16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4998
Registration Code: S-H1473800357

STRUCTURAL OBSERVATIONS - M7.8 - APRIL 16, 2016 ECUADOR EARTHQUAKE

R. Gilsanz[(1)], X. Vera-Grunauer[(2)], S. Nikolaou[(3)], E. Miranda[(4)], V. Diaz[(5)], L. Hernandez[(6)], C. Arteta Torrents[(7)], G. Diaz-Fanas[(8)], R. Luque[(9)],

(1) *Gilsanz Murray Steficek LLP, USA, ramon.gilsanz@gmsllp.com*
(2) *Instituto de Ingeniería, Universidad Católica Santiago de Guayaquil, Geoestudios, Ecuador, xvg@geoestudios.com.ec*
(3) *WSP|Parsons Brinckerhoff, USA, nikolaous@pbworld.com*
(4) *Civil and Environmental Engineering, Stanford University, USA, emiranda@stanford.edu*
(5) *Gilsanz Murray Steficek LLP, USA, virginia.diaz@gmsllp.com*
(6) *Gilsanz Murray Steficek LLP, USA, laura.hernandez@gmsllp.com*
(7) *Universidad del Norte, Colombia, carteta@uninorte.edu.co*
(8) *WSP|Parsons Brinckerhoff, USA, diazfanasg@pbworld.com*
(9) *UC Berkeley, USA, obluque@gmail.com*

Abstract

On Saturday, April 16, 2016 a massive magnitude-7.8 earthquake rocked Pedernales Canton, Ecuador. Widespread damage was caused across Manabí province, with structures hundreds of miles from the epicenter collapsing. In general, all levels of damage were observed, from small cracks to completely collapsed buildings. The damage in each building was dependent on the structural system, poor seismic detailing, poor construction practices, quality of materials, and intensity of the ground motion.

This paper presents selected structural reconnaissance observations from the main M7.8 Pedernales, Ecuador earthquake, including types of construction, common practices, failures and typical damage observed and will focus on the typical construction type of buildings observed in the affected areas: reinforced concrete structures with flat slabs. The complete report will be shared by the US-Ecuador Geotechnical Extreme Events Reconnaissance (GEER) team via the GEER website: http://www.geerassociation.org/.

Keywords: earthquake reconnaissance, structural observations, types of construction, common practices, damage.

1. Introduction

On Saturday April 16th at 6:58 pm (local time) a 7.8 magnitude earthquake struck Ecuador and caused severe damage in the country. At least 663 people are known to have been killed, more than 6,200 were injured, and almost 30,000 more were affected and moved to shelters.

The earthquake struck near the Pedernales Canton on the western coast of Ecuador. Instituto Geofísico of Escuela Politécnica Nacional has reported 2,284 aftershocks since the event, with at least nine measuring greater than magnitude 6.0. Initially after the event, there were concerns of a potential tsunami; however tsunami warnings were withdrawn later that same day. During the seismic event, numerous buildings and houses in the northwest of Ecuador were damaged. Most of the structural damage was caused by the first major earthquake.

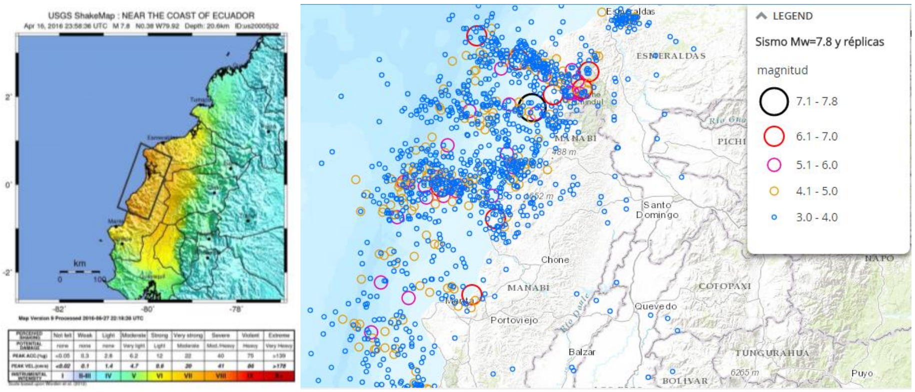
In general, all levels of damage were observed, from small cracks to completely collapsed buildings. The damage in each building was dependent on the structural system, seismic detailing, construction practices, quality of materials, and intensity of the ground motion. Of the places visited by the reconnaissance team, the towns and cities with the most damaged buildings were Pedernales (~35 km from the epicenter), Canoa (~58 km from the epicenter), Portoviejo (~169 km from the epicenter) and Manta (~172 km from the epicenter).

This paper presents selected structural reconnaissance observations from the main M7.8 Pedernales, Ecuador earthquake, including types of construction, common practices, failures and typical damage observed. It will focus especially on the analysis and review of the most common building type observed in the affected areas - reinforced concrete buildings with a modified two-way joist waffle slabs system, supported on reinforced concrete columns. The complete report will be shared by the US-Ecuador Geotechnical Extreme Events Reconnaissance (GEER) team via the GEER website: http://www.geerassociation.org/.

2. Affected Areas

The earthquake struck near the Pedernales Canton on the western coast of Ecuador. It was felt mainly in locations near the epicenter, located between the provinces of Manabi and Esmeraldas. The Manabi Province suffered the most damage. Among the towns and cities within the Manabi Province, Pedernales (one of the closest to the epicenter), Bahia de Caraquez, Manta, and Portoviejo were the most affected.

After the earthquake, the Pacific Tsunami Warning Center located in Hawaii (United States), issued a precautionary tsunami warning for Ecuador, Colombia, Costa Rica, Panama and Peru; the warning was withdrawn at approximately midnight the same day.



a) b)

Fig. 1**:** a) USGS Shake Map of Muisne, Ecuador M7.8 (http://earthquake.usgs.gov/earthquakes/eventpage/us20005j32#shakemap) b) Earthquake and aftershocks since April 16th. Instituto Geofisico-Escuela Politecnica Nacional. (http://www.igepn.edu.ec/mapas/mapa-evento-20160416.html)

3. Building Inventory and Construction Types

The reconnaissance trip focused on the province of Manabí and observed the following building types in the earthquake-affected areas:

- Reinforced Concrete (RC) Buildings: these can be subdivided into three categories based on the construction type:
  - Reinforced concrete buildings with a modified two-way joist waffle slabs system, supported on reinforced concrete columns. Typically, the form blocks in the waffle slabs are not removed after slab placement.
  - Reinforced concrete buildings with one-way beams and waffle slabs, supported on reinforced concrete columns.
  - Reinforced concrete buildings with moment resisting concrete frames and two-way waffle or flat slabs, supported on reinforced concrete columns
- Steel Framed Buildings
- Wood Framed Buildings: these were typically two-story buildings and single-story residences with metal roof decks.

In general, all these structures had masonry infill, hollow brick masonry partitions and unreinforced hollow clay masonry.

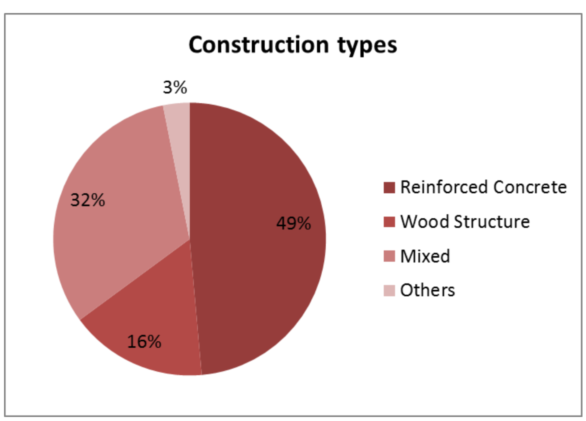


Fig. 2**:** Construction types, data collected from Gestion de Riesgos Ecuador –Mesa #3 up to June 22, 2016. (http://gestionriesgosec.maps.arcgis.com/apps)

3.1 Reinforced Concrete (RC) Buildings with a Modified Two-Way Joist Waffle Slabs System, Supported on Reinforced Concrete Columns

The majority of the buildings observed were reinforced concrete structures with a modified two-way joist waffle slabs system, supported on reinforced concrete columns. Typically, forms were concrete hollow blocks in waffle slabs and were not removed after slab placement.

a) b) c)

Fig. 3: a) Residential building under construction with two-way waffle slabs in Tarqui, Manta. (GPS coordinates: 0°57'28.67"S, 80°42'32.41"W). b & c) Details of beam reinforcement near a beam-column joint in the back of the house (GPS coordinates: 0°57'28.67"S, 80°42'32.41"W). (Photos by GMSLLP & Droneando ©)

a) b)

Fig. 4: a) New construction where the form blocks can be observed in the waffle slab in Tarqui, Manta (GPS coordinates: 0°57’27.3”S, 80°42’32.9”W). b) Residential building under construction with two-way waffle slabs in Manta (GPS coordinates: 0°57’8.1”S, 80°42’26.9”W). (Photos by GMSLLP)

Residential reinforced concrete buildings are typically two to five stories in height with an additional metal deck roof that covers a roof terrace. The first floor of these residential buildings is generally commercial space. Some floors cantilever more than 5 ft. past the ground floor footprint. In general, the slabs in these building are 8 in. (20 cm) thick composed of concrete hollow blocks, with a 2-3 in. (4-5 cm) thick layer of concrete topping (approx. weight is 100 psf or 480 kg/m2). The spacing of the columns is 10-13 ft. (3-4 m), and the typical story height is 11 ft. (3.30 m). During an earthquake event, the mass of the slab will cause a large lateral load that cannot be resisted by the column system only. In most buildings in Ecuador with this type of construction system, there is a lack of shear walls or moment frames to resist seismic loads. In most affected areas, the reconnaissance team observed a lack of earthquake resistant details.

There is no formal organized education system for the builders of this region. In coastal cities, it is common practice to use beach sand and sea water in the concrete. This practice leads to rapid corrosion of the steel reinforcing in the concrete. Several examples of corroded reinforcing steel were observed in the areas visited.

3.2 Reinforced Concrete Detailing

There is a lack of seismic detailing as well as typical gravity detailing in existing and new construction. This was observed in the majority of the buildings. Common findings included:

- Dowels missing in slab and column connections.
- Hoops that were made with smooth steel with an approximate diameter of 1/4 in. (6.4 mm) in most cases.
- Stirrup spacing that seemed to be as large as the effective element depth for beams and columns.
- Large stirrup spacing in two-way slabs.
- Columns that were not confined.
- Stirrups spacing that did not decrease towards the ends of columns.
- Smooth longitudinal steel in the columns of some older multi-story moment frame buildings.

a) b)

Fig. 5: a) A first floor column in the three-story Hotel Las Gaviotas in Tarqui, Manta. There is significant spalling which can be attributed to both previously corroded steel and the seismic demand imposed by the earthquake (GPS coordinates: 0°57’5.7”S, 80°42’48.5”W). b) Small-diameter-hoop spacing details of a first floor unconfined column in a four-story commercial building in Tarqui, Manta (GPS coordinates: 0°57’14.9”S, 80°42’53.9”W). (Photos by C. Arteta Torrents)

Fig. 6: Damage at the base of six-story mixed-occupancy building in Tarqui, Manta. There is significant spalling at the bottom of the first floor columns, exposing smooth longitudinal rebar and hoop spacing of approximately 2/3 of the column width. (GPS coordinates: 0°57'14.55"S, 80°42'53"W). (Photos by C. Arteta Torrents)

a) b)

c) d)

Fig. 7: a) & b) Failure of first floor columns in a building under construction in Canoa. The column has large stirrup spacing. c) The slab to column connection at the edge shows a lack of dowels and therefore provides no structural integrity (GPS coordinates: 0°27'42.67"S, 80°27'20.67"W) (Photos by GMSLLP & C. Arteta Torrents) d) Failure of first floor columns in building under construction in Canoa. The slab to column connection at the edge shows a lack of dowels and therefore provides no structural integrity (GPS coordinates: 0°27'42.67"S, 80°27'20.67"W) (Photos by GMSLLP)

Evidence of good transverse reinforcement detailing was scarce. Columns in multi-story RC buildings are subjected to combined flexural-tension and flexural-compression actions due to the demand imposed by earthquake loading. Proper transverse/seismic longitudinal and transverse reinforcement layouts in columns must ensure the protection of the concrete core when the concrete cover spalls-off due to the aforementioned actions. Such proper reinforcement layouts generally comprise of closely spaced hoops and crossties, both with seismic 135-degree hooks anchored into the core, along with closely space longitudinal steel in the perimeter of the column. This creates a tight reinforcing cage that guarantees concrete core confinement, thereby ensuring adequate ductility of the structural element. Figure 8 shows a column that maintained an apparently healthy core following the earthquake thanks to proper longitudinal and transverse reinforcement detailing. The column was found in Zona Cero (Ground Zero) of Portoviejo, an area of the city that suffered heavy damage and was cordoned off by the military.

Fig. 8: Column with spalled-off concrete cover and evidence of healthy a core thanks to closely spaced perimeter hoops and cross-ties. Zona Cero in Portoviejo. (GPS coordinates: 1°3'13.53"S, 80°27'8.60"W) (Photo by E. Miranda)

4. Main Structural Observations and Structural Behavior

Generally there was medium to severe damage. In residential areas along the coast, buildings were significantly damaged. The following categories characterize the typical types of damage observed in the commercial and residential reinforced concrete buildings in these areas.

Soft story damage: Various buildings had a commercial first floor with residences on the upper floors. Several of these had soft story damage where one or two floors had been completely crushed. Significant hinging of the first floor columns occurred in some of these damaged structures which may have been due to the change in stiffness at the compromised story. Typically, the compromised story was surrounded by stiffer stories with larger masonry infill densities. These stiffer stories were located either above or above and below the compromised stories.

a) b) c)

Fig. 9: Soft story failure. a) The first floor of this building in Manta collapsed. Some of the rebar in the columns that failed were corroded. Additionally, the columns were not confined (GPS coordinates: 0°57'14.8"S, 80°42'31.6"W). b) The first floor of this building in Tarqui, Manta collapsed. Column confinement was not apparent (GPS coordinates: 0°57'29.9"S, 80°42'42.1"W). c) The second floor of this building in Portoviejo collapsed (GPS coordinates: 0°57'29.9"S, 80°42'42.1"W). (Photos by GMSLLP)

Fig. 10: Plastic hinging in the first floor columns of this residential building with first floor commercial occupancy in Tarqui, Manta (GPS coordinates: 0°57'7.1"S, 80°42'55.3"W).

Fig. 11: Plastic hinges formed in the first floor columns of this building in Manta (GPS coordinates: 0°57'9.5"S, 80°42'49.4"W). (Photos by C. Arteta Torrents)

Captive columns: For some buildings, the stiff partial-height nonstructural masonry walls or concrete blocks between columns restrained the column height. This exacerbates the shear demand on the column when plastic flexural demand concentrates at their ends.

a) b)

Fig. 12: a) The fourth and fifth floors collapsed in this residential building in Portoviejo (GPS coordinates: 1°3'13.53"S, 80°27'8.60"W). b) The concrete blocks restrained the column height, causing captive column failure for this column. (Photos by GMSLLP)

Rebar corrosion: There was significant corrosion observed in the rebar in reinforced concrete structures. This was likely caused by the common practice of using of salty sand and/or salty water in the concrete admixture. The corrosion could have also been caused by the extended exposure of the rebar prior to pouring concrete. Observations in the field indicate that for some structures, the diameters of bars of longitudinal and transverse reinforcement were reduced due to corrosion.

a) b)

Fig. 13: a) Rebar corrosion in a beam-column connection, and slab reinforcement in a three-story building located in Tarqui, Manta (GPS coordinates: 0°57'7.94"S, 80°42'41.90"W). b) Rebar area reduction at the base of a column and failure due to soil liquefaction in a two-story house located in Tarqui, Manta (GPS coordinates: 0°57'19.77"S, 80°42'40.68"W). (Photos by C. Arteta Torrents)

Pounding: In highly populated areas such as in the Zona Cero (Ground Zero) in Manta and Portoviejo, separation between adjacent structures was not typical. This facilitated unfavorable interaction between structures that had no evident seismic gap. During the earthquake, the building drifts caused them to pound against each other which caused severe damage in columns, and/or caused permanent displacement for some buildings.

a) b)

Fig. 14: a) Pounding of independent buildings at the Bahia Airport (GPS coordinates: 0°36’5.3”S, 80°24’27.0”W). b) Pounding of two buildings in Portoviejo. The reconnaissance team observed that the roof metal deck is continuous at the separation (GPS coordinates: 1°3’11.6”S, 80°27’8)

Fig.15: Pounding evidence in Hotel Las Gaviotas in Tarqui, Manta (GPS coordinates: 0°57'6.08"S, 80°42'48.85"W) (Photos by GMSLLP & C. Arteta Torrents)

Failure of nonstructural walls: Most interior and exterior walls were composed of masonry, brick, hollow clay or concrete blocks. These walls were most likely conceived and constructed as nonstructural elements. However, during the earthquake these walls were subjected to seismic loads and functioned as part of the lateral load resisting system due to their large in-plane stiffness. The walls were not detailed to resist such loads and failed. These walls have little strength and ductility. Most walls were cracked or, in severe cases, collapsed out-of-plane. There were no concrete shear walls observed. The collapse of these nonstructural walls was the most life-threatening failure, apart from complete structural collapse.

a) b)

Fig. 16: a) Concrete building with wood and metal deck extension in Portoviejo. Nonstructural wall completely collapsed (GPS coordinates: 0°57’14.6”S, 80°42’38.5”W). b) Concrete building in Canoa where brick and masonry exterior walls collapsed. (GPS coordinates: 0°27'46.59"S, 80°27'23.56"W). (Photos by GMSLLP)

a) b)

Fig. 17: a. Residential building in Tarqui, Manta, where the exterior walls collapsed. The roof also fell in this property. (GPS coordinates: 0°57’14.6”S, 80°42’38.5”W). (Photos by GMSLLP). b. This is a site of new construction. These are dowels at the concrete columns to be attached to the nonstructural walls (GPS coordinates: 0°57'7.31"S, 80°42'26.44"W). (Photo by GMSLLP)

Building Collapse: Often partial or total collapse of structures, many of them due to the failure on upper floors was observed. During the reconnaissance trip many of the collapsed buildings were being removed by the government to prevent future damage.

a) b)

Fig. 18: a) Sideway collapse of residential structure in Pedernales (GPS coordinates: 0°4'4.8"N, 80°3'23.5"W). (Photo by GMSLLP) b) Building collapse in Pedernales. The columns shown have hinges at both ends (GPS coordinates: 0°4'3.94"N, 80°3'24.6"W) (Photo by Photos by GMSLLP)

Fig. 19: a) Collapse of building with flat slab construction in Pedernales (GPS coordinates: 0°4'2.5"N, 80°3'33.9"W) (Photo by GMSLLP). b. Collapsed building that was under construction. The construction type was reinforced concrete two-way flat slabs supported on columns (GPS coordinates: 0°27'43.8"S, 80°27'21.0"W). (Photos by GMSLLP)

5. Construction Means/Methods/Implementation

A common practice is building additional floors on top of existing buildings when more space is required. This is a typical type of structural alteration that was observed. This increases not only the gravity and wind loads, but also significantly increases the seismic load because each additional floor adds mass to the structure at a greater height off the ground.

The GEER team also observed that in the majority of the buildings, dowels were left exposed on top of columns without protection in anticipation of future structural additions. This practice can lead to rebar corrosion, which in turn can lead to a discontinuity being built into the structure at the interface between the new addition and the existing building when an addition is constructed.

The Unidad Educativa "Linus Pauling," a school located at 108 Street and 111 Avenue in Tarqui, Manta was comprised of the original five-story reinforced concrete building attached to a newer building of the same height. The older portion of the building completely collapsed; the newer portion did not have significant visible structural damage except for the area where it attached to the older building. The reconnaissance team was informed by neighbors that the school grew "a couple of stories" in the last years.

a) b)

Fig. 20: a) Unidad Educativa "Linus Pauling" in February 2015 (Google Maps ©2015 Google Inc.). b) Image taken during reconnaissance observation. The older portion of this structure collapsed (GPS coordinates: 0°57'23.3"S, 80°42'41.0"W). (Photos by GMSLLP)

a)

b)

Fig. 21: a) Side view of Unidad Educativa "Linus Pauling" in February 2015 (Google Maps ©2015 Google Inc.). b) Reconnaissance photos of collapsed building after the earthquake (GPS coordinates: 0°57'23.3"S, 80°42'41.0"W). (Photos by GMSLLP)

5.1 Materials

Several existing reinforced concrete structures were built using aggregates containing salty sand or salt water. This causes significant corrosion in the rebar which alters the strength of rebar and the bond to the concrete. For example, in Manta which is adjacent to the Pacific Ocean, observations in the field indicate that exposed rebar in structurally damaged buildings was previously corroded in some cases, with an effective reduction in diameter of the longitudinal, as well as the transverse steel.

a) b)

Fig. 22: Building materials near Los Esteros Market in Tarqui, Manta. a) Fine aggregate with sea shells. b) Good quality coarse aggregate (GPS coordinates: 0°57'8.94"S, 80°42'29.38"W). (Photos by C. Arteta Torrents)

a)

b)

Fig. 23: Signs of severe corrosion on reinforcing steel prior to the earthquake. a) Collapsed electric pole with signs of reinforcement corrosion and reduction of effective area of longitudinal steel in Tarqui, Manta (GPS coordinates: 0°57'29.92"S, 80°42'36.45"W). b) Signs of severe corrosion in the steel at the base of a 1st story column of a three-story building tagged for demolition in Tarqui, Manta (GPS coordinates: 0°57'9.04"S, 80°42'41.54"W). (Photos by GMSLLP & C. Arteta Torrents)

In some existing buildings, there were some rebar sticking out from the top of columns, presumably so a floor could be added to the building in the future. However, leaving the rebar exposed for extended periods of time in a marine environment causes it to corrode.

a)

b)

Fig. 24: Dowels sticking out from the top of the columns, presumably so a floor could be added to the building in the future a) Buildings in the coastal strip of Pedernales (GPS coordinates: 0°4'4.8"N, 80°3'23.5"W) b) Pedernales (GPS coordinates: 0°4'4.8"N, 80°3'23.5"W) and Tarqui, Manta (GPS coordinates: 0°57'9.04"S, 80°42'41.54"W). (Photos by GMSLLP)

6. CONCLUSIONS

This paper presented select structural reconnaissance observations, types of construction, common practices, failures and typical damage. The majority of buildings observed were reinforced concrete buildings with a modified two-way joist waffle slabs system supported on reinforced concrete columns. There was a lack of earthquake resistant details and structural integrity. The use of sand and sea water as materials in the concrete is a common practice. Buildings were regularly observed to have additional floors on top when more space was required. Finally, there is a necessity of implementation of general procedures for construction, material quality assurance and training programs for the builders in these seismic areas.

7. REFERENCES

[1] GEER Association Report, upcoming Nikolaou, S., Vera-Grunauer, X., Gilsanz, R., Diaz-Fanas, G., Diaz, V., "2016 Ecuador GEER Report version 1". To be published in geerassociation.org

[2] USGS, United States Geological Survey "M7.8 - 29km SSE of Muisne, Ecuador". (URL : http://earthquake.usgs.gov/earthquakes/eventpage/us20005j32#executive)

[3] ATC (Applied Technology Council), 2005. Postearthquake Safety Evaluation of Buildings, Field Manual ATC-20-1, 2nd Edition, Redwood City, CA.

[4] American Concrete Institute (2011). Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary.

[5] Instituto Geofisico-Escuela Politécnica Nacional, Ecuador.(URL: http://www.igepn.edu.ec/mapas/mapa-evento-20160416.html)

[6] Secretaria de Gestion de riesgos de Ecuador, 2016 (URL: http://gestionriesgosec.maps.arcgis.com/home/index.html)

[7] MIDUVI (Ministerio de Desarollo Urbano y Vivienda) and COE3 (Comité de Operaciones de Emergencias), (http://www.habitatyvivienda.gob.ec/)

[8] Norma Ecuatoriana de la Construcción (NEC-15). MIDUVI, Ministerio de Desarollo Urbano y Vivienda. Ecuador, 2015.

[9] Sjoerd Nienhuys "Reinforced Concrete Construction Failures Exposed by Earthquakes," May 2010.