Invited papers
Lessons learned from the 2016 Mw 7.8 Muisne-Ecuador earthquake

R. Verdugo
CMGI Ltda, Santiago de Chile, Chile

F.A. Ochoa-Cornejo
Department of Civil Engineering, University of Chile, Santiago de Chile, Chile

ABSTRACT: The Muisne Earthquake, of magnitude Mw 7.8, is among the strongest earthquakes in the recorded history of Ecuador. The ground motion produced the collapse of buildings, houses, and lifelines, causing more than 600 casualties, 1500 people missing, 3000 injured, and a cost of ~4 billion USD, equivalent to 4% of the Gross Domestic Product. A maximum horizontal acceleration of 1.41g was recorded in Pedernales. The most severe and common geotechnical damages were: soil liquefaction, landslides, slope failure in roads, site effect, and damage caused by the activation/disruption of geological faults. In particular, the liquefaction phenomenon was observed throughout all the cities inspected. Important settlements of houses, ejected sand cones, ejected sand cracks, and lateral spreading were observed. Significant ground displacements due to liquefaction and lateral displacements were observed in the accesses of bridges. The use of the Spectral Threshold Displacement Method is used to explain the observed structural damages.

1 INTRODUCTION

The Muisne Earthquake occurred in Ecuador on April 16th of 2016 at 18:58 local time, with a magnitude Mw 7.8, at an average depth of 20 km, and a rupture length of approximately 200 km (Beauval et al. 2017). It is among the strongest earthquakes in the instrumentally recorded history of Ecuador. This seismic event had its epicenter in the town of Muisne, located in the northern coastal area of Ecuador, close to the border with Colombia. One month after the main-shock, two strong aftershocks of Mw 6.7 and Mw 6.8 hit the same area, triggered by the same seismic mechanism. The Muisne Earthquake was of thrust nature, confirming the high subductive activity between both the Nazca and the South American plates. This seismic event has similar features with other strong earthquakes that previously affected the same region, such as the 1906 (Mw=8.8), the 1942 (Ms=7.9), the 1958 (Ms=7.8), and the 1979 (Ms = 7.7) earthquakes (Parra et al. 2016).

The ground motion induced by the Muisne Earthquake caused more than 650 deaths, 12 missing people, more than 4500 injured, and more than 80,000 people displaced, without their homes, due to the damage/collapse of more than 29,000 structures such as buildings, houses, and lifelines (INEC 2017). The earthquake-induced catastrophic damage in structures, ports, bridges, roads, and slopes, through several locations, in several cities such as Esmeralda, Muisne Island, Jama, Canoa, Bahia, Manta, Portoviejo, and San Isidro. The total reported financial cost for Ecuador was around USD 3.3 billion, which represents close to 1% of the PGD of Ecuador (INEC 2017).

After the main shock and the two strong aftershocks, the authors completed an earthquake reconnaissance campaign in the epicentral area to address the damages, focusing on those of geotechnical nature. The reconnaissance was completed covering the most affected facilities such as bridges, roads, ports, residential buildings, slopes, etc. The acceleration time histories of the seismic event are analyzed in the framework of their capability of inducing structural damages.
2 THE 2016 Mw 7.8 MUISNE EARTHQUAKE

The coastal area of Ecuador is located on the subductive margin originated by the collision of Nazca and South American plates with more than 750 km in length. A convergence velocity of up to 58 mm/year in the northern part of the country has been estimated (Trenkamp et al. 2002). This subductive environment has three main sections: 1) South Coast 2) Central Coast, and 3) Northern Coast. These areas have been the scenario of significantly strong earthquakes. The central coast has been affected by the earthquakes of 1896 (Mw 7.1), 1907 (Mw 7.4), 1942 (Mw 7.9), 1956 (Mw 7.4), 1998 (Mw 7.1), 2016 (Mw 7.8). The northern coast has been the scenario for the earthquakes of 1906 (Mw 8.8), 1958 (Mw 7.7) y 1979 (Mw 8.2) (Beauval et al. 2010, Chlieh et al. 2014). This sequence of seismic events suggests that Ecuador undergoes a severe-to-devastating earthquake, of magnitude over Mw7.5, every 20 (+/- 5) years.

Figure 1 shows both the geographic location and magnitude of some of the most important earthquakes that have struck Ecuador since 1906. The black star corresponds to the epicenter of the 1906 Mw 8.8 Great Ecuador Earthquake, and the black dotted line shows the area of rupture originated by this seismic event. The rupture area originated by the 1906 earthquake includes other rupture zones originated in subsequent significant seismic events, of magnitude

![Figure 1](image1.png)

Figure 1. The seismogenic setting of the subductive environment of Ecuador. The black star is the great 1906 event, while the red star is the epicenter location of the Muisne Earthquake. Modified and adapted from Chlieh et al. (2014).

![Figure 2](image2.png)

Figure 2. The empirical relationship between rupture length and moment magnitude. Modified and adapted from Wells & Coppersmith (1994).
higher than Mw7.0, such as those of 1942, 1958, 1979, and 1998 (Chlieh et al. 2014), which epicenters are indicated by white stars. The black-white crossed circle is the epicenter of the 2016 Muisne Earthquake, which is within the rupture area developed during the 1906 event.

The Muisne Earthquake had a moment magnitude Mw=7.8 and a maximum Mercalli Intensity VIII. The epicenter was located near the cities of Muisne and Pedernales, 170 km to the west of Quito; these cities were the most severely affected by the earthquake, presenting heavy damages and the collapse of several buildings, houses, and commercial infrastructure. The ground motion was recorded at 30 seismic stations of the Geophysical Institute of Ecuador (IGEPN 2016 - www.igepn.edu.ec/).

The length of the rupture zone of this earthquake was estimated of approximately 200 km, at an average depth of 20 km (IGEPN 2016). Figure 2 shows the relationship between rupture length and Moment Magnitude, adapted from the work of Wells & Coppersmith (1994), where data of two significant Chilean earthquakes are also included, which are associated with a similar subduction environment. The magnitude Mw7.8 of the 2016 Muisne Earthquake and the rupture length –plotted as a triangle– are in good agreement with this well-known correlation.

The largest peak horizontal and vertical accelerations were 1.41g (E-W component) and 0.74g, respectively, recorded at the APED station, located in the area of Pedernales, 33 km to the south of the epicenter. The second highest recorded accelerations also occurred in the area of Pedernales (station PDNS), with maximum horizontal and vertical accelerations of 1.06g, and 0.57g, respectively. In Figure 3 are presented the three components of the accelerations recorded in APED station and the corresponding elastic response spectra of pseudo-accelerations and displacements (considering 5% of the critical damping). It is important to mention that for predominant periods greater than 0.8 s, the spectral displacements are around 40 cm, which implies an important seismic demand in terms of deformation for the structures with natural periods in that range. This aspect is analyzed below.

3 FIELD RECONNAISSANCE OF THE EPICENTRAL AREA

As a result of the main shock of Muisne Earthquake, significant damage was observed in structures, slopes, and roads, particularly to the south of the epicentral area. In this context, the authors completed a reconnaissance campaign, one month after the earthquake, through some of the most affected cities: Esmeralda, Muisne Island, Jama, Canoa, Bahia, San Isidro, and Porto Viejo, addressing the damage, and focusing mainly in the geotechnical aspects. The

Figure 3. Acceleration records and elastic response spectra. Seismic station APED.
approximate distance between Esmeralda and Manta is about 200 km, a dimension equivalent to the length of the fault rupture induced by the Muisne Earthquake.

During the field reconnaissance, the geotechnical damage observed ranged in magnitude from cracks in pavements, or settlement in earth fill structures, to the liquefaction and failure of the ground, causing large deformations, affecting bridges, ports, industrial and residential facilities. Also, it was observed the activation of a geological fault that caused large deformations of the ground. Thus, the damage description classifies as follows: 1) damages affecting the serviceability of road infrastructure, 2) instability and failure of slopes of significant magnitude, 3) liquefaction and 4) activation of a geological fault. Additionally, an attempt to explain the significant damages observed in buildings is presented.

3.1 Roads and slopes

Minor, yet recurrent, the damage was observed in the road infrastructure of the epicentral area. This type of damage is illustrated in Figure 4. Figure 4 (a) shows the heave and cracking of pavement as a consequence of upstream slope failure. Figure 4 (b) shows the failure of the pavement as a consequence of the slope failure downstream. Figure 4 (c) shows the settlement, cracking, and misalignment of the pavement due to ground deformation, which might be associated with the activation of a fault line perpendicular to the axis of the road. Figure 4 (d) shows the settlement of the access fill to a bridge, which in some cases were larger than 20 cm, impeding the transit of vehicles across the bridge (See also Chunga et al 2018 and Chunga et al 2019).

Although the above-described damages can be classified as minor, because they were repeated in a large number of cases, their actual impact on the serviceability was tremendous. As a result, the traffic of the country following the earthquake was severely affected.

On the other hand, important slope failures seriously affected the infrastructure of Ecuador. It was recurrently observed the failure of slopes of sandstone, clayey soils, and residual soils, very characteristic of tropical climates such as that present in Ecuador. Among these slope failures, the most serious occurred in an area adjacent to the Main Pacific Road, 4 km south of the town of Canoa. The large slide had a total length of nearly 500 m, covering an important part of the road. Figure 5 shows the magnitude of this landslide two days after the earthquake. Before the earthquake, this slope was almost vertical, with a height of approximately 40 m. After the failure, the exposed face showed several planes of failure, suggesting the slope could have had a pre-existing plane of weakness. The material of this slope is sandstone, geologically young, which means that it presents incipient cementation, and therefore, it is a material in its transition from soil to rock. This is a complex material that requires a stability analysis considering both soil and rock mechanics.

Figure 4. The various types of damage observed in roads due to slope failure and ground displacement.
3.2 Liquefaction

Liquefaction failure was recurrently observed throughout the field reconnaissance post-earthquake, particularly in the coastal part of the epicentral area. Below are described the observations made in Muisne, the city of Manta and its port, and the Mejia Bridge.

Muisne is a small island in the north of Ecuador, very close to the continent, but accessible only by ferry. This small city presented a significant number of sites with minor-to-moderate liquefaction, which evidence is depicted in Figure 6. The uplift of a water lifeline entrance (manhole) is shown in Figure 6 (a), while Figure 6 (b, c) show the settlement of the ground as well as ejection cones. Figure 6 (d) shows the effect of differential settlement due to these phenomena on a residential house. The moderate effects of liquefaction can be explained on the little sloping ground of the island, preventing the occurrence of significant lateral movement of the ground. The observed settlements were also small, suggesting that the thickness of the liquefiable soil layer is small.

Manta is one of the most important cities on the coast of Ecuador. In this city, its port suffered significant earthquake-induced damage mainly due to liquefaction. Figure 7 shows pictures of different views of the port infrastructure. Figure 7 (a) shows the area for car storage (yard 500), which presented liquefaction and lateral spreading with maximum deformations a bit lower than half a meter. Figure 7 (b), taken by Nikolaou & Vera-Grunauer (2016), shows a significant amount of ejected sand spread on the surface of this sector, as well as the tension

Figure 5. Slope failure on a sandstone material.

Figure 6. Liquefaction in Muisne Island. (a, b) Liquefaction settlement of the ground, c) Sand ejection cones, and d) Effect of liquefaction settlement on a house.
cracks on the pavement. Yet significant, the deformations in this area were limited, with no catastrophic damage. The port was able to continue with its operations partially; many areas require significant repair due to relative displacements, settlements, and structural damage, as observed in Figure 7 (c).

It is also important to mention that the main breakwater of the Port of Manta presented damages like settlement and local instabilities of the riprap slope on the inner side also due to liquefaction of loose sands below the sea bottom as seen in Figure 7 (c). The depth of the

Figure 7. Damage in the port of Manta. a) Ejected sand through pavement cracks from liquefaction, b) Lateral spreading of the car storage area (Nikolau et al. 2016), c) Damage on pavements, d) Cracks and displacements in retaining walls, e) Failure due to liquefaction, f) settlement of the road that accesses to the marginal wharves, and g) Failure of South Access of Mejia Bridge.
stratum of this loose sand is around 2.20 meters. Lateral displacements at the breakwater ranged between 0.20 to 0.60 meters. The internal roads were also affected as seen in Figure 7 (d). The width of the longitudinal cracks reached maximum values of 0.20 meters at the roads that access to the international piers. Liquefaction and the associated lateral spreading caused severe structural damage at some piles of the marginal wharf and the two international piers, as depicted in Figure 7 (e). The marginal wharf was 620 meters long and 12 meters wide. The two international piers are 200 meters long and 45 meters wide. The significant settlement was also observed, as much as 0.50 meters, at the internal road that accesses to the marginal wharves and international piers (Figure 7 (f)).

The most severe liquefaction failure was observed in the Mejia Bridge, close to the city of Portoviejo. In this case, the earth fill abutment of the south access experienced significant settlement and lateral spreading due to the liquefaction suffered in the natural soil beneath of the earth fill slope close to the shore of the river, as indicated in Figure 7 (g). From a structural point of view, the Mejia Bridge had a very good response to the earthquake, presenting no damage.

3.3 Evidence of the activation of a geological fault

Evidence of the possible activation of a geological fault was observed in the San Isidro area, approximately 200 km to the east of Bahia de Caraquez. As a consequence, the ground settled and displaced catastrophically, for several meters, in an extension of many kilometers. Should this area have been populated, it would have cost significant losses. Figure 8 shows one of the areas where the ground significantly displaced, inducing the collapse of minor local constructions. The vertical slope shows the magnitude of the displacements observed in this area of San Isidro, which were of the order of 5 meters. This case, where it seems that a hidden geological fault already existed, and the earthquake triggers its activation in terms of both vertical and horizontal displacements, is of great importance for the earthquake engineering because it shows a real possible scenario. The strong tectonism existing in several seismic areas inevitably induces faults, which can be abruptly activated by large earthquakes, with consequences that are not yet considered in the seismic risk analyses.

4 BUILDING DAMAGE AND THE THRESHOLD DISPLACEMENT SPECTRUM

4.1 Observed damages

There were areas in the cities of Manta and Portoviejo where it was possible to observe concentrated damage and a significant amount of building collapse. The authorities designated these areas as “ground zero” areas, with restricted access and military vigilance. Figure 9 shows the catastrophic damage observed in these areas. Figures 9 (a,b) show two of the many buildings that collapsed in the city of Portoviejo. Figures 9 (c,d) are from the “ground zero” area of Manta.

There is no significant amount of public information regarding the geotechnical and geological information of the subsoil in Manta. Therefore, it is unclear if the damage
concentration is due to site effects and ground motion amplification. However, in Tarqui, one of the neighborhoods of the “ground zero” area of Manta, it was observed liquefaction. Figure 10 show the settlement of one, out of many, structures that suffered liquefaction in this sector. These observations suggest the ground presents –mainly- low-to-medium relative density sand deposits. This area was less than 1 km from the beach. Also, during the field reconnaissance, it was observed that the water table was at a depth less than 2 meters. Therefore, the conditions of this area indicate the existence of low stiffness soil deposits, which could induce large displacements in flexible structures, suggesting the damage could be due to the occurrence of site effect. Likewise, the “ground zero” area of Portoviejo presents no available information regarding the ground conditions. However, there were areas with a significant amount of liquefaction, especially close to the area where the river originally flowed. These observations suggest that the “ground zero” area of Portoviejo might have experienced a similar effect to that observed in the “Ground Zero” area of Manta.

4.2 Ecuadorian provision

According to the NEC-SE-DS (MIDUVI 2015), the coastal area of Ecuador classifies as a seismic zone type VI, of high seismic risk. This area considers a maximum acceleration—in rock—of approximately 0.5g, with a 10% of probability to be exceeded in 50 years. The seismic records that exceeded accelerations of 0.5g were stations APED, APDN, and AMNT. In this

Figure 9. a) and b) Partial and total collapse of buildings in the “ground zero” area of Portoviejo, c) and d) partial collapse of buildings in the “ground zero” area of Manta.

Figure 10. Ground settlement due to liquefaction onset, in the “ground zero” area of Manta.
context, Figure 11 (a) shows the elastic pseudo-acceleration response spectra, calculated with 5% of damping, associated with the time histories recorded in these stations in both NS and EW. Also, the five possible design spectra depending on the type of soil are plotted. The records obtained in Pedernales present a response spectra that exceed the design spectra, regardless of the type of soil. This situation was also observed in the 2010 Great Maule Earthquake and 2015 Illapel Earthquake. Figure 11 (b) shows the results of the design spectra for any type of soil, and how they are exceeded by the calculated response spectra obtained by the acceleration time history of these earthquakes.

4.3 Results from applying the “Spectral Threshold Displacement Method.”

The seismic response of the structures is strongly governed by their deformation capacity, so it is necessary to keep in mind that the displacements could be more important than the force-resistance characteristic of a structure. The design method based on displacements is gaining more popularity among engineers because the deformation capacity allows a better image of structural performance under lateral seismic stresses (Priestley et al. 2007).

In order to analyze the lateral displacements induced in a structure by an earthquake, it is useful to consider the well-known empirical relationship between the number of levels of a building, NL, and its fundamental period of vibration, $T_f$ (Verdugo et al. 2018):

$$ T_f = \frac{NL}{\lambda} \text{(seconds)} $$

(1)

The empirical parameter $\lambda$ is associated with the lateral stiffness of the building, with units 1/s. This classic empirical relationship can be rewritten in function of the total height, H, of a building. An average story height of 2.7 m is estimated representative of residential buildings. Accordingly, the total height is $H = NL \times 2.7$. Then, the fundamental period of a building can be estimated as:
On the other hand, a relevant parameter to estimate the seismic performance of buildings is the lateral drift ratio (LDR) defined as the ratio between the maximum roof displacement, \( RD_{\text{max}} \), and the total height \( H \) of the building, that is:

\[
LDR = \frac{RD_{\text{max}}}{H}
\]  

(3)

The maximum roof lateral displacement, \( RD_{\text{max}} \), can be estimated from the elastic displacement of multi-degrees of freedom system, which can be correlated with the maximum elastic displacement, \( D_{\text{max}} \), of one degree of freedom system, of the same natural period. The difference is of the order of 15 to 26\% (Moehle 1992, Chopra et al. 2001). Therefore, 30\% is considered conservative, which allows the following relation:

\[
LDR = \frac{1.3D_{\text{max}}}{H}
\]  

(4)

Combining expressions (2) and (4), the following correlation is obtained for the maximum lateral displacement as a function of the fundamental period of a building:

\[
D_{\text{max}} = \frac{2.7 \times LDR \times \dot{\lambda}}{1.3} T_f \text{ (in meters)}
\]  

(5)

If a value of the lateral drift ratio, \( LDR \), is adopted, such that it is associated with a condition of initiation of inelastic behavior, this expression represents a limit displacement spectrum or a threshold spectrum. For example, in the case reinforced concrete buildings this value is in the range of 0.004 to 0.007, and a representative value is: \( LDR = 0.006 \). Thus, the displacement threshold spectrum for reinforced concrete buildings is:

\[
D_{\text{max}} = S_d = 0.01246 \times \dot{\lambda} \times T_f \text{ (in meters)}
\]  

(6)

The structural systems used in Ecuador are mainly flat slabs on columns, without girders, and reinforced concrete frames. In general, columns of buildings up to five-six stories are very slender. In Figure 12, a typical heavy damaged building is shown, where the slender columns and the absence of beams are observed. For this type of flexible structures, the value of \( \lambda \) is low, being possible to consider \( \lambda = 9 \). Therefore, the expression of the Threshold Displacement Spectrum can be written as:

\[
S_{d-\text{limit}} = 0.1121 \times T \text{ (in meters)}
\]  

(7)
Taking into account that the elastic response spectra of both pseudo-acceleration, $S_a$, and displacement, $S_d$, are directly related through the natural period, $T$:

$$S_d = \frac{T^2}{4\pi^2} S_a$$  \hspace{1cm} (8)

A criterion of spectral pseudo-acceleration threshold can be equivalently established. In the case of reinforced concrete buildings with the typology used in Ecuador, the following expression is obtained:

$$S_{a-limit} = \frac{4.427}{T} \left( \frac{m}{S^2} \right)$$  \hspace{1cm} (9)

The elastic response spectra of displacements and pseudo-accelerations from the acceleration records of stations ACHN, AMNT, APED, APO1, and ASDO, are plotted in Figure 13, with the previously deduced threshold displacement and pseudo-acceleration spectra. It is observed that buildings in a large range of natural periods were subjected to lateral displacements that induced a lateral drift ratio larger than 0.006, and therefore, seismic-induced damages are apparent. These data show that the limit spectra are exceeded, explaining the significant damage in buildings.

5 CONCLUDING REMARKS

The Muisne Earthquake, with $Mw = 7.8$, of subduction nature, hit Ecuador on April 16th of 2016, with a rupture length of approximately 200 km and an average depth of 20 km, in the same subduction environment where past strong earthquakes have affected Ecuador. The highest registered accelerations were 1.41g (horizontal) and 0.74g (vertical), in the area of Pedernales. The ground motion caused more than 28,000 damaged/collapsed urban and industrial facilities throughout the affected area, with a direct cost of USD 3.34 billion, close to 1% of its PGD. The most affected area was to the south of the epicenter, in cities like Esmeralda, Muisne Island, Jama, Canoa, Bahia, Manta, Portoviejo, and San Isidro. Evidence of liquefaction was extensively observed, and recurrent failures of roads seriously affected transportation.
after the earthquake. Two particular failures can be considered new lessons for the earthquake
tectonic engineering: the week seismic behavior of young geological sandstone, which
cementation is rather incipient, responding as a transition material between soil and rock, and
the abrupt activation of hidden geological faults that can exist in a region with strong tecton-
ism. Additionally, the concept of a threshold displacement spectrum to establish the level of
allowable lateral displacement of RC building was used. It is shown that the acceleration
records of several seismic stations exceeded the threshold displacement spectrum, which
clearly explains the significant observed damages in buildings.

ACKNOWLEDGEMENTS

Funding from the Department of Civil Eng. of U. of Chile and CMGI are gratefully appreci-
ated. The collaboration and assistance of the faculty of ESPOL, as well as the contribution of
G. Valladares (CMGI), P. Pizarro, C. Rodriguez, and R. Castro (U. of Chile) are also
acknowledged

REFERENCES

Beauval, C., Marinière, J., Laurendeau, A., Singaucho, J.-C., Viracucha, C., Vallée, M., Maufroy, E.,
Attenuation for the 16 April 2016 Mw7.8 Ecuador Megathrust Earthquake and its Two Largest Afters-
shocks with Existing Ground Motion Prediction Equations. Seismological Research Letter, 88(2A),

magnitudes of historical earthquakes in the Sierra of Ecuador (1587–1996). Geophysical Journal In-
ternational, 181(3),1613–1633.

Chlieh, M., Mothes, P. A., Nocquet, J. M., Jarrin, P., Charvis, P., Cisneros, D., Font, Y.,Rolandone, F.,
Vallée, M., Régnier, M., Segovia, M., Martin, X., Yepes, H., Mothes, P. A., Nocquet, J. M. -, Collot,
J. - Y., Villegas-Lanza, J. - C. 2014. Distribution of discrete seismic asperities and aseismic slip along
10.1016/j.epsl.2014.05.027.

ment for pushover analysis of buildings. PEER Report 2001/16, Univ. of California Berkeley.

Chunga, K., Livio, F., Mulas, M., Ochoa-Cornejo, F., Besenzon, D., Ferrario, M. F., & Michetti, A. M.
2018. Earthquake Ground Effects and Intensity of the 16 April 2016 Mw 7.8 Pedernales, Ecuador,
of the Seismological Society of America, 108(6),3384-3397.

Chunga, K., Ochoa-Cornejo, F., Mulas, M., Cruz, M. & Menendez, E. 2019. Characterization of seismo-


Directorio de Comunicación Social, Ministerio de Desarrollo Urbano y Vivienda.

conference, Balkema, Rotterdam (pp. 4299-4302).

Nikolaou, S. & Vera-Grunauer, X. 2016. GEER-ATC Earthquake reconnaissance April 16th 2016,
Muisne, Ecuador. DOI: doi:10.18118/G6F30N.


Trenkamp, R., Kellogg, J. N., Freymueller, J. T. & Mora, H. P. 2002. Wide plate margin deformation,
southern Central America and northwestern South America, CASA GPS observations. Journal of

in areas with large earthquakes. Soil Dynamics and Earthquake Engineering.

Length, Rupture Width, Rupture Area, and Surface Displacement. Bulletin of the Seismological Soci-
ety of America, 84(4),974–1002.