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SPECTRA FOR VERTICAL EARTHQUAKE GROUND MOTION

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SUMMARY

The vertical component of earthquake ground motion has been the focus of attention in the past ten years, following field observations pointing towards damage patterns that could have only been caused by severe vertical vibrations. Since the vertical component is rarely used in analysis to evaluate design actions, it follows that there is a potential built-in deficiency in the majority of structures and their foundations to resist vertical earthquake-induced vibrations. The authors have independently used different earthquake data sets to study the characteristics of vertical ground motions, focusing on the vertical spectra for seismic design code applications. Issues of maximum amplification, corner periods, decay exponent, suitable damping values and response modification factors have been addressed. In this paper, the two studies are reassessed within a common framework with additional vertical motion records from the 1999 Chi-Chi, Taiwan and the 1999 Kocaeli and Duzce, Turkey, earthquakes. The agreement on amplification factors and corner periods is interesting and detailed comparisons with natural ground motion at different site-to-source distances are reassuring. Spectra, representative of the available worldwide earthquake data bank, are recommended for vertical seismic design and analysis at various damping ratios. Inclusion of such spectra in design will help safeguard future infrastructure development from a serious source of sever damage, as confirmed by earthquake field observations worldwide.

INTRODUCTION

Since the vertical component is rarely used in analysis to evaluate design actions, it follows that there is a potential built-in deficiency in the majority of structures and their foundations to resist vertical earthquake-induced vibrations. Field observations have pointed towards structural damage patterns that could have only been caused by severe vertical vibrations (Papazoglou and Elnashai [1]).

The importance of earthquake vertical motion to structures, the inadequacy of related studies and the deficiency in design practices have motivated efforts devoted to the characteristics of vertical spectra for

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seismic design code applications. The study of Elnashai and Papazoglou [2] explored and documented the characteristics of near-field vertical ground motions. Vertical spectra were proposed for near-field ground motions based on worldwide strong motion records. Suitable damping ratios and response modification factors were presented.

Elgamal and He [3] investigated the characteristics of the spectra of both near-field and far-field vertical ground motions based on another independent dataset. Response modification factors for different damping ratios were studied. Near-field and far-field design spectra were proposed. Envelopes of response spectra were also proposed for various damping ratios.

This paper briefly summarizes the studies of Elnashai and Papazoglou [2] and Elgamal and He [3]. Strong motion records from the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and the 1999 Duzce, Turkey earthquakes are studied to complement the vertical spectra proposed by these two studies. All of the results are then merged in order to obtain spectra representative of the available worldwide earthquake data bank. Based on the merged results, spectra are recommended for vertical seismic design and analysis at various damping ratios.

RESPONSE SPECTRUM FOR VERTICAL EARTHQUAKE GROUND MOTIONS

Elastic spectrum

A spectrum represents the maximum response of a single degree of freedom (SDOF) system to a given input motion, as a function of natural frequency and damping. Generally, vertical vibration of a structure is asymmetric with respect to the horizontal plane due to preloading from gravity load (Elnashai and Papazoglou [2]). As discussed by Elnashai and Papazoglou [2], upwards and downwards spectra are needed ideally to describe the impact of vertical ground motions on structures. For simplicity, Elnashai and Papazoglou [2] defined a single elastic response spectrum for each vertical motion record, without consideration of vertical preload. Spectral shape for each record was obtained through normalizing its response spectrum by its peak vertical acceleration. Average spectrum and standard deviation were then computed based on the spectral shapes of their data set. Elgamal and He [3] used similar methods to study both near-field and far-field response spectra. The results of the two studies are summarized below. New insights from the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and the 1999 Duzce, Turkey earthquakes are presented.

Data set used

The data set used by Elnashai and Papazoglou [2] was selected base on the following three criteria: 1) event surface wave magnitude, $M_s \geq 5.0$, 2) event focal depth ≤ 25.0 km, and 3) peak vertical acceleration (PVA) ≥ 0.3 g. This data set consists of 35 free-field strong motion records during 15 worldwide earthquakes.

Elgamal and He [3] used another independent data set. It consisted of 111 free-field strong motion records during 6 major California earthquakes. The PVA of the 111 records is greater than 0.1 g. These records were divided into two groups, near-field and far-field, according to their closest distance to causative fault. The adopted threshold was 15 km suggested by Ambraseys and Simpson [4] and Ambraseys and Douglas [5]. Accordingly, among the 111 records are 50 near-field records and 61 far-field records.

This paper attempts to further investigate vertical spectra using additional free-field vertical strong motion records from the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and the 1999 Duzce, Turkey earthquakes. While abundant free-field vertical motion records with PVA greater than 0.1 g are available from the Chi-Chi earthquake, such records are unfortunately not readily available for the two Turkey earthquakes.

Records from stations housed in basements are thus examined herein to shed some light on vertical spectra for these two Turkey earthquakes.

The 1999 Chi-Chi, Taiwan earthquake (M_W=7.6) occurred on September 21, 1999 at 1:47 a.m. local time. The epicenter was near the town of Chi-Chi (Figure 1). This earthquake was generated by reverse, left lateral slip of the Chelungpu Fault, characterized by a long rupture of more than 80 km (Figure 1) and long duration of about 30 s (Ma *et al.* [6]). It originated at a very shallow focal depth of about 7 km. Ground shaking exceeded 1.0 g in many places and triggered hundreds of strong motion instruments across Taiwan. Locations of the free-field stations that recorded vertical motions during this earthquake are shown in Figure 1. A total of 52 free-field records with PVA greater than 0.1 g from this earthquake were investigated in this study. They were divided into near-field and far field records according to the threshold of 15 km used by Elgamal and He [3]. Accordingly, among the 52 records are 37 near-field records (Table 1) and 15 far-field records (Table 2).

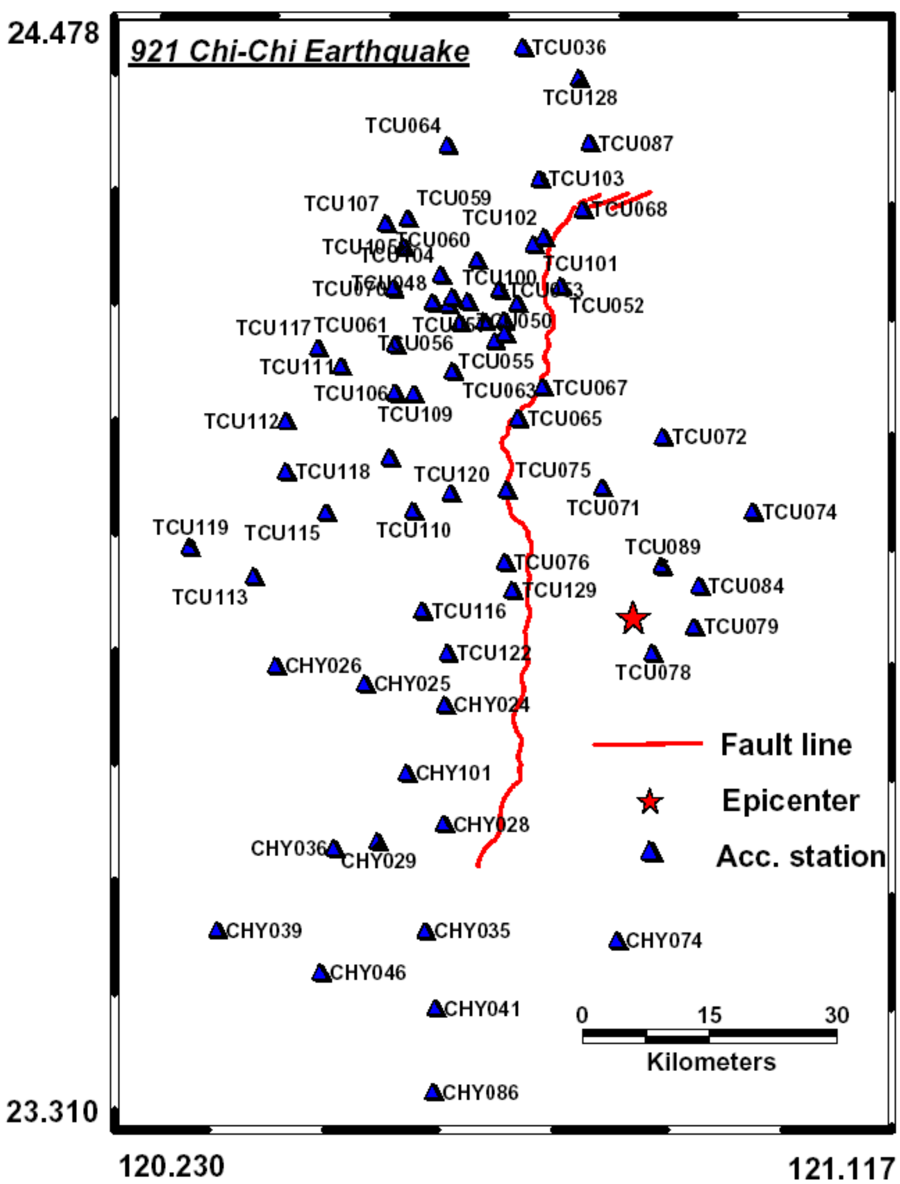

Figure 1. Locations of stations during the 1999 Chi-Chi, Taiwan earthquake (after Wang *et al.* [7])

Table 1 Near-field vertical motion records from the 1999 Chi-Chi, Taiwan earthquake

Station	Station latitude	Station longitude	Station structure	Epicentral distance (km)	Closest distance to fault (km)	PVA (g)
CHY006	23.581	120.552	Free-field	39.90	14.50	0.215
CHY024	23.757	120.606	Free-field	22.80	9.26	0.144
CHY028	23.632	120.605	Free-field	32.10	8.67	0.342
CHY080	23.597	120.678	Free-field	31.70	3.10	0.727
CHY101	23.686	120.562	Free-field	30.90	13.31	0.165
TCU049	24.179	120.690	Free-field	37.00	3.27	0.181
TCU051	24.160	120.652	Free-field	36.50	6.95	0.112
TCU052	24.198	120.739	Free-field	37.90	1.84	0.198
TCU053	24.194	120.669	Free-field	39.20	5.45	0.123
TCU054	24.161	120.675	Free-field	35.70	4.64	0.135
TCU055	24.139	120.664	Free-field	33.80	5.58	0.156
TCU056	24.159	120.624	Free-field	37.60	9.76	0.119
TCU063	24.108	120.616	Free-field	33.20	10.31	0.136
TCU065	24.059	120.691	Free-field	24.60	2.49	0.263
TCU067	24.091	120.720	Free-field	26.80	1.11	0.235
TCU068	24.277	120.766	Free-field	46.30	3.01	0.529
TCU071	23.986	120.788	Free-field	13.90	4.88	0.424
TCU072	24.041	120.849	Free-field	20.60	7.87	0.280
TCU074	23.962	120.962	Free-field	20.00	13.75	0.275
TCU075	23.983	120.678	Free-field	18.40	3.38	0.228
TCU076	23.908	120.676	Free-field	13.70	3.17	0.281
TCU078	23.812	120.846	Free-field	7.10	8.27	0.197
TCU079	23.840	120.894	Free-field	9.90	10.95	0.391
TCU082	24.148	120.676	Free-field	34.20	4.47	0.132
TCU084	23.883	120.900	Free-field	10.50	11.40	0.318
TCU088	24.253	121.176	Free-field	58.00	13.20	0.228
TCU089	23.904	120.857	Free-field	7.50	8.33	0.194
TCU101	24.242	120.709	Free-field	43.30	1.90	0.167
TCU102	24.249	120.721	Free-field	43.80	1.19	0.177
TCU103	24.310	120.707	Free-field	50.70	2.42	0.145
TCU109	24.085	120.571	Free-field	34.00	14.69	0.136
TCU116	23.857	120.580	Free-field	22.30	12.46	0.121
TCU120	23.980	120.613	Free-field	23.20	9.87	0.170
TCU122	23.813	120.610	Free-field	20.00	9.22	0.241
TCU129	23.878	120.684	Free-field	11.90	2.21	0.341
TCU136	24.260	120.652	Free-field	46.80	7.50	0.113
TCU138	23.922	120.595	Free-field	21.90	11.30	0.110

Table 2 Far-field vertical motion records from the 1999 Chi-Chi, Taiwan earthquake

Station	Station latitude	Station longitude	Station structure	Epicentral distance (km)	Closest distance to fault (km)	PVA (g)
CHY010	23.465	120.544	Free-field	50.90	22.40	0.143
CHY025	23.780	120.514	Free-field	30.50	18.78	0.173
CHY029	23.614	120.528	Free-field	38.90	16.40	0.161
CHY035	23.520	120.584	Free-field	43.60	15.20	0.108
CHY036	23.607	120.479	Free-field	43.10	21.46	0.106
CHY041	23.439	120.596	Free-field	51.10	21.94	0.125
CHY092	23.791	120.478	Free-field	33.60	22.50	0.113
CHY104	23.670	120.465	Free-field	40.10	23.10	0.131
TCU039	24.492	120.784	Free-field	70.00	17.50	0.123
TCU045	24.541	120.914	Free-field	76.30	24.70	0.338
TCU047	24.619	120.939	Free-field	85.20	33.00	0.263
TCU095	24.692	121.013	Free-field	94.60	41.40	0.256
TCU106	24.083	120.552	Free-field	35.30	16.66	0.118
TCU118	24.003	120.424	Free-field	41.40	29.26	0.100
TCU141	23.834	120.464	Free-field	34.3	24.20	0.109

The 1999 Kocaeli, Turkey earthquake (M_W=7.4) occurred on August 17, 1999 at 3:01 a.m. local time. The epicenter was approximately 11 km southeast of Izmit, an industrial city approximately 90 km east of Istanbul. This earthquake was generated by right lateral strike slip of the North Anatolian Fault (NAF) system, characterized by a long rupture of about 110 km section of the northernmost strand of the NAF. It originated at a focal depth of about 17 km (Erdik [8]). The 1999 Duzce, Turkey earthquake (M_W=7.1) occurred on November 12, 1999 at 6:57 p.m. local time. The epicenter is located near the town of Duzce, 70 km east of Adapazari and 170 km northwest of Ankara. This earthquake was generated by reverse, left lateral slip of the Duzce Fault and had a focal depth of 14 km (Erdik [8]). Tables 3 and 4 list the 5 and 2 vertical motion records studied in this paper from the 1999 Kocaeli and 1999 Duzce Turkey earthquakes, respectively.

Table 3 Vertical motion records from the 1999 Kocaeli, Turkey earthquake

Station Name	Station geology (Rathje *et al.* [9])	Station structure	Closest distance to fault (km)	Epicentral distance (km)	Hypocentral distance (km)	PVA (g)
DZC	Geomatrix (D) USGS (C)*	Basement, 1-story reinforced concrete	12.7	21.9	26	0.229
FAT	Geomatrix (D) USGS (C)	Basement, 1-story Masonry	-	89.7	91.3	0.128
GBZ	Geomatrix (A) USGS (A)	Basement, 4-story reinforced concrete	13.5	-	-	0.203
IZT	Geomatrix (A) USGS (A)	Basement, 3-story reinforced concrete	5	-	-	0.146
YPT	Geomatrix (D) USGS (C)	Basement, 3-story reinforced concrete	2.6	15	22.7	0.242
*USGS Site Classification (Average shear wave velocity to a depth of 30m) A = > 750 m/s, B = 360-750 m/s, C = 180-360 m/s, D = < 180 m/s						

Table 4 Vertical motion records from the 1999 Duzce, Turkey earthquake

Station Name	Station geology (Rathje *et al.* [9])	Station structure	Closest distance to fault (km)	Epicentral distance (km)	Hypocentral distance (km)	PVA (g)
BOL	Geomatrix (D) USGS (C)	Basement, 3-Story reinforced concrete	17.6	-	-	0.203
DZC	Geomatrix (D) USGS (C)	Basement, 1-Story reinforced concrete	8.2	21.9	26	0.357

Near-field and far-field response spectra suggested by earlier studies

Elnashai and Papazoglou [2] and Elgamal and He [3] developed near-field response spectra at various levels of damping using different data sets. The average spectra at 2% damping from the two studies are shown in Figure 2. It was found that average response spectra from the two studies were remarkably close to each other. At 2% damping (Figure 2), both have about the same peak amplification of 3.48 and the peaks occur at approximately the same period of about 0.10s (frequency = 10Hz), which is very close to the resonant periods of certain reinforced concrete structures (Papazoglou and Elnashai [1], Papazoglou [10]). Elgamal and He [3] therefore suggested that the reference design response spectrum proposed by Elnashai and Papazoglou [2] (also shown in Figure 2) be used for near-field design at 2% damping. This reference spectrum has a peak amplification of 3.48 with corner periods 0.05 s and 0.15 s.

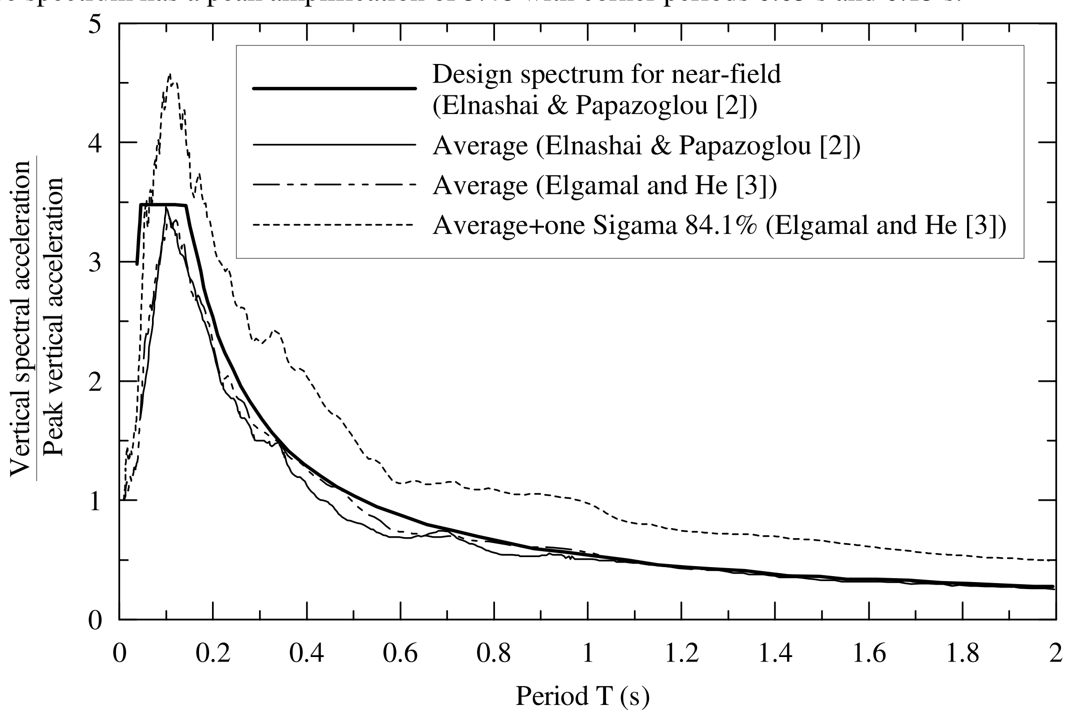

Figure 2. Near-field response spectra at 2% damping (after Elgamal and He [3])

Elgamal and He [3] further studied far-field response spectra using 61 far-field records. Far-field average response spectrum at 2% is compared with near-field in Figure 3. It can be seen that far-field peak response occurs at a period about 0.15s, longer than the near-field period of 0.10s. The 2% damping response spectrum peak of 3.65 is somewhat higher than the near-field 3.48 peak. The longer period of the far-field peak response agrees well with the shift towards longer period as the distance from source increases (Abrahamson and Silva [11]). Consequently, Elgamal and He [3] suggested a distinction between near-field and far-field response spectra and recommend corner periods of 0.05 s and 0.20 s for far-field design. At damping ratios other than 2%, amplification correction factor η given by Elnashai and Papazoglou [2] was found to be most representative (Elgamal and He [3]):

$$\eta = \sqrt{\frac{2.72}{0.72 + \xi}} \tag{1}$$

where ξ is damping ratio in percent. Maintaining the suggested corner periods, design spectra at damping ratios other than 2% can then be obtained using the amplification correction factor η given by Eq.(1).

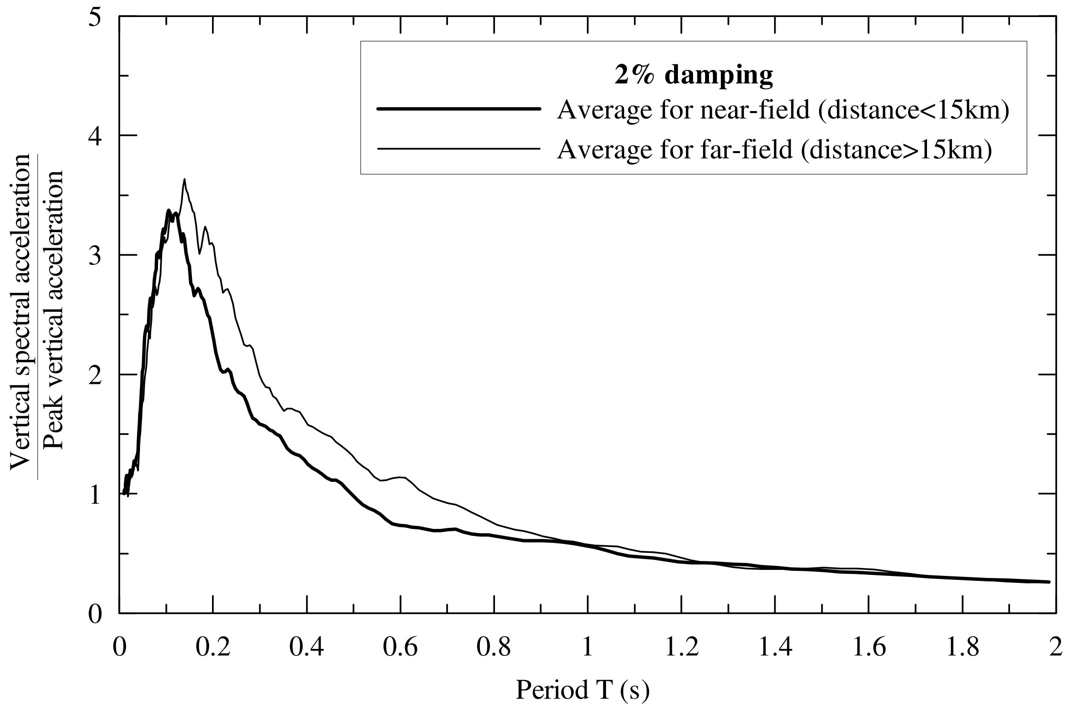

Figure 3. Near-field and far-field average response spectra (after Elgamal and He [3])

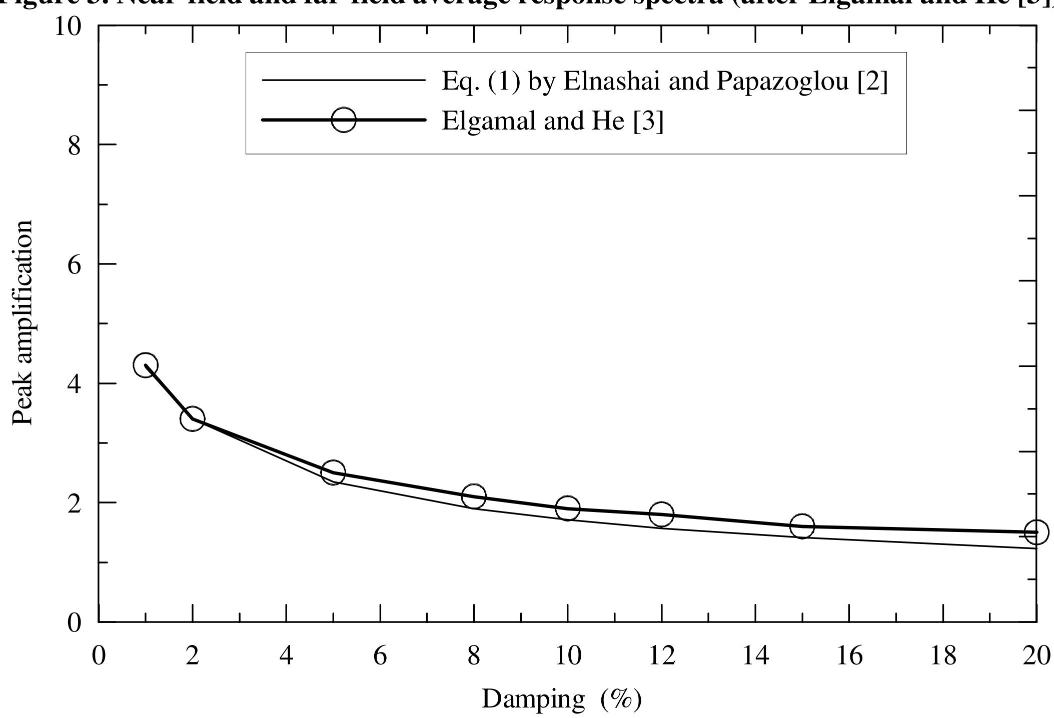

Figure 4. Peak amplification at different levels of damping (after Elgamal and He [3])

Response spectra of the 1999 Chi-Chi, Taiwan, Records

Figures 5 and 6 show respectively typical near-field and far-field response spectra of the Chi-Chi earthquake at 2% damping. The response spectrum varies significantly from one record to the other. Nevertheless, all records consistently show a peak at a period of about 0.1-0.15 s. Besides, many records, especially far-field records, contain significant long period amplification up to a period of about 5 seconds, as discussed by Wang et al. [7], which is much different from earlier observations (Figure 3).

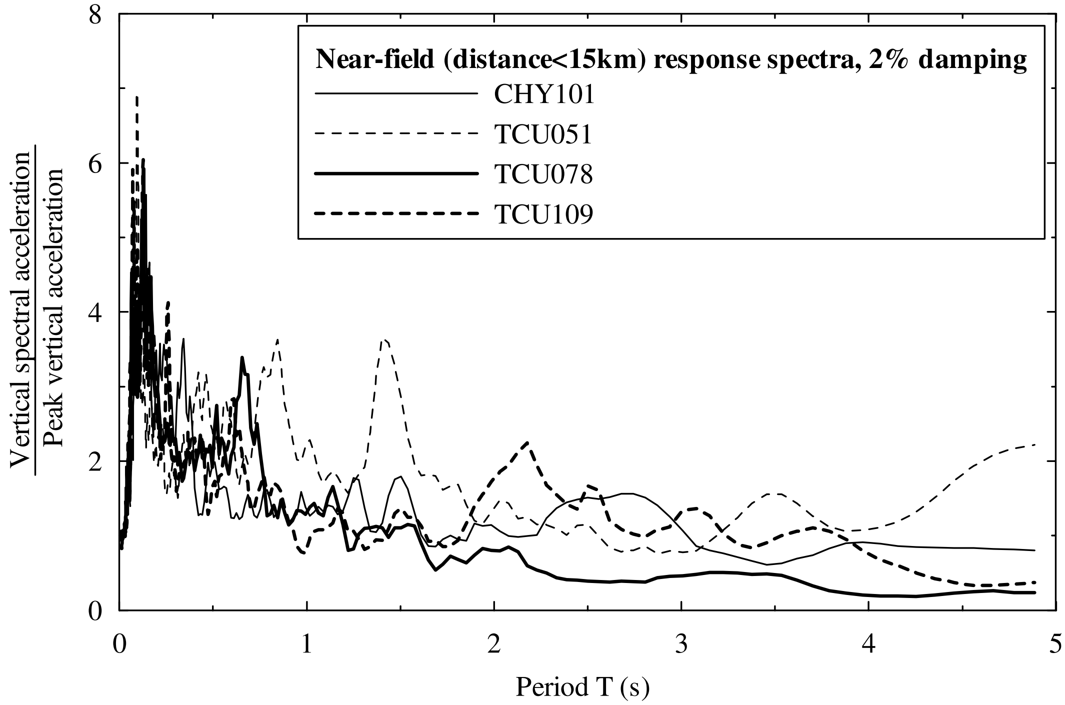

Figure 5. Typical near-field response spectra of the 1999 Chi-Chi, Taiwan earthquake

Figure 7 shows averages of the near-field and far-field spectra at 2% damping (records of Tables 1 and 2). Similar to typical individual records shown in Figures 5 and 6, peak amplifications and corresponding periods as well as short period response agree well with earlier studies (Elnashai and Papazoglou [2], Elgamal and He [3]). However, long period amplification is higher. In addition, the two averages for near-field and far-field are close, without noticeable shift towards longer period in far-field. In this regard, delineation of near-field versus far-field records by the 15 km closest distance to fault does not appear to be an effective approach. As mentioned earlier, the fault line (Figure 1) is more than 80 km long, and recording stations are present on both sides of this line within a range of about 40 km.

Figure 8 shows the different near-field average response at 2% damping including and excluding the 1999 Chi-Chi, Taiwan, earthquake in the entire data set of Elgamal and He [3]. The average of the Chi-Chi earthquake alone is also shown in Figure 8. As may be expected from Figures 5 - 7, this earthquake hardly modifies the short period and the peak response spectra of Elgamal and He [3]. In contrast at longer periods, the average spectrum of overall near-field records is consistently and significantly higher when the 1999 Chi-Chi, Taiwan, earthquake is included. The average of the Chi-Chi earthquake alone is much higher at longer periods.

The same agreement with the earlier study of Elgamal and He [3] is noted with regard to the average spectra at short period and the peak in far-field records (Figure 9). However, inclusion of this earthquake only results in slightly higher response at longer periods in the case of far-field records (Figure 9), while Chi-Chi earthquake itself has much higher response spectra at longer periods.

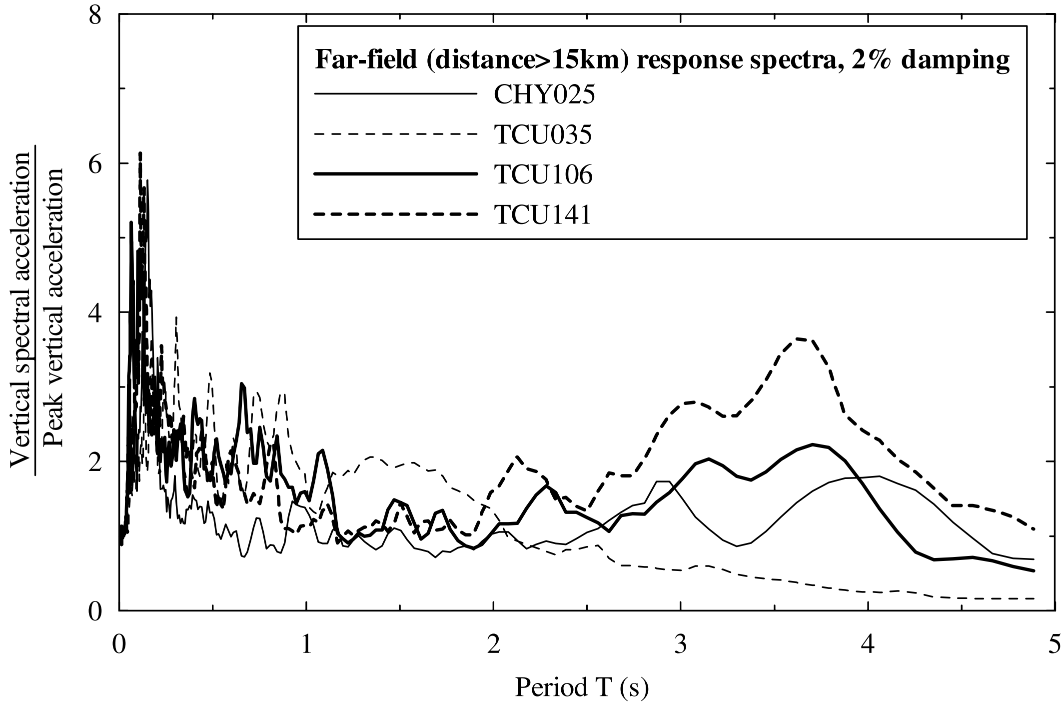

Figure 6. Typical far-field response spectra of the 1999 Chi-Chi, Taiwan earthquake

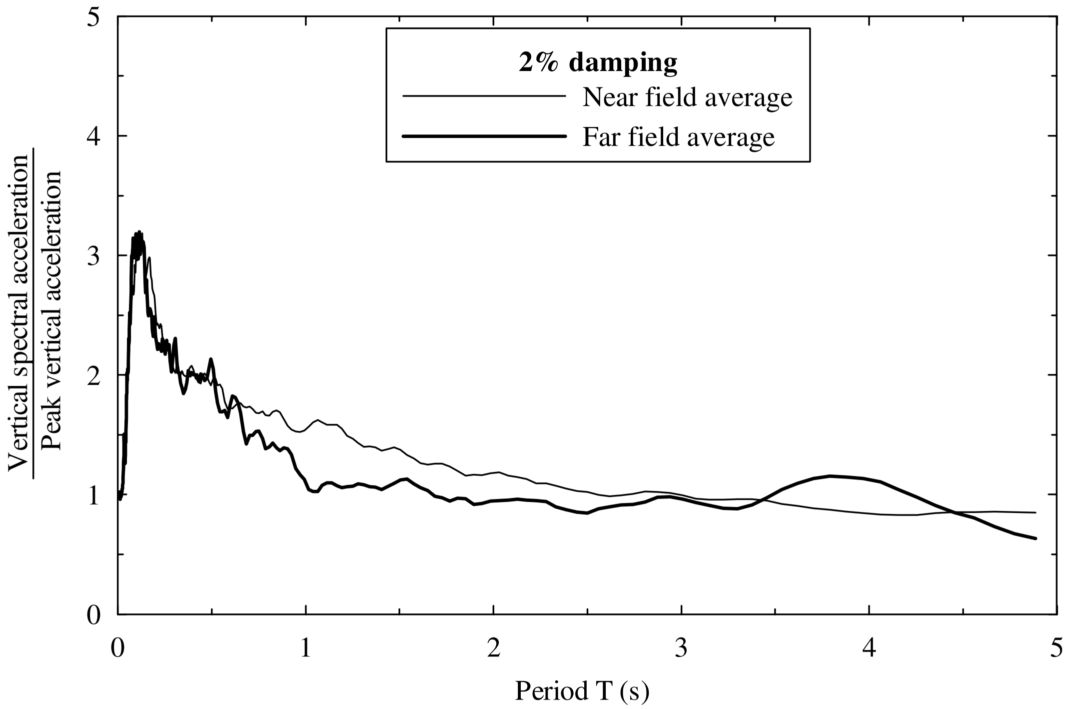

Figure 7. Average response spectra of the 1999 Chi-Chi, Taiwan, earthquake at 2% damping

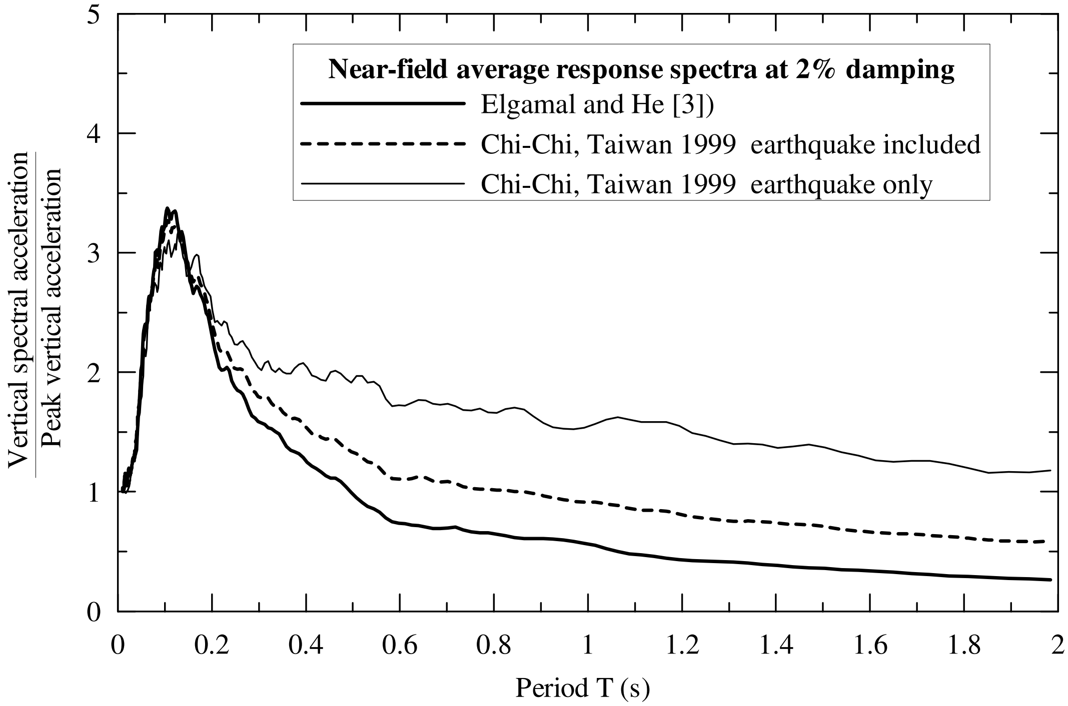

Figure 8. Near-field average response with and without the 1999 Chi-Chi, Taiwan, earthquake records at 2% damping

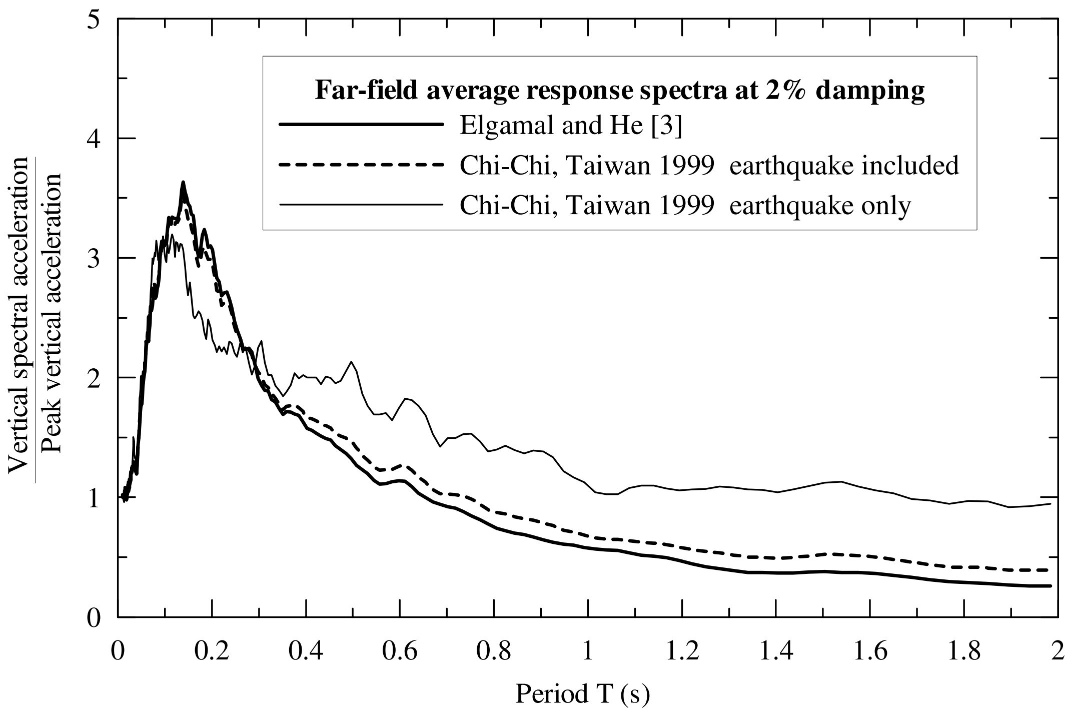

Figure 9. Far-field average response with and without the 1999 Chi-Chi, Taiwan, earthquake records at 2% damping

Response spectra of the 1999 Kocaeli and Duzce, Turkey earthquake records

Figures 10 and 11 show the response spectra of the 1999 Kocaeli and the 1999 Duzce, Turkey earthquakes at 2% damping. Peak response of all near-field records occurs at a period of about 0.1 second. BOL is the only far-field record with distance to causative fault of 17.6 m (Table 4). Compared to near-field record, the BOL contains energy over a longer period range, with a smaller peak response occurring at a somewhat longer period (Figure 11). This observation agrees well with that of Elgamal and He [3].

Figure 12 compares the near-field average spectrum of the two Turkey earthquakes with those of Elgamal and He [3] based on California earthquakes, showing good agreement in the short period range. Averages of both Turkey and Elgamal and He [3] have peak amplification at a period of about 0.1 second although the Turkey average has a somewhat larger peak response. At longer period, the average of Turkey is somewhat higher. When the Turkey earthquakes are included in the entire data set, no appreciable difference is observed (Figure 12). As there is only one far-field record from the Turkey earthquakes, no comparison of far-field averages is made herein, with results of earlier studies.

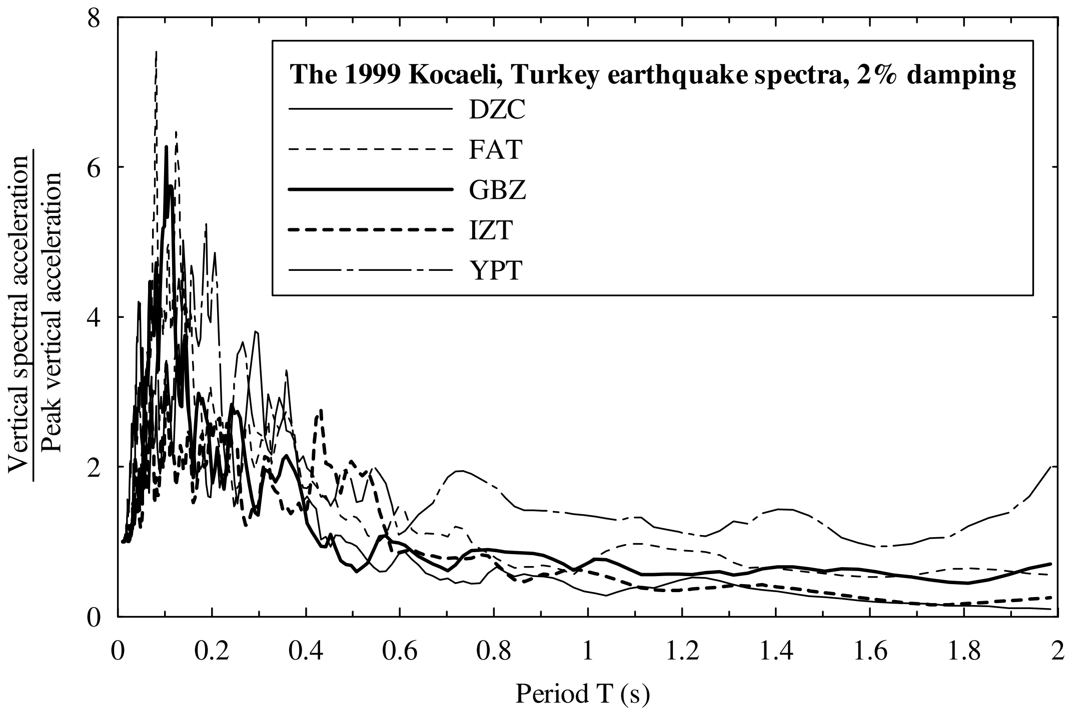

Figure 10. Response spectra of the 1999 Kocaeli, Turkey earthquake at 2% damping

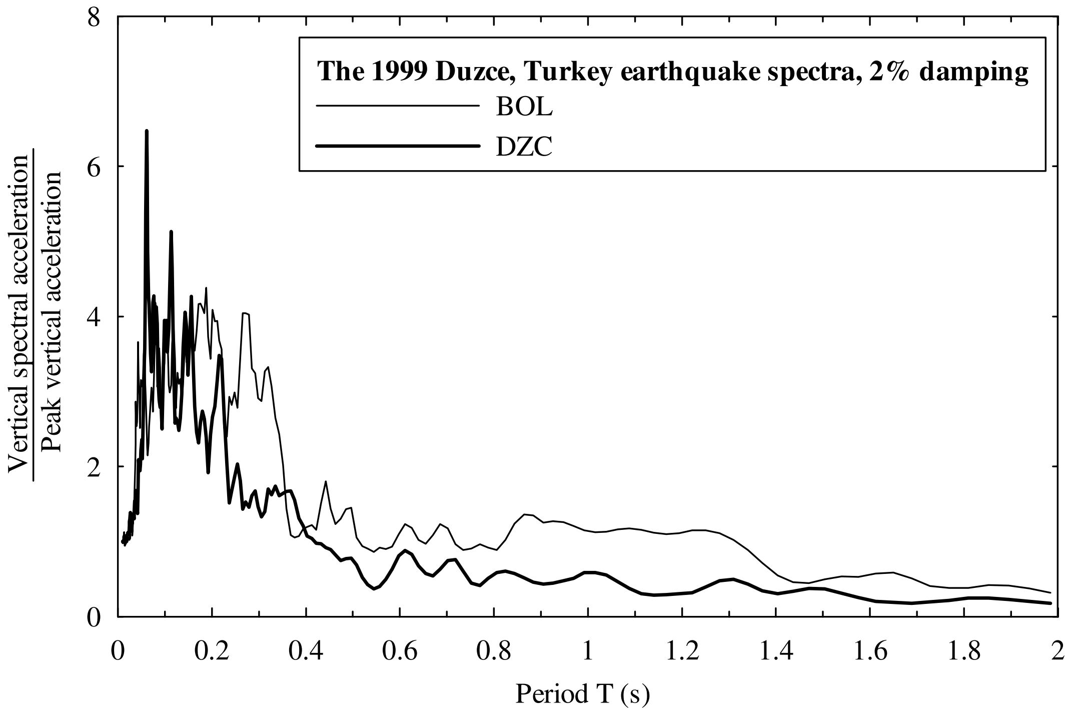

Figure 11. Response spectra of the 1999 Duzce, Turkey earthquake at 2% damping

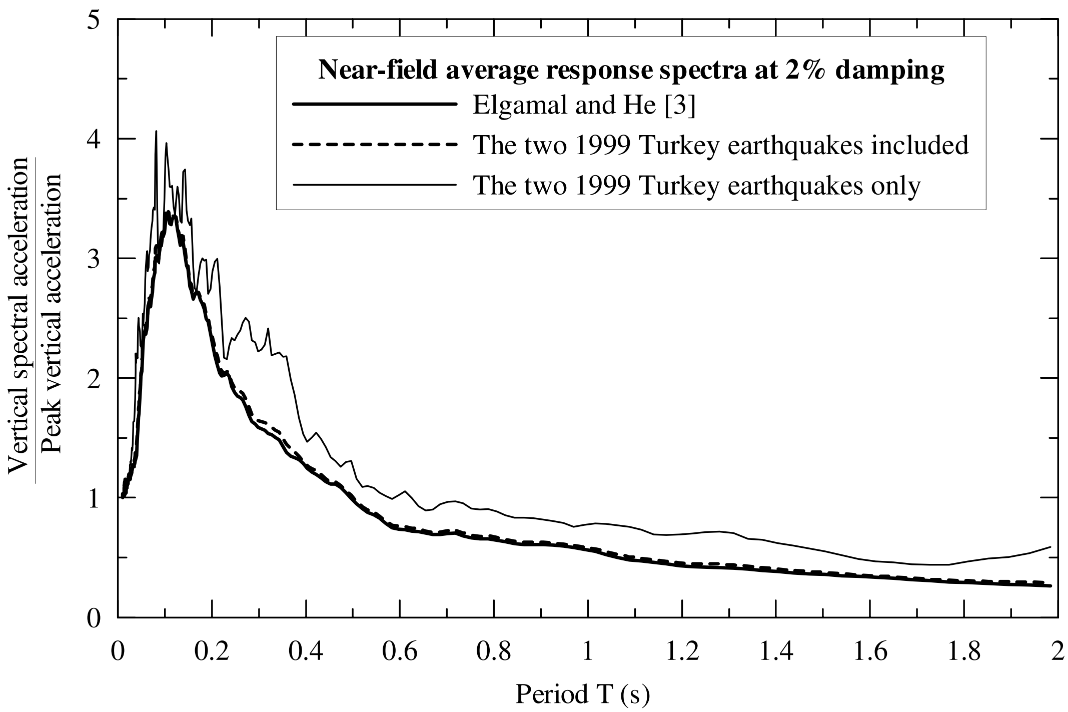

Figure 12. Comparison of the near-field average spectrum for the two Turkey earthquake with that of Elgamal and He [3] based on California earthquakes

Design spectra for vertical ground motions

The averages of the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and the 1999 Duzce, Turkey vertical earthquake records are in agreement with the short period and peak spectral values of earlier studies (Elnashai and Papazoglou [2], Elgamal and He [3]). However, the 1999 Chi-Chi, Taiwan earthquake requires an increase in the decay portion of the design spectra at longer periods, since this earthquake generally displayed noticeably higher longer period content.

Considering the quite complex source of the 1999 Chi-Chi, Taiwan earthquake (Shin and Teng [12]), design spectra for vertical ground motions (based on average spectral response) are recommended for the following three situations while maintaining the distinction between near-field and far-field cases (Figures 13 and 14):

1) Excluding the 1999 Chi-Chi, Taiwan earthquake records, and
2) Including the 1999 Chi-Chi, Taiwan earthquake records,
3) Exclusively for the 1999 Chi-Chi, Taiwan earthquake records

Based on average response spectra, Figure 13 and Figure 14 show the three situations for near-field and far-field respectively. The key parameters that define these shapes at 2% damping are listed in Table 5. Note that the cases excluding the Chi-Chi earthquake are essentially the ones recommended by Elnashai and Papazoglou [2] and Elgamal and He [3]. Spectra for other damping ratios can be defined with the aid of Figure 4.

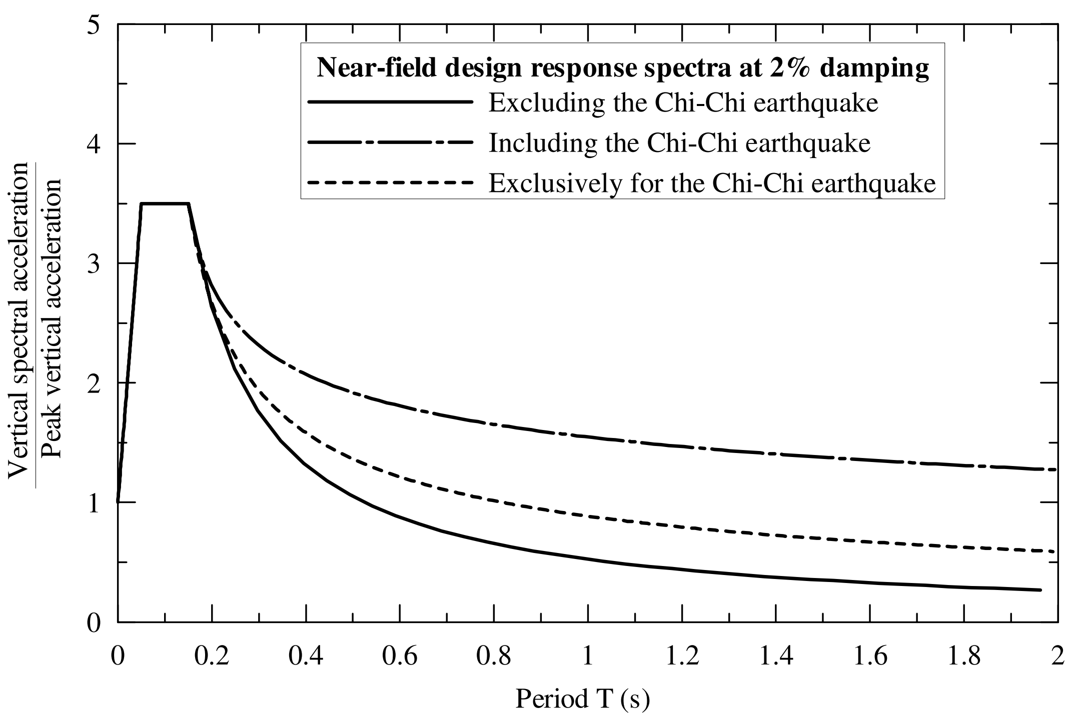

Figure 13. Near-field design response spectra at 2% damping

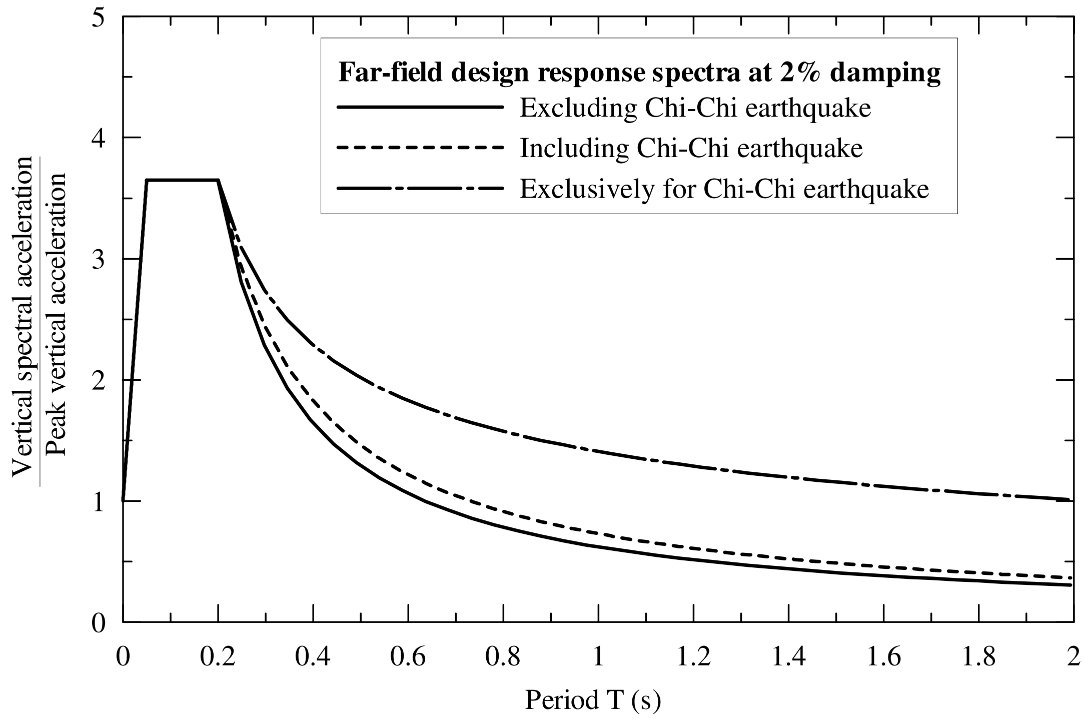

Figure 14. Far-field design response spectra at 2% damping

Table 5 Key parameters of the recommended near-field and far-field design spectra (2% damping)

Site-source-distance	Near-Field				Far-Field			
Parameters	Peak	Corner period		Decay after plateau	Peak	Corner period		Decay after plateau
		T_1 (s)	T_2 (s)			T_1 (s)	T_2 (s)	
Excluding Chi-Chi	3.48	0.05	0.15	0.525/T	3.65	0.05	0.20	0.6/(T-0.035)
Including Chi-Chi				$0.85/(T-0.07)^{0.56}$				0.73/T
Exclusively for Chi-Chi				$1.5/(T-0.111)^{0.26}$				$1.35/(T-0.09)^{0.45}$

CONCLUSIONS

In this paper, previous studies by the authors and their collaborators have been reassessed and cast in a common framework and consolidated conclusions have emerged. A summary of the main conclusions, also given in the body of the paper, is presented below:

1. Significant high frequency (about 8 Hz and higher) was found to prevail in all vertical records. Noting that vertical periods of most structural systems are shorter than their horizontal counterparts, this observation is potentially very important for seismic risk assessment.

2. Records from the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and the 1999 Duzce, Turkey earthquakes further confirmed the peak amplifications and corresponding corner periods for vertical spectra. For near-field sites, the Elnashai and Papazoglou [2] corner periods of 0.05s and 0.15s were most representative. For far-field sites, corner periods of 0.05s and 0.20s were suggested (Elgamal and He [3]).

3. Spectra for vertical ground motions are recommended at various damping ratios for near-field and far-field cases with and without considering the 1999 Chi-Chi, Taiwan earthquake, through the recommended damping correction factor (Figure 4) in combination with the 2% design spectra (Figures 13 and 14 or Table 5).

4. The recommended vertical spectra are representative of the available worldwide earthquake data bank today and are therefore suitable for use in modern seismic design practice.

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