LESSONS LEARNED FROM THE OCTOBER 15, 2006 HAWAI`I EARTHQUAKE AND THE AUGUST 15, 2007 PERU EARTHQUAKE

Qisong "Kent" Yu[1] and David Gonzalez[2]

[1] *Associate Principal, Degenkolb Engineers, Portland, Oregon, USA*
[2] *Associate Principal, Degenkolb Engineers, Seattle, Washington, USA*
Email:kyu@degenkolb.com, dgonzalez@degenkobl.com

ABSTRACT:

In this paper, the authors first discussed the seismological background, typical construction practices, and the observed seismic performance of engineered and non-engineered building structures based on the earthquake reconnaissance of two recent earthquakes: the October 15 Kona, Hawai`i, USA Earthquake (Mw = 6.7) and the August 15, 2007, Ica-Pisco Peru Earthquake (Mw = 8.0). Despite the difference in the construction practices and the construction materials used in both countries, some structural damage and structural collapse were evidently predictable and could be avoided through appropriate enforcement of the building construction regulations and mandatory seismic retrofit of collapse prone structures. The authors then focused on the discussion of lessons learned from seismic performance of school and hospital structures as well as pre-disaster mitigation planning, post-earthquake response and structural repair strategies. It is concluded that disastrous consequences are bound to happen again if the lessons are not learned and appropriate measures are not implemented.

KEYWORDS: Earthquake Reconnaissance, earthquake lessons, seismic mitigation

1. OCTOBER 15, 2006 HAWAI`I EARTHQUAKE

At approximately 7:07 am on October 15, 2006 the first earthquake struck the Kiholo Bay located in the northwest coast of the Big Island. The first earthquake had a magnitude Mw6.7. A few minutes later a second earthquake was measured with a magnitude Mw6.0. There were a few aftershocks for the next few days. The reported shake intensity reached level VIII in the Modified Mercalli Scale.

1.1. Seismicity

The Mw6.7 earthquake epicenter was located at 19.878°N and 155.935°S at a depth of approximately 39 kilometers. Only minor injuries with no fatalities were reported. Figure 1 shows the peak ground acceleration (PGA) recorded at four seismographic stations. The highest measured PGA was 1.05 g recorded at the Waimea Fire Station.

Station	Distance to Epicenter (km)	PGA (g)		
		90 Deg	360 Deg	UP
Kona Fire Station	26.2	0.27	0.26	0.24
Waimea Fire Station	32.8	1.05	0.69	0.74
HonoKaa Police Station	54.2	0.65	0.65	0.36
Kona Hospital	39.5	0.52	0.37	0.29

Figure 1 – Seismographic recording Stations

The Kiholo Bay earthquake had very high frequency content as compared to earthquakes in California and the mainland's West Coast. The USGS also found that ground accelerations in Hawai`i are substantially higher than what the average intensity would indicate in California.

1.2. Non-engineered and Historic Structures

Although the structural and nonstructural damage was relatively small in terms of economic losses, there were certain types of structures that sustained more damage than others. Historic and non-engineered structures constructed with unreinforced masonry suffered the most significant structural damage. The historic Kalahikiola Congregational Church in Ka`apau was built in the mid 1800's with lava stones walls supporting heavy timber trusses. The walls were approximately 36 inches thick. The heavy unreinforced walls were not anchored to the diaphragms and failed in an out-of-plane mode. Other examples of historic structures that were damaged are the Hulihe`e Palace built in the early 1800's with lava stones and the Mokuaikaua Congregational Church. Both of these buildings were deemed unsafe for occupancy and were *red tagged*.

1.3. Residential Construction

Residential construction in the rural part of North Kona normally consists of wood construction very similar to that used in the mainland United States. However, due to termite problems, the first floor is elevated from the ground a few feet. The first floor is normally supported on a wood beam and post system founded concrete blocks colloquially referred as "tofu blocks". Most of the structural damage observed in residences consisted of "soft-story" deformation and the displacement of the wood posts off the concrete blocks. Figures 2 and 3 show typical residential construction and damage.

Figure 2 – Typical residential construction

Figure 3 – Wood posts displaced out of "tofu blocks"

However, perhaps the most noticeable economic loss was nonstructural damage. In at least one case, a tank gas dislodged from its foundation and caused a fire that destroyed approximately half of a residence. In other cases, heavy contents and furniture displaced causing damage and minor injuries to occupants.

1.4. Medical Facilities

Engineered structures also suffered structural and nonstructural damage. Modern hospitals like Kona Community Hospital, North Hawai`i Community Hospital and Hale Ho`ola Hamakua experienced minor structural damage and moderate nonstructural damage. Kona Community Hospital is a 94-bed hospital was constructed with concrete frames and reinforced concrete and masonry shear walls. Although it does not appear the hospital was detailed to perform in a similar manner to those medical facilities located in California and Western, the construction type is commonly used in many areas of the United States. The nonstructural damage consisted mostly of fallen ceiling, lights and some partitions as shown in Figure 3. Hale Ho`ola Hamakua is a nursing care facility with several one-story reinforced concrete and masonry shear wall buildings. The building was constructed in the mid-1990's and suffered minor structural damage and moderate nonstructural damage. Most of the nonstructural damage was due to the lack of seismic detailing of ceiling systems and bracing of heavy contents.

Figure 3 – Kona community hospital structural and nonstructural damage

1.5. Schools

Schools in the North Kona area suffered minor structural damage and moderate to considerate nonstructural damage. Fortunately, there were only very few minor injuries and all the facilities were reopened within a few days after the seismic event. Kohala, Waikoloa and Honoka`a Elementary Schools were the closest to the epicenter and therefore sustained most of the damage. The nonstructural damage consisted of fallen ceilings and light fixtures, broken pipes and toppled heavy furnishings (see Figure 4).

Figure 4 – Waikoloa elementary nonstructural damage

2. AUGUST 15, 2007 PERU EARTHQUAKE

2.1. Seismological Aspects

On August 15, 2007, at 6:40 PM local time, an Mw 8.0 earthquake shook the coast of central Peru. The earthquake epicenter was located off the Pacific coast about 45 km west of Chincha Alta, 105 km Northwest of Ica and 150 km from Lima. The earthquake occurred 39 km below the ground surface at the boundary between the subducting Nazca plate and the overriding South American tectonic plate. There have been many very large earthquakes along the central coast of Peru to northern Chile, including the August 13, 1868 Arica Peru Earthquake (Mw = 9.0), the October 3, 1974 Lima Peru earthquake, and the June 23, 2001 Southern Peru (Mw=8.4). This earthquake has caused a total death of about 600, with majority of fatalities from Pisco and Chincha areas, where significant amount of adobe buildings collapsed. Unlike California, the strong ground motion recordings in Peru were scarce. Ground motion recordings in Ica show a PGA of 0.34g and approximately 2.5 minutes strong shaking.

2.2. Non-engineered and Historical Buildings

In Pisco and Chincha areas, almost all the adobe buildings suffered at least partial collapse. The adobe construction has been a traditional construction in Peru for more than 200 years. The building of this type is one-story high with rectangular configuration in plan. The adobe walls are made of adobe blocks laid in mud mortar, and range from 12 inches to 30 inches in thickness. The roof framing is typically made of timber beams and timber planks covered with a mud mortar overlay. In some cases, bamboo tubes are used in lieu of timber beams for supporting bamboo sheets covered with a mud mortar overlay. The adobe walls have limited out-of-plane resistance. Furthermore, the roof diaphragm provides little bracing at the top of the adobe walls. Thus, this type of construction is seismically vulnerable and prone to collapse (see Figure 5). Many historic church temples, as old as 400 years, made of adobe block walls experienced complete or partial collapse. Figure 6 shows that a historical church in Pisco downtown collapsed and killed more than one hundred and forty people.

Figure 5 Collapsed building in San Jose Hospital of Chincha

Figure 6 Collapsed church in Pisco Downtown

2.3. Modern Construction

The engineered structures having concrete floor slabs as rigid diaphragms can be categorized into four types: (1) lightly reinforced concrete frames with brick infill, (2) concrete moment frames with brick infill as partition, (3) concrete shear walls with lightly reinforced concrete frames and brick infill, and (4) concrete moment frames with isolated brick infill. The modern residential buildings are made of lightly reinforced concrete frames with brick infill. The other types are typically used for schools, hospitals, and commercial buildings. Among these

four types, the concrete moment frame with isolated brick infill and the concrete shear walls tended to perform very well. However, we observed several buildings of the first two categories suffered severe damage and dramatic failure. The failure is typically attributed to (1) torsional response due to the window openings at street sides (see Figure 7), (2) torsional response due to shifting of the center of mass from irregular floor addition, (3) torsional response due to the irregular plan configuration, (4) captive columns, (5) concrete frame joint failure due to inadequate joint shear reinforcement, (6) inadequate masonry walls, and (7) foundation failure due to the unconsolidated landfill (see Figure 8).

Figure 7 Torsional response and weak story leading to the failure of this building in Pisco

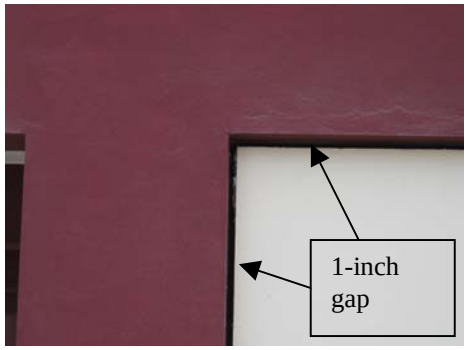
Figure 8 Structural collapse of this "Titanic" building due to failure of the unconsolidated landfill

2.4 Schools

2.4.1 Geotechnical Engineering Laboratory of a University in Ica, Peru

The 'Laboratorio de Mecanica de Suelos' is located at the south side of Universidad Nacional San Luis Gonzaga De Ica campus. It is a two-story rectangular concrete frame structure with masonry infill (see Figure 9a). The construction of the building was completed in 2000. Each masonry infill, either partial height or full height, was confined with a secondary concrete frame made of a pair of concrete columns and a beam atop the wall. The column reinforcement was anchored in the supporting concrete floor beams, which makes the walls act as cantilever walls to provide out-of-plane support of the infill. A 1-inch wide isolation joint filled with some elastomeric material was created between the concrete framing and the infill masonry (see Figure 9b). The isolation joint helps avoid creating the short column condition. Several infill walls were found out of plumb. A couple of full-height masonry infill walls experienced some minor to moderate damage of the plaster cover at the corners. However, the concrete frames did not experience any damage. Overall this building performed very well, although the building experienced a base shear of at least 70% its self-weight.

(a) A University laboratory



(b) A gap created around infill for isolation

Figure 9 Brick infill isolated from surrounding concrete moment frame

2.4.2. Alexander Von Humboldt in Pisco, Peru

The 'Alexander Von Humboldt' school is a private school located in the downtown area of Pisco, just a few blocks away from the central plaza. This campus, built in 1997, consists of four buildings forming a 'U' shape in plan. The lateral force resisting system of the buildings is typically made of concrete moment frames with un-reinforced masonry walls. The main classroom building is five stories tall and has two classrooms at each level except the first floor being used for parking. The secondary classroom building is four stories plus a basement, and has one classroom at each level with its basement space for bathrooms. The stair tower is located in between both classroom buildings, with its intermediate landing at the same floor level of the secondary classroom building. A one-inch seismic joint was used to separate the structures at all levels. Although compressible foam was used in the seismic joint, grouting was found to infill the top of the seismic joint. The main lateral system of all the buildings suffered insignificant damage. But the un-reinforced masonry walls suffered significant damage during the earthquake (see Figure 10). Most of these walls need to be demolished and replaced. Several partial brick infill wall next to the corridor completely collapsed.

2.4.3. The Instituto Superior Tecnologico Estatal Pisco in Pisco, Peru

The classroom complex consists of four two-story buildings, including two classroom buildings, a stairwell and a restroom/storage building. The buildings were designed in 1995. The buildings are typically separated with a 2-inch seismic joint at both levels. The joint was somehow reduced to less than one inch at the second story between the classroom building and the restroom building. This resulted in pounding damage. Each classroom building has two identical classrooms at each level. It consists of concrete frames with masonry fill with floor and roof concrete slabs. In the transverse direction, it has five lines of reinforcement concrete frames. Both the two end frames and the middle frame have two bays with complete masonry infill. The other two frames are one-bay moment frames without any infill, and columns orient in the strong wall. In the longitudinal direction, there are two lines of concrete frames with partial height masonry infill. The brick infill in the front is about one and half times higher than that in the back, resulting in an aspect ratio of about two and four for the columns in the front and back, respectively. This resulted in severe shear failure of the columns in the front, which were on the verge of losing gravity carrying capabilities (see Figure 11). The windows next to the short columns fractured and fell on the floor. The front masonry infill in the first-story also experienced the moderate diagonal cracking.

Figure 10 Extensive masonry wall damage

Figure 11 Shear failure of corridor columns

2.5 Medical Facilities

2.5.1 The Hospital Regional De Referencia Ica

The Hospital Regional De Referencia Ica is the largest hospital in the region. It consists of approximately 16 buildings, most of which were designed and constructed in 1964. The main hospital consists of three four-story wings in a T configuration and a five-story elevator tower in the center, separated with a 2-inch seismic joint at all levels. The typical lateral system of each wing is made of four lines of concrete moment frames in the longitudinal directions with brick infill mostly at each side of the corridor, and seven lines of concrete frames in the transverse direction with brick infill partitions. The elevator tower has a concrete shear wall core as its lateral force system. Exterior moment frames of each wing typically showed no sign of stress except significant pounding between the wings and the elevator tower. The infill walls at the corridor experienced extensive damage of architectural finishes. Significant pounding occurred at the seismic joints between the wings and the elevator tower, and was partially attributed to the use of grouting to infill the seismic joints at the top and bottom of the floor edge beam (see Figure 12). Mechanical pipes and medical equipment and supply racks were not seismically braced, resulting in extensive nonstructural damage. As a result of extensive damage to architectural and mechanical components, the main hospital was abandoned. Next to the main hospital, there is an emergency power/mechanical building. It is a one-story concrete moment frame structure with brick infill in both directions. The exterior brick infill in the longitudinal direction created short column conditions. This resulted in severe shear failure of the exterior columns, which were on the verge of losing gravity carrying capabilities (see Figure 13).

Figure 12 Pounding due to seismic Joints partially filled with grouting in Ica Hospital

Figure 13 Emergency power building Short column failure in Ica Hospital

2.5.2 The San Jose Hospital in Chincha

The San Jose Hospital in Chincha is the second largest hospital in the region. Almost all the buildings are one-story structures. After a seismic assessment of the hospital was completed around 2004, it has been replacing the old hospital buildings including many adobe buildings. At the time of the earthquake, at least three new reinforced CMU buildings were near the completion of construction, and they performed very well. Several existing adobe buildings were used for storage, as a morgue, and to house the emergency generator. During the earthquake, almost all the adobe buildings experienced partial collapse. The hospital had to borrow a new emergency generator for emergency treatment. Other existing engineered structures built in 1989 performed well, except that one corridor structure experienced significant damage due to pounding because the contractor used the grouting to infill the seismic joint. The mechanical pipes, mechanical equipment as well as medical equipment and supply racks were typically not seismically braced. After the earthquake, a majority of the medical supplies were destroyed, and the hospital was without oxgen, electricity or water for a couple of days. The patients stayed outside for four days after the quake and then moved into the newly constructed buildings.

2.5.3 The Pisco Hospital

The Pisco Hospital has about 18 structures, two of which were reinforced concrete wall buildings and near the completion of construction. The majority of the original hospital buildings were one-story rectangular buildings constructed about 74 years ago. The transverse direction of these buildings typically consists of two interior and two exterior lines of CMU walls. The exterior walls have either a door opening in the center or two window openings. In the longitudinal direction, they have two lines of exterior CMU walls with window and door openings. Extensive cracks were observed between window openings, causing spalling of the plaster cover. The only original construction that did not experience any structural damage is the Kitchen/Mechanical Equipment Building. This is due to its lateral force system consisting of multiple lines of concrete shear walls in each direction. After the earthquake, the hospital salvaged medical beds and medical equipment and supplies and moved them into the newly constructed buildings. Figure 14 shows the structural damage of an original building with window openings at one end and a door opening at the other end. Significant torsional response of this building caused the wall piers adjacent to the windows to suffer more damage, resulting in the out-of-place collapse of the windows and the walls. Figure 15 shows structural damage of another hospital building that was originally a one-story concrete moment frame building having marginal joint shear reinforcement. Brick infill walls in each of the longitudinal exterior side created a captive column condition. A new addition was built on top of the southern half of the building. This irregular addition shifted the center mass, and created an undesirable torsional response. This building experienced short column failure in the longitudinal direction, joint shear failure in the transverse direction, as well as large twist with 10-in permanent drift in the transverse direction at the north end.

Figure 14 Structural damage of one-Story hospital building

Figure 15 Torsional response, short columns and lack of joint reinforcement leading to the collapse of this building in Pisco Hospital

3. LESSONS LEARNED

Code enforcement and construction inspection are very important. Regulations and oversight by jurisdictions and building officials are important mechanisms to assure good designs are properly implemented. All the parties involved should work together to make sure structural safety is achieved through proper design and construction.

Nonstructural seismic bracing is very important. Often, the bracing of nonstructural components is neglected or attention is not paid to the detailing. Essential facilities need to develop a seismic mitigation plan to ensure entire system including architectural, mechanical and electrical components to function after a major earthquake. It is not acceptable to place emergency generator in a collapse prone structure.

Pre-disaster mitigation and post-disaster response plans need to be developed. Communities must develop strategies to reduce the number of casualties and property losses through systematic retrofit of existing collapse-prone buildings. Public and private entities must work together to educate the population. This effort must encompass federal, state and local governments as well as non-government organizations in order to reach out to as many people as possible.