Kappa ($\kappa$) model for Kachchh region of Western India

Santosh Kumar$^a$, Dinesh Kumar$^b$, B. K. Rastogi$^a$ and A. P. Singh$^a$

$^a$Department of Science and Technology, Institute of Seismological Research, Gandhinagar, Gujarat, India; $^b$Department of Geophysics, Kurukshetra University, Kurukshetra, India

**ABSTRACT**

The empirical factor Kappa ($\kappa$), governs the rapid decay of spectral amplitude at high frequencies. It is one of the important parameters required in the simulations of earthquake strong ground motions. The present study estimates $\kappa$ for 16 sites of Kachchh region of Gujarat (India). The Kachchh region is one of the most seismically active intraplate regions of the world that has experienced shocks of magnitude up to 8.0 in past. We have analyzed 159 accelerograms of 34 earthquakes of magnitude range 3.3–4.9 to estimate the $\kappa$. The estimated values of $\kappa$ vary from 0.016 to 0.045 with an average of 0.023. Our results show no significant dependence of $\kappa$ on distance ($R$) for the region. The analysis based on two sites shows that $\kappa_0$ ($\kappa$ at $R=0$) is lower for the hard rock site (0.016) as compared with the value for the soft rock site (0.0201). One of the important observations of this study is that $\kappa$ is not the source property for Kachchh region. The estimated values of the $\kappa$ are useful for the stochastic simulation of earthquake strong ground motions.

**KEYWORDS**

Kachchh; seismic hazard; attenuation; kappa $\kappa$; earthquake

1. Introduction

The spectrum of earthquake strong ground motions has been found to be attenuated more rapidly at high frequencies above the corner frequency than predicted from the Brune (1970) model. The attenuation can be considered as decrease of amplitude with distance or time. The effective attenuation within the crust is modelled by the inverse of quality factor (Q). It was recognized that the decay of acceleration spectra at high frequencies could not be explained by whole path attenuation within the crust as it is also influenced by shallow layers at the site. Hanks (1982) introduced a frequency parameter, $f_{\text{max}}$ to explain the rapid decay of acceleration spectra at high frequency. According to this model, the acceleration spectra are flat above the corner frequency (as per Brune model), and fall off rapidly above a second corner frequency ($f_{\text{max}}$) mainly due to propagation path effects/local site effects. Hanks (1982) called this phenomenon of high-frequency band limitation of radiated earthquake energy as ‘the crashing spectrum syndrome.’ Boore (1983) considered this high frequency decay as high-cut filter in the generalization of his stochastic technique of simulating accelerograms. Papageorgiou and Aki (1983) agreed with Hank’s $f_{\text{max}}$ but suggested that its origin was related to the source rather than the site attenuation. Singh et al. (1982) introduced a site attenuation parameter, $t^*$, as $e^{-\pi f t^*}$ to explain the spectral attenuation of the SH waves. A similar formulation was proposed by Cormier (1982). The $t^*$ has been considered as the predecessor of the most frequently used factor to model high-frequency spectral attenuation (Ktenidou et al. 2013).
This spectral decay parameter was introduced by Anderson and Hough (1984) and denoted by \( \kappa \) (Kappa). This factor was introduced on the basis of observation that in log-linear space the decay of the acceleration spectrum, \( A(f) \), can be considered as linear for the frequencies higher than a specific frequency, \( f_E \) (Anderson and Hough 1984):

\[
A(f) = A_0 \exp \left( -\pi \kappa f \right) \quad \text{for} \quad f > f_E
\]  

(1)

\( A_0 \) depends on source properties, epicentral distance and other path-related factors; \( f_E \) is the frequency above which the spectral shape is linear on log-linear scale.

A linear relation between the observed values of \( \kappa \) and the distance was suggested where the intercept of the \( \kappa \) variation with distance (\( \kappa_0 \)) corresponds to the attenuation of S waves and slope of the variation corresponds to the incremental attenuation (\( \kappa_R \)). The linear relation can be written as

\[
\kappa = \kappa_0 + \kappa_R R
\]  

(2)

The above relation is based on the observation that the intercept varied systematically according to the different site conditions and distance dependence was not correlated and therefore assumed to be same for all the sites. There is no theoretical basis to assume a linear dependence of \( \kappa \). The studies have been done to estimate the dependence of \( \kappa \) on various factors. These studies revealed the different shapes of distance dependence of \( \kappa \) including non-linear (Anderson 1991), concave shape dependence (Gentili and Franceschina 2011), convex shape dependence (Fernández et al. 2010) and also no significant correlation with distance (Kilb et al. 2012). According to a model proposed by Tsai and Chen (2000), the \( \kappa \) has been found to be depending primarily on the source, secondarily on the site and only slightly on distance. The studies have been done to suggest that \( \kappa \) depends strongly on source (magnitude and focal mechanism) effects (Papageorgiou and Aki 1983; Petukhin and Irikura 2000; Purvance and Anderson 2003; Halldorsson and Papageorgiou 2005; Pavel and Vacareanu 2015). A few researchers argued about both source and site components contribution to the measured \( \kappa \) value (Tsai and Chen 2000; Purvance and Anderson 2003). On the other hand, Houtte et al. 2014 argued that the \( \kappa \) parameter primarily depends on path and site attenuation.

These above-mentioned studies indicate that the debate on origin, physical meaning and its dependence on various factors continues. However, \( \kappa \) is being used in a number of applications like for the computation of site amplification factors (Boore and Joyner 1997); simulation of ground motion and calibration of ground motion prediction equations (Rovelli et al. 1988; Beresnev and Atkinson 1997; Toro et al. 1997; Castro et al. 2001; Campbell 2003; Bindi et al. 2004; Atkinson and Boore 2006); for the characterization of sites (e.g. Awashti et al. 2010; Drouet et al. 2010); for its correlation with the engineering parameters such as peak ground acceleration (pga) and Arias intensity (Mena et al. 2010).

From seismic hazard point of view, \( \kappa \) has been found to be a very useful parameter for modelling the acceleration spectra at high frequencies and therefore necessary to constrain the attenuation and pga values. The lower values of \( \kappa \) have been cited as one of the reasons why high frequency strong ground motions in stable regions are generally higher than in active regions for the same magnitude and distance (Douglas et al. 2010).

In the present study, the high frequency spectral amplitude decay of local earthquakes has been analyzed by estimating \( \kappa \) for Kachchh/Bhuj region of Gujarat, India. The Bhuj earthquake of Mw 7.7 that occurred on January 26, 2001 in Kachchh region of western India is one of the largest and deadliest intraplate earthquakes in the World (Gupta et al. 2001; Singh et al. 2001), and the region is still active. The kappa model has been developed by estimating \( \kappa \) at different sites as well as for different source–station distances. The possible dependence of \( \kappa \) using small and moderate earthquakes in the region has been discussed.
2. Seismotectonics of Kachchh

The Kachchh region is a failed Mesozoic rift basin which is characterized by uplifted highlands and islands surrounded by the plains of the Great Rann, Banni, Little Rann, and is having many small and big faults. It is bounded between North Kathiawar Fault (NKF) in south and Nagar Parkar Fault (NPF) in north. Main faults of the Kachchh region are Katrol Hill Fault (KHF), Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Island Belt Fault (IBF), Allah Bund Fault (ABF), Nagar Parkar Fault (NPF), Banni Fault (BF), Gedi Fault (GF) and a blind North Wagad Fault (NWF) (Figure 1).

The KMF is a prominent fault of about 180 km length and demarcates the northern margin of the mainland uplift. The eastern part of this fault, where it overhangs the SWF, is the most strained region (Biswas 2005). The northern most boundary of this strained zone has been demarcated as NWF. Along the northern border of the mainland uplift, the Tertiary rocks steeply dipping, are faulted against the folded Mesozoic rocks. The KMF strikes NW-SE near Lakhpat and changes its orientation to E-W from Dudhai and further East. It is a reverse fault with regional dip towards south at steep angle near the surface, but may be flattening at depth. The KHF runs parallel to the mainland fault and south of it in E-W to ESE-WNW direction and extends about 60 km from Nana Hill to Samprada. The fault brings up the Charwar range with profound uplift feature. The IBF, an E-W to NW-SE trending fault, demarcates the northern margin of the Pachham, Khadir and Bela uplifts (islands). In the Rann of Kachchh, close to the Pakistani border, lies the Allah Bund Fault on which an earthquake of M8.0 occurred in 1819. Lying almost parallel to it, but further north of Pachham and Khadhir Islands in the Great Rann lays the NPF. IBF lies at the northern ends of the islands and the BF is south of the islands. Gedi Fault lies between IBF and SWF, and was most active in 2006.

Figure 1. Map showing the major tectonic features in the Kachchh region of Gujarat, namely ABF, Allah Bund fault; KHF, Katrol Hill fault; BF, Banni fault; GF, Gedi fault; IBF, Island belt fault; KMF, Kachchh mainland fault; NPF, Nagar Parkar fault; NKF, north Kathiawar fault; NWF, north Wagad fault; and SWF, south Wagad fault. The stars mark the epicentres of past damaging earthquakes in the region; (inset) the location map of the study region.
Earthquake tomography studies reported crustal heterogeneities in the Kachchh region (Kayal et al. 2002; Singh et al. 2012, 2016) and inferred that the main shock occurred in a distinct source zone characterized by low P-wave velocity \(V_p\) associated with a high Poisson’s ratio within a higher \(V_p\) mafic body at the hypocentre depth of the main shock. Mishra et al. (2014) reported high crack density, high saturation rate and low porosity in the source zone. A few researchers suggested the intersection fault zones at depths in the Kachchh rift basin generated the main shock (Bhatt et al. 2009; Singh et al. 2015).

### 3. Data used and methodology

A total of 159 accelerograms of 34 earthquakes with a magnitude range 3.3–4.9 recorded on GSNet (Chopra et al. 2008, Kumar et al. 2012) have been analyzed to develop \(\kappa\) model for Kachchh region. The N-S and E-W component of accelerograms has been used in the present analysis. Table 1 gives the list of the earthquakes used for estimation of \(\kappa\). Figure 2 shows the location of epicentres and recording stations.

Ktenidou et al. 2014 has informed a number of different approaches to estimate \(\kappa\). These include use of displacement spectra (Biasi and Smith 2001), fitting of observed response spectra (Silva and Darragh 1995; Silva et al. 1997), full inversion of source, path and site parameters (Margaris and Boore 1998; Drouet et al. 2010; Oth et al. 2011) and broadband inversions (Anderson and Humphrey 1991; Humphrey and Anderson 1992). In this study, we follow the classical method of Anderson and Hough (1984) which is still one of the most widely used method (e.g. Douglas et al.

| Sr. No. | DD | MN | Year | Hr | Min | Latitude | Longitude | Depth |
|--------|----|----|------|----|-----|-----------|-----------|-------|
| 1      | 13 | 5  | 2007 | 13 | 41  | 23.443    | 70.453    | 14.8  |
| 2      | 27 | 2  | 2007 | 17 | 29  | 23.491    | 70.405    | 17.1  |
| 3      | 8  | 10 | 2007 | 1  | 12  | 23.341    | 70.107    | 13.2  |
| 4      | 15 | 4  | 2008 | 18 | 22  | 23.773    | 70.739    | 11.5  |
| 5      | 12 | 10 | 2006 | 7  | 32  | 23.31     | 70.46     | 21.7  |
| 6      | 20 | 8  | 2006 | 2  | 37  | 23.503    | 70.535    | 7.4   |
| 7      | 9  | 3  | 2008 | 11 | 10  | 23.391    | 70.331    | 30.1  |
| 8      | 24 | 5  | 2007 | 12 | 54  | 23.298    | 70.026    | 9.9   |
| 9      | 1  | 3  | 2008 | 21 | 41  | 23.465    | 70.3      | 24.1  |
| 10     | 26 | 4  | 2008 | 9  | 0   | 23.56     | 70.288    | 14.1  |
| 11     | 7  | 7  | 2007 | 6  | 18  | 23.752    | 70.658    | 17.6  |
| 12     | 13 | 4  | 2007 | 16 | 20  | 23.383    | 70.396    | 25.6  |
| 13     | 8  | 6  | 2008 | 21 | 19  | 23.367    | 70.357    | 23.6  |
| 14     | 20 | 7  | 2008 | 09 | 39  | 23.467    | 70.293    | 23.3  |
| 15     | 15 | 11 | 2007 | 15 | 26  | 23.375    | 70.319    | 9.6   |
| 16     | 23 | 2  | 2007 | 3  | 50  | 23.492    | 70.376    | 25.1  |
| 17     | 5  | 9  | 2009 | 3  | 50  | 23.405    | 70.228    | 26.4  |
| 18     | 10 | 4  | 2006 | 2  | 45  | 23.44     | 70.4      | 27.3  |
| 19     | 7  | 3  | 2006 | 18 | 20  | 23.79     | 70.73     | 3     |
| 20     | 12 | 4  | 2009 | 18 | 42  | 23.416    | 70.138    | 18.7  |
| 21     | 28 | 6  | 2009 | 8  | 32  | 23.378    | 70.351    | 25    |
| 22     | 8  | 10 | 2009 | 6  | 21  | 23.426    | 70.276    | 15    |
| 23     | 23 | 2  | 2007 | 3  | 50  | 23.49     | 70.37     | 25.1  |
| 24     | 28 | 10 | 2009 | 13 | 40  | 23.71     | 69.91     | 8.5   |
| 25     | 1  | 3  | 2007 | 6  | 8   | 23.515    | 70.354    | 10.3  |
| 26     | 6  | 4  | 2010 | 12 | 56  | 23.376    | 70.347    | 12    |
| 27     | 19 | 9  | 2010 | 17 | 26  | 23.47     | 70.537    | 9     |
| 28     | 13 | 8  | 2011 | 2  | 59  | 23.454    | 70.393    | 22.2  |
| 29     | 17 | 5  | 2011 | 16 | 0   | 23.552    | 70.574    | 17.9  |
| 30     | 19 | 6  | 2012 | 20 | 15  | 23.65     | 70.28     | 11.1  |
| 31     | 14 | 4  | 2012 | 3  | 23  | 23.391    | 70.537    | 18.9  |
| 32     | 12 | 8  | 2012 | 7  | 6   | 23.134    | 70.422    | 21    |
| 33     | 30 | 3  | 2013 | 6  | 34  | 23.567    | 70.38     | 24.4  |
| 34     | 25 | 4  | 2013 | 5  | 57  | 23.493    | 70.473    | 9.5   |
According to this classical method, Equation (1) can be written as

$$\log [A(f)] = \log (A_0) - \pi \kappa f \log (\epsilon)$$

(3)

This implies that $\kappa$ can be estimated with a linear least square fit to the log-linear observed spectra. The spectral decay parameter $\kappa$ is given by

$$\kappa = \frac{\lambda}{\pi \log (\epsilon)}$$

(4)

$\lambda$ is the slope of the linear fit. The $\kappa$ has been determined in the present study using the following steps:

1. Select the S-wave portion of the corrected acceleration time history.
2. Compute the Fourier amplitude spectrum and plot it on log-linear scale i.e. with a logarithmic y-axis (amplitude) and a linear x-axis (frequency).
3. The two frequencies are selected by visual inspection of Fourier spectrum: first from the start of the linear downward trend in the acceleration spectrum (F1) and second (F2), end of the linear downward trend. The F1 and F2 have been selected to the right of the corner frequency.
4. Fit a line in a least square sense between F1 and F2 and estimate $\kappa$ using Equation (4).

The two frequencies F1 and F2 have been selected manually to reduce the bias estimates of $\kappa$ as F1 is found to be varied from seismogram to seismogram. Also, F2 shows variation to different signal to noise ratios. The technique used to estimate the $\kappa$ value in the present study has been exemplified as a flow chart (Figure 3).

Figure 2. Map showing the station and epicentres of shocks used for study. The minimum and maximum distance between station and epicentre is 20 and 120 km, respectively.
In the present work, the corner frequencies have been estimated using Andrews’s method and have been reported earlier (Kumar et al. 2014). This approach helps significantly minimizing the error associated with the visual estimation of corner frequency, $f_c$, given by

$$f_c = (S_{v^2} / S_{d^2})^{1/2} / 2\pi$$

where $S_{v^2}$ and $S_{d^2}$ are evaluated using the following integrals

$$S_{v^2} = \int v^2(f) \, df \quad \text{and} \quad S_{d^2} = \int d^2(f) \, df ;$$

where $v(f)$ and $d(f)$ are the velocity and displacement spectra, respectively.

4. Results and discussions

Figure 4 shows the log-linear plots of the acceleration spectra along with the best fitted line between F1 and F2. By visual inspection, F1 is found to be lying in the range 3–8 Hz and F2 is in the range 42–50 Hz. The average values of $\kappa$ estimated for different sites are given in Table 2. We observe that the value of $\kappa$ varies from 0.016 to 0.045 with an average of 0.023. We note that Narsaiah and Mandal (2014) have also estimated $\kappa$ for the Kachchh region using different data-set and method. They have obtained the values as 0.02–0.03 which are in agreement with those estimated in the present study. Douglas et al. (2010) have estimated average value of $\kappa$ for mainland France as 0.022. From Table 3, it is clear that the $\kappa$ value for Sino-Korean paraplatform has been found to vary from 0.022 to 0.039 (Chandler et al. 2006).
Figure 4. Log linear plot of acceleration spectra along with best fitted line for Kachchh region of Gujarat. F1 is taken right of fc. Gray lines are noise spectra.

Table 2. Average Kappa values at different stations in Kachchh.

| Sr. No. | Station     | Code | Geology      | No. of records | Average |
|---------|-------------|------|--------------|----------------|---------|
| 1       | Anjar       | ANJ  | Quaternary   | 3              | 0.028   |
| 2       | Badargarh   | BDR  | Jurassic     | 9              | 0.031   |
| 3       | Bela        | BEL  | Jurassic     | 8              | 0.022   |
| 4       | Bhachau     | BHU  | Jurassic     | 15             | 0.019   |
| 5       | Chobari     | CHO  | Cretaceous   | 6              | 0.019   |
| 6       | Desalpar    | DES  | Quaternary   | 3              | 0.018   |
| 7       | Dudhai      | DUD  | Cretaceous   | 4              | 0.039   |
| 8       | Fathegarh   | FAT  | Jurassic     | 2              | 0.025   |
| 9       | Kandla      | KAN  | Quaternary   | 6              | 0.02    |
| 10      | Khavda      | KHA  | Jurassic     | 12             | 0.026   |
| 11      | Lakadia     | LAK  | Quaternary   | 16             | 0.027   |
| 12      | Lodrani     | LOD  | Jurassic     | 7              | 0.027   |
| 13      | Nakhatara   | NAK  | Cretaceous   | 5              | 0.029   |
| 14      | Rapar       | RAP  | Jurassic     | 15             | 0.016   |
| 15      | Suva        | SUV  | Cretaceous   | 16             | 0.02    |
| 16      | Vamka       | VAM  | Cretaceous   | 8              | 0.016   |
The distance dependence of $\kappa$ for all the stations is shown in Figures 5 and 6. A linear fit to this gives the relation

$$\kappa = 0.00004458 R + 0.0208$$  \hspace{1cm} (5a) \\
$$\kappa = 0.00009021 H + 0.0381$$  \hspace{1cm} (5b)

This implies that the dependence of $\kappa$ with distance is not significant in Kachchh region. Similar observations have been found in many other studies (Tsai and Chen 2000; Purvance and Anderson 2003; Kilb et al. 2012). Figure 7 shows the variation of $\kappa$ with distance for two sites of Kachchh region located on soft soil (Lakadiya) and hard rock (Rapar) where sufficient numbers of earthquakes have been recorded. Sites are classified on the basis of the local geology (Table 2 and Figure 2).
The equations of the best fit lines are

$$\kappa = 0.000062R + 0.016$$  for the hard rock site

and

$$\kappa = 0.000222R + 0.0201$$  for the soft soil site
We note that the dependence of $\kappa$ on distance is similar for these sites and $\kappa_0$ ($\kappa$ at $R = 0$) is lower for the hard rock site (0.016) as compared with the value for the soft rock site (0.0201). This indicates the difference in site characteristics for these two sites. Douglas et al. (2010) developed a regional $\kappa$ model for mainland France and found that kappa depends on both local geology (soil or rock) and source to site distance, and estimated $\kappa_0$ (soil) = 0.0270 and $\kappa_0$ (rock) = 0.0207. Similarly, $\kappa_0$ (soil) and $\kappa_0$ (rock) have been found to be 0.036 and 0.030 for Southern California (Kilb et al. 2012). Lai et al. 2016 estimated $\kappa_0$ values varying between 0.032 to 0.097 at surface and 0.012 to 0.078 s in borehole (may be considered as hard rock site) for Taiwan region, and suggested geologic formations being primarily responsible for observed change in $\kappa_0$-values at different stations. Our results are analogous with the global observations.

In order to investigate the dependency of $\kappa$ on earthquake size, the estimated values of $\kappa$ have been plotted versus magnitudes in Figure 8 for different sites. We note that there is no significant correlation between $\kappa$ and magnitude at most of the stations for Kachchh region. This implies that $\kappa$ is not related to source effect for the region, however, the magnitude range is small. Biasi et al. 2007 suggested that it is acceptable to use the average value of kappa for earthquakes under magnitude 4.0 for estimates of the spectral fall off of ground motions of earthquakes with $M > 6$, however,
Figure 8. (Continued)

Figure 9. Plot between ‘F1’ and ‘F2’ kappa for earthquakes of $M \geq 4.0$. 
kappa should be estimated using sufficient number of shocks as it is generally scattered at smaller magnitudes. A plot between F1 and F2 for earthquakes of $M \geq 4.0$ shows no correlation between them (Figure 9). Further, the use of ‘kappa’ as determined from small events at lower frequencies must be scaled to be correctly applicable to large earthquakes (Purvance and Anderson 2003).

5. Conclusions

The average value of $\kappa$ is found to be 0.023 for the Kachchh region of Gujarat with lower value for hard rock site as compared to sediment sites. The values of $\kappa$ estimated in the present study have been found to be comparable with those of other similar regions of the world. One of the important findings of the present study is that $\kappa$ is not source dependent for the small and moderate magnitude earthquakes. The distance dependence of $\kappa$ is not significant, however, it is noteworthy that local site conditions are playing a major role in estimation of $\kappa$. The $\kappa$ value is higher for soft soil and lower for hard rock site in Kachchh. Soil effects will play a significant role in modifying the characteristics of the earthquake shaking in thick sediments. In Kachchh, most of the rocks are Quaternary, and the sedimentary thickness varies from around 500 m in the north to over 4000 m in the south and from 200 m in the east to over 2500 m in the west (Biswas 2005). Hence, the estimated $\kappa$ values are useful for the stochastic simulation of earthquake strong ground motions in the Kachchh region and therefore important for the evaluation of seismic hazard of the region.

Acknowledgments

The authors sincerely thank the Editor-in-Chief and anonymous reviewers for their constructive comments, which improved the manuscript significantly. S. Kumar is thankful to Dr M. Ravi Kumar, Director General and Dr Sumer Chopra, Director for their encouragement and kind permission. Authors are also thankful to technical assistants of ISR for their help in data collection from the seismic stations. This research work was supported by Department of Science and Technology (DST), Government of Gujarat.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Anderson JG. 1991. A preliminary descriptive model for the distance dependence of the spectral decay parameter in Southern California. Bull Seism Soc Am. 81(6):2186–2193.
Anderson JG, Hough SE. 1984. A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. Bull Seism Soc Am. 74:1969–1993.
Anderson JG, Humphrey JR Jr. 1991. A least-squares method for objective determination of earthquake source parameters. Seis Res Lett. 62:201–209.
Atkinson GM, Boore DM. 2006. Earthquake ground-motion prediction equations for eastern north. Bull Seism Soc Am. 96(6):2181–2205.
Awasthi DK, Shende VJ, Gupta ID. 2010. Estimation of $\kappa$ factor for two types of sites in northeast India. Indian Geotechnical Conference–2010; GEOtrendz. Dec 16–18.
Beresnev IA, Atkinson GM. 1997. Modelling finite fault radiation from the $\omega^2$ spectrum. Bull Seism Soc Am. 87:67–84.  
Bhatt KM, Andreas H, Kumar S. 2009. Seismicity analysis of the Kachchh aftershock zone and tectonic implication for 26 Jan 2001 Bhuj earthquake. Tectonophysics. 465(1):75–83.
Biasi G, Anderson JG, Smieciniski AJ. 2007. Measurement of the parameter kappa, and reevaluation of kappa for small to moderate earthquakes at seismic stations in the vicinity of Yucca Mountain, Nevada. TR 07-007.University of Nevada , Las Vegas (UNLV). Available at: https://digitalscholarship.unlv.edu/yucca_mtn_pubs/53
Biasi GP, Smith KD. 2001. Site effects for seismic monitoring stations in the vicinity of Yucca Mountain, Nevada. A report prepared for the US DOE/University and Community College System of Nevada (UCCSN) Cooperative Agreement. MOL20011204.0045.Nevada (US).
Biswas SK. 2005. A review of structure and tectonics of Kutch basin, Western India with special reference to earthquakes. Current Sci. 88:1592–1600.
Boore DM. 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull Seism Soc Am. 73:1865–1894.

Brune JN. 1970. Tectonic stress and spectra of shear waves from earthquakes. J Geophys Res. 75:4997–5009.

Campbell KW. 2003. Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground motion (attenuation) relations in eastern North America. Bull Seism Soc Am. 93:1012–1033.

Castro RR, Rovelli A, Cocco M, Di Bona M, Pacor F. 2001. Stochastic simulation of strong-motion records from the 26 September 1997 (Mw 6), Umbria-Marche (central Italy) earthquake. Bull Seism Soc Am. 91:27–39.

Chandler AM, Lamb NTK, Tsang HH. 2006. Near-surface attenuation modelling based on rock shear-wave velocity profile. Soil Dynam Earthq Eng. 26:1004–1014.

Chopra S, Yadav RBS, Hardik P, Kumar S, Rao KM, Rastogi BK, Abdul H, Srivastava S. 2008. The Gujarat (India) seismic network. Seism Res Lett. 79(6):806–815.

Cormier VF. 1982. The effect of attenuation on seismic body waves. Bull Seism Soc Am. 72:S169–S174.

Douglas J, Gehl P, Bonilla LF, Gélis C. 2010. A $\kappa$ model for mainland France. Pure Appl Geophys. 167:1303–1315.

Drouet S, Cotton F, Philippe G. 2010. $V_S0/\kappa$, regional attenuation and Mw from accelerograms: application to magnitude 3–5 French earthquakes. Geophys J Int. 182:880–898.

Fernández Al, Castro Raúl R, Huerta Carlos I. 2010. The spectral decay parameter Kappa in Northeastern Sonora, Mexico. Bull Seism Soc Am. 100(1):196–206.

Gentili S, Franceschina CG. 2011. High frequency attenuation of shear waves in the southeastern Alps and northern Dinarides. Geophys J Int. 185:1393–1416.

Gupta HK, Harinarayana T, Kousalya M, Mishra DC, Mohan I, Rao NP, Raju PS, Rastogi BK, Reddy PR, Sarkar D. 2001. Bhuj earthquake of 26 January 2001. J Geol Soc Ind. 57:275–278.

Halldorsson B, Papageorgiou AS. 2005. Calibration of the specific barrier model to earthquakes of different tectonic regions. Bull Seism Soc Am. 95:1276–1300.

Hanks TC. 1982. $f_{\text{max}}$. Bull Seism Soc Am. 72:S169–S200.

Houtte CV, Ktenidou OJ, Larkin T, Holden C. 2014. Hard-site effects and attenuation in the 2014 Christchurch, New Zealand, earthquake. Bull Seism Soc Am. 104(4):1899–1913.

Humphrey JR Jr., Anderson JG. 1992. Shear wave attenuation and site response in Guerrero Mexico. Bull Seism Soc Am. 81:1622–1645.

Kayal, JR, Zhao D, Mishra OP, De R, Singh OP. 2002. The 2001 Bhuj earthquake: tomographic evidence for fluids at the hypocenter and its implications for fluid nucleation. Geophys Res Lett. 29(24):51–54.

Kilb D, Biasi G, Anderson J, Brune J, Zhigang P, Vernon FL. 2012. Comparison of spectral parameter Kappa from small and moderate earthquakes using Southern California ANZA seismic network data. Bull Seism Soc Am. 102(1):284–300.

Ktenidou OJ, Cotton F, Abrahamson N, Anderson J. 2014. Taxonomy of kappa: a review of definitions and estimation approaches targeted to applications. Seism Res Lett. 85(1):135–146.

Ktenidou OJ, Gelis C, Bonilla F. 2013. A study on the variability of kappa in a borehole, implications on the computation method used. Bull Seism Soc Am. 103:1048–1068.

Kumar S, Chopra S, Choudhury P, Singh AP, Yadav RBS, Rastogi BK. 2012. Ambient noise level in Gujarat State (India), seismic network. Geomatics Nat Hazards Risk. 3(4):284–304.

Lai TS, Mittal H, Chao WA, Wu YM. 2016. A study on Kappa value in Taiwan using borehole and surface seismic array. Bull Seism Soc Am. 106:1509–1517.

Margaris BN, Boore DM. 1998. Determination of $\sigma$ and $\kappa_0$ from response spectra of large earthquakes in Greece. Bull Seism Soc Am. 88:170–182.

Mena B, Mai PM, Olsen KB, Purvance MD, Brune JN. 2010. Hybrid broadband ground-motion simulation using scattering Green’s functions: application to large-magnitude events. Bull Seism Soc Am. 100:2143–2162.

Mishra OP, Singh AP, Kumar D, Rastogi BK. 2014. An insight crack density, saturation rate, and porosity model of the 2001 Bhuj earthquake in the stable continental region of western India. J Asian Earth Sci. 83:48–59.

Narsaiah R, Mandal P. 2014. Source parameters of the 2001 Mw 7.7 Bhuj Earthquake, Gujarat, India, aftershock sequence. J Geol Soc Ind. 83:517–531.

Oth A, Bindi D, Parolai S, Giacomo Di D. 2011. Spectral analysis of K-NET and KiK-net data in Japan, Part II: attenuation characteristics, source spectra, and site response of borehole and surface stations. Bull Seism Soc Am. 101:667–687.

Papageorgiou AS, Aki K. 1983. A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. Part II. Applications of the model. Bull Seism Soc Am. 73(4):953–978.

Pavel F, Vacareanu R. 2015. Kappa and regional attenuation for Vrancea (Romania) earthquakes. J Seismol. 19:791–799.

Petukhin A, Irikura K. 2000. A method for the separation of the source and site effects and the apparent $Q$ structure from strong-motion data. Geophys Res Lett. 27:3429–3432.

Purvance MD, Anderson JG. 2003. A comprehensive study of the observed spectral decay in strong-motion accelerations recorded in Guerrero, Mexico Bull Seism Soc Am. 93:600–611.
Silva WJ, Darragh R. 1995. Engineering characterization of earthquake strong ground motion recorded at rock sites. Palo Alto, CA: Electric Power Research Institute. TR-102261. California (US), [publisher unknown]

Singh AP, Dorbath C, Kumar MR, Kumar S, Chaudhary I, Kayal JR. 2016. Fault geometry of the Mw 7.7 western India intraplate earthquake constrained from double difference tomography and fault plane solutions. Bull Seism Soc Am. 106(4):1446–1460.

Singh AP, Indrajit GR, Kumar S, Kayal JR. 2015. Seismic source characteristics in Kachchh and Saurashtra regions of western India: b-value and fractal dimension mapping of aftershock sequences. Nat Hazards. 77:33–49.

Singh AP, Mishra OP, Yadav RBS, Dinesh K. 2012. A new insight into crustal heterogeneity beneath the 2001 Bhuj earthquake region of Northwest India and its implications for rupture initiations. J Asian Earth Sci. 48:31–42.

Singh RP, Sahoo AK, Bhoi S, Girish Kumar M, Bhuiyan CS. 2001. Ground deformation of the Gujarat earthquake of 26 January 2001. J Geol Soc Ind. 58:209–214.

Singh SK, Apsel RJ, Fried J, Brune JN. 1982. Spectral attenuation of SH waves along the imperial fault. Bull Seism Soc Am. 72:2003–2016.

Toro GR, Abrahamson NA, Schneider JF. 1997. Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties. Seis Res Lett. 68:41–57.

Tsai CP, Chen KC. 2000. A model for the high-cut process of strong motion acceleration in terms of distance, magnitude, and site condition: an example from the SMART1 array, Lotung, Taiwan. Bull Seism Soc Am. 90:1535–1542.

Van Houtte C, Drouet S, Cotton F. 2011. Analysis of the origins of $k$ (kappa) to compute hard rock to rock adjustment factors for GMPEs. Bull Seism Soc Am. 101:2926–2941.

Kumar S, Kumar D, Rastogi BK. 2014. Source parameters and scaling relations for small earthquakes in the Kachchh region of Gujarat, India. Nat. Haz.. 73::1269:1289.

Boore DM, Joyner WB.. 1997. Site amplifications for generic rock sites. Bull Seism Soc Am. 87::327–341.

Bindi D, Castro RR, Franceschina G, Luzi L, and Pacor F 2004, The 1997–1998 Umbria-Marche sequence (central Italy): Source, path and site effects estimated from strong motion data recorded in the epicentral area., J. Geophys. Res. 109; doi:10.1029/2003JB002857.

Rovelli A, Bonamassa O, Cocco M, Di Bona M, and Mazza S. 1998. Scaling laws and spectral parameters of the ground motion in active extensional areas in Italy. Bull Seism Soc Am.. 78:530–560.

Silva WJ, Abrahamson N, Toro G, and Costantino C. 1997. Description and Validation of the Stochastic Ground Motion Model, Report submitted to Brookhaven National Laboratory, Associated Universities, Inc., Upton, New York 11973. Contract No. 770573. Available at: https://www.nrc.gov/docs/ML0423/ML042310562.pdf.