# A STUDY ON HIGH FREQUENCY DECAY PARAMETER (KAPPA) FROM VARZAGHAN-AHAR DOUBLE EARTHQUAKES, NORTHWESTERN IRAN ($M_W$ 6.5 & 6.3)

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## ABSTRACT

The high frequency decay parameter, kappa and its variations in distance is evaluated using 114 three-component strong motion records from two moderate events in NW Iran. We show that in classical method of estimating kappa, the results are very sensitive to the choices of $f_E$ and $f_X$ and automated procedures for estimating kappa are likely to lead to a biased estimation. For the present database, we found an obvious concavity in dependency of kappa with distance. The kappa values in distance were regressed to a piecewise bilinear shape. Based on this piecewise bilinear shape the zero distance kappa are 0.044 and 0.023 for horizontal and vertical components respectively.

## INTRODUCTION

In stochastic ground motion simulations, one of the most important issues is knowledge about the shape of Fourier acceleration spectra. Fourier acceleration spectra decay rapidly at high frequencies. In strong ground motion generation computer programs like SMSIM (Boore, 2005) or ESXIM (Motazedian and Atkinson, 2005), this high frequency decay is incorporated into the program based on two models: first, the parameter $f_{max}$ presented by Hanks (1982) and second, kappa developed by Anderson and Hough (1984). This study addresses the issues about the second model using a database of two recent moderate earthquakes in Iran.

On 2012 August 11th two destructive earthquakes occurred 11 minutes apart near two towns of Varzaghan and Ahar in Northwestern Iran; the first with moment magnitude of 6.5 at 12:23 UTC and the second with moment magnitude of 6.3 at 12:34 UTC (Iranian Seismological Center (IRSC) homepage), resulting in over 300 deaths and 3000 injuries. These earthquakes have two important aspects: first, they are the biggest events recorded in Northwestern Iran and second, they are very well recorded events, being recorded on more than 60 strong motion stations on Iran Strong Motion Network (ISMN) out to hypocentral distances of more than 200 km (Iran Strong Motion Network (ISMN) homepage)(Table 1 and Figure 1). These strong motion accelerograms have provided us with excellent database to study the earthquake parameters in the region.

Our goal in this paper is to estimate the values of kappa for observed strong ground motions and their behavior in distance. We also evaluate issues in extrapolating the estimated kappa values to zero distance.

These issues attracted our attention in a recent study on the source spectra of Varzaghan-Ahar earthquakes by the authors (Samaei and Miyajima, 2015b).

## DATABASE

The data used in this study were all recorded by Iran Strong Motion Network (ISMN), which have been installed and maintained by Building and Housing Research Center (BHRC). The BHRC ground-motion database has been expanded continuously during the past decades due to the added new strong-motion stations and occurrence of large earthquakes. So far, more than 10000 strong motion records have been obtained by ISMN since its inception in 1973. (Iran Strong Motion Network (ISMN) homepage)

As we noted earlier Varzaghan-Ahar earthquakes are recorded on more than 60 strong motion stations comprised database of 114 three component records. All the stations were equipped with three component digital SSA2 accelerographs where the transducer response for them is flat up to 50 Hz. This makes no necessity of correction for instrument response. The sampling rates of the records are 200 Hz . Table 1 shows the earthquakes information and Figure 1 shows the location of earthquakes and stations.

Table 1. Earthquakes information

| **Event** | **Date** | **Time** | **Latitude** | **Longitude** | **Depth (km)** | **Magnitude** | **Reference** | **No. of records** |
|---|---|---|---|---|---|---|---|---|
| First shock | 8/11/2012 | 12:23:15 | 38.433 | 46.812 | 9 | Mw 6.5 | IRSC* | 49 |
| Second shock | 8/11/2012 | 12:34:35 | 38.423 | 46.802 | 4 | Mw 6.3 | IRSC* | 65 |

* Iranian Seismological Center

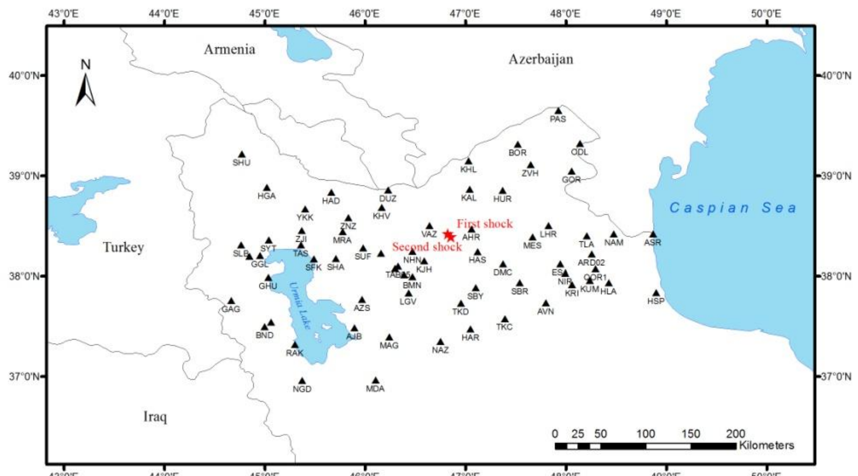


Figure 1. Location of events and stations. Red stars denote the location of events and black triangles show the stations.

## PROCESSING OF THE RECORDS

Signal processing for the recordings is discussed in details in Samaei and Miyajima (2015a), and here is just briefly explained.

After a zero order baseline correction (Boore, 1999), S wave Fourier Amplitude Spectra (FAS) of the acceleration time series were computed using time windows that start with the first arrival of the S wave and end when 90% of the total energy is reached. Time windows were tapered with a 5% cosine taper before calculation of FAS.

Since we work with the data in frequency domain, the most important issue would be the bandwidth that can reliably be used. At high frequencies FAS starts to fall toward higher frequencies until it flattens and touches the noise floor(Anderson and Hough, 1984); we have used the data out to the frequency that FAS touches that floor. This is most recognizable in frequency-FAS plot when frequency is in normal units (not in log units).

The lowest usable frequency is chosen mostly based on the shape of FAS and filtering and inspecting integrated time series. The shape of FAS should be relatively falling toward lower frequencies based on theoretical models of source spectra and integrated acceleration time series to velocity and displacement should be physically available (Boore and Bommer, 2005).

## KAPPA ESTIMATION

Based on some observations of Fourier acceleration spectra from California earthquakes, Anderson and Hough (1984) recognized that when amplitude spectrum plot is in log-normal units (amplitude in log and frequency in normal units) spectral amplitude at a specific frequency (well above the corner frequency) starts to decay linearly toward higher frequencies. They proposed that this "decay" has the following functional form:

$$A(f) = A_0 \exp(-\pi\kappa f), \qquad f > f_E \tag{1}$$

Where $A(f)$ is observed spectrum, $\kappa$ (kappa) is "spectral decay factor", $A_0$ is the constant term and $f_E$ is the frequency that amplitude starts falling. This equation holds true to the frequency of $f_X$ where the spectrum touches the noise floor.

Anderson and Hough (1984) found a dependency between kappa and distance. They and Anderson (1986) proposed a linear dependency but admitted that this is just an approximation not a definitive shape:

$$\kappa(R) = \kappa_0 + mR \tag{2}$$

where $m$ is the slope and $\kappa_0$ is the intercept at zero distance.

Later on Anderson (Anderson, 1991) generalized the dependency between kappa and distance:

$$\kappa(R) = \kappa_0 + \tilde{\kappa}(R) \tag{3}$$

In which $\tilde{\kappa}(R)$ is a nonparametric shape that accounts for all the dependency between kappa and distance. This generalization let for more complexity to appear in kappa and distance dependency.

Anderson and Hough (1984), Anderson (1986), and Hough et al. (1988), regarded kappa as a site term. It might be useful to note that for accounting high frequency decay parameter (kappa or its predecessor $f_{max}$) as a site term there is no consensus among researchers. Some studies refer to high frequency decay as a source term (i.e. Papageorgiou and Aki (1983), Tsai and Chen (2000), Tsurugi et al. (2008)). Here we do not argue that if kappa is a site or source term, we simply consider it as a regional effect that appears in observed spectra.

In this study, we first obtain the high spectral decay for all the records then discuss the extrapolation to estimate zero distance kappa.

Figure 2 shows some examples of the linear fit in log-linear plot to the acceleration spectra according to equation (1). For obtaining these fits, $f_E$ and $f_X$ are visually chosen for each record since there is a wide variability in these parameters. There are two obvious points in Figure 2, first: Vertical components tend to touch the noise floor later than horizontal components do; second (and more importantly): $f_X$ has clear dependency to distance.

These facts are better illustrated in Figure 3, which plots $f_E$ and $f_X$ versus distance. Our reason for showing this figure is to point out that typical values for these parameters (Especially for $f_X$) may lead to a biased estimation of κ. This is a point also made by Douglas et al. (2010), where they adopt a non-automatic procedure for studying kappa and its variability in France.

Figure 4 shows kappa behavior in distance. As we noted earlier a linear trend is a first approximation. However, what we observe is a distinct concavity in values of kappa versus distance. It seems that kappa at far distances increases with a higher rate than in short distances. In Figure 4, a polynomial fit is also displayed which is a clear promotion to the linear fit. Of course, we do not state that a polynomial fit is what would be needed in general case. Our point is that a linear fit to the kappa values in distance might be a very poor representation and accordingly extrapolating the values to zero distance and obtaining $\kappa_0$ in this way may not be appropriate. In our case, based on linear fit $\kappa_{0(v)}$=0.0009 and $\kappa_{0(h)}$=0.0195 where seem to be too low.

Some other researchers also report what we observe here. Gentili and Franceschina (2011) found kappa dependence with distance to be concave and modeled it with a piecewise bilinear function. Kilb et al. (2012) found no significant dependency of kappa with distance for epicentral distances smaller than 40 km. Boore (2014, written communication) has noticed that kappa is sometimes not a linear function of distance, appearing rather flat to distances of some tens of km before increasing.

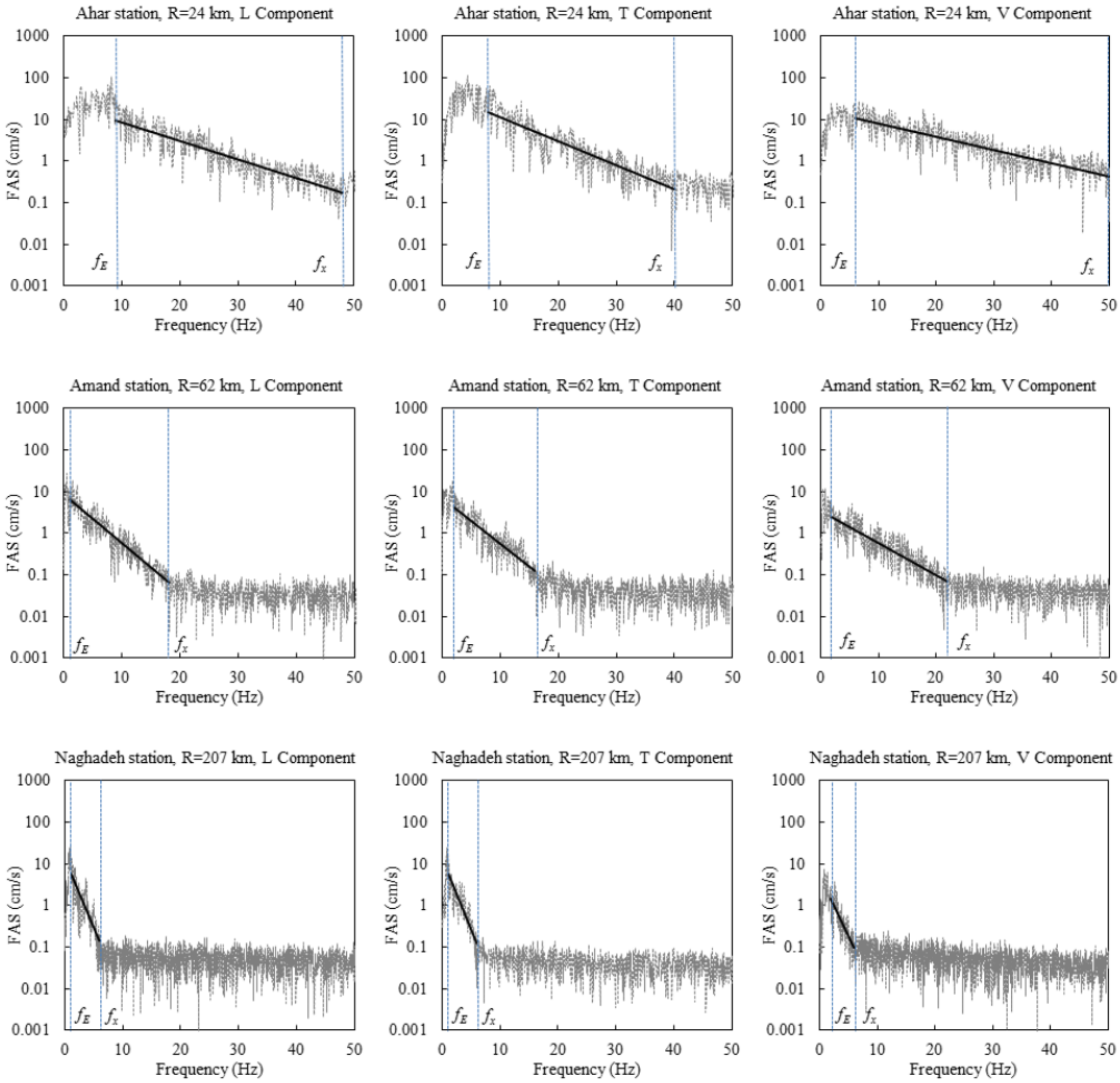


Figure 2. Some examples of linear fit based on equation (1) to log-normal plot of Fourier amplitude spectra. $f_E$ is the frequency where the spectrum starts to fall and $f_X$ is where it approaches the noise floor. Variability of $f_E$ and $f_X$ is apparent. All the examples are from the first event.

To the extent of our knowledge, no research in Iran has reported such a “concavity” in kappa values (Motazedian, 2006, Motazedian and Moinfar, 2006, Hassani et al., 2011, Zafarani et al., 2012, Zafarani and Soghrat, 2012, Safarshahi et al., 2013, Meghdadi and Shoja-Taheri, 2014, Mahood et al., 2014). None of these studies mentions the nonlinear dependency of kappa with this distance. We could think of some possible reasons for this: First, some of these studies have observed kappa in limited distance range (e.g. 100 km), in these ranges (as we will show subsequently), the nonlinearity becomes less important. Second, these studies may have not found this nonlinearity important enough in their dataset to mention, considering the big scatter in the data. Third, as many of these studies have used automated procedures in estimating kappa (Typical $f_E$ and $f_X$), their kappa estimation might be biased especially at far distances where $f_X$ might be very low. Not to mention some of these studies have fitted equation (1) to the smoothed Fourier amplitude spectra where $f_X$ may not recognizable at all.

In this study, kappa versus distance is fit to a bilinear function with two slopes where the second being

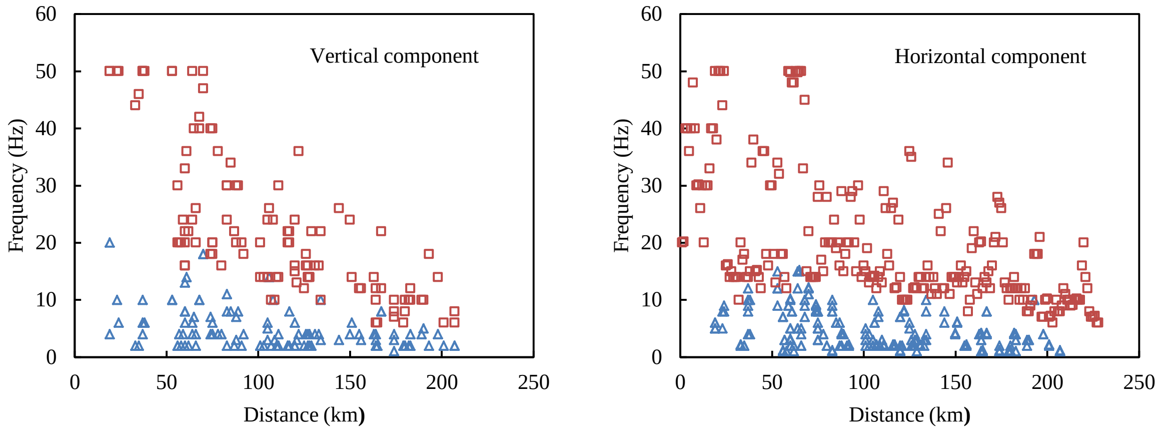


Figure 3. Variability of $f_E$ and $f_X$ in distance. Triangles and squares demonstrate $f_E$ and $f_X$ respectively. Values of $f_X$ are limited to frequency of 50 Hz for which the transducer response for recording is flat.

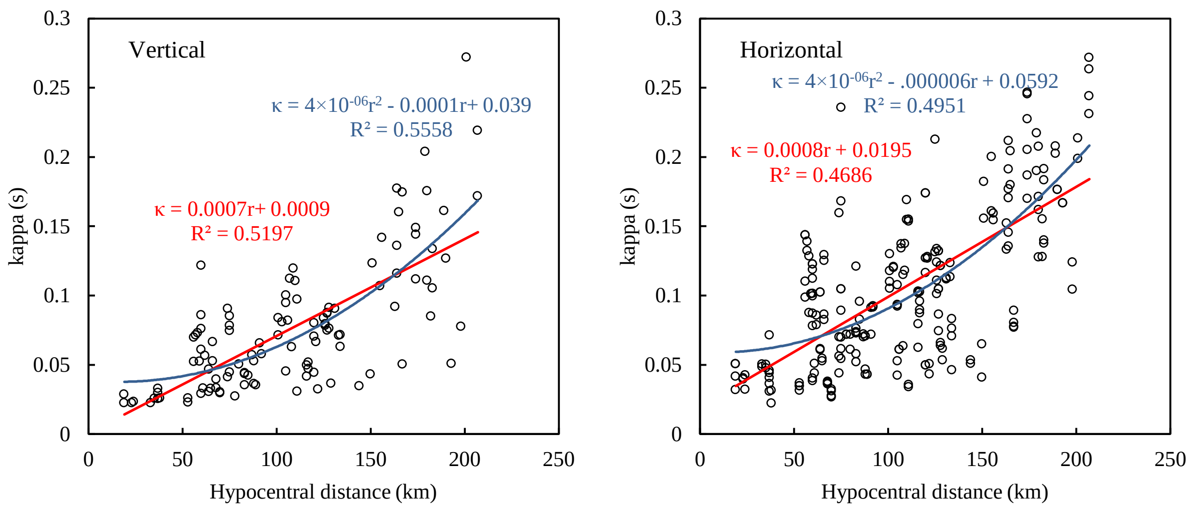


Figure 4. Plots of kappa versus distance; there is an obvious concavity and a polynomial fit is a better representation of data.

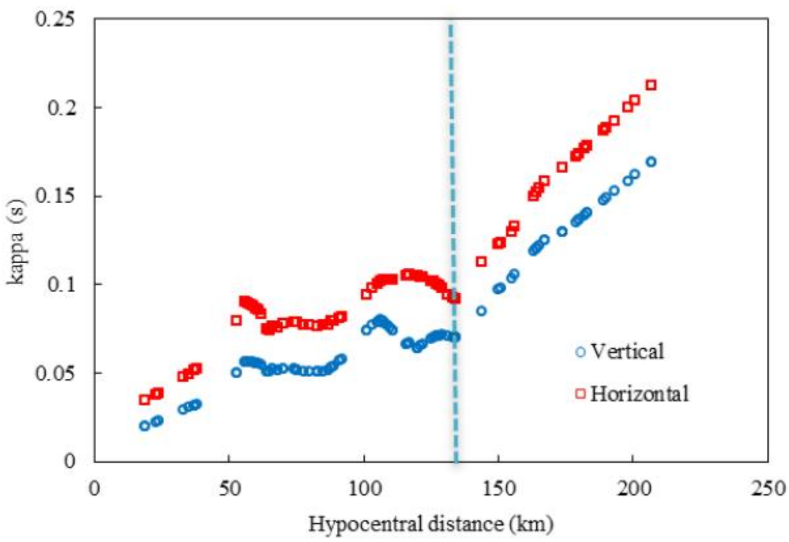


Figure 5. Smoothed kappa versus distance using lowess method. A hinge point at distance of about 130 km can be found.

Being steeper than the first as proposed by Gentili and Franceschina (2011). The function has the following general form:

$$\kappa(R) = \begin{cases} \kappa_0 + c_1 R & R \le R_1 \\ \kappa_0 + c_1 R_1 + c_2 (R - R_1) & R > R_1 \end{cases} \quad (4)$$

where $c_1$ and $c_2$ are first and second slopes respectively and $R_1$ is the hinge point.

For visually finding the optimal hinge point we used a locally weighted scatterplot smoothing algorithm called Lowess (Cleveland, 1979, Cleveland, 1993). The method uses locally weighted linear regression to smooth the data. The smoothing process is local because it calculates each smoothed value (fitted line) by a set of neighboring data points. The smoothing process is weighted because a regression weight function is defined for the data points contained within the data spans. Figure 5. shows the smoothed data based on this method. It is obvious from this figure that the hinge point can be set around distance of 130 km.

Table 2. Results of regression based on piecewise bilinear shape of equation (4)

| | $\kappa_0$ | $c_1$ | $c_2$ | $R_1$ |
|---|---|---|---|---|
| Horizontal | 0.044 | 0.00048 | 0.00092 | 130 |
| Vertical | 0.023 | 0.0004 | 0.00125 | 130 |

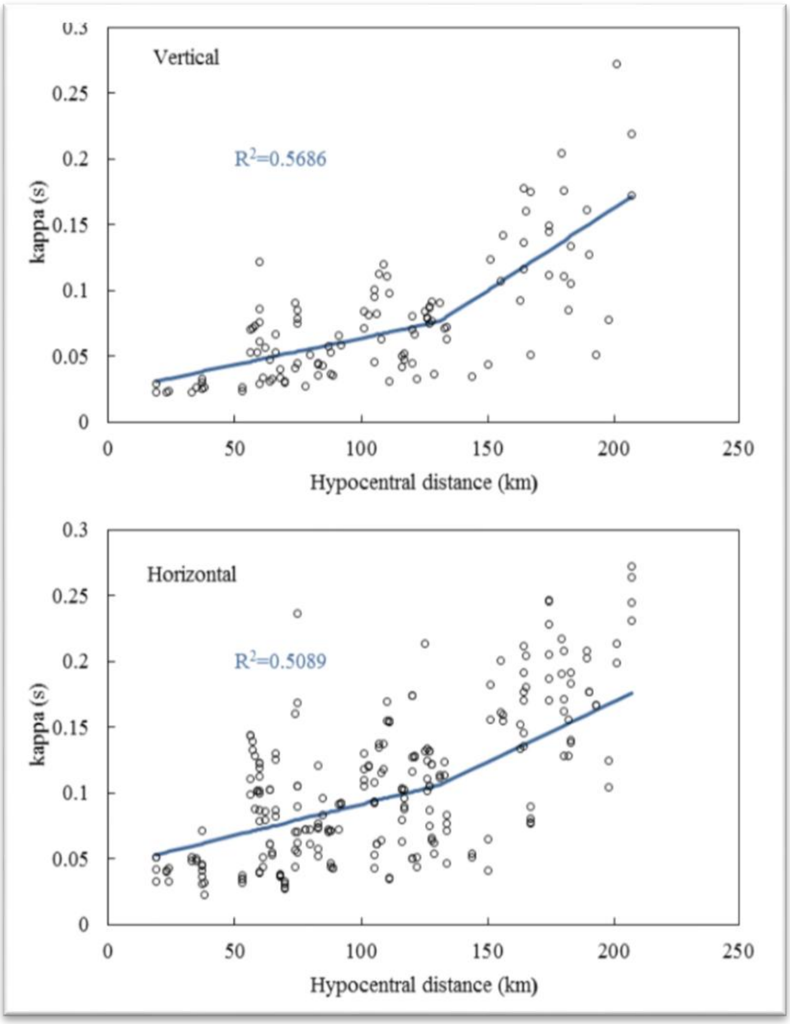


Figure 6. Illustration of piecewise bilinear regression.

Based on the hinge point of 130 km a simple regression is done and the results are shown in Tabel 2 and Figure 6. The obtained results for $\kappa_0$ values are comparable with kappa estimates in other studies in the region (Motazedian, 2006, Motazedian and Moinfar, 2006, Hassani et al., 2011, Zafarani et al., 2012, Zafarani and Soghrat, 2012, Safarshahi et al., 2013, Meghdadi and Shoja-Taheri, 2014, Mahood et al., 2014). We observed that limiting the data to shorter distances (e.g 100 km) and considering only one line doesn't alter the estimated $\kappa_0$ values significantly. In studying source spectra, $\kappa_0$ values in the range of table 2 for horizontal and vertical components, which are usually reported for Iran, have been used successfully for removing the site effects from observed spectra in an earlier work (Samaei et al., 2013).

## CONCLUSIONS

In the present study, we evaluated the high frequency decay parameter kappa and its variations in distance. We showed that in classical method of estimating kappa (Anderson and Hough, 1984) the results are very sensitive to the choices of $f_E$ and $f_X$ and automated procedures for estimation kappa are likely to lead to a biased estimation (For other methods of estimating kappa refer to Kilb et al. (2012) and Ktenidou et al. (2014)). For the present database, we found an obvious concavity in dependency of kappa with distance so a linear representation of this dependency might be too simplistic. The kappa values in distance were regressed to a piecewise bilinear shape, this pricewise bilinear shape leaded to more logical values of $\kappa_0$ compared to a linear shape.

High frequency decay parameter evaluated to the possible extent allowed by the present database. Certainly, a more comprehensive database would allow for more detailed evaluation. For example, a database of ground motions in a wide range of magnitudes recorded in many station would allow for evaluation of the dependency of kappa to source or local site condition. Study of kappa using borehole arrays might be useful in evaluating the effect of top soil layers of local site, which is of engineering interest.

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