The 6 September 1997 (M_w 4.5) Coatzacoalcos-Minatitlán, Veracruz, Mexico earthquake: implications for tectonics and seismic hazard of the region

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Resumen

Analizamos el sismo del 6 de septiembre de 1997 (M_w 4.5), que se produjo a unos 25 km al SE de Coatzacoalcos, Veracruz. El sismo fue registrado por la estación local TUIG de banda ancha de (tiempo S-P = 5 s). Las polaridades de la onda P a distancias regionales y telesísmicas, y el modelado de las formas de onda de desplazamiento en TUIG sugieren un mecanismo focal inverso ($\phi = 150°$; $\delta = 70°$; $\lambda = 90°$). En la misma región ocurrió un sismo destructivo el 26 de agosto de 1959 (M_w 6.4), a una profundidad similar y con un mecanismo similar. El análisis del sismo de 1997 refuerza la conclusión anterior de que la corteza inferior bajo la cuenca del Coatzacoalcos-Minatitlán, está en un régimen de esfuerzos de fallamiento inverso, en contraste con la parte superficial de la corteza que se caracteriza por un fallamiento normal; esto implica una permutación con la profundidad de los esfuerzos principales máximo y mínimo. Esto está de acuerdo con las observaciones, en otros sitios, que el estado de esfuerzos en las cuencas sedimentarias pueden ser diferentes del que se tiene a mayor profundidad.

Mecanismos focales están disponibles para siete sismos en y cerca del Golfo de México. Todos estos eventos muestran en la región una corteza media y baja en un régimen de fallamiento inverso. La tendencia observada de los ejes P de estos sismos se puede explicar por una o más de las siguientes causas: acoplamiento fuerte a lo largo de la interfase de la placa en subducción fuera de la costa en Tehuantepec; el movimiento absoluto de la placa de América del Norte; y el hundimiento de la litosfera debido a la acumulación de la carga de los sedimentos.

Usamos los registros del sismo de 1997 como función de Green empírica para simular los movimientos de tierra en la región epicentral de un sismo de M_w 6.4 postulado en la cuenca Comalcalco. Bajo supuestos razonables, los valores esperados de aceleración, velocidad y desplazamiento picos son 120-260 gales, 12 a 28 cm/s, y 6 a 11 cm, respectivamente. La extensa licuefacción reportada en Coatzacoalcos durante el sismo de 1959, M_w 6.4, sugiere que los sedimentos de la cuenca se comportan de manera no lineal bajo tal excitación.

Palabras clave: Sismo de Jáltipan, movimientos fuertes, tectónica del Golfo de México, peligro sísmico del Golfo de México.

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Abstract

We analyze the 6 September 1997 M_w4.5 earthquake, which occurred about 25 km SE of Coatzacoalcos, Veracruz. The earthquake was recorded by the local broadband station TUIG (S-P time = 5 s). P-wave polarities at regional and teleseismic distances and modeling of the displacement waveforms at TUIG yields a thrust-faulting focal mechanism (ϕ = 150º; δ = 70º; λ = 90º). In the same region a destructive M_w6.4 earthquake occurred on 26 August 1959 at a similar depth and with a similar mechanism. The analysis of the 1997 event reinforces a previous conclusion that the lower crust beneath the Comalcalco basin is in a thrust-faulting stress regime, in contrast to the shallow part of the crust, which is characterized by normal-faulting; this implies a permutation with depth of the maximum and minimum principal stresses. It agrees with observations elsewhere that the state of stress in sedimentary basins can be different from the one at greater depth.

Focal mechanisms are available for seven earthquakes in and near the Gulf of Mexico. All of these events indicate a thrust-faulting type stress regime at mid- and lower-crustal levels. The observed trend of the P axes of these earthquakes can be explained by one or more of the following causes: strong coupling along the subduction plate interface offshore Tehuantepec; absolute motion of the North American plate; and downwarping of the lithosphere due to sediment loading.

By using the recordings of the 1997 event as empirical Green's function, we simulate the ground motions in the epicentral region of a postulated M_w6.4 earthquake in the Comalcalco basin. Under reasonable assumptions, the expected peak acceletion, velocity and displacement are 120-260 gal, 12-28 cm/s, and 6-11 cm, respectively. The extensive soil liquefaction in Coatzacoalcos during the 1959, M_w6.4, earthquake suggests that the sediments of the basin behave nonlinearly under such excitation.

Key words: Jáltipan earthquake, strong motion, tectonic of the Gulf of México, seismic hazards of the Gulf of México

Introduction

A detailed analysis of the M_w4.5 earthquake of 6 September 1997, which occurred near Coatzacoalcos-Minatitlán, Veracruz, is of interest for three reasons. First, the surface and the near-surface information from volcanic alignments, borehole elongations, and unpublished PEMEX seismic sections points to active normal-faulting in the region (Suter, 1991). The focal mechanism of an earthquake which occurred nearby on 26 August 1959 (M_w6.4), however, shows thrust faulting at a depth of about 26 km (Wickens and Hodgson, 1967; Suárez, 2000; see Figure 1). It is, therefore, of interest to know whether the 1997 earthquake confirms such a change in the stress regime (permutation of the least and maximum principal stresses) with depth in the region. In most regions, the stress regime at relatively shallow depth agrees with that at mid-crustal depth. There are some exceptions (see, e.g., Zoback and Zoback, 1991) and one such exception appears to be the coastal plain of the Gulf of Mexico (Frohlich, 1982; Zoback and Zoback, 1991; Suter, 1991). Another classical example is the decoupling of the stress field across the basal detachment of the Jura fold-thrust belt; the near-surface stress field is different from that in the basement (Becker *et al*., 1987).

Second, the earthquake of 26 August 1959 caused serious damage to the towns of Jáltipan, Coatzacoalcos, and Minatitlán (Figueroa, 1964; Rosenblueth, 1964; Reséndiz, 1964). The latter two towns have become important industrial centers related to the intense activity of PEMEX, the national petroleum company, and population has grown by 22% in the last 10 years to reach more than half million people (INEGI, 2010). For this reason, it is important to estimate ground motions that may be expected in these towns if an earthquake, such as that of 1959, were to recur in the region. We may use the records of the 1997 earthquakes obtained at the near-source broadband station of TUIG as empirical Green's function to simulate the corresponding motions from an M_w6.4 event. Although the station is about 25 km SE of Coatzacoalcos-Minatitlán, the geology of these sites is roughly similar; to a first approximation, the results for the TUIG site may be valid for the entire region in case of an earthquake at about the same focal distance from TUIG as the event of 1997.

Finally, a study of the 1997 earthquake (and other events in and along the Gulf of Mexico) has an important bearing on the seismic safety of the Laguna Verde nuclear power plant (Figure 1) as well as the hydrocarbon exploration and production facilities in this region.

Figure 1. Earthquakes in and near Gulf of Mexico with known focal mechanism. Source parameters of the events are listed in Table 2. Focal mechanisms show that the mid- and lower crust of the Gulf is under compressive stress regime. Dotted lines indicate the bathymetry of the Gulf and gray dashed lines denote the limits of the buried salt deposits. LVPP = Laguna Verde Power Plant. Triangle shows location of station TUIG.
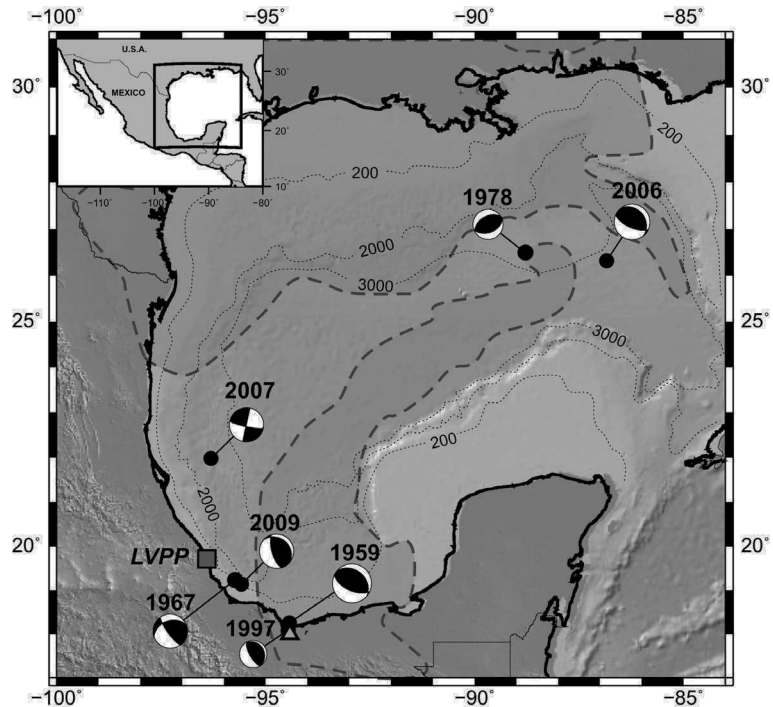

Data and analysis

The 1997 earthquake was recorded by the local broadband station TUIG (S-P time = 5 s) and by seven other broadband stations of the National Seismological Service (SSN), which were located at epicentral distances greater than 260 km. The reported coda-wave magnitude, M_c, is 4.3. The epicenter of the event, given by the SSN, is 18.146 ºN and 94.499 ºW. However, its focal depth could not be constrained. The epicenter and focal depth reported by the National Earthquake Information Center (NEIC), U.S. Geological Survey, are 18.017 ºN and 94.396 ºW and 33 km, respectively. This depth was fixed by NEIC in the location of the earthquake.

For moderate Mexican earthquakes it is now possible to obtain a regional centroid moment tensor (CMT) solution using relatively long-period regional waveforms (see, e.g., Pacheco and Singh, 1998). Unfortunately, the seismograms of the 1997 earthquake show little energy at periods greater than 10 s because of its relatively small magnitude. At shorter periods, a detailed three-dimensional crustal structure is needed to model the observed seismograms but is currently lacking for the region. For these reasons it was not possible to obtain a CMT solution by inverting the regional waveforms.

A single, near-source, three-component broadband recording can be used to find a reliable location, origin time, and focal mechanism of an earthquake, provided that a rough initial guess of the mechanism is available from other data (see, e.g., Kanamori *et al.*, 1990; Singh *et al.*, 1997, 2000a). The calculation of the location and origin time requires clear first arrivals on each of the three components of the ground motion as well as the knowledge of the local crustal structure. Figure 2 shows acceleration, velocity and displacement traces at TUIG during the 6 September 1997 earthquake. Figure 3 illustrates the initial part of the three components of displacement at TUIG. Note that the horizontal components have been amplified by a factor of 20. The incidence of initial P-wave at the station is nearly vertical. Nevertheless, it can be seen that the station is located in the NW quadrant with respect to the source. The amplitude towards west at time 0.172 s is 3.5 times that towards north. It follows that the station azimuth, ϕ_s, is 286º. Before proceeding further with the analysis of the source parameters of this earthquake, we summarize our knowledge of the local crustal structure.

Crustal structure of the region

The P-wave speed, α, in the shallow crust south and near Coatzacoalcos is available from
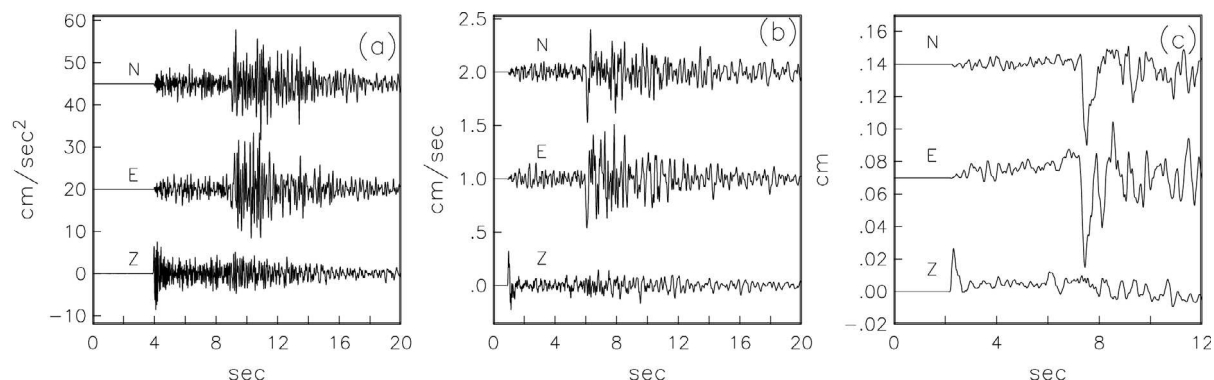
Figure 2. Seismograms at station TUIG during the 6 September 1997 earthquake. (a) Acceleration, (b) velocity, and (c) displacement. The traces in (b) and (c) have been obtained by integration of the accelerograms shown in (a).
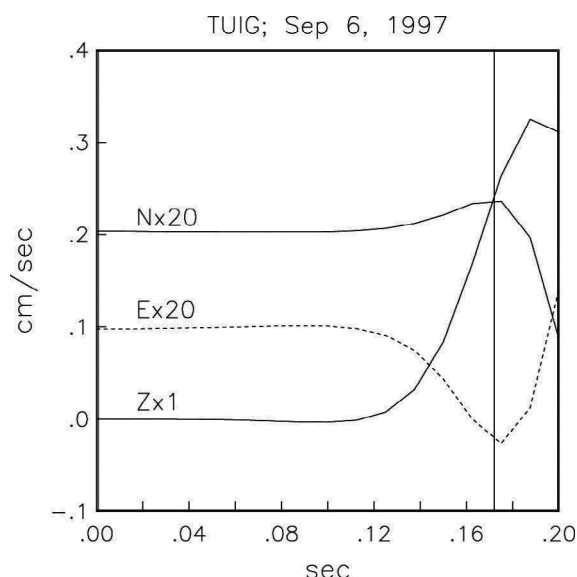
Figure 3. Initial part of the three components of displacement at TUIG. The horizontal components have been multiplied by 20.

exploration seismology carried out by PEMEX (A. Camargo, personal communication, 1997). The crust consists of a 1.8 km thick layer with α = 2.5 km/s, overlying a layer of α = 4.25 km/s. The thickness of the second layer exceeds 3.4 km, the maximum depth reached by boreholes.

Based on receiver function analysis, Cruz-Atienza (2000) reports sediment thickness of 16 km below TUIG. N. Shapiro (unpublished report) inverted group velocity dispersion curve corresponding to the region between the City of Oaxaca and TUIG. In the inversion, Shapiro fixed the thickness of the first layer and α values of the first and the second layers to the values given by PEMEX. The shear-wave speeds, β, of the first and second layers were taken as 1.4 km/s and 2.4 km/s, respectively. The crustal model adopted from the results of Cruz-Atienza (2000) and N. Shapiro, and used by us in generating synthetic seismograms, is given in Table 1. In this table, the densities and the quality factors, Q, of the layers have been taken arbitrarily; the results are not very sensitive to their choices.

Source parameters of the earthquake

Based on the crustal model in Table 1 and the (S-P) time of 5 s at station TUIG, the maximum depth of the earthquake, Hmax, assuming the station to be located directly above the focus, is 30.9 km. If the thickness of the second layer in Table 1 is taken as 10 km, then Hmax becomes 34.8 km. Near-vertical incidence at TUIG may be a consequence of both small epicentral distance as compared to the source depth, and refraction of waves caused by progressively lower seismic speeds near the surface.

Table 1. Crustal model near Coatzacoalcos used in the synthesis of ground motion.

Layer	Thickness km	P-wave speed α, km/s	S-wave speed β, km/s	Density gm/cm³	Quality Factor Q_α	Q_β
1	1.8	2.80	1.40	2.70	80	40
2	15.6	4.25	2.40	2.80	300	200
3	∞	6.50	3.75	2.85	400	300

Figure 4, top, shows P-wave first-motion polarities at those Mexican and teleseismic stations where they could be read unequivocally. These data suggest a thrust-faulting earthquake with possible strike-slip component. The first motion polarities provide some constrains on the azimuth ($140º \leq \phi \leq 190º$) and the dip ($45º \leq \delta \leq 85º$) of one of the nodal planes but the rake, λ, of this plane can vary between $35º$ and $120º$. To determine the focal mechanism, we performed a waveform inversion of the displacement traces recorded at TUIG. For the inversion the event was approximated by a point-source shear dislocation. Synthetic seismograms include near- and intermediate-field contributions (Singh *et al.*, 2000a). The effect of the free surface is approximately taken into account by multiplying the infinite-space synthetics by two. This approximation is acceptable if the epicentral distance, Δ, is smaller than the depth, H. We took the station azimuth, ϕ_s, as $286º$, the take-off angle from the source, i_h, as $170º$, and the angle of incidence at the surface, i_O, as $5º$ from the vertical. Based on the observed P-pulse on the Z-component (Figure 2c), we chose a triangular source with duration, τ, of 0.38 s. We varied the azimuth, dip, and rake within the ranges mentioned above. No contradiction of the first motion polarities was allowed. The two nodal planes obtained from the inversion are: $\phi = 150º$; $\delta = 70º$; $\lambda = 90º$ and $\phi = 330º$; $\delta = 20º$; $\lambda = 90º$. The observed and synthetic seismograms are shown in the bottom left of Figure 4.

We generated synthetic seismograms corresponding to this focal mechanism and the crustal model given in Table 1. Bouchon's (1982) discrete wave number algorithm was used in the computation. We again took $\phi_s = 286º$ and $\tau = 0.38$ s. A good fit between observed and synthetic seismograms at TUIG was found for an epicentral distance of 7 km, a depth of 30 km, and $M_0 = 6.0 \times 10^{15}$ N-m ($M_w 4.5$) (Figure 4, bottom right). Table 2 summarizes the relevant source parameters of this earthquake.
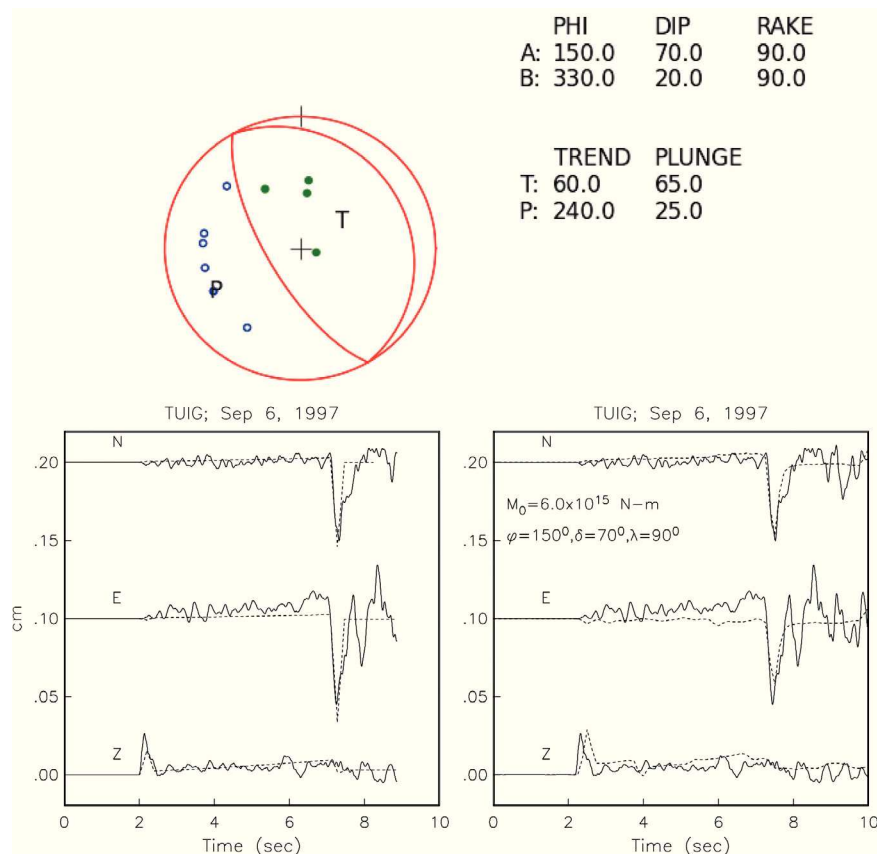
Figure 4. (Top) *P*-wave first motions of the 1997 earthquake plotted on lower-hemisphere, equal-area projection. With the exception of TUIG, all Mexican broadband stations recorded dilatation (open circles). Three teleseismic stations and TUIG show compression (solid circles). Focal mechanism, $\phi = 150º$; $\delta = 70º$; $\lambda = 90º$, which satisfies first-motion data, and the waveform at TUIG is shown. (Bottom, left) Comparison of observed and infinite-space synthetic seismograms at station TUIG. (Bottom, right) Comparison of observed and synthetic seismograms at station TUIG. Synthetics were computed using crustal model and focal parameters given in Tables 1 and 2, respectively.

Stress regime of the Gulf coast region of Coatzacoalcos-Minatitlán

In spite of some uncertainty in its focal mechanism, there is no doubt that the 1997 earthquake was a thrust event with, probably, some strike-slip component. Its source was below the Comalcalco basin at a depth of about 30 km. As mentioned earlier, the surface and the near-surface information from volcanic alignments, borehole elongations, and unpublished PEMEX seismic sections in the Gulf coast basin region of Coatzacoalcos-Minatitlán suggest active normal-faulting in the upper few kilometers (Suter, 1991). Thus, there is a change of stress regime from extension in the sediments of the upper crust to shortening in the mid- and lower crust indicated by focal mechanisms (Figure 1). A similar change of stress regime with depth is reported in the central Gulf of Mexico by Frohlich (1982) from an analysis of an earthquake in 1978 at the edge of the Mississippi Fan at a depth of 15 km (Figure 1). Other cases of stress change below sedimentary basins are discussed in Zoback and Zoback (1991). Extension in upper part of crust is probably controlled by gravitational load and major topographic gradient, at least in the adjacent Veracruz basin.

Table 2 lists seven intraplate earthquakes located in and near the Gulf of Mexico with known focal mechanisms. It includes the earthquakes of 1978 and 1997. The locations of these events and their focal mechanisms are illustrated in Figure 1. For the earthquakes of 2007 and 2009, more than one solution is available (Table 2). For these two earthquakes, the Global CMT location and focal mechanism is shown. As most intraplate regions, the Gulf is characterized by thrust-type stress regime (Zoback et al., 1989). The orientations of the P-axes of the 1959, 1967, 2006, 2007 and 2009 earthquakes range between N30ºE and N65ºE. These are consistent with reported offshore stress orientations near the same region, inferred from breakouts (Zoback et al., 1990; Suter, 1991; World Stress Map, http://dc-app3-14.gfz-potsdam.de/, 12 May 2015). These orientations fall between the directions of: (1) the relative convergence of the Cocos and North American plates and (2) the absolute motion of the North American plate. Perhaps both the relative convergence and the absolute motion are responsible for the observed P-axis, with the former playing a more dominant role for events in and near the SSW Gulf due to their relative proximity to the middle America subduction zone (earthquakes of 1959, 1967, 1997, and 2009) and the latter being dominant for the events of 2006 and 2007 which are relatively far from the plate boundary. For the 2006 earthquake, sliding of Sigsbee salt and landslide have also been suggested as possible causes (Nettles, 2007; Franco et al., 2013).

Table 2. Source parameters of earthquakes in and near Gulf of Mexico.

No.	Date	Latitude ºN	Longitude ºW	Depth km	M_w	Focal Mechanism ϕ'º	δ'º	λ'º
1[a]	26 Aug 1959	18.26	94.43	21	6.4	309	32	102
2[b]	11 Mar 1967	19.23	95.74	26	5.7	250	39	20
3[c]	24 Jul 1978	26.49	88.79	15	5.0	225	49	111
						240	63	52
4[d]	06 Sep 1997	18.08	94.47	30	4.5	330	20	90
5[e]	10 Sep 2006	26.32	86.84	30	5.9	324	28	117
6[e]	23 May 2007	21.98	96.31	24	5.6	102	80	-1
		(22.02	96.27	11	5.6	95	71	-16)[f]
		(21.98	96.14	44	5.5	106	83	8)[g]
7[e]	29 Oct 2009	19.14	95.58	17	5.7	310	25	59
		(18.95	95.69	16	5.4	288	26	4)[g]

[a] Location from International Seismological Summary, ISS; depth, focal mechanism, and M_w from Suárez (2000).

[b] Location from International Seismological Centre, ISC; depth, focal mechanism, and M_w from Suárez (2000).

[c] Location, depth, and focal mechanism from Frohlich (1982). The two mechanisms are extreme types consistent with first-motion data.

[d] This study.

[e] Global Centroid Moment Tensor (CMT) catalog.

[f] Source parameters listed in http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20070523190916/index.html

[g] Franco et al. (2013)

Dewey and Suárez (1991) and Suárez (2000) suggest that the intraplate, mid- and lower-crust compression below the Comalcalco basin, as revealed by the 1959 and 1967 earthquakes, may be a consequence of strong coupling along the plate interface where the Tehuantepec ridge subducts below Mexico. This may also be true for the 1997 and 2009 earthquakes. If so, then, unlike subduction of many other ridges (Kelleher and McCann, 1976), the Tehuantepec ridge does not subduct aseismically. Since there is no clear evidence for major/great earthquakes in the Tehuantepec region during the last two centuries (see, e.g., Singh *et al*., 1981), it could mean that the recurrence period of such events in this segment is much greater than in other segments along the Mexican subduction zones where it is ~ 30 to 75 years (Singh *et al*., 1981; Astiz and Kanamori, 1984).

As for the 1978 Mississippi Fan earthquake (Figure 1), the P-axis does not follow the trend of the other events. The compressional nature of this earthquake was interpreted by Frohlich (1982) as a consequence of downwarping of the lithosphere due to sediment accumulation.

Expected ground motions in the Coatzacoalcos-Minatitlán region from a postulated M_w6.4 earthquake

The earthquake of 1959 destroyed a majority of the dwellings in the town of Jáltipan (Rosenblueth, 1964). Many buildings suffered structural or foundation failures in Coatzacoalcos and Minatitlán (Marsal, 1961; Reséndiz, 1964). The land near the port of Coatzacoalcos subsided. Some of the effects of the earthquake were attributed to partial liquefaction of sand and silt (Marsal, 1961). Modified Mercalli (MM) intensities in these towns during this earthquake were VIII (Figueroa, 1964). The 1959 earthquake was not an isolated event. The epicenter of the earthquake of 11 January, 1946 was apparently close to that of 1959 (Figueroa, 1964). The earthquake of 1946 was assigned a magnitude of 6.0 (Figueroa, 1970) and a MM intensity of VII in Coatzacoalcos (Figueroa, 1964). The towns of Coatzacoalcos and Minatitlán are now important centers of national petroleum activity. Thus, it is of significant earthquake engineering interest to estimate the ground motions in these towns during a future local M_w6.4 earthquake.

To estimate the ground motions from an M_w6.4 earthquake, we used the recording of 1997 earthquake as an empirical Green's function (EGF) and a method proposed by Ordaz *et al*. (1995) which is based on adding N scaled EGF records, each differed in time by a random delay. The probability distribution of the delays is such that, on average, the simulations follow an ω^2-spectral scaling at all frequencies. The method requires specification of the seismic moment, M_0, and the stress drop, $\Delta\sigma$, of both the EGF and the target earthquake. In our case, M_0 of the EGF is 6×10^{15} N-m and that of the target event is 5×10^{18} N-m (M_w6.4). A rough estimate of the static stress drop of the EGF can be obtained from the following considerations. For a circular rupture, the radius, a, of the fault can be estimated by (Boatwright, 1980):

$$a = (v\,\tau_{1/2})/(1 - v\sin\theta/c), \qquad (1)$$

where $\tau_{1/2}$ is the rise time of the far-field pulse, v is the rupture speed, c is the wave speed, and θ is the take-off angle measured from fault normal. For this event, $\tau_{1/2}$ is about 0.19 s (Table 2, Figure 2c). For S wave, $c = \beta$, which we take as 3.75 km/s (Table 1). Assuming $\phi = 330^\circ$; $\delta = 20^\circ$; $\lambda = 90^\circ$ as the fault plane and $i_h =170^\circ$, θ is ~10°. For $v = 0.9\beta$, we obtain a fault radius $a = 0.76$ km (equation 1). For a circular fault, $\Delta\sigma$ is related to M_0 and a by (Keilis-Borok, 1959):

$$\Delta\sigma = (7/16)(M_0)/a^3, \qquad (2)$$

which gives $\Delta\sigma$ of ~ 6 MPa for the EGF. In the simulations, we take $\Delta\sigma$ of the EGF and the target event to be either 6 MPa or 12 MPa. Typical simulated acceleration, velocity, and displacement traces, corresponding to $\Delta\sigma = 6$ MPa for both events, are illustrated in Figure 5. In the figure, we compare deterministic, synthetic displacement seismograms with ones obtained by random summation of EGF. The synthetics were generated at TUIG for an event with $M_0 = 5\times10^{18}$ N-m (M_w6.4), located at the same focus as the 1997 earthquake, and having the same focal mechanism. The duration of the source time function, τ, of Mexican earthquakes is related to their seismic moment by

$$M_0 = (6.7\times10^{16})\tau^s \qquad (3)$$

(Singh *et al*., 2000b). Thus, the estimated τ for the target event is 4.2 s. A point source with a triangular source-time function of 4.2 s duration and the crustal structure given in Table 1 were taken for the computation. The *PGD* values are within a factor of two of each other. Both calculations show important near-field contribution (the ramp-like wave between P and S wave).
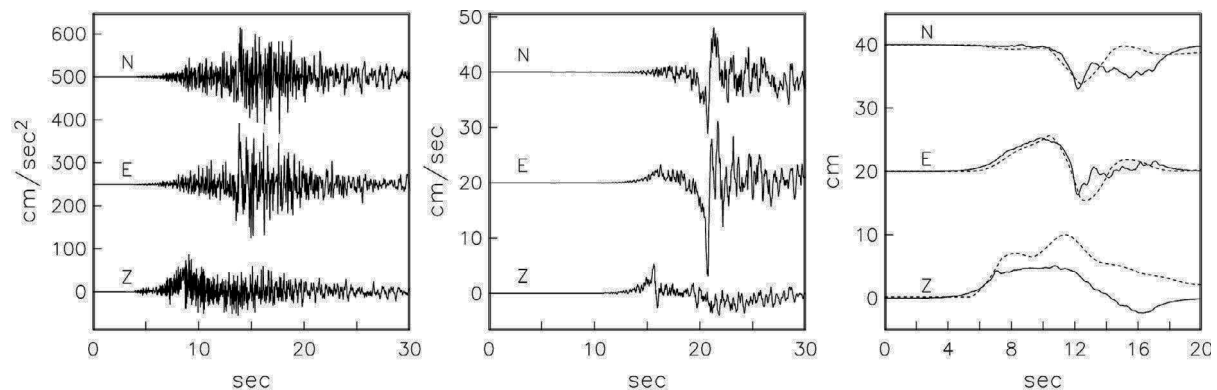
Figure 5. An example of simulated acceleration, velocity, and displacement traces in the epicentral region from a postulated M_w6.5 earthquake, using recording of the 1997 earthquake as empirical Green's function (stress drop of EGF = stress drop of target earthquake = 6 MPa). The right frame also shows, by dashed lines, the deterministic, synthetic displacement seismograms at TUIG for an M_w6.5 earthquake located at the focus of the 1997 event.

Results of simulation for various combinations of $\Delta\sigma$ are summarized in Table 3. The expected horizontal *PGA*, *PGV*, and *PGD* range between 120 and 260 gal, 12 and 28 cm/s, and 6 and 11 cm, respectively.

Although the ground motions estimated by random summation of the EGF are reasonable, there are several factors which introduce uncertainties in these results. The stress drop of the EGF event is uncertain and that of the target earthquake is assumed. The directivity of the source may give rise to greater or smaller ground motions than those computed by our method. Finally, a single EGF may not be adequate to sample the entire fault plane of an M_w6.4.

We emphasize that this synthesis of the ground motion is based on the assumption of linear elastic response of the sediments. Almost certainly the shallow sediments of the Gulf basin will behave nonlinearly under such excitation, as was the case during the 1959 earthquake. In view of the uncertainties, the observed ground motions may easily differ by a factor of 2 or 3 from the expected ones. This however is usually the case in ground motion predictions.

Conclusions

Our analysis shows that the 6 September 1997 earthquake (H = 30 km; M_w4.5), like the nearby earthquake of 26 August 1957 (H = 21 km; M_w6.4), was a thrust event. The event confirms a previous conclusion that while the upper sediments of the Gulf coast basins are in an extensional (normal fault-type) stress regime, the mid- and lower crust is in a shortening (thrust fault-type) stress regime (Dewey and Suárez, 1991; Suter, 1991), which implies a permutation between the vertical and maximum horizontal principal stresses. Upper crust is under extension probably because of gravitational loads and high topographic gradient; the stress field of middle to lower crust may be controlled by far-field loads at convergent plate margin and/or absolute plate motion.

Our estimation of ground motion in the epicentral region of Comalcalco basin due to a postulated M_w6.4 earthquake indicates that peak acceleration, velocity, and displacement (assuming linear behavior of the sediments) may be in the range of 120-260 gal, 12-28 cm/s, and 6-11 cm, respectively. These, then, are also

Table 3. Simulated peak ground motions for a postulated M_w6.4 earthquake using recordings of the 1997 earthquake as EGF.

Stres Drop, MPa EFG/Target	PGA, cm/s²			PGV, cm/s			PGD, cm		
	N	E	Z	N	E	Z	N	E	Z
6/6	146	173	103	13.2	18.7	6.8	8.8	6.5	6.1
6/12	213	262	161	20.0	27.6	9.2	10.7	7.2	6.4
12/12	171	198	124	17.9	25.8	8.7	10.6	7.1	6.3
12/6	121	127	88	11.8	17.5	6.0	8.5	6.4	6.0

our estimations of the ground motions during the 1959, M_w6.4, earthquake. These estimations were obtained using 6 September 1997 event as an empirical Green's function under various simplifying, though reasonable, assumptions. They are valid for sites with local geology similar to that of station TUIG. The estimation of ground motions at other nearby sites, such as Minatitlán, may be calculated if their site responses are known. Subjected to such ground motions the sediments of the Gulf Coast are likely to behave nonlinearly and may liquefy, as was the case during the 1959 earthquake.

Acknowledgments

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