Reconnaissance Report of the May 28, 2009 Honduras Earthquake, M 7.3

A team sponsored by the Earthquake Engineering Research Institute (EERI) and the Geoengineering Extreme Event Reconnaissance (GEER) Association carried out a field investigation in conjunction with Honduran colleagues from June 18-23 to document effects of the May 28 earthquake. The EERI-GEER team was invited by Mr. Marco Sandoval, Executive Director of the Comisión Ejecutiva Valle de Sula (CEVS). Mr. Sandoval sent a team of engineers to accompany the EERI-GEER team. The team included experts in structural, geotechnical engineering, as well as in disaster response and recovery. The investigators were supported by EERI: Abdeldjelil Belarbi and GEER: Ronaldo Luna and Kermit Applegate, all from Missouri S&T, Rolla. The CEVS team consisted of Humberto Calderon, Osvaldo Rivera, and Luis Alonso Lopez. Observations of other individuals who visited the earthquake-affected region have also been incorporated in this report. This material is based upon work supported by the National Science Foundation through the GeoEnvironmental Engineering and GeoHazards Mitigation Program under Grant No. CMMI-0825734. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The GEER Association is made possible by the vision and support of the NSF Geoenvironmental Engineering and GeoHazards Mitigation Program Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill. GEER members also donate their time, talent, and resources to collect time-sensitive field observations of the effects of earthquakes. The EERI efforts were supported through the Learning From Earthquakes (LFE) program which is also funded by the National Science Foundation.

Introduction

An earthquake of magnitude M 7.3 struck the Atlantic coast of Honduras on May 28, 2009. The epicenter was located 63 km north of Roatán (Bahía Islands) and 125 km NNE of La Ceiba. This has been the strongest earthquake felt in Honduras in the past 3 decades. The earthquake event and aftershocks were felt in Honduras, Belize, Nicaragua, El Salvador and Guatemala. Several smaller events followed the main event, such as the June 8th and 15th events with magnitudes 5.4 and 4.8, respectively. The earthquake event was of significant magnitude and with limited consequences. At least 7 people were killed and 40 injured with damage to more than 150 buildings. Some of the country's major infrastructure, such as port terminals, bridges and levees were seriously damaged. The following sections address the seismological setting, geotechnical and structural aspects and the socio-economic impact. Several GoogleEarth .kmz files complement this report, which contain GPS tracks, waypoints, and additional photographs for every day of the reconnaissance effort. They can be accessed at the following website: http://www.geerassociation.org/Post_EQ_Reports.html.

1. Tectonic Setting and Seismological Records

According to the USGS interpretation of the seismological data the location and focal mechanism of the Honduras earthquake of May 28, 2009, imply that the shock occurred as the result of left-lateral strike-slip faulting. This event was located on the Swan Islands Transform Fault, a segment of the boundary between the North America and Caribbean plates. It has been estimated that in this region the plate boundary has a 20 mm/yr slip. (USGS, 2009)

The North America/Caribbean plate boundary has generated strong earthquakes before; thirty three years ago the 1976 Guatemala earthquake, M 7.5, produced more than 23,000 fatalities. The 1976 earthquake occurred on the Motagua fault, a segment of the plate boundary that lies about 400 kilometers southwest of the 2009 Honduras offshore hypocenter.

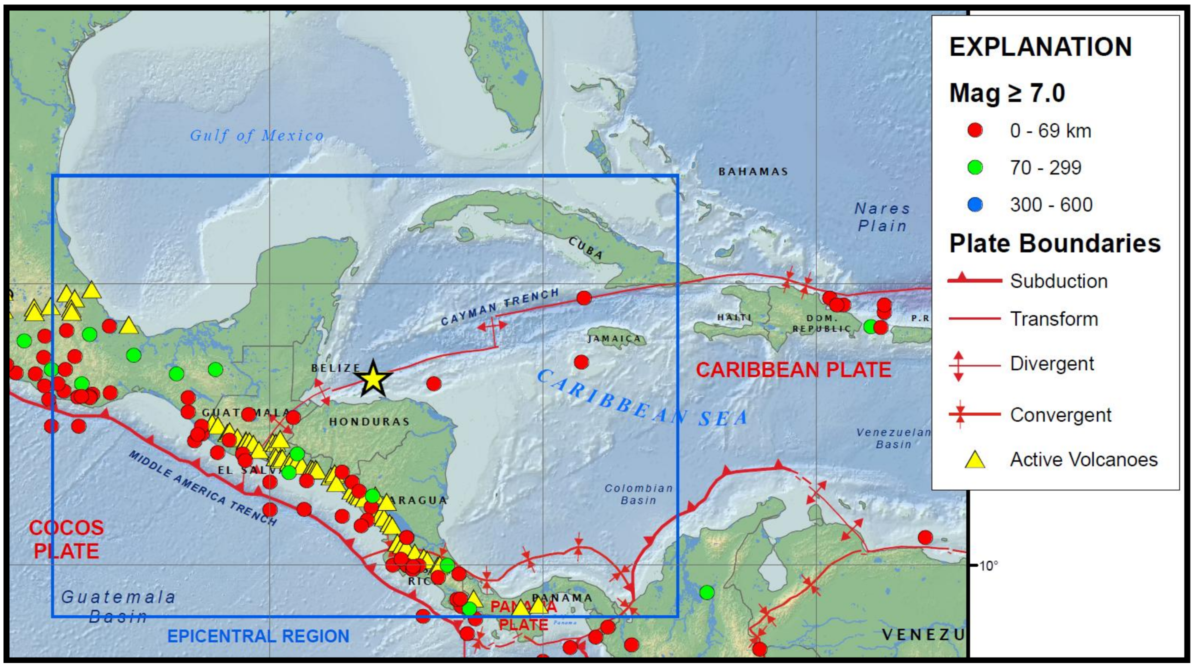


Figure 1 – Tectonic Setting (USGS (2009))

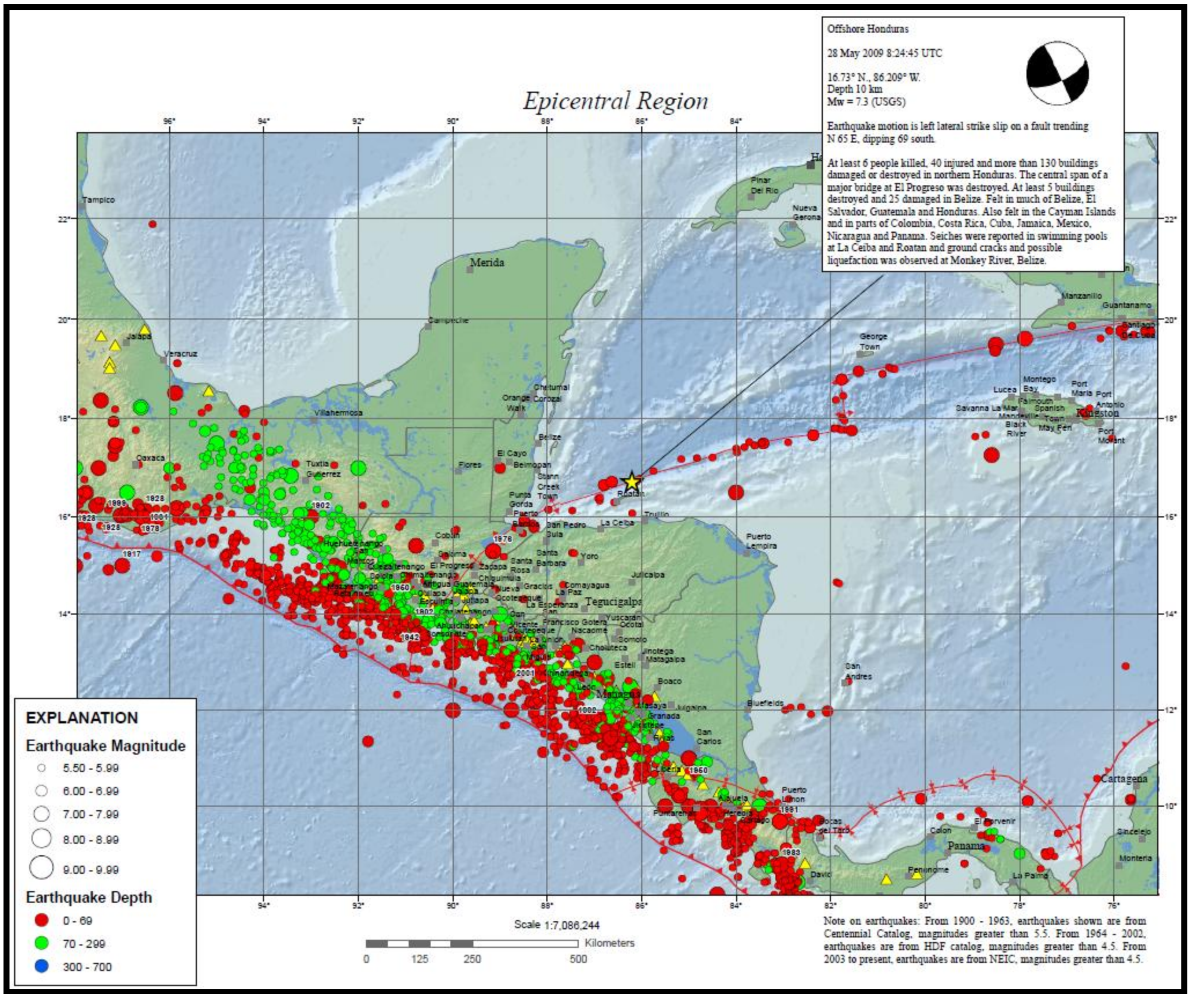


Figure 2 – Epicentral Region (USGS, 2009)

The seismological records in Honduras are scarce. A recent station was installed by the USGS in Tegucigalpa, the capital city. The record from this station is more than 310 km away from the epicenter. Another seismograph has been in operation for some time now at the El Cajon dam site about 260 km away from the epicenter. Both seismograph instruments recorded data and preliminary review indicates low quality records. The few stations that have been installed are monitored and supported by the INETER from Nicaragua. Additionally, three accelerographs are also installed at the dam at the base and other two within the concrete structure, the records were obtained from Rolando Rodriguez, dam safety engineer.

2. Geotechnical Aspects

Local Site Effects

The seismic event produced strong ground motion throughout the region, but its effects were amplified primarily within the alluvium valley of the Ulua and Chamalecon Rivers. Damage was selective of those structures that were supported on soft foundation soils and/or supported on filled or reclaimed land. This was evident at sites located in San Pedro Sula and Puerto Cortés. The most obvious example of local site effects was at the Supreme Court Building located on the Segunda Circunvalación Road in San Pedro Sula. The Supreme Court building is a three story reinforced concrete frame which underwent structural damage (see Figure 11). The building is supported on about 3 m of fill underlain by soft and compressible organic soils. In contrast to this structure, a multi-story reinforced concrete stadium located less than half a mile away did not experience this level of damage.

Liquefaction

Liquefaction was widespread in areas underlined by granular saturated sediments. Sand boils, surface cracks, and lateral spreads were evident in many areas near Puerto Cortes and towards the town of Omoa on the Caribbean Sea coast. The structures impacted by the widespread liquefaction were petrochemical terminals, ports, wharfs, roadway embankments and other smaller buildings.

Of particular interest was the damage encountered at the Chevron Terminal in Puerto Cortés. This area was built on sandy fill. Liquefaction sand boils were wide spread throughout the terminal within tanks, pipe racks and small buildings (see Figure 3). Damage to tanks was not evident, except a pressurized vessel that settled more than 2 ft on one side tilting the entire tank, which was supported on shallow foundations (see Figure 4). Small structures supported on shallow foundations were damaged, such as the laboratory and office buildings (see Figure 5). Safety inspection requirements and repairs of tanks and pipeline systems will take more time.

Figure 3 – Chevron Terminal remains closed as of 06/28/2009.

(a) Note inundation due to wide spread liquefaction [05/28/2009 N15.848287, W87.958041],
(b) Same entrance location 3-weeks later [06/20/2009 12:40PM, N15.848287, W87.958041], and
(c) Multiple pipeline deformation and breaks [06/20/2009 1:24PM, N15.849177, W87.959274]

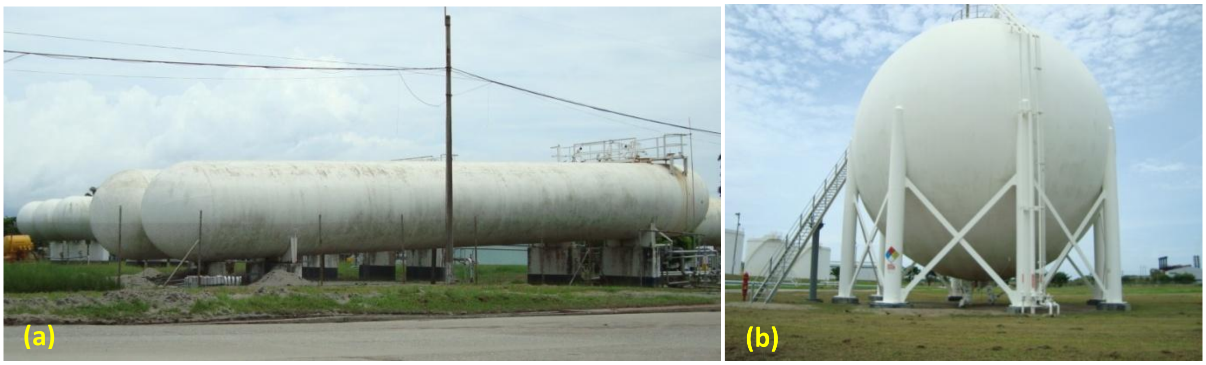


Figure 4 – (a) Tanks supported on shallow foundations sank and tilted, notice sand boil piled up next to foundation on left [6/20/2009, 1:12PM, 15.851061, -87.956882], and (b) those supported on piles performed well [06/20/2009, 1:16 PM, N15.851226, W87.958534].

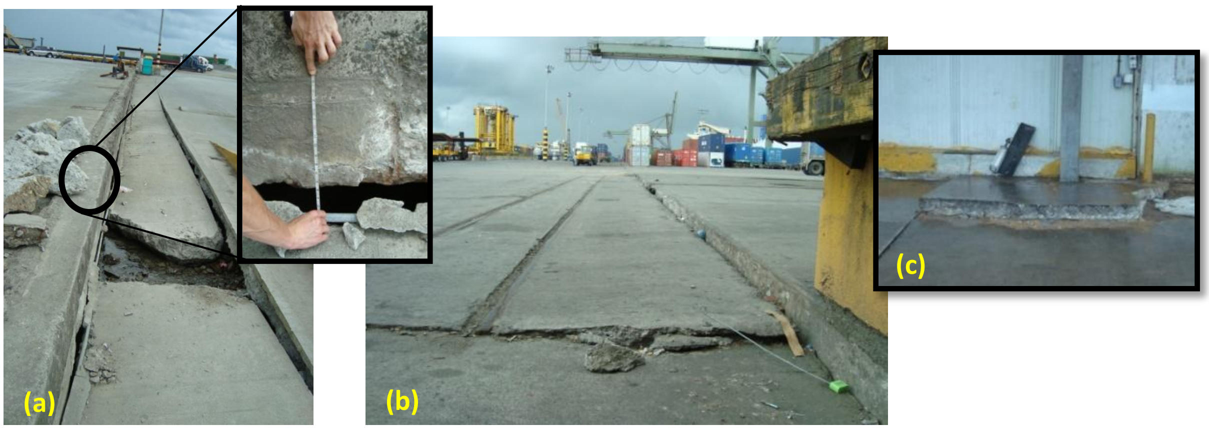
Figure 5 – (a) Buildings and small structures sank up to 3 ft and were flooded with liquefied sand [06/20/2009, 1:08 PM, N15.849851, W87.95793], and (b) vehicles sank into sand boils, see carport automobile was already extracted [06/20/2009, 1:25 PM, N15.848216, W87.958604].

Other buildings and residences were damaged in the central zone of Puerto Cortés due to the wide spread liquefaction and ejected sand. Buildings tilted and became inundated, leaving much sand behind. The surface storm sewer system was clogged for weeks until the municipality and neighbors were able to excavate the drains. A recently build roadway embankment that contains a major utility on the south side of the city was seriously affected by lateral spreading. (Figure 6)

Figure 6 – Temporary repair of roadway embankment, due to lateral spreading [06/20/2009, 1:25 PM, N15.848216, W87.958604].

Port Facilities

Earthquake damage at the most important port in Honduras was localized even though it remains in operation. Most of the damage was concerning movement of slabs and wharfs causing joints to move in the vertical and horizontal directions. In some cases the slabs collapsed due to the loss of subgrade support (Fig 7a and 7b). It was reported that some of the pile supported wharfs moved upwards by several inches. Some foundations appeared to have moved upward, but this differential movement is all relative to the surrounding ground subsidence, which needs to be confirmed by precision survey (Fig. 7c). Fuel tanks supported on concrete mats experienced large deformations due to widespread liquefaction and surface rupture of fill materials, see Figure 7(d).



(a) Up to 0.46m at the main dock [06/20/2009, 3:37PM, N15.843718, W87.951739],
(b) 0.2m near port warehouses [06/20/2009, 3:49PM, N15.8424, W87.94941], and
(c) Relative foundation displacement up to 0.15m [06/20/2009, 4:00PM, N15.841912, W87.941644].

(d) Three view of fuel tanks and multiple ground fissures due to wide spread liquefaction [06/20/2009, 3:12PM, N15.846936, W87.963225]

Figure 7 – Liquefaction induced deformations at Puerto Cortés – Slabs on grade and Tanks.

Levees

The valley of the Ulúa and Chamalecón rivers (Valle de Sula), runs north towards the Caribbean Sea. A system of levees protects the agricultural activities, urban and residential areas. A preliminary survey completed by the Comisión Ejecutiva Valle de Sula (CEVS) identified 58 km of levee damage due to the earthquake event. Lateral spreading was observed along the banks of the Ulúa River. On the edge of a sugar cane plantation, about 250 meters from the river edge, long fissures opened in the direction parallel to the river (Figure 8). The crack openings ranged from 10 to 50cm with a depth of about one meter. *Allochthonous sand ejecta* ware present along the length of the fissures, and sand boils were scattered amongst the sugar cane plantations.

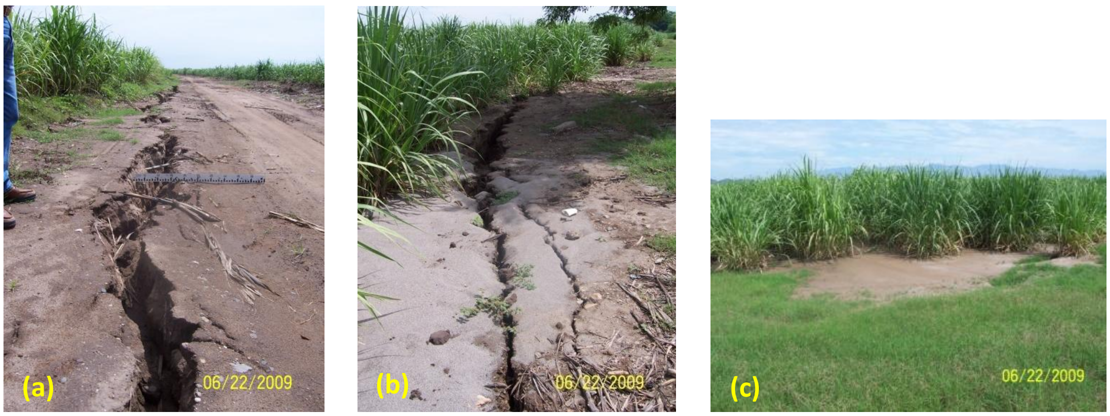


Figure 8 – (a) Longitudinal cracks along roadways [06/22/2009, 10:03AM, N15.368726, W87.861301], (b) with sand at surface [06/22/2009, 10:10AM, N15.369316, W87.860965], (c) sandboils within plantations [06/22/2009, 10:06AM, N15.368988, W87.861209].

Near the edge of the Ulua River, on the unprotected zone of the levee system, extreme lateral spreading was evident. Gaping fissures up to 5 meters wide and two meters deep have indelibly altered the landscape (Figure 9). This will have serious consequences as the rainy season approaches and the levee system is not able to keep the flood water out of the protected zones (plantations and rural residences).

Figure 9 – Multiple views of severe lateral spreading between levees and river [06/22/2009, 10:25AM, N15.391266, W87.845191].

Along the crest of the levee system, a network of smaller cracks (about 5-10 cm wide and several meters deep) has rendered nearly 60 km of the levee system ineffective (Figure 10). CEVS is currently undergoing an emergency earthwork operation to reinstate levee geometries to its pre-earthquake conditions.

Figure 10 – Cracks at the crest of levees exceeding 1.5m deep
[06/22/2009, 11:57AM, N15.344505, W87.868515].

3. Structural Aspects

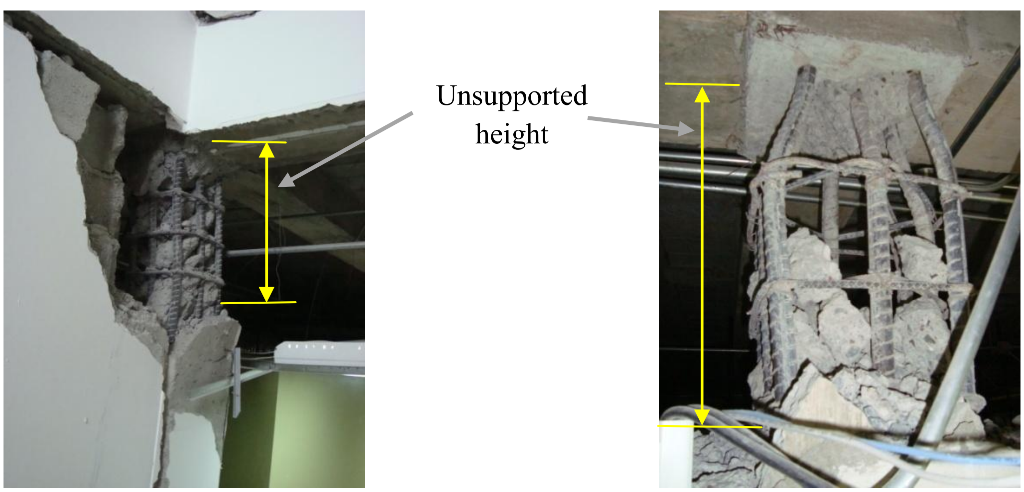
Buildings

The Supreme Court building, located on the Segunda Circunvalación Road in San Pedro Sula, is a three story reinforced concrete frame which underwent structural damage. Each story is about 4 m high with columns and beams with the same (350 mm x 350 mm) cross-section. The building had frames with concrete beams running in orthogonal directions. The concrete frames were in-filled with brick masonry. Typical failures of these in-filled masonry walls are shown in Figure 11.

Inside the building and some locations, these frames were partially filled with masonry walls. This in turn causes the reduction in height of the column resulting in increased lateral shear during earthquakes. This is also called as short column effect. This failure mode, also called captive-column or captured-column, is very common in RC frames with infill walls. This failure happens when an infill wall is extended into a frame from the floor level up to another level to form a window, leaving a short free space in the top portion. The column in such a structure is partially restricted by the wall. This shortened column develops large shear force which may exceed the shear capacity of the column, resulting in failure. The problem is well known but is often ignored in practice. In some cases, the infill walls are separated from the column to allow flexure of columns. But insufficient gaps produced the same consequences. Figure 11b shows a reinforced column failed by shear. The column is constrained by masonry infill walls in perpendicular direction. Shear cracks were developed from masonry wall which led to shear failure of columns. Figure 11c shows the failure due to short column effect from a masonry infill wall. These columns had No. 3 ties spaced at 6 to 8 inches. This seems to be an inadequate detailing for seismic loading. The large spacing of lateral ties did not provide the required confinement to the core concrete.

Infill walls, usually located between RC columns and beams, can suffer out-of-plane overturn due to inertial forces during an earthquake. Because infill walls are non-load-bearing elements, they tend to be thin and cannot rely on the additional shear strength that accompanies vertical compressive loads. If infill walls are not properly restrained in out-of-plane direction, walls can collapse during strong ground shaking, producing damages to inhabitants and properties. If walls on the façade of a structure collapse, the consequences could be deadly to pedestrians. Figure 11a shows a typical in-fill wall failure.

(a) Overall damage including out-of-plane failure of masonry infill wall
[06/19/2009, 5:53PM, N15.472899, W88.018565].



(b) Column failure at the infill wall frame interface
[06/19/2009, 5:08PM, N15.473038, W88.018103]

(c) short column effect failure
[06/19/2009, 5:31PM, N15.473346, W88.018592]

Figure 11 – Supreme Court Bldg. structural damage due to local site effects and aseismic design.

Bridges

Two bridges suffered serious consequences by the seismic events of May 28th, 2009. The reinforced concrete 3-arch bridge, entitled "La Democracia", crosses the Ulua River near the town of El Progreso. The bridge connects this town to the major city of San Pedro Sula in northern Honduras. The bridge that experience collapse of the middle span was built in 1965 by a team of French engineers. The structure consists of two middle supports with nearly symmetric monolithic arches, with the middle span complemented by a straight beam span. The total length of the bridge was 258 m. The middle span was 36 m. These middle components consist of four simply supported T-beams. All supports, including abutments, consist of steel plate bearings. Figure 12 shows the collapsed middle span and in the background the newer 2005 twin bridge built by the Japanese, which still is in service taking the traffic towards el Progreso. The bearings on the abutments moved more than 250 mm in the horizontal direction. This bridge had shear key only in the longitudinal direction to support the T-beams. This simply supported girder Type Bridge had inadequate seating and no provisions like lateral restraint to prevent unseating. The lack of redundancy in the simply supported beam also prevented formation of alternate load path which resulted in the fall of the beams and consequently the middle span.

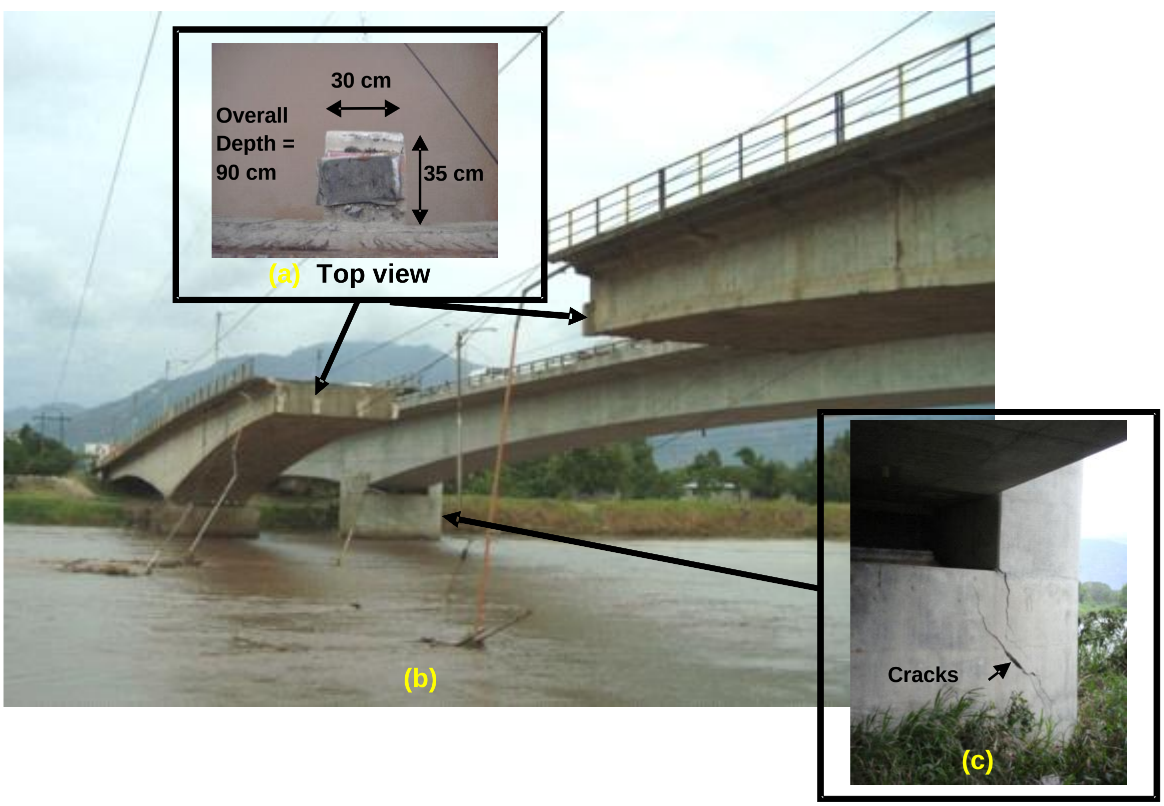


Figure 12 – La Democracia twin-bridge with middle span collapsed.
(a) Top view of shear key [06/19/2009, 6:45PM, N15.404139, W87.820174.],
(b) Overall view of the twin bridge [06/19/2009, 6:45PM, N15.40478, W87.819967], and
(c) cracking due to lateral restraint in the new bridge [06/19/2009, 6:58PM, N15.40408, W87.820615].

In contrast, the new bridge, which consists of a single monolithic concrete arched structure, has neoprene elastomeric bearings and shear keys at the supports. The shear keys suffered diagonal cracks, evidence that they engaged in keeping the bridge on its bearings during the seismic event. A transverse crack on the bridge (western bank) was identified. Liquefaction sand boils and significant settlement of the banks and possible lateral spreading was evident on the river banks. In some locations cracks and settlement exceeding 250 mm was observed (See Figure 13).

Figure 13 – Settlement of ground around abutments due to liquefaction
(a) Old bridge westbound [06/19/2009, 6:36PM, N15.404409, W87.821095], and
(b) New bridge, eastbound [06/19/2009, 6:52PM, N15.40422, W87.821021].

The other bridge that suffered damage during the seismic event was the bridge near Santa Rita over the Humuya River (Figure 14). The foundation support was already weakened due to scour, which historically has damaged the bridge and scour continues to aggravate the situation. The most common cause of bridge failure is structural instability and undermining caused by movement of column bent exaggerated by excessive scouring. Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams, and from around the piers and abutments of bridges.

This two-lane bridge consists of 8 spans of 5 simply supported reinforced concrete girders (1m x 0.6m x 30m) built in the 1970s. Two supports experienced significant movement and the third column bent was tilted and rotated causing settlement and a reduction in the bearing support of the girders The fourth span had only about 5 to 6 cm of bearing on the third column bent as shown in Figure 14. The night of June 28th several spans collapsed as shown in Figure 15.

Figure 14 – Santa Rita Bridge over the Humuya River after the earthquake and before collapse
(a) [06/21/2009, 6:08PM, N15.191548, W87.82559]
(b) [06/21/2009, 5:43PM, N15.191017, W87.8922393]
(c) [06/21/2009, 5:40PM, N15.190907, W87.892658]

Figure 15 – Collapse of the 2 to 3 spans of the Sta. Rita Bridge over the Humuya River post-earthquake [06/28/2009, N15.191019, W87.892095] (source: LaPrensa.hn).

El Cajon Dam

A visit by the recon team was made on June 21st consisting in meeting with the director of dam safety at the dam site and external and internal visit of this concrete arch dam. The dam is 227 m high arched dam and it forms a reservoir 94km^2. This dam is the most significant civil infrastructure in northern Honduras and continued normal operations during and after the event. However, the response of the dam to the earthquake was successfully recorded by the instrumentation monitoring system at the site, including one seismograph and three accelerographs. After the event a visual inspection was made by the safety inspection squad and was followed by a more detailed data collection survey of the installed instrumentation. The following is a summary of the measurements and observations made immediately after the earthquake event.

Accelerographs: Historic values were reached during the event. At the top of the dam (El. 291m) the Dam registered its maximum value of -0.081g was recorded. At the bottom of the dam (El. 78m) the maximum acceleration was recorded as 0.010g. The maximum value obtained before this event was of -0.045g on July 11, 1999.

Seismograph: During the following 13 hours after the main event, 23 events were registered in the seismograph, which is located on rock below the safety engineering station on the west abutment. The seismograph data was delivered to INETER in Nicaragua for interpretation.

Pendulums: There are 21 pendulums which measure the deformation of the dam. The readings of these instruments are not outside the normal parameters because there was not a deformation in the dam. Evidently, during the event the alarm went off because the dam moved.

Extensometers: These instruments measure the deformation of the rock in the base of the dam. The readings from these devices are between the same parameters as before the event, so there is no value outside the boundaries.

Filtration Flow and Drainage: The increments in the flow are not significant. The change in flow after the event was noteworthy, from about 138 lt./sec. to 167 lt./sec. Turbidity was detected in the downstream outflows shortly after the event (3 days), but none was observed during our visit. This is evidence of adjustments within the rock and soil that may promote continued filtration through the curtain.

Figure 16 – (a) Weir passing turbid water at base of dam [05/28/2009, N15.03096, W87.747885], and (b) reflected in downstream river [05/28/2009, N15.03096, W87.747885].

Pore pressures: In general the behavior of the impermeable curtain was not significantly impacted. However, four piezometric instruments in the G78 gallery present increments equivalent to about 16 to 19 m of pressure head. This coincides with the location of the “Fault III” within the dam site, suggesting movement during the event.

Figure 17 – (a) Turbid seepage at base of dam [05/28/2009, N15.03096, W87.747885], and (b) clear seepage at base of dam [06/21/2009, 11.55AM, 15.03096, -87.747885]

Powerhouse: There are no seepage increments in the filtration paths of the north well and GL11 spring (old access), but the water is showed high turbidity. At a joint of the access tunnel I17 similar situation was observed with higher temperatures reaching 34.6°C.

Even though the dam safety instrumentation measured the impact of the earthquake event on the dam, the structure is considered safe and continues to operate normally. The dam safety plan did not require any further action, as none of the thresholds were reached. However, a grouting plan programmed for the near future to seal the existing grout curtain is currently being re-assessed.

4. Socio-economic Impact

Several major civil infrastructures in the north of Honduras along the Valle de Sula (Petrochemical Terminals, Bridges, and Levees) were crippled by the earthquake events of May 28th, 2009 and will have a lasting impact on the socio-economic recovery. The Chevron Terminal at Puerto Cortés has been closed for more than a month due to safety concerns, most tanks have been emptied and gasoline distributed on trucks. This terminal supplies about 40% of the gasoline to the country and in some service stations gasoline is becoming scarce. The 60km of damage levees due to large longitudinal cracks and lateral spreading are currently being repaired by the CEVS corps of engineers. However, these weakened earth structures will remain vulnerable to flood events during hurricane season which starts in September. Other building damage, primarily residential and small commercial, was also observed throughout the region and was not the focus of this investigation. The officials at the local municipality in Puerto Cortés, in conjunction with COPECO, conducted a detailed damage assessment survey and identified more than a thousand damaged residences.

5. References

U.S. Geological Survey (2009). "M7.3 Honduras Earthquake of 28 May 2009", Poster, ftp://hazards.cr.usgs.gov/maps/sigeqs/20090528/20090528.pdf, (June 20, 2009)

LaPrensa (2009). "Puente sobre el río Humuya se desploma", http://www.laprensahn.com/Pa%C3%ADs/Ediciones/2009/06/29/Noticias/Puente-sobre-el-rio-Humuya-se-desploma, (July 7, 2009).

Elnashai, A.S., Alva-Hurtado, J., Pineda, O., Kwon, O., Moran-Yanez, L., Huaco, G., Pluta, G., (2008). "The Pisco-Chincha Earthquake of August 15, 2007; Seismological, Geotechnical and Structural Assessments" 2nd Edition of Peru Report, Report No. 08-01, Mid American Earthquake Center, Illinois, USA. URL: https://www.ideals.uiuc.edu/handle/2142/9460

O'Connor , J.S., Mesa, L. and Nykamp, M., (2007). "Damage to the Highway System from the Pisco, Peru Earthquake of August 15, 2007", Report No: MCEER-07-0021, December 10, 2007, University at Buffalo, New York.
URL: http://mceer.buffalo.edu/publications/Reconnaissance/07-0021/07-0021web.pdf