Optimum sea surface displacement and fault slip distribution of the 2017
Tehuantepec earthquake (Mw 8.2) in Mexico estimated from tsunami
waveforms

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Key Points:

1. Tsunami waveforms resolve the optimum sea surface displacement with maximum
   sea surface uplift of 0.5 m and subsidence of 0.8 m.
2. Large fault slip (3 – 6 m) located at depths between 30 – 90 km is estimated from the
   optimum sea surface displacement.
3. Large tsunami amplitudes up to 2.5 m due to edge waves are estimated inside and
   around a lagoon between Salina Cruz and Puerto Chiapas.
Abstract

The 2017 Tehuantepec earthquake (Mw 8.2) was the first great normal fault event ever instrumentally recorded to occur in the Middle America Trench. The earthquake generated a tsunami with an amplitude of 1.8 m (height=3.5 m) in Puerto Chiapas, Mexico. Tsunami waveforms recorded at coastal tide gauges and offshore buoy stations were used to estimate the optimum sea surface displacement without assuming any fault. Our optimum sea surface displacement model indicated that the maximum uplift of 0.5 m is located near the trench and the maximum subsidence of 0.8 m on the coastal side near the epicenter. We then estimated the fault slip distribution that can best explain the optimum sea surface displacement assuming ten different fault geometries. The best model suggests that a compact region of large slip (3 – 6 m) extends from a depth of 30 km to 90 km, centered at a depth of 60 km.

Keywords: the 2017 Tehuantepec earthquake, tsunami waveform inversion, optimum sea surface displacement, fault slip distribution, tsunami simulation.
1. Introduction

Subduction of the Cocos Plate beneath the North American Plate and the Caribbean Plate is marked by the Middle America Trench. The relative convergence rate at the Middle America Trench offshore Chiapas and Oaxaca states is approximately 6.8 cm/yr (DeMets et al., 2010). In this area, the Cocos Plate is divided by the aseismic Tehuantepec Ridge (Figure 1a), where the age of crust in the northwest is 10 – 25 My younger than that to the southeast of the ridge (Couch and Woodcock, 1981; Pardo and Suárez, 1995). No major (M>7) interplate earthquake with thrust fault mechanism within the Tehuantepec seismic gap has occurred for at least 100 years (McNally and Minster, 1981; Franco et al., 2005).

A great normal fault earthquake with moment magnitude (Mw) 8.2 (Global Centroid Moment Tensor solution) occurred offshore Chiapas and Oaxaca states, Mexico on 8 September 2017. According to the Servicio Sismológico Nacional (SSN) of Mexico, the hypocenter is located at 94.11°W, 14.85°N and a depth of 58 km, with earthquake origin time of 04:49:18 UTC (http://www.ssn.unam.mx). The epicenter is located at the Tehuantepec seismic gap in the Middle America Trench. The hypocenters of the mainshock and the aftershocks (M≥4) are located within a depth range of 10 – 100 km (SSN earthquake catalog).

The aftershock distribution shows that the fault geometry of the earthquake is steeply dipping to the northeast. The hypocenter, focal mechanism, and plate interface model of SLAB1.0 (Hayes et al., 2012) suggest that the normal fault earthquake occurred within the oceanic Cocos Plate.
Mexico had experienced destructive tsunamis in the past from thrust fault earthquakes in the Middle American Trench (National Oceanic and Atmospheric Administration [313x797]https://www.ngdc.noaa.gov/hazard/tsu_db.shtml). In 1985, a great interplate earthquake (Mw 8.0) generated a large tsunami up to 3 m along the coast of Michoacan (Mendoza and Hartzell, 1989; Farreras and Sanchez, 1991; Lander et al., 2003). Another tsunamigenic interplate earthquake (Mw 8.0) occurred on the coast of Colima and Jalisco states in 1995 and generated up to 11 m tsunami (Courboulex et al., 1997; Lander et al., 2003). A great tsunamigenic earthquake (Mw ≥ 8.0) with a normal faulting mechanism has not been instrumentally recorded in this region. Great normal fault earthquakes have occurred and generated devastating tsunamis in other regions such as in Japan in 1933 (Mw 8.4) and in Indonesia in 1977 (Mw 8.3) (Kanamori 1971, Abe 1973, Lynnes and Lay, 1988; Astiz et al., 1988; Gusman et al., 2009). Those earthquakes occurred in the outer-rise region whereas the 2017 Tehuantepec earthquake occurred in a deeper part of the oceanic plate, making the current event a rare case of tsunamigenic earthquakes.

The sea level monitoring stations such as coastal tide gauges and DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys surrounded the earthquake source area and recorded tsunami waveforms to constrain a tsunami source model. We use tsunami waveforms recorded at 12 coastal tide gauges and four DART buoys, to find an optimum initial sea surface displacement by a Genetic Algorithm – Pattern Search (GA-PS) method (Mulia and Asano, 2015; 2016) without assuming any fault. Rather than applying the traditional approach of estimating fault slip distribution by tsunami waveform inversion (e.g., Satake 1987; Fujii and Satake, 2006; Gusman et al., 2015), we apply a new approach in which the fault slip distribution is estimated from the sea surface displacement. We evaluate a
set of fault geometries with a variable location, dip, and strike angles to find a fault slip distribution that can best explain the optimum sea surface displacement.

2. Tsunami observations

The tsunami of the 2017 Tehuantepec earthquake was recorded at tide gauges located across the Pacific Ocean as far as 12,000 km from the epicenter. The tsunami was also observed at DART stations located in the deep ocean (Figure 2). To extract the tsunami waveforms, the original records are bandpass filtered with cutoff periods of 100 min (0.000167 Hz) and 5 min (0.00333 Hz). The bandpass filter removes the ocean tides and high-frequency waves from the record.

The arrival times of the maximum tsunami are highly variable. At the tide gauges, the maximum amplitudes are not registered as the first tsunami peak but observed during the later phases (Figure 3). For example, at Puerto Chiapas, the first tsunami arrived at 70 min after the earthquake with an amplitude of 0.2 m, but the maximum amplitude of 1.8 m appeared four hours after the first tsunami arrival. At Salina Cruz station, the maximum amplitude was registered during the second cycle of the tsunami wave, whereas at Acajutla station it arrived 12 hours after the first peak amplitude.

For tsunami source inversion, we use tsunami waveforms recorded at 12 coastal tide gauges and four DART buoys (Figures 2b and 3). Among them, four tide gauges (Puerto Angel, Huatulco, Salina Cruz, and Puerto Chiapas) are in the proximity of the source area (within 300 km), and the others are located within 3,000 km from the source area. The station distribution gives azimuthal gaps of less than 120° and the smallest gap is 5°.
3. Methodology

3.1. Tsunami numerical simulation

We use a tsunami numerical model that solves the linear shallow water equations using a finite difference method with a staggered grid scheme in a spherical coordinate system (Gusman et al., 2010). The dispersion effects of the surface gravity wave and those from the elastic loading, gravitational potential change, and seawater compressibility are included in the synthetic tsunami waveforms by a phase correction method (Watada et al., 2014). The bathymetry data used for the numerical tsunami simulation is based on the 30 arc-sec GEBCO-14 gridded bathymetry data (Weatherall et al., 2015). For tsunami propagation modeling, we use three modeling domains with different grid sizes of 30, 90, and 270 arc-sec. The modeling domain (91° – 99° W and 10°– 18° N) with a grid size of 30 arc-sec covers stations located very close to the epicenter. The 90 arc-sec modeling domain is 75° – 110° W and 20° S – 25° N, and the 270 arc-sec modeling domain is 160° E – 65° W and 60° S – 50° N. The tsunami waveforms that are used for the waveform inversion are either computed on the 30 or 90 arc-sec modeling domains.

3.2. Genetic Algorithm-Pattern Search (GA-PS) method for sea surface displacement inversion

To estimate the sea surface displacement by tsunami waveform inversion, we use the B-spline function (Koketsu and Higashi, 1992) as the unit sources. A distribution of B-spline unit sources provides a high degree of flexibility in determining the sea surface displacement because they are not constrained by the assumed faulting mechanism or location of the fault. The B-spline function can be written as
\[ f(x, y) = \sum_{i=0}^{3} \sum_{j=0}^{3} c_{k+i,l+j} B_{4-i} \left( \frac{x - x_k}{h} \right) B_{4-j} \left( \frac{y - y_l}{h} \right), \]

(1)

where,

\[ B_i(r) = \begin{cases} \frac{r^3}{6}, & i = 1 \\ \frac{-3r^3 + 3r^2 + 3r + 1}{6}, & i = 2 \\ \frac{3r^3 - 6r^2 + 4}{6}, & i = 3 \\ \frac{-r^3 + 3r^2 - 3r + 1}{6}, & i = 4 \end{cases} \]

(2)

and \( x_k = \left\lfloor \frac{x}{h} \right\rfloor h, k = \left\lfloor \frac{x_k}{h} \right\rfloor, y_l = \left\lfloor \frac{y}{h} \right\rfloor h, l = \left\lfloor \frac{y_l}{h} \right\rfloor \). Also, \( x \) and \( y \) are for grid coordinate, \( h \) is the point source spacing, \( c_{1,1} \) is 1 m and the other \( c \) values are zero. When 16 B-splines are combined, they will make a symmetrical shape with a steep slope and a flat top. This unit source is assumed to occur instantaneously which is valid due to the long period nature of tsunami wave and the short 40 sec main rupture duration of this event (USGS). For the Green’s functions, the synthetic tsunami waveforms at the stations originating from each unit source are simulated using the numerical method mentioned above.

We use a Genetic Algorithm – Pattern Search (GA-PS) method for tsunami source inversion (Mulia and Asano, 2015; 2016, Gusman et al., 2016) to estimate the sea surface displacement. A total of 70 unit sources with a spatial interval of 40 km are initially distributed in the tsunami source area (green circles in Figure 4). The GA-PS uses a least squares method (Lawson and Hanson, 1995) iteratively in two stages to find the optimal number and distribution of unit sources. In the first stage, the algorithm removes any unit source that has similar information in terms of sea surface elevation from the adjacent source points. In the second stage, the locations of the remaining unit sources are adjusted to
minimize the tsunami waveform misfit. The GA-PS will produce an optimum sea surface displacement for the tsunamigenic earthquake.

3.3. Fault slip inversion

We estimate the fault slip distribution from the optimum sea surface displacement. Two focal mechanisms for the earthquake are available from the Global CMT and USGS W-phase MT solutions. Each of the solutions provides two possible fault geometries, but only the steep fault geometry dipping to the northeast is consistent with the aftershock distribution (Figure 1b). The strike, dip, rake angles for the steeply dipping plane and depth from the GCMT and USGS solutions are slightly different. The GCMT solution gives a strike of 320°, dip of 77°, rake of -92°, centroid depth of 50 km, while the USGS W-phase solution gives a strike of 314°, dip of 73° rake of -100°, and centroid depth of 46 km. We evaluate five fault locations with an interval of 7 km for each solution (Figure S1) to find a fault slip distribution that can best explain the optimum sea surface displacement. The shallowest fault edge is located at a depth of 15 km. We arrange 10 × 6 subfaults with a subfault size of 20 × 20 km (Figures 5a and b). The vertical seafloor displacement is assumed to be the same as the sea surface displacement. For the Green’s functions, the synthetic vertical sea surface displacement from each subfault is calculated by the model of Okada (1985). A spatial smoothness constraint for the slip distribution is applied through a Laplacian operator. The weight for the smoothness constraint of 0.4 is used. We solve the slip amount at each subfault by a non-negative least square algorithm (Lawson and Hanson, 1995).

4. Results and Discussion

4.1. Optimum sea surface displacement
The GA-PS method reduces the initial number of unit sources from 70 to 36, and it also gives an optimum non-equidistance unit source distribution. The initial and optimum distributions of the unit source locations are shown in Figure 4. A total number of 260 iterations of the GA-PS was done to obtain the optimum sea surface displacement (Figure S2). The sea surface displacement pattern shows that the maximum subsidence of 0.8 m is located close to the coastline (Figure 4). The maximum sea surface uplift of 0.5 m is located very close to the trench approximately 50 km outside the aftershock area. The sea surface uplift also extends beyond the trench. The dimension of the main sea surface displacement is 200 km by 150 km. A total gravitational potential energy from the initial sea surface displacement is calculated to be $3.17 \times 10^{13}$ J. Figure 3 shows that the simulated tsunami waveforms from the optimum sea surface displacement can reproduce the observations very well.

4.2. Fault slip distribution

Among the ten different fault geometries, the one on which the SSN hypocenter is located with the GCMT solution (strike of 320°, dip of 77°, and rake of -92°) best explains the optimum sea surface displacement. The best fault location is consistent with the aftershock distribution as shown in Figure 1a (blue rectangle) and Figure 1b (blue line). The slip distribution on this fault plane has a spatially compact region of large slip ($3 - 6$ m) with a dimension of 100 km along the strike and 60 km along the dip. The major slip region is located at depths between 30 and 90 km (Figure 5a). The largest slip amount of 6 m on a subfault is located at a depth of 60 km (Figure 5b). These depths are larger than typical tsunamigenic interplate earthquakes, making this event an unusual tsunamigenic event. The seismic moment is calculated as $1.95 \times 10^{21}$ Nm (Mw 8.2) from the slip distribution with an assumed rigidity of $6 \times 10^{10}$ Nm$^{-2}$. These estimated values are consistent with the Global
CMT solution \((2.65 \times 10^{21} \text{Nm}, \text{Mw 8.2})\) and the W-phase moment tensor solution by the USGS \((2.16 \times 10^{21} \text{Nm}, \text{Mw 8.2})\).

The calculated sea surface displacement from the slip distribution gives maximum uplift of 0.5 m and subsidence of 1.0 m (Figure 5a). The general locations and sizes of main uplift and subsidence from the fault slip distribution and the optimum sea surface displacement model are the same (Figures 5a and 4), but the optimum sea surface displacement model provides a more detailed pattern than the one from the fault slip distribution. The tsunami waveform calculated from this displacement fits at the tide gauges and DART stations (Figure 5c) well (normalized root-mean-square error, NRMSE=0.91), but the agreement was better for the waveforms calculated from the optimum model (NRMSE=0.89).

4.3. Tsunami propagation

We simulate the tsunami propagation using the optimum sea surface displacement model. The tsunami is estimated to produce maximum amplitude larger than 1 m along the coastline of 500 km in Oaxaca and Chiapas, Mexico. Large tsunami amplitudes up to 2.5 m are predicted inside and around a lagoon located between Salina Cruz and Puerto Chiapas (Figure S3). As previously mentioned, the maximum tsunami amplitudes were observed during the later phases of waveforms recorded at the tide gauges. Tsunamis are known to generate edge waves, which are trapped on continental shelf by refraction and propagating along the shoreline and cause large late phase (González et al., 1995; Bricker et al., 2007; Geist, 2013). The animation of tsunami simulation shows that edge waves are propagating along the coast near the epicenter (Movie S1). The amplitude of these edge waves can be similar to or even larger than the initial tsunami that hit the coast (Figure 3).
simulation suggests that the later phase of the tsunami waveforms at stations along the coast of Mexico and El-Salvador were mostly formed by edge waves.

Sea level oscillation during the later phases can be well reproduced at most of the tide gauges, but the maximum tsunami amplitude is underestimated at Puerto Chiapas and Lazaro Cardenas (Figure 3). It appears that the GEBCO 30 arc-sec gridded bathymetry data are good enough for accurate later phase simulation at most of the tide gauges, but not for the protected shallow waters of Puerto Chiapas and Lazaro Cardenas. More accurate bathymetry data may be needed for further investigation on how tsunami later phases are amplified in the protected waters.

Strong tsunami signal appeared at around 4 hours after the earthquake at D32411 station but the tsunami simulation underestimates the signal (Figure 3). Our tsunami propagation model suggests that the strong signal was from tsunami waves reflected by the coast near the source area. Again, more detailed coastal bathymetry may be needed to accurately reproduce such later phases from coastal reflection.

Tide gauge records show that the tsunami does not always become smaller with distance. The Santa Cruz (Galapagos, Ecuador), San Antonio (Chile), and Owenga (New Zealand) tide gauge stations are located approximately 2000, 6000, and 11,000 km from the tsunami source area, respectively, but the maximum tsunami amplitude recorded at those stations are all about 30 cm (Figure 2c). The energy radiation pattern of the simulated tsunami (Figure 2a) and local bathymetry effects can explain the observed tsunami amplitude distribution. The tsunami energy was propagated mainly to the southwest of the source area and this direction is perpendicular to the strike of the earthquake (Figure 2a). Due to ocean
bathymetry, the tsunami energy focused along several directions between west-southwest and south-southwest. The recorded tsunami at each tide gauge might have gone through different shoaling processes depending on the local shallow bathymetry. The pattern of simulated coastal tsunami amplitude is consistent with the observations, although the tsunami modeling with 270 arc-sec grid can produce only 60% of the observed coastal tsunami amplitude on average. While the later phases of a tsunami can be difficult to model especially at far field tide gauges, the tsunami at the deep ocean is usually rather easy to reproduce (Figures 2a and 3).

5. Conclusions

Tsunami waveforms at 12 coastal tide gauges and four DART buoys were used to estimate the optimum sea surface displacement of the earthquake. Tsunami source representation by a distributed B-spline unit sources at the sea surface is very flexible to fit the tsunami waveform data. As a result, we obtained an optimum sea surface displacement that can reproduce the tsunami waveforms with high accuracy. The optimum displacement model suggests that the sea surface uplifted up to 0.5 m and subsided down to 0.8 m.

Ten fault geometries were evaluated to find a fault slip distribution that can best explain the optimum sea surface displacement. The best fault location contains the hypocenters of mainshock and many aftershocks. The strike, dip and rake angles of the best geometry are 320°, 77°, and -92°, respectively (GCMT solution). The estimated fault slip distribution has a compact large slip region (3 – 6 m) and centered at a depth of 60 km northwest of the epicenter. The depth of the large slip region is larger than typical tsunamigenic interplate earthquakes, making this event an unusual tsunamigenic event. The
seismic moment calculated from the estimated slip distribution is \(1.95 \times 10^{21}\) Nm or equivalent to Mw 8.2.

The tsunami is estimated to produce maximum amplitude larger than 1 m along a 500-km coastline in Oaxaca and Chiapas, Mexico. Large tsunami amplitudes up to 2.5 m are estimated inside and around a lagoon located between Salina Cruz and Puerto Chiapas on the modeling domain with a grid size of 30 arc-sec (Figure S3). The tsunami simulation shows that the amplitude of edge waves can be similar to or even larger than the incident waves.

Acknowledgments

Tide gauge records are available from the Intergovernmental Oceanographic Commission - United Nations Educational, Scientific and Cultural Organization sea level monitoring (http://www.ioc-sealevelmonitoring.org/index.php). DART buoy records are available from the National Oceanic and Atmospheric Administration – National Data Buoy Center (http://www.ndbc.noaa.gov/dart.shtml). The mainshock and aftershock hypocenters are available from the Servicio Sismológico Nacional (http://www.ssn.unam.mx). This study was supported by JSPS (Japan Society for the Promotion of Science) KAKENHI (Grants-in-Aid for Scientific Research) Grant Numbers JP17K12998 (ARG), JP17F17055 (IEM) and JP16H01838 (KS).
Figure 1. a) Tectonic settings and seismicity around the 2017 Tehuantepec earthquake. Yellow circles indicate the aftershock (M≥4) occurred within three days after the mainshock (SSN earthquake catalog), red star indicates the earthquake epicenter, and the Global CMT focal mechanism is shown. Red contours represent the plate interface based on the SLAB1.0 model (Hayes et al., 2012). Gray circles indicate earthquakes that are larger than M7 since 1921 (USGS earthquake catalog). Blue rectangle outlines the fault model of this study. b) Cross section of mainshock (red star), aftershock (yellow circles) hypocenters, and the plate interface (red line) along the line A-B. Blue line indicates the estimated fault geometry of the earthquake.
Figure 2. a) Observed maximum tsunami amplitudes at sea level observation stations (colored circles) overlaid with simulated maximum tsunami amplitude. Black contours are theoretical tsunami travel time from the epicenter with a contour interval of 1 hour. b) Tide gauge and DART buoy stations used for tsunami waveform inversions. Solid black lines are theoretical tsunami travel time with an interval of 1 hour, and thin black lines are those with an interval of 30 min. c) Observed maximum tsunami amplitude at tide gauges against the distance from the epicenter.
Figure 3. Tsunami waveform comparison for the optimum sea surface displacement of the 2017 Tehuantepec earthquake. Black lines are the observed tsunami waveforms, blue lines are the observed tsunami waveforms that are used for the inversion, and red lines are the simulated tsunami waveforms.
Figure 4. Optimum sea surface displacement estimated by the GA-PS method. Red contours are for the uplift and blue contours are for the subsidence with a contour interval of 0.1 m. Black dots represent the optimum central location of B-spline unit sources and green dots represent the initial central location of B-spline unit sources. Red star indicates the epicenter, yellow circles indicate the aftershocks, and red triangles indicate tide gauge locations.
Figure 5. a) Fault slip distribution for the 2017 Tehuantepec earthquake and its corresponding coseismic seafloor displacement. Red contours are for uplift and blue contours are for the subsidence with a contour interval of 0.1 m. b) A plot of the estimated fault slip distribution for the earthquake along the strike and dip. c) Comparison of observed (black lines) and simulated (red lines) tsunami waveforms from the fault slip distribution.
References


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