Learning from Earthquakes

Preliminary Observations on the Hawai`i Earthquakes of October 15, 2006

This report was compiled by EERI member Gary Chock of Martin & Chock, Inc., Honolulu, Hawai`i. He drew on his own observations as well as information from and materials prepared by a number of other professionals: Ian Robertson, Peter Nicholson, and Horst Brandes, the University of Hawai`i at Manoa; Edward Medley, the Geo-Engineering Earthquake Reconnaissance Association; Paul Okubo, the Hawaiian Volcano Observatory; Barry Hirshorn, the Pacific Tsunami Warning Center; Jiro Sumada, the County of Hawai'i Department of Public Works; Ernest Lau, State of Hawaii Department of Accounting and General Services; Afaq Sarwar, Sarwar Structural Engineering; John Dal Pino, Albert Chen, David Gonzalez, William Grogan, Brenda Guyader, Lisbeth Blaisdell, and Wayne Low, Degenkolb Engineers; and William Holmes, Rutherford & Chekene and EERI Learning from Earthquakes Program Committee chair.

A number of organizations were also involved in the post-earthquake reconnaissance: ATC-20 building safety engineers from the Structural Engineers Association of Hawai`i; the Hawai`i State Earthquake Advisory Committee of State Civil Defense, and the U.S. Geological Survey's National Strong Motion Program. Several reports, with many additional figures and photos, are available in their entirety on the EERI web site at ***http://www.eeri.org/lfe/usa_hawaii.html****.*

The publication of this report is funded by EERI's Learning from Earthquakes Program, under National Science Foundation Grant # CMS-0131895.

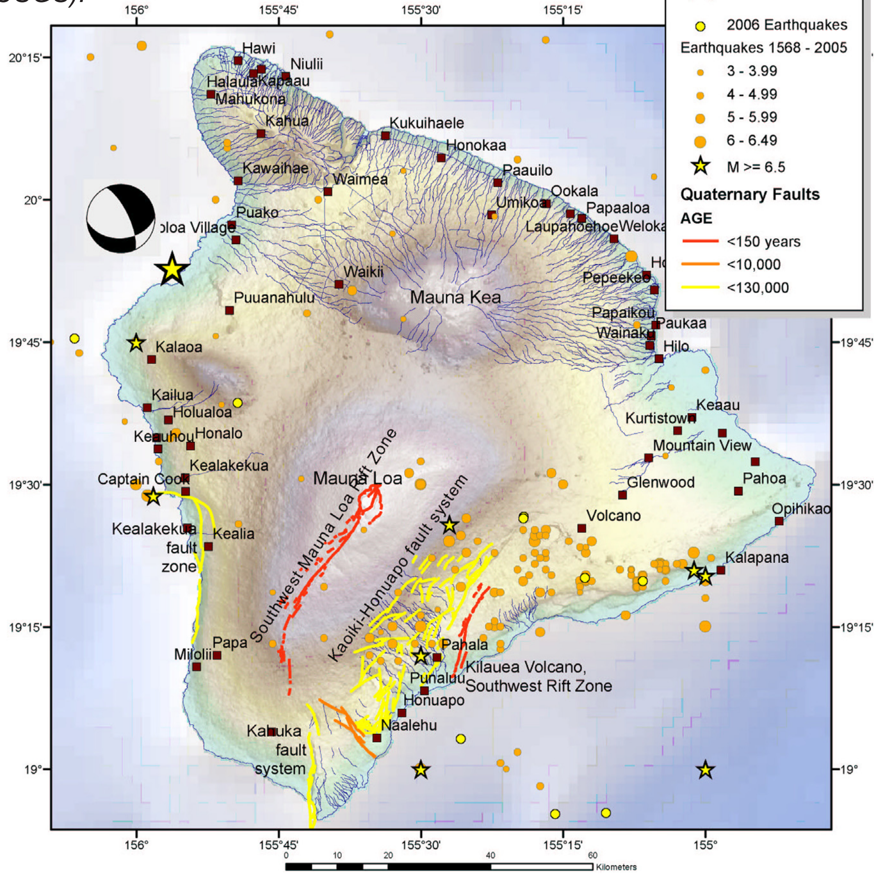
Introduction

Beginning at 7:07 a.m. local time on October 15, 2006, two earthquakes with magnitudes of M_w6.7 and M_w6.0 struck in close succession just off the northwest coast of the big island of Hawai`i (see Figure 1). Shaking reached Intensity VIII on the Modified Mercalli Scale (MMI), as reported by residents.

No deaths were attributed to ground shaking, and only minor injuries were reported. Damage caused by these earthquakes was estimated at more than $120 million as of mid-November, without including damage to private residences. Most of the built infrastructure in the vicinity of the earthquake epicenters survived with little or no apparent damage. The low rates of injury and economic loss are attributed in part to the relatively rural area in which the earthquakes struck, and the focal depth (39 km) of the M_w6.7 Kiholo Bay earthquake. It was also fortunate that the earthquakes struck just after sunrise on a Sunday morning.

There were numerous rockfalls and landslides in road cuts, embankments and natural slopes on Hawai`i Island, and road transportation was disrupted in some places. There was damage to dams and irrigation ditches in the Waimea area. Two

Figure 1. *Epicenter of the October 15 Kiholo Bay earthquake and the locations of island of Hawai`i towns (USGS).*



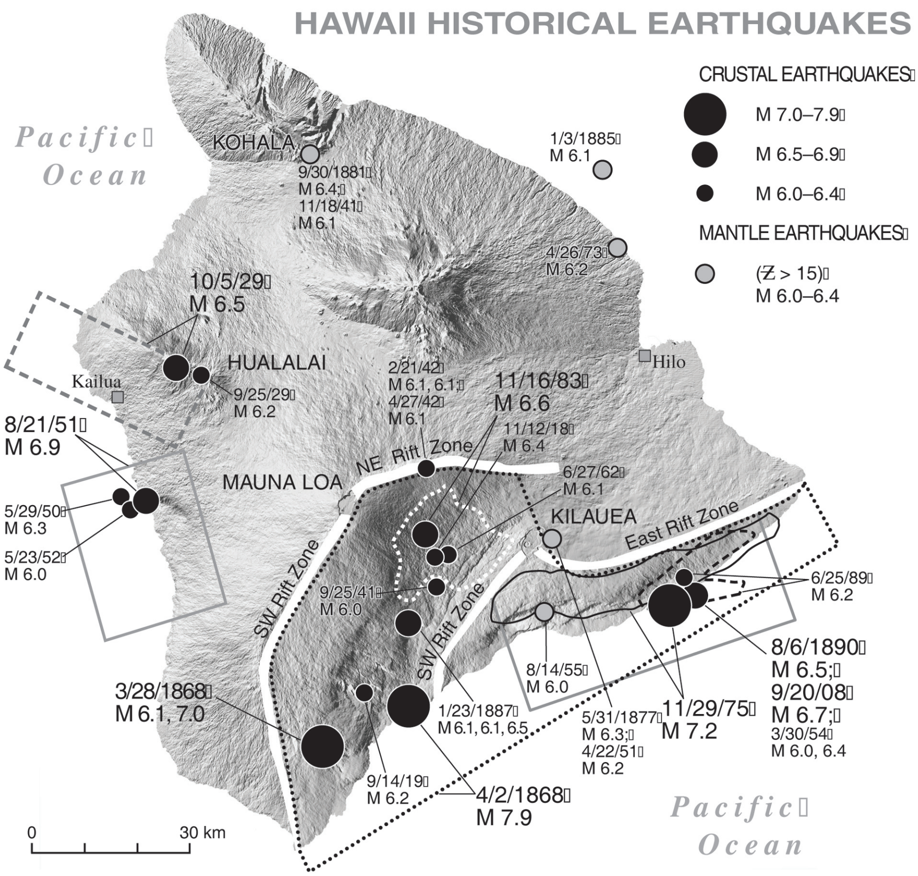


Figure 2. *Hawaii historical earthquakes and the inferred rupture zones of the larger events (figure: Klein, F., USGS).*

dams had earth fill disturbance and cracks along their crests, while at least two others showed clear evidence of incipient slope failure on their embankments. A system of irrigation ditches feeding some of the reservoirs was interrupted due to debris blockage. One of the two major commercial ports on the island, Kawaihae Harbor, sustained major damage from liquefaction and lateral spreading. This facility is located less than 24 km (15 miles) from both earthquake epicenters.

Most modern engineered buildings performed well, with some exceptions. Healthcare and school facilities had little structural damage, but considerable damage to their nonstructural systems, principally T-bar lighting and ceiling systems and fire sprinkler systems. As a result, they were not fully operational in the weeks following the earthquakes. Close to the epicenters, older churches and historic buildings with thick bearing walls constructed of unreinforced lava rocks sustained the most dramatic and potentially life-threatening damage.

Over 1,800 individual residences—less than 5% of the single family home inventory—were damaged to varying degrees. Many of the most severely damaged homes were constructed on post and pier foundation systems resting on small unanchored concrete foundation blocks. Several residences also had damage to lava rock retaining walls—typically consisting of individual, rough lava rocks stacked dry, or with minimal mortar.

Seismotectonics

Earthquakes on the island of Hawai`i are not rare. The ground shaking hazard in Hawai`i County ranks among the highest in the United States. For example, the Kealakekua fault zone on the southern Kona coast was the site of an earthquake of about magnitude 6.9 on August 21, 1951, which damaged scores of homes on the Kona coast and triggered numerous damaging landslides (see Figure 2).

The Mw6.7 Kiholo Bay earthquake struck at 7.07 a.m. local time with an epicenter location of 19.878°N, 155.935°W, and a focal depth of approximately 39 km (24 miles). It was followed by the Mw 6.0 Hawi earthquake at 7.14 a.m. local time with an epicenter location of 20.129 N, 155.983 W, and a focal depth of approximately 19 km (12 miles). Strong ground motions lasted for approximately 20 seconds during the Kiloho Bay earthquake, and 15 seconds during the Hawi earthquake. While the two events were only seven minutes apart, the difference in depths and aftershock epicenters suggests that the M6.0 may not be an aftershock of the M6.7, and that they were events from different seismic sources.

Historically, the largest earthquakes in Hawai`i have occurred beneath the flanks of the Kilauea, Mauna Loa, and Hualalai volcanoes. The flanks of these volcanoes adjust to the intrusions of magma into their adjacent rift zones by storing compressive stresses and occasionally releasing it in crustal earthquakes. The active fault surfaces for these large earthquakes are associated with a near-horizontal basal décollement separating the ancient oceanic crust from the emplaced volcanic pile, lying approximately 10 km beneath the earth`s surface. (A décollement is a tectonic surface that acts as a plane of detachment between two masses.) Examples of such crustal or décollement earthquakes are the 1975 M7.2 Kalapana earthquake beneath Kilauea`s south flank, and the 1868 M7.9 earthquake beneath the Kau district on Mauna Loa`s southeast flank, the largest earthquake in recorded Hawaiian history.

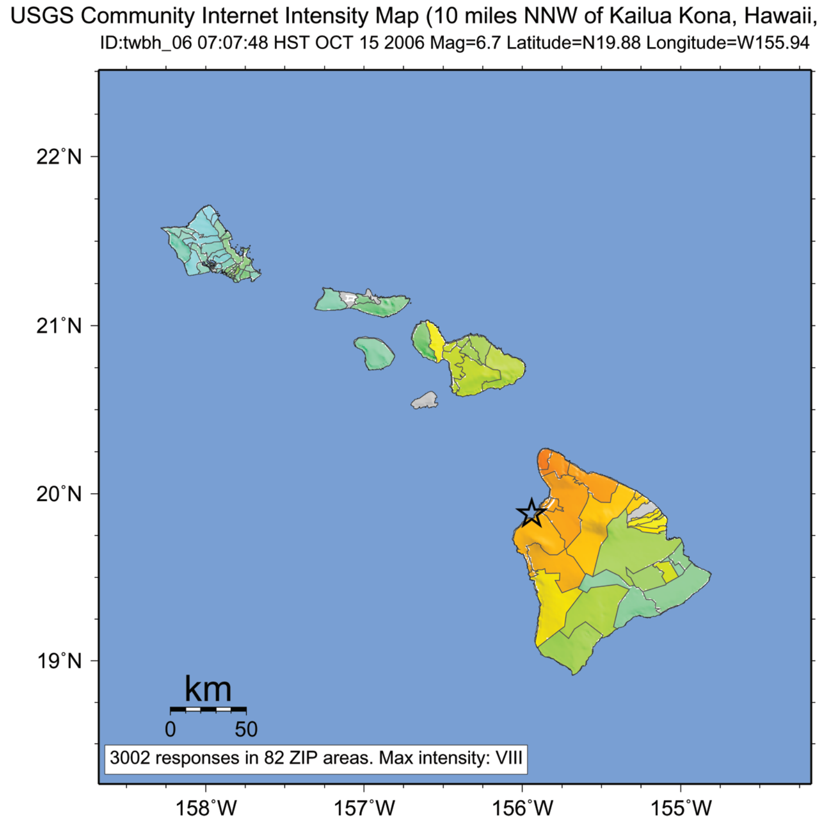


Figure 3

INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

The Kiholo Bay earthquake probably reflected the long-term accumulation and release of lithospheric flexural stresses. The long-term stresses are generated in the crust and mantle by the weight of the volcanic rock that composes the islands. Deeper mantle earthquakes at approximately 30-40 km depth result from flexural fracture of the underlying lithosphere in long-term geologic response to the load of the island mass. Past examples of such “mantle” earthquakes include the 1973 M6.2 Honomu (on the northeast coast of Hawai`i island), the 1938 M7 Maui, and the 1871 M7 Lanai earthquakes.

The effects of the earthquakes were felt on all islands in the state of Hawai`i. Figure 3 shows the USGS Community Internet Intensity Map based on 2,900 individual reports received during the week following the earthquakes. The maximum Mercalli Intensity VIII was reported close to the Hawi epicenter, and personal communications with residents of the North Kohala area indicate that its effects in their area were as severe as, or even worse than, those of the Kiholo Bay event. The shallower Hawi hypocenter would plausibly increase the severity of the local effects of the smaller magnitude event. Soil development on Hawai`i Island is most apparent at the older northern end of the island (Kohala) and along the wetter northeastern side (Hamakua).

In USGS Bulletin 2006, Wyss and Koyanagi (1992) made a compilation of 56 moderate to large Hawaiian earthquakes that occurred between 1823 and 1989, mostly of magnitudes 5.4 to 6.6. This study developed isoseismal maps for historic and instrumentally recorded events. Several empirically derived relationships between intensity, peak ground accelerations, and magnitudes suggested that Hawaii may not follow the typical models utilized in California and the mainland United States. The USGS found that accelerations in Hawaii are substantially higher than average for a given intensity. Hawaiian earthquakes have to register at least a unit in magnitude greater than those in California to produce the same maximum intensity.

Seismographic recordings of the October 15 earthquake showed a predominance of high frequency vibration (high accelerations with very short cycles) as compared to the types of earthquake motions in California earthquakes. Due to the atypically low amount of damage thus far observed (relative to U.S. mainland experience for a similar sized event) for the Kiholo Bay and Hawi earthquakes, it may be appropriate to further study whether certain seismic source regions of Hawaiian earthquakes produce ground motion with atypical frequency content and whether the fractured volcanic crust might lead to unique characteristics of frequency-banded ground motion attenuation.

Three minutes after the initiation of rupture at the first event’s hypocenter, the Pacific Tsunami Warning Center issued a Local Tsunami Information Bulletin (LTIB) for the state of Hawai`i. The LTIB stated that a large earthquake had occurred, but that there was no danger of a destructive tsunami. The scientists were able to determine rapidly that the rupture mechanism had a very small vertical displacement component. The System for Processing Local Earthquakes in Real Time (SPLERT) triggered this response by paging duty scientists with an accurate location 26 seconds after the origin time of the earthquake. A small tsunami did result, but at 8 cm (trough to peak) just north of the epicenter, it was negligible.

Figure 4. *Highway embankment failure.*

Geotechnical Observations

Large landslides occurred in Kealakekua Bay, located south of Kailua-Kona and near the Captain Cook Monument, resulting in the closure of the waters near the shore and of nearby roads and hiking trails because of unstable ground and fear of landslides. Numerous rockfalls and slides occurred in road cuts, embankments and natural slopes (Figure 4). Virtually every steep road cut North of Kailua-Kona and North of Hilo exhibited some degree of rockfall or debris slide. These occurred most often in slopes and cuts steeper than 1H:1V. Instabilities occurred in nearly every road cut steeper than 1H:1V, but they were significantly less prevalent in cuts that were less steep. The resting configuration of many cuts into rock approached 1H:1V after sliding.

Often the instability of the steep cuts was a result of geologic layering. Rock produced from the volcanoes is generally either *a'a* or *pahoehoe* basalts. A'a basalts are characterized by alternating layers and inclusions of massive, very hard and strong basalt, surrounded by various thicknesses of clinker, composed of poorly to loosely welded, irregularly-shaped and rough-surfaced rocks ranging between gravel to boulders in size (Figure 5a). The discontinuous and often contorted inclusions of massive basalt are irregularly fractured.

During the earthquakes, the loose a'a clinker raveled and removed support from overlying massive blocks (Figure 5b). The blocks can sustain significant cantilevers, influenced by the extent, spacing, and nature of the internal discontinuities, but many overhanging blocks failed during the earthquakes. In particular, large boulders fell where there was a noticeable layering of volcanic rock strata with dense, blocky basalt overlying more friable pyroclastic tuff, ash, and clinker. The underlying weaker layers typically consist of smaller rock units, which are less resistant to shearing, and therefore provide minimal stability with respect to lateral loading.

In one case, the failure of a highway embankment resulted in the collapse of a traffic lane on the approach to a bridge (Figure 6). For a number of hours after the earth-

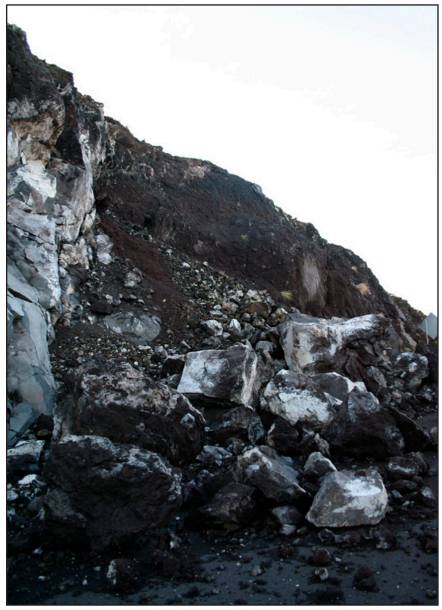


Figure 5a. *Rockfall typical at steep roadcuts.*

Figure 5b. *Example of discontinuous geology where dense basalt rock overlies weaker, less stable clinker.*

Figure 6. *Failure of bridge approach embankment on Highway 19 (photo: State of Hawaii Dept. of Transportation, Highways Division).*

quakes, the area of North Kohala, including the town of Hawi, was cut off from the rest of the island because of road closures on highways 250 and 270, the only access roads to this region. Fortunately, the rockfalls and landslides caused by these earthquakes could be cleared relatively easily, and all roadways on Hawai`i Island were open to at least one-lane traffic within two days of the earthquakes.

In addition to the island of Hawai`i (Figure 7), the island of Maui was also impacted by earthquake-induced rockfalls. Highway 31 (Figure 8) along the southeastern coast of Maui was closed near the Kalepa cliffs (approximately the 38-mile marker along Hwy 31) (Figure 9). About 500 Maui residents were cut-off between the rockfall hazard closure of that road in the Manawainui area and a bridge closure due to abutment erosion at Pa`ihi. A temporary bridge was being installed. Sections of that highway along the coastline are inherently vulnerable to rockfalls and landslides. Road cuts in massive a‘a generally require blasting, a necessary excavation technique which induces additional mechanically induced fractures in the massive rock.

Some damage occurred to dams and irrigation ditches in the Waimea-Kamuela area, where recorded peak ground acceleration exceeded 1g (soil depths are greater in that region than along the rocky coast nearest the epicenter). Most dams in Hawai`i are old earthen berm reservoirs built during the plantation era for irrigation purposes. At least two dams cracked along their crests, while at least two others showed clear evidence of incipient slope failure on their embankments. Two dams located above Waimea were drained after excessive seepage, and "water boils" were observed five days following the earthquakes. The State Department of Land and Natural Resources had in place post-earthquake dam inspection procedures that call for inspections of dams within 75 miles of the source of an earthquake of between magnitude 6 and 7. The U.S. Army Corps of Engineers was undertaking these comprehensive inspections.

Hilo and Kawaihae harbors are the only two ports on Hawai`i Island capable of handling the barges that transport most of the island's supplies from Honolulu Harbor. The harbors are an essential lifeline for the inhabitants of the island. No damage was noted at Hilo Harbor on the east side of the island. Kawaihae, which handles approximately 60% of the cargo coming to the Big Island, was closed immediately after the earthquake due to ground subsidence, lateral spreading, and soil liquefaction that made continuing port functions unsafe. Much of the fill material under the shipping container-handling yard consists of dredged fill. As this material liquefied, the resulting lateral spreading caused significant vertical settlement of the asphalt pavement (see Figure 10), and lateral displacement of the pile-supported concrete piers. Pier 1 displaced 6-12 inches laterally towards the harbor.

Figure 7. *Massive coastal escarpment landslides into the ocean (photo: Hawai`i County Civil Defense Agency [HCDA]).*

Figure 8. *A potential rockfall area along Maui Highway 31 (photo: Maui CDA).*

Figure 9. *Maui rockfall near Kalepa cliffs (photo: Maui CDA).*

This movement indicates that the piles were moved and/or distressed by the lateral spreading of the liquefied soil beneath and landward of the pier. Gasoline and diesel fuel lines on the north end of Pier 2, supported from the undersides of the piers, were also damaged, and some had reportedly fallen from their hangars into the waters of the harbor. Three days after the earthquake, Pier 2B was opened, but Piers 1 and 2A remain closed indefinitely.

Bridges

Only one bridge structure—Honokoa--suffered major structural damage during the earthquakes, requiring closure of one traffic lane. A number of bridges exhibited minor spalling and other signs of pounding at abutments or between bridge segments, indicating appreciable movement of the superstructure during the earthquakes. These bridges all remained open to traffic.

Built in 1965, the Honokoa Bridge is located just north of Kawaihae on the west coast of Hawai`i Island. It is within 24 km (15 miles) of both earthquake epicenters. The bridge consists of two spans of simply-supported AASHTO prestressed concrete bridge girders supporting a reinforced concrete bridge deck. Significant damage was noted to the webs of the AASHTO girders at the abutments.

It appears that the longitudinal motion of the bridge was effectively resisted by pounding against the abutments, while transverse motion was prevented by concrete shear keys between the bottom bulbs of the bridge girders. Unfortunately, the bulkhead or bridging beams at the supports were only partial depth and did not extend to the bottom bulbs.

Therefore, lateral restraint of the bridge deck had to transfer through the relatively thin girder webs, resulting in high transverse shear and flexural stresses, for which the webs were not adequately designed. The bottom edge of the bridging beams showed a tendency to separate from the webs because of the large transverse inertial forces.

Figure 10. *Liquefaction induced lateral and vertical displacements of approximately 6 inches at port facility, Kawaihae Harbor.*

***Figure 11.** Roof trusses supported by interior columns and window frames after wall collapse.*

Non-Engineered Buildings

Churches and Historic Buildings: The older churches and historic buildings, as a class of building, sustained the most dramatic and potentially life-threatening damage. These buildings were designed and built with traditional construction techniques, long before the advent of building codes. While they were well-built for gravity and wind loads, they lacked seismic detailing. The State Historic Preservation Division (SHPD) and National Park Service conducted their own preliminary assessments of about 15 historic buildings on the state and national registers of historic places on the Big Island. The SHPD contracted with preservation architecture and archeology firms to provide damage assessments for historic properties on the Big Island.

The historic Kalahikiola Church in Hawi, North Kolaha, suffered extensive damage to the exterior rock-masonry walls supporting the roof trusses (Figure 11). This 1855-vintage stone church was constructed with rough lava stone walls and a wood roof of "barn-type" construction having interior wood columns. The walls appeared to be approximately three feet thick, and the interior and exterior faces of the walls were covered with a plaster. The end wall fell outward due to a lack of lateral restraint; the two side walls failed similarly, but to a lesser degree. Total collapse of the roof system appears to have been prevented by a single line of interior columns supporting the center of each roof truss, and door and window frames supporting the eaves.

The unreinforced rock-masonry walls were grouted with low-strength mortar, similar to many other rock-masonry walls built in the 19th and early 20th centuries. Many of these walls suffered damage in the form of cracking, partial collapse, or complete collapse. The other end of the building is constructed with a wood end wall and wood tower. This end of the building appeared unscathed. The timber-framed bell tower appeared to have survived the earthquake with limited damage.

The historic Hulihe`e Palace in Kailua-Kona on the west side of Hawai`i Island was built in 1838 and renovated by King Kalakaua in 1886. Its bearing walls were constructed using lava basalt field stones, mortared together with a lime mortar using local beach sand. The beach sand used is primarily coralline in nature, but with a significant amount of finely pulverized basalt sand. The lime was made from burning coral on the site. The palace suffered extensive damage and was deemed unfit for occupancy. Typical diagonal cracking occurred in the cementitious plastered exterior masonry walls of the building, particularly around door and window openings. There is an extensive amount of damage to interior finishes and separation gaps in the floors and ceilings.

Residential: There are approximately 50,000 single-family and duplex (two-unit) homes on Hawai`i Island. Most of these are wood-frame construction, with 60% being of conventional stud and sheathed walls (known in the local vernacular as "double" walls), and about 40% consisting of what is locally known as "single-wall" construction. "Single-wall" construction typically utilizes ¾-inch to 1-inch thick tongue and groove cedar or redwood boards placed vertically to form a load-bearing exterior wall without studs. A flat, wood top plate is attached against the vertical siding board to serve as a ledger for attachment of the ceiling and nailing of the roof truss rafter. Roof construction in single-wall residences is typically light non-engineered framing with composition shingles on tongue and groove (T & G) wood decking, or corrugated metal deck roofing directly attached to shallow wood rafters. Full plywood sheathing of the roof is not provided, and rafters are sometimes spaced up to four feet apart in the T & G roofed systems.

Approximately 30% of the total, or about 15,000, utilize a post-and-pier-supported elevated first floor, where the bottom of the exterior wallboard is nailed to a rim joist or sill beam, transferring its roof and wall load through vertical shear through the nails rather than bearing

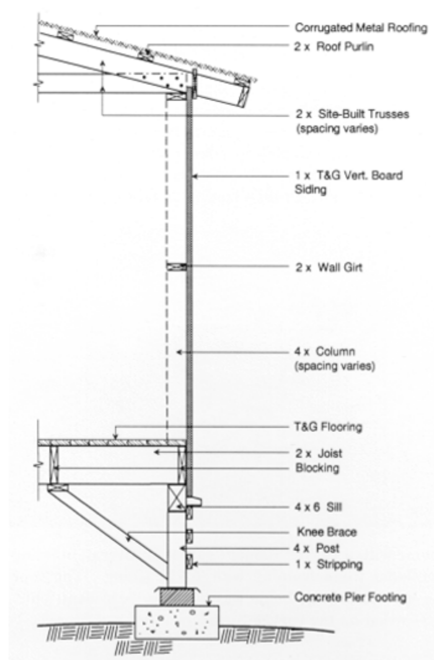


***Figure 12.** Example of one style of Hawaii single-wall construction on post and pier (there are several variations from this style).*

Figure 13. *Rotational instability of a post and beam "single" wall home on a sloping hillside site.*

(Figure 12). The soft-story lateral resisting "system" below the floor consists of toenailed 2x4 braces in each direction and no shear walls. Each individual post is supported on unanchored small concrete blocks locally known as "tofu blocks," which in turn rest on 18"x18"x9" unreinforced concrete foundation blocks that have little or no embedment into the soil. The height of piers can vary from just over a foot to much more than 12 feet high.

Up until the mid-1970s, this type of construction made up a significant portion of the affordable housing stock due to its simplicity, affordability, and the absence of thermal insulation requirements in the tropical environment of Hawai`i. The post-and-pier construction allowed the homebuilder to minimize site grading expenses, since the shallow piers could be placed directly on the existing grade, and the height of posts adjusted to accommodate a wide range of footing elevations on steep slopes. On Hawai`i Island, where the depth of soil may be shallow overlying fractured lava, avoiding excavation and regrading of volcanic rock can be economically attractive. In rural areas of underdeveloped infrastructure, it allowed flexibility in bringing utilities on site with little (or sometimes no) embedment depth, as well as elevating the first floor above periodic surface flooding. The typical size of this style of home is approximately 1,000 to 1,300 sf. Connections are typically of minimal uplift and lateral capacity. Based on property tax records, less than 10% of these single-wall homes are estimated to have utilized metal plate connectors and straps; the majority are framed using toenails only. The current building code of the County of Hawai`i still permits single-wall construction by a local code amendment.

During the first week after the earthquakes, County of Hawai`i engineers and inspectors used the ATC-20 Rapid Evaluation procedure to assess the safety status of approximately 1,000 homes. Staff for these inspections were drawn from county building department engineers and construction inspectors. To fulfill this need, the county shut down all normal building permit reviews and construction inspections. The Structural Engineers Association of Hawai`i activated inspection teams to perform additional evaluations. Under Hawaii State Law, persons engaged in civil defense functions cannot be held civilly liable. The county representative was a key factor in the efficiency of the inspections. The County of Hawai`i received over 1,300 individual requests to evaluate building damage in the first two weeks. As of a month after the event, about 70 homes were red-tagged, and 230 were yellow-tagged based on potential hazardous conditions, out of a total of approximately 1,700 inspections. This number does not include about ten homes destroyed outright.

Almost all of the single-family homes that were red-tagged as unsafe were of single-wall or similar post- and-pier construction (see Figure 13). Failure modes observed were posts shaken off the small footing or smaller upper "tofu" pedestal, post rotation due to inadequate lateral bracing, splitting at the bases of the heavier loaded posts, or overturned footings. As a result, such homes were vulnerable to lateral sideway displacement, dropping, potential collapse of the first floor, and severing of utilities. In some cases, the building collapsed and was totally destroyed.

Retaining Walls: Many residences had damage to lava rock retaining

Figure 14. *Collapse of concrete trellis frame at Mauna Kea Hotel.*

walls. These walls typically consisted of individual rough lava rocks stacked dry, or with minimal mortar. The walls were commonly 3-5 feet in height, though in some cases taller. In the County of Hawai`i, the building code allows walls of up to six feet to be constructed without engineered drawings. Many minimally mortared or dry-stacked rock walls failed during the earthquake.

Engineered Buildings

The County of Hawai`i has used the 1991 *Uniform Building Code* from 1993 to the present. The 1991 *UBC* placed the Big Island in Zone 3, and this was not corrected until the 1997 *UBC*. The County of Hawai`i realigned to the Zone 4 designation in mid-1999, but only as an amendment to the 1991 *UBC*. Structural (special) construction inspections have been required in Hawai`i County only since 1993. The state of Hawai`i has no statewide building code, and each of four counties (Kauai, Honolulu, Maui, and Hawai`i) adopts building codes on independent schedules. The other counties of Kauai, Honolulu, and Maui currently use the 1997 *Uniform Building Code*. State building construction follows the county building codes, so there is the possibility of obsolete seismic provisions being used for public sector work. Earlier this year, the County of Hawai`i announced the intent to adopt the *2006 International Building Code*.

Hotels and Resorts: The hotels and resorts, as a whole, performed fairly well, and all of them remained in operation. The Mauna Kea Resort, one of the first major hotels in the north Kona area, suffered the most damage. The Hapuna Prince Beach Resort sustained significant water damage to the main ballroom due to broken sprinkler lines. The Hilton Waikoloa Resort had minor cracks in shear walls of one building and some localized trellis damage. The Sheraton Keahou had numerous cracks in cementitious plaster finishes and some limited damage to pedestrian bridges, but it was able to provide temporary housing in its ballroom to long-term-care patients evacuated from the Kona Community Hospital.

The Mauna Kea Hotel is located on the shoreline just 11 miles from the Kiholo Bay earthquake epicenter. A reinforced concrete trellis structure above the low-rise four-story south wing of the hotel collapsed (Figure 14). This failure is attributed to combined vertical and horizontal ground shaking causing separation of the precast trellis elements from the supporting cast-in-situ cantilever beams. Fortunately, no injuries resulted from this collapse. Damage to a balcony below this structure was probably the result of impact from falling debris. The north and south exterior shear walls are configured as a series of vertically discontinuous leaning “stair-step” panels that are supported by cantilever transfer girders. Horizontal buttress beams transmit the leaning force of the walls to the elevator shaft walls. Portions of the upper buttress beams suffered some damage. There was significant damage to the concrete surrounding two connector plates and the construction joint between a precast exhaust flume and the ele-

Figure 15. *This wall was grouted at the end cells, but apparently not in the main body of the wall.*

vator shaft wall of the north wing. Other structural damage included cracked and spalled spandrel beams and some cracking at the base of cruciform column/walls.

A number of localized but severe areas of damage occurred in the Paniolo Club condominiums, a cluster of two-story and three-story buildings built in the mid-1970s. The framing system is comprised of load-bearing concrete masonry unit walls and wood-framed floors and roofs. The exitways and stairs are on the exterior, supported by masonry piers. The masonry walls are partially grouted (Figure 15). The roof is configured with gable ends where the main roof beams and rim rafters bear on angled masonry walls. The roofing consisted of concrete tiles on straight sheathed wood decking. The CMU at the tops of the gable-ended masonry walls suffered out-of-plane dislodgements, particularly at the roof beam pockets. In some cases, portions of the wall fell out onto the grounds or onto the floor of the units. The most severely damaged buildings were red-tagged as unsafe due to the potential collapse hazard of the bearing walls and roof.

Healthcare and Emergency Response Facilities: Healthcare facilities had significant damage to their nonstructural systems, principally T-bar lighting and ceiling systems and fire sprinkler systems (Figure 16). The Kona Community Hospital is a 94-bed hospital (49 acute, 11 psychiatric, and 34 long-term care). The hospital reported primarily nonstructural damage, in the form of fallen ceilings, light fixtures, and other nonstructural elements. These failures are attributed to the lack of adequate seismic bracing for nonstructural components. Following the earthquake, patients were evacuated and temporarily housed at the Sheraton Keauhou Bay Resort and Spa's convention center, or transferred to the Hilo Medical Center, or to medical facilities in Honolulu.

The ceiling damage at the hospital was to older lay-in suspended ceilings without seismic restraints, i.e., wire suspension with no diagonals or compression struts (Figure 17). It appeared that partitions were continuous to the floor above, and ceilings therefore abut the partitions of each room and rest on a small ledger angle attached to the partition. There was apparently no attachment from suspended ceiling "T-bar" to this perimeter angle. Compressive buckling of the T-bar system caused many tiles to fall and created many precariously supported light fixtures. T-bars pulled off the angle in tension not hung off nearby suspension wires were bent down, also allowing tiles to fall and light fixtures to become dislodged. In addition to the tiles falling, bent support Ts and partially dislodged light fixtures, decades of dust on the ceiling tiles were deposited over the rooms. Seven minutes after the main shock, the second shock exacerbated the conditions, so a decision was made to evacuate. When power was lost, the emergency generator was started,

Figure 16. *Typical nonstructural damage: ceiling in the weight room at Hisaoka Gym/Kamehameha Park (photo: Troy Kindred).*

but none of the elevators was on emergency power, and the evacuation was done on stairways.

The Hale Ho`ola Hamakua facility provides 48 long-term care or nursing facility beds and two acute beds, in addition to emergency room and health center services. The facility consists of several large one- and two-story steel-framed buildings with concrete masonry unit (CMU) and concrete walls. The facility was opened in 1995 to replace the original Honoka`a Hospital that opened in 1951. The main two-story building sustained significant nonstructural damage to the exterior cladding and soffits and to the interior ceiling and wall systems, mainly as a result of broken sprinkler lines and broken water piping. Following the earthquake, the 49 patients at Hale Ho`ola Hamakua were evacuated and housed in tents until accommodations were made in the facility's original building.

Although the building is of recent construction, the ceiling systems were not laterally braced, did not have compression struts to prevent vertical movement, and were not isolated by means of a gap from the surrounding walls. The design of the building made it difficult and impractical to install diagonal bracing wires because of the great distance between the ceiling and the high-pitched roof. The damage suggests that the ceilings were forced laterally against the walls, causing a buckling and failure of the T-bar grid that allowed the ceiling tiles, and in some cases the fluorescent light fixtures, to fall to the floor. The interaction of the ceiling system and the fire sprinkler system, which was only nominally braced, broke a number of sprinkler heads, resulting in flooding of the building. Water piping in the walls also broke and contributed to the flooding.

In addition to the interior damage, the exterior cladding and soffit system, consisting of heavy cement plaster on metal lath, generally failed and collapsed, blocking building exits and producing a serious life-safety threat.

Schools and Libraries: Waikoloa Elementary, Honoka`a Elementary, and Kohala Elementary schools sustained most of the damage. Waikoloa Elementary, less than ten years old, suffered considerable nonstructural damage. Many classrooms were closed because of an extensive amount of fallen ceilings, light fixtures, and other nonstructural items. Virtually no structural damage was reported at these schools. The Honoka'a Elementary, an older school dating to the 1950s, sustained moderate structural damage to concrete masonry block (CMU) walls that support the roof girders. Kohala Elementary sustained damage to a two-story classroom building with wall cracking and ceiling damage. All schools on the island were able to open one week after the earthquake, sometimes utilizing alternative rooms.

Figure 17. *Kona Community Hospital Operating Room (photo: Glenn Miyasato).*

Lifelines

Power outages impaired public information and media communication efforts on the day of the earthquake. Oahu and the entire City of Honolulu was unexpectedly placed in an island-wide power blackout when the earthquake set-off alarms at the main generating plant at Kahe on the west coast of Oahu. The alarms caused some manual shutdowns by operators of about 15% of the power generators, and this initiated a progressive sequence of load shedding which was not able to prevent automatic shutdowns of the remaining generators triggered by load imbalances. Within 20 minutes of the earthquake, all 19 generators on Oahu with a combined capacity of 1045 megawatts had shutdown.

It took nearly 19 hours for the Hawaiian Electric Company (HECO) to restore power to 99.2% of its 291,000 customers. Concerned about balancing power generation with the electrical demand by customers, the utility had to restore power gradually. HECO officials indicated that if supply and demand had become unbalanced, it could have resulted in much longer outages from damaged equipment or having to restart the restoration. The basic process of powering up the grid can take four to eight hours with HECO's large steam-generator units.

Having simpler systems with less demand, Hawaii Electric Light Co. (HELCO) on the island of Hawai`i, never lost its entire grid and restored power to 95 percent of its customers by noon and to all of its customers by 11 p.m. Likewise, Maui Electric Company faced an island-wide blackout, but it was back to full power with its diesel generators by 3:30 p.m.

On Oahu, HECO has repeatedly stated that it needs more capacity and an additional transmission line to meet energy demands, and it has submitted an application to the Public Utilities Commission to build a new 110-megawatt generating unit. The new unit, planned for operation in 2009, could save several hours in the first phase of a power restoration by bringing an initial increment of electrical capacity on line faster. Until capacity is increased, it appears that an island-wide blackout on Oahu would be unavoidable under similar circumstances in the future.

FEMA Response and Insurance

FEMA has a Pacific Area Office in Honolulu, and representatives of that office were stationed at the State Emergency Operations Center within a few hours of the earthquake. A Major Disaster Declaration (FEMA-1664-DR-HI) was signed by the President on October 17, 2006. This initially included public assistance for all counties in the state, and was later amended to add individual assistance and permanent repairs for the County of Hawai`i. Government and nonprofit agencies will be eligible for reimbursement of 75% of their costs. In the weeks following the earthquake, FEMA and the state successively opened Disaster Recovery Centers in South Kona, Waimea, Honoka'a, North Kohala, Hilo, and Na'alehu. The centers provided information about grants, low-interest loans, and other aid available to residents affected by the earthquakes. Individuals, households and businesses are eligible for federal loans of up to $200,000; those who don't qualify for loans can get grants of up to $25,000.

Unless residents are qualified for some form of government assistance, they will need to fund the entire cost of repairs to their homes, because earthquake insurance for homeowners is not generally offered on the Hawai`i Island. For example, there are only about 120 homeowners insured for earthquake losses by State Farm in the state, none of these on Hawai`i Island. On the other hand, it is very common for homeowners throughout the state to have hurricane insurance, which is normally a requirement of lenders. The state also has a Loss Mitigation Grant Program for hurricane retrofits, in which homeowners may be eligible for subsidy reimbursement grants of 35% of the cost to install five options for hurricane protective devices, up to a maximum limit of $2100. There is no such program for seismic retrofits.

References

Brandes, H. G., April 2004. "Hawai`i Dam Safety Guidelines: Seismic Analysis & Post-Earthquake Inspections," Dept. of Land and Natural Resources, State of Hawai`i, Circular C131.

Chock, G., and Sgambelluri, M., Feb. 2005. "Earthquake Hazards and Estimated Losses in the County of Hawai`i," Dept. of Civil Defense, State of Hawai`i.

Klein, F. W., et al., June 2001. "Seismic Hazard in Hawai`i: High Rate of Large Earthquakes and Probabilistic Ground-Motion Maps," *Bulletin of the Seismological Society of America,* Vol. 91, No. 3, pp. 479-498.

Robertson, I. N., Nicholson, P. G. and Brandes, H. G., October 2006. "Reconnaissance following the October 15, 2006, Earthquakes on the Island of Hawai`i," Research Report UHM/CEE/06-07, Univ. of Hawaii College of Engineering, Dept. of Civil and Env. Engineering; 65 pp.

Segal, D., 2006. "HECO Talks," *Honolulu Star-Bulletin,* October 20, **http://starbulletin.com/2006/10/20/news/story01.html**

URS Group, Inc., "Developing a Hawai`i Island NEHRP Site Class Map for Use in HAZUS-MH Earthquake Loss Estimation," June 9, 2006, Draft (report in publication for FEMA).

Wyss, M., and Koyanagi, R. Y., 1992. "Isoseismal Maps, Macroseismic Epicenters and Estimated Magnitudes of Historic Earthquakes in the Hawaiian Islands," *USGS Bulletin 2006*, 93 pp.