THE SPECTRAL DECAY PARAMETER κ (KAPPA) FOR HARD ROCK STRONG GROUND MOTION STATIONS IN TURKEY

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Abstract

The spectral decay parameter κ (kappa) is one of the most important parameters in ground motion evaluation and seismic hazard and risk analysis at sites and basically measures and/or represents the decay of high-frequency ground motion amplitudes for each ground motion acceleration time history record at one location. The parameter is used in many applications, mainly to remove path and site effects, to simulate ground motion acceleration, to correct for high frequency attenuation and host-to-target adjustments of ground-motion prediction equations (GMPEs). During the past years, multiple approaches were developed for its estimation, which led to inconsistencies and uncertainties. The effect of κ on seismic hazard calculations were observed such that it could have high impact on seismic hazard values by increasing the high-frequency ground motions depending on the site conditions, especially in host-to-target adjustment of GMPEs, where the host represents soft rock and the target represents hard rock sites. For this reason, the scientific community has lately focused on gathering hard rock based station seismic data to evaluate the spectral decay parameter to be able to assign reliable target κ values for hard rock sites. Here in this paper, the strong ground motion recordings from Disaster and Emergency Management Agency (AFAD) stations with $V_{s30} \geq 720$ m/s were selected within Turkey. In order to reduce the uncertainties and the reliability of the outcomes being compared, the κ parameter was given a consistent representation with its measurements. For this purpose, the strong ground motion recordings with hypocentral distance, $R_{hyp} \leq 50$km and $R_{hyp} \leq 100$km with local magnitude, $M_L \geq 3.5$, where different magnitude bins are taken into account, were compared for the resulting κ_0, κ at zero epicentral distance. The results are station based and could give good indication for site-specific κ_0 values for further scientific and engineering usage.

Keywords: κ (kappa), stochastic simulation of strong ground motion, host-to-target adjustments of GMPEs

1. Introduction

The spectral decay parameter κ (kappa) was first introduced by Anderson and Hough [1] and has been used in different applications, such as to remove path and site effects, to simulate ground motion acceleration, to correct for high frequency attenuation, and host-to-target adjustments of ground-motion prediction equations (GMPEs – former attenuation relationships) since then.

κ basically measures the decay of high-frequency ground motion amplitudes for each record at one location. κ_0, κ at zero epicentral distance for the same location, then is evaluated from all records, modeled as a function of site and distance by linearly regressing over distance.

Lately it is discovered that κ_0 has high impact on seismic hazard and risk. In probabilistic seismic hazard assessment (PSHA) for critical facilities with high frequency contents and/or low natural period, GMPEs are adjusted from host to target regions. Biro and Renault [2] showed that the κ_0 corrections could lead up to a factor up to 3 on the seismic hazard, depending on the target κ_0 values (Fig.1 – Example of V_S and κ correction functions). In the same figure (Fig.1), it can be observed that only kappa κ_0 corrections would lead up to 6 times higher correction factors depending on the host and target kappas. The lower the decay of high-frequency ground motion amplitudes (low κ_0,), the higher the seismic hazard is (Fig.2 – Hazard sensitivity for different target kappas). Its biggest impact could be seen at the higher frequencies up to peak ground acceleration, PGA.

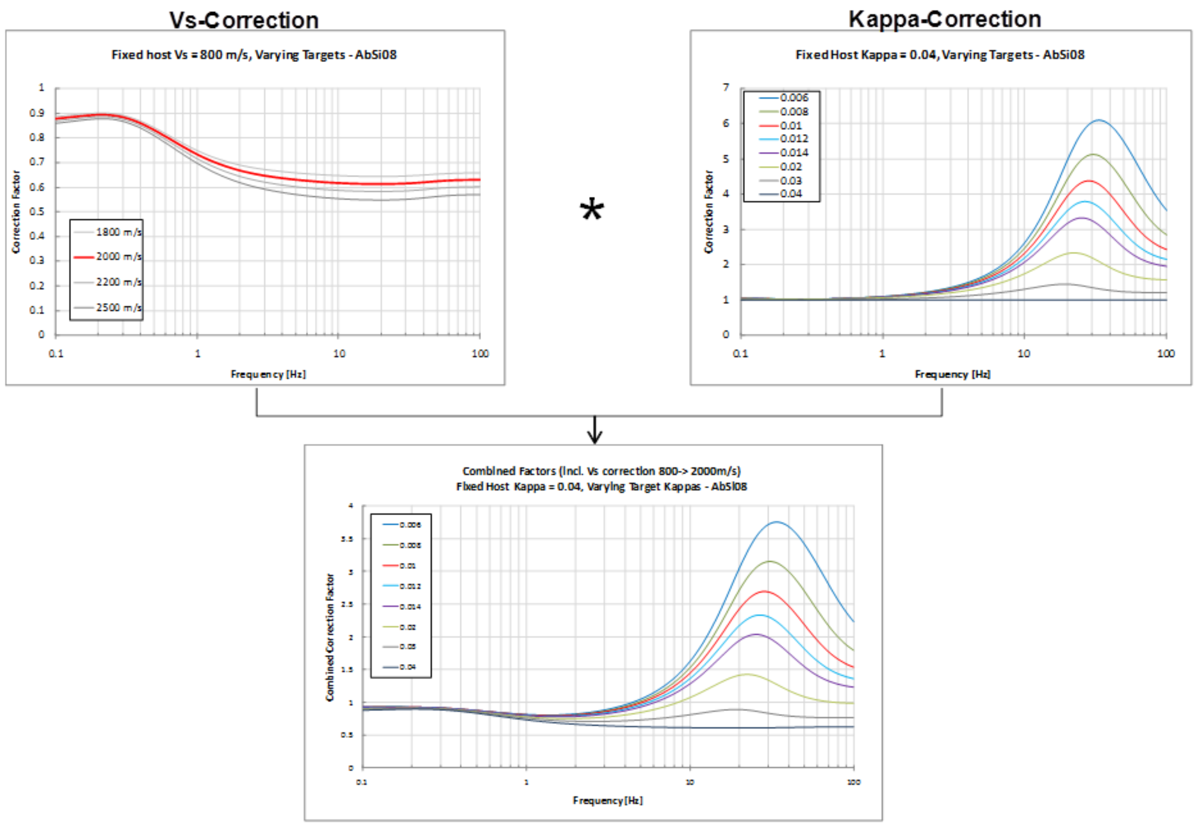

Fig. 1 – Example of V_S and κ correction functions [2]

As another application, in the creation of and calibration of GMPEs based on stochastic simulations, near-surface attenuation is implicitly considered through a set of κ_0 values considered applicable to the region. It is for this reason important to find the applicable values for the region in consideration.

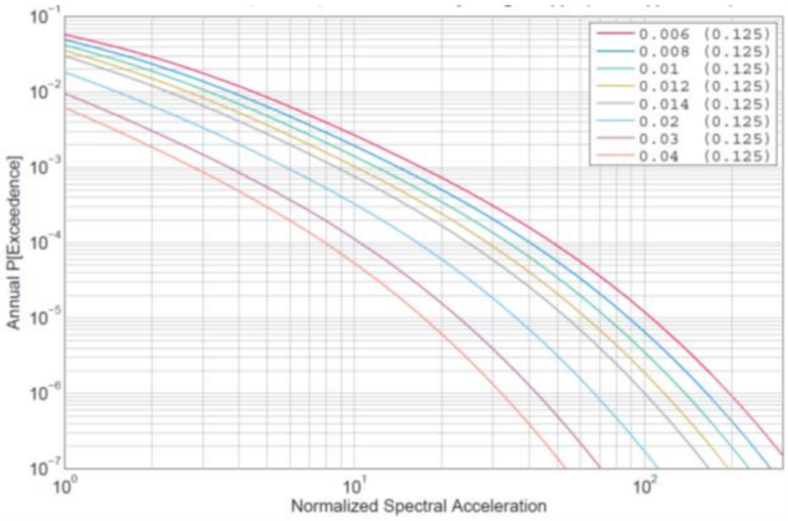

Fig. 2 – Hazard sensitivity for different target kappas [2]

For site response applications, which are basically controlled by the velocity profile and rock damping characteristics, the integration of site-specific κ_0 effect in empirical model appears essential to more accurately describe the rock-and-stiff-soil-site function. Indeed, the simulations show that κ_0 variations produce large ground-motion differences [3].

For all these applications of κ_0, multiple approaches were developed for its estimation, which led to inconsistencies and uncertainties in the past. Due to this large impact on ground-motion and seismic hazard, in order to reduce these uncertainties and the reliability of the outcomes being compared, the parameter should always be given a consistent representation with its measurements.

Ktenidou et. al. [4] reviewed four of the main approaches currently used for estimating κ_0 in a PEER report and suggested to use hypocentral distances, R_{hyp} closer than 20 km, depending on the availability of data, due to high scatter of the κ values estimated effected by the path attenuation *Q(f)* from far field recordings unless the far field Fourier Amplitude Spectrum, FAS is corrected for *Q(f)* for each record. They used roughly 20-30 km range for western USA and 50-100 km for eastern USA. They also suggested that the application could be extended towards lower magnitudes depending on the stress drop and the available bandwidth of the data in this report.

Finally, the authors mentioned about the inconsistencies between the κ_0 scale factors for analytical modeling and the empirical observations and for this reason suggested and planned the EPRI 1993 report [5] data should be re-evaluated in a future work for the following next 2 years. This attempt is now taking place in the SIGMA-2 Project [6] under Action 3.1.1. “Ground motion high frequency attenuation proxy (Kappa Project)”.

Ktenidou et. al. [7] evaluated kappa, κ, for the data combined from PRP, Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites (PEGASOS) Refinement Project, RESOURCE Project (Reference database for Seismic grOund-motion pREdiCtion in Europe), and BCHydro databases for British Columbia. They also evaluated κ for NGA-West2 and NGA-East recordings separately. For NGA-East database, they assigned a fixed V_{s30} data due to the lack of site characterization in that region. They assumed that for the events that occurred at distances closer than 100 km, the κ values can be set as κ_0 at surface of the stations. They derived mean FAS from stacking all recordings per station for estimating κ_0 at surface. These evaluated κ_0 values were estimated from the part of mean FAS with a fixed band of frequencies between 15-30 Hz.

Ktenidou et. al. [8] have developed a framework for estimating κ_0 and addressing uncertainties often imposed in practice due to limited records, maximum usable frequency, low magnitudes and large uncertainty in stress drop. In this paper the authors mentioned they could not yet resolve the stress drop within the bandwidth.

Previous calculations of kappa for the events in Turkey were estimated for mainshock and aftershocks of the important seismic events all together and the effect of the distance of the recordings were not taken into consideration. Instead, all event recordings in all stations that recorded the events were taken into account, regardless how far the events were from the station that recorded them. As κ is controlled by the attenuation along the path and at the site, the path attenuation $Q(f)$ from far field recordings interferes when the event is far away from the station that recorded it. Lately new publications on the Turkish data considers each recording site individually. These kappa estimations are mainly focused in western Turkey region.

Askan et. al. [9] have examined a strong ground motion dataset from Northwestern Turkey to generate a regional κ model and validated their results with proposed κ model with 1999 Gölkaya (M_w=5.2) and 1999 Düzce (M_w =7.1) earthquakes. The dataset used here is with magnitudes between $3.0 < M_w < 6.0$, where 60 out of 142 events are between magnitude bin $3.0 < M_w < 4.0$, and the events within 200km epicentral distance were employed. Kappa estimations were performed for 5 s S-wave windows instead of the full range of FAS of S-wave. In this paper, the authors proposed a site depended κ estimation by specifying the station site conditions, while taking all kappas from stations with same site characteristics to result the κ_0 for that site. As site conditions in their database, they took only two distinct values, NEHRP site classes, Site C and Site D. For Site C class they obtained κ_0 value (horizontal) of 0.0377s for northwestern Turkey region. They found no indication of magnitude dependency in their study, but suggested further evaluation with more complete datasets that might yield different results for magnitude dependency of the κ parameter.

Kurtulmus and Akyol [10] analyzed micro and moderate size local earthquakes in the central west Turkey, with magnitude range of $2.0 < M_L < 5.6$ and hypocentral distance ranging from 3.5 km to 205 km. They used generalized inversion technique (GIT) to the spectra. The GIT vertical motion results were compared to horizontal-to-vertical spectral ratio (HVSR) estimates and as a result they concluded that HVSR might underestimate the site response. For the κ estimations, the authors assumed to be off the regional Q attenuation effect. They have suggested that there are weak distance dependencies of κ values in their study. They also mentioned that the variability of estimated κ values could be related with not only source but also whole propagation path effects. They averaged out κ_0 values of 27 different sites for their dataset. They obtained an array average near source attenuation parameter κ_0 value as 0.031 (±0.009) s for the western Turkey region.

Tanircan and Dikmen [11] have estimated horizontal average κ values for three downhole arrays and two engineering bedrock situated instrument recordings at the western side of the Bosporus, Istanbul with a magnitude range of $3.0 \leq M_L \leq 4.8$, with up to 200 km epicentral distance. Depending on the magnitude and distance of the earthquakes, 5-15 s portion of the S and noise window was selected for spectral analysis. They used constant Q by noting that when compared with frequency dependent $Q(f)$, the resulting κ values are smaller as a result. Moreover, they pointed out that Q dominates the κ value in large distances, hence uncertainty in κ increases with increasing distance. κ_0 values were evaluated for each instrument separately and were compared. The results were also investigated whether they correspond to the V_{s30} - κ_0 relations with hard rock conditions included in the literature. They noted that the recordings of downhole arrays, except the surface recordings, are more or less affected by reflections from different velocity interfaces depending on the depth they are overlain, and added that kappa values might be overestimated.

Due to the effect of kappa on seismic hazard calculations, especially in host-to-target adjustment of GMPEs, where the host represents soft rock and the target represents hard rock sites, the scientific community has focused lately on gathering hard rock based station seismic data to evaluate the spectral decay parameter to be able to assign reliable target κ values for hard rock sites. For this reason, in this paper, the focus is on the estimation of κ_0 at the Disaster and Emergency Management Agency (AFAD) strong motion stations with $V_{s30} \geq 720$ m/s within Turkey region.

During the study it was observed that change in the selection and application criteria could have significant effect on the resulting kappas. For this reason, only the preliminary results for hard rock based station surface kappas are presented here in this paper. Further analysis continues on the selection criteria to observe the effects of such criteria on the resulting κ_0 values. The preliminary results are compatible when compared with hard rock κ_0 values presented in related literature.

2. Data and methodology of kappa estimations

The strong ground motion recordings used for analyses are from 1984 until November 2019 from Disaster and Emergency Management Agency (AFAD) strong motion hard rock based stations with $V_{s30} \geq 720$ m/s in Turkey. The events were selected with hypocentral distance, $R_{hyp} \leq 100$km and with local magnitude, $M_L \geq 3.5$. The V_{s30} values of these stations are indicated in Table 1. Some hard rock based AFAD stations were excluded and are not listed here due to not enough events or the selection criteria such as signal to noise ratio, SNR. Also, only the free field stations are taken into consideration.

The hypocentral distances, R_{hyp}, were calculated for each recording and where there was no depth information, the epicentral distances, R_{epi} were used. In Fig.3, only the selected events, at total 711, are represented to illustrate the distribution of R_{hyp} vs V_{s30}. In further analysis some eliminated stations could as well be included if enough event is recorded and the uncertainties and errors could be resolved.

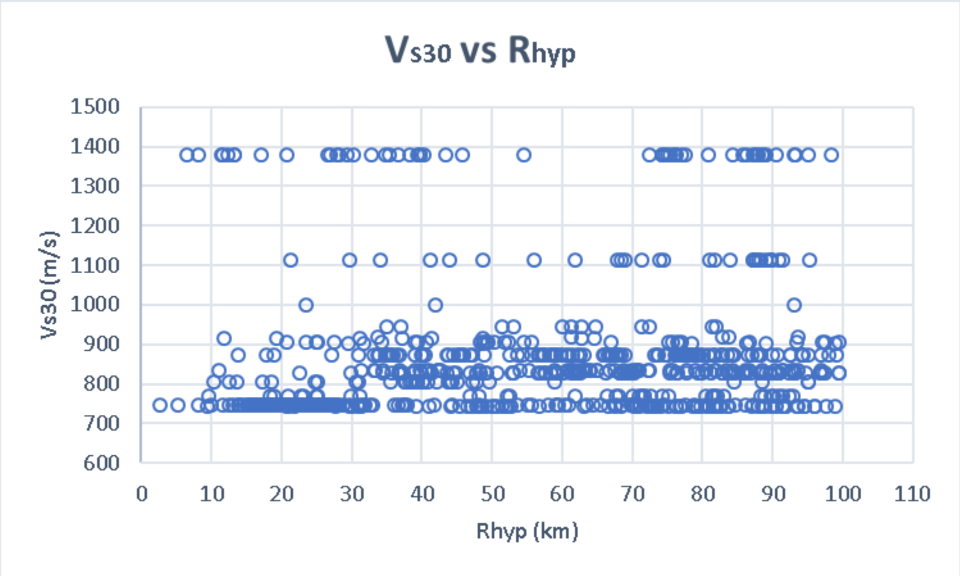

Fig. 3 – Distribution of selected events in terms of R_{hyp} and V_{s30} for AFAD hard rock stations.

This distribution gives a fair number of events to evaluate κ with only $R_{hyp} \leq 50$ km for hard rock case. At some stations even $R_{hyp} \leq 30$ km can be evaluated with many event input data.

Estimation of κ was done by the original method of Anderson and Hough [1] for each selected strong ground recording the components of NS, and EW separately. The method indicates a frequency spectral decay modeled as:

$$A(f) = A_0 e^{\pi\kappa f} \qquad f > f_E \tag{1}$$

where amplitude A_0 depends on source and path properties and f is the frequency. f_E indicates the specific frequency that the spectral decay begins on a log-lin amplitude vs frequency plot of the S wave spectrum.

For the horizontal recordings the mean value of the two estimated horizontal κ is calculated as a resulting κ value for that event. First the spectral decay parameter κ was estimated by obtaining a linear least square fit to the logarithm of S wave spectrum of acceleration versus frequency of each recording between f_E, the frequency where the spectral amplitude acquires a maximum, and f_x, the frequency where the exponential decay of the acceleration spectrum becomes flat [1]. While processing the data, the selection of f_E and f_x were made both as automated fixed values, and by visual examination and interactive manual selection to see the difference in the effect of the selection. For the final outcome of the estimated κ values, the manually selected f_E and f_x are favored.

Finally, after calculating the κ value for each horizontal component of the event at a distance to the recording hard rock based AFAD stations, the value of the spectral decay parameter at zero epicentral distance (κ_0), as an approximation, was evaluated considering with linear distance dependency (Eq. 2).

$$\kappa = \kappa_0 + \kappa_R R_{hyp} \tag{2}$$

Table 1 – AFAD hard rock stations and κ_0 evaluations

Stn #	**LAT**	**LON**	**City**	**Province**	**V_{s30} (m/s)**	**κ_0 (s)**	**$M_{L,min}$**	**$M_{L,max}$**	**Remarks**
118	37.0362	35.3184	Adana	Cukurova	946	0.019	3.5	4.5	$50<R_{hyp}\leq 84$km
701	36.8944	30.6667	Antalya	Muratpasa	920	0.010	4.2	5.2	
705	36.1951	29.6474	Antalya	Kas	1113	0.029	3.5	6.0	$R_{hyp}>40$km
1101	40.14106	29.9774	Bilecik	Merkez	901	0.039	3.6	5.2	
2016	37.80441	29.24003	Denizli	Honaz	805	0.041	3.5	6.0	
2302	38.39231	39.67541	Elazig	Maden	907	0.028	3.5	5.2	
3506	38.39443	27.08211	Izmir	Konak	771	0.012	3.5	5.3	$R_{hyp}\leq 100$km
3506	38.39443	27.08211	Izmir	Konak	771	0.022	3.5	5.3	$R_{hyp}\leq 50$km
3511	38.4213	27.2563	Izmir	Pinarbasi	827	0.009	3.5	6.2	
3514	38.4762	27.1581	Izmir	Bayrakli	836	0.005	3.5	6.2	
3520	38.478	27.2111	Izmir	Bornova	875	0.027	3.5	6.2	
3525	38.3723	27.1084	Izmir	Yesilyurt	745	0.011	3.5	6.2	$M_L\geq 3.5$
3525	38.3723	27.1084	Izmir	Yesilyurt	745	0.019	4.0	6.2	$M_L\geq 4.0$
4404	38.19588	38.87385	Malatya	Puturge	1380	0.049	3.5	5.5	$R_{hyp}\leq 100$km
4404	38.19588	38.87385	Malatya	Puturge	1380	0.024	3.6	4.2	$R_{hyp}\leq 30$km
4802	37.03304	27.43997	Mugla	Bodrum	747	0.021	3.5	5.3	$R_{hyp}\leq 100$km
4802	37.03304	27.43997	Mugla	Bodrum	747	0.014	3.5	5.3	$R_{hyp}\leq 30$km
8105	40.90278	31.15198	Duzce	Merkez	914	0.023	3.6	4.7	

3. Results

The κ_0 evaluations carried out for the strong ground motion recordings at hard rock based AFAD stations are listed in Table 1. Different windows for f_x - f_E band were selected for some stations after visual inspection to evaluate κ where a fixed frequency band could not capture the decay of the event. The mean value of two horizontal κ values resulted as κ estimations for that event in consideration. If the two horizontal estimated κ values differ from each other more than %25, they were excluded. For every selected event, the mean κ values then were calculated and plotted versus R_{hyp} to get the zero epicentral distance spectral decay parameter, κ_0 values as in Eq. 2 for that station.

As mentioned above, at some stations $R_{hyp} \leq 30$ or $R_{hyp} \leq 50$ km can be evaluated with many event input data. Both $R_{hyp} \leq 30$ km and $R_{hyp} \leq 100$ km κ_0 estimations are given in Table 1. At station 3506, where V_{s30}=771 m/s, $R_{hyp} \leq 50$ km events resulted $\kappa_0 = 0.022$ s, whereas if all the events up to R_{hyp} = 100km are taken into account the resulting κ_0 was estimated as 0.012 s. This may be due to two 1977 event recordings giving high kappa values around 0.050 s with $M_L = 4.8$ and $M_L = 5.3$ in $R_{hyp} \leq 30$ km distance. In another station, 4404 with V_{s30}=1380 m/s, $R_{hyp} \leq 30$ km selection criteria gave κ_0=0.024 s, whereas if all events are included up to R_{hyp}=100km, κ_0 is estimated 0.049 s. Same trend as in station 4404 is seen at station 4802 (V_{s30}=747 m/s), where κ_0=0.014 s when the maximum R_{hyp} is 30 km, and κ_0=0.021 s if $R_{hyp} \leq$100km. In Fig.4 the $R_{hyp} \leq 100$ km cases of stations 4404 and 4802 are illustrated in red, when $R_{hyp} \leq 30$ or 50 km is applicable. For the case of station 3506 we favored the $R_{hyp} \leq 100$ km κ_0 estimation at this moment.

The κ estimations were also checked if $M_L \geq 3.5$ and $M_L \geq 4.0$ selection criteria defers in the resulting κ_0 values. Only in Station 3525 there was a significant difference and is listed in Table 1. $M_L \geq 4.0$ case is favored at Fig.4. Station 701 has only $M_L \geq 4.2$ events recorded and could be compared with $M_L \geq 4.0$ selection criteria.

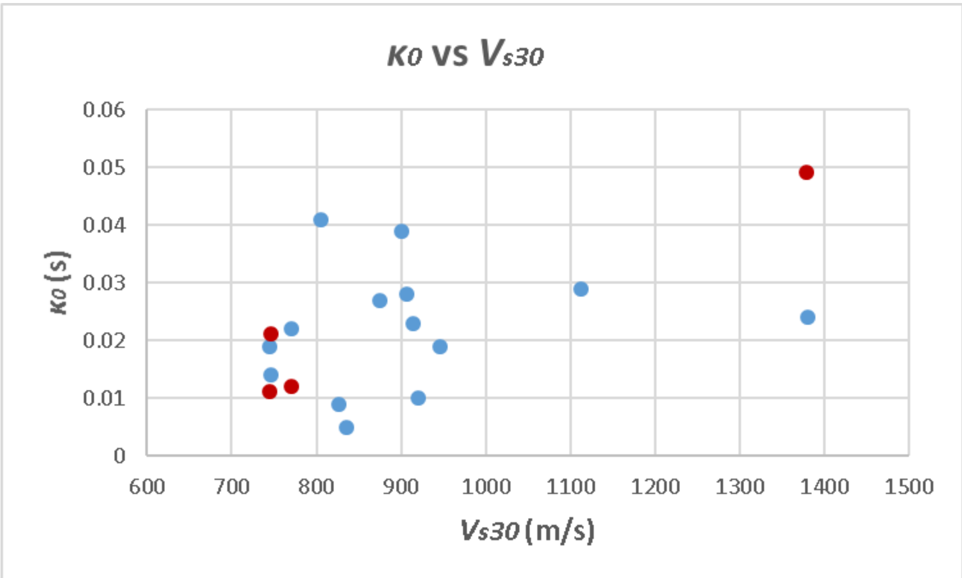

Fig. 4 – Distribution of evaluated κ_0 values with V_{s30} for AFAD hard rock stations.

4. Conclusion

In this paper, kappa values were estimated from 711 events (1422 horizontal components) recorded in 14 hard rock based AFAD stations with $V_{s30} \geq 720$ m/s. The event magnitude range in overall database is between $3.5 \leq M_L \leq 6.2$ and are changing according to the events recorded at the stations (Table 1). The maximum hypocentral distance, R_{hyp}, was set to 100 km initially. When applicable, shorter distances were set as maximum R_{hyp}.

Depending on the availability of data different magnitude bins were taken into account. κ estimations were checked if they pass the %25 maximum difference between two horizontal values, and finally, κ_0 values were evaluated for each station.

The resulting surface κ_0 values are compatible for the hard rock kappa studies published in the related literature. Further analysis will be performed on different magnitude bins and sets of f_x - f_E band in the future.

5. References

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