Original paper

Observed Seismic Intensities and Damage Pattern in Central Mexico during Intraslab Earthquakes of 1999 (Mw6.9) and 2017 (Mw7.1)

Danny Arroyo[1], Shri Krishna Singh[2], Mario Ordaz[3], Roberto Meli[3] and Mario Ramírez[1]

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Resumen

El patrón y nivel de daño en la región de México Central durante el sismo de septiembre de 2017 Mw7.1 en Morelos-Puebla son diferentes a los observados durante el sismo de Tehuacán (Mw6.9) en 1999 a pesar de que ambos sismos intraplaca tienen magnitudes similares y profundidades focales comparables 57 km y 60 km, respectivamente. El sismo de 2017 causo claramente mas daño en la región de México Central. Los epicentros de ambos eventos están separados 127 km. Mediante el análisis de los registros sísmicos de México Central encontramos que el área expuesta a diferentes niveles de aceleración máxima del suelo y velocidad máxima del suelo es comparable para los dos eventos. Por ejemplo, el área expuesta a aceleraciones máximas del suelo mayores a 150 cm/s^2 es de 12,700 km^2 para el sismo de 1999 y 15400 km^2 para el sismo de 2017. La forma de los contornos de intensidades y localización epicentral sugiere una ruptura bilateral para el evento de 2017 y una ruptura con directividad hacia el norte para el sismo de 1999. Los cocientes espectrales para los dos eventos revelaron una fuente más energética hacia el norte para el sismo de 1999 que para el sismo de 2017 lo cual es consistente con resultados reportados previamente de directividad en la ruptura. Se concluye que la distinta localización de los dos eventos junto con la diferente distribución de las poblaciones, monumentos históricos y el incremento de población desde 1999 fueron las principales causas de la diferencia de los daños entre los dos eventos.

Palabras clave: sismo 2017 Morelos-Puebla, sismo 1999 Tehuacán, registros de movimiento fuerte, mapas de intensidades

Abstract

The pattern and level of damage during the 2017 Morelos-Puebla (Mw7.1) earthquake in central Mexico differ from those observed during the 1999 Tehuacán (Mw6.9) earthquake. Although these two intraslab events had similar magnitudes and depths, 57 km and 60 km respectively,

*Corresponding author
aresda@correo.azc.uam.mx

[1]*Departamento de Materiales*
Universidad Autónoma Metropolitana

[3] *Instituto de Ingeniería*
UNAM

the 2017 earthquake caused significantly more damage in central Mexico. The epicenters of the two events were separated by 127 km. From the analysis of strong-motion recordings in central Mexico, we find that the areas within different PGA and PGV contours during the two earthquakes are roughly equal. For example, PGA contour of 150 cm/s2 encloses 12,700 km2 and 15,400 km2 during the 1999 and 2017 events, respectively. The shape of the contours and the location of the epicenter suggests a bilateral rupture during the 2017 earthquake and a rupture directivity to the north for the 1999 earthquake. Spectral ratios of the two earthquakes reveal a more energetic 1999 source to the north than that of 2017 which is consistent with the previously reported rupture directivity. This leads us to conclude that the distinct locations of the two earthquakes along with uneven density of population, dwellings, and historical monuments, and demographic increase since 1999 were the principal causes of the difference in damage during the two earthquakes.

Key words: 2017 Morelos-Puebla Earthquake, 1999 Tehuacán Earthquake, strong ground motion records, intensity maps

Introduction

Intraslab earthquakes in central Mexico occur in the subducted Cocos plate at a depth of ~ 40 to 80 km and involve normal faulting. The recent intraslab earthquake of 19 September 2017 (Mw7.1) was located near the border of the states of Morelos and Puebla (18.41 ºN, -98.71 ºE; depth H = 57 km) (Figure 1). It caused severe damage in central Mexico and Mexico City. Several towns in the epicentral region were almost completely destroyed. Extensive damage was reported in the states of Morelos and Puebla. In Mexico City 44 buildings collapsed and approximately 600 buildings were severely damaged. It was the second most destructive earthquake in the history of the city, next only to the 1985 Michoacán (Mw8.0) earthquake. The PGA at CU, a strong-motion station in the hill-zone of Mexico City that has been in continuous operation for the last 54 years, was 57 cm/s2, the highest ever recorded. In comparison, the PGA at CU during the 1985 earthquake was 29 cm/s2.

It is well known that intraslab earthquakes pose significant seismic hazard to cities in central Mexico (see, e.g., Singh *et al.*, 2018 for a brief review). In 1931 a Mw7.8 earthquake devastated the city of Oaxaca; in 1973 a Mw7.0 earthquake damaged some cities of Veracruz; a Mw7.0 earthquake in 1980 caused severe damage in the state of Oaxaca; in 1999 a Mw6.9 earthquake caused damage to the city of Tehuantepec and the states of Puebla and Morelos and Oaxaca; and the great intraslab earthquake of 8 September 2017 (Mw8.2), which occurred off the coast of Chiapas and Oaxaca, caused wide-spread destruction to the coastal towns of these states. Figure 1 shows epicenters of 4 significant, recent intraslab earthquakes in and near Morelos-Puebla region (06/07/1964, Mw7.3; 24/10/1980, Mw7.0; 15/06/1999, Mw6.9; 19/09/2017, Mw7.1). The earthquake of 2017 is the closest, reliably located, intraslab earthquake to Mexico City (Singh *et al.*, 2018).

The 2017 and 1999 earthquakes were well recorded at many stations in central Mexico and Mexico City. The epicenters of the two events are separated by 127 km; the epicentral distance to CU in Mexico City from the 2017 and 1999 earthquakes are 113 km and 218 km, respectively (Figure 1). Here we analyze the accelerograms of the two earthquakes to relate the recorded seismic intensities with observed damage patterns. We then investigate whether the location alone can explain the difference in the pattern and level of damage during the two earthquakes or other factors also played a role. Our focus is central Mexico excluding Mexico City.

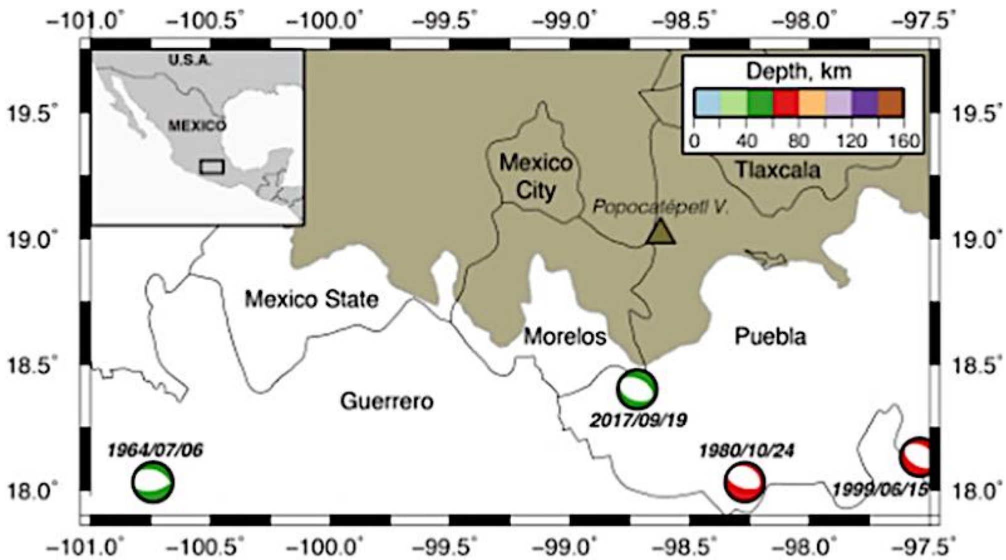

Figure 1. Map of central Mexico showing epicenters and focal mechanisms of four, recent significant intraslab earthquakes in the region. The epicenter of the 2017 earthquake is closer to Morelos and Mexico City than the other earthquakes.

Recorded Strong Ground Motions

The 1999 earthquake was recorded in 33 stations on firm soil sites listed (Table 1). The largest recorded intensities (PGA= 184 cm/s^2 and PGV=17 cm/s) were observed at CSER station located roughly 100 km from the epicenter. We constructed PGA and PGV contours via the Bayesian Kriging technique proposed by Kitanidis (1986). We first used the ground motion prediction equation (GMPE) proposed by Garcia *et al.* (2005) for Mexican intraslab earthquakes to generate prior median values of the intensities at different sites on a grid; these values were then updated with intensities listed in Table 1 via Bayes theorem. It is worth noting that 1999 data were used to construct the Garcia's GMPE therefore it fits well the 1999 data. We excluded recordings in Mexico City from the analysis because of the well-known large site effects. Figures 2a and 3a show PGA and PGV contours during the 1999 earthquake. The contours are elongated towards northwest from the epicenter suggesting rupture propagation towards this direction. This source directivity was previously documented from an analysis of the recorded waveforms (Singh *et al.*, 1999) as well as from PGA contours constructed using an interpolation technique based solely on the recorded data. The figures also show towns in the State of Puebla with population larger than 15,000.

Table 1. Recorded PGA and PGV during the 1999 earthquake

Station	Lat	Long	R, km	PGA*, cm/s2	PGV*, cm/s	Station	Lat	Long	R, km	PGA*, cm/s2	PGV*, cm/s
AGCA	16.837	-99.645	275	10.11	0.80	RABO	18.569	-98.445	124	141.59	11.01
ATYC	17.213	-100.432	331	7.25	0.54	RIOG	16.014	-97.439	245	5.71	0.46
CHFL	17.969	-97.866	73	106.96	10.69	SMLC	16.655	-96.729	196	13.29	0.67
COMD	18.122	-100.524	323	15.56	0.89	SMR2	16.774	-99.438	261	7.57	0.75
COPL	16.611	-98.984	239	9.59	0.81	TAMA	16.261	-96.575	240	6.68	0.54
COYC	16.998	-100.090	307	8.32	0.66	TEAC	18.618	-99.454	219	33.30	2.68
COYQ	17.380	-101.057	389	9.14	0.50	TNLP	18.096	-99.561	224	35.79	2.31
CSER	18.989	-97.377	112	184.47	17.39	UNIO	17.988	-101.811	458	2.43	0.38
JAMI	16.284	-97.821	218	17.18	0.55	VIGA	16.759	-99.233	246	17.73	0.81
LANE	15.940	-97.180	255	5.94	0.47	VNTA	16.914	-99.819	286	6.06	0.49
OCLL	17.037	-99.879	285	7.81	0.55	YAIG	18.862	-99.067	191	43.16	3.42
OMTP	16.689	-98.398	197	21.11	0.61	CUER	18.984	-99.230	211	42.99	2.89
OXLC	17.065	-96.703	160	20.74	1.80	LVIG	19.723	-96.418	218	4.91	0.54
PANG	15.667	-96.491	303	4.51	0.28	MEZC	17.930	-99.591	228	27.44	1.62
PET2	17.535	-101.263	406	3.41	0.40	OXIG	17.072	-96.733	158	28.53	1.40
PHPU	19.044	-98.168	135	170.34	15.81	BHPP	19.109	-98.227	143	58.55	5.51
POZU	17.090	-99.598	257	18.42	0.71	PLIG	18.392	-99.502	218	20.88	1.49

* PGA and PGV are the geometric mean of two horizontal components

The 2017 earthquake was recorded at 64 firm soil sites (Table 2). The highest intensities were observed at FTIG station (PGA= 369 cm/s2 and PGV=12.7 cm/s) located roughly 100 km southeast from the epicenter. The PGA and PGV contours, shown in Figures 2b and 3b, were constructed following the same procedure as described before. The contours for this earthquake are elongated in the NW-SE direction with the epicenter in the middle, suggesting a bilateral rupture. Slip distribution on the fault plane of this earthquake has been mapped from the inversion of teleseismic waveforms (L.Ye, personal communication, 2018) as well as from the inversion of regional data (Melgar *et al.*, 2017; A. Iglesias, personal communication, 2018). Not surprisingly, directivity is not discernible in the teleseismic inversion because of the relatively small magnitude of the event. Inversion by Melgar *et al.* suggests a directivity towards NW, which is contrary to Iglesias´ inversion that supports rupture propagation predominantly towards SE.

The area under PGA contour of 150 cm/s2 in 2017 is roughly 15,400 km2, slightly greater than the corresponding area of 12,700 km2 in 1999. This PGA contour during 2017 covers 75%, 20%, 4% and 2% of the states of Morelos, Puebla, Guerrero, and Oaxaca, respectively; the corresponding numbers during 1999 are 0%, 35%, 0%, and 2%. In 2017, 24%, 45%, 17%, and 14% of the total area under the 150 cm/s2 contour fall in the states of Morelos, Puebla, Guerrero, and Oaxaca, respectively (Table 3). In contrast, in 1999 the total area under the same PGA contour was distributed as follows: 0%, 84%, 13%, and 3% in the states of Morelos, Puebla, Oaxaca, and Veracruz, respectively.

Table 2. Recorded PGA and PGV during the 2017 earthquake

Station	Lat	Long	R, km	PGA*, cm/s2	PGV*, cm/s	Station	Lat	Long	R, km	PGA*, cm/s2	PGV*, cm/s
hlig	17.830	-97.800	128	227.98	14.29	cuer	18.984	-99.230	102	158.94	18.88
hmtt	17.800	-98.560	90	170.55	12.10	ftig	17.908	-98.133	100	368.52	12.51
phpu	19.040	-98.170	107	141.73	9.84	lvig	19.723	-96.418	287	1.84	0.37
ppig	19.070	-98.630	94	112.62	12.96	plig	18.392	-99.502	101	61.45	5.85
tlig	17.560	-98.570	111	110.70	3.90	pzpu	19.055	-98.227	105	105.35	13.67
teju	18.900	-100.160	172	83.30	3.53	rabo	18.569	-98.445	81	141.50	7.99
meig	17.920	-99.620	124	74.59	2.42	sxpu	19.040	-98.215	104	127.41	18.99
tpig	18.420	-97.360	153	71.34	7.41	tgbt	16.777	-93.089	624	0.88	0.12
acp2	16.870	-99.890	219	35.36	1.35	thez	18.478	-97.383	151	157.41	11.34
oxlc	17.070	-96.700	265	22.52	1.34	tnlp	18.096	-99.561	112	58.25	3.62
atyc	17.210	-100.430	233	18.69	0.67	pb1	18.240	-98.700	81	201.21	7.19
coyc	17.000	-100.090	222	18.32	0.86	pb2	18.330	-98.260	81	223.43	15.12
oxbj	17.070	-96.720	264	18.11	1.45	gr	18.330	-99.190	81	258.29	7.86
vnta	16.910	-99.820	212	10.63	0.89	huig	15.768	-96.108	407	4.11	0.32
pet2	17.540	-101.260	292	10.03	0.44	peig	15.999	-97.147	320	10.88	0.92
xala	19.530	-96.900	234	8.28	1.50	pnig	16.392	-98.127	239	6.63	0.82
caig	17.050	-100.270	231	8.07	0.42	toig	18.096	-97.065	186	19.36	1.40
unio	17.990	-101.810	336	6.08	0.42	txig	17.254	-97.761	172	41.42	5.20
urua	19.420	-102.070	375	6.04	0.86	yoig	16.858	-97.546	219	9.43	1.63
nilt	16.570	-94.620	482	5.98	0.29	cdgu	19.700	-103.448	521	1.95	0.70
pang	15.670	-96.490	389	4.68	0.51	coll	19.191	-104.681	637	1.38	0.17
acam	20.040	-100.720	284	4.48	1.31	jami	16.284	-97.821	260	15.30	1.43
ziig	17.610	-101.460	309	4.19	0.50	lane	15.948	-97.187	322	5.50	0.77
cmig	17.090	-94.880	434	2.99	0.35	lmpp	19.001	-98.182	103	37.13	3.33
dhig	20.300	-99.040	221	2.73	0.80	nux2	17.217	-100.791	263	7.66	0.51
coma	19.330	-103.760	544	2.23	0.44	ocll	17.037	-99.879	204	17.49	0.88
chpa	16.250	-93.910	565	2.16	0.27	pbp2	19.045	-98.208	105	95.98	15.31
mmig	18.290	-103.350	493	2.14	0.34	rpig	21.885	-99.983	413	4.41	1.29
tuig	18.030	-94.420	458	2.07	0.33	sjal	18.585	-103.670	527	3.31	0.22
yaig	18.862	-99.067	85	202.00	13.00	slu2	17.281	-100.935	273	11.78	0.53
arig	18.281	-100.344	182	31.44	1.73	smlc	16.655	-96.729	292	10.50	1.11
chfl	17.969	-97.866	116	76.38	7.30	tama	16.261	-96.575	333	7.30	1.00

* PGA and PGV are the geometric mean of two horizontal components

1999

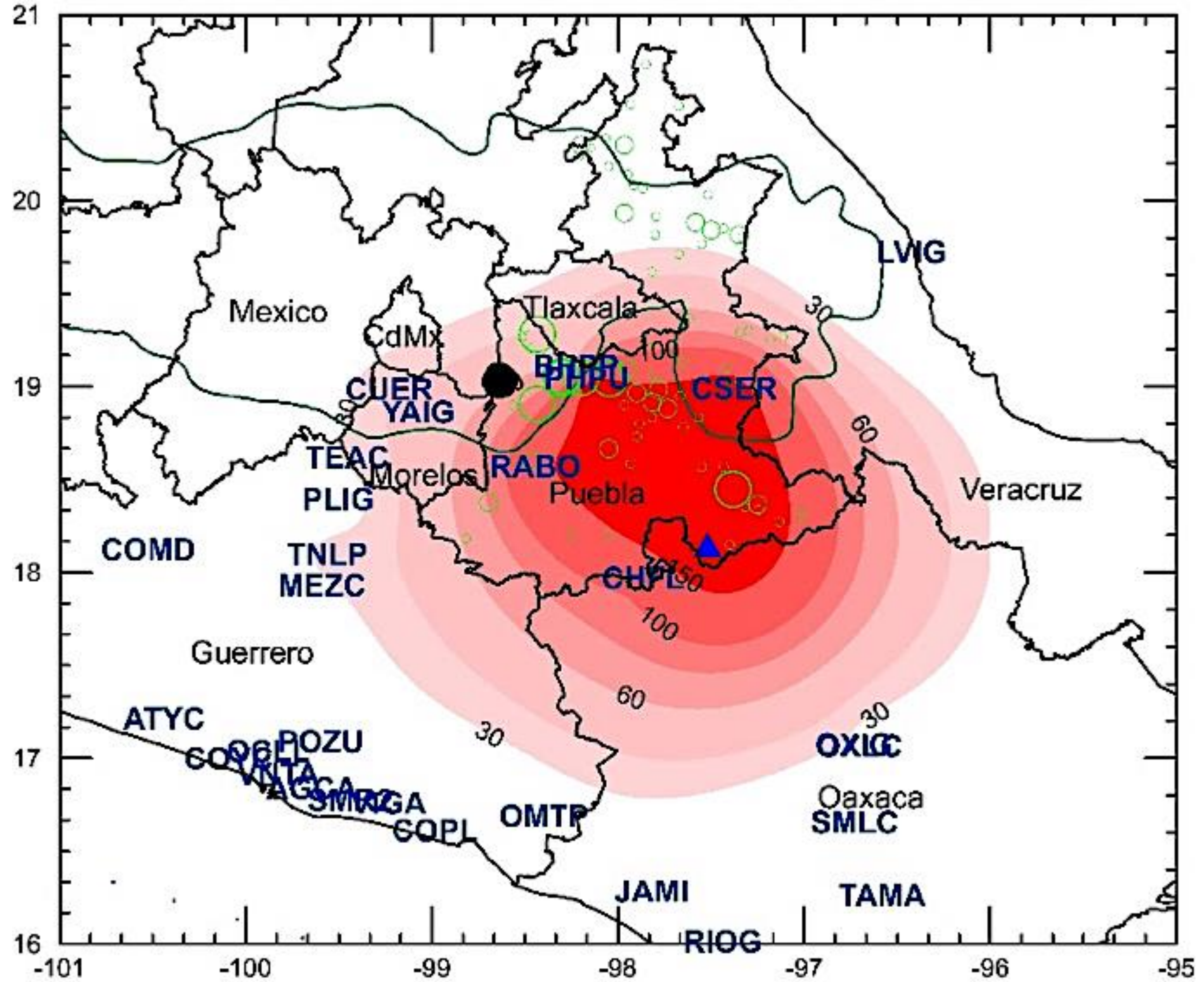

Figure 2. a) PGA contours during 1999 (Mw6.9) earthquake (top), and b) 2017 (Mw7.1) earthquake (bottom) in cm/s^2. Triangle: epicenter. Station code is given by letters and is plotted at its location. Black dot: Popocatepetl volcano. Green contour: Mexican Volcanic Belt. Large, medium and small green circles are towns in Puebla with population > 100,000, 50,000 - 100,000 and 15,000 - 50,000, respectively

2017

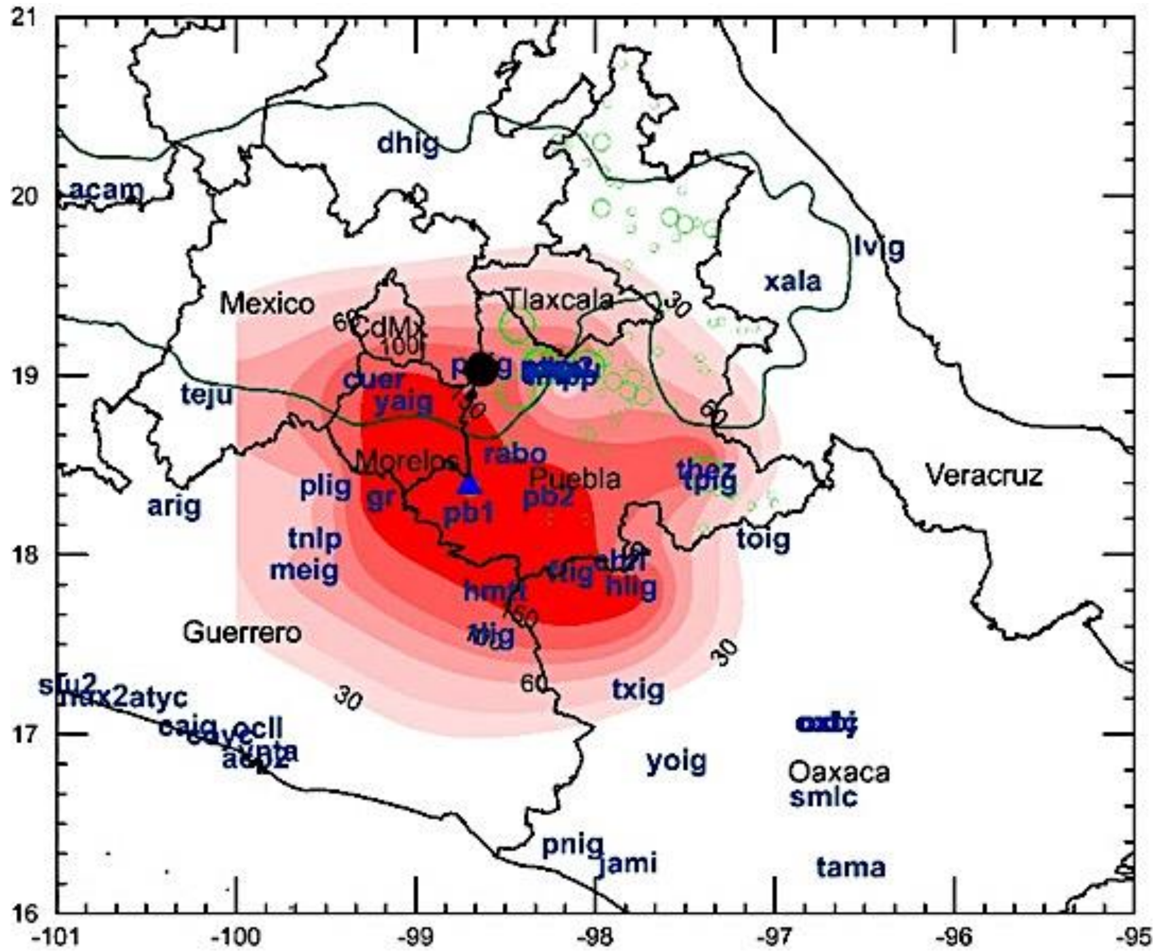

Figure 2 b)

Table 3. Percentage of total area and population under PGA contour of 150 cm/s^2 in different states in central Mexico during the 1999 and 2017 intraslab earthquakes. Total area under this contour was $1.27x10^4$ km^2 and $1.54x10^4$ km^2 during 1999 and 2017, respectively.

State/ area	Year	Population	% of total area under 150 cm/s^2 contour	Inhabitants under 150 cm/s^2 contour
Morelos / $4.96x10^3$ km^2	1999	-	0	0
	2017	$1.97x10^6$	24	$1.46x10^6$
Puebla / $3.429x10^4$ km^2	1999	$5.00\ x10^6$	84	$1.57x10^6$
	2017	$6.37\ x10^6$	45	$1.30x10^6$
Guerrero/$6.36x10^4$ km^2	1999	-	0	0
	2017	$3.65\ x10^6$	17	$1.23x10^5$
Oaxaca/$9.38x10^4$ km^2	1999	$3.44x10^6$	13	$6.05x10^4$
	2017	$4.10x10^6$	14	$9.42x10^4$
Veracruz/$7.28x10^4$ km^2	1999	$6.91x10^6$	3	$3.62x10^4$
	2017	-	0	0

Estimated number of persons living within PGA contour of 150 cm/s^2: $1.67x10^6$ in 1999 and $2.98x\ x10^6$ in 2017.

Seismic Intensities and Reported Damage

From the PGA contours shown in Figures 2 to 3, assuming uniform density of population and construction throughout the region, we expect:

a) Extensive damage in the State of Morelos in 2017 but little damage in 1999.

b) More damage in the State of Puebla and the city of Puebla during 1999 than in 2017.

c) Lesser damage to the south of the epicenter in 1999 but nearly equal damage to NW and SE of the epicenter in 2017.

d) Marginally more damage during 2017 than in 1999.

1999

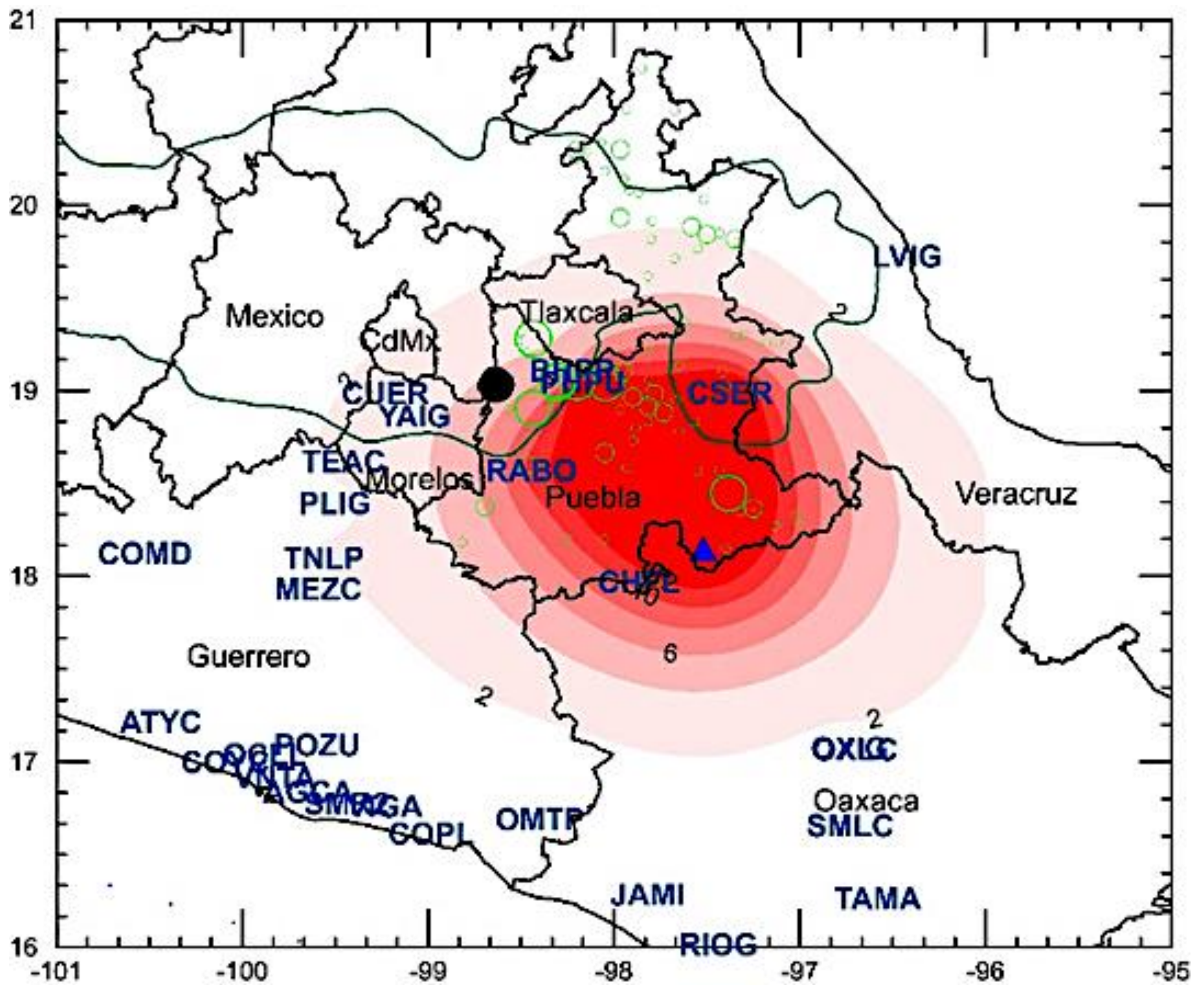

Figure 3. a) Same as Figure 2 but for PGV in cm/s

2017

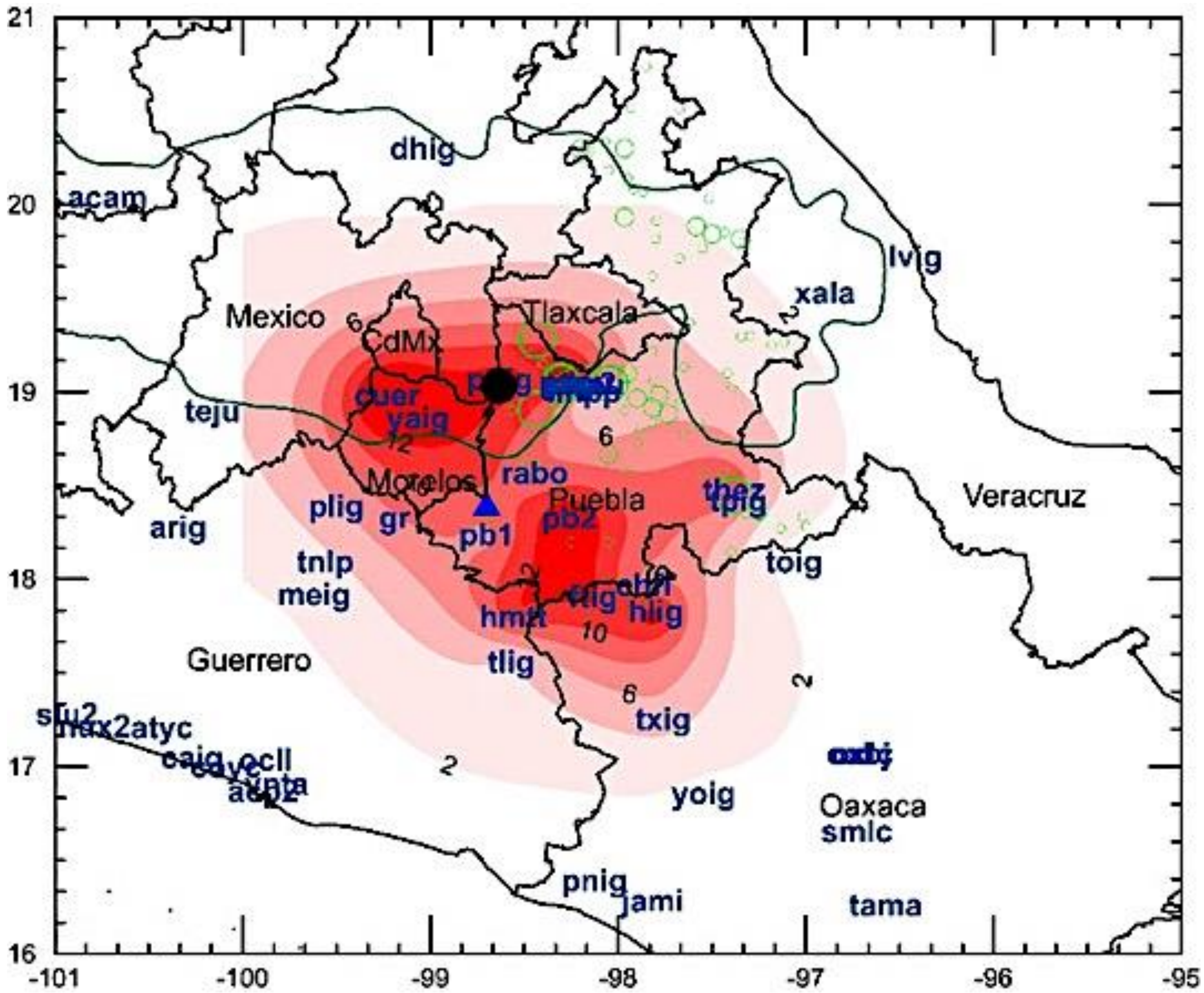

Figure 3) b)

A detailed description of the damage during the 1999 earthquake is given by Alcocer *et al.* (1999). Information on damage during 2017 in central Mexico has been compiled by E. Reinoso and his colleagues (personal communication, 2018). A preliminary estimation of damage to historical monuments is available to us (Secretaría de Cultura, 2018). The municipalities receiving funds for reconstruction from the government program for natural disasters (FONDEN) in 1999 and 2017 should, in principle, provide information on the damage. In 2017, the municipalities receiving funds, generally, fall within the PGA contour of 60 cm/s2 (Figure 4). However, the correlation between PGA and municipalities receiving funds from FONDEN during the 1999 earthquake is poor (Figure 4). This may be a consequence of the fact that FONDEN became operational in 1999. The criteria for assigning funds in 1999 may have been different from those in 2017.

1999

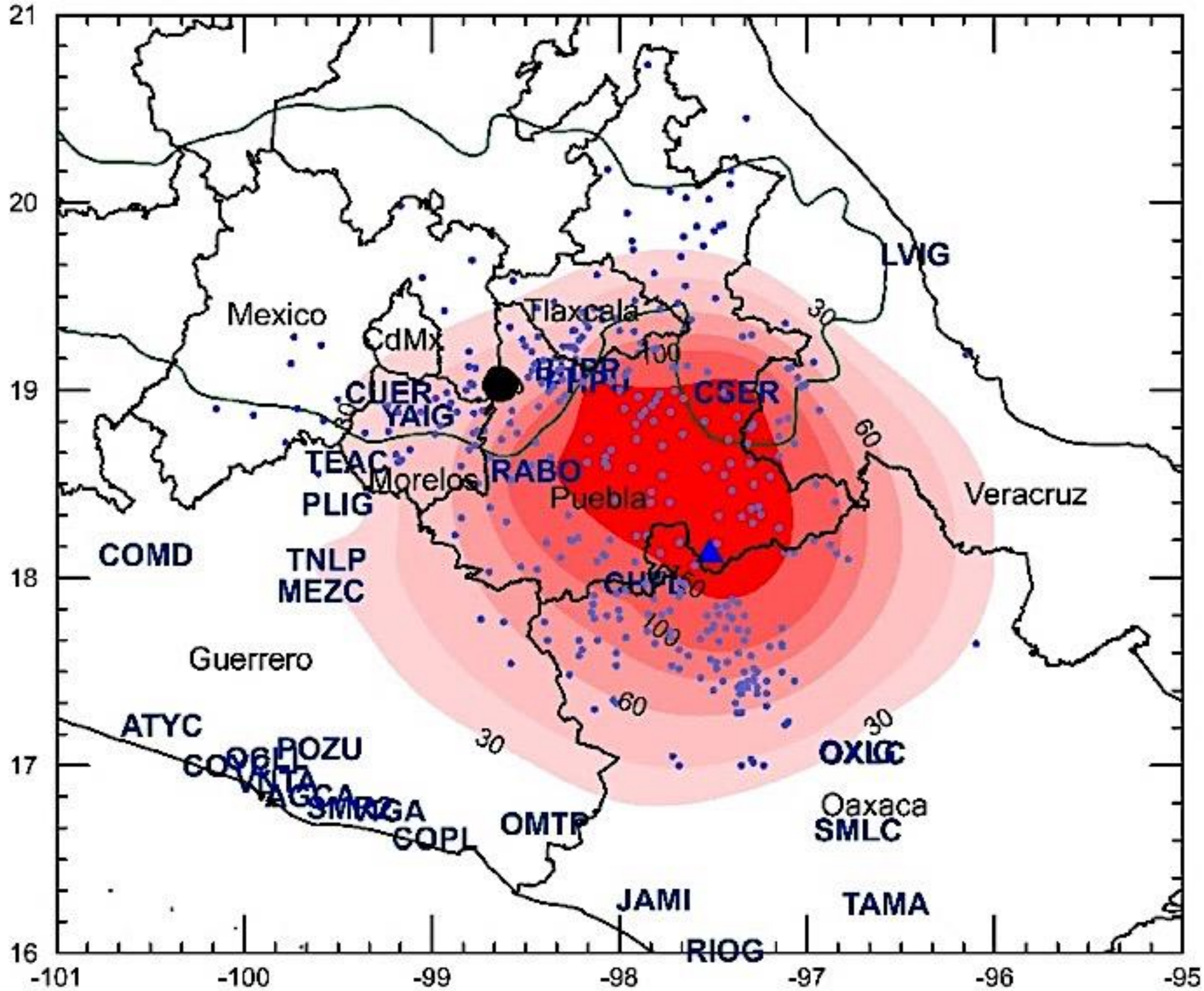

Figure 4. a) PGA contours in cm/s2 for 1999 (top) and b) 2017 (bottom) earthquakes and municipalities that received funds for reconstruction from FONDEN.

2017

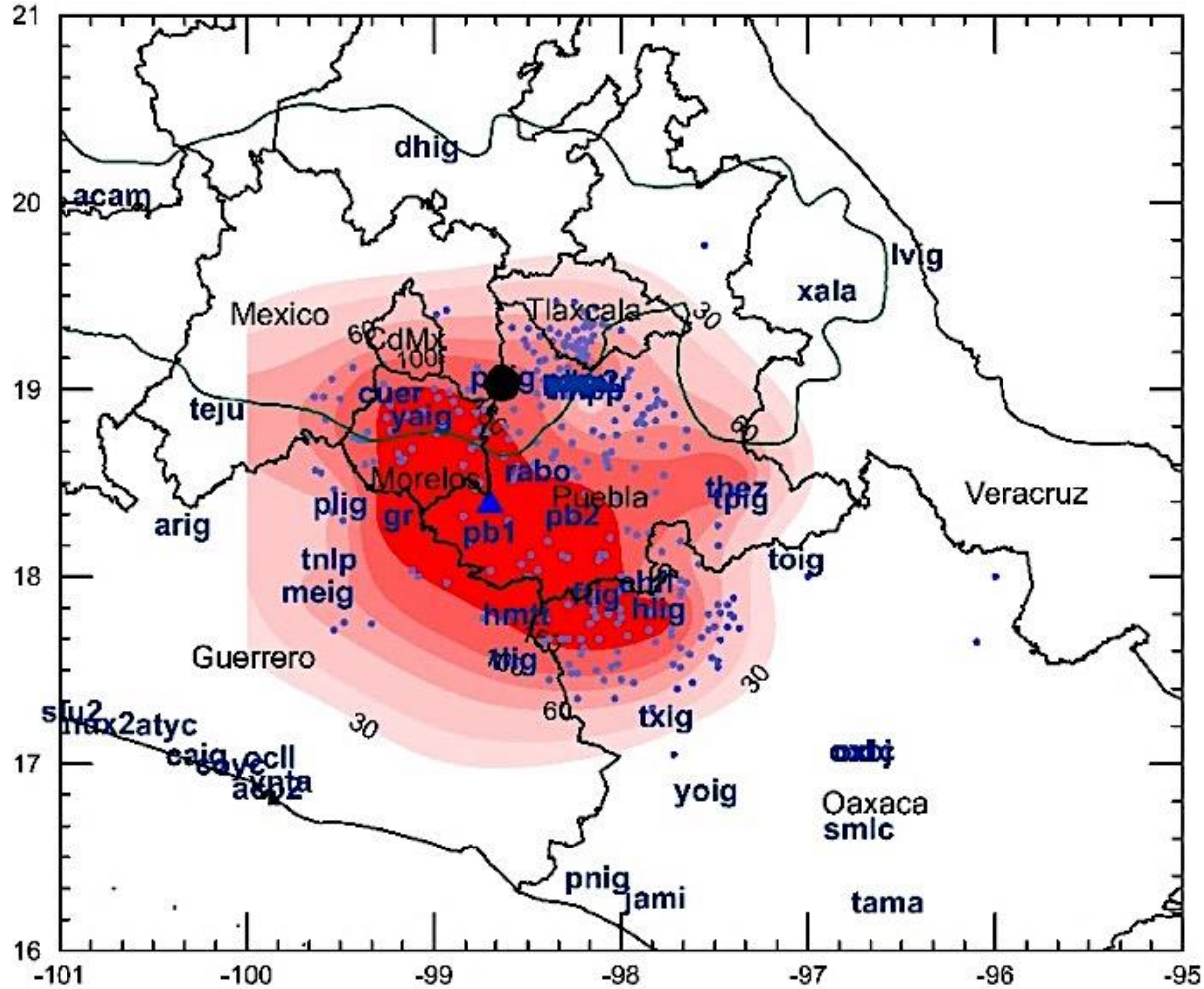

Figure 4. b)

Since the available damage reports during the two earthquakes were not elaborated using the same criteria, it is difficult to relate seismic intensity contours of the two earthquakes with ensuing reported damages. Even so, a rough comparison is possible. There were no fatalities reported in Morelos in 1999 (Alcocer *et al.*, 1999); in 2017 there were 74. Although 45 fatalities are reported in Puebla in 2017 and only 15 in 1999 (Alcocer *et al.*, 1999), it is generally accepted that the damage in the state was more severe in 1999 than in 2017. This is also in agreement with damage to historical monuments (churches, monasteries, and government buildings) during the two earthquakes. The 1999 and 2017 earthquakes caused damage to 1124 and 448 historical monuments, respectively (Secretaría de Cultura, 2018). Less damage to the south of the 1999 epicenter is partly supported by the geographical distribution of municipalities receiving funds from FONDEN (Figure 4).

If we assume that the area of severe damage is proportional to the area under the PGA contour of 150 cm/s2 then we expect only marginally more damage in 2017 than in 1999. Yet, there is consensus that the damage in 2017, even excluding Mexico City, was far greater than in 1999. One possibility is that the area of high seismic intensities in 2017 coincided with that of high density of population and historical monuments. Since areas under PGA and PGV contours during the two earthquakes are roughly similar, the difference in their source strength is unlikely to be the cause of much higher damage in 2017. Even so, we first explore, in more detail, the source characteristics of the two earthquakes and its effect on the damage pattern. We then return to distinct locations of the two earthquakes along with uneven density of population, dwellings and historical monuments, and demographic increase since 1999 as the principal causes of the difference in damage during the two earthquakes.

Possible Source Effect on Ground Motion and Damage Distribution

PGA and PGV values as function of minimum distance to the rupture area, R, during the 1999 and 2017 earthquakes are illustrated in Figure 5. The figure also includes predicted median values from the ground motion prediction equation by Garcia *et al.* (2005), henceforth called the G05 model. In general, PGA and PGV values are similar for the two earthquakes. G05 model fits well the PGA data but underestimates observed PGV, except for the 1999 earthquake at sites at R greater than about 200 km located to the south of the epicenter. We note that PGA and PGV for 2017 at sites north and south of the epicenter follow the same attenuation trend. During 1999, however, the PGA, but especially PGV values, are greater to the north and smaller to the south with respect to the trend. This is in agreement with bilateral and northward rupture propagation during 2017 and 1999 earthquakes, respectively, mentioned before. PGA at CU, a firm site in the UNAM campus, Mexico City, during the two earthquakes are in agreement with G05 model but PGV values are much higher than predicted by the model.

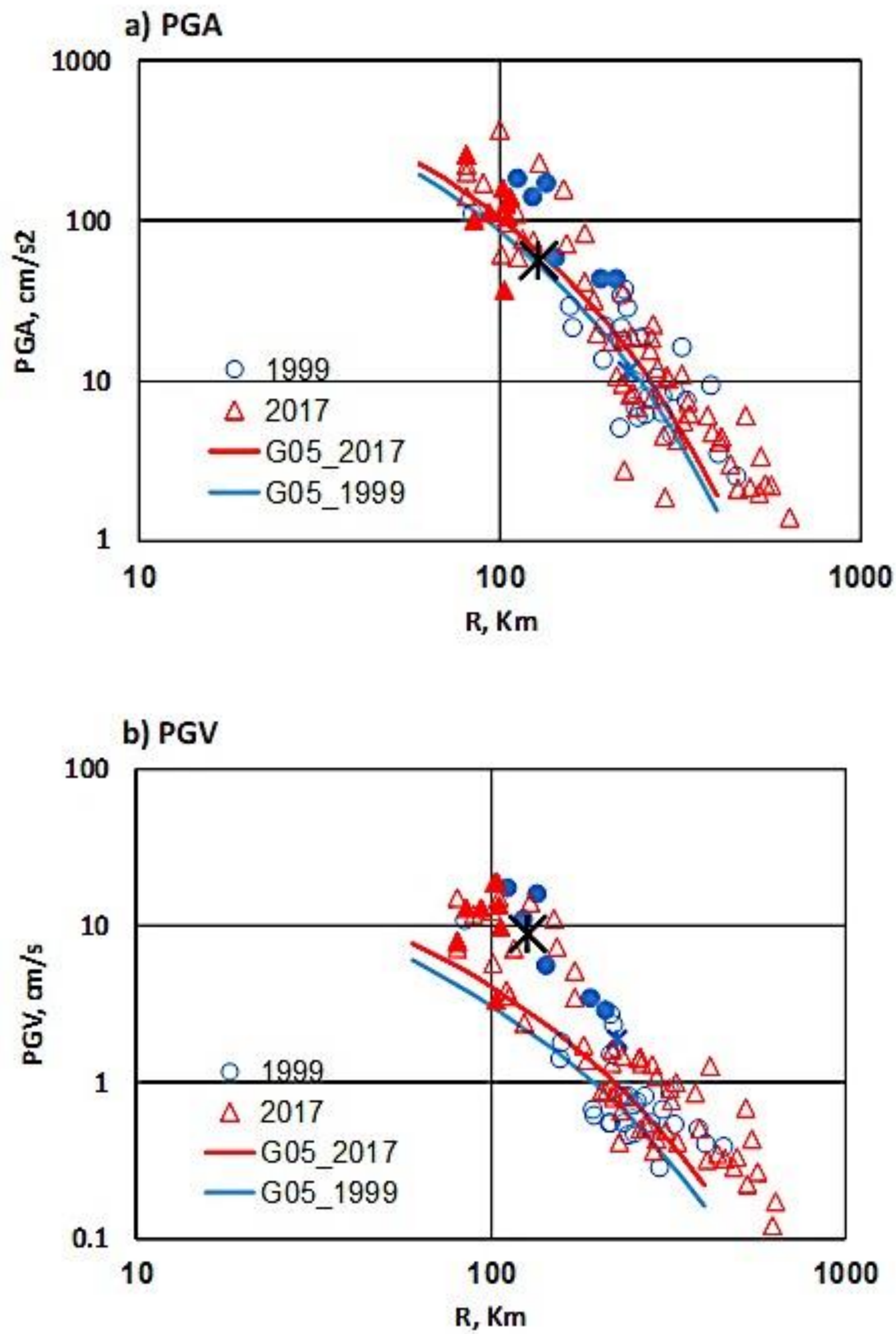

Figure 5. a) PGA and b) PGV during the 2017 and 1999 earthquakes as a function of minimum distance to the fault, R. The filled symbols are sites to the north of the epicenter and the star is CU station in Mexico City. G05: prediction from GMPE of García *et al.* (2005). Observed PGV is greater than G05 model prediction, except at sites south of the 1999 epicenter.

Several stations recorded the ground motion during both earthquakes. This permits a comparison of Fourier amplitude spectra of the two earthquakes and, hence, probe their relative source strength. For the comparison, we reduced the spectra of the 1999 earthquake to the same hypocentral distance as the 2017 earthquake by correcting for geometrical spreading, G(R), and quality factor, Q. Following García *et al.* (2004), we take G(R) = 1/R and Q=251f0.58. The geometric mean of two horizontal components of the reduced spectra are shown in Figure 6. The reduced spectra at sites PHPU, YAIG, RABO and PLIG are greater in 1999 than 2017 at frequencies close to 1 Hz. At CUER, the two reduced spectra are similar or somewhat smaller in 1999. At CHFL the reduced spectrum in 1999 is slightly smaller than in 2017. The spectra in Figure 6 are consistent with rupture propagation to the north in 1999.

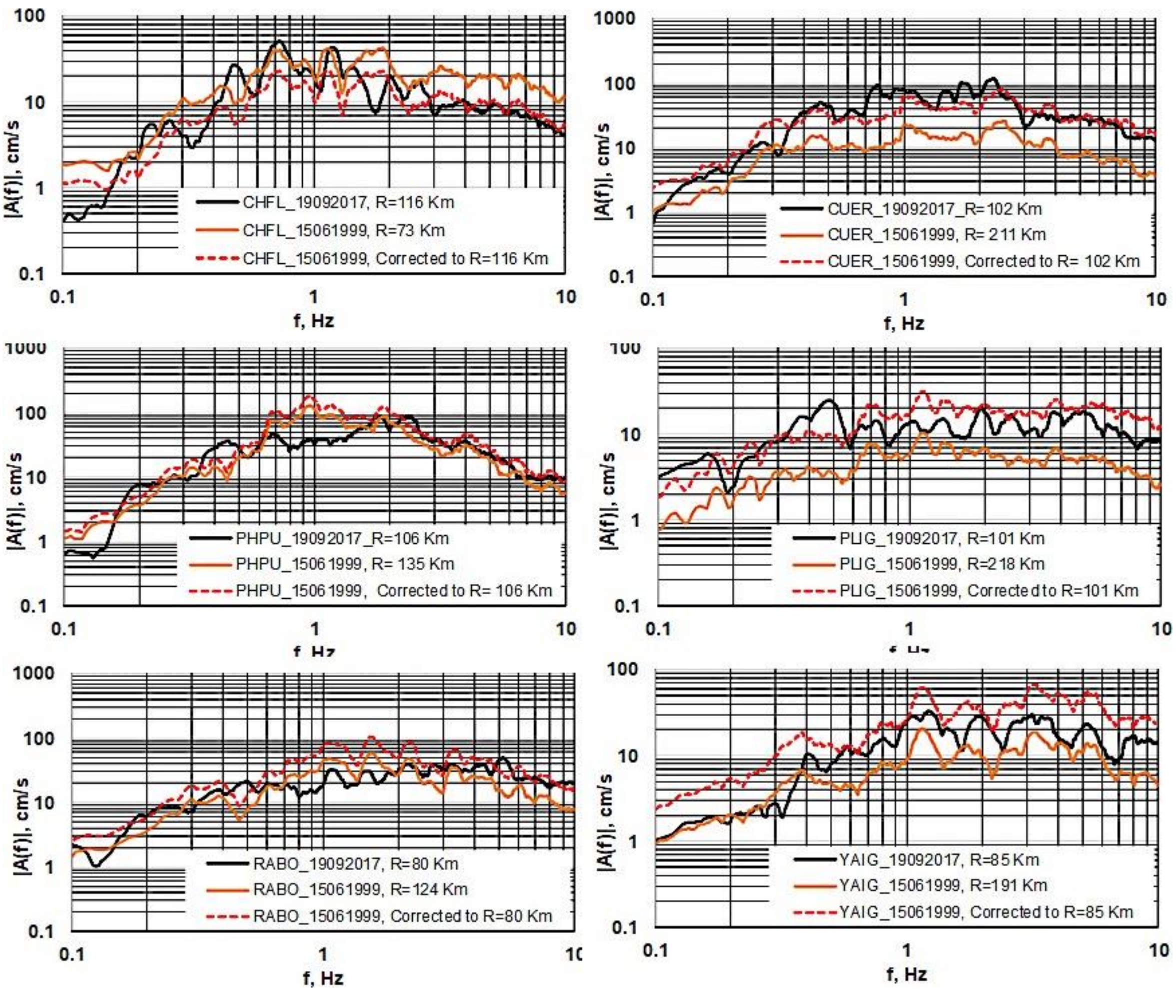

Figure 6. Fourier acceleration amplitude spectra at some stations that recorded the 2017 and 1999 earthquakes. The 1999 spectra, reduced to the same distance at which the 2017 earthquake was recorded by correcting them for geometrical spreading and anelastic attenuation, are also shown.

From the above, we expect the reduced 1999 spectrum at CU in Mexico City to be higher than the 2017 spectrum. Figure 7, however, shows just the opposite; the 2017 spectrum near 1 Hz is significantly higher than the 1999 spectrum. The reason, as discussed by Shapiro *et al.* (2002), is that the seismic waves from 1999 earthquake reaching CU traversed below the active

Popocatepetl Volcano and suffered high attenuation. During the 2017 earthquake the wave path to CU does not pass through the volcano (Figures 1, 2, and 3). A test of this hypothesis is provided by the 2017 recordings at DHIG and PNIG that are located at roughly the same distance (~ 230 km) from the epicenter (Figure 2). The path to DHIG, however, crosses the volcano. As expected, the spectrum at DHIG relative to PNIG is depleted at f > 0.8 Hz (Figure 8).

To summarize, we find that the 1999 source was more energetic to the north of the epicenter than the 2017 source. It follows that the significantly larger damage in central Mexico during 2017 as compared to 1999 can´t be attributed to the source. The 2017 earthquake produced severe damage to certain zones in Mexico City while the 1999 earthquake was only moderately felt. The difference in the damage can be attributed to the fact that the 2017 earthquake was closer to Mexico City (R=127 km) than the 1999 earthquake (R=226 km). High attenuation due to wave path crossing Popocatepetl during 1999 was also partly responsible. The 2017 earthquake occurred closer to more densely populated towns and cities of the State of Morelos than the 1999 earthquake. Next, we explore the effect of location of the earthquakes on the damage.

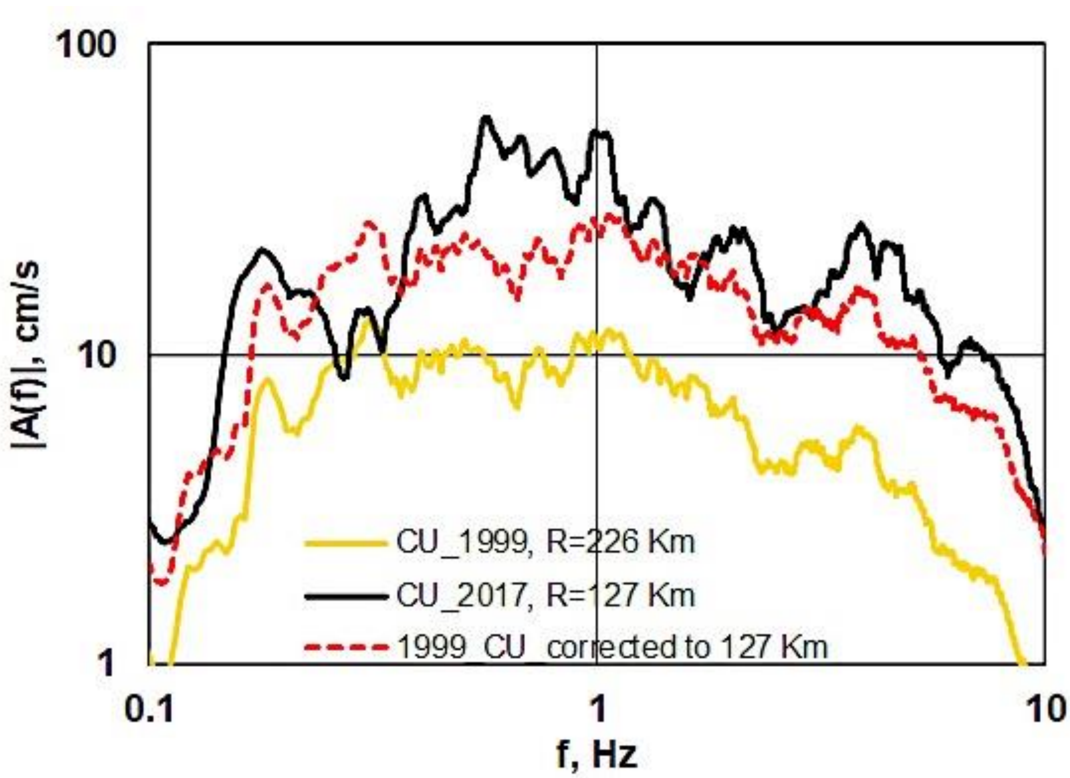

Figure 7. Fourier amplitude acceleration spectra at CU in Mexico City during the 2017 and 1999 earthquakes. The station is located at hill zone. The 1999 spectrum was corrected for geometrical spreading and anelastic attenuation to reduce it to the same distance at the which the 2017 earthquake was recorded.

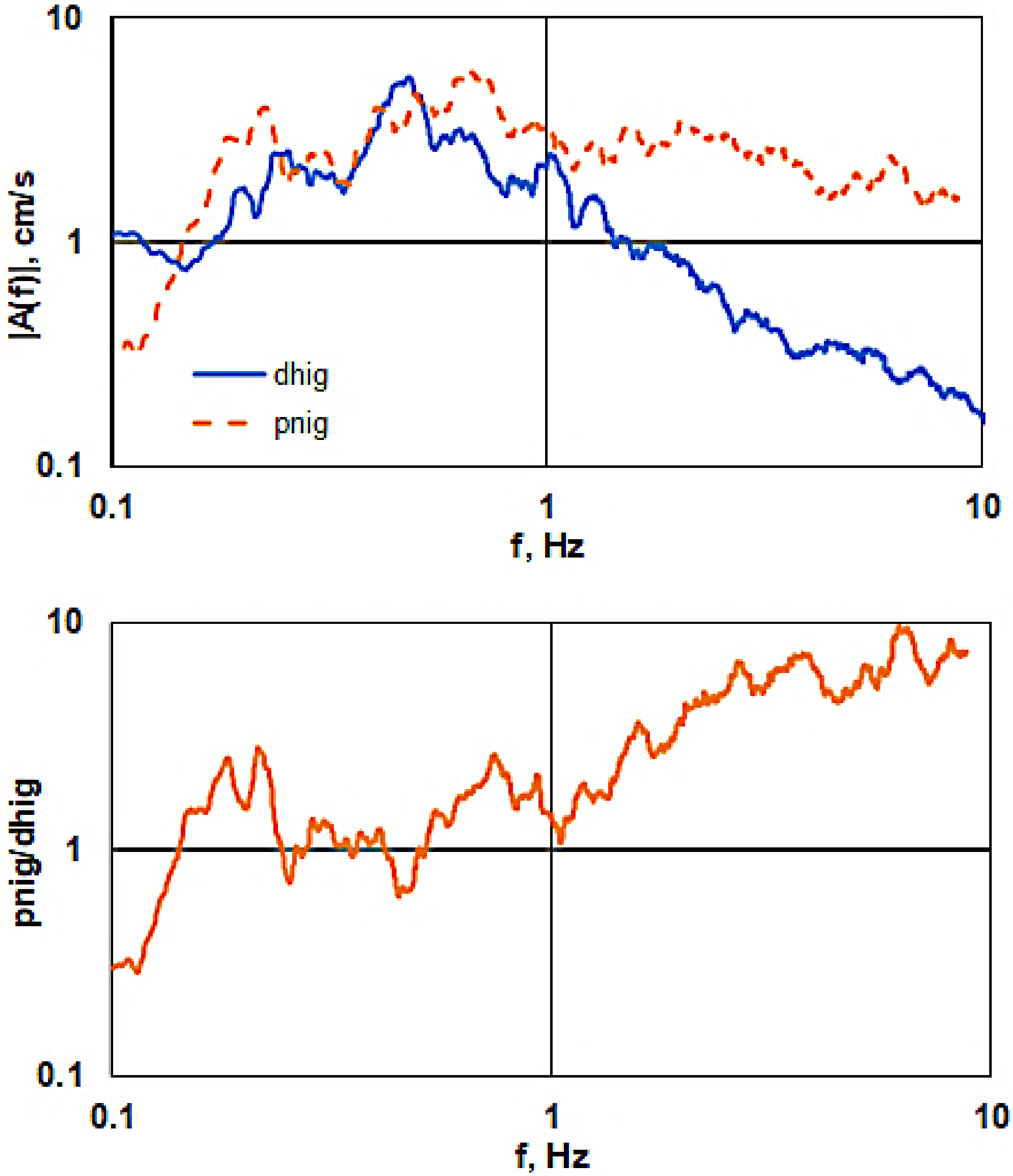

Figure 8. a) (Left) Fourier amplitude acceleration spectra at stations DHIG and PNIG during the 2017 earthquake (see Figure 1 for location of the stations). The stations are located at nearly the same hypocentral distance from the earthquake (~230 km). b) (Right) PNIG to DHIG spectral ratio.

Effect of Location of the 1999 and 2017 Earthquakes on the Damage in Central Mexico

We assume that the damage is proportional to the area enclosed in the PGA contour of 150 cm/s2. As mentioned earlier, these areas were 1.24x104 and 1.54x104 km2 during 1999 and 2017, respectively. The distribution of these areas in different states is given in Table 3, along with the total area and number of inhabitants of each state. A demographic increase of 1.65% per year has been assumed in the estimation of number of inhabitants. As given in the table, the total number of inhabitants within the PGA contour of 150 cm/s2 during 1999 and 2017 were ~ 1.67x106 and 2.98x106, respectively. These simple calculations suggest roughly two times more damage in 2017 as compared to 1999. Note that the affected number of inhabitants in 2017 in the states of Morelos and Puebla are 1.46x106 and 1.30x106, respectively. This implies only slightly higher damage in Morelos than in Puebla. E. Reinoso (personal communication, 2018), however, reports 1432 and 464 damaged structures in Morelos and Puebla, respectively. Clearly, our estimation of damage is over simplified. It, nevertheless, provides a gross overview of the damage.

Conclusions

From the analysis of strong-motion recordings during the 1999 and 2017 intraslab earthquakes in central Mexico, we conclude that: (1) The rupture during 1999 propagated towards north while the directivity was bilateral during 2017. (2) PGA and PGV contours during the two earthquakes had similar areas, suggesting roughly similar source strength. PGA and PGV as function of distance were also similar during the two earthquakes. However, PGV values during 1999 at stations to the south, in the direction away from rupture propagation, were, relatively, smaller. (3) The GMPE for Mexican intraslab earthquakes (García at al., 2005) predicts well the observed PGA during the two earthquakes but grossly under estimates PGV. (4) At a finer level, the 1999 source was somewhat more energetic to the north of the epicenter than that of 2017. (5) Path effect may significantly affect the ground motion and, hence, the damage pattern

In view of the above, we would have expected a similar level and pattern of damage during the two earthquakes or even larger damage to the north of the epicenter during the 1999 earthquake. In reality, the pattern and level of damage during the 2017 differ from those observed during the 1999 and the 2017 earthquake caused significantly more damage in central Mexico. This leads us to conclude that the distinct locations of the two earthquakes along with uneven density of population, dwellings, and historical monuments in the region, and the demographic increase since 1999 were the principal causes of the difference in damage during the two earthquakes. Changes in construction quality may also have played a role in the observed differences. Finally, path effect may significantly affect the ground motion and, hence, the damage pattern. This is especially true for waves traversing Popocatepetl volcano which greatly attenuates of high-frequency shear waves.

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