STRONG MOTION ESTIMATION IN COSTA RICA AT SPECIFIC SITES USING SPECTRAL INVERSION METHOD

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ABSTRACT
The complex tectonic setting of Costa Rica implies the necessity of a real seismic hazard scenario characterization for lifeline facilities and the country. In this paper, one of the conventional spectral inversion technique is applied to strong ground motion records to separate the site effect, the source spectra and the path effect. To assure the quality of the results, the broadband station JTS000 of IRIS/IDA is also incorporated. Two newly developed consistency checks were established to assure the appropriateness of the input data using the individual site effects and Fourier synthetic spectra. The frequency dependent quality factor $Q = 179f^{0.5598}$ was obtained for the northern and central part of Costa Rica. Also, synthetic amplification spectra for the 2012 Sámara earthquake of Mw 7.6 at specific stations were calculated, showing consistency with the intensity anomaly observed for this earthquake. This new method allows the estimation of acceleration spectra of important seismic events.

Keywords: Synthetic acceleration spectra, Q value, Consistency check method

1. INTRODUCTION

The subduction of the Cocos plate and the Nazca plate under the Caribbean plate defines the tectonic frame of Costa Rica (Figure 1). The stress generated this convergence, among different bathymetry features at Cocos plate, caused crustal deformation resulting in the formation of important fault systems. Also, one of the notable important geological features in Costa Rica are the volcanic deposits, that cover the major part of the country. The soft deposits due to this volcanism and sedimentary basins can cause a significant amplification during a major earthquake. This influence was observed during the 2012 Sámara earthquake (Mw 7.6 (R.S.N., 2012)), where an anomalous intensity distribution in central Costa Rica was observed (Figure 2).
Therefore, such tectonic frame requires a special hazard assessment to estimate the site effect at sites of interest. For this purpose, in this study I separate the source, the path and the site effect using the spectral inversion method at different strong motion stations. In parallel I establish a way to check the input data of the inversion.
Based on this separation, a comparison of synthetic spectra with the observed ones is performed to assure the quality of the results. Once the good condition of the separation is

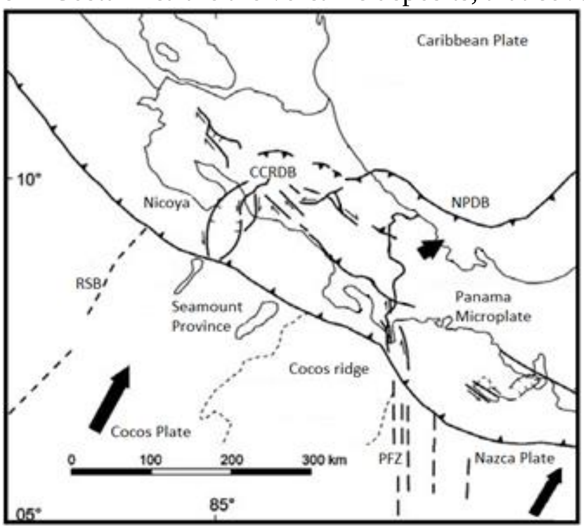

Figure 1. Tectonic setting of Costa Rica. Modified from Montero (2001).

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assured, a synthetic reproduction of the 2012 Samara earthquake at stations that were not available at the moment of the event is perform. 2International Institute of Seismology and Earthquake Engineering, Building Research InstituteThis information is used to estimate the site effect, i.e., amplification at those stations during a major earthquake. The target frequency range is from 1 Hz to 10 Hz, but the data processing is done in the working frequency range from 0.5 Hz to 10 Hz to expect the good results in a wider range.

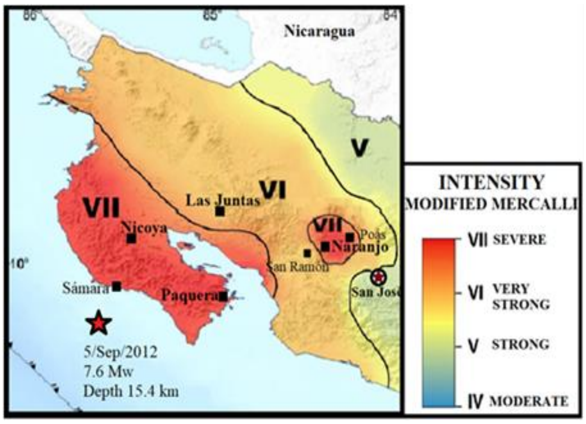

Figure 2. Anomalous intensity at the 2012 Sámara earthquake (R.S.N., 2012).

2. METHODOLOGY

Spectral Inversion Method

The Spectral Inversion Method (Moya and Irikura, 2003) is applied to separate the source effect $S_i(f)$, the propagation path effect, and the site amplification $G_j(f)$, from acceleration spectra $O_{ij}(f)$ observed at the j-th site during the i-th event using some reference events as the constraints based on the ω^{-2} source spectral model (Aki, 1967). The requirements to implement this method suggested by Moya and Irikura (2003) are that the seismic moment and the corner frequency of the reference events should be accurate. The empirical frequency-dependent radiation-pattern proposed by Satoh (2002) is used to correct the horizontal components of strong motions based on the ω^{-2} model by studying the ratio of SV/SH.

Synthetic Spectra

Once the inversion results are obtained, it is possible to estimate the acceleration spectra of the target record $O_{IJ}(f)$, i.e., the record at the J-th station during the I-th event, even though not recorded in reality. However, two element records are required together with the results of the spectral inversion: one observed record of the i-th event at the J-th station $O_{iJ}(f)$ that shares the station with the target record, the other record of the I-th event at the j-th station $O_{Ij}(f)$ that shares the event.

3. SEISMIC NETWORK

The present study is performed using strong motion records from the National Seismological Network of Costa Rica (R.S.N.), which is a collaboration program between the Costa Rican Electricity Institute (I.C.E) and the University of Costa Rica (U.C.R). To constrain the determination of the corner frequency of the reference event, the broadband station JTS000 from IRIS/IDA was also included (Figure 3). Nineteen earthquakes with a magnitude between 5.0 and 7.6 catalog were selected from 2009 to 2019 (Figure 4). All the records were converted into the KNET (NIED, 2020) format using the program developed by Dr. Yokoi at Building Research Institute (B.R.I.). An orientation correction was also performed to the stations that were not aligned in the conventional NS/EW. In general, the I.C.E. stations obtained better signal to noise ratio (SNR). For this reason, the I.C.E stations along with the IRIS station JTS000 were selected to perform the inversion, while the Sixaola stations (U.C.R) were used for the synthetic spectra calculation.

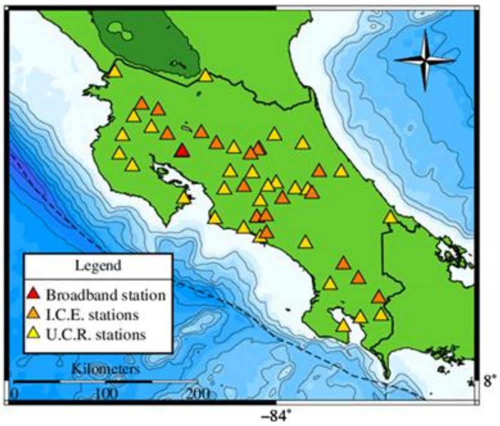

Figure 3. Distribution of selected stations.

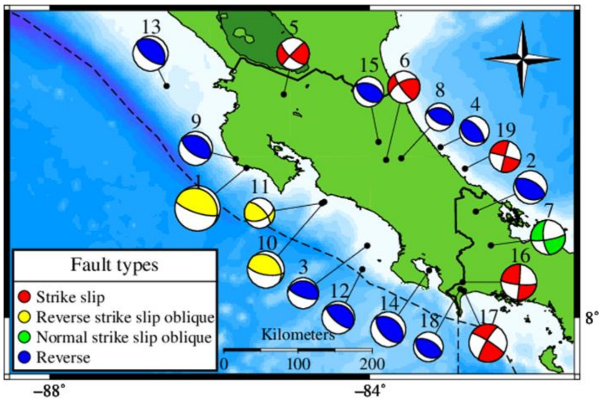

Figure 4. Distribution of the selected events.

4. ANALISIS AND RESULTS

The determination of acceleration source spectra for the reference events is performed to set the input acceleration as a base for the spectral inversion. For this purpose, direct fitting method was chosen to constrain the source spectra. This method was applied through the direct fitting of the synthetic acceleration spectra to the observed ones of the broadband station JTS000. The four events in figure 5 shown by broken curves don't follow the ω^{-2} source spectral model and may have intermediate segment of source spectra between the corner frequency of displacement spectra and that of acceleration spectra. Therefore, I did not use these four events to prevent unnecessary complication. Other six events have their corner frequency f_0 sufficiently lower for that the flat level of acceleration may cover the target frequency range. In this condition, it doesn't matter if the events follow the ω^{-2} source spectral model
or not.

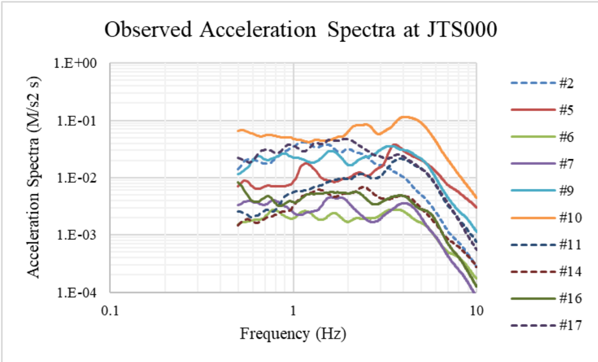

Figure 5. Observed acceleration Spectra obtained at JTS000.

Consistency check

Due to an abrupt instability of the output from the spectral inversion, a suspicion arose on the correctness of the input data themselves and the following way of the consistency check was conducted for all 20 stations. In the spectral inversion, it is assumed that each site must have its unique site effect although various earthquakes were observed there. For each of the six reference events, it is possible to calculate the ratio of the observed spectra to the basement input, which is the product of the given source effect and the path effect. Here it is called "individual site effect". These for a site should be similar to each other. Therefore, the first consistency check method consists in obtaining the individual site effect of the used stations for the reference events to detect the outlier curves (Figure 6). As the correct values are not known, I cannot conduct anything except to eliminate the records that correspond to the outlier curves from the input data of the spectral inversion.

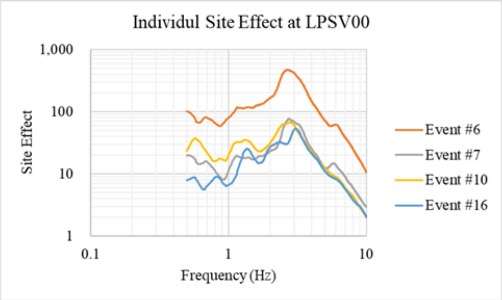

Figure 6. Example of an outlier curve (orange line) detected using the Individual Site Effect consistency check for LPSV00.

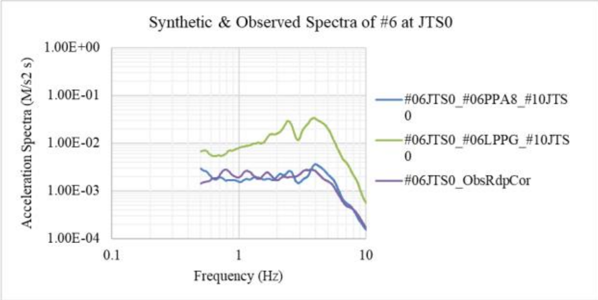

Figure 7. Consistency Check using Synthetic Spectra. “#06JTS0_#06LPPG_#10JTS” and “#06JTS0_#06PPA8_#10JTS” consist of the target record and two elements: one shares the event, the other shares the station with the target record. “ObsRdpCor” denotes the observed record.

The second consistency check consist in comparing the synthetic records obtained using the results of the inversion with the real observed one. I compare the synthetic spectra using various combination of two element records and check outlier curves, and also the standard deviation among estimated curves. For example, the event #6 (EQ1612010025) recorded at JTS000 was reproduced by two sets of element records: one for #06 at PPA800 and #10 (EQ1711130228) at JTS000, the other for #06 at LPPG00 and #10 at JTS000 (Figure 7). The synthetic one by the former pair shows an acceptable similarity with the observed one, however the latter pair shows a drastic discrepancy. This seems to be caused by the record of #6 at LPPG00 because the other element record was shared. Thus, this record was eliminated from the inversion. This second consistency check was conducted for all possible target records where observed records exist.

Results of the Spectral Inversion

By the final spectral inversion, the value of $Q = 179f^{0.5598}$ was calculated. The site effects are shown in their normalized version (Figure 8), along with the source spectra for the six reference events and event #1 (2012 Sámara earthquake).

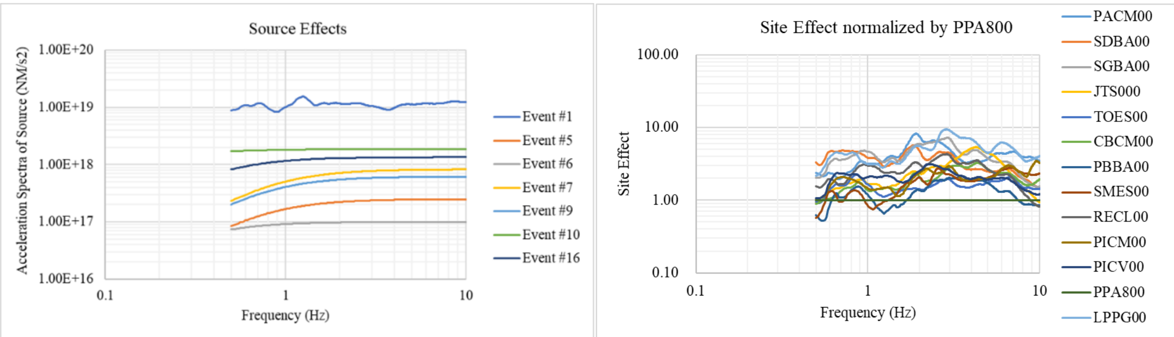

Figure 8. Source spectra and Site Effects normalized ones by PPA800 results from the spectral inversion.

Reproduction of Fourier Amplitude Spectra of the 2012 Sámara earthquake.

The capacity to reproduce the synthetic spectra can be checked by comparing the average synthetic spectra with the observed ones and the standard deviation. The synthetic spectra can be calculated using all the stations available and compare then with the real observed spectra, to confirm the quality of the final result. Taking this into account, the synthetic acceleration spectra during the 2012 Sámara earthquake were calculated at the stations where observed records do not exist. The Sixaola station NICO00 located at the colonial city of Nicoya is the closest one to the epicenter of the 2012 Sámara earthquake. Of the synthetic reproduction, this station had more stable behavior, without high frequency decay and with some peaks at 1.3, 1.9 and 6.6 Hz (Figure 9). The Sixaola station PAQE00, located in Paquera at southeast of the Nicoya peninsula, showed clearly bigger amplification around 2Hz in

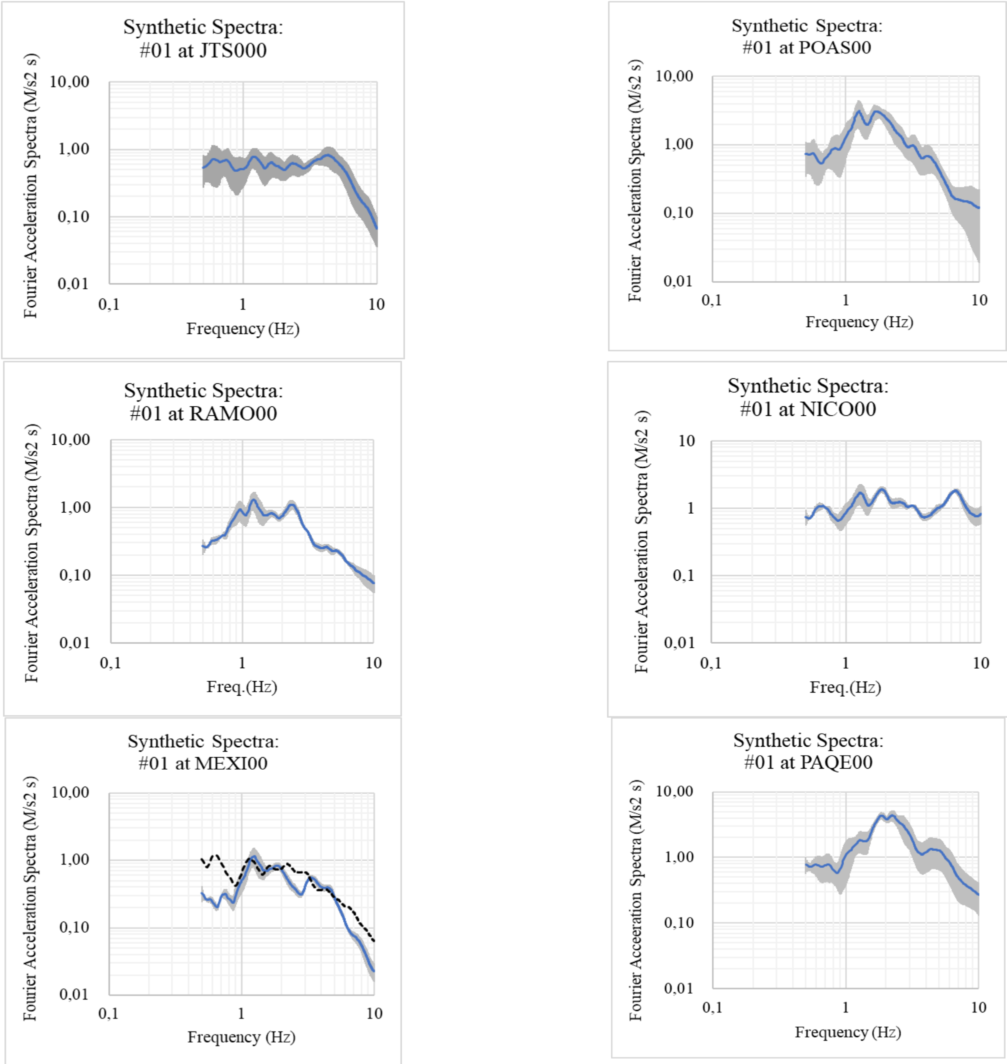

Figure 9. Examples of reproduction of Fourier Acceleration Spectra of the 2012 Sámara earthquake at stations where the strong motion record was not obtained: JTS000 (top - left), Sixaola stations POAS00 (top - right), RAMO00 (middle left), NICO00 (middle right), MEXI00 located in the national capital with the observed spectra at SGBA00 (dotted curve, bottom- left), and PAQE00 (bottom right). Gray shadow shows the standard deviation.

comparison with NICO00. To analyze the anomalous amplification for the Sámara earthquake at Naranjo town, the synthetic acceleration spectra of the Sixaola stations RAMO00 and POAS00 were also obtained. RAMO00, located in San Ramón at 9 km of Naranjo town, showed amplifications around 1 Hz and 2.5 Hz (Figure 9). Its amplitude is comparable with the NICO00 but smaller than PAQE00. On the other hand, POAS00 located in San Pedro de Poás at 14 km east of Naranjo town, showed amplification comparable with PAQE00 with the peaks around 1.3 and 2 Hz. Finally, the Sixaola station MEXI00 is located at the center of the capital city San José. This station showed peaks at 1.2 Hz with a strong decay at high frequencies. Its acceleration spectra show a similarity with those of SGBA (Black broken curve) suggesting the MMI VI in MEXI. Thus the reproduced acceleration spectra show a consistency with an anomalous intensity distribution in Figure 9.

5. DISCUSION AND CONCLUSION

Costa Rica requires the implementation of suitable seismic hazard assessment. the understanding of the site effect at specific sites can be vital for a proper design. Moya and Irikura (2003) proposed a method to quantify the site effect through the separation of the source and the path. For this, it is necessary that the reference event follows the ω^{-2} source spectral model. However, this requirement was not always satisfied. The separation of the corner frequencies into an intermediate segment and the exceptionally high frequencies in some cases reflect the necessity for further source process studies in the region. The events that did not follow the ω^{-2} model were excluded from the analysis.

The direct fitting method was applied to constrain the source spectra for the inversion. This method was applied using the JTS00 broadband station of IRIS/IDA. The synthetic amplification spectra method proved to be suitable as a checking method to assure the quality of the inversion results, and also as a method to reproduce the Fourier amplitude spectra. The exclusion of outliers records was necessary due to the low SNR and strange behavior of some of the records. The resulting value of $Q = 170f^{0.5598}$ is considered representative for the north and central part of Costa Rica. This value has a good agreement with the study of Moya (2009), in which the author estimated a value of $Q = 131.6f^{1.1}$ for the central part of the country. The attenuation values can be associated to the volcanic deposits and the crustal deformation of this region.

Using the inversion results, the synthetic amplification spectra method was implemented to calculate the 2012 Sámara earthquake (Mw 7.6) amplification at Sixaola stations. The Sixaola stations (R.S.N.- U.C.R.) NICO00 and PAQE00, located at Nicoya peninsula and the closest to the epicenter, show very different amplification behaviors related to the difference of the surface geology. The synthetic results of Sixaola stations RAMO00 and POAS00 reflected important peak accelerations around 1.3 and 1.8 Hz. The acceleration estimated for POAS00 station goes up to 300 gal. These results have a good agreement with the intensity anomaly reported during the 2012 Sámara earthquake, with MMI modified Mercalli Intensity up to VII were reported in the area R.S.N. (2012).

The acceleration spectra obtained at MEXI00 station, located at the central part of the capital, showed amplifications similar to the observed ones at SGBA00 during this event. The estimation of an MMI intensity of VI for the capital has a good agreement with the eyesight reports (R.S.N., 2012).

The results obtained at the present work need to be extended with a bigger database for the South part of Costa Rica and North Panama. The synthetic spectra method applied in this study can be used in the future for further estimations at areas of interest.

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