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Preliminary Reconnaissance Report - 12 January 2010 Haiti Earthquake

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Introduction

After 240 years of inactivity, the Enriquillo Plantain Garden Fault ruptured on 12 January 2010 at 4:53PM local time, resulting in a 7.0 magnitude (USGS) earthquake in the vicinity of Port-au-Prince, Haiti. The epicenter was located at 18.457°N and 72.533°W and 25 km (15 miles) WSW of Port-au-Prince. The rupture occurred at a shallow depth of 13 km (8.1 miles).

The earthquake has been an unmitigated disaster for Haiti; at the time of this writing there are 170,000 confirmed deaths with estimates of over 200,000 deaths. Thousands more are injured, thousands are homeless, and thousands have already fled Port-au-Prince. The *New York Times* reported on January 28, 2010, that 20,000 commercial structures and 225,000 residences had collapsed or suffered severe damage and will need to be demolished. The Haitian government is in shambles; the National Palace, Palace of Justice, National Assembly, Supreme Court, Prison Civile de Port-au-Prince, and buildings housing the ministries of finance, education, public works, communication, and culture have all been damaged. Municipal government buildings in Port-au-Prince suffered similar damage. Power, water, and communications have been disrupted. In spite of international efforts, there are desperate shortages of water, food, and medical care. The Minister of Education stated that the education system in Haiti had "totally collapsed"; half the nation's schools and the three main universities suffered severe damage. (Wikipedia)

As the poorest nation in the western hemisphere, Haiti has been struggling to pull its people out of poverty. It is perhaps not surprising that few Haitians appeared to have any awareness that they were living in an active seismic zone; 240 years is a long time to nurture a memory of earthquakes when hunger and hurricanes are more immediately pressing concerns. Nevertheless, the consequences of building without seismic detailing have been staggering.

This preliminary report is based on field reconnaissance by Eduardo Fierro, President of BFP Engineers, Inc. in Berkeley, California. Mr. Fierro has performed reconnaissance after many previous earthquakes and has established relations with the seismic engineering community in the Dominican Republic where he and Prof. Vitelmo Bertero have been lecturing on seismic design since 2003. A center dedicated to the study of protection against natural disasters was founded in Santiago DR in 2008 bearing the name of Prof. Bertero (Instituto Dominicano de Ingenieria Superior y Desastres Naturales "Vitelmo Bertero" Inc. (IDISDEN)).

Mr. Fierro left Berkeley on January 12, traveled to Santiago DR, and along with several Dominican engineers from IDISDEN, was on the ground in Port-au-Prince on Thursday January 14. His photos and observations were made from January 14 to 20, 2010. The primary objective of this initial trip was to observe the performance of building structures, industrial facilities, and infrastructure from a structural engineering perspective. Extensive information about this earthquake and its effects are available on the internet and from various media sources. This report documents places and structures that Mr. Fierro personally observed during his initial visit including Port-au-Prince, Cite Soleil, Petion Ville, Carrefour, and other towns en route to Leogane. He currently plans to return to Haiti in mid-February.

Seismic Setting

Haiti shares the island of Hispaniola with the Dominican Republic; Haiti occupies roughly the western third of the island. The northern shore of Hispaniola lies near the boundary separating the Caribbean plate and the North American plate. This plate boundary is dominated by left-lateral strike slip motion and compression, and accommodates about 20 mm/y slip, with the Caribbean plate moving eastward with respect to the North American plate. The island is crossed by several strike-slip faults including those which make up the Enriquillo Plantain Garden Fault Zone on the south. This fault zone starts offshore to the west of Haiti, bisects the Haitian peninsula, and then extends eastward towards Santo Domingo in the Dominican Republic (see Figure 1).

Although there have been no recent significant earthquakes in Haiti, several earthquakes were recorded by French historian Moreau de Saint-Méry (1750–1819) during the French colonial period. He wrote that in Port-au-Prince, "only one masonry building had not collapsed" in the earthquake of 1751 and that the "whole city collapsed" in the earthquake of 1770 (Wikipedia). At the 18th Caribbean Geological Conference in 2008, Paul Mann et al. stated that the fault had been locked for over 200 years and the period of inactivity was likely at an end (Mann, 2008).

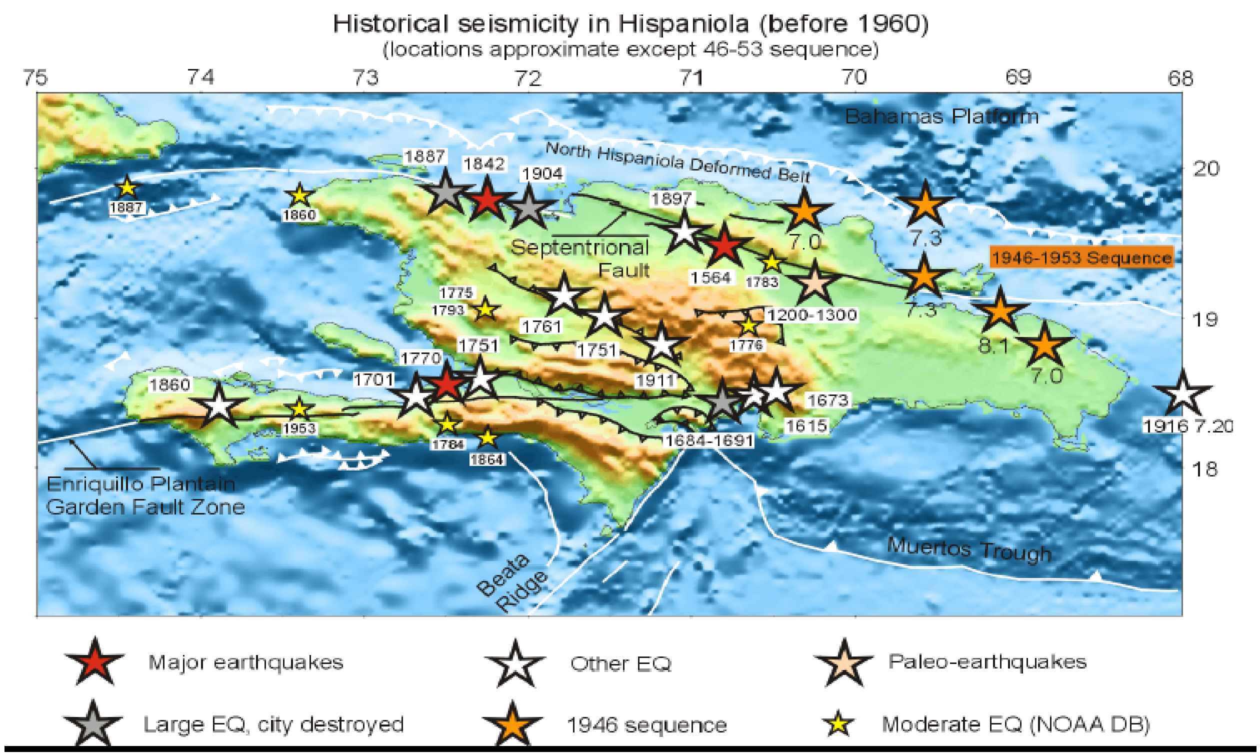

Figure 1: Historical Seismicity in Hispaniola prior to 1960. Last major earthquake near Port-au-Prince was in 1770.

Ground Motion Estimates

The USGS has published Shakemap instrumental intensity estimates (Figure 2) and estimated peak ground accelerations (PGA) (Figure 3). Note that the blue dots in Figure 3 indicate instrument locations; the one instrument located in Haiti is along the north coast, far from the epicenter. Figure 3 shows a maximum PGA of 0.30g. Based on the observed damage, Mr. Fierro estimates the PGA was more likely 0.45g in Port-au-Prince and possibly higher west of the epicenter in the direction of the rupture due to forward directivity. Structures in Leogane and other communities west of Carrefour suffered a higher level of damage than similar construction in Port-au-Prince.

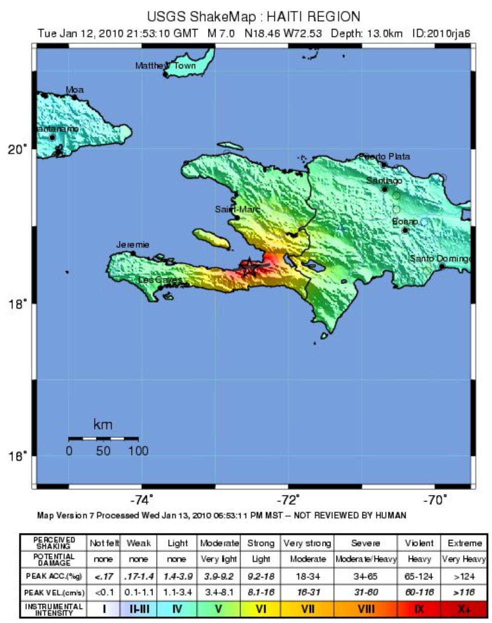

Figure 2: MMI Intensity (USGS Shakemap)

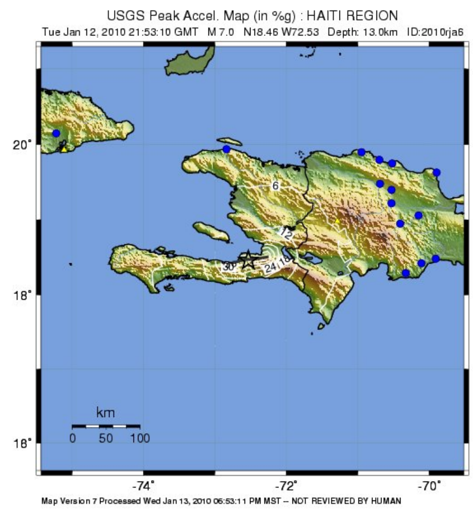

Figure 3: Peak ground acceleration (USGS)

Geotechnical Observations

The epicentral region includes low-lying coastal areas as well as coastal mountains with elevations in the range of 500-2000 meters. Landslides were a common sight on hillsides surrounding Port-au-Prince. Landslides and rock falls blocked roads, brought down utility poles, and resulted in damage or collapse of many hillside structures. Maps of damaged areas in Port-au-Prince show pockets with relatively more or less damage than the surrounding areas, indicating that local soil conditions may have contributed to the variation in damage. Dramatic evidence of liquefaction and lateral spreading was evident at the port where several docks and port structures were damaged or disappeared completely into the harbor.

Figures 4, 5, 6, 7 (clockwise): Landslide caused collapse of power pole; Failure of rubble and unreinforced masonry retaining walls; Landslide west of Port-au-Prince; Landslides contributed to damage of shanties on hillside near Petion Ville.

Construction Standards for Buildings in Haiti

The most striking aspect of the Haitian earthquake is the complete absence of seismic detailing in Haitian construction, from informal housing to recent multistory buildings in downtown Port-au-Prince, only a handful appeared to have been built with any awareness of the most basic principles of seismic design and construction. It appears there is no building code in Haiti and there are no licensing requirements for architects, engineers, or contractors. Seismic design is not included in the engineering curriculum in Haiti. Engineers who use any type of code have apparently used the French code (Beton Arme aux Etats Limites (BAEL)) which does not include any provisions for seismic design, or they have used the gravity load provisions from the American Concrete Institute code (ACI-318). While there are some laws on the books requiring building permits and inspections, it appears these are neither followed nor enforced. (Fouche, 2010)

The predominant style of construction is what is known in some parts of the developing world as confined masonry, relatively small reinforced concrete frames with unreinforced concrete masonry unit (CMU) infill. Tragically, the Haitian version has the outward appearance of confined masonry but had been built without the requisite seismic detailing to provide the confinement, resulting in thousands of catastrophic failures. Thus, this unconfined masonry construction had been used on multistory buildings up to 5-6 stories but performed no better than unreinforced masonry construction.

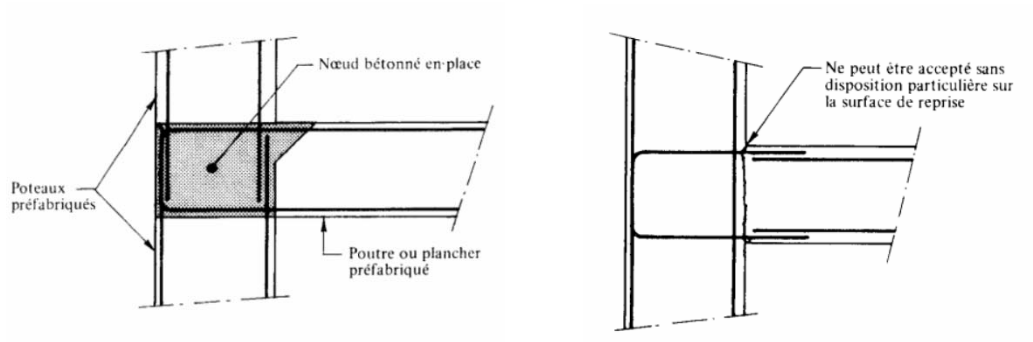

Figure 8: Beam-column joint details A & B from Regles BAEL 91 (Beton Arme aux Etats Limites), 2006. Details show column bars spliced in the beam-column joint and beam bars spliced at the face of the joint

Figures 9, 10, 11 (clockwise): Typical concrete details with undersized members, mixed use of smooth and deformed reinforcing bars, undersized rebar often #3 and #4, shear reinforcing provided by smooth ¼" diameter open hoops, no hoops in joint. Columns often sized to match width of 6" or 8" CMU block. Poor quality concrete, lack of consolidation, and corrosion of bars also seen widely. The combination of heavy construction and the complete lack of ductility resulted in thousands of collapsed structures and many thousands of fatalities.

Nonductile concrete, unreinforced masonry, and unconfined masonry are all structural systems with little lateral capacity and are known to perform poorly in earthquakes. Irregular configurations with soft, weak stories or captive columns are also known to perform poorly. Poor quality materials, poor workmanship, poor maintenance, and use of corrosive materials such as beach sands in the concrete result in structures that perform poorly. Construction without any engineering design or oversight, without any standards, much less seismic standards, and without any type of inspection cannot be expected to fare well during a major earthquake.

Response of Building Structures

As noted above, the building stock in Haiti is largely brittle and weak and was not designed to resist earthquakes. The difference between those that collapsed and those still standing may be a very small margin of reserve strength, since virtually none of these structures were designed for seismic forces. Although there are many buildings still standing, buildings of all sizes, materials, and vintages did poorly. A small sample of these are shown below (see Figures 12-19):

Figure 12: Presidential Palace. E-shaped plan; completed 1920; partial collapse. Many 1st story windows unbroken but cupola and much of 2nd story collapsed.

Figure 13: Port-au-Prince Cathedral. Built 1884-1914; collapse of roof and upper walls. Archaic reinforcing dangling from above; light steel roof framing visible in wreckage.

Figure 14: Modern 4-story colonial-style building (est. 5 yrs old), partial collapse of bottom 2 floors.

Figure 15: 5-story building; bottom two stories collapsed. Close-up of 1st-2nd story joints in Fig. 11.

Figure 16: 3-story structure; never completed; collapsed at 1st floor and leaning on adjacent structure. Few transverse walls, heavy slabs, undersized and weak columns, and complete lack of ductile detailing all contributed to collapse.

Figure 17: Close-up from 3-story collapse at left. Column dimensions 6"x12". Note column bars spliced inside the beam-column joint.

Figure 18: 2-story school in Leogane; complete collapse with many fatalities.

Figure 19: 3-story university building in Leogane, still under construction with weak columns and little or no masonry infill. Complete collapse.

Response of Infrastructure

The infrastructure of Haiti will take many years to recover from this devastating earthquake. The main port in Port-au-Prince had two primary docks; one of these collapsed completely and the other suffered a partial collapse (see Figures 20-22). The adjacent fuel port lost the seaward end of the dock and the piles supporting the remaining section were all misaligned (Figures 23-27). The glazing all fell from the control tower at the international airport and masonry infill walls in the terminal were cracked, closing the airport temporarily. The team visited two electric power plants; neither one was in operation. The first was out primarily due to failures in the distribution system outside the plant; the second was down due to the failure of a fire water tank. The tank farm adjacent to the fuel port suffered extensive damage. Roads and bridges throughout the area suffered damage.

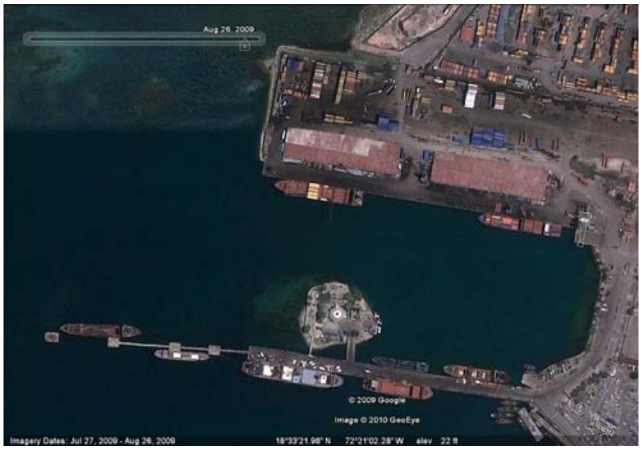

Figure 20: Port-au-Prince main commercial port prior to earthquake. (Google Earth images used for Figures 20, 21, 24, and 25).

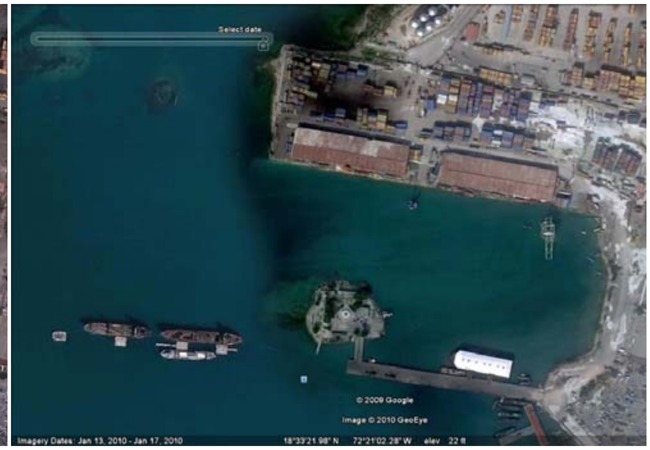

Figure 21: Note traveling crane at top of photo now immersed in water; no sign of dock. Half of dock at bottom of photo also gone. Note white patches onshore indicating residue from sand boils.

Figure 22: Commercial port; dock collapsed and crane immersed underwater. Signs of liquefaction, sand boils, and lateral spreading throughout port area.

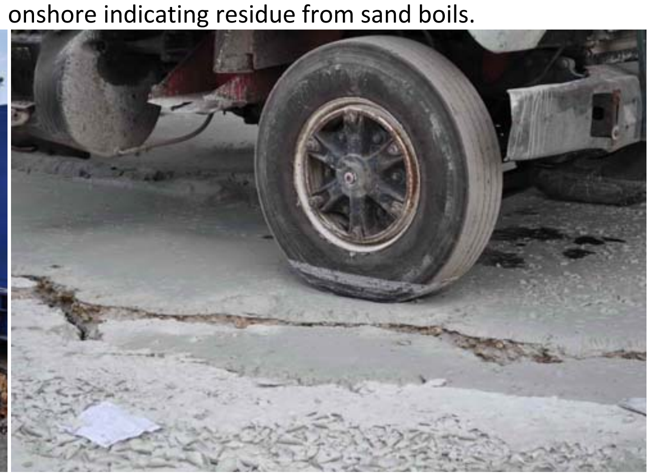

Figure 23: Mark on tire indicates height of sand flow at commercial port.

Figure 24: Fuel port prior to earthquake.

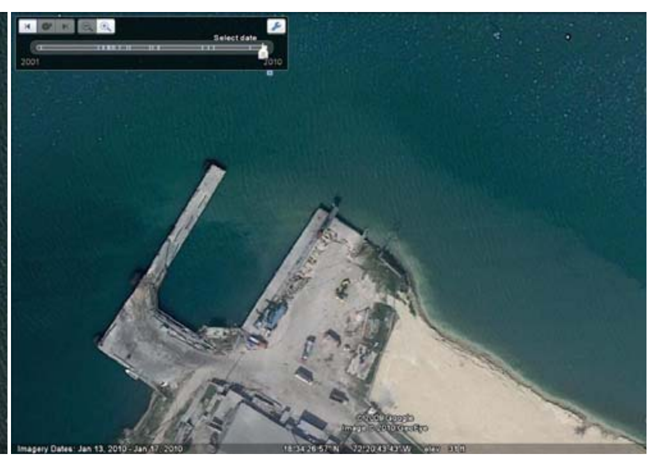

Figure 25: Fuel port; dock collapsed (note green truck visible hanging off end of remaining section).

Figure 26: Fuel port, end of remaining section of dock.

Figure 27: Precarious support for remaining section of dock at fuel port; all piles misaligned.

Figure 28: All glazing fell from control tower; Port-au-Prince International Airport. Infill walls in terminal cracked; mostly nonstructural damage.

Figure 29: Bridge along main road into Port-au-Prince from the east. Damage at girder seats; all locations.

Figure 30: Electric power plant; one of six unanchored transformers jumped the rails. No damage to ceramic components.

Figure 31: Tank farm at fuel port. Widespread tank damage; tank shown had "elephant foot" and "elephant knee."

Response of Industrial Facilities

Mr. Fierro visited a steel factory in Port-au-Prince and a cement plant located near Aubry to the north of Port-au-Prince. The cement plant was still operating the day of the visit. This plant had a dedicated pier, many conveyors, silos, tanks, etc. While the team observed damage to many structures at the plant, the plant manager indicated that most of the observed damage affected structures or equipment that was not actively in use. The steel plant imports large rolls of Dominican steel wire and cuts and straightens the bars for sale as deformed #3 bars, deformed #4 bars, and smooth ¼" diameter bar used for transverse ties. The roof of the steel plant collapsed; the facility was not in operation.

Emergency Response

One of the most tragic aspects of this earthquake was the complete absence of emergency responders in the initial hours and days following the earthquake. Haitian government officials were overwhelmed by family tragedies of their own; government ministries were in ruins; and communications were severed. On January 14, Mr. Fierro did not see any search and rescue teams, any police presence, any caution tape, any clean-up crews, any heavy equipment, any food or aid stations, any assistance of any kind. While this situation changed in the following days, as international aid poured in, the lack of immediate assistance may have cost many their lives.

Conclusions and Recommendations

It would be easy for those in the developed world to look at this tragedy and think that this cannot happen here. Unfortunately for all of us, there are many locations in the world that build today without appropriate seismic detailing; there are many vintage structures throughout both the developed and developing world without appropriate seismic detailing; there are many locations where the current generation has no memory of seismic activity and earthquake preparedness is not on the list of priorities. As the world population grows and urban areas become more densely populated, the worldwide earthquake hazard is increasing rather than decreasing.

Nevertheless, successful seismic resistant schools, hospitals, commercial structures, and residences can be built utilizing the same concrete, steel, and concrete block used in Haiti. Other countries such as Peru and Turkey share many of the problems seen in Haiti, and use confined masonry for the majority of their building structures. Since 1999, schools in Peru have been built following a standard design that has been shown to resist ground motion on the order of 0.50g without any damage. The government of Peru also sponsored the production and dissemination of a handbook for property owners and laborers showing cartoon-style how to build a confined masonry home, including step by step instructions for digging footings, mixing concrete, arranging the bars, etc. (Blondet). Several pages from the Spanish language version of this booklet are shown in Figure 32.

The people of Haiti need to rebuild quickly; on January 19th Mr. Fierro saw masons reconstructing collapsed walls using the exact technology that caused them to fall. The international aid and engineering communities need to help educate Haitians regarding the earthquake hazards and provide basic, easy to understand guidance on how to rebuild their society in a more earthquake resilient fashion. This should not involve reinventing the wheel; most of Haiti's problems have previously been

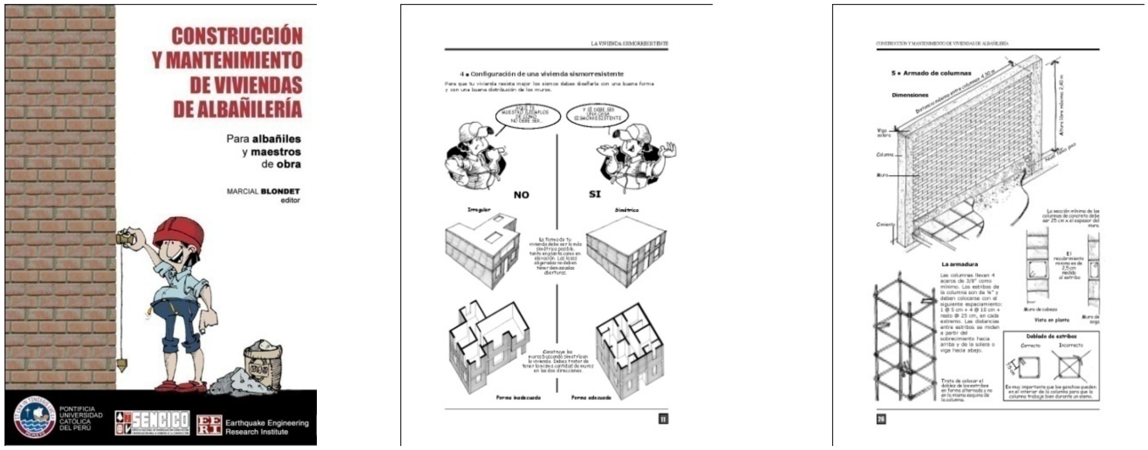

Figure 32: Peruvian booklet on confined masonry construction; sample pages. (Blondet)

addressed elsewhere. Some ideas might include:

- Provide immediate assistance to the government of Haiti to develop and adopt a provisional building code that includes seismic provisions. Countries such as the Dominican Republic or Peru have codes that might be readily adapted for Haiti.
- Provide immediate assistance to existing Haitian architecture, engineering, and construction professionals to educate them on the principles of seismic design and construction; such educational seminars should be organized as soon as possible, since reconstruction is already under way.
- Translate the Peruvian booklet on confined masonry construction into Kreyol or French and make it available for free; provide training and demonstrations in public parks, schools, or locations that sell building supplies, to show proper construction techniques.
- Use international aid money to sponsor the construction of one great school in each affected town following the plans developed in Peru; these plans are readily available and show a proven technology that utilizes confined masonry.
- Devise a mechanism to tie aid money for reconstruction to the use of seismic detailing and seismic resistant construction.
- Create an avenue for engineers and inspectors from developed countries to help with design, plan review, and construction inspection during the initial reconstruction period. We have received a number of requests from American professionals asking how they can volunteer.
- Provide scholarships to existing Haitian students studying architecture and engineering to go abroad to finish their studies, since many Haitian universities are not currently able to function and do not have the appropriate curriculum in seismic design. This could involve both short- and long term-scholarship arrangements.

In closing, here are photos of school construction in Peru (Figures 33-34). The school shown at left (Figure 33) and the school in the background in Figure 34 both experienced ground motion of 0.5g during the 2007 Pisco, Peru Earthquake. This was a magnitude 7.9 event; 80,000 structures collapsed in Pisco, but these schools were undamaged. The wing in the foreground (Figure 34) was under construction during July 2008. At that time, we met a woman who identified herself as the Engineer of Record and had designed the school; she was in the field personally tying all the bars for the column cages because she said no one else could be trusted with such an important task. May engineers everywhere take a lesson from her.

Figure 33: School in Pisco, Peru survived 7.9M 2007 Pisco earthquake without damage (PGA 0.5g). Peruvian government developed standard plans for school construction in 1999.

Figure 34: School under construction, Pisco, Peru July 2008. Building has 1m T-shaped longitudinal wall at location of each transverse wall; rest of transverse wall is solid unreinforced concrete block masonry infill.

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