NUMERICAL SIMULATION OF SEISMIC WAVES FOR MEXICAN BASIN

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ABSTRACT

We performed numerical simulation for seismic waves propagation from the Mexican Pacific to Mexico basin. We improved the 2-D elastic code developed by a previous study based on the finite difference method including the radiation pattern for a point shear dislocation of arbitrary orientation. The anelastic attenuation effects were incorporated using a time domain attenuation operator and the nonreflecting boundary conditions were included. To approximate the line source solution obtained by the 2-D method to 3-D source solution we mapped the seismograms using a correction filter for the difference in the pulse shape between the line and the point source solution. Finally, we matched synthetic seismograms with the observed data using the convolution of the source function. All this process allowed us to follow the 2.5-D method and obtain a code for a staggered-grid formulation with a few computational requirements for a current personal computer.

In order to compare results of our code, we used two scenarios and two models based on gravity and seismic data from previous studies. Both models were similar in the upper mantle and crust and different in the Trans-Mexican Volcanic Belt (TMVB) and basin. The first scenario was taken from the 2014 Papanoa, Guerrero, earthquake. The model for the basin and TMVB was constructed by isostatic compensation for this scenario. The second scenario was taken from the 2007 Guerrero earthquake. For this scenario we used a basin and TMVB structure derived from gravity data.

We found that the synthetic seismograms match well with the observed data when the distance between the 2-D model and station location was not large. Second scenario matched better than the first one when we used the velocity model with gravity information and distance between the line structure and a station was not large. This method and code can be applied to other basins and to active volcanos in future works.

Keywords: Seismic Modelling, Wave Propagation, 2.5-D Method.

1. INTRODUCTION

Mexico basin is located in the central portion of the Trans-Mexican Volcanic Belt (TMVB), whose anomalous arc is oblique to the subduction zone and extends from the Pacific to the Gulf of Mexico. The basin has a limestone Mesozoic basement followed by sequences of pyroclastic products, volcanic rocks, and fluvial sediments represented by clays, silts and sands. These deposits play an important role in the local amplification of strong ground motion (Singh 1988). One of the four different kinds of seismic sources that affect the basin is the inslab earthquakes (M≤8.2) generated in the subduction zone due the Cocos plate is subducting the North America plate. These kind of earthquakes are simulated in this study using a 2-D method and the synthetic seismograms are approached by the 2.5-D method.

2. DATA

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We used 26 strong ground motion data records from national networks during the event of the 2014 Papanoa Guerrero earthquake M_w7.2 (Figure 1), that was converted into velocity record with SAC transfer command and we applied a highpass filter of 0.2 Hz cut-off frequency for the analysis. Furthermore, we used 22 velocity waveform data from the Meso-America Subduction Experiment (MASE) during the event of the 2007 April 13 earthquake M_w6.0 (Figure 2).

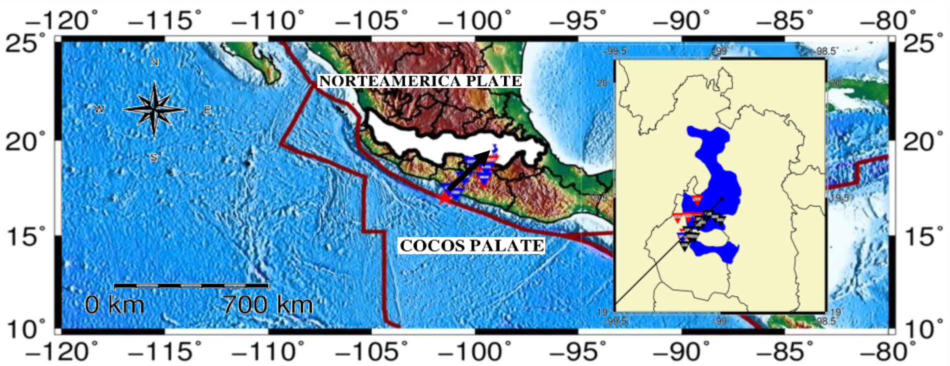

Figure 1. National Accelerograph Networks. The red star indicates the location of the 2014 Guerrero earthquake, (Mw7.2). Red inverted triangles indicate the station location of the National Center for Disaster Prevention (NCDP). Blue inverted triangles indicate the station location of the Engineering Institute (EI). White shape shows the area in surface from the Transmexican Volcanic Belt. Black arrow indicates the line model from source to the basin. (after Mexican National Seismological Service (MNSS), NCDP and EI).

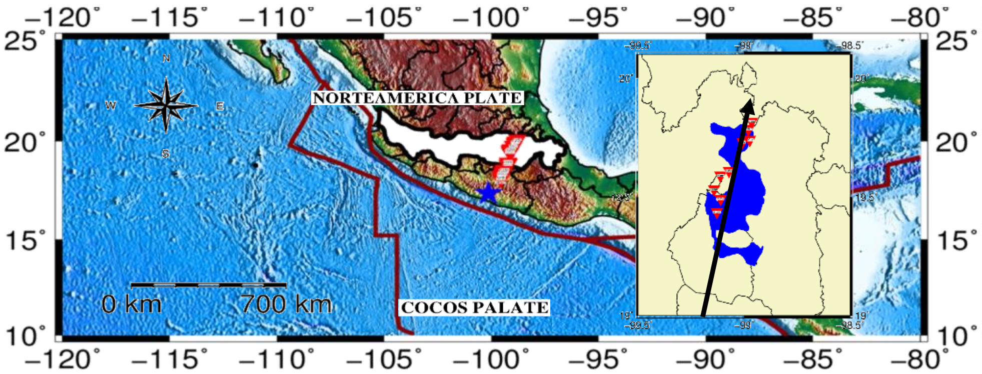

Figure 2. Meso-America Subduction Experiment (MASE) array. The red inverted triangles indicate the location of the velocity sensors. The blue star indicates the location from the 2007 April 13 earthquake and the map from the basin shows the array into the basin. Black arrow indicates the line model from source to the basin (after MASE 2007).

3. METHODOLOGY

3.1. Equation of motion and numerical scheme

We used a 2-D Finite Difference Method Center (FDMC) scheme, with second order accuracy in space and time for x-z plane. This staggered-grid numerical scheme allows us to obtain the numerical solution for the differential equations that govern the movement in a continuous media. The code follows the unitary cell based on the principle of discretization from Madariaga (1976) and Hayashida et al. (1999), the numerical algorithm from Virieux (1986) for the P, SV and Rayleigh waves solution in the x-z plane, and the free irregular surface is adopted for two-dimensional case from the three-dimensional elemental cell developed by Ohminato and Chouet (1997). The grid is constructed with the (i,j,k) indexes for the dimensions (x,z,t) and discrete steps Δx, Δz and Δt, where the velocity is calculated instead of the displacement. Moreover, we assigned constant spatial intervals (Δx=Δz=Δh) in order to avoid the numerical dispersion phenomena and the stability condition was satisfied using the maximum P wave velocity of propagation in the media. One of the advantages of the staggered-grid formulation is that the source can be expressed in terms of velocity or stress (Graves, 1996; Pitarka, 1999). We included the radiation pattern for a point shear dislocation of arbitrary orientation according to Aki and Richards (2002) for the x-z plane that use combined properties of the moment tensor with the properties of the Green's function.

In our 2.5-D scheme the fault strike should be measured from the radial direction for each station since in our finite-difference computation the x-axis is set to the radial direction. Source model was represented as a double-couple point source that had a Gaussian bell-shape source time function with period T_0 of one second width and area equal one. The anelastic attenuation effects was included using a quality factor of the medium Q (Takenaka and Nakamura, 2010), with a technique for modeling spatially varying viscoelastic media using a time domain attenuation operator Q (Graves, 1996).

Furthermore, we included nonreflecting boundaries conditions based on gradual reduction of the amplitudes in a strip of nodes along the boundaries of the mesh (Cerjan et al., 1985). In order to approximate the solution from 2-D to 3-D point source solution we added the Green's functions, of which each component was obtained by the 2-D FDM, after weighting them with the moment tensor components and mapped the line source solution into the point source solution using the following filter

$$v_{3d}(t) = \frac{1}{\sqrt{R}}\frac{d}{dt}\left[\frac{1}{\pi}\frac{1}{\sqrt{t}} * v_{2D}(t)\right] \quad (1)$$

where * denotes the convolution operator, R is the distance between source and observation position, $v_{2D}(t)$ is the added Green's function obtained by the 2-D FDM and $v_{3d}(t)$ is the converted waveform that corresponds to the displacement excited by a double-couple point source (Wang et al., 2001). Furthermore, filter analysis is used in the frequencies of interest. In this study we used two ranges of band pass filters, the first one is from 0.1 to 0.14 Hz in order to observe the fundamental mode of Rayleigh waves (R_0) and the second one is from 0.222 to 0.333 Hz in order to observe the first higher mode of Rayleigh wave (R_1) and R_0 diffracted and propagated by the TMVB and the basin according to Chávez-García and Salazar (2002). Finally, in order to match our 2.5-D solution with the observed data, we obtained the source function by the deconvolution process and we convolve the source function with all the obtained synthetics. This process allowed us to match the waveform package and amplitude with the observed data.

3.2. Velocity, Density and Quality Structure Models

Velocity, density and Q values from the upper mantle and crust were taken from previous works derived by refraction experiments, seismicity and gravity data (Valdés and Mayer 1996; Kostoglodov et al., 1996). The shape of the Mohorovicic discontinuity was taken from the CRUST 1.0 model and the models for the basin were taken from Cruz-Atienza et al. (2016). We used this model in order to compute numerical simulation for both scenarios for the 2007 and the 2014 Guerrero earthquakes. The differences between the scenarios are the azimuth from source to the basin, the topography, the length of the basin and the shape of the TMVB. The first scenario has a shape of the TMVB deduced by isostatic compensation. The structure of the TMVB for the second scenario was deduced by gravity survey, which was acquired in 2016 by the National Polytechnic Institute (NPI). The models have 615 km length from the Pacific Coast to Mexico basin and 80 km depth. The models were discretized in 0.222 km with a uniform grid along the x-z axis. The number of mesh elements is 2,774 × 383=1,062,442. We used 20 grid per minimum wavelength in order to satisfy the free surface condition. The simulation was parallelized using PGI compilers

The points for which synthetic seismograms were calculated were placed on the model by two criteria. The first one uses the distances between the epicenter and each station to project the station onto the 2-D model. This projection can be used regardless of the length of the arc only when the station can be relocated onto the structure with the same characteristic (e. g. lake zone to lake zone). If the location of the station onto the 2-D model is not consistent in terms of the characteristics, the second criterion was used. The station is positioned parallel to the line of the model. The station location is projected on the velocity model so that the line connecting the station and the projection point is perpendicular to the 2-D velocity model. The second criterion was also used when the offset between the station and the model line is large. In case the first criterion is used the arrival times of the seismic waves are expected to match with the observed data. In case, the second criterion is used arrival times of seismic waves will be different. If a station is located close to in the line of the model, arrival time and phases will be expected to be similar to those observed.

4. RESULTS AND DISCUSSION

4.1. Results from the scenarios

In our results, the synthetic seismograms show good agreement with the observed data recorded at the stations placed between the epicenter and the TMVB, which is located in a range between 250 and 310 km from the epicenter in the first scenario. The main wave packet is similar in both frequency ranges. However, there are some differences in arrival times in some stations, for which the second criterion for station location was used. For the first scenario (Figure 3), the durations and amplitudes of the observed data are larger than those synthetic seismograms located in the basin for both range of frequencies.

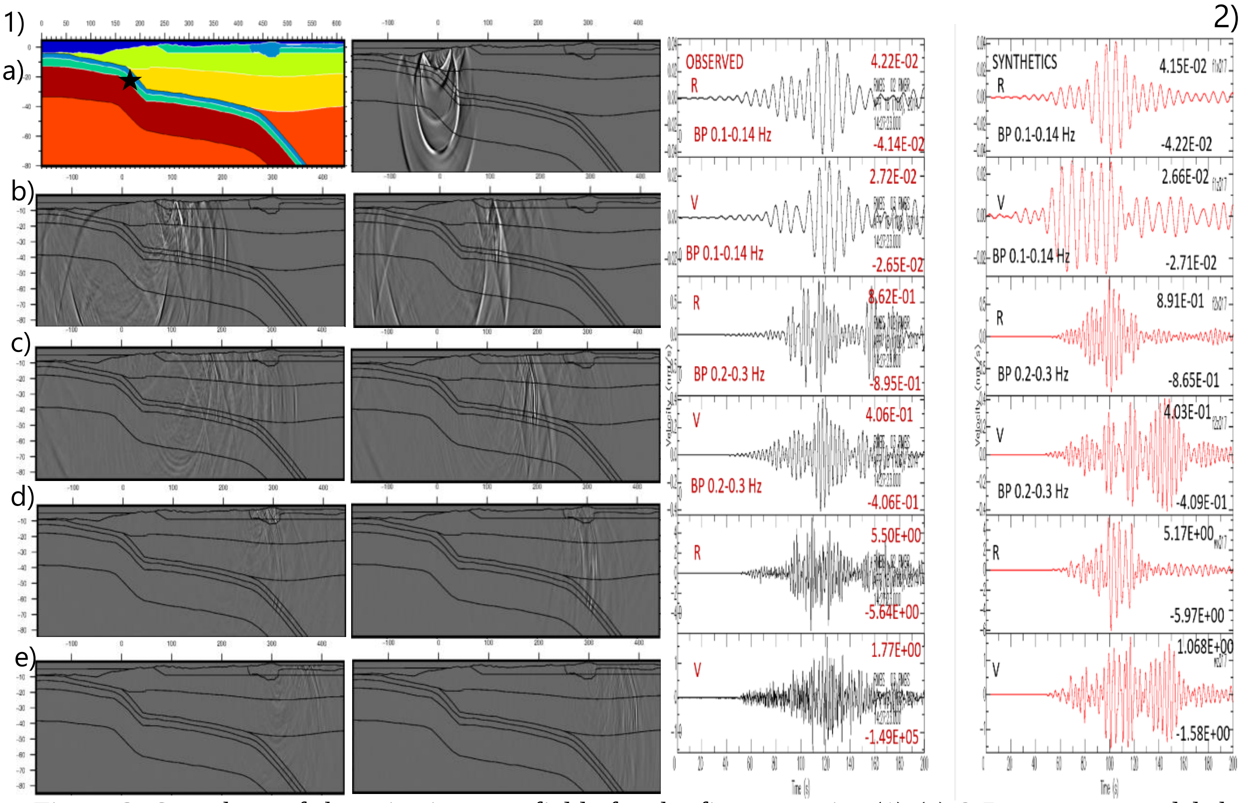

Figure 3. Snapshots of the seismic wave fields for the first scenario. (1)-(a) 2-D structure model the black star indicates the location from the source. (1) The radial (left) and the vertical (right) components. Snapshots at (a)10, (b) 30, (c) 50, (d) 80, and (e) 100 seconds after the origin time. Comparison with the observed data (black) and the synthetic seismograms (red) from RMBS station (2). The station location is in Mexico basin in the transition zone. On the top radial and vertical components in a range frequency between 0.1-0.14 Hz, in the middle, radial and vertical components in a range frequency between 0.222-0.333 Hz and on the bottom, radial and vertical components. The numbers at the right for each component indicates the maximum and minimum amplitude respectively.

In addition, the arrival time for the computed seismograms is different than the recorded data, as expected since the location of the station was fixed in the correspondent velocity model by using the second criterion. However, only the main wave packet corresponds to the observed records.

For the second scenario (Figure 4), is possible to observe that the shape of the TMVB deduced by gravity allows the diffracted waves packet to travel efficiently towards the basin, generating multiples or reverberations as expected. The synthetic seismogram has a good agreement with the observed data for almost all the stations. The wave packets match well and the arrival time are quite similar. Observed data show long durations and amplifications at stations in the basin located 250 km or more from the epicenter. This phenomenon corresponds to the regional amplification.

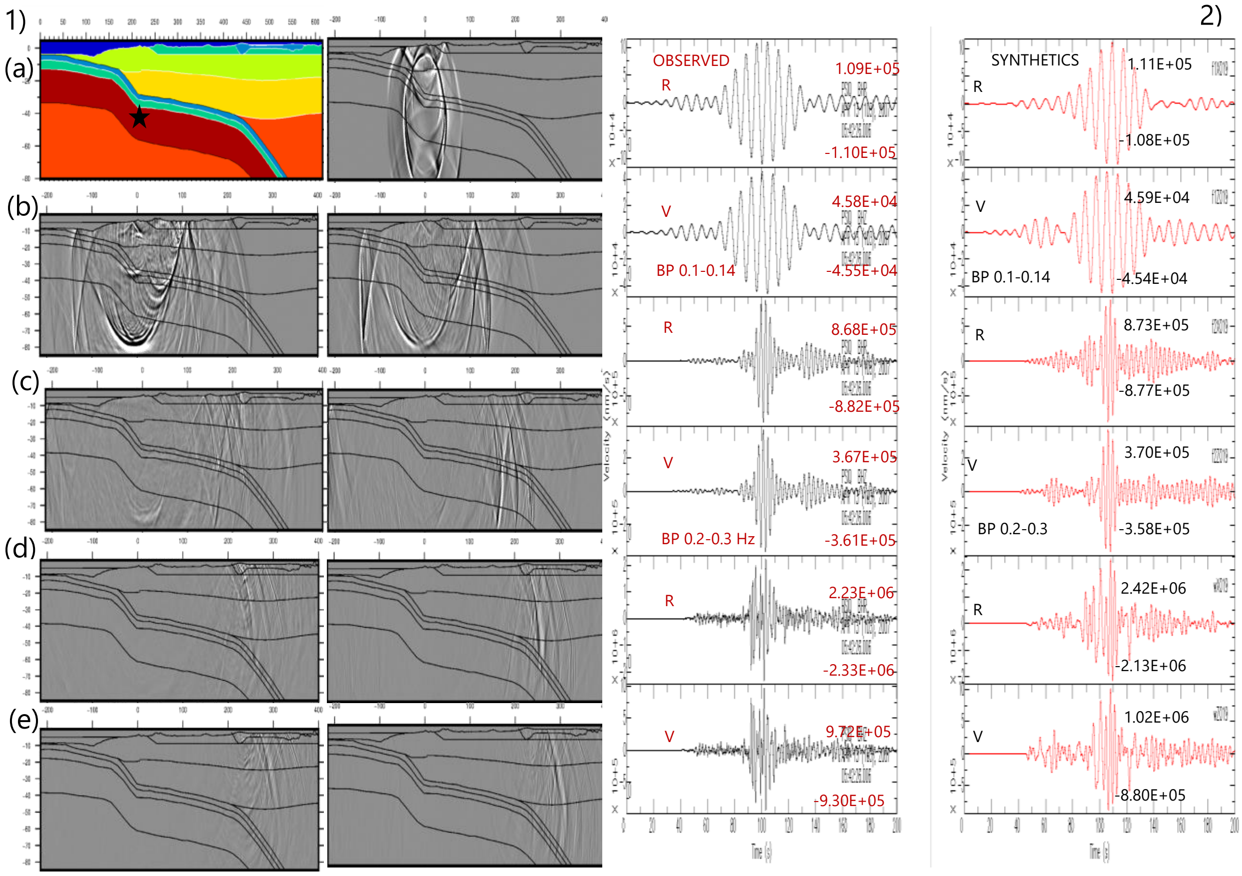

Figure 4. Snapshots of the seismic wave fields for the second scenario. (1)-(a) 2-D structure model the black star indicates the location from the source. (1) The radial (left) and the vertical (right) components for the first scenario. Snapshots at (a)10, (b) 30, (c) 50, (d) 70, and (e) 80 seconds after the origin time. Comparison with the observed data (black) and the synthetic seismograms (red) from PSIQ station (2). The station location is in Mexico basin in the bed-lake zone. On the top radial and vertical components in a range frequency between 0.1-0.14 Hz, in the middle, radial and vertical components in a range frequency between 0.222-.333 Hz and on the bottom, radial and vertical components. The numbers at the right for each component indicates the maximum and minimum amplitude respectively

5. CONCLUSIONS

We improved the program code of Salazar L. for seismic wave propagation and included the radiation pattern for a point of shear dislocation of arbitrary orientation that combined properties of the moment tensor with the properties of the Green’s function that allow us to include a double-couple point source. Furthermore, we included the frequency-independent quality factor and the nonreflecting boundaries conditions. We mapped the line solution obtained by the 2-D FDM to an approximate 3-D point source solution using a correction filter for the difference in the pulse shape between the line and the point source solution. This allowed us to obtain a methodology and a code that follow the 2.5-D method for seismic wave propagation for near to middle field with a few computation time required in a commonly used laptop computer.

We composed the synthetic waveforms using the convolution of the source function and found that the synthetic seismograms show good agreements in time and amplitude with those stations before the TMVB in both scenarios. The synthetic seismograms from those stations located in the basin presented good agreement only in the second scenario since the velocity model of the TMVB was constructed by gravity data and the first scenario by isostatic compensation. The differences between the waveforms in Mexico City and those at other stations are larger at the frequency range between 0.222 and 0.333 Hz than at that between 0.1 and 0.14 Hz for the first scenario. Moreover, the duration and amplitude for the fundamental Rayleigh wave R_0 has a little decrement for the stations located in the north at distances greater than 300 km from the epicenter in the second scenario. It is possible to observe the increment in duration when the train of Rayleigh waves reaches the basin, and different durations when the waves cross through the basin. One possible cause is that the thickness and shape of the bedrock is different at the north of the basin. Differences between both results let us think that the methodology must be applied to direct lines between source and station location in order to avoid differences between observed data and synthetic seismograms due to the velocity model and the distance between line solution and stations location. Furthermore, we found that the properties of the TMVB and the basin as the shape and thickness increase the amplitude and duration of the guided train of Rayleigh waves as was predicted by Chavez-Garcia and Salazar (2002).

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