looking at the study results; The approach of ground classifications, the fact that the acceleration values of the Kahramanmaraş earthquake remained above the curves of the attenuation relations and the failure to consider different earthquake characteristics have shown that the current attenuation relations are weaknesses. It has been observed that earthquake data deviate in a certain distance region in all attenuation relations. The GMPEs generally did not show high agreement with the Kahramanmaraş earthquake data. For this reason, the situations that should be taken into consideration when preparing a new decay relationship are examined. Finally, it was concluded that the higher-than-expected vertical earthquake effects were not assessed correctly in the code and therefore the vertical acceleration spectra given in the code should be updated.

Keywords: GMPEs, Kahramanmaras earthquakes, Seismic codes, Vertical earthquake effect.

1 INTRODUCTION

There are 3 main stages to assess earthquakes. These are before the earthquake, during the earthquake and after the earthquake. Before an earthquake occurs, precautions are taken to minimize the damage that earthquakes will cause. During an earthquake, personal protection is required and afterward, it is necessary to move away from the structures with minimum impact. In the post-earthquake stage, there are search and rescue activities, damage assessment and debris removal and finally reconstruction processes. Among these processes, if the earthquake that occurs after the earthquake is a destructive earthquake, the damage assessment stage is an important stage in terms of precautions to be taken for subsequent earthquakes.

There are many studies in the literature on the structural damages that occurred after the February 6, 2023 Kahramanmaraş earthquakes and the causes of these damages. The studies conducted are on the assessment of seismic hazard, examination of earthquake characteristics, structural and non-structural damages, types of damage in reinforced concrete structures, examination of damage in masonry structures, damages in industrial structures, and assessment of losses.

The February 6, 2023 Kahramanmaraş earthquake caused severe damage to masonry buildings in Adıyaman. The collapse mechanisms of these buildings were examined, spectral acceleration values were analyzed, and reinforcement recommendations were presented [1]. The February 6, 2023 Kahramanmaraş earthquake caused serious damage to industrial structures; various structural damages were observed in liquid storage tanks, grain silos, prefabricated reinforced concrete structures and steel industrial structures[2]. In another study, the causes of damage to reinforced concrete buildings in Adıyaman were evaluated in terms of material quality, design errors and reinforcement details [3]. After the Kahramanmaraş earthquake, seismic analysis of historical masonry buildings was evaluated with field observations and advanced calculations. Nonlinear finite element analyses performed on a historical building in Hatay confirmed the observed damage mechanisms and reinforcement recommendations were presented [4]. The February 6, 2023 Kahramanmaraş earthquake caused major structural damage in Hatay. In the study, the causes of damage to reinforced concrete and steel structures were examined, construction defects and design errors were evaluated and recommendations based on TSC-2018 were presented [5]. High PGA values were measured in Kahramanmaraş earthquakes. When Disaster and Emergency Management Affair (DEMA) stations were examined, the highest PGA was seen in the east-west component of station 4614 for the Pazarcık epicenter earthquake. The value measured as 2.006g exceeds the design spectrum with a return period of 2475 years specified in the Turkish Seismic Code 2018[6]. Other stations with high PGA values are 3135, 3129, 3125 and 3126, respectively [7].

One of the most important areas of earthquake science is seismic hazard analysis. With seismic hazard analysis, the data of past earthquakes and the effects of expected future earthquakes can be predicted. In seismic hazard analysis, there are two approaches as probabilistic and deterministic seismic hazard analysis.

In deterministic hazard analysis, analysis is carried out for the largest earthquake and the most unfavorable single earthquake at the shortest distance [8]. In probabilistic seismic hazard analysis, analysis is carried out with a probabilistic approach, thinking about every magnitude and every earthquake distance that is likely to occur within the study area. Seismic hazard analysis consists of 4 stages in the most general sense (Figure 1). These stages are as follows:

● Modeling of seismic sources

●Magnitude-Recurrance relationships

●Attenuation models

●Probabilistic acquisition of probabilistic probabilities of exceeding an earthquake parameter (obtaining Earthquake Hazard Maps)

These stages are followed sequentially, and seismic hazard analysis are carried out and the effects of earthquakes (e.g. S_a, PGA, PGV, etc.) are predicted. One of the most important steps in making these predictions correctly is the correct selection of the attenuation relations to be used. The attenuation model should reflect the earthquake, fault characteristics, earthquake magnitude, distance of the earthquake to the study area, and specific earthquake characteristics caused by the earthquake well and accurately. For this reason, when performing seismic hazard analyzes in a region, the most appropriate GMPE should be determined for the region or new GMPEs should be created and used for that region [9].

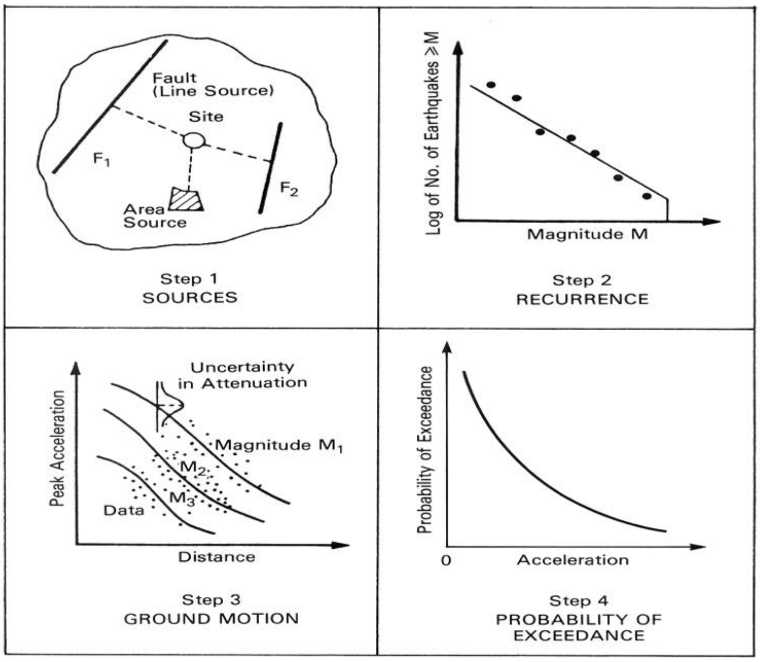

Figure 1. Stages of seismic hazard analysis[8].

Seismic hazard analyses for cities in Türkiye are available in the literature [10]. Seismic hazard analyses were performed for Sakarya province, and peak ground acceleration and spectral acceleration maps were produced according to different exceedance probabilities. In addition, possible fault distances and earthquake magnitudes were determined, and comparisons were made with the seismic code. It was observed that the accelerations obtained after the hazard analysis had values above the hazard maps [11]. The seismic hazard of Kahramanmaraş and its surroundings was assessed by the probabilistic method, and the East Anatolian Fault and Bitlis Thrust Belt were determined as the riskiest regions. The calculated acceleration values were compared with the Türkiye Earthquake Zones Map and regional harmony was analyzed [12]. Probabilistic seismic hazard analysis was performed for Van province and maximum acceleration values were determined for different exceedance probabilities. The obtained results were compared with the components of the 2011 Van earthquakes and the spectrum curves recommended in the Turkish Earthquake Code. Simulated earthquake records were obtained to be used for performance analysis of buildings in Van province [13]. According to the probabilistic seismic hazard analysis results for Bingöl province, the peak ground acceleration values with a probability of being exceeded within 50 years of 2%, 10% and 50% in Bingöl province were determined as 1.03 g, 0.58 g and 0.24 g, respectively, and the recurrence periods were calculated as 42, 105, 266 and 670 years for earthquakes of magnitude 6.0, 6.5, 7.0 and 7.5, respectively. The results obtained reveal that the region is under high seismic hazard and the earthquake effect must be taken into consideration in the design of structures [9].

Attenuation relations are mathematical equations that model the interaction between ground and structures during an earthquake and predict the effects of ground motion on structures. These relations are used primarily in engineering applications to calculate the magnitude and propagation of ground motion based on factors such as soil class, distance, and local ground conditions. Using accurate attenuation relations plays a critical role in improving the safety and durability of buildings and other structural systems. In addition, these relations help optimize earthquake engineering designs and more accurately assess the effects of local fault zones and structural weaknesses. Therefore, the development and proper application of attenuation relations are of great importance in risk analysis and damage estimation.

During recent seismic events, it has been observed that the vertical component of ground motion surpasses the horizontal component. This is contrary to the assumption in current codes that the vertical motion is 1/2 to 2/3 of the horizontal component. Immediately after destructive earthquakes, engineers report that structural damage such as buckling in large columns or fractures in large reinforced concrete columns used in highway and building structures are caused by strong vertical ground motion. These findings indicate that seismic designs that ignore the vertical ground motion component pose serious safety risks, especially for structures constructed near active fault lines, and may increase the risk of collapse [14]. The general view of code engineers is that the vertical component of ground motion is lower than the horizontal component and the V/H ratio remains less than 1. Many codes recommend scaling a single spectrum obtained for the horizontal component using an average V/H ratio of 2/3. However, in this approach, it is assumed that all components of the vertical motion have the same frequency content. However, studies in nearby fault areas prove that the V/H ratio may be below 2/3 [15].

In this study, the compatibility with Kahramanmaraş earthquake data was evaluated by using various GMPEs used in Türkiye and the world. The aim of this study is to observe how the existing GMPEs converge with an up-to-date earthquake data. Thus, by revealing the weaknesses and strengths of these attenuation relations, it will be seen which situations should be assessed when creating a new GMPE for this region. In addition, an evaluation of the horizontal and vertical acceleration values obtained from the stations that took records in the Kahramanmaraş earthquakes was also made in the study. This evaluation was compared over the spectra in the Turkish seismic code. In the following sections of the review, the results obtained are examined with their justifications.

2 MATERIAL AND METHOD

2.1 06 February 2023 Earthquakes and Seismicity of the Region

The East Anatolian Fault Zone (EAFZ) is one of the active fault zones that has produced significant earthquakes throughout history. It has come to the fore especially with the 2020 Sivrice, Elazig and 2023 Kahramanmaraş earthquakes that have occurred in recent years and has been the center of attention of researchers [16], [17], [18]. This fault zone, which starts from the Karlıova district of Bingöl and extends to Hatay, fully meets the characteristics of lateral slip faults. Figure 2; It shows important active fault zones and plates in Türkiye [19], [20].

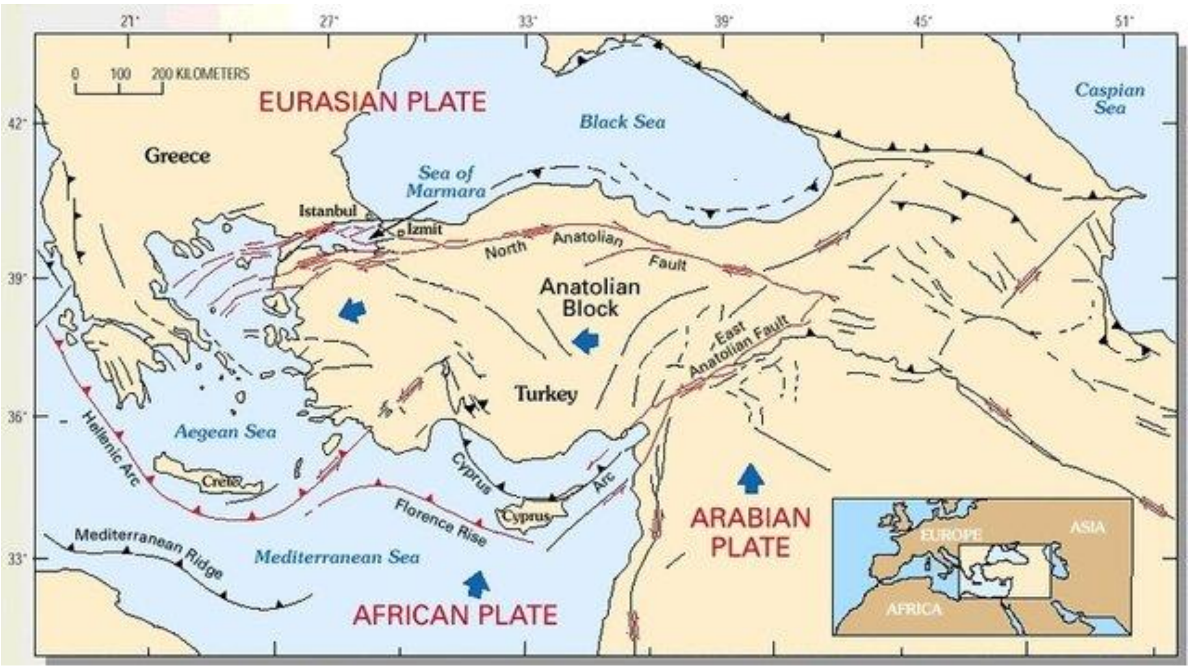

Figure 2. Important active fault zones in Türkiye [20].

This fault line (EAFZ), located at the junction of the Arabian plate and the Anatolian plate, produced 2 major earthquakes on February 6, 2023, 9 hours apart [21]. Some views suggest that the first earthquake (Pazarcık M_w 7.7) that occurred on February 6, 2023 did not start directly on the East Anatolian Fault, but instead occurred on the previously unmapped Narlı Fault. However, other studies argue that the earthquake started directly on the East Anatolian Fault. Therefore, there are different scientific approaches to the earthquake's starting point and the rupture mechanism on the fault plane [22] [23]. The epicenter of the first earthquake was Pazarcik, with a magnitude of 7.7 M_w [24]. The surface deformation on this earthquake-induced fault is about 300 km [25]. The second earthquake occurred at noon on the same day with a magnitude of 7.6 M_w centered in Elbistan [24]. These two earthquakes caused significant structural damage and loss of life. 11 provinces in Türkiye were affected by the earthquake [26]. The earthquake was also felt in Syria and caused casualties. According to official data, the loss of life in 11 provinces caused by the 2023 Kahramanmaraş earthquakes is over 50000. The provinces affected after the earthquake are larger than many countries in Europe in terms of surface area. The map showing the epicenter of the earthquake and aftershock activity is given in Figure 3.

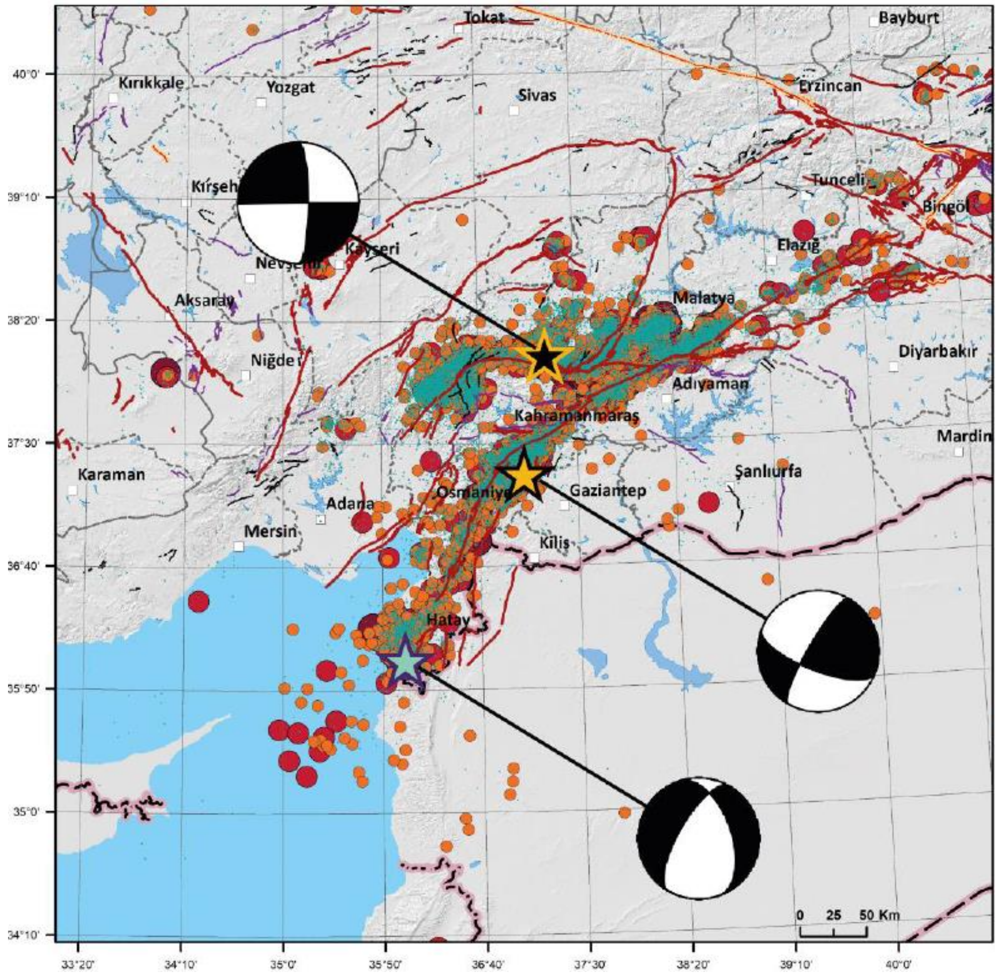

Figure 3. Epicenters of the earthquake, mainshock and aftershock activities [24].

After such a big earthquake, many researchers have carried out studies in the field and continue their research [5], [16], [27]. Having very important data in this field is seen as an advantage. Because it has benefited from significant advancements in earthquake science after every major earthquake.

2.2 Selection of Earthquake Records

To make a comparison with the attenuation relations, the stations that took records in the 2023 Kahramanmaraş earthquakes andT the data of these stations were used. The stations used in the study are the stations belonging to Disaster and Emergency Management Affair (DEMA). Figure 4 below shows the distribution of the stations that take records.

The records used in the study were filtered by considering the distance class evaluated by the attenuation relations. The records used in this study include records of stations at 200 km or less from the epicenter. Table 1 provides information about the stations used in the study. The horizontal and vertical components of the greatest ground acceleration are the R_{JB}, R_{rup}, R_{epi} and R_{hyp} distances, Vs_{30} values and the soil classification made according to Eurocode8 [28] (according to Eurocode8 Table 3.1) is the information given in Table 1. R_{epi} is the distance from the epicenter, i.e. the point on the ground where the earthquake occurred, to the study area. R_{hyp} is defined as the distance between the focus of the earthquake and the study area. R_{rup} is defined as the distance between the fracture caused by the earthquake and the study area, while the Joyner-Boore distance, i.e. the distance between the fracture projection on the plane and the study area. In another definition, the Joyner-Boore distance is defined as the shortest distance to the fault surface. In general, when the studies are examined, the R_{rup} and R_{JB} values are accepted as equal [29]. In the examination, stations with unknown Vs_{30} value were considered in the study as D ground class. Its acceptance as D ground class was determined by making an acceptance as in the report published by Boğaziçi University. In the Bogazici earthquake report, ZC ground class was accepted for stations whose ground class was unknown [21].

Table 1. Codes of 105 stations belonging to the DEMA observation network used in the study.

Station Codes							
0118	2712	3147	4620	0210	3134	4409	5807
0119	2718	3301	4621	0213	3135	4410	5809
0120	3112	3303	4624	0214	3136	4412	5810
0122	3115	3305	4625	2107	3137	4413	6203
0123	3116	3802	4628	2309	3138	4414	6302
0124	3123	3803	4629	2310	3139	4611	6303
0125	3124	3804	4630	2409	3140	4612	6304
0127	3125	3805	4631	2703	3141	4613	6305
0128	3126	4404	4632	2704	3142	4615	6306
0129	3129	4405	4701	2707	3143	4616	7901
0130	3131	4406	5102	2708	3144	4617	8002
0201	3132	4407	5103	2709	3145	4618	8003
0208	3133	4408	5805	2711	3146	4619	8004
NAR				Note: The stations used are the stations belonging to the DEMA observation network.			

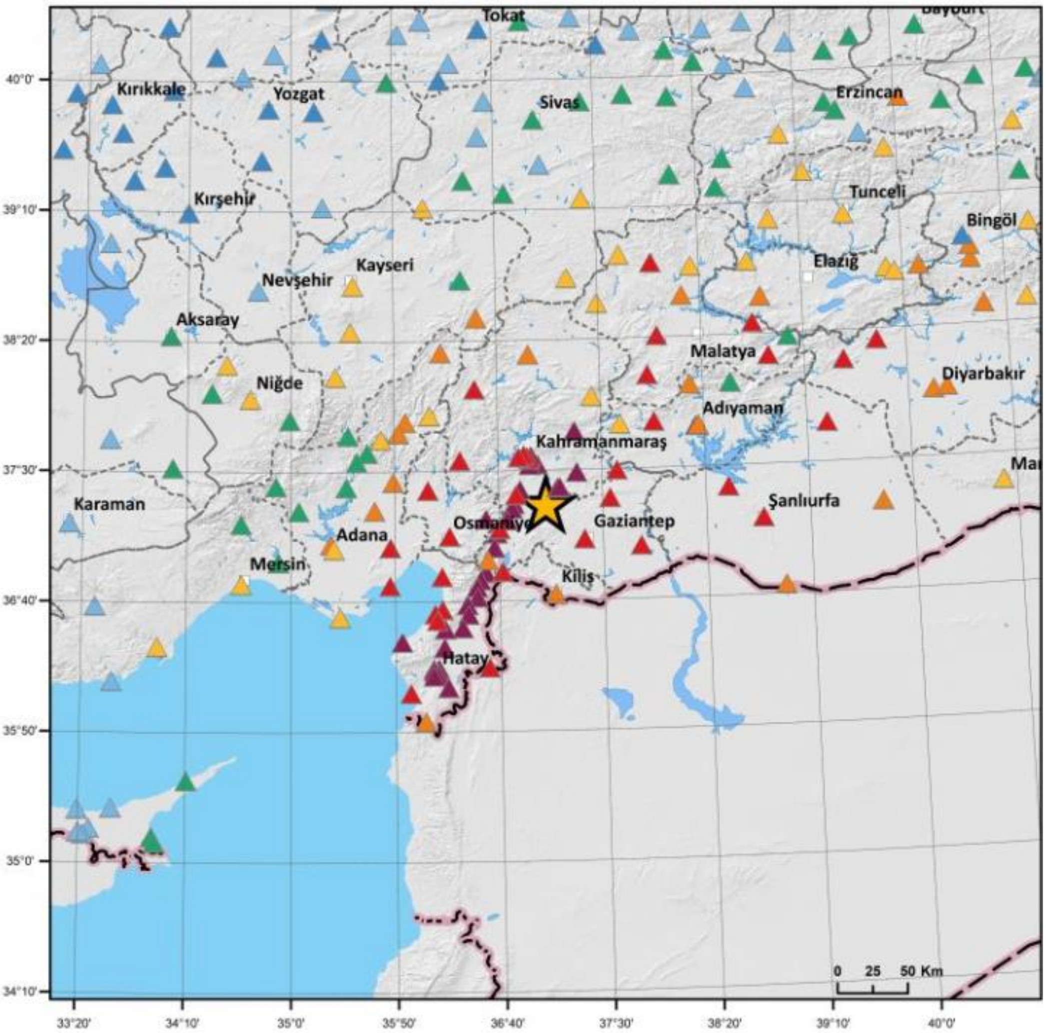

Figure 4. Distribution of record stations[24].

Records of a total of 105 stations were used in the study. The distribution of these records according to different soil classes is given in Table 2.

Table 2. Distribution of records used according to soil classes [28].

Soil Classes	Number of Records
A	11
B	56
C	12
D	26
Total	105

2.3 Ground Motion Prediction Equations (GMPEs)

In this study, a total of 6 GMPEs were used [30], [31], [32], [33], [34], [35]. All these relations are attenuation relations that have been developed for Türkiye and its surroundings or are suitable for use in Türkiye. GMPEs are usually prepared according to a specific region, country or faults with similar characteristics. In the studies carried out, the suitability of the GMPE to the regions belonging to which characteristics are specified. This situation was evaluated when selecting GMPEs [31]. From the attenuation relations, Abrahamson et al. (2014)[30] are the attenuation relations, It is a GMPE prepared for the NGAWest2[36], [37] project and has applicability in many regions of the world. The names of the attenuation relations and the information about these attenuation relations are given in the Table 3 below.

When the parameters in the equations given in Table 3 are examined, expressions such as a, b, a1, b1 define the regression coefficients. M represents the relevant earthquake magnitude (generally the moment magnitude), R represents the distance to the study area, G_1, G_2, F_N, F_R, S_A, S_B are constant coefficients reflecting the ground properties, and r represents the hypotenuse of the distance between the study area and the fault focal point.

Table 3. Information on the 6 GMPEs Used.

GMPE publication	Equation	Explanation
Energy Considerations in Ground Motion Attenuation and Probabilistic Seismic Hazard Studies [34]	$log\left(Y_{ij}\right) = a + b(M_i - 6) + c(M_i - 6)^2 + dlog\sqrt{R_{ij}^2 + h^2} + eG_1 + fG_2$	It was developed for the Northwest Marmara Region.
Site-Dependent Spectra Derived from Ground Motion Records in Türkiye[33]	$ln\, Y = b_1 + b_2(M - 6) + b_3(M - 6)^2 + b_5\, ln\, ln\, r + b_v ln\,(V_S/V_A)\quad r = \left(r_{cl}^2 + h^2\right)^{\frac{1}{2}}$	It has been developed for the whole of Türkiye.
A Local Ground-Motion Predictive Model for Türkiye, and Its Comparison with Other Regional and Global Ground-Motion Models[31]	$M \leq c_1$ $ln\,(Y) = a_1 + a_2(M - c_1) + a_4(8.5 - M)^2 + [a_5 + a_6(M - c_1)]\, ln\sqrt{R_{jb}^2 + a_7^2} + a_8F_N + a_9F_R$ $M \geq c_1$ $ln\,(Y) = a_1 + a_3(M - c_1) + a_4(8.5 - M)^2\,[a_5 + a_6(M - c_1)]\, ln\sqrt{R_{jb}^2 + a_7^2} + a_8F_N + a_9F_R$	It was developed for Türkiye using data sets belonging to Italy and Türkiye.
An attenuation based on Turkish strong motion data and iso-acceleration map of Türkiye[35]	$PGA = 2.18^{0.0218(33.3M_W - R_e + 7.8427S_A + 18.9282S}$	It is a GMPE developed for Türkiye. The equation is formed in an exponential simple form. The way the equation is formed is different from the general form.

Table 3 (Continued). Information on the 6 GMPEs Used.

GMPE publication	Equation	Explanation
Empirical Equations for the Prediction of PGA , PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East[32]	$log\,(PSA) = b_1 + b_2M + b_3M^2 + (b_4 + b_5M)log\sqrt{R_{jb}^2 + b_6^2} + b_7S_S + b_8S_A + b_9F_N + b_{10}F_R + \epsilon\sigma$	It has been developed for the Mediterranean, European and Middle Eastern regions.
Summary of the ASK14 Ground Motion Relation for Active Crustal Regions[30]	$= a_1 + a_5(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)]\ln(R) + a_{17}R_{RUP}$ $M>M_1$ $= a_1 + a_4(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)]\ln(R) + a_{17}R_{RUP}$ $M_2<M<M_1$	It was developed for different regions on Earth as part of the NGAWest project.

3 RESULTS AND DISCUSSION

3.1 Evaluation of GMPEs

Within the scope of the study, 6 different GMPEs compatible with Türkiye were used from the attenuation relations in the literature. In the evaluation, a comparison was made with the PGA parameters obtained from the stations after the Kahramanmaraş earthquake. When making the comparison, the Magnitude value in the attenuation relations was taken as the M value of 7.7 M_w given by the earthquake [21]. In addition, curves were obtained by considering the standard deviation values specified in the attenuation relations, considering the + and - standard deviation values. In the study, soil properties were classified as A, B, C and D soils according to the Vs_{30} value specified in the records of the stations and the soil classification specified in [9]. The soil classification differs in the GMPEs used. For each GMPE, the records were analyzed according to the different ground grouping procedure. In attenuation relations, the way in which the size, distance and soil properties to be used are evaluated differs. Since it is an examination made after the earthquake, the magnitudes examined are clear. These quantities were used in Mw. The distances to the epicenter of the earthquake were evaluated based on the distance of the stations to the epicenter. Here, Joyner-Boore (R_{JB}) distances are used, which are consistent with the attenuation relations used [38]. Soil classifications were carried out because of coefficients or shear wave velocity values compatible with the definitions of each attenuation relation. Ground classification was made with the Vs_{30} values obtained from the information of the stations, and the curves of the attenuation relations were grouped.

All the GMPEs used in the study were obtained according to the PGA value. The obtained curves are intended to be compared with the PGA values measured by the stations. The graphs from Figure 5 to Figure 10 show the curves of the GMPEs and the PGA values obtained from the station. While the darker of the curves gives the main curve of the attenuation relation, the gray curves above and below this curve show the curves obtained if the standard deviation is regarded. The point values in red show the distribution of the PGA values of the stations divided into different soil classes.

The curves of the Sarı's GMPE used are given in Figure 5. The soil classification of the GMPE is given according to Vs_{30} values. In the GMPE, A and B soil classification were evaluated together. Since the coefficients used in the soil classification in the GMPE are the same on the A and B coefficents, they are given on the same curve. When the standard deviations are deemed, it is seen that the curves of the GMPE and the PGA values obtained from the stations are generally compatible. However, low compliance is observed at values between 50 and 100 km.

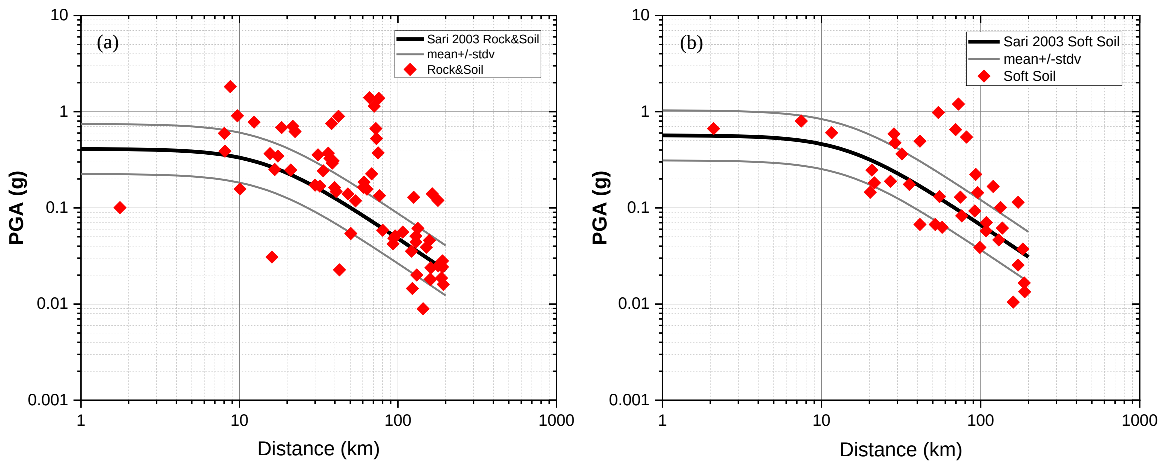

Figure 5. Comparison of Sari's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes (a) Rock&Soil (b) Soft Soil.

Three different soil classes are defined according to the GMPEs used. This soil classification is divided into three groups. As the ground classes decrease, the harmony between them decreases. The soil classification in this GMPE was made according to Vs_{30} values. Elaboration of the soil classification in attenuation relations will increase the harmony in attenuation relations. In Figure 6, the curves of the GMPE are given. Although the harmony of the curve obtained for soils with high shear wave value (>700 m/sec) seems high, the low number of records makes it difficult to make a clear interpretation on this issue.

Akkar&Çağnan study[31], all the records used in this study were compared over a single curve of the GMPE. All records evaluated due to the assessment for the single soil class are marked on the curve. Significant deviations were observed in records between 10 and 100 km. This is because attenuation relations are given for a single ground. It is predicted that these deviations will take lower values if the classification of different soil classes is possible. The curve of the GMPE is given in Figure 7.

As shown in Table 3, the GMPE proposed by Ulusay et al. [35] was developed using a different approach compared to the general GMPE formulation. Although an equation in exponential form is typically expected to exhibit low compatibility, it demonstrates a behavior relatively similar to other attenuation relationships. Again, deviations are seen in similar distance regions in this GMPE. As with other GMPEs, Kahramanmaraş earthquake data are generally concentrated on the upper side of the curve. The curves of the GMPE are given in Figure 8 according to different soil classes.

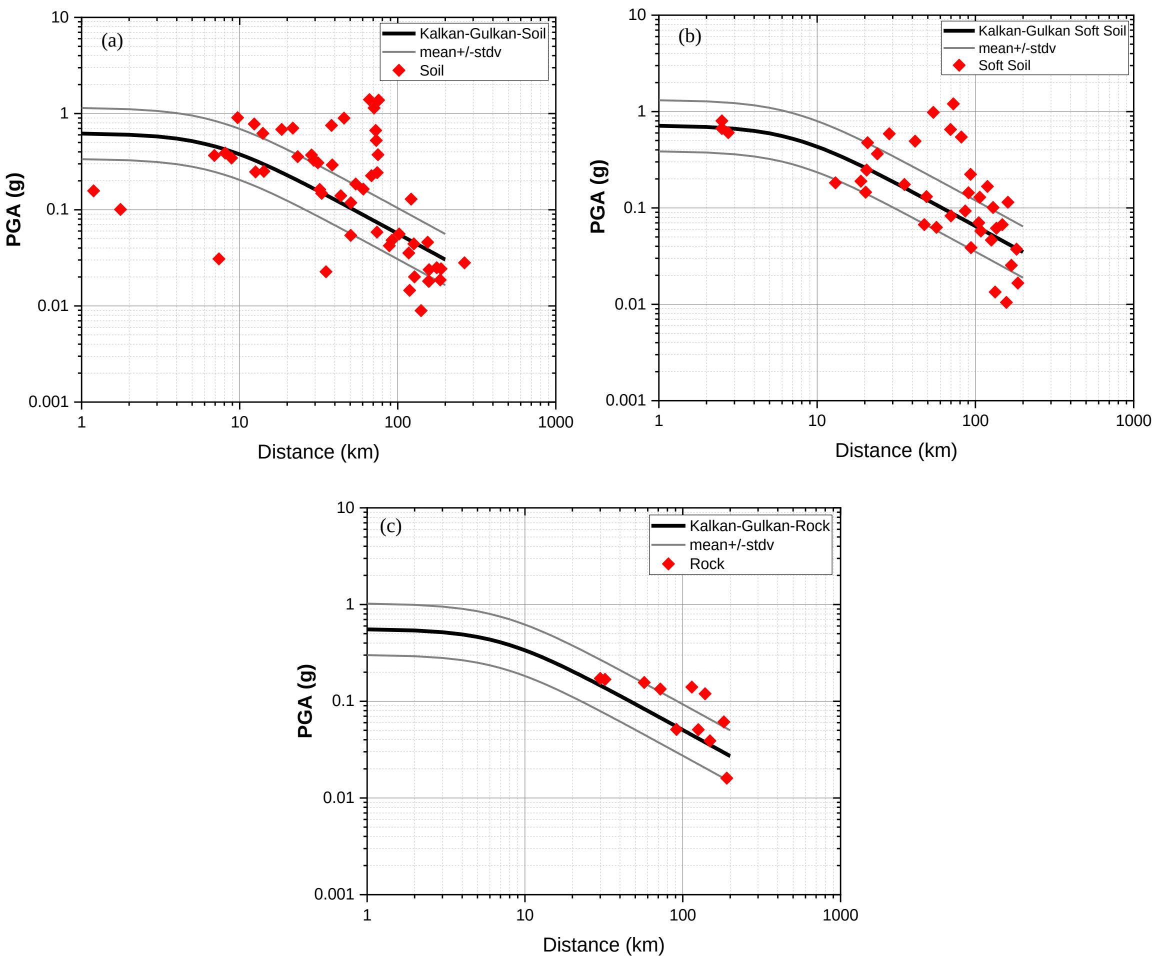

Figure 6. Comparison of Kalkan and Gülkan's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes (a) Soil (b) Soft Soil (c) Rock.

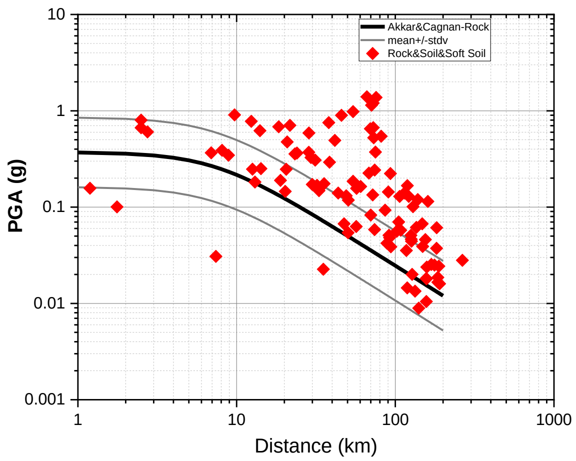

Figure 7. Comparison of Akkar&Çağnan's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes.

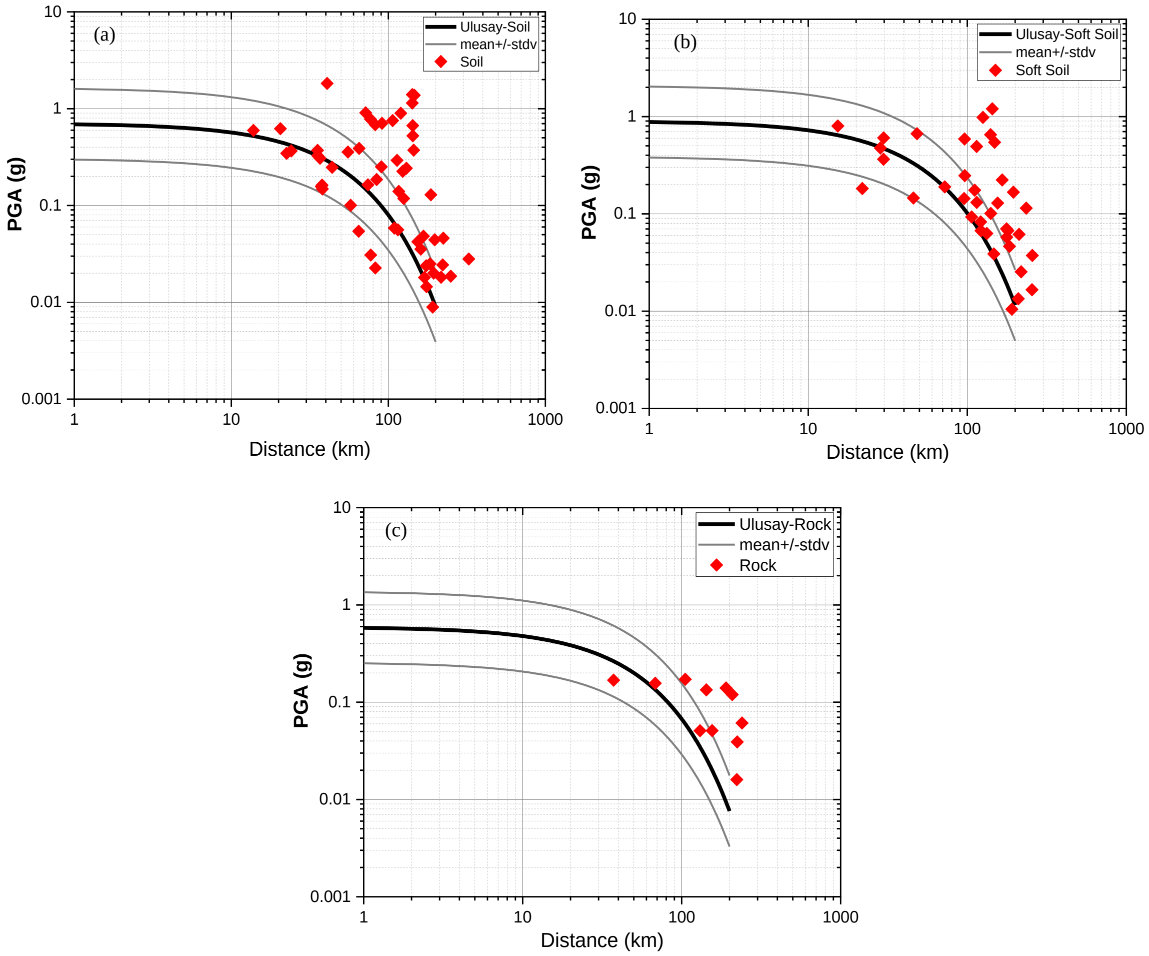

Figure 8. Comparison of Ulusay's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes (a) Soil (b) Soft Soil (c) Rock.

In this attenuation relation, two different curves of soil classification were obtained. The curve and earthquake data of the GMPE take values close to the curve on soft soils. However, the same deviations are present in similar distance zones. This situation is seen in all attenuation relations. These deviations may be related to the characteristics of the records. In addition, it may be due to the low reflectivity of the attenuation relations. The fact that the attenuation relations do not consider different earthquake characteristics (near fault effect, super-shear effect, orientation effects, etc.) and that the ground classifications make assumptions over the coefficients negatively affect the correct reflection. The curves of the GMPE are given in Figure 9. Abrahamson et al. [30], a GMPE prepared for different regions of the world, is given in Figure 10 for two different soil classifications. This GMPE proposes different equations by accepting a given Vs_{30} value and magnitude value as the threshold value. In Table 3, different GMPE equations of the study are given.

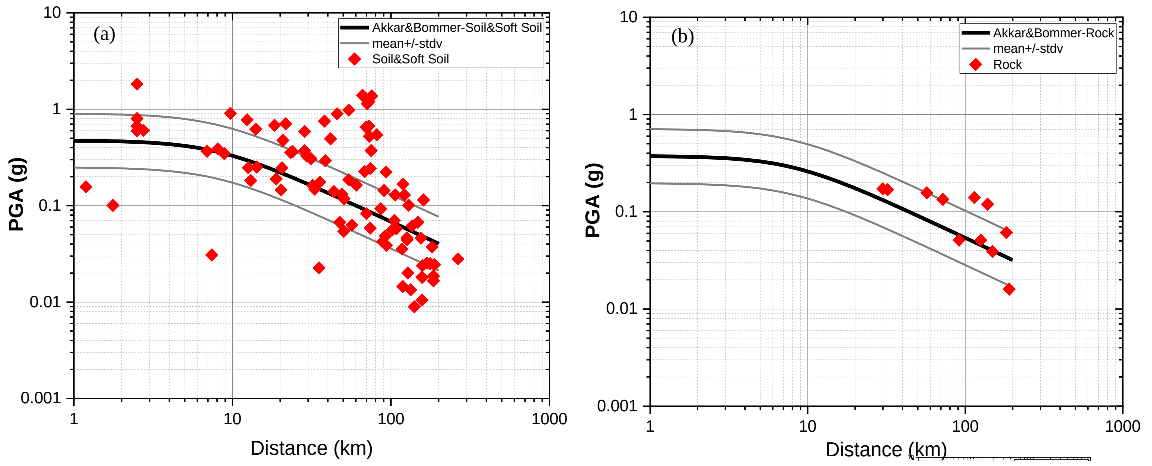

Figure 9. Comparison of Akkar&Bommer's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes (a) Soil-Soft Soil (b) Rock.

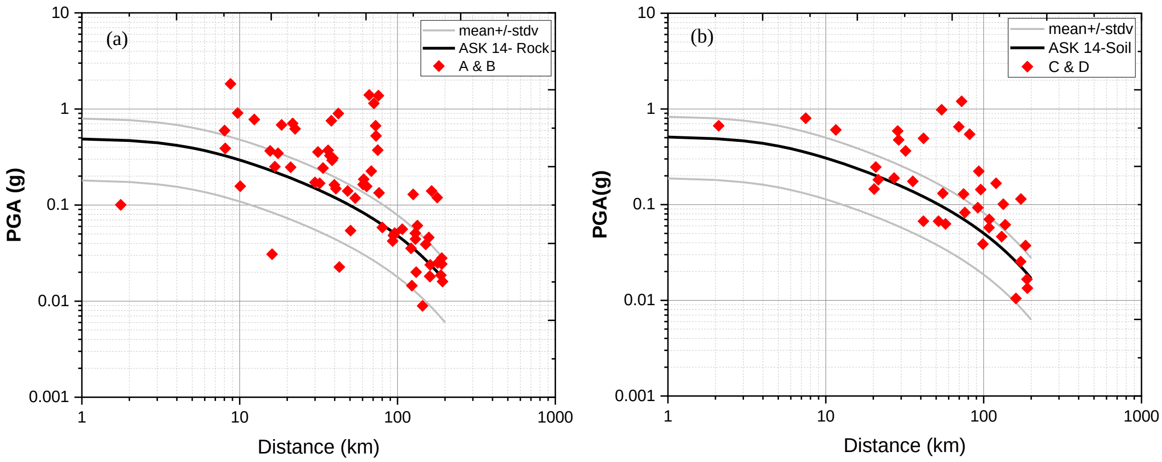

Figure 10. Comparison of ASK14's model prediction of pga with observed data from Kahramanmaras earthquake for all soil classes (a) A&B (b) C&D.

When we look at the agreement of the PGA values measured by the attenuation relations in the study, the agreement with the curves increases as the distance increases. As the ground class improves, the concordance of the attenuation relations and PGA values seems to be high, but the number of stations with good ground is low. Therefore, it becomes difficult to say that there is a connection between direct soil classification and PGA parameters. Since the characteristics of the earthquake under consideration are assessed differently in each GMPE, the power to predict the PGA parameters differs. For this reason, the different earthquake behaviors that occurred in the Kahramanmaraş earthquake make it difficult to comply with the PGA parameter of Altunsu et al. [5]. In the literature on the Kahramanmaraş earthquake, super-shear, near fault effect, basin effect, liquefaction and different ground behaviors do not coincide with the currently used GMPEs. This situation shows that there is a need for a new GMPE after the Kahramanmaraş earthquakes.

3.2 General assessment of GMPEs

The 6 different GMPEs used below, and the earthquake records used in the study of the Kahramanmaraş earthquake are given together. Although the agreement between PGA and GMPEs increases as we move away from the epicenter, it shows that it does not fully reflect the behavior of earthquake parameters. Different earthquake characteristics need to be taken into account and updated in GMPEs [39]. When the curves of the attenuation relations and the PGA values of the earthquake records are examined; it is seen that the earthquake records of the Kahramanmaraş earthquake take values above the attenuation relations. Although the standard deviation is examined for the + and – states for each attenuation relation, the standard deviation is positively dominant. In general, all the GMPEs reviewed remain under the Kahramanmaraş earthquake records. This situation reveals that the data sets need to be updated to predict high PGA values in the new GMPEs to be created.

Ground motion prediction equations (GMPEs) should account for significant earthquake characteristics such as near-fault effects, basin effects, and high vertical ground motion. Incorporating these factors into the equations will enhance the predictive accuracy of GMPEs. Although researchers like Somerville have conducted studies on integrating near-fault effects into attenuation relationships, these effects are not yet fully incorporated into contemporary approaches. Neglecting these factors may lead to an incomplete or inaccurate representation of the actual earthquake behavior.

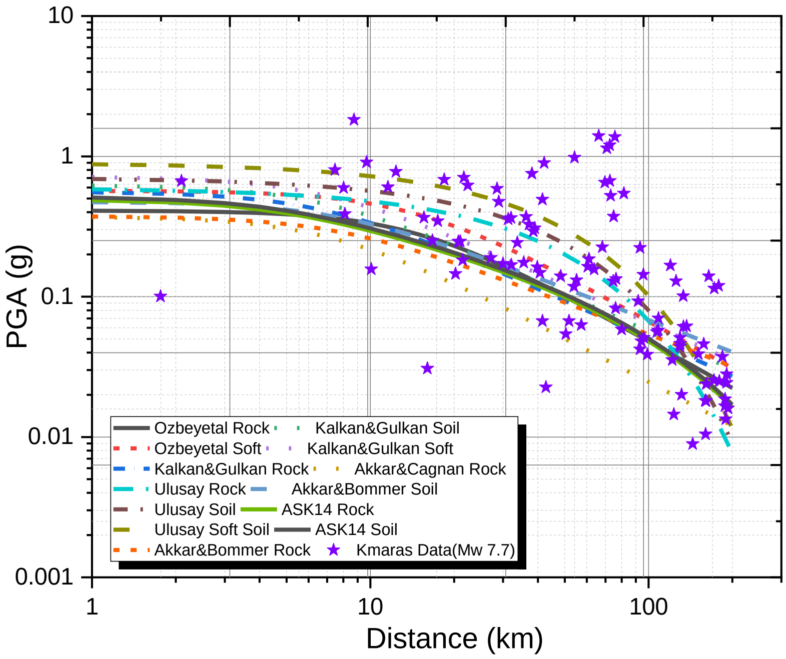

Figure 11. Comparison of the GMPEs.

4 EVALUATION OF HORIZONTAL AND VERTICAL EARTHQUAKE EFFECT

Kahramanmaraş earthquakes have shown us that the vertical earthquake effect is also a very important parameter. When the stations that take records are examined, very high vertical component values of the Kahramanmaraş earthquake are seen. Following the Kahramanmaraş earthquakes, it has been observed that the high vertical ground motion component contributed to increased structural damage levels. Figure 12 illustrates the damage caused by the high vertical ground motion effects during the Kahramanmaraş earthquakes. An analysis of earthquake records from the affected regions reveals the presence of high vertical ground motion components. Figure 13 presents the horizontal and vertical acceleration records from selected stations during the Kahramanmaraş earthquakes.

Figure 12. Damage caused by the high vertical earthquake effect.

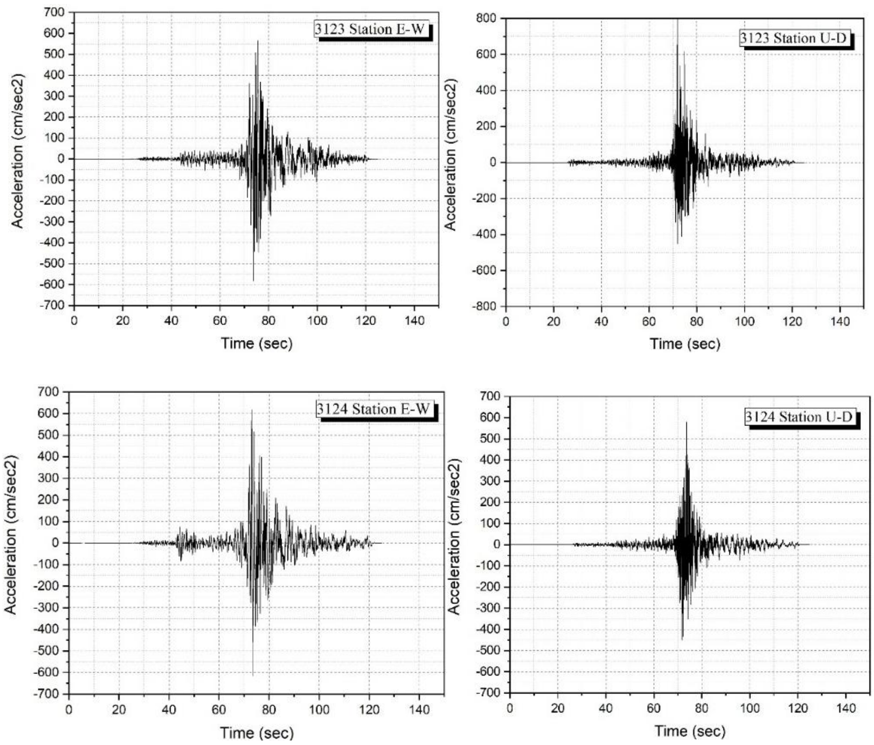

Figure 13. Horizontal and vertical acceleration time history for Kahramanmaraş Earthquake.

In this study, the ratios of the acceleration values of the largest component and the vertical direction from the horizontal components of the stations that took measurements in Kahramanmaraş earthquakes were obtained. The variation of these values with respect to R_{JB} distances is given in Figure 14. When Figure 14 is examined, the distribution of the change of the ratio of the vertical acceleration value to the horizontal acceleration value according to the distance is given. In this graph, a value of 0.8 is considered as the threshold value. The reason for this can be explained by the ratio between the spectra in the Turkish Seismic Code 2018[6].

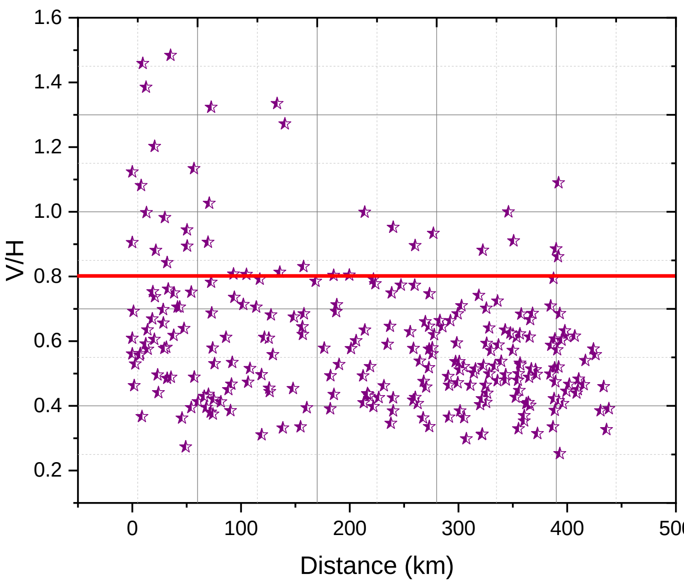

Figure 14. Variation of horizontal and vertical earthquake rates by stations[29].

Figure 15 shows the horizontal and vertical elastic spectra included in the Turkish Seismic Code 2018 (TSC 2018). When these spectra are examined, the minimum and maximum values of the spectral acceleration values of the spectrum are expressed with different values. There is a change of 0.8 between the values of the horizontal elastic spectrum and the vertical elastic spectrum. This situation means that; the earthquake code accepts that the ratio of horizontal and vertical earthquake effects to each other does not exceed 0.8. However, as can be seen in the figure above, there are many acceleration records in which the ratio of vertical and horizontal earthquake accelerations of Kahramanmaraş earthquakes exceeds 0.8. This situation shows that the vertical earthquake effect is a high effect in the Kahramanmaraş earthquake, and this effect should be considered in a different way in new studies and seismic codes. It has been observed that different characteristics of the earthquake, such as the vertical earthquake effect, should be analyzed correctly when considering the effects of the earthquake.

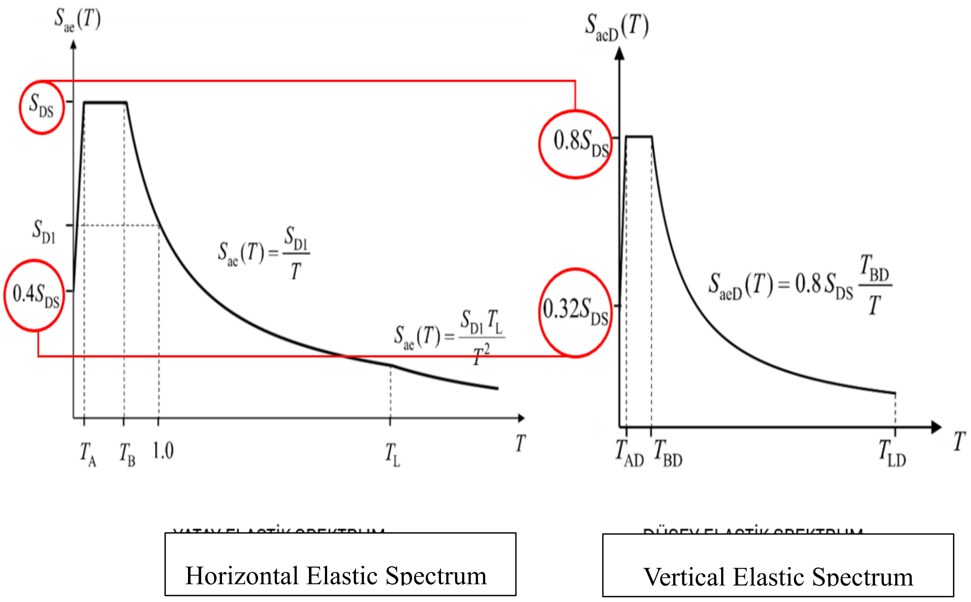

Figure 15. Comparison of horizontal and vertical spectra according to the TSC 2018.

When Figure 14 is examined, it is seen that the V/H ratio exceeds 0.8 in many records. This situation shows the lack of an approach to considering vertical earthquakes in seismic codes. The importance of vertical earthquake effects has emerged once again after the Kahramanmaraş earthquake. In addition, the records given in Figure 14 were obtained without any ground classification. By classifying according to ground classification, near fault conditions, basin effect, super shear effect, etc., the situations that increase the amplitude of the vertical earthquake component can be determined.

5 CONCLUSION AND SUGGESTIONS

After the Kahramanmaraş earthquakes, earthquake science will be updated at a significant level. In this study, attenuation relations, which are an indispensable approach in seismic hazard assessment, which is a special field in the field of earthquake engineering, were evaluated. These equations, which are used to predict the earthquake effect of a possible earthquake before the earthquake occurs, were tested with this study using the acceleration values of the Kahramanmaraş earthquake. In the study, the compatibility of 6 different GMPEs in the literature applicable to Türkiye with Kahramanmaraş earthquake data was examined. In addition, in the study, the change of the vertical earthquake effect with the horizontal earthquake effect was examined by examining the Kahramanmaraş earthquake data. The findings obtained because of this study were evaluated and the following results were obtained:

• With this study, some parts that are missing in a new GMPE to be prepared were evaluated. After these evaluations, it is expected to give an idea of how to consider the change of ground conditions, vertical earthquake effect and distance conditions that should be considered in a new GMPE.

• Deviations between earthquake records and curves are observed in a certain distance region. This is due to the different characteristics of the earthquake records and the lack of elaboration of the soil classifications.

• In general, the curves are below the actual earthquake data in the GMPEs examined in the study. This suggests that PGA values are indeed underestimated. Taking this situation into account in a new GMPE to be prepared for Türkiye, data sets should be updated.

• The necessity of different soil classification approaches was seen in this study. It is insufficient that soil classifications are generally limited to a single parameter or to affect the attenuation relations with a coefficient.

• Earthquakes have some special characteristics. These characteristics such as directivity effect, super shear effect, high vertical earthquake component, and ground behavior should be integrated into attenuation relations.

•If the vertical earthquake component is higher than expected, it shows the weakness of the seismic codes. In this context, it should be ensured that the vertical elastic spectra of the seismic codes are updated, and the vertical earthquake effect is accurately reflected.

• Evaluating the outcomes, it becomes clear that the attenuation relations should be updated with a more detailed, realistic approach and new data sets, or a new GMPE should be prepared for Türkiye.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was composed, revised, analyzed, and prepared without the aid of any artificial intelligence techniques. All content, encompassing text, data analysis, and figures, was exclusively produced by the authors.

Contributions of the Authors

Writing - review & editing, Ö.F.N.; Formal analysis,Ö.F.N.; Investigation,Ö.F.N.; Data curation, Ö.F.N. and A.S.; Conceptualization, A.S. and Ö.F.N.; Methodology, A.S. and Ö.F.N.; Validation, A.S. and Ö.F.N.

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