MAGNITUDE DEPENDENCY OF SPECTRAL DECAY PARAMETER (KAPPA) IN EAF RELATED EVENTS

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Abstract: *The decay of the high frequency ground motion amplitudes of Fourier spectrum, namely the spectral decay parameter, κ, is highly utilized and debated in the scientific community in the last decade due to its significant effect on earthquake hazard evaluations and results. A dataset with a good spread of magnitude variety in near site as well as far site recordings is needed to be able to check if this parameter is magnitude dependent or not. Due to paucity of data worldwide, especially at hard rock sites, this dependency was not debated in full coverage, and the parameter is assumed to have the same decay tendency for high magnitude possible events with the evaluated κ values from low seismic records in the low seismic target regions. AFAD station spread in East Anatolian Fault (EAF) has provided a decent dataset after the January 2020 Elazig earthquake of Mw6.8, and the Mw 7.7 and Mw 7.6 Kahramanmaras Earthquake Sequence of February 2023. Herein, the results of these datasets are given in terms of differences in different magnitude bins. Especially the results on AFAD Station 4404 with* V_{s30} *1380 m/s will provide insight for low seismic, hard rock regions if only taking the low seismic data to arrive at zero epicentral spectral decay parameter,* κ_0 *could be reasonable or not. Future investigations to account for magnitude dependency and its relations will be the next generation debate in terms of κ and hazard evaluations.*

1. Introduction

During the seismic hazard and related risk studies and/or projects, the estimation of ground motion prediction values plays an important role to represent the expected exposure at the target site or region. For the last decade, transformation of GMMs (Ground Motion Models), or formerly renamed as GMPEs (Ground Motion Prediction Equations), to especially low seismic site or region target prediction values is a challenge.

The highest impact on evaluated hazard results comes from the spectral decay of Fourier amplitude spectrum, κ, for especially higher frequencies of the ground motion. Biro and Renault (2012) investigated the host-to-target GMPE conversions and presented their impact on hazard results for Swiss Nuclear Power Plants on hard rock sites under the scope of PEGASOS Refinement Project (PRP). Their findings indicted that the lower the decay of high frequency ground motion amplitudes (low target zero epicentral spectral decay parameter, κ_0), the higher the seismic hazard is even as high as almost six times the spectral acceleration hazard value for hard rock sites before the de-amplification effect of soil to hard rock estimations. It is for this reason important to find the appropriate target κ_0 value for the target site/region in consideration.

In Earthquake Engineering, κ evaluations influence also mainly the practices of nonlinear structural analysis with representative or simulated earthquakes as well as soil-structure interaction analysis besides the practice of hazard calculations for either seismic codes or for structures that has specific importance. In these evaluations, taking the GMMs directly as they are formulized for the regions and for the specific structures that sustainability is at high importance, could no longer represent the effective hazard and risk values, especially if the GMMs show diversity with what is actually recorded in the region.

In low seismic regions, due to lack of high magnitude event records, assigning the reasonable target κ_0 value from low seismic event records for the expected high magnitude event is also a big challenge if the parameter is actually magnitude dependent. Also, the variety of the κ_0 value evaluated from recorded κ values at distance has high importance, if the lower magnitude seismic record resulting κ_0 values are explicitly different than the high magnitude event record resulting κ_0 values.

At this point, κ_0 parameter is assumed to be magnitude independent during the host-to-target GMM transformations. In addition to that, due to lack of data at some regions, the solution is usually taking the κ_0 values what was assigned or evaluated before from similar regions with possible similar site properties.

All these assumptions are causing additional inconsistencies at the resulting target κ_0 values to be used during the hazard calculations besides the fact that from the same datasets, different researchers are arriving at different target κ_0 values due to inconsistencies of evaluation phases of individual event κ and station based κ_0 values. Perron et. al. (2017) named the uncertainty of individual event κ estimate values as “interoperator variability”, therefore it will be mentioned as such herein, although the possible reasons are not going to be presented in detail except the effect of the selection of spectral flattening frequency (f_x), as this parameter seems to have high impact on interoperator variability.

In this paper, the magnitude dependency tendencies are going to be discussed as well as the f_x selection effects will be illustrated to bring the sensitivity in the scientific community to decide if low seismic event record κ values could really represent the possible expected earthquake hazard and risk at the region under investigation.

2. Magnitude dependency discussions

Traditionally κ is treated with the pre-assumption that this parameter is magnitude-independent, but high uncertainty in low magnitude events is observed. Also, the magnitude dependency tendency is encountered when the magnitude range in the databases used for κ_0 evaluations have enough range of magnitude events to be taken into account. Some scientists tried to explain this phenomenon via stress drop (i.e., Ktenidou et. al. (2017)) but could not conclude with a resolution, some indicates the tendency and yet due to not having enough data for each magnitude bin for the same site and from the same source they continue the evaluations with the assumption of magnitude independency. The possibility that κ is dependent on the magnitude have been strongly mentioned in some research (i.e., Papageorgiou and Aki (1983), Aki (1987), Papageorgiou (1988, 2003), Gariel and Campillo (1989), Wen and Chen (2012), Perron et. al (2017)) and still needs to be investigated in detail.

While the uncertainties for estimating κ_0 in terms of maximum usable frequency, low magnitudes were addressed in Ktenidou et. al. (2017) also stress drop issue was discussed, and the large uncertainty in stress drop (corner frequency, f_c) for low magnitudes between 1.2 ≥ M_L ≥ 3.4 (at 300 km epicentral distance) was reported as not yet being resolved. It is also important to point out that due to instrument responses the maximum usable frequency (f_x) was set to 16 Hz in their study.

Also, while evaluating the site-specific component of κ_0 on the magnitude dependency of within event aleatory variabilities in ground motion models, Brooks and Douglas (2021) have demonstrated variation in stress drop parameter and found out minimal contribution to magnitude dependency, unlike the site-specific component of κ_0. They concluded that in simulations at least κ_0 was partially responsible for the magnitude dependency captured in the aleatory variability components of some recent GMMs.

It is also worthwhile to indicate a study in Japan pointing out the seismic moment, M_o dependency while checking two different models for spectral decay. The commonly used worldwide κ model was compared with commonly used in Japan f_{max} (cut-off frequency) model by Tsurugi et. al. (2020). They studied high frequency spectral decay characteristics of 105 earthquakes with 3.3 ≤ M_w ≤ 7.1 for inland crustal earthquakes in Japan and compared the results from these two models. They concluded that both are applicable for the region they studied to characterize the high frequency spectral decay. In their study the difference from the common general estimation of κ from each individual event is that the authors estimated κ from average observed spectra obtained from the records, assigning an average distance to the spectra. They also re-estimated κ for individual observed spectra for seven selected big earthquakes from their dataset and compared their results with the average value of κ suggesting the influence of the Q factors used for the analysis was small. While evaluating the κ for individual record, they used the vector summation of the two horizontal components and a frequency range between the spectral amplitude frequency where the exponential decay clearly starts, f_E and 30 Hz. In their findings they summarized that f_{max} in the f_{max} model and f_E in the κ model tended to be smaller for large earthquakes than moderate and small earthquakes and they concluded that this tendency demonstrated a seismic moment dependency.

Biro et. al. (2022) study showed a tendency of magnitude dependency for the events recorded by Kandilli Observatory and Earthquake Research Institute (KOERI, Istanbul) stations located around the Sivrice-Pütürge segment of EAF, even when restricted by picking the dataset of events only occurred in this segment under investigation as single fault source. The dataset for this study is for events until June 2020, including the main event of January 24, 2020 Elazig earthquake with M_w6.8.

In this paper presented here, AFAD (Prime Ministry Disaster and Emergency Management Authority, Ankara) station, Stn4404 with V_{s30} = 1380 m/s results are obtained for events up to September 2023 including also the two major Kahramanmaras Earthquake Sequence of February 2023 earthquake records with M_w7.7 and M_w7.6 as well as January 2020 M_w6.8 Elazig earthquake.

Before presenting the evaluations and results, it is crucial to indicate some of the inconsistencies encountered during different κ and κ_0 evaluations.

3. Inconsistencies in κ and κ_0 evaluations

3.1. Inconsistencies in κ evaluations

It is important to first indicate the comparisons made between the κ results of many different studies could mislead as if the same procedure is applied as a method to obtain the individual event κ values. These values can be used also during the magnitude dependency/independency, soil type dependency studies as well and yet cannot be identified if they are comparable due to the methodology behind the calculations. Anderson and Hough (1984) and "Broadband Inversion κ, κ_{BB}" by Ktenidou et. al. (2014) or "Broad-band Fitting, κ_{BB}" by Edwards et. al. (2015) are going to be mentioned herein:

Not selecting a pertinent frequency band $f_E - f_x$ while applying Anderson and Hough (1984) method introduces vast uncertainty to κ evaluations. The selection of f_E is agreed in scientific committee. The selection of f_x however, is not addressed due to the tapering and filtering applied to the datasets, as these applications could demolish the visually selectable FAS flattened portion in low magnitude seismic events. However, this band selection is reported to have high impact on resulting κ values by many authors (i.e., Douglas et. al. (2010), Perron et. al. (2017)). Douglas et. al. (2010) mentions that f_x shows large variations due to varying signal-to-noise ratios and therefore it was not possible to use a constant value for all records in their dataset since it is time consuming. Many authors deal with the same problematic issue of selecting individually the f_x, and therefore ignore its high influence and take a constant value for f_x. A fixed range of $f_E - f_x$ might sometime give negative κ values illustrated such as in Ktenidou et. al. (2021) while aiming estimation of κ_0 values for rock sites in Central and Eastern North America, CENA. In this article the authors have given illustration of example κ fits to FAS where they flag the records without any visible FAS trend and records with clear down going trend in the FAS, as well as records that exhibit significant near-surface site amplification. They also tried different fixed $f_E - f_x$ ranges and provided the results. Due to paucity of the new database for CENA, κ values with all flags at all distances from all stations are together taken for κ_0 estimation in this study.

During a broad-band fitting of the velocity spectrum for low magnitude events, κ_{BB} is derived from attenuation time (t^*) definition in Cornier (1982) indicated in Anderson and Hough (1984). While calculating the t^*, simultaneous broadband inversion of the whole velocity spectrum resolving for corner frequency, f_c, and seismic moment, M_o is used and the regression for f_c resolution fit to the signal is then applied to the whole spectrum to evaluate t^* and therefore, κ_{BB}. The broad-band fitting of a signal of a low magnitude event including the lower frequencies to the fit therefore, causes a higher fit to the higher frequencies of the spectrum and results with a lower value of κ for the higher frequencies where the κ is defined in Anderson and Hough (1984) method. This may even result with negative values of κ as if the seismic wave does not attenuate but rather escalate at high frequencies.

The danger rises with the assumption of magnitude independency for κ evaluations and applying the same resulting κ values for expected high magnitude earthquakes while evaluating the seismic hazard and risk of the region in hand. As the focus is on f_c, and therefore f_E, for small magnitude events, the noise floor where the spectrum is flattened is usually missed during these calculations, especially due to the filtering, tapering (sometimes double tapering), and/or smoothing phases while calculating the corner frequency, f_c.

Biro et. al. (2022) proposed an automated f_x selection procedure, that is also applied herein, that is believed to help reduce the interoperator variability and take the load off the time-consuming evaluation phase mentioned by Douglas et.al. (2010) by making sure the f_x selection is no longer out of its first meaning: that is "the end of the linear downward trend of FAS" or "when the S-wave spectrum approaches the noise spectrum" or "the beginning of flattened shape of the FAS". The uncertainties of individual resulting κ values herein have been highly reduced when compared with literature uncertainties reported in related publications.

3.2. Inconsistencies in κ_0 evaluations

While comparing the κ_0 results from different studies, it is also important to check if the datasets are consisted of only a limited range of magnitude, distance, etc. Also, during the evaluation phase of κ_0, there are some pre-set assumptions observed in some studies, such as the assumption that κ_0 is magnitude independent, taking different κ versus R_{epi} tendencies or simply neglecting a tendency, assuming an unconstrained or constrained fit to overall κ values within the R_{epi} to reach κ_0, etc.

The limitation of maximum distance is important in terms of Q interference. Usually if the database allows, near field events are in value to be able to reduce this interference. To understand the trend in the region under investigation, it would be ideal to have records of different magnitude, and different distances that could give a good correlation. This is not usually the case in the literature due to the paucity of data. The low seismic regions have absence of the large magnitude event records that are close enough to the site under investigation, whereas the high seismic regions could miss the near site records of high magnitude events due to saturation of the recording device of the investigated site. When the datasets cannot provide a correlation on any relation related to the source, path and site, some pre-assumptions are made and should be taken into consideration when comparing the resulting κ_0 values with each other. It is also important to mention to check if the κ versus R_{epi} fit is constrained or unconstrained during estimation of κ_0 values for a site.

If the dataset of recorded seismic events utilized to estimate κ_0 does not cover a wide range of magnitude, distance and are from different seismic sources with sparse coverage of station locations, defining a regional path attenuation (Q) would not be easy or even at some cases possible if no special Q model is delivered. In such cases, if there are enough near field events recorded at the site under investigation, then κ vs R_{epi} fit may be unconstrained due to lack of Q model and/or estimate and this fit may represent vaguely the path attenuation. This assumption is widely used in scientific community. When there is a possibility to assign a path attenuation estimation for a region with many recordings from many stations, then the κ vs R_{epi} fit for a site can be constrained according to this regional path correction. Such studies with constrained fit however show that the unconstrained fit may give unrealistic κ_0 estimations, especially for sites with databases that consist of far field events.

4. κ evaluations for EAF related events

4.1. Methodology and Dataset

In the widely commonly used Anderson and Hough (1984) methodology, while dealing with an earthquake database to evaluate κ parameter from FAS, pre-selected assumptions that are made during the evaluation phase differs from scientist to scientist. Some of the main inconsistencies that can be listed in here are, the selection procedure applied to define the S-wave portion of the signal, the duration of the selected S-wave being restricted to a period of time (i.e. 5 s) or taking the whole S-wave selection of the signal, taking the geometric mean of the east-west and north-south horizontal FAS of the record and evaluate one κ for this mean FAS, the selection of f_E, the assignment of f_x by pre-setting the value, a fixed f_E – f_x selection without checking if each and every recorded earthquake signal FAS really suits, applying different filtering, smoothing and tapering procedures which effects both amplitudes as well as flat FAS identification, calculating κ from different approaches rather than applying straight forward the Anderson and Hough (1984) methodology but yet are compared with κ results that are evaluated with Anderson and Hough (1984) method.

Anderson and Hough (1984) method has been used widely and mostly in literature of κ evaluations, and many authors have indicated that this approach is better used for relatively large magnitude events. When used for smaller earthquakes, the selection of f_E was focused more than the selection of f_x due to trial of the method applied to the smaller magnitude events at the regions where large magnitude event records are not available, where there is low seismicity, such as Switzerland, eastern USA, and eastern Canada, etc.

Here, a danger rises up for these small magnitude events that the record is relatively close to the signal of the noise and a clear definition of flattened portion of the Fourier Amplitude Spectrum (FAS) may no longer be identified as realized in large magnitude event records. Even for the moderate to large earthquake records, from the same databases, this rather straight forward method could give different resulting κ values if not checked for the f_x.

Anderson and Hough (1984) have indicated that “the points at 25 Hz falling above the level consistent with exponential decay may result from the noise of the records” in their original paper after checking the records visually and they mention about the necessity of setting the spectral flattening frequency, f_x at 12-15 Hz instead of 25 Hz in their database.

Herein, the dataset that the Anderson and Hough (1984) method is applied consists of acceleration records from the strong motion station Stn4404 of AFAD network between June 2011 until September 2023 including the major events of January 2020 M_w6.8, February 2023 M_w7.7 and M_w7.6 earthquakes of Eastern Anatolian Fault (EAF). The events with $M_w \geq 3.5$ and with epicentral distance, $R_{epi} \leq 200$ km are considered for evaluation. After selecting the S-wave portion of the signal visually for each record, signal-to-noise ratio is checked for SNR > 3, the minimum Δf between f_E and f_x are set to 8 Hz and the difference between two horizontal κ values (κ_{EW} and κ_{NS}) are allowed to be 25%. f_E is set to 1.5 times the corner frequency, f_c following the trend lately in recent publications. With these initial boundaries, the total number of events that are available for each magnitude bin κ_0 evaluations at Stn4404 are listed in Table 1.

Table 1.The number of events after the selection criteria for κ_0 evaluations at Stn4404.

Magnitude bin	**Epicentral distance range (km)**	**# of events**
$3.5 \leq M_w < 4.0$	$7 \leq R_{epi} \leq 81$	119
$4.0 \leq M_w < 4.5$	$8 \leq R_{epi} \leq 156$	134
$4.5 \leq M_w < 5.0$	$9 \leq R_{epi} \leq 194$	51
$5.0 \leq M_w < 5.5$	$13 \leq R_{epi} \leq 200$	24
$M_w \geq 5.5$	$25 \leq R_{epi} \leq 198$	5

4.2. Automatic selection of spectral flattening frequency (f_x)

As mentioned before, even though due to paucity of the datasets, it is reported that the selection of f_x is time consuming and is neglected. It could be seen in Table 1 that event for one selected AFAD station, the usable dataset is quite good especially in terms of magnitude and distance coverage for Eastern Anatolian Fault (EAF). To solve the obstacle of time consuming f_x selection, the proposed automated f_x selection procedure/method by Biro et. al. (2022) is applied here.

During the application of Biro et. al. (2022) method, if the fitted polynomials do not intersect, an initial f_{xi} is set to check the smallest difference between them. The final list of κ values is always formed from the direct intersected f_x and the selected f_{xi} selections according to visual checks for each and every record automated figures. Usually, the reasonable f_{xi} selection for one station approaches to always the same value, even though for this paper a variation of f_{xi} selection is made to validate the Biro et. al. (2022) method. The variation of f_{xi} seems not to follow a trend by V_{s30} values in EAF dataset in hand. Even though only results for Stn4404 with V_{s30} = 1380 m/s are discussed herein, two extra examples from AFAD stations, Stn2414 with V_{s30} = 372 m/s and Stn0204 with V_{s30} = 555 m/s, can be mentioned herein in terms of applicable maximum f_{xi} selection to suggest there seems to be no V_{s30} correlation for station based f_{xi} selection. Stn4404 f_{xi} selection yields more to around 20 Hz, whereas Stn0204 to more than 30 Hz and Stn2414 to less than 15 Hz. The reason why each station tends to have a maximum applicable f_{xi} value needs further investigation.

4.3. Effect of spectral flattening frequency (f_x)

If chosen a fixed value for f_x, the effects on resulting κ_0 values are illustrated in Figures 1 to 3 for the AFAD station 4404 (Stn4404) for R_{epi} of 100km. This station is chosen to illustrate due to its representation of hard rock site case with V_{s30} = 1380 m/s. f_E is set to be 1.5*f_c in all calculations as mentioned before. It should be noted that if there is intersection of fitted polynomials in Biro et. al. (2022) method application, then the resulting f_x from those records are selected. The resulting κ_0 values for different maximum R_{epi} in consideration are listed in Table 2. It is clearly seen that choosing different f_{xi} pre-set values can cause vast differences in the resulting κ_0 values.

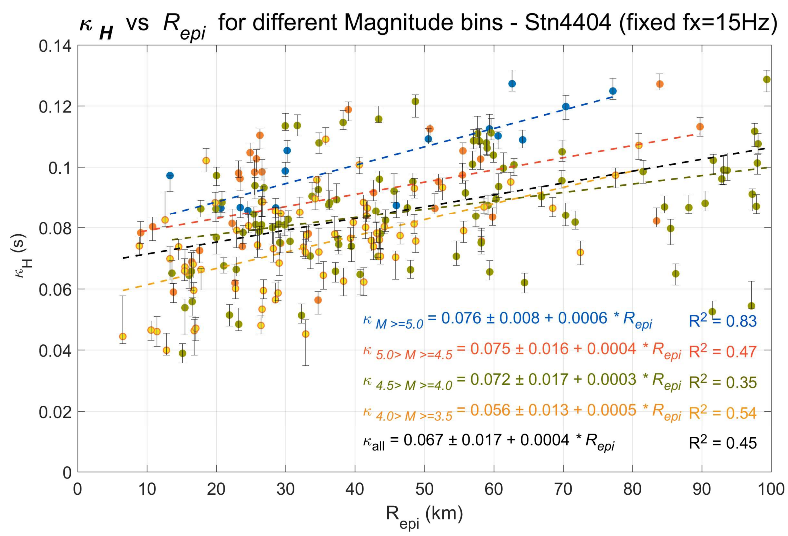

*Figure 1.*The horizontal event kappa, κ_H vs R_{epi} up to 100 km with f_{xi} =15 Hz at different magnitude bins via robust multiple linear regression model for Stn4404 with V_{s30} = 1380 m/s.

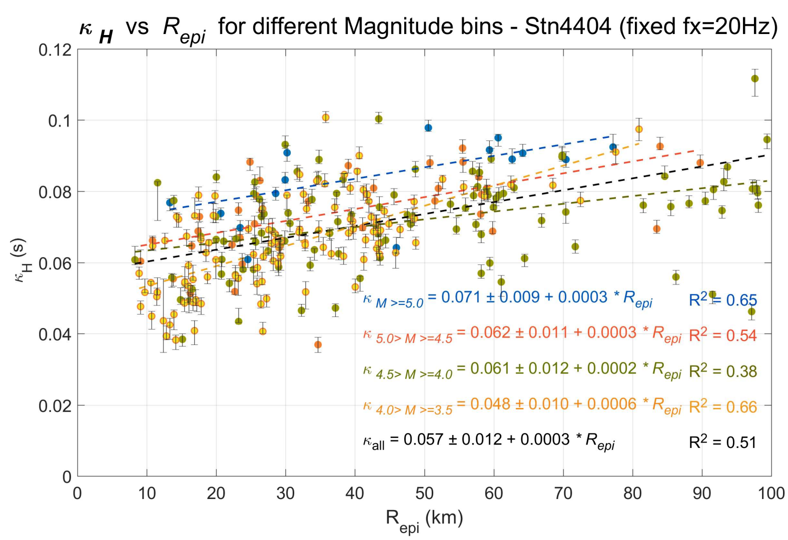

Figure 2. The horizontal event kappa, κ_H vs R_{epi} up to 100 km with f_{xi} =20 Hz at different magnitude bins via robust multiple linear regression model for Stn4404 with V_{s30} = 1380 m/s.

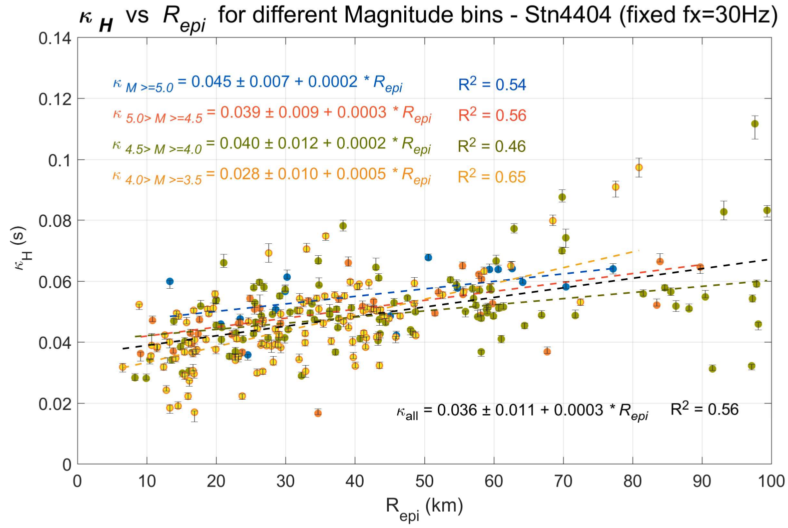

Figure 3. The horizontal event kappa, κ_H vs R_{epi} up to 100 km with f_{xi} =30 Hz at different magnitude bins via robust multiple linear regression model for Stn4404 with V_{s30} = 1380 m/s.

Table 2.The resulting κ_0 values for different maximum R_{epi} and different f_{xi} selection at Stn4404.

R_{epi} (km)	**f_{xi} (Hz)**	**κ_0 (ms) for 3.5≤M_w<4.0**	**κ_0 (ms) for 4.0≤M_w<4.5**	**κ_0 (ms) for 4.5≤M_w<5.0**	**κ_0 (ms) for M_w≥5.0**	**κ_0 (ms) overall**
100	15	56 ± 13	72 ± 17	75 ± 16	76 ± 8	67 ± 17
100	20	48 ± 10	61 ± 12	62 ± 11	71 ± 9	57 ± 12
100	30	28 ± 10	40 ± 12	39 ± 9	45 ± 7	36 ± 11
200	15	56 ± 13	73 ± 16	83 ± 19	98 ± 19	72 ± 18
200	20	48 ± 10	61 ± 14	67 ± 19	79 ± 20	60 ± 15
200	30	28 ± 10	35 ± 15	34 ± 21	55 ± 26	35 ± 16

It is clearly seen that a change of f_x value can deliver very different κ_0 results and therefore the proper selection that really defines the spectral flattening frequency is very crucial.

Also, that is clearly seen herein that κ_0 values decrease when the magnitude bins are descending, suggesting clear indication that κ and for that reason κ_0 is actually magnitude dependent. Even though one would neglect this trend and assume κ_0 is magnitude independent, f_x value selection influences κ_0 estimates extensively. If maximum R_{epi} is chosen 100 km for Stn4404, then the difference in κ_0 estimations for f_{xi} = 30 Hz and f_{xi} = 15 Hz will be between 0.031 ± 0.006 s.

It should be noted that Table 2 κ_0 values are not final values selected after each and every record has been checked and validated if the decay of FAS is really captured. The final results are given under "κ evaluations for EAF related events" section of this paper.

5. *κ* estimations for EAF related events

According to the methodology chosen and dataset with events passing the initial criteria, the resulting κ values has also the magnitude dependency tendency as final estimation values. As mentioned before while applying Biro et. al. (2022) method, when the polynomials do not intersect, most suitable f_{xi} value seems to be around 20 Hz for Stn4404. It is allowed to have f_{xi} value of 30 Hz to 40 Hz if the event record allowed to fit the decay on the FAS. The direct f_x value is taken if the polynomials intersect. Usually, the direct selected f_x value gives good indication on what the f_{xi} value could be. All the event κ estimations are visually checked, with all f_{xi} values under consideration, and then a final list of κ values is chosen from the most suitable cases.

The final results are presented in Figures 4 and Figure 5 with Table 3.

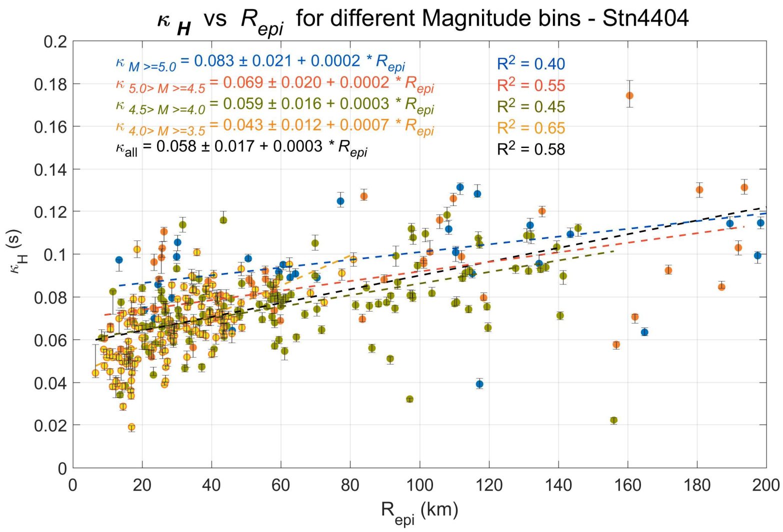

*Figure 4.*The final horizontal event kappa, κ_H vs R_{epi} up to 200 km at different magnitude bins via robust multiple linear regression model for Stn4404 with V_{s30} = 1380 m/s.

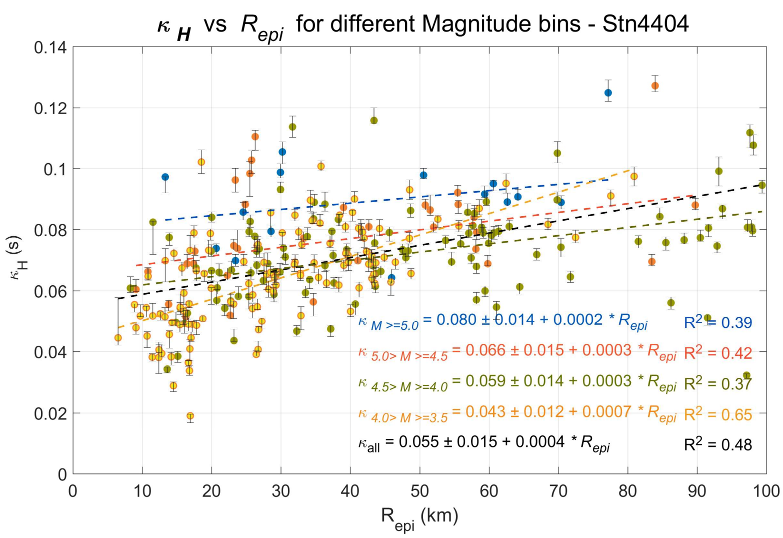

*Figure 5.*The final horizontal event kappa, κ_H vs R_{epi} up to 100 km at different magnitude bins via robust multiple linear regression model for Stn4404 with V_{s30} = 1380 m/s.

Table 3.The resulting κ_0 values for different maximum R_{epi} and different f_{xi} selection at Stn4404.

R_{epi} (km)	**κ_0 (ms) for 3.5≤M_w<4.0**	**κ_0 (ms) for 4.0≤M_w<4.5**	**κ_0 (ms) for 4.5≤M_w<5.0**	**κ_0 (ms) for M_w≥5.0**	**κ_0 (ms) overall**
100	43 ± 12	59 ± 14	66 ± 15	80 ± 14	55 ± 15
200	43 ± 12	59 ± 16	69 ± 20	83 ± 21	58 ± 17

κ_0 value for 4.0 > M_w ≥ 3.5 in case of maximum R_{epi} 100km, being 0.043 ± 0.012 s compared to κ_0 value for M_w ≥ 5.0 being 0.80 ± 0.014 s already indicates that for low seismic regions when the dataset is limited to magnitudes lower than 4.0, we might be no longer capturing a reasonable and reliable κ_0 value for an expected

M_w ≥ 5.0 event if we assume that κ is magnitude independent. The difference between these two magnitude bin κ_0 values are so vast that hazard values can be extremely impacted by the low target κ_0 values as indicated by Biro and Renault (2012) which no longer represents the real expected hazard for this region.

It is crucial to mention about the recent findings by Altindal and Askan (2022) that for Eastern Turkey region, κ values are estimated higher than the Western and Northwestern Turkey regions suggesting that the parameter has regional dependencies as well. A magnitude dependency is reported to be observed and an adjustment factor for earthquake magnitude is introduced to all models investigated in their study.

It is clear that further investigations needed to be done in well recorded regions with high seismicity, to be able to understand the regional dependency as well as the relationship between low magnitude and high magnitude event κ_0 values, so that a realistic target κ_0 value could be chosen for maximum expected magnitude event in low seismic regions.

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