

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 - 20 June 2019.

Evidence of two peaks response spectra (2PRS) due to separated effects of soil and source in recent subduction earthquakes

G.R. Saragoni

Structure-Construction-Geotechnical Engineering Division, Department of Civil Engineering, University of Chile, Santiago, Chile

M.F. Gallegos

Department of Structural and Geotechnical Engineering, Pontifical Catholic University of Chile, Santiago, Chile

ABSTRACT: Accelerograms of large subduction earthquakes are characterized by their long duration of some minutes leading in some cases to absolute response spectra with two clear peaks. This particular feature is associated with the separated participation effect of source from soil response in different stages of energy release from the dominating asperities of subducted plate. In this paper, 2PRS obtained from the accelerograms of 2010 Chile, 2015 Nepal, 2016 Ecuador, and 2017 Mexico earthquakes are analyzed, showing 2PRS for large subduction earthquakes are the rule for soft soils. In addition, it is demonstrated that period of soil peak coincides with the one estimated by Nakamura method. The actual importance of 2PRS for earthquake engineering is that source peak affects houses or middle-rise buildings and soil peak affects high-rise buildings or base-isolated buildings. Therefore, design response spectra considered in seismic codes for soft soils should be modified in future in order to consider both effects.

1 INTRODUCTION

Both the largest earthquakes and the majority of mega-earthquakes occur at subduction zones. Although these extraordinary events cause extensive destruction to cities and their structures, they are also a valuable source of information for research. The damaging acceleration recorded by accelerographs is a good example of this information. Generally, strong-motion accelerograms are characterized by their amplitude, frequency content, and duration.

Accelerograms of large subduction earthquakes have a long duration of some minutes due to their fault rupture length of hundreds of kilometers. These long durations are in contrast with the short duration of ten seconds of most crustal earthquakes related to fault length of few ten kilometers. The difference leads that in long-duration accelerograms of mega-earthquakes is possible to observe in response spectra the separated participation effect of the source from the soil response in different stages of the energy release from the dominating asperities of the subducted plate (Saragoni & Ruiz 2012). This attribute of subduction accelerograms registered in epicentral or near-field sites leads to absolute response spectra with two separated clear peaks for source and soft soil effects.

Saragoni et al. (1986) reported two peaks response spectra (2PRS) for the first time worldwide after analyzing acceleration time histories of the M 7.8 Central Chile earthquake occurred in 1985. They found 2PRS in Viña del Mar station (near the epicenter) for both horizontal components. Later, motivated by the low representativeness of response spectra achieved as a result of averaging accelerograms, Lobos (1999) studied the accelerograms of the 1985 Central Chile earthquake, and Gómez (2002) studied the accelerograms obtained for 1985 Mexico earthquake recorded in the Mexico City basin. Both authors proposed the need to develop response spectra with more than one peak representing the periods observed in the studied accelerograms.

Chile, unlike other countries, has registered accelerograms of mega-earthquakes in epicentral locations over the years; this fact has allowed studying the seismic behavior of soils in conditions close to the design cases. Analyzing these accelerograms, Saragoni & Ruiz (2004) identified the presence of two characteristic peaks in Chilean earthquakes, concluding that one is due to seismic source and another due to soil period. Later, Ruiz & Saragoni (2005) proposed absolute acceleration design spectra for the “NCh 433 Of. 96” Chilean seismic code considering two peaks as a consequence of the soil effect and the type of earthquake, being pioneers in this type of initiative. Finally, Ruiz & Saragoni (2008) found 2PRS, using the accelerograms from epicentral areas of large magnitude earthquakes close to the design magnitude, avoiding mixing with small amplitude accelerograms corresponding to earthquakes of small and moderate magnitudes. This regard was considered because the energy in seismic source periods was observed exclusively in epicentral accelerograms of large earthquakes. The main conclusion was that the proposed design 2PRS contemplated the Nazca plate subduction, but it might be expanded to other subduction or non-subduction zones.

In summary, 2PRS were often detected in epicentral accelerograms recorded in soft soils after the occurrence of subduction earthquakes in the last century. The first peak in short periods is due to source effect and the second peak in longer periods is due to soil response effect. Usually, the soil peak is similar or larger amplitude than the source peak. This fact has a huge incidence because the source peak could affect houses or middle-rise buildings and the soil peak could affect high-rise buildings or base-isolated buildings. In the case of rigid soils, the effect of the source is superposed with the soil response in almost one peak; therefore, it cannot explain this amplitude with soil dynamic amplification effect only.

To achieve the objectives, 2PRS corresponding to accelerograms registered in soft soils for latest subduction earthquakes are investigated in this paper. The selected earthquakes produced significant building destruction and consequently losses of lives in the last decade: M 8.8 El Maule, Chile, 2010; M 7.8 Gorkha, Nepal, 2015; M 7.8 Muisne, Ecuador, 2016; and M 7.1 Puebla - Morelos, Mexico, 2017. Besides, natural periods are estimated for the relating soil deposits applying both Nakamura method and spectrogram technique, demonstrating that the peak in longer periods is always related to soil deposit response.

2 ANALYSIS OF RECENT SUBDUCTION EARTHQUAKES

2.1 2010 El Maule earthquake (Chile)

On February 27, 2010, a magnitude M 8.8 earthquake struck the south-central part of Chile. The rupture occurred in the contact between the Nazca and the South American plates, with an approximate extension of 500 km in the north-south direction. As the rupture spread, the fault slip generated earthquake shaking and warped the ocean floor, triggering a tsunami along the fault-rupture area (Hayes et al. 2017). The earthquake had an approximate duration of 5 minutes and affected an area of 160,000 km², which houses approximately 75% of the population of Chile.

Free vibration of soils frequently occurs during some large earthquakes, perhaps seeming like a paradox. This fact could be due to the energy released from seismic sources, especially of their asperities, is not stationary in time, allowing relaxation intervals in between without important seismic wave arrivals in which free vibration of soil happens (Ruiz & Saragoni 2009). The occurrence of El Maule earthquake offered a great opportunity to validate those assumptions. The natural period of free vibrations from acceleration time histories of the 2010 event was estimated by Saragoni & Ruiz (2012), applying two techniques: autocorrelograms and Fourier spectra. The observed free vibrations of soil satisfied the 1D elastic S-wave propagation theory, where the free vibration modal periods obeyed the natural period equation:

$$T_n = \frac{4H}{V_s(2n-1)} \quad (1)$$

where T_n = natural period; H = soil depth; V_s = soil shear wave velocity; and n = mode number.

The research findings are illustrated in Figures 1 and 2. Figure 1a depicts the longitudinal component of the accelerogram recorded in the Concepcion Centro station, where free vibrations are indicated. Comparison of displacements calculated by integrating the accelerograms for the records of Concepción Centro and Concepción San Pedro stations are shown in Figure 1b. The free vibrations of soil were observed in the displacement time history of Concepcion Centro station, in the interval of relaxation without the arrival of important seismic waves that occur between the arrival of two seismic pulses 1 ($t_1=13$ sec) and 2 ($t_2=29$ sec). Pulses are similar in both stations (related with two main asperities of Nazca plate), confirming that these were due to the seismic source. Field soil studies suggest the natural period of soil in downtown Concepcion is 2.1 seconds whereby Figure 1b presents a lower number of cycles for Concepcion Centro station in the relaxation interval, concerning the number of cycles for San Pedro station.

Figure 2a depicts absolute acceleration response spectra for 5% critical damping, corresponding to Concepción Centro accelerograms. When the soil response is deterministically dominated in most of the accelerograms, response spectra are characterized to have a single peak as indicated by most seismic design codes. However, when the accelerations are recorded at epicentral areas specifically in soft soils, the response spectra are more complex presenting two clear peaks such as Concepcion Centro response spectra (for both horizontal components). The spectrum for longitudinal component presents one peak around 2.1 seconds, which would belong to the free vibrations of soft soil; and another peak between 0.3 and 0.7 seconds, due to probably the interaction of the waves associated with the seismic source and the response of higher ground modes (second and third vibration modes). Figure 2b presents the acceleration time history for Concepcion Centro station for the longitudinal component. Free vibrations of 2.1 seconds (0.5 Hz) for this accelerogram can be seen in the time interval of relaxation between 16 – 27 seconds in the spectrogram of Figure 2c. This period would coincide with a depth to bedrock of 120 m and a shear wave velocity of 250 m/s for the sandy soil of Concepcion (Saragoni & Ruiz 2012). The great relevance of the Concepcion accelerogram is due to this record was obtained few blocks from where a 15-story reinforced concrete building collapsed. The iconic “Alto Rio” building collapsed in the first 20 seconds during the

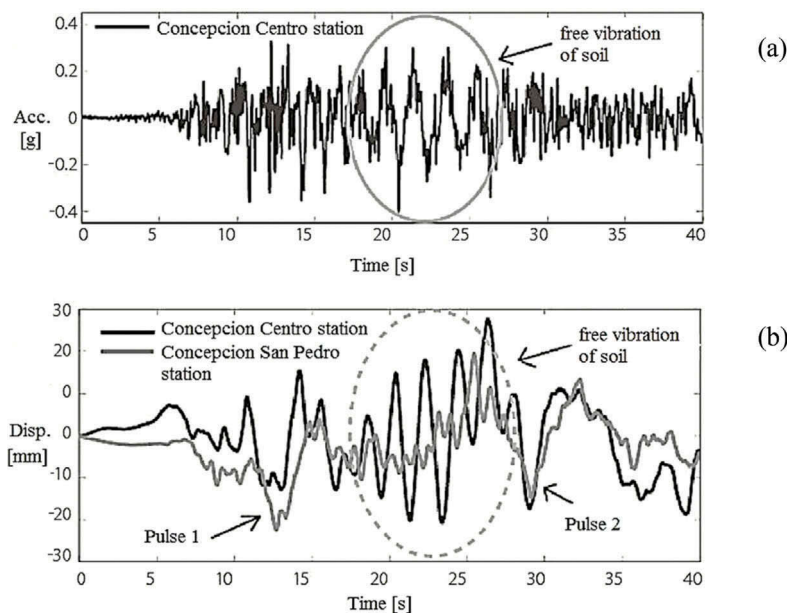


Figure 1. 2010 Chile earthquake: (a) Accelerogram of Concepcion Centro station with free harmonic vibration of soil. (b) Comparison of ground displacements of Concepcion Centro and San Pedro stations, indicating similar seismic pulses. (modified from Saragoni & Ruiz 2012).

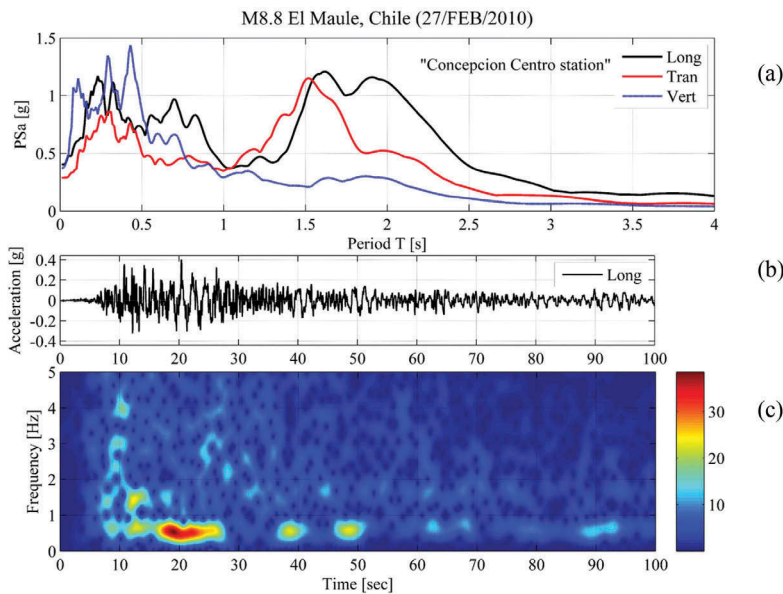


Figure 2. 2010 Chile earthquake recorded at Concepcion Centro station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for longitudinal component. (c) Spectrogram for longitudinal component. (after Saragoni & Ruiz 2012).

source effect without soil response influence (Sandoval & Saragoni 2015) showing the importance of 2PRS in the current seismic design.

2.2 2015 Gorkha earthquake (Nepal)

The M 7.8 earthquake of April 25, 2015, struck central Nepal with its epicenter located in Gorkha district, about 80 km NW of Kathmandu. At the location of this earthquake, the India plate is converging with Eurasia at a rate of 45 mm/yr towards the north-northeast—a fraction of which (about 18 mm/yr) is driving the uplift of the Himalayan Mountain Range. (Hayes et al. 2017). The Himalayan region is one of the most seismically active regions in the world producing significant seismic events. This event caused an unprecedented loss of life and devastation.

The ground motions of this event were registered at USGS/CESMD station KATNP, Kathmandu. According to Figure 3a, response spectra of the recorded ground motions are presented. It is clear that in the short period range, the spectrum for the N-S component presents one peak around 0.5 seconds; while the second peak is evident between 4.0 and 6.0 seconds. The global V_{s30} indicates that central part of Kathmandu valley has soft soil deposits that are typically NEHRP site class D (V_{s30} between 180 and 360 m/s), and geologic studies show that thick semi-consolidated quaternary sediments cover the valley with the maximum depth of 550 m in its central part (Rai et al. 2015). According to the period equation (Equation 1), the natural period would approach to 6 seconds (0.17 Hz), which could be due to the complex influence of underlying unconsolidated quaternary sediments in the basin. This period is in accordance with $T = 6$ sec (0.17 Hz) identified in the spectrogram of Kathmandu station, N-S component (Figure 3c).

2.3 2016 Muisne earthquake (Ecuador)

The earthquake of April 16, 2016, was a powerful natural event, which occurred off the Ecuadorian Pacific coast. The M 7.8 earthquake occurred as the result of shallow thrust faulting generated at the gently sloping plate boundary fault that conveys the Nazca plate eastward and downward beneath the South America plate. The fault rupture, largely offshore, exceeded 60 km in width and extended nearly 160 km parallel to the coast (USGS 2016). Large damages

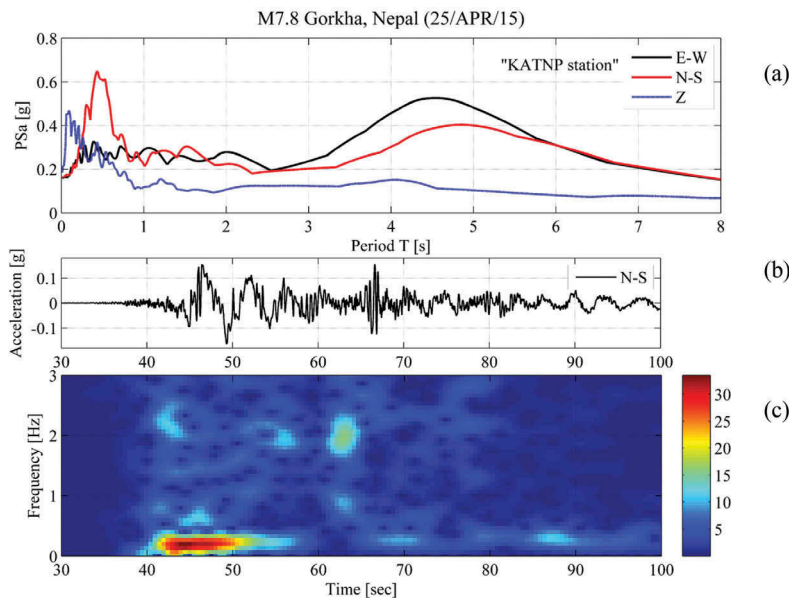


Figure 3. 2015 Nepal earthquake recorded at Kathmandu station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for N-S component. (c) Spectrogram for N-S component.

and multiple building collapses in various cities (like Pedernales, Portoviejo, Manta, and Chone) were reported by reconnaissance teams (EERI 2016).

This event is one of the few subduction zone earthquakes well registered in terms of the closeness of the accelerographic stations to the seismic source (36 km SW of the epicenter). Gallegos & Saragoni (2017) performed a comprehensive analysis of the strong-motion accelerograms for 21 IG-EPN stations. The findings indicated higher values of peak ground acceleration (PGA), Arias Intensity (Ia), destructiveness potential factor (Pdh) and acceleration spectral ordinates (Sa) than those found for previous Chilean and Mexican earthquakes. These outcomes confirmed the observations indicating that Muisne earthquake was destructive. Six stations presented accelerograms with destructive characteristics, which correspond to cities where damaging conditions and building collapses were largely observed.

Absolute acceleration response spectra, for 5% critical damping, for Pedernales and Chone stations were computed (Figures 4a and 5a), which exhibit remarkable behaviors. On the one hand, Pedernales (the nearest station to the epicenter) is characterized to have both horizontal spectra with two peaks. One of them around 0.2 sec, and another peak between 0.5 and 0.8 seconds. The spectrogram of the Figure 4c for the N-S component depicts energy pulses at periods of 0.5 sec (2.0 Hz) and 0.2 sec (4 Hz) in most of the acceleration time history. On the other hand, the spectra of Chone (station located far away from the epicentral area) reveal that second peak (1.5 sec) exceeds the first one. This feature is related to both the distance and site effect of soft soils that are typical of the coastal zone of Ecuador. Figure 5b shows the Chone station accelerogram for N-S component where soil free harmonic vibrations between 5 to 20 seconds are observed. In the spectrogram of Figure 5c, the intervals where the soil responded freely at a period of 1.5 s (0.67 Hz), between the arrivals of energy corresponding to higher frequencies, are seen. Evident soil effect due to soft soils was observed in Chone. Free soil vibration phenomenon confirms the observations that explain the collapse of some houses and middle-rise buildings in the downtown of this city (EERI 2016).

Similar to the 2010 earthquake case, the findings for the Muisne earthquake expose that accelerograph records had a dual behavior, in which the accelerograms recorded away from the rupture area are characterized due to free vibrations exceed seismic waves, whereas the seismic source waves are predominant for epicentral acceleration records.

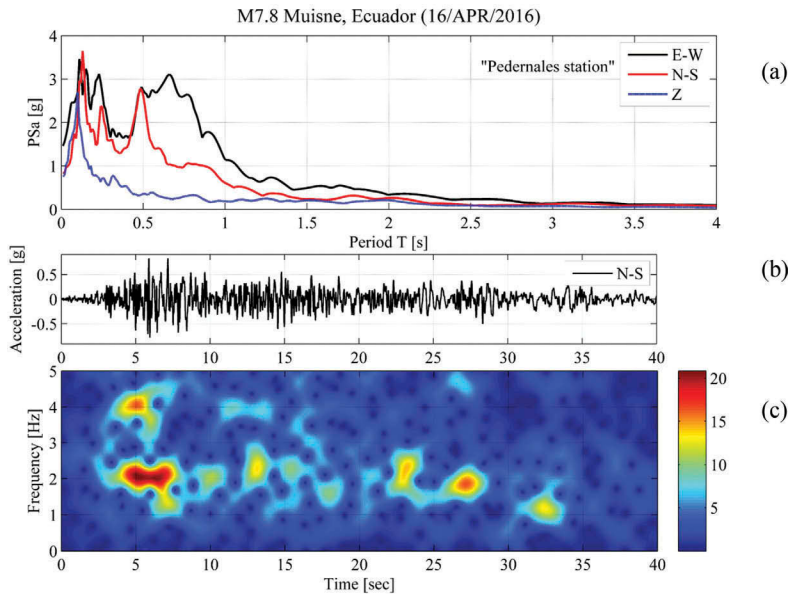


Figure 4. 2016 Ecuador earthquake recorded at Pedernales station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for N-S component. (c) Spectrogram for N-S component.

The horizontal-to-vertical spectral ratio RH/V , defined by Nakamura (1989), was determined for Pedernales and Chone stations, considering temporary windows in the coda of acceleration time histories (Figures 4b and 5b). It is possible that this part of accelerograms contains surface waves and free vibration of the soil deposit after large earthquakes, which is demonstrated in

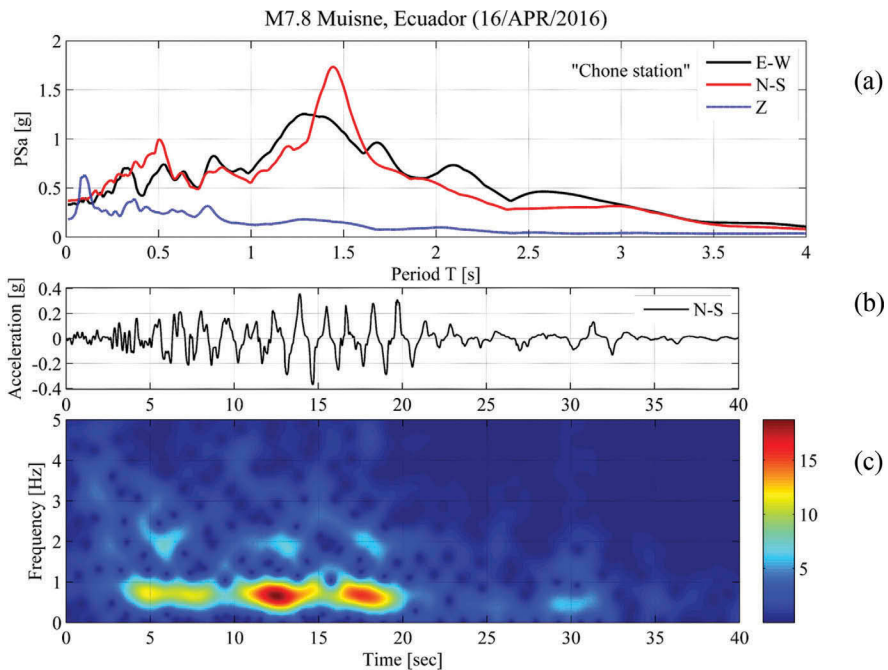


Figure 5. 2016 Ecuador earthquake recorded at Chone station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for N-S component. (c) Spectrogram for N-S component.

this seismic event. Figure 6 presents a predominant period of the soil deposit of 0.5 s (2.0 Hz) and 1.5 sec (0.67 Hz) for Pedernales (Figure 6a) and Chone (Figure 6b), respectively. These periods have a good correlation with those values obtained from both second peaks of acceleration spectra (Figures 4a and 5a) and low energy pulses in spectrograms (Figures 4c and 5c), due to soil response.

2.4 2017 Puebla - Morelos earthquake (Mexico)

September 19, 2017, M 7.1 earthquake in central Mexico occurred as the result of normal faulting at a depth of 48 km. The event is near, but not directly on, the plate boundary between the Cocos and North America plates in the region. The location, depth, and normal-faulting mechanism of this earthquake indicate that it is likely an intraplate event, within the subducting Cocos slab, rather than on the shallower megathrust plate boundary interface (USGS 2017).

Ground motions of this event were registered at CIRES/RACM station Cibeles (CI05), Mexico City, located in the zone of soft soils (transition - lake edge) where buildings of 4~7 stories collapsed. Figure 7a illustrates absolute acceleration response spectra for 5% critical damping and shows the common 2PRS again, especially for the E-W component. The spectrum presents one peak around 0.4 sec and another peak between 1.6 and 1.7 seconds. Acceleration time history for this component is depicted in Figure 7b. Further, pulses of energy at 1.65 s (0.6 Hz) due to soil response and 0.4 s (2~3 Hz) due to the source are identified in the spectrogram (Figure 7c).

On the other hand, basin effect is exemplified in Figure 8 for the notable 1985 Michoacán, Mexico subduction event recorded in SCT1 station in Mexico City (lake zone) located at a distance of 300 km from the epicenter. The normal attenuation law suggests that a low level of ground motion would be expected, however Communications Center (SCT) building partway collapsed due to the great amplification of the ground motion. According to Figure 8a, soil peak has a larger amplitude than the source peak due to long distance. Soil peak period at 2.0 s has a good correlation with the value found from low energy pulses around 0.5 Hz in its spectrogram (Figure 8c), related to soil deposit response.

3 CONCLUSIONS AND COMMENTS

Since the M 7.8 Central Chile earthquake in 1985, two peaks response spectra (2PRS) have been systematically reported after subduction mega-earthquakes. Recent evidence studied in this paper for 2010 Chile, 2015 Nepal, 2016 Ecuador, and 2017 Mexico earthquakes confirm

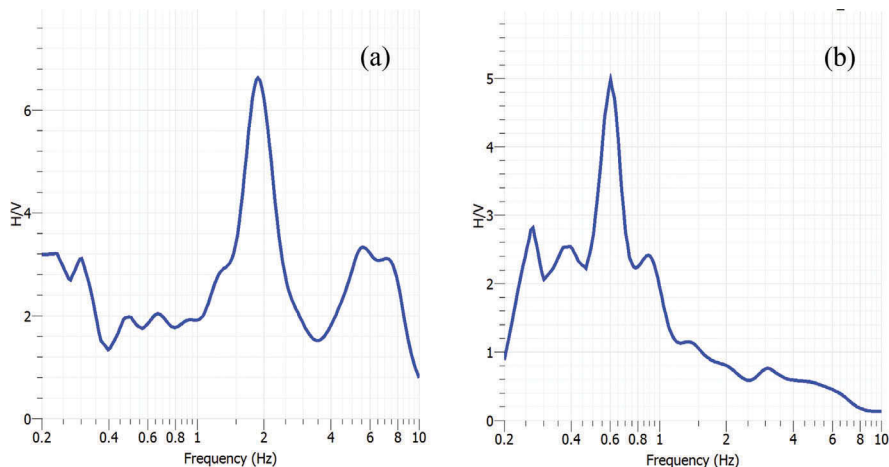


Figure 6. H/V spectral ratio (Nakamura method) obtained from the accelerogram codas of 2016 Ecuador earthquake for N-S components: (a) Pedernales station. (b) Chone station.

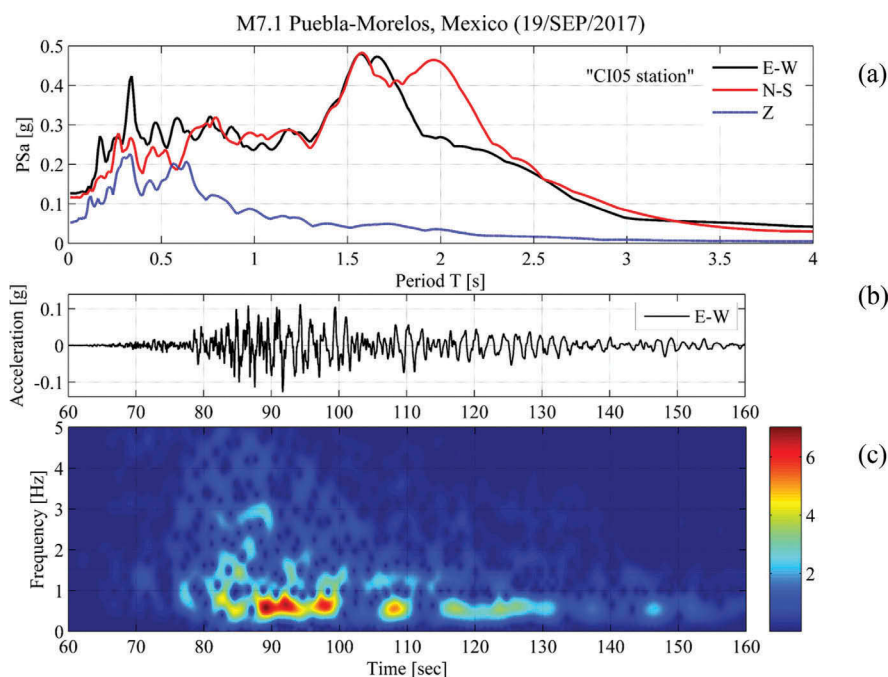


Figure 7. 2017 Mexico earthquake recorded at CI05 station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for E-W component. (c) Spectrogram for E-W component.

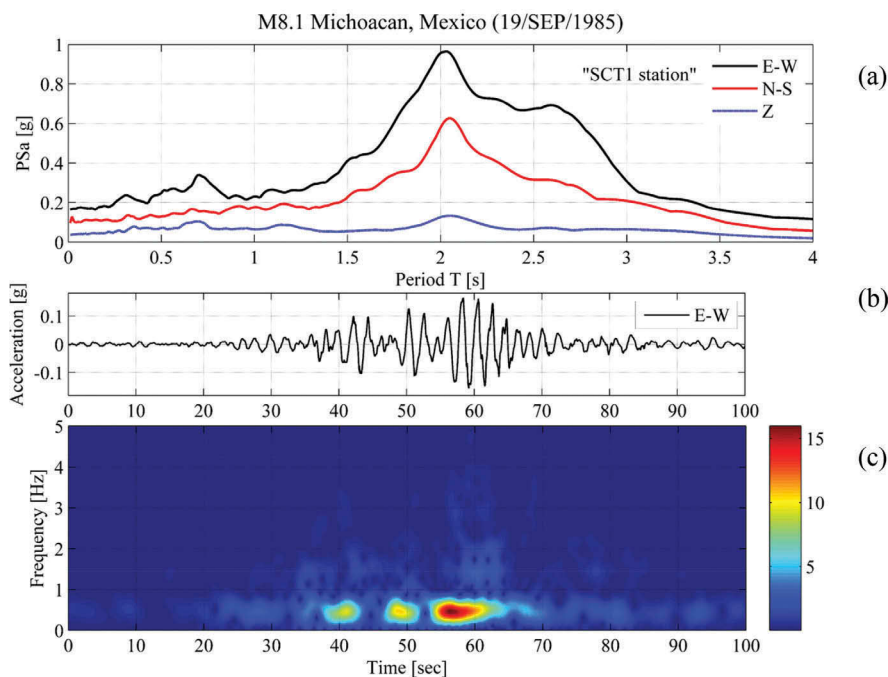


Figure 8. 1985 Mexico earthquake recorded at SCT1 station: (a) 5% damped acceleration response spectra (2PRS). (b) Acceleration time history for E-W component. (c) Spectrogram for E-W component.

that 2PRS for large subduction earthquakes are the rule for soft soils in epicentral areas due to separated effects of soil and source.

The first peak in short periods is due to source effect and the second peak in longer period is due to soil response effect. Also, the outcomes reveal that the period of soil peak has a good correlation with both the one estimated by Nakamura method and the other from low energy pulses detected in spectrograms.

The actual importance of 2PRS for earthquake engineering is that source peak affects houses or middle-rise buildings and soil peak affects high-rise buildings or base-isolated buildings. Therefore, design response spectra considered in seismic codes for soft soils should be modified in the future in order to consider both effects.

REFERENCES

- EERI 2016: M7.8 Muisne, Ecuador Earthquake on April 16, 2016. *EERI Earthquake Reconnaissance Team Report*. EERI.
- Gallegos, M.F. & Saragoni, G.R. 2017. Analysis of strong-motion accelerograph records of the 16 April 2016 Mw 7.8 Muisne, Ecuador earthquake. *Proc. 16th World Conference on Earthquake Engineering*. Santiago, Chile .
- Gómez, B.A. 2002. Interpretation of Soil Effects in Mexico Valley using the High-Density Accelerographic Network. *Ph.D. Thesis, National Autonomous University of Mexico*. Mexico. (in Spanish)
- Hayes, G.P., Myers, E.K., Dewey, J.W., Briggs, R.W., Earle, P.S., Benz, H.M., Smoczyk, G.M., Flamme, H.E., Barnhart, W.D., Gold, R.D., and Furlong, K.P. 2017. Tectonic summaries of magnitude 7 and greater earthquakes from 2000 to 2015. *Open-File Report 2016–1192*: 148 p. Virginia: U.S. G.S.
- Lobos, C. 1999. Effects of Source, Surface Waves and Soils in the Accelerograms of March 3, 1985, Chile Earthquake”. *Thesis, Civil Engineering Department, University of Chile*. Santiago. (in Spanish)
- Nakamura, Y. 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Reports of the Railway Technical Research Institute*, (30). 25–33.
- Rai, D.C. Singhal, V.Raj, B.Sagar, S.L.2015. Reconnaissance of the effects of the M7.8 Gorkha (Nepal) earthquake of April 25, 2015. *Geomatics, natural hazards, and risk*. Taylor & Francis.
- Ruiz, S. & Saragoni, G.R. 2005. The proposition of 2 Peaks Acceleration Response Spectra for the Chilean Seismic Code Considering the Effects of Soil and the Type of Subduction Earthquake. *Proc. IX Chilean Congress on Seismology and Earthquake Engineering*. Concepción. (in Spanish)
- Ruiz, S. & Saragoni, G.R. 2008. Two peaks response spectra (2PRS) for subduction earthquakes considering soil and source effects. *Proc. 14th World Conference on Earthquake Engineering*. China.
- Ruiz, S. & Saragoni, G.R. 2009. Free Vibration of Soils During Large Earthquakes. *Soil Dynamic and Earthquake Engineering* (29): 1-16.
- Sandoval, M. & Saragoni, G.R. 2015. Analysis of Seismic Demand in the Collapse of Alto Rio Building considering the propagation of waves during the earthquake of February 27, 2010. *Proc. XI Chilean Congress on Seismology and Earthquake Engineering*. Santiago, Chile. (in Spanish)
- Saragoni, G.R. Gonzales, P. Fresard M., 1986. Analysis of the Accelerograms of March 3, 1985, Chile Earthquake”. Chapter 3. *Book: “The March 3, 1985, Chile Earthquake ”*. J. Monge Editor. CAP. Santiago, Chile. (in Spanish)
- Saragoni, G.R. & Ruiz, S. 2004. Elastic Model 1D for the Soil Dynamic Response Obtained from the Analysis of Accelerograms of Chile Central Earthquake”. *Proc. 5th Chilean Congress of Geotechnics*. Chile. (in Spanish)
- Saragoni, G.R. & Ruiz, S. 2012. Implication and New Challenges for the Seismic Design from the 2010 Chile Earthquake. *Book: “M=8.8 Earthquake in Chile, February 27, 2010”*. University of Chile. (in Spanish)
- USGS 2016. M 7.8-27km SSE of Muisne, Ecuador. (*Last revised: March/2019*). <http://earthquake.usgs.gov/earthquakes/eventpage/us20005j32>
- USGS 2017. M 7.1-1km E of Ayutla, Mexico. (*Last revised: March/2019*).<https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20/executive>