The April 16 2016 M_w7.8 Muisne Earthquake in Ecuador – Preliminary Observations from the EEFIT Reconnaissance Mission of May 24 - June 7

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Abstract

On April 16 2016 an M_w7.8 earthquake with epicentre 29km south-southeast of Muisne in northern Manabí caused around 700 fatalities, injured 30,000 and destroyed several sections of the towns of Pedernales, Portoviejo, Canoa, Bahía de Caráquez and Manta, most of them important centres of tourism on the coast of Ecuador. During May 24-June 7 a team was deployed by the Earthquake Engineering Field Investigation Team (EEFIT) with the objective of surveying the damage and recording observations that would help the scientific and professional community understand the event and its consequences. The team, all co-authors of this paper, investigated structural damage patterns, surveyed 1,332 buildings, validated landslide data obtained from satellite imagery for 30 sites, and interviewed 120 families at 3 shelters. The damage observed in low- and mid-rise buildings seems to correlate well with the spectral response measured in Manta, Portoviejo, and Pedernales. Satellite-based landslide identification proved effective in an 80-90% of the cases investigated. The immediate unemployment spike, based on our limited survey, seemed to reach about 50% in the affected population.

Keywords: Ecuador, Muisne, earthquake, reconnaissance, damage survey, Latin America, EEFIT.

1. Introduction

1.1 The Muisne M_w7.8 Event

A megathrust earthquake measuring M_w7.8 shook Ecuador on the evening of April 16 2016 at 18:58 local time (23:58 UTC). The hypocentre of the earthquake was located approximately 29km SSE of Muisne, and 168km from the country's capital Quito at 0.371°N, 79.94°W and at a depth of about 19.2km [1] (Figure 1). This 2016 earthquake is henceforth referred to as the 'Muisne event' in this paper. Much of the observed damage due to the event extends south from the hypocentre in the Manabí region, following the direction of the fault rupture propagation. The coastal towns – particularly Pedernales, Canoa, Bahía de Caráquez, Manta and Portoviejo – suffered extensive damage after the main shock, with associated intensities of VI-VIII on the Modified Mercalli Intensity (MMI) scale (Figure 1). The resulting peak ground accelerations (PGA) recorded at seismometer stations by the Instituto Geofísico ranged from 0.51g in Portoviejo to 1.55g in Pedernales [2]. Several of these towns are sited on young quaternary sediment deposits [3]. Many aftershocks occurred, including several events greater than M_w5, such as the M_w6.7 and M_w6.9 aftershock events on May 18, a week before the EEFIT mission.

The seismicity of Ecuador is associated with the eastward subduction of the Nazca plate beneath the South America plate at a velocity of about 61mm/year [1]. The Manabí and Esmeraldas provinces in particular have a history of large seismic events exceeding M_w7. The epicentre of the 2016 earthquake is located at the southern end of the 400-500km long rupture area of the 1906 M_w8.8 event which generated a tsunami that killed hundreds of people [1]. Closer to the 2016 epicentre, a M_w7.8 earthquake occurred in 1942, 43km south of the recent April event, and a M_w7.2 event in 1998 close to Bahía de Caráquez. These earthquakes, including the 2016 sequence of events, all relate to the interface seismicity of the northern central section of the Ecuadorian subduction which is characterised by greater dip angles (~16-25°) and larger recorded magnitudes associated to shallower interface events than the southern section of the subduction which dips at an angle of about 10° and whose seismicity is governed mostly by in-slab events [4, 5, 6, 7]. This seismicity distribution may be explained by the presence of the Carnegie Ridge [8, 9].

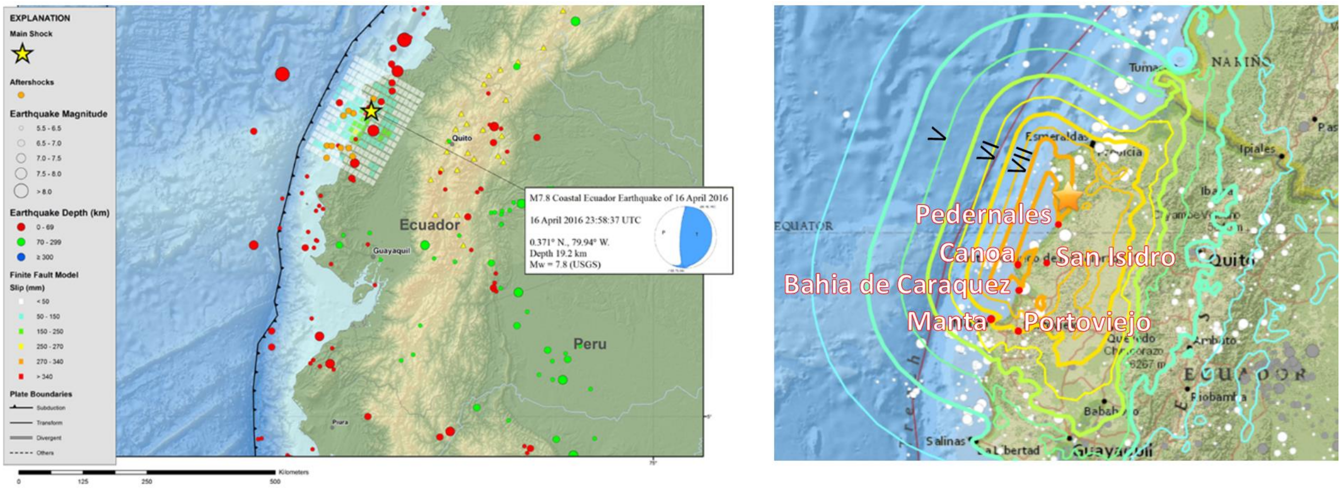

Figure 1 – Regional seismicity and 2016 event characterisation (left) and PAGER Intensity map (right) [1].

1.2 The EEFIT Mission

The Earthquake Engineering Field Investigation Team (EEFIT) was deployed to Ecuador on May 24 2016 and remained on site for approximately two weeks until June 7. The objectives of the team were: to carry out a general assessment of damage to the building stock and other structures; to document and observe soil failures, landslides, liquefaction and faulting; to obtain measurements and acquire data whenever possible; to develop a view on the response to the event, and to investigate the socioeconomic context through interviews. Several disciplines were represented by the team members such as structural engineering, architecture, social sciences, and geotechnical engineering. Included with the team's equipment were a microtremor instrument (TROMINO) and an unmanned aerial vehicle (UAV) or quadcopter drone. These instruments allowed the team to collect data useful in understanding the event.

The team also included co-author Major Manuel Querembás, director of the School of Military Engineering of the Ecuadorian Army. The access enjoyed to restricted sites, bridges, etc. was enabled by Major Querembás and his superiors who ensured all doors were open to the team. As anyone who has done this kind of work in the field knows, this unrestricted access and logistical support was a luxury that allowed the team to maximise its efficiency.

2. Structural Damage Reconnaissance

The EEFIT team aimed to survey the levels of damage to different building typologies throughout the affected areas and to identify the primary drivers for these impacts. This section presents a brief summary of the methodologies used and a description of the typical design and construction issues encountered. In addition, it documents the concerns that have arisen on the building tagging and demolition processes.

2.1 Survey Methodologies

Rapid surveys based on existing standards [10] were derived for this particular study. These were completed at a slow walking pace, collecting the GPS location, the main structural material, and the EMS-98 [11] damage grade (where structural and non-structural damage descriptions did not match for a single EMS-98 damage grade, preference was given to the structural damage grade). Note that the structural surveys were conducted over a month after the earthquake occurred and therefore many of the buildings had already been demolished. In those cases, the GPS location was noted to allow later verification of the original structure, where possible, with Google Street View or other media. In some cases, local people were happy to offer information on the buildings that previously stood on the sites. Where verification was not possible, the ratio of non-demolished building typologies was used to estimate the proportions of typologies of demolished buildings.

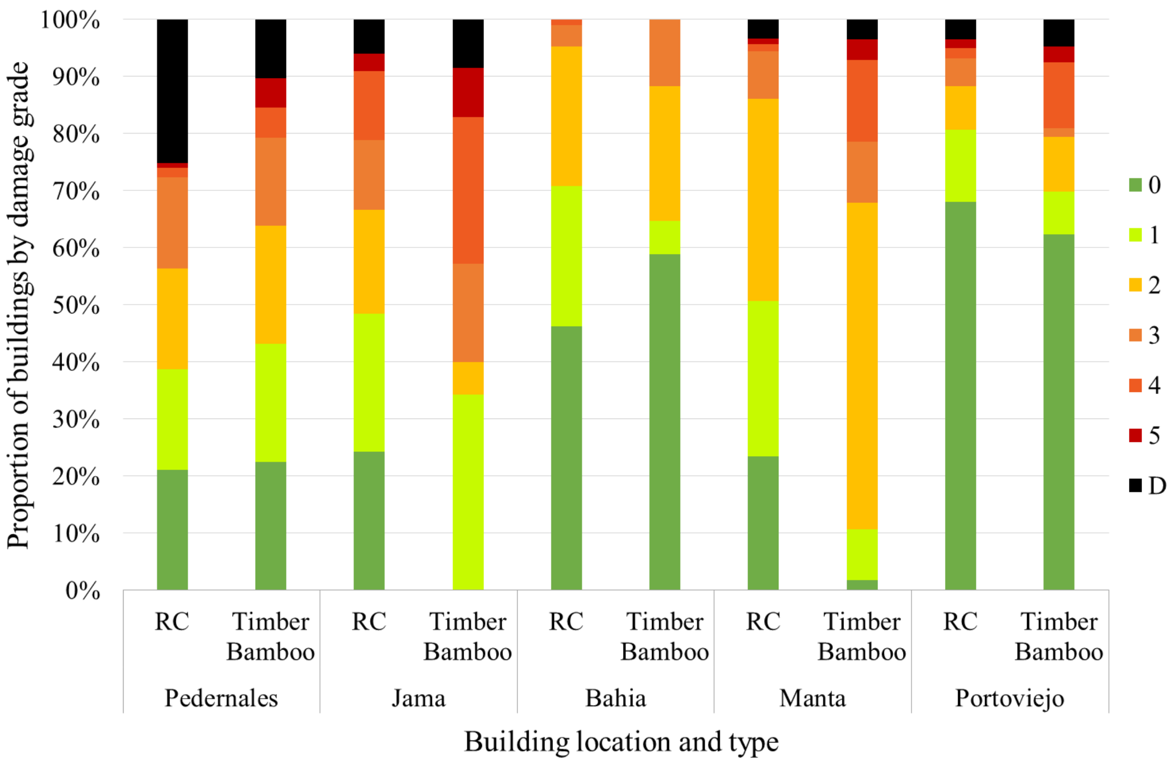

Figure 2 – Damage survey results by area and by EMS-98 damage grade ("D" denotes demolished).

A total of 1,332 buildings were assessed using rapid surveys in Manta (224), Portoviejo (732), Bahía de Caráquez (127), Jama (102), and Pedernales (147). The survey routes attempted to provide an unbiased representation of damage. This was not always possible, however. In Manta and Portoviejo, for instance, the surveys focused primarily on Tarqui and on the central business district, respectively. Both areas showed quite a high concentration of damage in relation to the rest of their urban environments. Various other biases due to lack of data from demolished buildings, surveyor subjectivity, and the inspection methodology selected are present in the data, along with the fact that the survey only covers a relatively small number of buildings.

The proportion of buildings surveyed at different damage states is summarised in Figure 2. Even considering the caveats above, Figure 2 indicates that RC buildings experienced greater levels of damage than timber/bamboo buildings, and in addition that Pedernales experienced the greatest level of damage out of the towns the team visited.

Detailed surveys were used to collect information on key structures such as churches, public facilities, hospitals, and high-rise apartment blocks. The results of these surveys are available in the final report [12].

2.2 Preliminary Observations on Structural Failures

The majority of the surveyed buildings with identifiable construction type were reinforced concrete (RC) frame structures with block or brick masonry infill (~72%). Buildings that incorporated timber and/or bamboo into the structure, including *quincha* and *bahareque* [13], were the second most prevalent (~23%). Other structures of steel and unreinforced masonry were observed but were few in number (~5%).

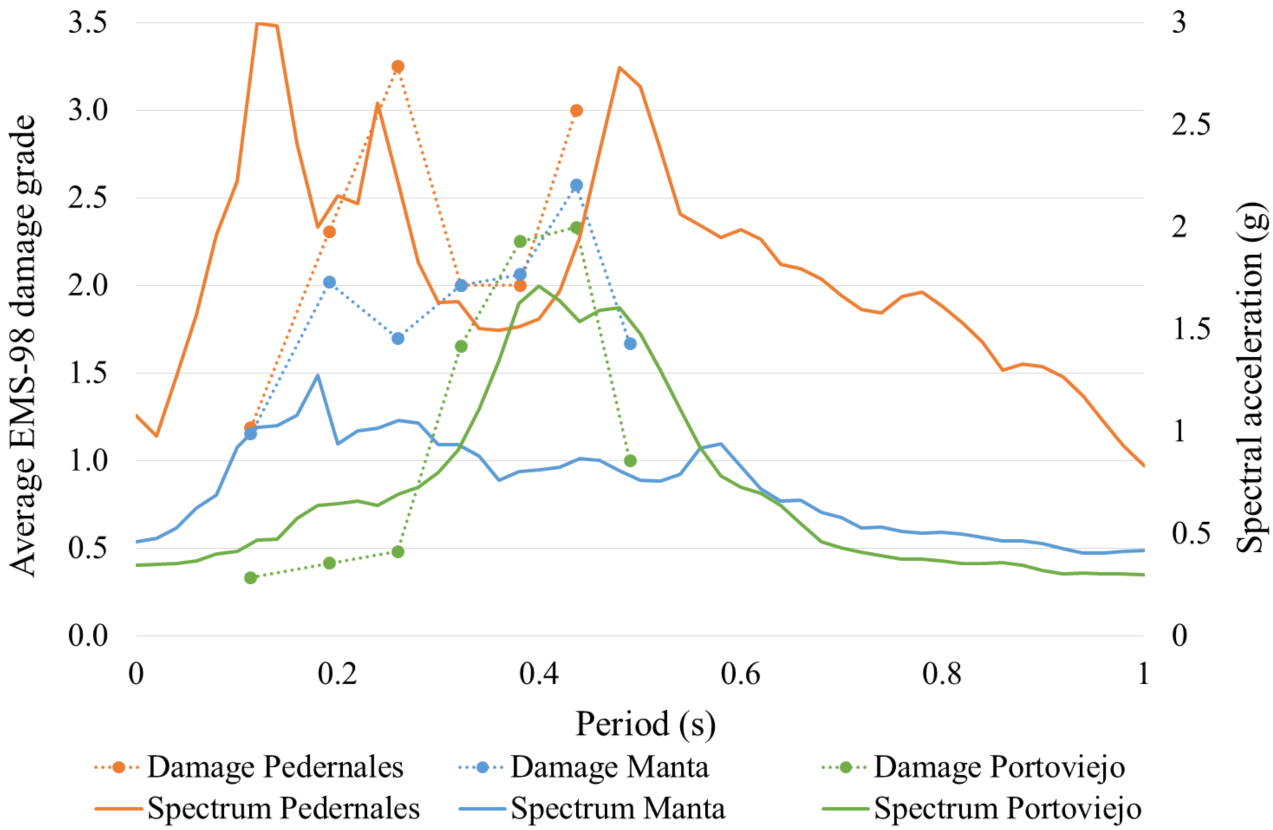

Figure 3 – Relationship between response spectra from recorded ground motions [14] and surveyed damage.

Figure 3 compares the spectral accelerations recorded at stations in Pedernales, Manta, and Portoviejo, with the average damage grades of RC and timber/bamboo structures of different heights surveyed in those locations whose fundamental periods are estimated using Eurocode 8 [15]. In Portoviejo the damage correlates well, and similarly in Pedernales except for the first peak (at just over 0.1s). For Manta, the correlation is weaker although it is difficult to tell without any major peaks in the recorded spectral acceleration. This comparison tends to confirm the expected relationship between shaking frequency and damage to structures of certain height.

The most salient structural failures observed throughout the trip are presented in the following sections.

Failure at upper levels: Upper floor soft/weak storey failures were observed in a number of buildings. It is suspected that this could be due to constructing upper floors long after the bottom floors are completed (as extensions of the building when new resources become available or when new needs arise; see Figure 4A). The joints between new and old are typically poorly executed with insufficient lapping of the rebar, resulting in local reduction in capacity promoting failure in these areas (Figure 4B). This localised upper storey damage may also be attributed to all rebar being lapped at one height, resulting from the use of the same length bars in all columns. Additionally, some upper storey failures could be attributed to changes in plan or elevation at specific levels, resulting in a weak/soft storey.

Inadequate design and detailing of RC moment frames: RC moment frames in seismic areas require several key considerations to ensure they behave safely in an earthquake: 1) Sufficient overall moment and shear capacity, 2) Columns' flexural strength should exceed that of the beams, such that flexural failure occurs first in the beams, 3) Columns and beams should be stronger in shear than in flexure, such that a ductile flexural failure mode occurs before a brittle shear failure mode, and 4) Adequate detailing of the reinforcement in all elements. Damaged RC structures observed generally failed some or all of these requirements (see Figure 4C).

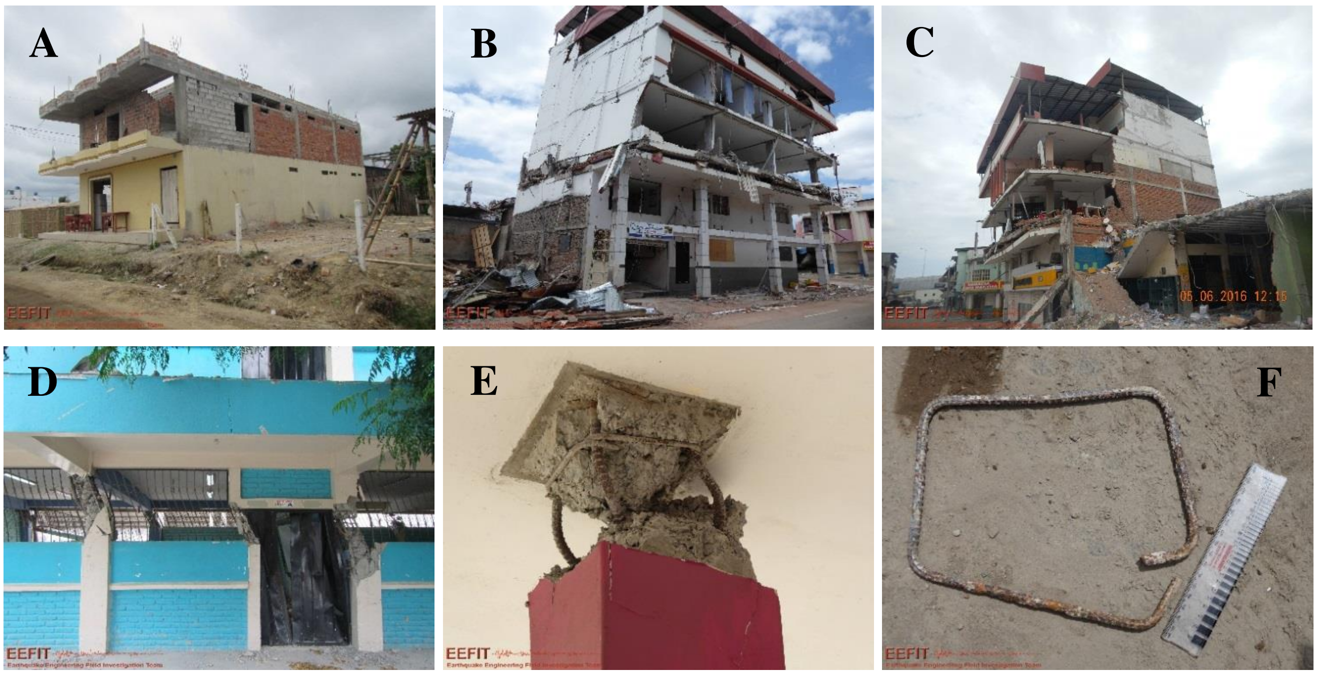

Figure 4 – Two-storey building with columns' rebar left sticking out of roof for future extension (A). Weak/soft storey failure at upper level (B). Inadequate design/detailing of RC frame and infills (C). School building with short column failure (D). Column head failure showing insufficient and poor shear design and detailing (E). Column link with no 135º-bend (F).

Inadequate masonry infill design and construction: The masonry used to infill frames in facades and partition walls was inadequate in both design and detailing, and this was observed in many buildings (see Figure 4C). Typical shortcomings included: 1) Connections between columns and masonry walls were often insufficient; in many buildings no reinforcement bars existed connecting the two. This lack of a proper connection at the column interface led to the walls failing out-of-plane. 2) Where reinforcement bars did exist connecting the columns to the masonry, the masonry was often too thin and the mortar of too poor quality to enable the bars to properly bond to the masonry. 3) The aspect ratio of the panels was in nearly all cases too large for the thickness of the masonry, which led to both in- and out-of-plane failures. 4) Where the designated lateral load-resisting system is a moment frame, the masonry should be decoupled from the frame through the introduction of a 'soft' joint on three sides of the masonry panel, filled with a compressible material. This 'best-practice' was not observed.

Short columns: This failure mode was seen in a number of buildings, with a reoccurring detail of high level windows for the full length of the frame bays (see Figure 4D).

Inadequate design and detailing for shear: In many RC buildings surveyed there was poor detailing of shear reinforcement, with sparsely-spaced links and with poor/no anchorage of these links into the columns (i.e. no 135º-bends in links; see Figures 4E & 4F).

Insufficient cover to rebar: Sufficient cover is required to protect the reinforcement against corrosion. However cover was reduced or missing (0-20mm) in some observed cases, which caused corrosion to the steel.

Poor quality concrete: The concrete used was observed to be of low quality in some areas, likely due to: 1) Inadequate mix design where some concrete clearly had too much, too little, or incorrectly-sized coarse aggregate, 2) Excess water in construction which weakens the concrete, 3) Poor vibration where some concrete had not been properly compacted and voids were evident, especially at the bottom of pours, and 4) Use of sea sand, which was mentioned by a number of local engineers, but which could not be verified visually by the team.

Rot and damage due to insects in timber/bamboo structures: The majority of the damaged timber or bamboo buildings showed evidence of severe damage due to rot, termites or beetles, or a combination thereof. This is due to: 1) Lack of appropriate prior treatment of the materials, 2) Inadequate selection of durable timbers, 3) Inadequate design leading to large areas of the walls fully exposed to the elements, 4) A general lack of maintenance, including the replacement of damaged elements and painting, or 5) The casting of timber or bamboo into concrete to connect to the foundation.

In general, the main issues with the structures observed are a fundamental lack of: 1) Employment of fundamental seismic design principles, 2) Design for lateral loads, and 3) Quality construction. Indiscriminate vertical growth and extension of buildings has made this situation worse, by increasing loads without well-designed and well-constructed elements and/or connections. Additionally, masonry infill walls were inadequately designed and poorly connected to the frames. Sometimes this affected the structure causing damage to the frame and likely caused injury and casualties due to debris impact.

In summary, safer construction may be achieved by the following:

- Improved knowledge and application of basic fundamental structural and seismic design principles
- Better reinforcement detailing, notably detailing of links and rebar overlaps, and increased cover
- Better masonry infill walls and bed joints, better seismic connections to frames, and better materials
- Superior construction quality standards, especially concrete
- Better building maintenance, especially for timber or bamboo structures

2.3 Additional Observations on the Building Tagging and Demolition Processes

It was observed that the 'traffic light' tagging system used in the affected areas varied in interpretation in the different cities and towns. For instance, 'red' in one area was understood by some to mean demolition needed, whereas in other areas it meant 'do not enter' as it was deemed a life hazard. This confusion was shared amongst the locals, building surveyors and those responsible for demolition. With such rapidly moving demolition post-event, it has been reported that buildings that could have been repaired and retrofitted were demolished unnecessarily.

It was also observed that in some cases people may have inadvertently assumed that "green" meant the structure was safe against future earthquakes, as opposed to just being "safe to occupy due to not having experienced significant damage during the previous earthquake". During the mission, buildings with 'red' and 'yellow' tags were currently being demolished. In smaller towns like Canoa and Jama the demolition process appeared to have almost finished and in some of the smaller lower-income areas, building owners were carrying out their own demolition and reconstruction. It is likely that these works are being carried out without any engineering oversight and contributing to perpetuating seismic vulnerability.

3. Landslide Reconnaissance

Many co-seismic landslides were observed across the Manabí region. This included deep and shallow seated landslides in both coastal cliffs to the south of the epicentre and in low-lying mountainous regions to the south-east of the epicentre. A few of these are suspected to be natural slope failures, but most of them man-made slope failures. These are likely to have been due partly to the ground motion of the earthquake and partly due to other possible comingling effects such as: 1) Saturated soil from the heavy rainfalls around the time of the earthquake; 2) Lateral spreading from liquefaction of soft alluvial and marine soil layers; 3) Fault ruptures (e.g. Bahía de Caráquez or San Isidro); 4) Lack of stabilization in man-made slopes; 5) River banks management measures that created increased stream velocities and erosion of embankments; and 6) Flood plains next to vulnerable man-made slopes (e.g. in Portoviejo).

It is worth noting that little information on geology, tectonics, and soils seems to exist in the region. The geological map by Reyes & Michaud [3] and the tectonic map for Ecuador [16] are both published at relatively small scales, challenging the identification of detailed local features. With little detailed information it is difficult to provide a comprehensive interpretation of the observations made in the field at this stage although efforts are ongoing to acquire additional borehole and soil data to enhance our analyses. Preliminary assessments, however, seemed to indicate that the damage severity observed in Manta, Portoviejo, and Pedernales appear to coincide with young quaternary sediments in the surface geology [3], which may have amplified the ground motion at surface. This is being further investigated with the analyses of the microtremor tests [12].

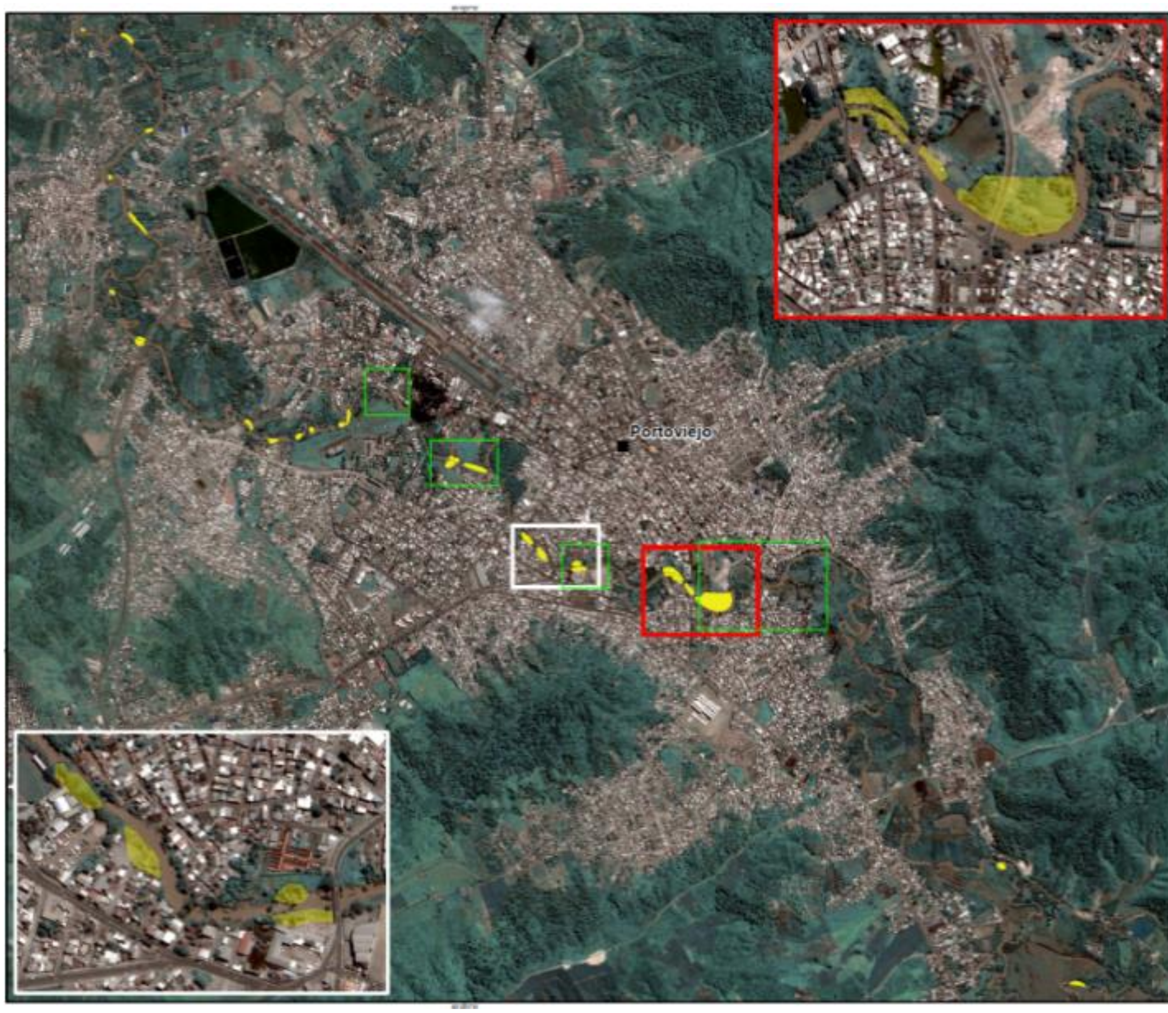

Figure 5 – Portoviejo landslides (in yellow) identified from satellite imagery (British Geological Survey).

3.1 Satellite-Based Landslide Identification by the British Geological Survey (BGS)

As part of the team's landslide reconnaissance, a ground-truthing exercise was undertaken in collaboration with the British Geological Survey (BGS) to provide field validation for their preliminary landslide assessment, initiated by a request from the UK Department for International Development (DfID) and based on satellite imagery from UNITAR/UNOSAT [17]. Photographic and drone imagery were taken on site and interviews were conducted at locations of identified landslides. 13 sites were surveyed in Portoviejo [18] and 17 in the vicinity of Bahía de Caráquez [19] as part of this exercise. Guided by the BGS satellite images, the team visited these locations and provided observations (see Figure 5 & Table 1 as an example for Portoviejo).

During the survey, the team confirmed that the satellite-imagery interpretation had been mostly successful in correctly identifying landslides in the areas surveyed. A few small-scale additional landslides to those mapped in the rapid co-seismic preliminary assessment were observed and a couple of locations associated to greater uncertainty in the assessment were confirmed not to correspond to landslides after all. On the other hand, satellite-based analysis made it possible to identify extensive landslides attributed to liquefaction mapped along the Chone Estuary, close to Bahía de Caráquez, that were difficult to access due to dense vegetation and instable soil boundaries. Following the map and talking to the local community, the team was able to corroborate the preliminary assessment, observing signs of landslides such as drift of trees in the estuary.

This small ground-truthing campaign and the ongoing collaboration with BGS could further improve early satellite-based landslide assessments after an earthquake, in turn enhancing response operations, road clearing, and emergency route identification. The combination of drone imagery with photographs with 60% overlap taken from different angles when possible should help reconstruct a 3D image of the slope. This 3D data will help determine the scale and triggering mechanisms of the landslide (e.g. translational, rotational).

Table 1. Ground-Truthing Exercise Observations for Portoviejo.

Lat (º), Long (º)	Identified Correctly	Observations
-1.062656, -80.449346	No	Large polygon identified is not entirely correct. Area likely to have been flooded during the earthquake. Some limited lateral spreading.
-1.062988, -80.449746	Yes	River bank to north east side of Puerto Real. Road approach to bridge on north side had cracks parallel and perpendicular to road. Cracks had been filled in, but looked like slight spread of road to sides.
-1.062683, -80.450329	Yes	River bank to north west side of Puerto Real. Large crack has formed, approx. 60 cm wide, running parallel to the river for over 30m, located between house and river. Close to edge of river, spreading of land into river.
-1.063181, -80.450495	No	River bank to south west side of Puerto Real. Significant amount of lateral spreading observed. Large cracks at top of slope.
-1.061453, -80.451259	Yes	To north east of footbridge. Evidence of liquefaction-induced lateral spreading. Portal frame structure suffered significant settlement and rotation.
-1.061275, -80.451510	Yes	North bank of river at footbridge. Significant rotation of bridge foundations into river. Evidence of liquefaction induced lateral spreading.
-1.060450, -80.457982	No	Liquefaction-induced lateral spreading. Didn't seem altered post-earthquake.
-1.060591, -80.458651	Yes	Some work done post-earthquake. Fill may have been more affected than natural ground, hard to be certain due to clearing up works. Movement of land into river Portoviejo, along embankment, away from bridge. Lots of cracking in concrete slabs, less settlement observed along lines of some pipes.
-1.060063, -80.458596	Yes	Potential scar and small slide noted. Appears to have been land movement closer to the bridge than mapped by BGS.

4. Community Vulnerability

Assessing community vulnerability in a disaster risk reduction (DRR) framework is an important aspect that is often neglected. 'No people, no disaster' –this is the core concept of prioritising vulnerable communities and bringing the social issues to the fore when addressing DRR. Therefore, during the reconnaissance mission, the team strived to capture the perception of people at risk through 120 interviews conducted at three different earthquake shelters in Manabí. These shelters (Figure 6) were located at the Aeropuerto Reales Tamarindos, Portoviejo (1°2'45"S, 80°28'5"W), Canoa (0°27'42"S, 80°27'8"W) and in Pedernales (0°4'43"N, 80°2'52"W).

Note that these interviews represent only affected people living in these three formal shelters. Mostly, people seemed content with the facilities and services provided at the shelters but not all families were allowed to seek refuge in them. Only families who lost their homes or were unable to live in them due to the earthquakes obtained access. Therefore, views and opinions discussed here do not represent the whole affected community.

Figure 6 – The earthquake shelters in Portoviejo (left) and Canoa (right).

4.1 Homes and Damages

The affected people interviewed were mostly owners of one storey buildings made of mixed RC construction. Survey data (see Figure 7) suggests that people with affected homes resided in buildings mostly built in the 2000s (42%), 18% in even more recent constructions (>2010), and 24% in houses built in the 1990s. Their damaged houses were mostly one (46%) and two storeys high (45%). Note that this does not contradict the conclusions from the structural assessment of Figure 3. Instead it may point at the obvious fact that most of the housing stock consists of one- and two-storey buildings. Mixed structures (RC, brick and timber) represented the most damaged group (39%) followed by concrete structures (31%). A slight majority (58%) enjoyed ownership and the rest rented their homes. Affected families mostly came from urban areas (93%) and they reported that most of their houses were completely destroyed (65%).

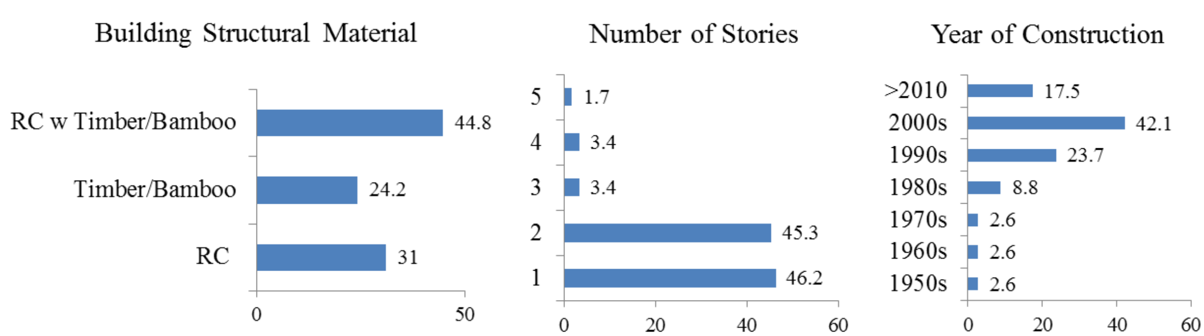

Figure 7 – Distribution of building characteristics derived from 120 interviews at shelters (in %).

4.2 Economic Activity

Members of families surveyed were working-class adults between 18 and 65 years of age and without higher educational background (most having completed a primary level). Family size was on average 4 with persisting gender balance. They represented low-earning households with a monthly income of about US$75-300 and were involved in a variety of economic activities. After the earthquake, changes in primary household occupations were found to be a major issue. Approximately 55% of the 120 respondents became unemployed because of the disaster. Mostly people lost jobs (see Table 2) in retail (17%), fisheries (7%), construction (4%), hotels (4%), day labour (3%), and in tourism (3%). Their first priority was to recover some sort of economic activity.

Families surveyed did not seem to be prepared for this earthquake disaster. Very few had knowledge of or had seen a seismic risk map of Ecuador. Thinking about the future, many expressed an immediate predilection for one-story buildings made of wood or bamboo, and they wanted to continue living in urban areas.

Table 2. Changes in Occupational Patterns.

Occupation	BEFORE		AFTER		Change
	Freq	%	Freq	%	(%)
Bartender	2	1.67	0	0	-1.67
Beauty Parlour	1	0.83	1	0.83	0
Business	1	0.83	0	0	-0.83
Butcher	1	0.83	0	0	-0.83
Carpenter	1	0.83	0	0	-0.83
Coconut Sell	1	0.83	1	0.83	0
Construction	11	9.17	6	5.00	-4.17
Cook	2	1.67	1	0.83	-0.84
Day Labour	7	5.83	4	3.33	-2.5
Delivery	1	0.83	1	0.83	0
Driver	6	5.00	4	3.33	-1.67
Engineer	1	0.83	0	0	-0.83
Fisheries	15	12.50	7	5.83	-6.67
Garments	1	0.83	0	0	-0.83
Hotel	5	4.17	0	0	-4.17
Housemaid	2	1.67	1	0.83	-0.84
Housewife	6	5.00	3	2.50	-2.5
Job Others	2	1.67	2	1.67	0
Laundry	1	0.83	1	0.83	0
Magazine Sell	1	0.83	0	0	-0.83
Professor	1	0.83	1	0.83	0
Public Job	7	5.83	6	5.00	-0.83
Retail	25	20.83	5	4.17	-16.66
Security Guard	3	2.50	0	0	-2.5
Singer	1	0.83	1	0.83	0
Teacher	2	1.67	1	0.83	-0.84
Technician	4	3.33	2	1.67	-1.66
Tourism	3	2.50	0	0	-2.5
Unemployed	**5**	**4.17**	**71**	**59.17**	**+55**
Waste Collect	1	0.83	1	0.83	0
Total	120	100	120	100	0

5. Conclusions & Additional Remarks

The 2016 Ecuador event had a significant impact on the country, causing large destruction in its coastal building stock and disruption to the country's economic activity.

Most of the damage to housing in the earthquake was traced to one- and two-storey, predominantly reinforced concrete or mixed reinforced concrete, structures built during the last two decades in urban areas. In addition, taller concrete structures in commercial centres, for instance in the area of Portoviejo, also showed significant damages that the team was able to correlate with the seismic response peaks observed in the towns of Pedernales and Portoviejo. Much of the damage to structures, as well as that observed in landslides, was located in areas with quaternary, soft deposits that may have suffered high levels of saturation due to the heavy rains and floods that were experienced just before the main event. This fact may have further exacerbated the damage.

Although based on a small sample of interviews, observations seem to point to immediate increases in unemployment levels among the affected population. As it stands at the time of writing this paper, the Post-Disaster Needs Assessment indicates a total economic loss of US$3 billion. On April 20 2016 the Inter-American Development Bank also activated a US$300 million credit line to support the Ecuadorian government with losses and emergency expenses (this is an interesting process in itself since it used an innovative derivative triggering system [20]).

The mission also served to validate a satellite-based landslide identification process developed by the British Geological Survey. Out of 30 landslide locations investigated, about 80-90% of these were correctly identified by the system. This small ground-truthing campaign seemed to confirm the promise that these systems offer in response operations. It also highlighted some limitations in the system.

Finally, it was patent throughout the investigation that the emergency response had been carried out effectively by the Armed Forces of Ecuador (never mind that the mission was carried out in close association with these Armed Forces). Constant contacts with the general population and questions asked throughout the mission seemed to confirm the feeling of gratefulness that the community felt for the services provided by the Army, Navy and Air Force. Although it has been pointed out in the past that the emergency response operations should remain in the hands of civilian authorities (and this experience does not contradict that statement), it seems evident that the Armed Forces can play a major role. Contrasting to previous events, and to the 2010 Maule event in Chile in particular [21, 22], the quick deployment of the Army seems to have made a notable difference. While conclusions are premature at this stage, the response protocols set in action in Ecuador may contain important lessons worth considering for the future.

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