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The High Frequency Decay Parameter κ (Kappa) in the Region of North East India

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Abstract

The high frequency decay parameter κ has been considered as one of the important parameters required in the simulation of earthquake strong ground motions necessary for the proper evaluation of seismic hazard of a region. The present study estimated "κ" for the highly seismic active region of North East India. The spectral analysis of 598 accelerograms of 32 earthquakes has been done using [1] approach for this purpose. The average values of "κ" have been found to be 0.049, 0.047 and 0.040 for L-, T- and V-component respectively. The distance dependence of κ is not significant in the region. The κ_0 (κ at R = 0) for soft rock stations is found to be more than those of hard rock sites in consistent with other similar studies. The correlation between "κ" and earthquake magnitude at most of the stations for the region under study is not significant which indicates that κ depends on the site conditions in the region. The κ values estimated in the present study are useful for the evaluation of seismic hazard of the region.

Keywords

Kappa, GMPE, Strong Ground Motion, Simulation, Seismic Hazard

1. Introduction

The spectral shape of earthquake strong ground motions plays an important role in the simulation of realistic accelerograms using different techniques. The simulated accelerograms are crucial for the proper evaluation of seismic hazard of a region. Different factors including attenuation, velocity and site conditions etc. control the spectral characteristics of the strong ground motions. It has been suggested that the spectrum of strong ground motion from earthquakes is flat above the corner frequency [2] to the maximum frequency (f_{max}) after which the spectrum decays fast [3]. This phenomenon of high-frequency band limitation of radiated earthquake energy has been given the name "the crashing spectrum syndrome" by [4] and attributed this primarily to the local site effects. [5] suggested the source (fault nonelasticity) as cause for "f_{max}" not the site. [6] described a site attenuation parameter "t^*" in the form of exponential decay term $e^{-\pi f t^*}$ to the spectral attenuation of the waves.

[1] introduced a spectral decay parameter—κ (Kappa) to model the high frequency spectral attenuation. They defined the parameter "κ" as:

$$A = A_0 e^{-\pi f}; f > f_E \tag{1}$$

where A_0 depends on the source, epicentral distance and other factors, f_E is the frequency above which the spectral amplitude follows an exponential decay. The studies have been done to attribute the origin of "κ" to source, site and/or path attenuation. [7] and [8] have suggested that "κ" represents the near surface as well as propagation path attenuation. Some studies suggest that "κ" is source related [9] [10] [11] [12]. [13] assumes "κ" as a parameter related either to source or site effects. It is considered as site parameter by [14] [15] found that "κ" was independent of earthquake size within magnitude range M < 3.5 for the events occurred in the region of Northeastern Sonora, Mexico. [16] also found no correlation between "κ" and magnitude.

In spite of the lack of agreement on the physical origin of "κ", it has been widely used in number of seismological applications like computation of site amplification factors, ground motion prediction equations [17] [18]. It has become a standard parameter to constrain attenuation, peak ground acceleration and spectral shape of stochastically generated accelerograms.

In the present study, the high frequency decay parameter "κ" has been estimated at different sites and source-receiver distances for the region of North East India. The possible dependence of "κ" on distance for hard rock sites and soft soil sites has been investigated. The dependence of "κ" on earthquake size has also been examined.

2. Study Area and Data Used

The tectonic map of the NE India region has been shown in **Figure 1**. The collision of India-Eurasian plate (developed Arakan Yoma belt) and under thrusting of Indian plate below the Myanmar plate gives rise to an intricate tectonic zone in North-East Indian region [19]. This region has experienced damaging earthquakes in the past including great earthquakes (1897 and 1950 Assam earthquakes), 1918 Srimangal earthquake (mb 7.6), 1930 Dhubri earthquake (M 7.1). Geologically, this region is mainly divided into five parts as eastern Himalaya, the Mishmi massif, the Indo Myanmar arc, the Brahmaputra valley, and the Shillong plateau [20]. The presence of Mishmi thrust, Lohit thrust, Po Chu fault, and Tidding suture makes the tectonic of Mishmi region more complex having predominant features like Tsangpo suture, Tuting and Bame faults. The Shillong highland is represented by N-S trending Dhansiri and Kulsi faults, N-E aligned

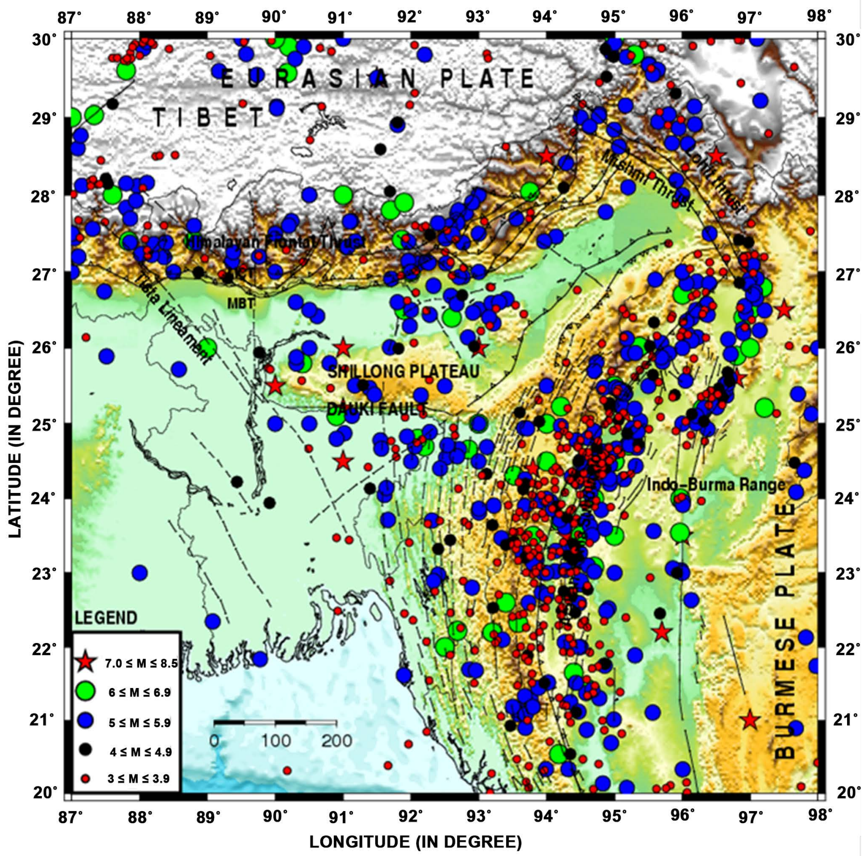


Figure 1. Seismicity along with tectonics of the North-East Region, India.

Barapani Shear region, and Mikir Hills, Dhubri, Sylhet and Duaki faults, and Dudhnai and Kulsi faults. The alignment of Kopili fault in NW-SE direction and in North Dhansiri fault separates Mikir Hills from Shillong highlands [21]. The NE India region is one of the seismically active regions of the world.

A strong motion accelerographs network has been installed in the region by Department of Earthquake Engineering, Indian Institute of Technology, Roorkee with the objectives of studying the strong ground motions characteristics for earthquake engineering purposes. The 598 accelerograms of 32 earthquakes (mb 3.9 - 6.8) recorded at this network has been used in the present analysis. **Figure 2** shows the locations of earthquakes and recording stations used in this study. The lists of the earthquakes along with recording stations and geology are given in **Table 1**.

3. Methodology

Different techniques have been reported in the literature to estimate "κ" including use of displacement spectra [22], full inversion of source, path and site parameters [23] [24] [25] and broad band inversions [26] [27]. In the present study, the widely used classical method of [1] has been adopted [28] [29] [16]. According to this classical method, Equation (1) can be written as:

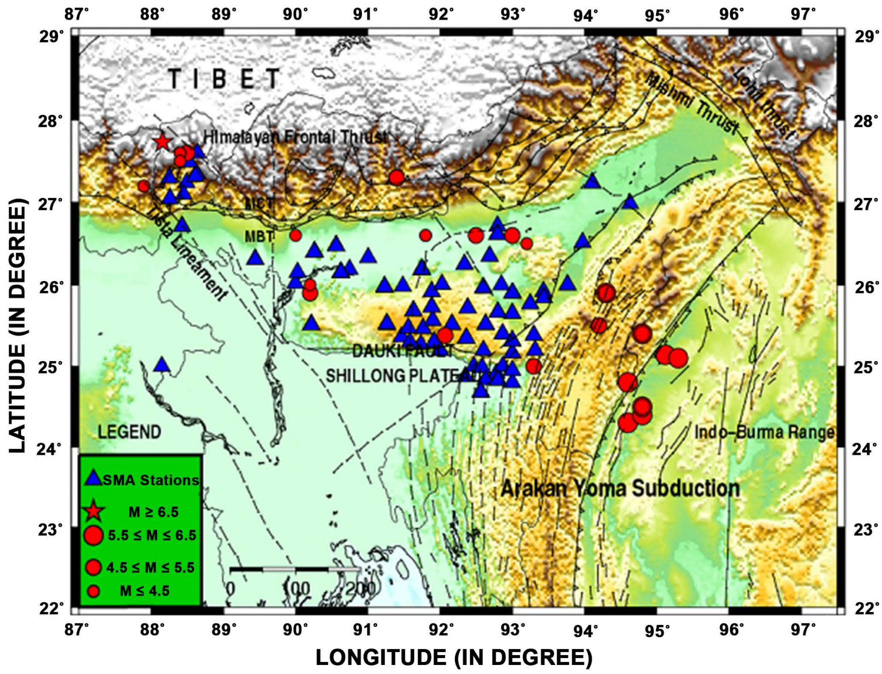


Figure 2. Location of earthquakes and recording stations used in present study.

$$\ln A = \ln A_0 - \pi \kappa f \tag{2}$$

This a linear equation between "ln$A$" and frequency "f". The "κ" can be estimated from the slope (m) of the line (Equation (2)) as:

$$\kappa = -m/k \tag{3}$$

The following procedure has been adopted for the estimation of "κ":

1) First the S-wave portion of the accelerogram is selected.

2) Fourier transform of the selected wave has been obtained using FFT and plotted the same on log-linear scale *i.e.* with a logarithmic y-axis (amplitude) and a linear x-axis (frequency).

3) Two frequencies have been selected by visual inspection of the spectrum of S-waves: first at the start of linear downward trend in the spectrum (f1) and second at the end of linear downward trend (f2). The visual inspection of S-wave spectrum in selecting the two frequencies is preferred over the automatic procedure as f1 and f2 vary from record to record. The visual inspection avoids the biased estimates of "κ". This procedure has been used in previous studies also (e.g. [28]).

4) A line has fitted between f1 and f2 in a least square sense on log-linear plot. The slope (m) of the line gives the value of "κ" (Equation (3)).

4. Results and Discussion

The values of "κ" have been estimated for the three components (N-S, E-W and Z) of the recorded accelerograms using the procedure described above. **Figure 3** shows the log-linear plots along with the best fitted lines for some of the records.

Table 1. List of Earthquakes along with recording stations used to compute κ and Ns is number of stations.

Sr. no	YYYY	MM	DD	LAT.(N)	LON.(E)	M_W	Depth(Km)	Stations	Ns
1	1986	09	10	25.38	92.07	5.2	43	BAIT, DAUK, KHLI, NONK, NONP, NONS, PANI, PYNU, SAIT, UMMU, UMRO, UMSN	12
2	1987	05	18	25.27	94.20	5.7	49	BAIT, BAMU, BERL, BOKA, DIPU, GUNJ, HAFL, HAJA, HATI, LAIS, NONP, PANI, SAIT, UMRO	14
3	1988	02	06	24.64	91.51	5.8	33	BAIG, BAIT, BAMU, DAUK, GUNJ, HAFL, HATI, KATA, KHLI, MAWP, NONK, NONP, PYNU, SAIT, SHIL, UNMU, UMRO, UMSN	18
4	1988	08	06	25.14	95.12	6.8	91	BAIG, BAIT, BAMU, BERL, BOKA, CHER, DAUK, DIPU, DOLO, GUNJ, HAJA, HARE, HOJA, JELA, JHIR, KALA, KATA, KHLI, KOOM, LOHA, MAWK, MAWP, MAWS, NONK, SILC, UMMU, UMRO, UMSN	28
5	2008	03	13	26.6	91.8	4.0	33	MNGB, MORB	2
6	2008	05	29	26.6	91.8	4.2	33	MNGB, MORB	2
7	2008	12	25	27.2	87.9	4.4	33	GANG	1
8	2009	02	15	26.0	90.2	4.4	39.3	BARP, BONG, DHBR, KOKJ, TURA	5
9	2009	02	24	25.9	94.3	4.8	10	DIPU, GOLA, LKHM	3
10	2009	08	11	24.4	94.8	5.6	22	BOKO, BONG, DIPU, GOLP, GWAT, HALK, KARM, KOKJ, NONG, SILC, TEJP, TURA	12
11	2009	08	19	26.6	92.5	4.9	20	BOKO, GWAT	2
12	2009	08	30	25.4	94.8	5.3	85	BOKO, DIPU, GWAT, LKHP, TURA	5
13	2009	09	03	24.3	94.6	5.9	100	BOKO, BONG, DIPU, GOLP, GWAT, HKDI, NONS, SILC, TURA	9
14	2009	09	21	27.3	91.5	6.2	8.0	BOKO, BONG, COVB, DRJL, DIPU, GANG, GOLP, GWAT, KOKJ, NAUG, NONS, LKHP, TEJP	13
15	2009	10	29	26.6	90.0	4.2	90	BONG, GOLP, KOKJ, NONS, TURA	5
16	2009	10	29	27.3	91.4	5.2	5.0	BONG, GOLP, KOKJ, NONG, TURA	5
17	2009	12	29	24.5	94.8	5.5	80	BONG, GOLP, GWAT, HKDI , TEJP, TURA	6
18	2009	12	31	27.3	91.4	5.5	7.0	BONG, GOLP, GWAT, KOKJ, TURA	5
19	2010	02	26	28.5	86.7	5.4	28	BONG, DRJL, GANG, GOLP, GWAT, KOKJ, SILI	7
20	2010	03	12	23.0	96.0	5.6	96	BONG, GOLP, GWAT, HALK, TURA	5
21	2010	09	11	25.9	90.2	5.0	20	BONG, GWAT, KOKJ	3
22	2010	12	12	25.0	93.3	4.8	15	KRMJ, NAUG	2

Continued

23	2011	02	04	24.8	94.6	6.4	30	COVB, GWAT, JORH, JOWI, KOKJ, NAUG, SIBS	7
24	2011	09	18	27.6	88.2	6.8	10	CHAN, CHPW, COVB, GANG, KRMJ, KOKJ, MALD, NAUG, PATI, RAXL, SIBS, SILI, UDHM	13
25	2011	09	18	27.6	88.5	5.0	16	COVB, GANG	2
26	2011	09	18	27.5	88.4	4.5	9	GANG	1
27	2011	09	18	27.6	88.4	4.2	28	GANG	1
28	2011	09	22	27.6	88.4	3.9	30	GANG	1
29	2011	11	21	25.1	95.3	5.8	80	GWAT	1
30	2012	05	11	26.6	93.0	5.4	20.0	GOLA, JORH, KOKJ	3
31	2012	07	10	26.5	93.2	4.5	56	NAUG	1
32	2012	07	14	25.5	94.2	5.5	35	GOLA, JORA, NAUG	3

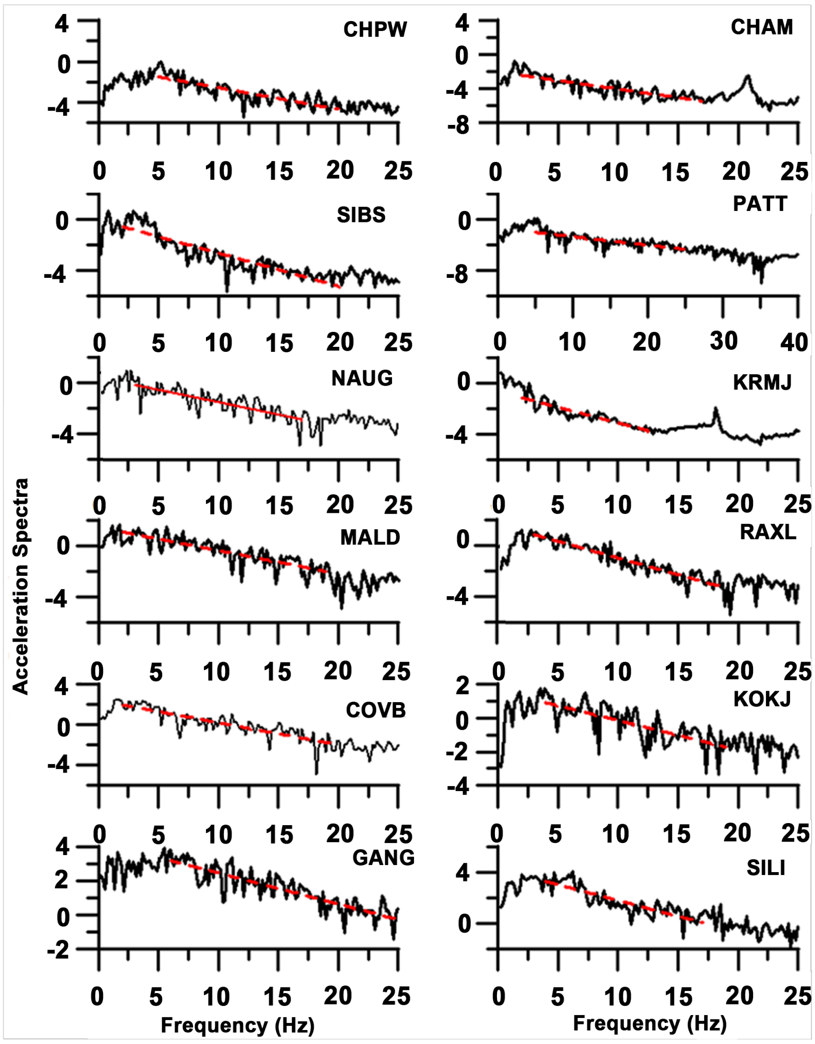


Figure 3. The log-linear plots for estimating "*κ*" along with the best fitted lines for some of the records.

It has been found that f1 lies in the range 2-13 Hz while f2 is in the range 20 - 28 Hz. The estimated values of "κ" corresponding to three components for the earthquakes and recording stations are given in **Table 2** along with the site geology. The standard deviations are also given in the table. The average values of "κ" has been found to be 0.049 (L-component), 0.047 (T-component) and 0.040 (V-component). A comparison between the κ values obtained from horizontal and vertical components is shown in **Figure 4**. The values are found to be similar for most of the events. The vertical estimates are smaller than those of horizontal estimates. This has been observed in other studies [28] [30]. The values obtained in the present study have been compared with those of other regions of the world in **Table 3**. The estimates are found to be consistent.

The distance dependence of κ has been analyzed using the following linear model [1]:

$$\kappa = \kappa_0 + \kappa_R \tag{4}$$

where κ_0 is the value of κ at distance $R = 0$. This model has been used in many studies due to its simplicity of formulation (e.g. [1]; [28]; [31]). κ_0 is believed to be station-dependent and may be related to the near surface attenuation. The distance dependence of κ estimated from horizontal and vertical components is shown in **Figure 5(a)** and **Figure 5 (b)**. The fitted linear model gives the regression.

$$\kappa = 0.037 + 0.0000158R \quad \text{For vertical component}$$

and

$$\kappa = 0.041 + 0.0000326R \quad \text{For horizontal component}$$

We note that distance dependence for both the components is not significant. The values of κ_0 as 0.041 (horizontal component) and 0.037 (vertical component) represent the overall value for the region. The difference in these two values indicates that site response is different for different components as has been observed in site amplification studies. The estimate of κ_0 (vertical) is useful along with H/V ratio for the first order estimation of site effect where site-specific borehole data is not available as suggested by [30].

Figure 6(a) and **Figure 6(b)** show the distance dependence of κ on hard rock sites and soft soil sites separately. The linear fit gives the following relations:

$$\kappa = 0.034 + 0.0000158R \quad \text{For hard rock sites}$$

and

$$\kappa = 0.037 + 0.000024R \quad \text{For soft rock sites}$$

The κ_0 for soft rock stations is found to be more than those of hard rock sites. The ratio of κ_0 for soft rock to hard rock is equal to 1.09. Similar observations have been found to be in different studies for other regions. [28] found that kappa depends on both local geology (Soil or Rock) and source to site distance in France. They have estimated κ_0 (soil) = 0.0270 and κ_0 (rock) = 0.0207. [32] has found κ_0 for soil as 0.036 and κ_0 for rock as 0.030 for Southern California.

Table 2. The estimated values of κ for the three components of earthquakes along with recording stations with site geology.

Sr. no.	Date of Event	Station	Kappa-L	SD	Kappa-T	SD	Kappa-V	SD	Geology
1	1986/09/10	BAIT	0.031	0.0051	0.011	0.0049	0.015	0.0039	Soft soil
		DAUK	0.053	0.0048	0.050	0.0048	0.037	0.0044	Soft soil
		KHLI	0.035	0.0046	0.033	0.0056	0.037	0.0052	Hard rock
		NONK	0.021	0.0050	0.028	0.0055	0.020	0.0036	Hard rock
		NONP	0.021	0.0032	0.014	0.0031	0.051	0.0057	Hard rock
		NONS	0.023	0.0033	0.029	0.0048	0.033	0.0040	Hard rock
		PANI	0.031	0.0032	0.018	0.0033	0.039	0.0062	Hard rock
		PYNU	0.036	0.0031	0.023	0.0045	0.019	0.0056	Hard rock
		SAIT	0.024	0.0037	0.026	0.0041	0.027	0.0041	Soft soil
		UMMU	0.035	0.0032	0.024	0.0041	0.043	0.0061	Hard rock
		UMRO	0.036	0.0055	0.027	0.0047	0.027	0.0056	Soft soil
		UMSN	0.013	0.0051	0.014	0.0044	0.030	0.0038	Hard rock
2	1987/05/18	BAIT	0.027	0.0032	0.023	0.0035	0.020	0.0049	Soft soil
		BAMU	0.024	0.0052	0.028	0.0062	0.034	0.0056	Soft soil
		BERL	0.036	0.0061	0.029	0.0057	0.024	0.0052	Soft soil
		BOKA	0.019	0.0040	0.034	0.0046	0.017	0.0048	Soft soil
		DIPU	0.042	0.0072	0.039	0.0070	0.028	0.0049	Soft soil
		GUNJ	0.031	0.0050	0.038	0.0048	0.027	0.0073	Soft soil
		HAFL	0.030	0.0039	0.029	0.0035	0.039	0.0073	Soft soil
		HAJA	0.026	0.0055	0.028	0.0054	0.029	0.0063	Soft soil
		HATI	0.032	0.0048	0.022	0.0045	0.027	0.0039	Soft soil
		LAIS	0.15	0.005	0.036	0.0037	0.043	0.0046	Hard rock
		NONP	0.022	0.0042	0.023	0.0040	0.041	0.0068	Hard rock
		PANI	0.032	0.0066	0.033	0.0068	0.030	0.0092	Hard rock
		SAIT	0.030	0.0075	0.022	0.0072	0.032	0.0119	Soft soil
		UMRO	0.053	0.0074	0.034	0.0063	0.033	0.0084	Soft soil
3	1988/02/06	BAIG	0.043	0.0049	0.041	0.0047	0.031	0.0072	Soft soil
		BAIT	0.052	0.0051	0.038	0.0047	-	-	Soft soil
		BAMU	0.028	0.0043	0.027	0.0048	0.051	0.0071	Soft soil
		DAUK	0.034	0.0040	0.033	0.0039	0.023	0.0080	Soft soil
		GUNJ	0.035	0.0037	0.033	0.0037	0.034	0.0052	Soft soil
		HAFL	0.026	0.0033	0.033	0.0035	0.043	0.0086	Soft soil
		HATI	0.034	0.0051	0.034	0.0045	0.036	0.0090	Soft soil
		KATA	0.012	0.0035	0.028	0.0031	0.035	0.0033	Soft soil
		KHLI	0.033	0.0059	0.034	0.0048	0.053	0.0084	Hard rock
		MAWP	0.019	0.0051	0.016	0.0048	0.032	0.0104	Hard rock
		NONK	0.040	0.0045	0.036	0.0038	0.015	0.0039	Hard rock
		NONP	0.034	0.0070	0.026	0.0064	0.050	0.0059	Hard rock

Continued

		PYNU	0.041	0.0047	0.040	0.0059	0.014	0.0052	Hard rock
		SAIT	0.027	0.0038	0.023	0.0055	0.015	0.0049	Soft soil
		SHIL	0.033	0.0050	0.029	0.0046	0.024	0.0053	Hard rock
		UMMU	0.045	0.0109	0.060	0.0134	0.049	0.0124	Hard rock
		UMRO	0.037	0.0048	0.033	0.0035	0.041	0.0050	Soft soil
		UMSN	0.017	0.0040	0.019	0.0033	0.024	0.0043	Hard rock
4	1988/08/06	BAIG	0.056	0.0053	0.018	0.0051	-	-	Soft soil
		BAIT	0.019	0.0040	0.019	0.0035	0.012	0.0126	Soft soil
		BAMU	0.026	0.0042	0.022	0.0036	0.033	0.0045	Soft soil
		BERL	0.034	0.0040	0.021	0.0032	0.021	0.0035	Soft soil
		BOKA	0.017	0.0039	0.007	0.0039	0.005	0.0035	Soft soil
		CHER	0.034	0.0037	0.032	0.0040	0.013	0.0034	Hard rock
		DAUK	0.036	0.0030	0.040	0.0034	0.021	0.0041	Soft soil
		DIPU	0.026	0.0039	0.029	0.0036	0.047	0.0116	Soft soil
		DOLO	0.036	0.0037	0.042	0.0036	0.016	0.0043	Soft soil
		GUNJ	0.027	0.0033	0.026	0.0042	0.027	0.0049	Soft soil
		HAJA	0.046	0.0102	0.033	0.0083	0.027	0.0074	Soft soil
		HARE	0.031	0.0040	0.036	0.0037	0.027	0.0039	Soft soil
		HOJA	0.021	0.0037	0.034	0.0057	0.014	0.0067	Soft soil
		JELA	0.042	0.0047	0.045	0.0051	0.037	0.0043	Soft soil
		JHIR	0.038	0.0047	0.042	0.0056	0.034	0.0062	Soft soil
		KALA	0.036	0.0047	0.042	0.0056	0.034	0.0062	Soft soil
		KATA	0.074	0.0097	0.074	0.0098	0.035	0.0050	Soft soil
		KHLI	0.024	0.0073	0.022	0.0115	0.026	0.0045	Hard rock
		KOOM	0.036	0.0041	0.045	0.0061	0.040	0.0057	Soft soil
		LOHA	0.041	0.0052	0.034	0.0057	0.029	0.0043	Soft soil
		MAWK	0.040	0.0082	0.029	0.0073	0.007	0.0105	Hard rock
		MAWP	0.026	0.0040	0.038	0.0037	0.018	0.0048	Hard rock
		MAWS	0.016	0.0031	0.015	0.0041	0.025	0.0062	Hard rock
		NONK	0.026	0.0032	0.030	0.0029	0.013	0.0056	Hard rock
		NONS	0.030	0.0081	0.042	0.0064	0.054	0.0071	Hard rock
		PANI	0.045	0.0087	0.020	0.0096	0.021	0.0048	Hard rock
		PYNU	0.035	0.0068	0.062	0.0082	0.019	0.0094	Hard rock
		SAIT	0.025	0.0048	0.022	0.0069	0.020	0.0108	Soft soil
		SHIL	0.028	0.0071	0.013	0.0082	0.046	0.0115	Hard rock
		SILC	0.039	0.0061	0.038	0.0054	0.035	0.0061	Soft soil
		UMMU	0.041	0.0084	0.044	0.0104	0.022	0.0143	Hard rock
		UMRO	0.040	0.0061	0.039	0.0052	0.029	0.0043	Soft soil
		UMSN	0.026	0.0077	0.011	0.0076	0.022	0.0089	Hard rock
5	2008/03/13	MNG	0.044	0.0047	0.038	0.0038	0.024	0.0042	Soft soil
		MOR	0.036	0.0037	0.028	0.0042	0.017	0.0056	Soft soil

Continued

6	2008/05/29	MNG	0.039	0.0034	0.036	0.0052	0.030	0.0048	Soft soil
		MOR	0.024	0.0041	0.028	0.0050	0.021	0.0053	Soft soil
7	2008/12/25	GANG	0.062	0.0068	0.081	0.0050	0.045	0.0073	Hard rock
8	2009/02/15	BARP	0.134	0.0195	0.116	0.157	0.020	0.0217	Soft soil
		BONG	0.036	0.043	0.034	0.061	0.049	0.0071	Soft soil
		DHBR	0.051	0.0050	0.054	0.0049	0.051	0.0058	Soft soil
		KOKJ	0.055	0.0089	0.030	0.0054	0.025	0.0129	Soft soil
		TURA	0.063	0.0067	0.067	0.0055	0.067	0.0067	Soft soil
9	2009/02/24	DIPU	0.024	0.0056	0.035	0.0058	0.025	0.0042	Soft soil
		GOLA	0.051	0.0081	0.043	0.0075	0.030	0.0068	Soft soil
		LKHM	0.075	0.0081	0.076	0.0069	0.045	0.0095	Soft soil
10	2009/08/11	BOKO	0.046	0.0069	0.036	0.0069	0.017	0.0061	Soft soil
		BONG	0.061	0.0073	0.067	0.0057	0.061	0.0065	Soft soil
		DIPU	0.054	0.0066	0.049	0.0054	0.032	0.0064	Soft soil
		GOLP	0.070	0.0090	0.053	0.0082	0.057	0.0059	Soft soil
		GWAT	0.037	0.0052	0.044	0.0050	0.062	0.0059	Soft soil
		HALK	0.121	0.0097	0.136	0.0093	0.104	0.0116	Soft soil
		KARM	0.109	0.0073	0.112	0.0087	0.062	0.0068	Soft soil
		KOKJ	0.049	0.0052	0.042	0.0057	0.044	0.0074	Soft soil
		NONG	0.031	0.0051	0.017	0.0053	0.017	0.0053	Hard rock
		SILC	0.105	0.0079	0.110	0.0094	0.058	0.0046	Soft soil
		TEJP	0.030	0.0065	0.029	0.0066	0.028	0.0076	Soft soil
		TURA	0.063	0.0069	0.063	0.0061	0.053	0.0056	Soft soil
11	2009/08/19	BOKO	0.029	0.0037	0.049	0.0039	0.025	0.0036	Soft soil
		GUAT	0.043	0.0031	0.041	0.0032	0.046	0.0035	Soft soil
12	2009/08/30	BOKA	0.029	0.0033	0.031	0.0034	0.020	0.0041	Soft soil
		DIPU	0.039	0.0037	0.041	0.0032	0.027	0.0026	Soft soil
		GUA	0.049	0.0036	0.048	0.0038	0.052	0.0040	Soft soil
		LKH	0.047	0.0037	0.054	0.0038	0.032	0.0036	Soft soil
		TURA	0.055	0.0031	0.059	0.0034	0.051	0.0036	Soft soil
13	2009/09/03	BOKA	0.026	0.0030	0.020	0.0037	0.007	0.0042	Soft soil
		BONG	0.052	0.0037	0.048	0.0047	0.068	0.0045	Soft soil
		DIPU	0.038	0.0042	0.034	0.0045	0.033	0.0037	Soft soil
		GOLP	0.027	0.0032	0.039	0.0035	0.032	0.0044	Soft soil
		GUA	0.042	0.0042	0.032	0.0040	0.036	0.0040	Soft soil
		HKD	0.090	0.0042	0.105	0.0041	0.061	0.041	Soft soil
		NONS	0.030	0.0046	0.023	0.0044	0.046	0.0045	Hard rock
		SILC	0.079	0.0039	0.087	0.0043	0.052	0.0054	Soft soil
		TURA	0.053	0.0043	0.039	0.0042	0.037	0.0039	Soft soil
14	2009/09/21	BOKO	0.051	0.0047	0.054	0.0033	0.042	0.0038	Soft soil
		BONG	0.062	0.0041	0.070	0.0040	0.057	0.0041	Soft soil

Continued

		COBV	0.086	0.0037	0.075	0.0036	0.063	0.0050	Soft soil
		DJL	0.071	0.0040	0.095	0.0050	0.062	0.0045	Hard rock
		DIPU	0.055	0.0041	0.072	0.0039	0.056	0.0039	Soft soil
		GANG	0.067	0.0032	0.078	0.0039	0.051	0.0039	Hard rock
		GOLP	0.068	0.0033	0.065	0.0045	0.062	0.0040	Soft soil
		GUAT	0.051	0.0050	0.041	0.0051	0.058	0.0043	Soft soil
		KOKJ	0.048	0.0036	0.053	0.0046	0.063	0.0047	Soft soil
		NAUG	0.070	0.0028	0.075	0.0030	0.069	0.0036	Soft soil
		NONS	0.057	0.0044	0.051	0.0049	0.074	0.0062	Hard rock
		LKH	0.076	0.0050	0.095	0.0039	0.061	0.0048	Soft soil
		TEJP	0.064	0.0037	0.065	0.0065	0.064	0.0046	Soft soil
15	2009/10/29	BONG	0.066	0.0063	0.076	0.0073	0.063	0.0048	Soft soil
		GOLP	0.092	0.0051	0.082	0.0060	0.065	0.0047	Soft soil
		KOKJ	0.078	0.0068	0.070	0.0069	0.037	0.0050	Soft soil
		NONS	0.078	0.0079	0.076	0.0079	0.065	0.0069	Hard rock
		TURA	0.111	0.0096	0.118	0.0091	0.123	0.0084	Soft soil
16	2009/10/29	BONG	0.050	0.0051	0.066	0.0050	0.066	0.0044	Soft soil
		GOLP	0.029	0.0097	0.022	0.0060	0.031	0.0103	Soft soil
		KOKJ	0.030	0.0064	0.018	0.0072	0.035	0.0132	Soft soil
		NONS	0.068	0.0054	0.058	0.0058	0.049	0.0049	Hard rock
		TURA	0.055	0.0063	0.052	0.0062	0.037	0.0053	Soft soil
17	2009/12/29	BONG	0.061	0.0058	0.055	0.0049	0.081	0.0076	Soft soil
		GOLP	0.066	0.0062	0.037	0.0091	0.051	0.0054	Soft soil
		GWAT	0.051	0.0068	0.036	0.0054	0.084	0.0067	Soft soil
		HALK	0.104	0.0053	0.101	0.0066	-	-	Soft soil
		TEJP	0.023	0.0055	0.028	0.0046	0.041	0.0050	Soft soil
		TURA	0.040	0.0057	0.040	0.0075	0.038	0.0045	Soft soil
18	2009/12/31	BONG	0.058	0.0056	0.063	0.0068	0.058	0.0048	Soft soil
		GOLP	0.056	0.0054	0.043	0.0047	0.057	0.0050	Soft soil
		GWAT	0.034	0.0061	0.035	0.0064	0.046	0.0052	Soft soil
		KOKJ	0.061	0.0053	0.071	0.0056	0.066	0.0059	Soft soil
		TURA	0.094	0.0050	0.091	0.0063	0.080	0.0042	Soft soil
19	2010/02/26	BONG	0.082	0.0067	0.070	0.0049	0.066	0.0051	Soft soil
		DRJL	0.062	0.0059	0.044	0.0054	0.031	0.0061	Hard rock
		GANG	0.069	0.0047	0.057	0.0070	0.014	0.0060	Hard rock
		GOLP	0.084	0.0047	0.087	0.0051	0.067	0.0051	Soft soil
		GWAT	0.069	0.0068	0.070	0.0057	0.063	0.0062	Soft soil
		KOKJ	0.063	0.0069	0.082	0.0064	0.033	0.0056	Soft soil
		SILI	0.070	0.0053	0.072	0.0056	0.025	0.0060	Soft soil
20	2010/03/12	BONG	0.041	0.0044	0.052	0.0052	0.076	0.0059	Soft soil
		GOLP	0.069	0.0121	0.060	0.0062	0.055	0.0084	Soft soil

Continued

		GWAT	0.028	0.0047	0.027	0.0071	0.061	0.0074	Soft soil
		HALK	0.095	0.0052	0.101	0.0056	0.030	0.0052	Soft soil
		TURA	0.062	0.0054	0.064	0.0055	0.054	0.0060	Soft soil
21	2010/09/11	BONG	0.032	0.0065	0.042	0.0048	0.049	0.0050	Soft soil
		GWAT	0.033	0.0044	0.033	0.0055	0.051	0.0046	Soft soil
		KOKJ	0.042	0.0059	0.044	0.0049	0.073	0.0048	Soft soil
22	2010/12/12	KRMJ	0.132	0.0077	0.144	0.0099	0.091	0.0078	Soft soil
		NAUG	0.060	0.0061	0.057	0.0058	0.049	0.0063	Soft soil
23	2011/02/04	COVB	0.059	0.0091	0.047	0.0082	0.038	0.0066	Soft soil
		GWAT	0.044	0.0040	0.034	0.0069	0.049	0.0047	Soft soil
		JORH	0.045	0.0039	0.035	0.0046	0.016	0.0050	Soft soil
		JOWI	0.049	0.0076	0.065	0.0073	0.011	0.0058	Soft soil
		KOKJ	0.030	0.0049	-	-	0.033	0.0057	Soft soil
		NAUG	0.029	0.0047	0.034	0.0047	0.028	0.0052	Soft soil
24	2011/09/18	CHAM	0.064	0.0057	0.093	0.0067	0.040	0.0048	Hard rock
		CHPW	0.081	0.0081	0.102	0.0093	0.019	0.0056	Hard rock
		COVB	0.069	0.0045	0.056	0.0043	0.037	0.0063	Soft soil
		GANG	0.057	0.0056	0.050	0.0061	0.046	0.0053	Hard rock
		KRMJ	0.078	0.0055	0.084	0.0077	0.102	0.0084	Soft soil
		KOKJ	0.055	0.0063	0.054	0.0062	0.049	0.0080	Soft soil
		MALD	0.058	0.0044	0.060	0.0044	0.077	0.0068	Soft soil
		NAUG	0.062	0.0061	0.067	0.0044	0.053	0.0052	Soft soil
		PATI	0.057	0.0086	0.081	0.0068	0.070	0.0071	Hard rock
		RAXL	0.083	0.0039	0.061	0.0037	0.022	0.0061	Soft soil
		SIBS	0.097	0.0077	0.098	0.0077	-	-	Soft soil
		SILI	0.079	0.0064	0.095	0.0074	0.032	0.0080	Soft soil
		UDHM	0.093	0.0067	0.077	0.0072	0.047	0.0064	Soft soil
25	2011/09/18	COVB	0.069	0.0066	0.097	0.0091	0.060	0.0075	Soft soil
		GANG	0.072	0.0058	0.032	0.0082	0.032	0.0076	Hard rock
26	2011/09/18	GANG	0.062	0.0054	0.054	0.0048	0.062	0.0101	Hard rock
27	2011/09/18	GANG	0.036	0.0053	0.041	0.0047	0.019	0.0071	Hard rock
28	2011/09/22	GANG	0.039	0.0051	0.028	0.0055	0.028	0.0062	Hard rock
29	2011/11/21	GWAT	0.035	0.0098	0.035	0.0098	0.017	0.0078	Soft soil
30	2012/05/11	GOLA	0.072	0.0186	0.026	0.0124	0.049	0.0153	Soft soil
		JORH	0.039	0.0085	0.040	0.0065	0.023	0.0070	Soft soil
		KOKJ	0.049	0.0057	0.043	0.0054	0.027	0.0058	Hard rock
31	2012/07/10	NAUG	0.045	0.0062	0.041	0.0085	0.057	0.0084	Soft soil
32	2012/07/14	GOLA	0.042	0.0051	0.033	0.0049	0.030	0.0063	Soft soil
		JORH	0.070	0.0053	0.072	0.0040	0.045	0.0044	Soft soil
		NAUG	0.035	0.0042	0.036	0.0058	0.047	0.0072	Soft soil

Table 3. Comparison of kappa value estimated in present study with those of different regions of world.

Sr. no.	Region	Kappa Value	Reference No.
1	North-eastern Sonora	0.04	[15]
2	California	0.05	[1]
3	France	0.04	[28]
4	Switzerland	0.015	[34]
5	Western Alps	0.012	[35]
6	Central Europe (Germany)	0.05	[36]
7	Guerrero Mexico	0.045	[11]
8	Greece	0.06	[23]
9	Eastern Canada & Western Canada	0.04	[37]
10	Southern California	0.06	[8]
11	North-East Himalaya	0.049 (L-comp), 0.047 (T-comp) and 0.040 (V-comp)	This study

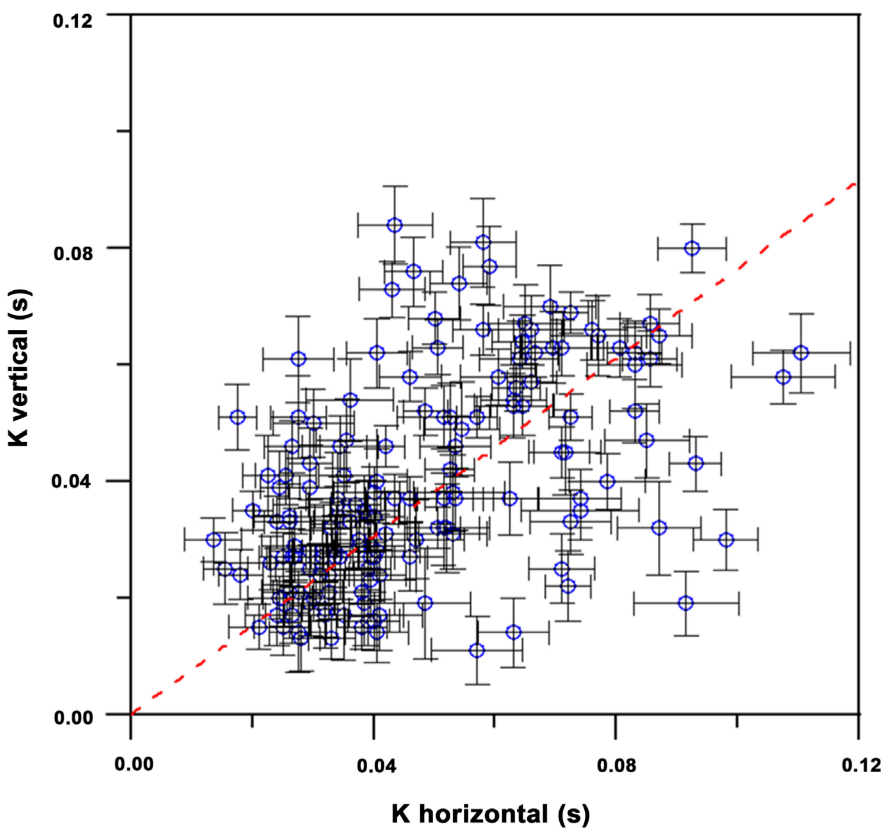
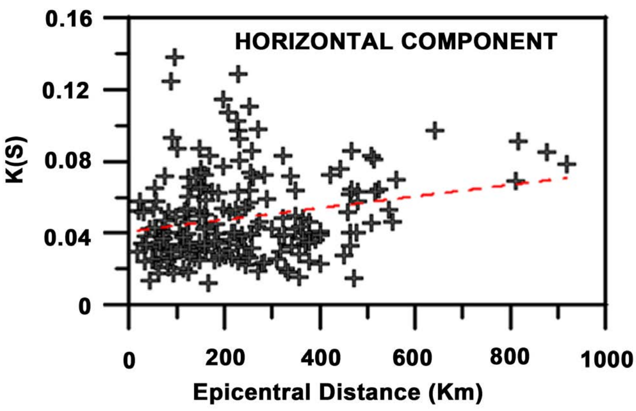
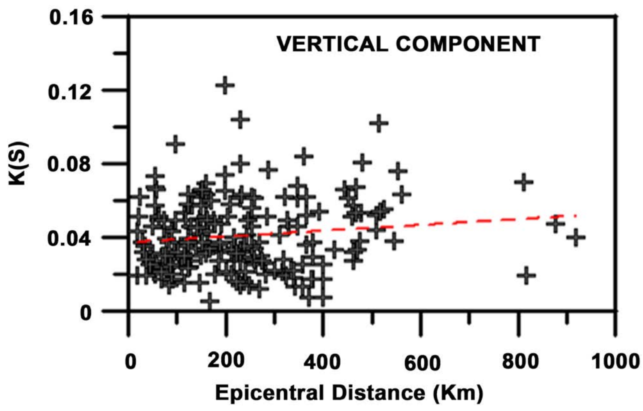


Figure 4. A comparison between the κ values obtained from horizontal and vertical components.

[33] has estimated κ_0 values varying in the range 0.032 - 0.097 at surface and in the range 0.012 - 0.078 in borehole (may be considered as hard rock site) for Taiwan region. [31] has found $\kappa = 0.016$ for hard rock site and 0.0201 for soft

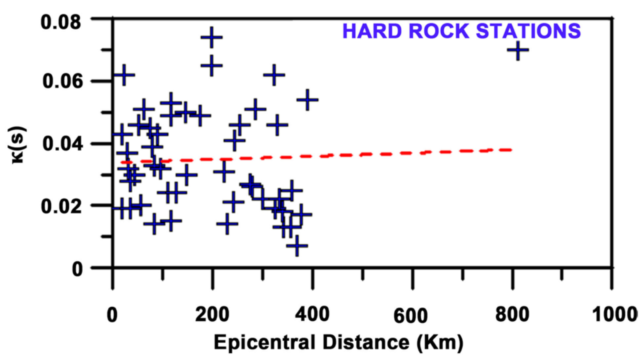


(a)

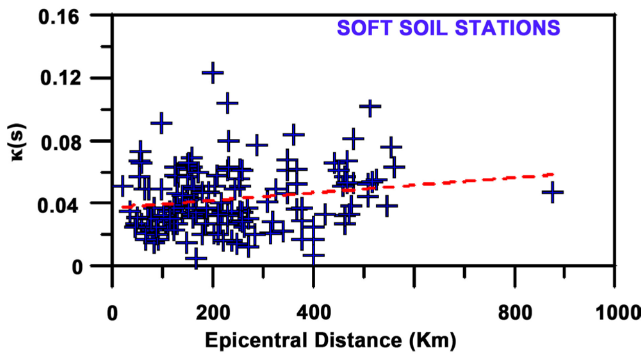


(b)

Figure 5. (a) Dependency of kappa (Horizontal) on Epicentral Distance; (b) Dependency of kappa (Vertical) on Epicentral Distance.



(a)



(b)

Figure 6. (a) Distance dependence of κ for hard rock sites; (b) Distance dependence of κ for soft soil sites.
$\kappa = 0.034 + 0.0000158R$ for hard rock sites and $\kappa = 0.037 + 0.000024R$ for soft soil sites.

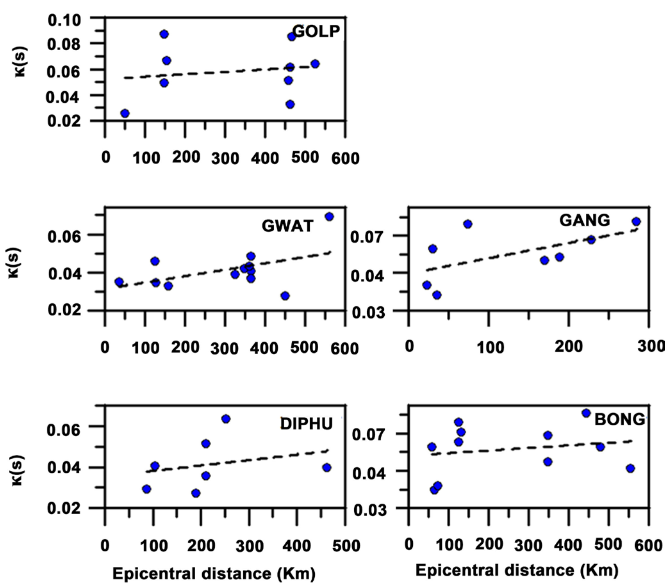


Figure 7. Distance dependence of κ for individual station where sufficient numbers of earthquake have been recorded.

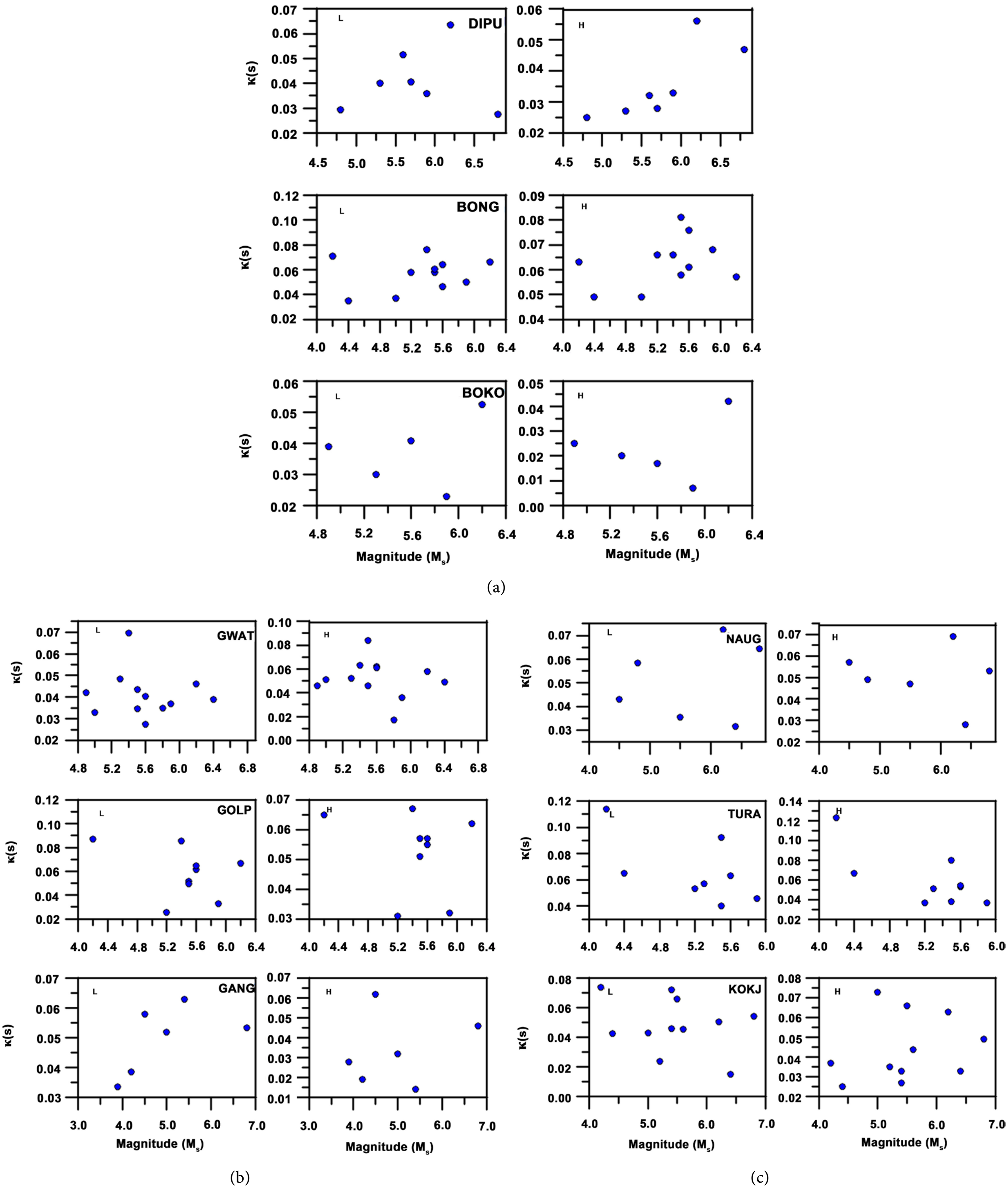


Figure 8. Magnitude dependency of kappa at some of the stations.

rock site in the Kachchh region of Gujarat, India. **Figure 7** shows the plots for the distance dependence of κ for individual stations where sufficient number of earthquakes have been recorded. The κ_0 values fall in the range 0.031 - 0.053. The change in the κ_0 values for different stations shows the effect of geological formations as suggested by [33].

The dependence of kappa values on earthquake size has been examined by plotting the estimated κ values with earthquake magnitudes for the stations where sufficient number of earthquake have been recorded. **Figure 8(a)-(c)** show such plots for some of the stations. We note that there is a scatter and the correlation between "κ" and magnitude at most of the stations for the region under study is not significant. This suggests that that "κ" is not related to source effect for NE Himalaya region. [31] has reported similar property of κ for smaller magnitude earthquakes occurred in Kachchh region of Gujarat, India. The analysis in the present study indicates that kappa for NE region is related with the high frequency attenuation in the top surface layer. One of the scientific discussions about κ is whether it is due to source effect or site effect or both. The different studies show different results for different regions of the world. The present study based on the available data found that κ is related to site effect in NE region. This is empirical inference drawn on the basis of recorded waveforms in the region. The same may be validated with more data whenever available.

5. Conclusions

The average value of κ estimated from the spectral analysis of horizontal components of 598 accelerograms for NE India region has been found to be in the range 0.047 - 0.049 and 0.040 for vertical component. The distance dependence of κ is not significant. The κ_0(soft site)/κ_0(rock site) ratio is found to be 1.09. The analysis shows that κ is not dependent on the magnitude but dependent on site-condition in the region for the range of magnitudes studies here. The study presents the κ model for NE India region which is first study of its kind in the region. The inferences drawn about κ in the NE region are based on the data available for the analysis. The same may be validated further as and when more data is available. With more data, the spatial distribution may also be investigated in the region. The other methods reported in the literature may also be applied to estimate κ in the region.

The estimated values of κ are useful in the studies of Ground Motion Prediction Equations (GMPE) as well as for the simulation of earthquake strong ground motions in the seismically active NE region. Thus this study is important for bearing on the seismic hazard studies of the region.

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