Compilation of Observations of the October 15, 2006 Kiholo Bay (Mw 6. 7) and Mahukona (Mw 6.0) Earthquakes, Hawai‘i

December 31, 2006

Kalahikiola Church in Hawi, North Kohala, Island of Hawai‘i

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Executive Summary

On October 15th, 2006, two earthquakes with magnitudes of M_w6.7 and M_w6.0 struck in close succession just off the Northwest coast of the Island of Hawai‘i.[1] No deaths were attributed to ground shaking, and only minor injuries were reported. Damage caused by these earthquakes had exceeded $100 million as of the writing of this report, without including damage to private residences. Overall, the vast majority of built infrastructure in the vicinity of the earthquake epicenters survived with little or no apparent damage. The low injury rate and economic loss is attributed in part to the relatively rural area in which the Kiholo Bay and Mahukona earthquakes struck, and the relatively large 39 km (25 miles) focal depth of the M_w6.7 Kiholo Bay earthquake. It was also fortunate that the earthquakes struck just after sunrise on a Sunday morning. Shaking reached Intensity VIII on the Modified Mercalli Scale (MMI) as reported by residents.

Numerous rockfalls and slides occurred in road cuts, embankments and natural slopes. Because of the lack of redundancy in the highway system on Hawai‘i Island, road closures due to rockfalls or landslides can have a debilitating effect on emergency response and economic recovery efforts.

Some damage occurred to earthen dams and irrigation ditches in the Waimea area. Two dams experienced 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 these 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. 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, and lateral displacement of the pile supported concrete piers. Remedial measures should be taken to replace or stabilize any fill material with liquefaction potential in critical harbor facilities to avoid loss of function of either of these ports during future earthquakes.

Much of the damage to buildings was in the form of failure of non-structural elements such as unbraced ceilings, light fixtures, plumbing and other utility lines. Structural damage occurred at a number of buildings, particularly those closest to the earthquake epicenters.

[1] In Hawaiian, the `okina is a glottal stop.

The older churches and historic buildings, as a class of building, sustained the most dramatic and potentially life-threatening damage. Many of these buildings were built with thick bearing walls constructed of unreinforced lava rocks.

Over 1,800 individual residences were damaged to varying degrees, which is less than 5% of the single family home inventory on the island of Hawaiʻi. Many of the homes that were destroyed or experienced severe damage were constructed on post and pier foundation systems resting on small unanchored concrete foundation blocks. The ground shaking resulted in lateral movement of the posts off these substandard foundations resulting in moderate to complete damage to the residences. Several residential properties experienced damage to lava rock retaining walls. These walls typically consisted of individual, rough lava rocks stacked dry, or with minimal mortar.

Most modern engineered buildings performed well, with some exceptions. Healthcare and school facilities were negatively impacted, not by structural concerns, but by damage to their non-structural systems, principally T-bar lighting and ceiling systems and fire sprinkler systems. As a result, some of these facilities were not fully operational in the weeks following the earthquakes.

Earthquakes of October 15, 2006

Two earthquakes and numerous aftershocks occurred off the northwest coast of the Island of Hawaiʻi on October 15th, 2006. The October 15, 2006 M_w6.7 Kiholo Bay, Hawaiʻi Island, Hawaiʻi Earthquake struck at 7.07 AM local time with an epicenter location of 19.878°N, 155.935°W, with a focal depth of approximately 39 km (24 miles). It was followed by the M_w6.0 Mahukona, Hawaii Island, Hawaiʻi Earthquake at 7.14 AM local time with an epicenter location of 20.129 N, 155.983 W, and focal depth of approximately 19 km (12 miles). Strong ground motions lasted for approximately 20 seconds during the Kiholo Bay earthquake, and 15 seconds during the Mahukona earthquake. While the two events were only 7 minutes apart, the difference in depths and aftershock epicenters suggests that the M_w6.0 was not an aftershock of the M_w6.7 and that they were events from different seismic sources (Figures 1 and 2). The Kiholo Bay earthquake mechanism is characterized as occurring on a normal fault.

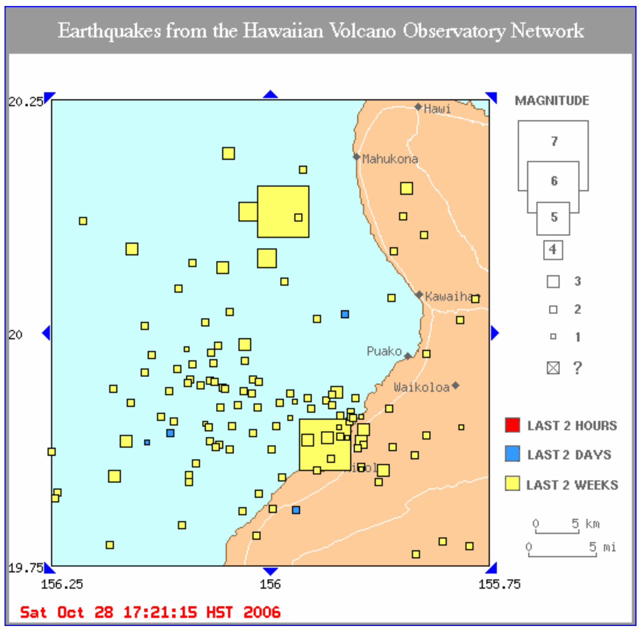

Figure 1 Map of Epicenters (by USGS)

Earthquakes on the Island of Hawaiʻi are not rare. The ground shaking hazard in Hawaii County ranks among the highest in the United States. For example, the Kealakekua fault zone on Hawaii's 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 south Kona coast and triggered numerous damaging landslides.

The main October 15 Kiholo Bay earthquake probably reflected the long-term accumulation and release of lithospheric flexural stresses. The long-term stresses consist in part of stresses generated in the crust and mantle by the weight of the volcanic rock that composes the islands. Such deeper mantle earthquakes at approximately 30 to 40 km depth result from flexural fracture of the underlying lithosphere in long-term geologic response to the load of the island mass. This is one of the seismotectonic mechanisms for damaging (but not the largest) earthquakes in the Hawaiian islands. Past examples of such “mantle” earthquakes include the 1973 M6.2 Honomu (on the northeast coast of the island), the 1938 M7 Maui, and the 1871 M7 Lanaʻi earthquakes.

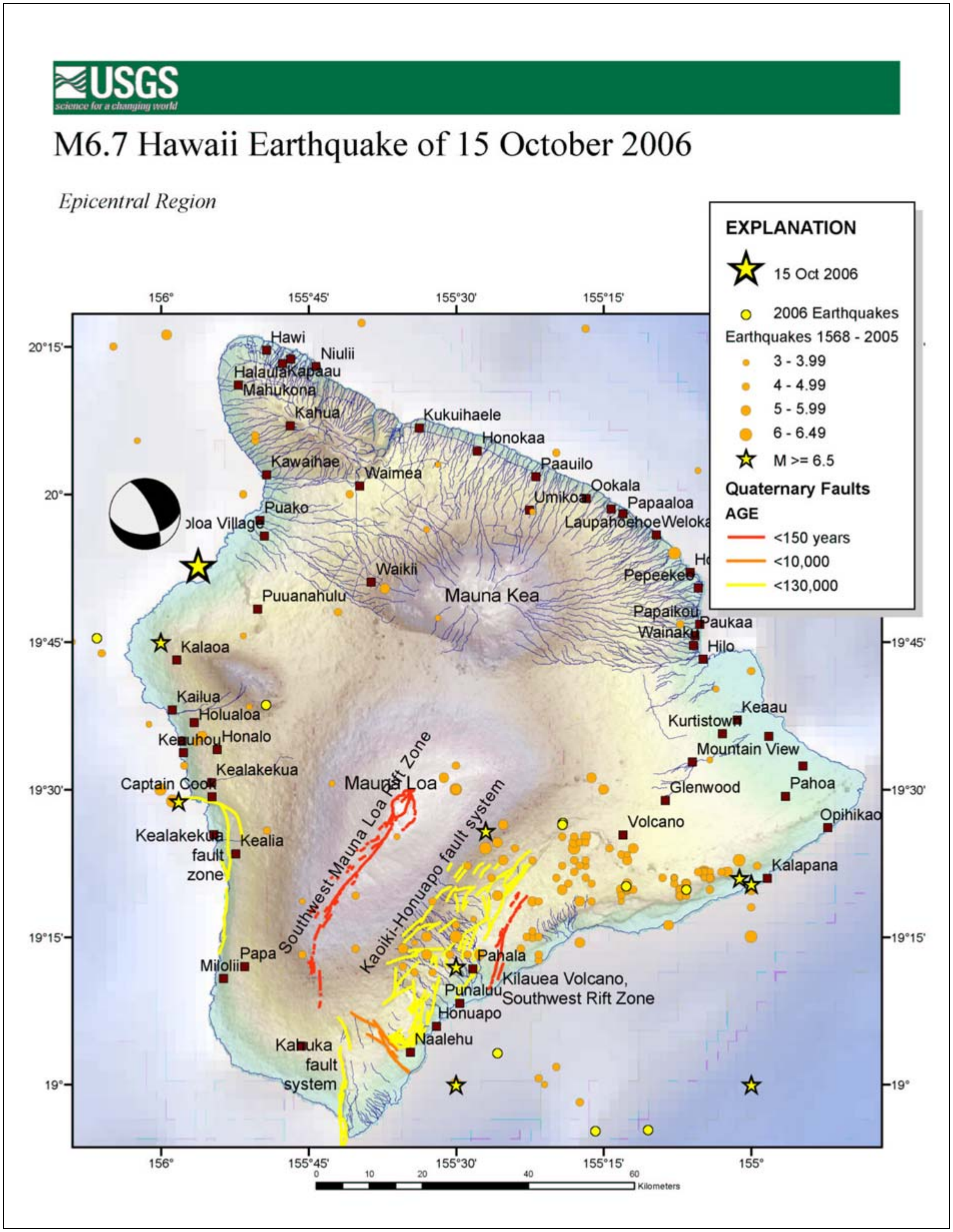

Figure 2 Epicenter of the October 15 Kiholo Bay Earthquake and the Locations of Island of Hawai‘i Towns (USGS, 2006)

Historically, the largest earthquakes in Hawai‘i have occurred at shallower depths, beneath the flanks of 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 is 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 occurred in 1975, the M7.2 (or greater) Kalapana earthquake beneath Kilauea’s south flank, and in 1868, the largest earthquake in recorded Hawaiian history beneath the Ka‘u district on Mauna Loa’s southeast flank, estimated as a M7.9 earthquake. (Figure 3 by Klein, et al, 2001).

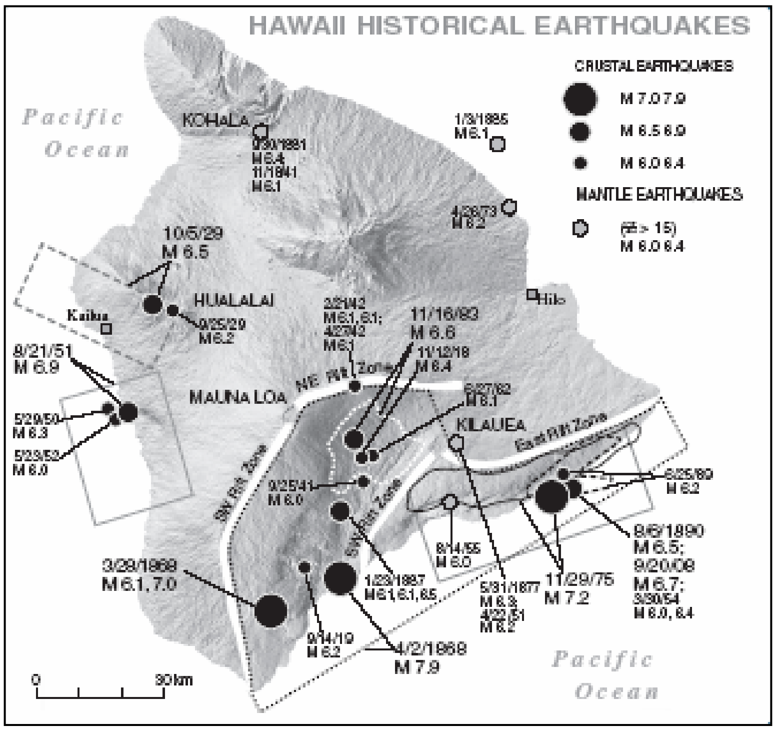

Figure 3 Hawai‘i Historical Earthquakes and Inferred Rupture Zones of the Larger Events (by Klein, F., et al, USGS, 2001)

Initial Earthquake Notifications

Role of the Pacific Tsunami Warning Center (PTWC) in rapid earthquake notification in Hawai‘i

Duty scientists at the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawai‘i, issued a “Heads Up” message to the Hawaii State Civil Defense (SCD) seconds before the seismic waves from the M_w6.7 Kiholo Bay Earthquake of October 15, 2006 reached them on the island of Oahu. At three minutes from the initiation of rupture at the event’s hypocenter, PTWC then issued a Local Tsunami Information Bulletin (LTIB) for the State of Hawaii. The LTIB stated that a large earthquake had occurred but that there was no danger of a destructive Tsunami. Since there was no local tsunami, the statewide emergency siren system was not activated. At 7:20 am, Hawaii County Civil Defense announced that there was no local tsunami

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TSUNAMI BULLETIN NUMBER 001
PACIFIC TSUNAMI WARNING CENTER
0712 AM HST 15 OCT 2006

TO - CIVIL DEFENSE IN THE STATE OF HAWAII
SUBJECT - LOCAL TSUNAMI INFORMATION BULLETIN

THIS BULLETIN IS FOR INFORMATION ONLY. NO ACTION REQUIRED.

AN EARTHQUAKE HAS OCCURRED WITH THESE PRELIMINARY PARAMETERS

   ORIGIN TIME - 0708 AM HST 15 OCT 2006
   COORDINATES - 19.9 NORTH  155.9 WEST
   LOCATION    - 6 MILES NNW OF PAUANAHULU  HAWAII
   MAGNITUDE   - 6.5

EVALUATION
 NO TSUNAMI IS EXPECTED. REPEAT. NO TSUNAMI IS EXPECTED.
 HOWEVER, MANY AREAS MAY HAVE EXPERIENCED STRONG SHAKING.

THIS WILL BE THE ONLY BULLETIN ISSUED FOR THIS EVENT UNLESS
ADDITIONAL DATA ARE RECEIVED.
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The System for Processing Local Earthquakes in Real Time (SPLERT) triggered this response by paging both Duty Scientists with an accurate location 26 seconds after the origin time of the earthquake. At SPLERT's heart is an automatic, real-time seismic p-wave phase associator. The Earth Worm Real Time Picker (RTP) automatically "picked" p-wave arrival times on seismograms from the PTWC's local seismic network, as well as from data provided by the USGS Hawaiian Volcano Observatory (HVO), atop Kilauea on the Island of Hawai'i. Some of this data was also provided by the USGS National Strong Motion Program (NSMP), based in Menlo Park, California.

After SPLERT paged them into action, the duty scientists estimated the size of the earthquake within 2 minutes of the origin time of the event, at Mw 6.5 using Seiji Tsuboi's P-wave moment magnitude from the seismic P-waves, Mwp, (BSSA, 1995) on data from two broadband seismometers funded by the National Tsunami Hazard Mitigation Program (NTHMP) for the Consolidated Reporting of Earthquakes and Tsunamis (CREsT) located on the Big Island of Hawai'I (Figure 4).

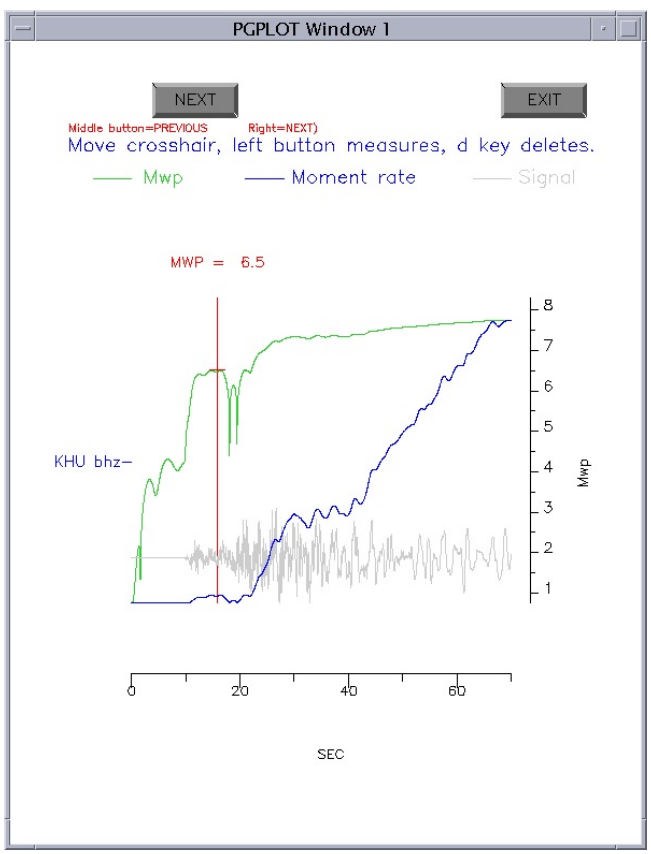


Figure 4
Moment Magnitude Estimation at Kahuku Ranch Site (Pacific Tsunami Warning Center)

PTWC's moment magnitude estimated from the initial P-waves (Mwp) of the earthquake recorded at Kahuku Ranch, 70km. to the SE of the epicenter. The grey trace is the vertical component, velocity seismogram, the blue trace is a proxy for the seismic Moment as function of time, Mo(t), and the green trace is the Moment Magnitude as a function of time, Mwp(t).

Local Seismic Recording and Coordination of Reporting Issues

Internet connectivity to the Hawaiian Volcano Observatory (HVO) was lost some 5 hours into the aftershock sequence until the next day, and the HVO earthquake information/map server went offline.

The first initially posted ANSS "*ShakeMap*" product was not supported by any local instrumental data (i.e., uncalibrated), and it was based only on an idealized source model (hypocenter, magnitude and point-source representation). (This first *ShakeMap* was not automatically delivered to Hawaii County or Hawaii State Civil Defense, Transportation, Utilities, Military or the Hawai'i-based FEMA Pacific Area Office.) Data retrieved by the National Strong Motion Program (NSMP) by midnight Sunday were incorporated into a manually-executed ShakeMap calculation on Monday October 16.

Data from 12 dialup strong motion sensors, operated by the USGS National Strong Motion Project (NSMP) were automatically transmitted to a USGS server in Menlo Park, operated by the Advanced National Seismic System (ANSS). However, these data were not incorporated into any USGS automated event processing. Data from three, recently installed ANSS strong motion (SM) stations on Hawaii were exported to the Pacific Tsunami Warning Center (PTWC). Records are available for download from the USGS website at
http://nsmp.wr.usgs.gov/data_sets/20061015_1707.html for the Kiholo Bay earthquake, and at http://nsmp.wr.usgs.gov/data_sets/20061015_1714.html for the Mahukona earthquake. The Peak Ground Acceleration (PGA) from each of the 12 SM stations is listed in Table 1 for the Kiholo Bay earthquake, and Table 2 for the Mahukona earthquake. Note that soil type conditions vary at these sites; for example, Waimea Fire Station is located in an area of volcanic ash deposits known to exhibit high amplification (about twice or more) of ground acceleration (Buchanan-Banks, 1987) and where Soil Type Sd commonly exists (URS, 2006). The Kealakekua Kona Hospital and Honokaa instrument sites also appear to be on Soil Type Sd. (Figure 5)

Nearly two-thirds of Hawai'i USGS/NSMP strong motion recorders are still film recorders with no communications. Other NSMP stations are digital but lack telemetry or communications capabilities. These data therefore can't presently contribute to immediate emergency response applications because the data must be retrieved manually at each site subsequent to the event. Processing of film records from this earthquake should now be assigned a high priority to have these important data available for shakemaps and analysis. Data for the islands of Maui and Oahu are not yet available as of mid-December, 2006, and the initially published shake maps were based on accelerations inferred from the Modified Mercalli Intensity reports for this region.

HVO's Earthworm systems implementation and upgrade is in progress. Automatic incorporation of local magnitude determinations into event processing and posting, earthquake quick review and feeding ShakeMap are among the anticipated products of the database implementation. NOAA has plans for a local broadband seismic network upgrade to eventually include 12 broadband stations Statewide. PTWC is collaborating with the USGS Advanced National Seismic System (ANSS), NSMP and the HVO to expand and upgrade seismic monitoring in the State by installing high-quality broadband seismometers and accelerometers on all of the

Hawaiian Islands. This effort is designed to enable scientists to record on-scale any earthquake occurring within the Hawaiian Islands.

Table 1 Summary Data from the 12 Dial-up Strong Motion Accelerometers, Kiholo Bay Earthquake

Mw 6.6, 10/15/2006, 17:07 UTC, 10/15/2006, 07:17 AM HST, 19.878 N, 155.935 W, 38.90 km depth, Regional Network ID# ustwbh

Sta	Inst	Inst	State: City; Recorder Location	Owner	Lat	Lon	Dist	Az	Ch	Sensor	Orient	PGA	PGV	PSA at:		
No	type	S/N			deg	deg	km	deg	No	type	deg	cm/s/s	cm/s	0.3 s	1.0 s	3.0 s
2810	Etna	1988	HI:Kailua-Kona, Hawai`i Is; Fire Sta	USGS	19.6477	-155.9923	26.2	193	1	EpiSen	90	268	18.90	95.5	22.20	2.06
									2	EpiSen	360	-259	13.60	59.6	9.58	1.90
									3	EpiSen	UP	233	-6.24	17.7	4.77	0.94
2825	K2	2000	HI:Waimea, Hawai`i Is; Fire Station	USGS	20.0230	-155.6614	32.8	61	1	EpiSen	90	-1030	42.00	165.0	18.50	1.10
									2	EpiSen	360	673	27.90	117.0	15.70	2.06
									3	EpiSen	UP	723	-20.00	64.1	8.32	1.12
2849	K2	1810	HI:KeaLakekua, HI;Kona Hospital	USGS	19.5215	-155.9181	39.5	177	1	EpiSen	90	508	14.00	59.0	8.81	1.92
									2	EpiSen	360	-362	-10.70	38.9	5.37	1.13
									3	EpiSen	UP	283	-4.79	16.4	1.76	0.57
2845	K2	1848	HI:Honaunau, Hawai`i Is; PO	USGS	19.4174	-155.8805	51.3	174	1	EpiSen	90	197	8.36	57.1	5.79	1.40
									2	EpiSen	360	-182	9.45	39.4	6.50	1.32
									3	EpiSen	UP	114	3.12	8.8	1.45	0.42
2832	K2	1819	HI:Honokaa, Hawai`i Is; Police Sta	USGS	20.0775	-155.4625	54.2	66	1	EpiSen	90	-640	14.80	60.7	13.10	0.80
									2	EpiSen	360	639	24.80	72.6	21.30	1.97
									3	EpiSen	UP	-350	-7.92	21.7	6.87	0.80
2833	K2	1849	HI:Laupahoehoe, Hawai`i Is; PO	USGS	19.9835	-155.2326	74.5	81	1	EpiSen	90	311	9.23	42.6	8.18	0.93
									2	EpiSen	360	-350	14.00	33.2	10.40	0.91
									3	EpiSen	UP	-196	4.47	19.9	3.65	0.52
2836	Etna	1984	HI:Volc Nat'l Pk, HI; HVO Srvc	USGS	19.420	-155.288	84.7	127	1	EpiSen	90	-56	6.01	15.1	6.36	2.00
									2	EpiSen	360	58	5.48	13.0	10.30	1.16
									3	EpiSen	UP	34	-1.86	6.7	2.03	0.76
2839	K2	1853	HI:Hilo, Hawai`i Is; Old Hospital	USGS	19.722	-155.115	87.6	101	1	EpiSen	90	-76	3.89	19.0	3.92	0.79
									2	EpiSen	360	54	-3.67	14.0	5.75	0.55
									3	EpiSen	UP	-32	-2.15	8.9	2.47	0.44
2818	K2	1855	HI:Hilo, Hawai`i Is; USDA Lab	USGS	19.7277	-155.0974	89.3	101	1	EpiSen	90	-215	-12.70	126.0	9.67	1.02
									2	EpiSen	360	232	13.50	116.0	9.03	0.70
									3	EpiSen	UP	-97	-3.25	10.4	2.18	0.42
2812	K2	1850	HI:Pahala, Hawai`i Is; Ka'u Hospital	USGS	19.1999	-155.4723	89.4	147	1	EpiSen	90	123	4.73	24.9	4.98	0.74
									2	EpiSen	360	176	7.17	24.0	5.41	1.07
									3	EpiSen	UP	-91	2.58	16.5	1.52	0.24
2817	Etna	1985	HI:Hilo, Hawai`i Is; Univ of Hawaii	USGS	19.7034	-155.0805	91.6	102	1	EpiSen	90	58	-4.88	13.6	7.38	0.99
									2	EpiSen	360	-45	-5.38	8.5	10.40	0.42
									3	EpiSen	UP	-30	-1.64	4.4	2.29	0.35
2816	Etna	1986	HI:Pahoa, Hawai`i Is; Fire Station	USGS	19.4934	-154.9466	112.0	112	1	EpiSen	90	64	3.22	11.4	3.52	0.53
									2	EpiSen	360	83	-3.11	18.4	4.57	0.56
									3	EpiSen	UP	29	-1.11	4.8	1.52	0.27

Table 2 Summary Data from the 12 Dial-up Strong Motion Accelerometers, Mahukona Earthquake

Mw 6.0, 10/15/2006, 17:14 UTC, 10/15/2006, 07:14 AM HST, 20.129 N, 155.983 W, 18.90 km depth, Regional Network ID# ustwbi

Sta	Inst	Inst	State: City; Recorder Location	Owner	Lat	Lon	Dist	Az	Ch	Sensor	Orient	PGA	PGV	PSA at:		
No	type	S/N			deg	deg	km	deg	No	type	deg	cm/s/s	cm/s	0.3 s	1.0 s	3.0 s
2825	K2	2000	HI:Waimea, Hawai`i Is; Fire Station	USGS	20.0230	-155.6614	35.6	109	1	EpiSen	90	-166.0	-3.92	9.2	2.40	0.265
									2	EpiSen	360	128.0	4.90	9.7	4.79	0.706
									3	EpiSen	UP	-129.0	-3.15	6.0	2.83	0.346
2810	Etna	1988	HI:Kailua-Kona, Hawai`i Is; Fire Sta	USGS	19.6477	-155.9923	53.3	181	1	EpiSen	90	-29.1	-3.10	6.9	2.87	0.782
									2	EpiSen	360	59.3	-6.19	13.9	4.69	0.566
									3	EpiSen	UP	-19.0	0.95	2.7	1.14	0.570
2832	K2	1819	HI:Honokaa, Hawai`i Is; Police Sta	USGS	20.0775	-155.4625	54.7	96	1	EpiSen	90	28.3	1.24	3.2	0.85	0.321
									2	EpiSen	360	-33.0	-1.51	2.4	1.10	0.372
									3	EpiSen	UP	29.3	0.54	1.8	0.39	0.151
2849	K2	1810	HI:KeaLakekua, HI;Kona Hospital	USGS	19.5215	-155.9181	67.6	174	1	EpiSen	90	16.6	1.50	3.5	1.39	0.371
									2	EpiSen	360	-25.1	-1.89	3.9	1.70	0.627
									3	EpiSen	UP	-13.6	-0.69	1.6	0.95	0.435
2845	K2	1848	HI:Honaunau, Hawai`i Is; PO	USGS	19.4174	-155.8805	79.5	172	1	EpiSen	90	-53.7	1.70	8.1	1.84	0.417
									2	EpiSen	360	46.6	-2.38	13.0	1.55	0.206
									3	EpiSen	UP	25.3	-0.87	3.0	1.14	0.170
2833	K2	1849	HI:Laupahoehoe, Hawai`i Is; PO	USGS	19.9835	-155.2326	80.1	101	1	EpiSen	90	18.2	-0.87	2.3	0.90	0.278
									2	EpiSen	360	-22.0	-0.83	2.6	1.11	0.346
									3	EpiSen	UP	14.7	0.39	1.0	0.45	0.117
2839	K2	1853	HI:Hilo, Hawai`i Is; Old Hospital	USGS	19.722	-155.115	101.4	116	1	EpiSen	90	-5.8	0.77	1.9	1.52	0.326
									2	EpiSen	360	-7.8	0.76	2.0	0.60	0.285
									3	EpiSen	UP	4.1	0.40	0.5	0.32	0.242
2818	K2	1855	HI:Hilo, Hawai`i Is; USDA Lab	USGS	19.7277	-155.0974	102.8	115	1	EpiSen	90	-28.9	-1.62	16.6	0.92	0.282
									2	EpiSen	360	29.1	-1.70	11.8	0.86	0.282
									3	EpiSen	UP	13.7	0.50	1.1	0.27	0.163
2817	Etna	1985	HI:Hilo, Hawai`i Is; Univ of Hawaii	USGS	19.7034	-155.0805	105.6	116	1	EpiSen	90	7.7	-0.92	1.9	1.51	0.420
									2	EpiSen	360	-6.0	0.81	1.0	1.10	0.272
									3	EpiSen	UP	-3.4	-0.37	0.4	0.37	0.213
2836	Etna	1984	HI:Volc Nat'l Pk, HI; HVO Srvc	USGS	19.420	-155.288	107.1	137	1	EpiSen	90	12.2	-2.15	1.7	4.04	0.938
									2	EpiSen	360	21.4	-2.68	2.9	6.73	0.592
									3	EpiSen	UP	4.6	0.47	0.9	0.92	0.133
2812	K2	1850	HI:Pahala, Hawai`i Is; Ka'u Hospital	USGS	19.1999	-155.4723	116.0	152	1	EpiSen	90	25.0	1.11	1.9	1.49	0.281
									2	EpiSen	360	18.0	-0.78	2.4	1.23	0.315
									3	EpiSen	UP	10.9	-0.55	0.8	0.69	0.273
2816	Etna	1986	HI:Pahoa, Hawai`i Is; Fire Station	USGS	19.4934	-154.9466	129.4	123	1	EpiSen	90	5.8	-1.02	0.9	0.85	0.619
									2	EpiSen	360	-4.7	0.83	0.8	1.10	0.314
									3	EpiSen	UP	2.0	-0.38	0.4	0.42	0.177

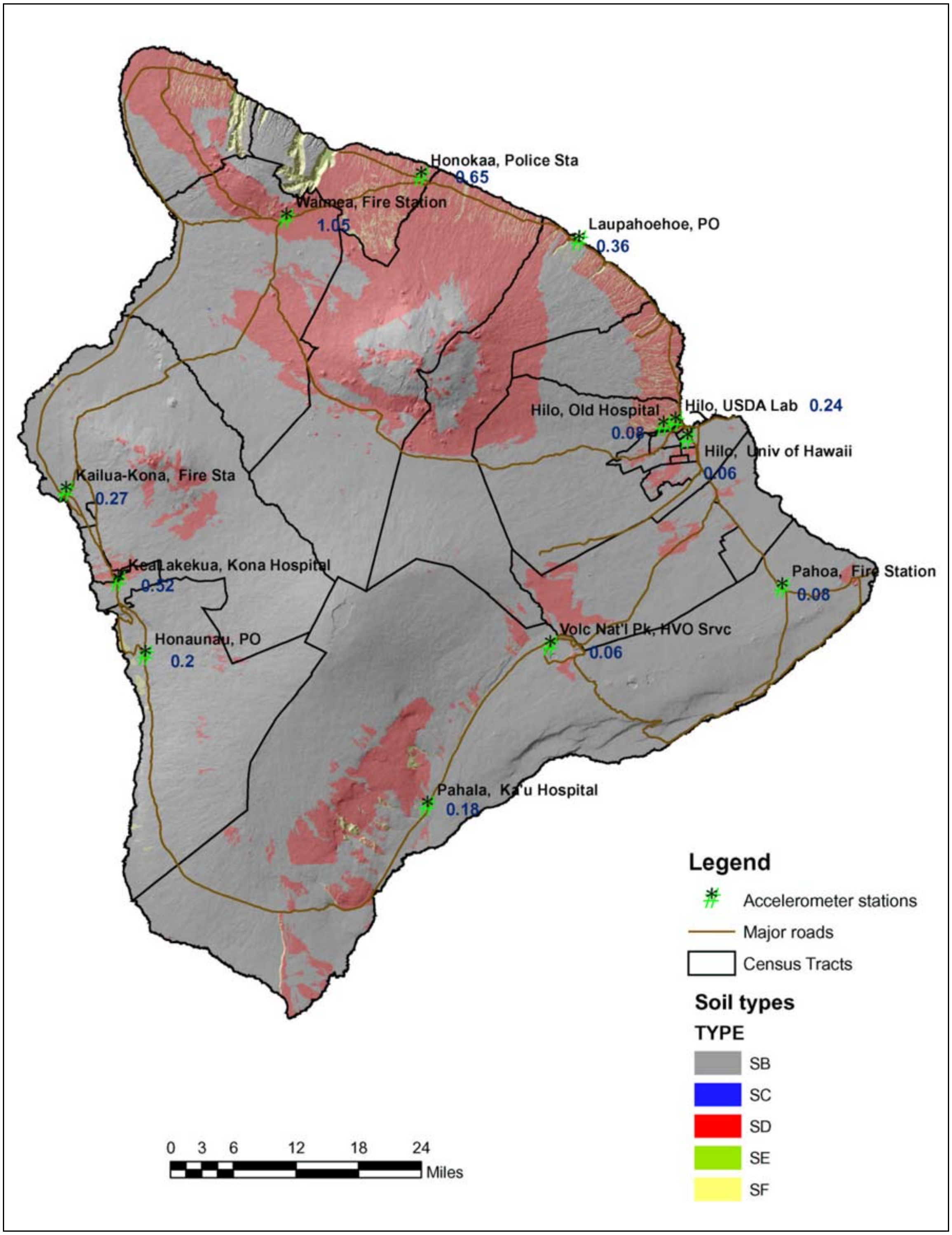
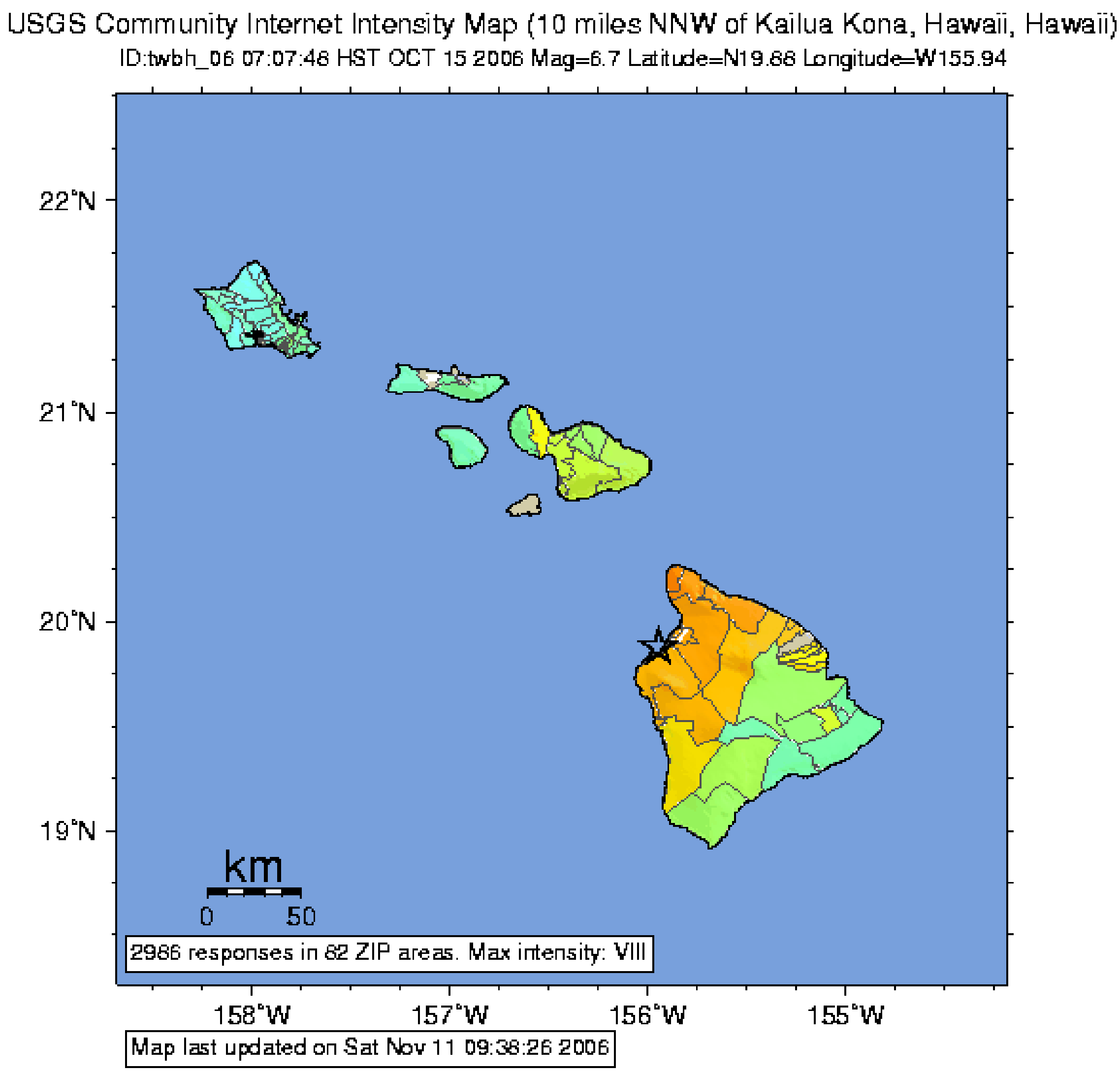


Figure 5 Locations of Dial-up Strong Motion Instrumentation and Peak Ground Accelerations; note that soil type conditions vary as estimated based on a (URS, 2006) compilation of soil boring data and geologic maps

Felt Intensities

The effects of the earthquakes were felt on all islands in the State of Hawaii. It is likely that this map reflects the public response to both Kiholo Bay and Mahukona earthquakes because the Kiholo Bay and Mahukona earthquakes occurred so close to one another in time. The MMI VIII was reported from close to the Mahukona epicenter, and residents of North Kohala reported (personal communications) that the second earthquake effects in their area were as severe as, or even worse than, those of the Kiholo Bay earthquake. The shallower Mahukona hypocenter would plausibly increase the severity of the local effects of the smaller magnitude event. Note that soil development on the island of Hawai'i is most apparent at the older northern end of the island (Kohala) and along the wetter northeastern side (Hamakua). Figure 6 below is the USGS Community Internet Intensity Map for the Kiholo Bay earthquake based on 2,986 individual reports received during the weeks following the earthquakes.



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

Figure 6 The USGS Community Internet Intensity Map for the Kiholo Bay and Mahukona Earthquakes

Some Intriguing Questions About Hawaii Seismic Events Originally Posed In 1992

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 U.S.:

- "We observe that the accelerations in Hawaii are substantially higher than average for a given intensity"
- "We find that 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 Mahukona 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.

A comparison of the USGS standard MMI to PGA conversion is shown in Table 3 below, followed by the conversion based on the relationships suggested by Wyss and Koyanagi in Table 4.

Table 3 USGS Typical Table Showing Approximate Correlation Between MMI and PGA

Standard USGS Conversion of MMI to PGA (%g) Values									
Near-Source Modified Mercalli Intensity (MMI)	I	II-III	IV	V	VI	VII	VIII	IX	X
Maximum Peak Ground Acceleration. (PGA) in %g	< .17	.17 – 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18	18 - 34	34 - 65	65 - 124	> 124
Perceived shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Moderate / Heavy	Heavy	Very Heavy

Table 4 Approximate Correlation of MMI to PGA for Hawaii based on Historical Calibration of Major Earthquakes (after Wyss and Koyangi, 1992)

Historical Conversion of MMI to PGA (%g) Values in Hawaii (Based on Wyss & Koyanagi 1992)									
Near-Source Modified Mercalli Intensity (MMI)	I	II-III	IV	V	VI	VII	VIII	IX	X
Maximum Peak Ground Acceleration. (PGA) in %g	< 3.2	3.2 - 8.1	8.1 - 13	13 - 20	20 - 32	32 - 51	51 - 80	80 - 128	> 128
Perceived shaking	Hardly Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage to Engineered Structures	None	None	None	Very Light	Light	Moderate	Moderate	Heavy	Very Heavy
Approximate Minimum. Magnitude	—	—	—	< 5.5	5.5	6.0	6.5	7.0	7.5

Interim Damage Reports

The location of the epicenters just offshore from relatively rural areas significantly reduced the potential for loss of life, injury and property damage that could be expected from earthquakes of this magnitude. The 40 km deep hypocenter of the Mw 6.7 Kiholo Bay earthquake also appears to have reduced the consequences at ground level. At the time of the writing of this report, no deaths had been attributed to the ground shaking, and only 25 injuries were reported, none of these requiring hospitalization. Damage reports for public buildings and infrastructure as of October 26 were announced by the County of Hawaii. The approximate rough order of magnitude figures in Table 5 are subject to revision.

Table 5 Damage Reports as of the close of 2006

Category	Number of Facilities with Major Damage	Number of Facilities with Minor Damage	Estimated Cost ($ millions)
Hawaii County Buildings	15	7	16
Hawaii State Buildings	1	21	0.5
University / Community Colleges	3	17	2.5
Public Schools	1	25	5
Libraries	0	3	0.2
Hospitals	2	3	3.5
Private Businesses	36	264	14
Private Residences	304	1705	Pending
Hawaii County Bridges			0.2
State Bridges			7
Hawaii County Roads			3
State Highways			31
Harbors	1	1	7+ (up to 30)
Electric Utilities			4
Agricultural Damage	2	1	12
Reservoirs		2	Pending
State and National Parks	5	16	7
Total of Preliminary Estimates	370	2063	$113

It is likely that the number of damaged private residences is underestimated in the table above because county evaluations are triggered by homeowner requests for safety inspections. The American Red Cross did a windshield survey and reported 40 homes destroyed and 280 with major damage, and about 2009 with minor damage. Repair costs for private residences had not yet been estimated by the county. The above estimate also does not include business interruption.

HAZUS 99 Loss Estimates

A HAZUS analysis of the Kiholo Bay earthquake was performed by the Hawaii State Earthquake Advisory Committee (HSEAC). As developed by the HSEAC, the HAZUS model region for the Counties of Hawaii and Maui utilized a locally validated building inventory database based on property tax records and calibration to historical building code adoption dates, a Hawai'i-derived attenuation function (Munson and Thurber, 1997) albeit one based on shallower epicentral depths, a soil profile mapping to census tract scheme based on soil boring surveys (Figure 7), customized census tract population centroid locations, and local construction cost data, along with a 0.2 magnitude reduction based on prior event calibration study conducted sponsored by the State of Hawaii Office of Planning. This specialized HAZUS model predicted 4 non-critical hospitalizations and 36 minor injuries. For residential buildings, it estimated 29 residential homes completely damaged, 318 extensively damaged, and 2,340 moderately damaged; these were primarily wood framed. Within this residential category, the post and pier supported single wall homes were the predominant type of construction damaged, with 25 completely damaged, 217 extensively damaged, and 1,369 moderately damaged. The model estimated 10 schools, 1 hospital, and 2 police stations to be moderately damaged. HAZUS predictions of economic losses totaled $145 million for structural and nonstructural building losses (and $43 million for business interruption loss). Given that the earthquakes occurred on a Sunday, the business interruption loss may be less than hindcasted. Further evaluation by HSEAC of the skill of the HAZUS software and modeling parameters for this event is ongoing. Given the amount of customizations implemented in the State of Hawaii Civil Defense model, users of any default HAZUS model should not expect the same results.

In 2005, State Civil Defense published a planning booklet with HAZUS summary reports charts, and GIS maps of anticipated damage for four worst case (maximum considered earthquake) scenarios (Chock and Sgambelluri, 2005).

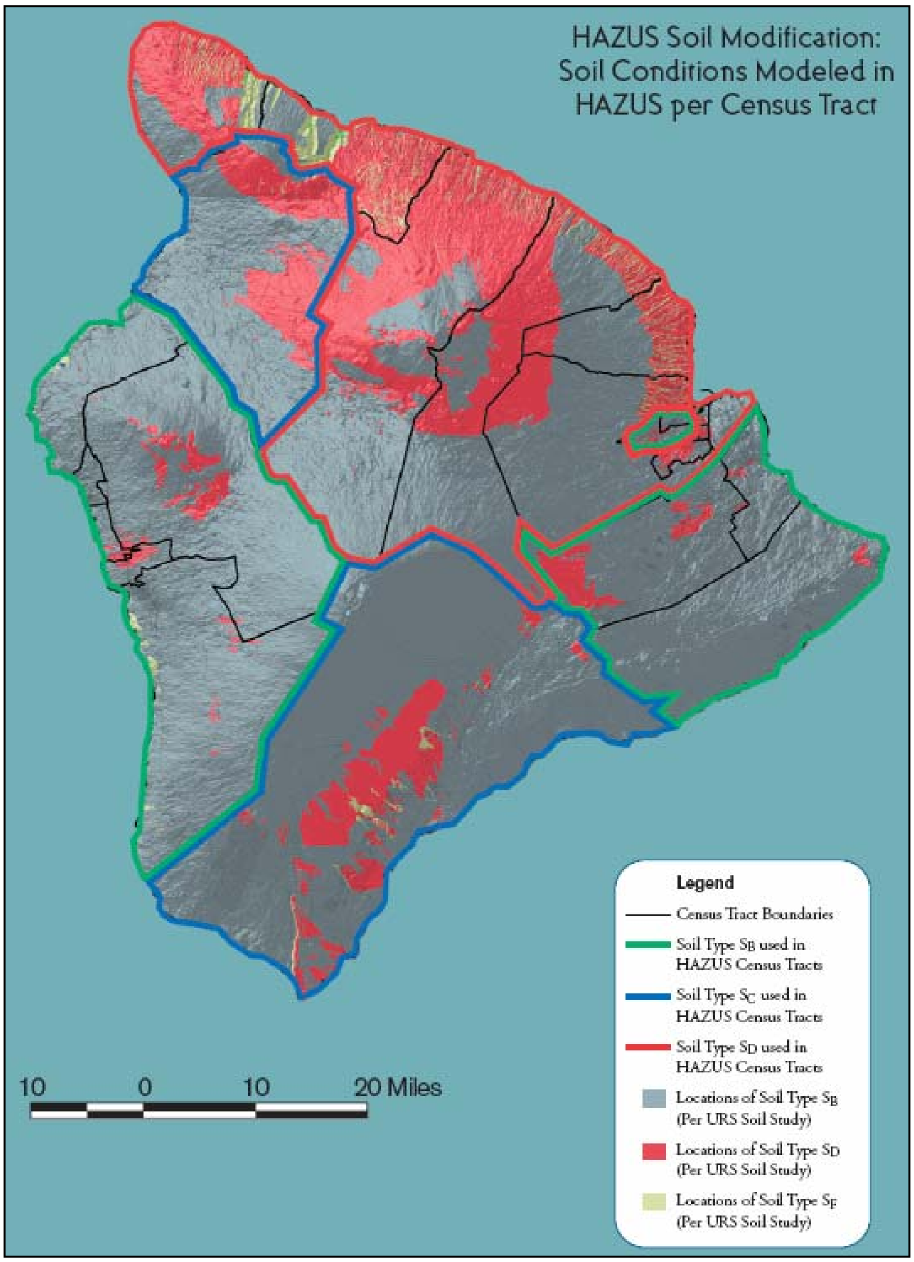


Figure 7
Soil Type Conditions Represented in HAZUS Based on a Compilation of Soil Boring Data and Geologic Maps (Chock and Sgambelluri, 2005)

Geotechnical Observations

A reconnaissance team from the Civil and Environmental Engineering Department at the University of Hawai'i at Manoa, visited over 40 sites on October 17 and 18, primarily to observe geotechnical effects and the performance of bridges and reservoirs. The UHM team consisted of Peter Nicholson, Ian Robertson and Horst Brandes. The assessment focused on areas North of Kailua-Kona and North of Hilo, where most of the damage was reported. A report of that reconnaissance was released on October 26th, just eleven days after the events and is available at http://www.cee.hawaii.edu. Ed Medley was subsequently dispatched by the Geo-Engineering Earthquake Reconnaissance Association (GEER) for additional detailed observations between October 20 and 23.

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 for fear of future landslides. Other landslides occurred along the northern Hamakua coast (Figure 8). Rockfalls and landslides in remote inland valleys and ravines blocked or destroyed many sections of critical aqueducts serving northern Hawai'i County, which is a key agricultural and ranching area.

Figure 8 Massive coastal escarpment landslides into the ocean, Hamakua Coast (Photograph courtesy of Hawaii Civil Defense Agency)

Numerous rockfalls and slides occurred in road cuts, embankments and natural slopes. Virtually every steep road cut North of Kailua-Kona and North of Hilo exhibited some degree of rockfall or debris slide (Figure 9). 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. The discontinuous and often contorted inclusions of massive basalt are irregularly fractured.

There is a considerable difference in the mechanical properties of the a‘a clinker and massive basalt. During the earthquakes, the loose a‘a clinker raveled and removed support from overlying massive blocks. 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 (Figure 10). 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.

The baked contact between lava flows and pre-existing ground surfaces is often marked by a zone of red soil and highly weathered rock resulting from accelerated weathering. A number of road cut failures were observed where the weaker basal soils failed, undermining the stronger rock above, in a fashion similar to that above described for aa/massive basalt sequences.

Although rock and soil slides in cuts above roadways were numerous, damage to road embankments and pavements was less prevalent, with a few exceptions (Figure 11). The most dramatic of these was the collapse of half of the roadway at Mile 35 on Highway 19 near Pa‘auilo, resulting in the closure of one lane of traffic (Figure 12). This was caused by failure of a 20-foot high embankment and rock wing wall on the approach to a concrete girder bridge. The cast-in-situ concrete girder bridge is supported on rock wall abutments. The bridge suffered no damage but the adjacent embankment failed. The wing wall consisted of mortared rock and was approximately 14 inches thick.

Because of the lack of redundancy in the highway system on the Island of Hawaii, road closures due to rockfalls, landslides or embankment slope instability can have a significant effect on emergency response and economic recovery efforts. For a number of hours after the earthquakes, 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 the Island of Hawaii were open to at least one-lane traffic within two days of the earthquakes.

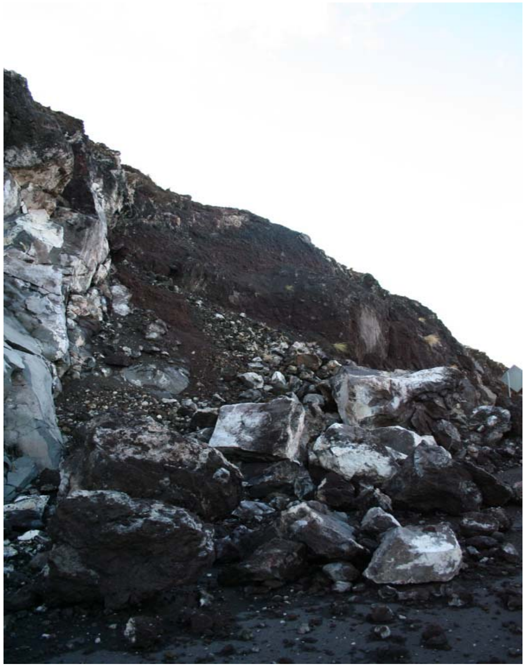


Figure 9 Rockfall typical at steep roadcuts

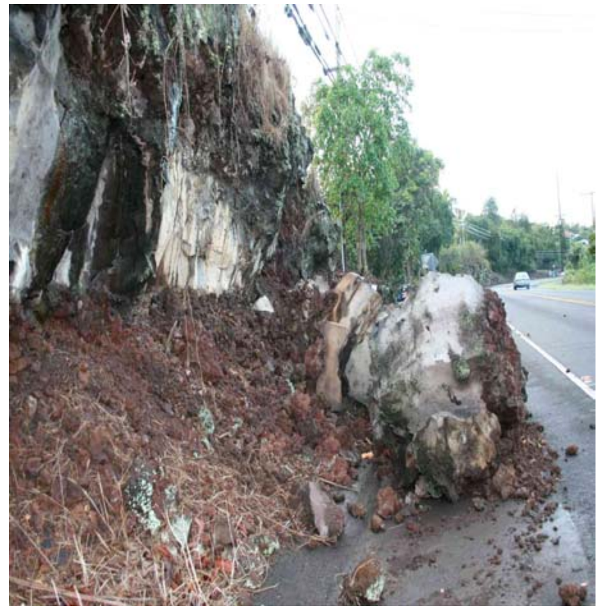


Figure 10 Example of discontinuous geology where dense basalt rock overlies weaker and less stable clinker

Figure 11 Highway Embankment and Roadway Failures

Figure 12 Failure of Bridge Approach Embankment On Highway 19 Due to a Retaining Wall Collapse (Photographs courtesy of State of Hawaii Dept of Transportation, Highways Division, and Hawaii County Civil Defense Agency)

The island of Maui was also impacted by several rockfalls induced by the earthquakes (Figure 13). Highway 31 along the southeastern coast of Maui was closed near Manawainui (Figure 14). Rockfall debris at the Kalepa cliffs impacted the highway (Figure 15). About 500 Maui residents were cut-off between an incipient rockfall hazard of that road in the Manawainui area and a bridge closure due to abutment erosion at Paʻihi. After an engineering evaluation and fast-track design, the installation of a temporary steel truss bridge was completed at the end of November. Sections of that highway along the coastline are inherently vulnerable to rockfalls and landslides (an example is shown in Figure 16). A few days after the opening of the temporary bridge, new rockfalls at Kalepa closed the highway again. The County of Maui is scaling loosened rocks and boulders from several vulnerable slopes. The discontinuous and often contorted inclusions of massive basalt are irregularly fractured.

Figure 13 Massive Landslides on the Southeastern Coast of Maui During the October 15, 2006 Earthquakes (Kalepa on the right)

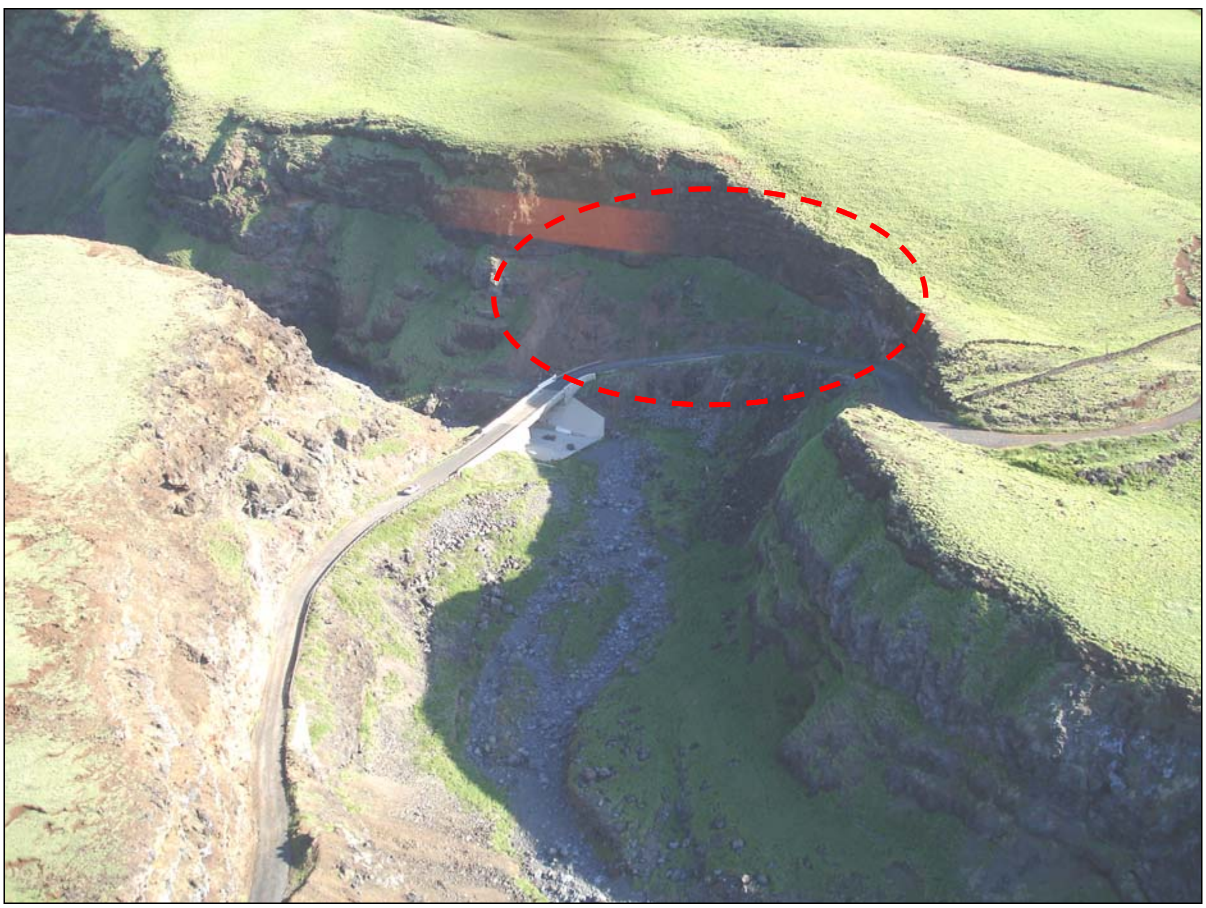


Figure 14 Manawainui, Maui (incipient rockfall over the roadway indicated on the photograph) (Photographs courtesy of Maui Civil Defense Agency)

Figure 15 Maui Rockfall at Kalepa cliffs (approx. the 38-mile marker along Hwy 31)

Figure 16 Example Area of Potential Rockfalls along Maui Hwy 31

(Photographs courtesy of the Maui Civil Defense Agency)

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 originally for irrigation purposes. At least two dams experienced cracks along their crests, while at least two others showed clear evidence of incipient slope failure on their embankments (Figure 17). The Pacific Disaster Center performed dam break simulations for Hawaii County Civil Defense. 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. The Hawaii Dam Safety Guidelines: Seismic Analysis & Post-Earthquake Inspections (Brandes, 2004) call for inspections of dams within 75 miles of the source of an earthquake of magnitude between 6 and 7. The U.S. Army Corps of Engineers was undertaking these comprehensive inspections.

Figure 17 Cracking and stability failures on the crest of reservoir dams

(Photographs courtesy of Peter Nicholson, University of Hawaii, Department of Civil Engineering)

Figure 18 Kawaihae Harbor

One of the two major commercial ports on the island, the commercial port facility at Kawaihae Harbor consists of two pile-supported concrete piers, a 500-foot long Pier 1 and the 1500-foot long Pier 2, which is operationally divided into Piers 2, 2A and 2B and a few warehouse and administrative buildings, and an asphalt paved shipping container yard (Figure 18). This facility is located less than 24 km (15 miles) from both earthquake epicenters.

Kawaihae Harbor sustained major damage from liquefaction and lateral spreading. Sand boils were observed throughout the harbor area (Figure 19). 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, and lateral displacement of the pile supported concrete piers. Large areas of the asphalt yard, had settled up to approximately 6 inches (Figure 20). Fine sand had been ejected from cracks in the asphalt pavement and through junctures between the paved fill area and the pile-supported concrete pier. A series of cracks with widths ranging from approximately 1/4 inch to several inches were observed roughly aligned parallel with the shoreline. Cumulatively, these cracks displayed lateral spreading of 6 inches or more. Personnel at the facility described fine sand and water "squirting out of the cracks" in the pavement immediately following the earthquakes. Pier 1 displaced as much as 6 to 12 inches laterally towards the harbor. 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. It is unknown at the time of writing this report if any damage had been incurred by the piles supporting this pier.

Figure 19 Examples of sand boils and lateral spreading, Kawaihae Harbor (Photographs courtesy of Peter Nicholson)

Figure 20 Liquefaction induced lateral and vertical displacements of approximately 6 inches at port facility, Kawaihae Harbor (Photograph by Peter Nicholson)

Damage to the port facilities resulting from liquefaction included:

- Total and differential settlement, as well as lateral displacements and associated separations within the shipping container yard (Pier 2). This damage created an immediate problem for loading/offloading of containers;
- Spreading of the shipping yard from the bulkhead and concrete pier also created serious concern for the fuel offloading pipelines which traversed the damaged area;
- Major torsional and longitudinal cracks in the beam along the edge of Pier 1 and damage to its adjacent approach apron forced closure of this portion of the port. This had the additional consequence of inaccessibility of the pneumatic Hawaiian Cement offloading pipelines. This is the only facility for unloading cement to the island and thus represents a severe problem for the construction industry.

The port was closed immediately after the earthquake due to ground subsidence, lateral spreading and soil liquefaction that made continuing port functions, which rely on the movement of heavy, containerized cargo, unsafe. Gasoline and diesel fuel lines on the north end of Pier 2 which are supported from the undersides of the piers, were also damaged and some had reportedly fallen from their hangars in the waters of the harbor. After determination that Pier 2B at Kawaihae Harbor was still usable, minor repairs were made to level the approach slab-to-dock transition on October 17th. Three days after the event, Pier 2B was re-opened, but Piers 1 and 2A remain closed indefinitely.

The lateral spreading also resulted in deformation of the pre-manufactured metal frame warehouses adjacent to the concrete piers. Although damage to these buildings is relatively minor, the potential remains for further liquefaction of the fill materials during future earthquakes. No damage was noted at Hilo Harbor on the east side of the island, however it is known that much of the harbor is also constructed on fill materials that are susceptible to liquefaction. Hilo and Kawaihae Harbors are the only two ports on Hawaiʻi Island capable of handling the barges that transport most of the island's supplies from Honolulu Harbor. As such, the harbors are an essential lifeline for the inhabitants of the island.

Bridges

At the time of the writing of this report, it appeared that only one bridge structure suffered major damage during the earthquakes, Honokoa Bridge 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 at the time of writing this report.

Honokoa Bridge

The Honokoa bridge, built in 1965, is located just north of Kawaihae on the west coast of the Island of Hawaiʻi. 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 (Figure 21). Figure 22 shows a schematic of the bridge cross-section. Significant damage was noted to the webs of the AASHTO girders at the abutments (Figure 23). Evidence of relative movement and pounding between bridge segments and between the bridge deck and the abutments was apparent from spalling damage to the bridge guardrails.

Figure 21 Honokoa Bridge (Photographs courtesy of Peter Nicholson)

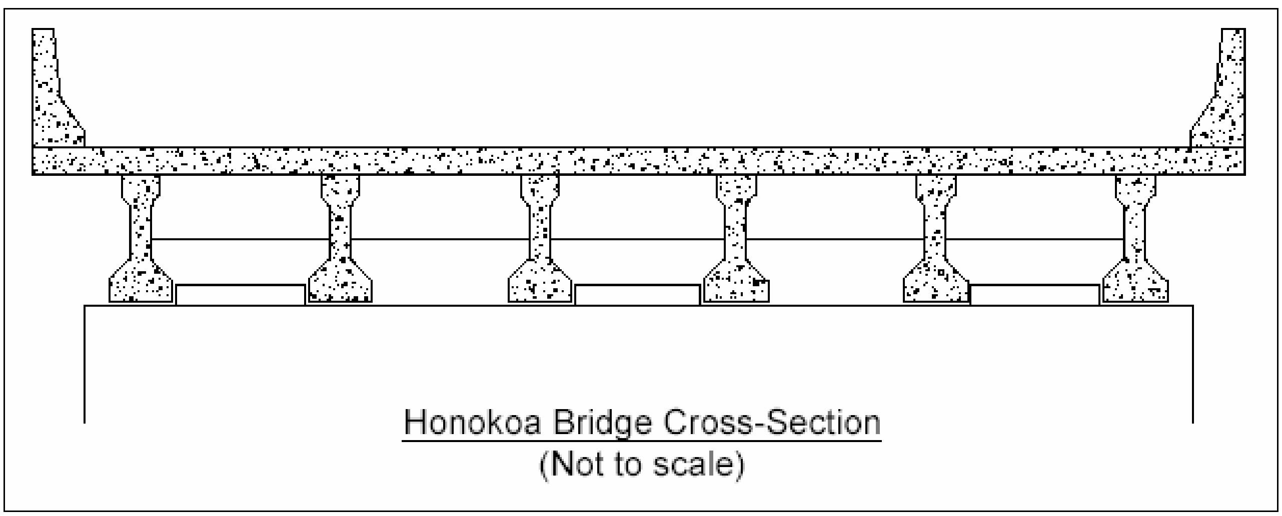


Figure 22 Cross-section through Honokoa Bridge. (Diagram by Ian Robertson)

Figure 23 Damage to web of AASHTO girder at Abutments
(Photograph courtesy of Ian Robertson)

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 (Figure 24) 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 24 Shear key and bridging beam between AASHTO bridge girders
(Photograph courtesy of Ian Robertson)

This bridge was scheduled for a seismic retrofit which was to include extending the bulkhead to the bottom of the girders. This retrofit had already been performed on three similar bridges on the Island of Hawaii, none of which experienced damage during the earthquakes.

ATC-20 Post-Earthquake Building Safety Evaluation Assessments

The County of Hawaii received over several hundred individual requests each day to evaluate building damage from October 15 up to the end of October. During the first week after the earthquakes, County of Hawaii engineers and inspectors used the ATC-20 Rapid Evaluation procedure to assess the safety status of approximately 1000 homes in just a week. Staffing for these inspections was drawn from county building department engineers and construction inspectors. To fulfill this need, the County temporarily shut down all normal building permit reviews and construction inspections.

The ATC-20 evaluations utilize the following designations:

- Green: Inspected; considered safe for lawful occupancy
- Yellow: Restricted Use; entry, occupancy, and lawful use are restricted
- Red: Unsafe; do not enter or occupy; it is NOT a condemnation or a demolition order.

Gary Chock, of Structural Engineers Association of Hawaii (SEAOH) (and member of EERI), was the association's designated point of contact with State Civil Defense and the State's Public Works Administrator / Coordinator for Emergency Support Function #3 of the National Response Plan, Public Works and Engineering. SEAOH members placed initial calls for pre-activation of potential volunteer SEAOH structural engineers on the day of the earthquake from the state Emergency Operations Center. However, many initial calls were not connected due to a day-long power outage on the island of Oahu (City and County of Honolulu) which disabled all cordless land line phones. Initial deployments of selected volunteer engineers began on October 16 for inspections of several essential facilities at the request of the State and Hawaii county. When the County of Hawaii requested assistance via State Civil Defense four days after the earthquakes, the Structural Engineers Association of Hawaii (SEAOH) activated two groups of structural engineers to assist the County of Hawaii Department of Public Works with post-earthquake safety evaluation of single family homes and other buildings during the second week after the earthquakes. The first group was deployed to the western "Kona" side , and a second group deployed to the eastern "Hilo" side of the island. Transportation, lodging, and meals were provided by the County of Hawaii.

Under Hawaii State Law (Hawaii Revised Statutes Chapter 128, Civil Defense and Emergency Act), persons engaged in civil defense functions (including volunteers whose services are accepted by any authorized person), cannot be held civilly liable for the death of or injury to persons, or property damage, as a result of any act or omission in the course of the employment or duties, except in cases of willful misconduct. Furthermore, all persons including volunteers whose services have been accepted by authorized persons, shall, while engaged in the performance of duty be deemed state employees or employees of a political subdivision, as the case may be, and shall have the powers, duties, rights, and privileges of such in the performance of their duties, including workman's compensation coverage by the State.

County inspectors were assigned as county representatives to each team of one or more structural engineers to accompany them to approximately 10 to 20 building damage sites each day. Besides ensuring that a county representative was present at every inspection, the county guide was a key factor in the efficiency of the inspections. The inspector put together a daily package of the Civil Defense call in forms describing each owner's assessment of damage and maps showing the call locations. Structural engineers were also requested to do Detailed Evaluations of homes previously red-tagged by county inspectors, which provided reassurance to the affected homeowners that professional engineers were involved in the posting. In general, the ATC-20 evaluations demonstrated that the county was attending to the safety of the public, and it helped remove the uncertainty about personal safety that many homeowners had prior to the evaluation.

A county database was used to initiate American Red Cross visits to the occupants of all red and yellow tagged homes. The local utility company, HELCO, also disconnected electrical service to the red-tagged homes. The County of Hawaii also announced that owners of yellow and red-tagged homes are allowed to submit their repair plans to the Building Division for review without paying any processing fees. About 70 homes were red-tagged, and 230 were yellow-tagged based on potentially hazardous conditions, out of a total of approximately 1,700 inspections as of a month after the event. This number does not include more than 10 homes destroyed outright. Figure 25 maps the spatial distribution of moderate to severe damage to these homes, suggesting the significance of soil amplification of ground motion.

Postings on the buildings can be revised when one of the following occurs:

- The unsafe condition(s) is repaired (at least to the pre-existing condition)
- There is a reevaluation by the Department of Public Works
- There is a reevaluation in more detail by a professional engineer
- Additional damage occurs or develops due to an aftershock

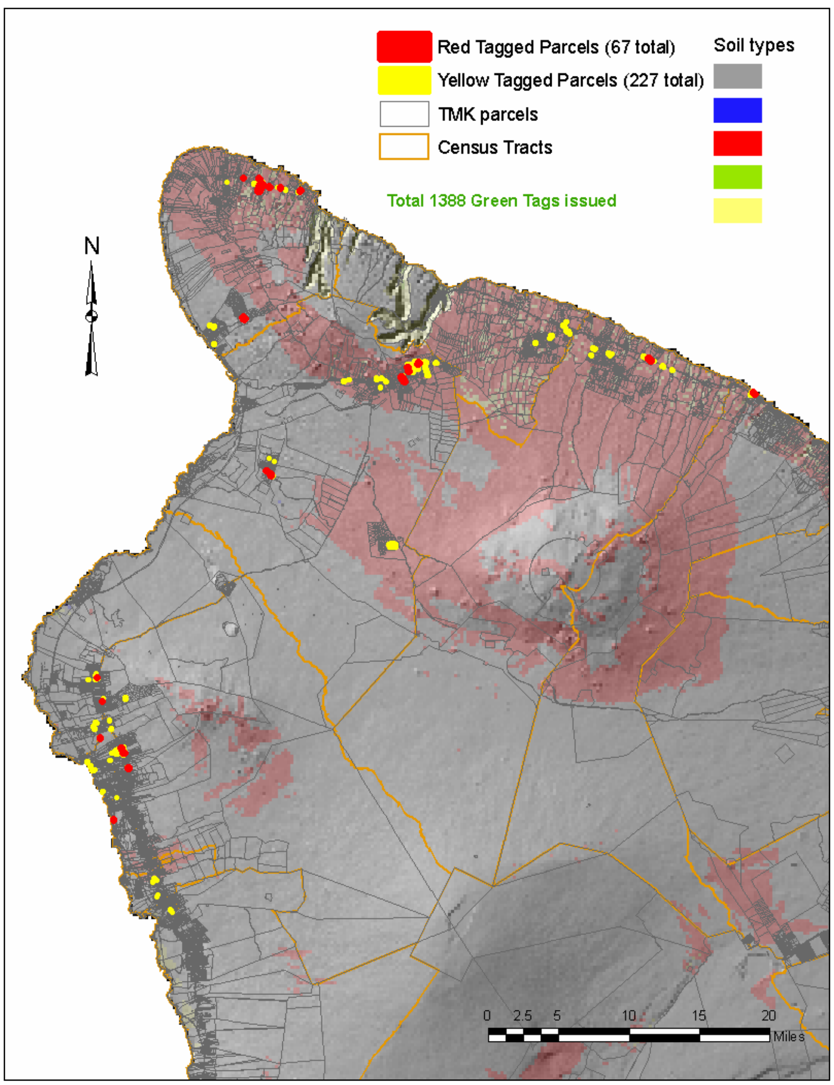


Figure 25 Red- and yellow-tagged homes overlaid on soil type

(Geocoded Map by Gary Chock)

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, and while well built for gravity loads, lacked seismic detailing. The Structural Engineers Association of Hawaii was contacted by the Historic Hawaii Foundation with a request to place historic preservation architects with every ATC-20 building safety evaluation team to prevent "premature" assessments of unsafe (red tag) conditions. This request was based on the misunderstanding that a red-tag status constituted a condemnation order, which it does not, and the request was declined after clarifying the public safety mission of the ATC-20 inspections conducted under the County Department of Public Works Building Division. Ultimately, the Historic Hawaii Foundation did not place volunteer architects in the field for safety evaluations.

The State Historic Preservation Division and National Park Service conducted their own preliminary assessments of about 15 historic buildings the state and national registers of historic places on the Big Island. The State Historic Preservation Division contracted with preservation architecture and archeology firms to provide damage assessments for historic properties on the Big Island. They focused first on properties on the historic registers and then moved to significant properties on the register-eligible inventory.

Kalahikiola Church

This 1855 vintage stone church was constructed with rough lava stone walls and a wood roof constructed with "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 historic Kalahikiola Church in Hawi, North Kohala, suffered extensive damage to the exterior rock-masonry walls supporting the roof trusses (Figure 26). 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 (Figure 27). 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 (Figure 28). Many of these walls suffered damage in the form of cracking, partial collapse or complete collapse. The other end of the building (where the pastor would preach) 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. Estimates are as high as $3 million to rebuild the Kalahikiola Congregational Church.

Figure 26 Kalahikiola Church in Hawi

Figure 27 Roof trusses supported by interior columns and window frames after wall collapse . (Photographs courtesy of Ian Robertson)

Figure 28 Unreinforced basalt rock-masonry walls filled with low strength mortar and smaller rubble (Photograph courtesy of Edward Medley)

Hulihe‘e Palace

The historic Hulihe‘e Palace in Kailua-Kona on the west side of the Island of Hawaii 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. Historic photographs indicate that the corners were formed of larger stones, flattened and interwoven to tie the corners together better. In other areas of the walls the stones used are more likely to be smaller and of irregular shape. The walls are almost 3 feet thick, although the gable ends, from the sills of the attic windows, appear to be about 2 feet thick.

The Palace suffered extensive damage and was at one point deemed unfit for occupancy. Typical diagonal cracking occurred in the cementitious plastered masonry exterior walls of the building, particularly around door and window openings (Figure 29). Hulihe‘e Palace was re-opened after consultants to the Department of Land and Natural Resources indicated that the damage was not to the extent of earlier concerns that it was not structurally sound. Although the building had initially been “red-tagged” by inspectors in the week after the earthquake, the hazard designation was later changed to a yellow tag. Access to the public was limited to the center room at the first floor and the oceanfront first floor lanai. Access to the other rooms in the Palace were restricted to staff and workmen. There is an extensive amount of damage to interior finishes and separation gaps in the floors and ceilings. Estimated repair cost was stated to be approximately $1 million.

Figure 29 Damage to the plaster finish and masonry of a gable end wall of Hulihe‘e Palace

(Photograph by Gary Chock)

Residential Damage

One of every 25 homes on the Big Island was damaged by the Oct. 15 earthquakes. There are approximately 50,000 single-family and duplex (two-unit) homes on the island of Hawaii. Most of these are wood-frame construction, with the majority being of conventional stud and sheathed walls (known in the local vernacular as "double" walls)and about 40% or 19,000 homes consist of what is commonly known in Hawaii 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 (Figure 30). 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 residences 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. 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. In more modern times, conventional wood stud wall framed and even light-gage steel post supported homes may still be found elevated on posts and piers for economy and convenience.

Up until the mid-1970's, this type of construction was commonly used for affordable housing construction, primarily because of its simplicity, minimal pieces, and absence of any thermal insulation requirements in the tropical environment of Hawaii. After that period, changes in material pricing of redwood and cedar as well as market expectations evolved towards sheathed, bearing stud wall construction. 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 the island of Hawaii, where the depth of soil may be shallow overlying fractured lava, avoiding excavations and re-grading of volcanic rock can be economically attractive. In this type of construction, termite treatment of the ground for the Formosan termite was also avoided. The notional concept shown in the illustration of a light-gage metal "termite-shield" was found to be totally invalid, and this unanchored thin plate was not necessarily installed in all homes. The height of piers can vary from just over a foot to much more than 12 feet high (Figure 31) Also, 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. Typical size of this style of home is approximately 1,000 to 1,300 square feet. Connections are typically of minimal uplift and lateral capacity. Based on Hawaii's historic building code provisions and property tax records, less than 10% of these single wall homes are estimated to have utilized metal plate connectors and straps; the predominant majority is framed using toenails only. The current building code of the County of Hawaii still permits single wall construction by a local code amendment.

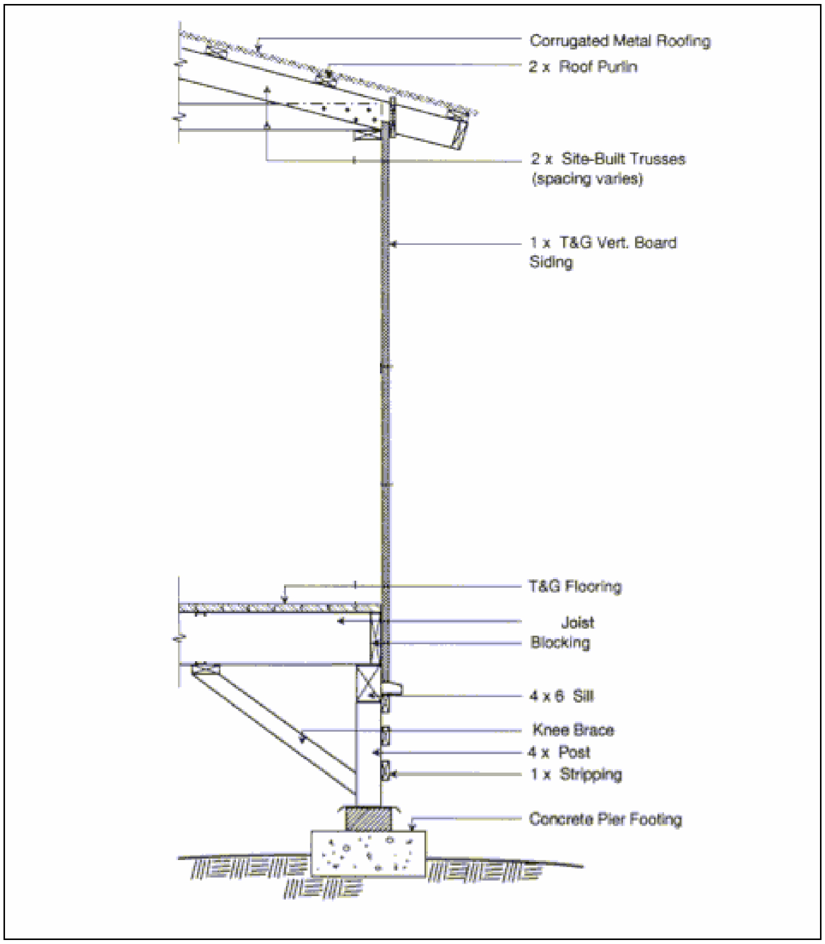


Figure 30 An Example of One Style of Hawaii Single-Wall Construction on Post and Pier (note that there are several variations from the original style shown in this illustration)

Figure 31 Tall unanchored posts on the verge of slipping off their foundation piers; note splitting of wood columns at their bases (Photograph courtesy of Kylie Yamatsuka)

Based on approximately 230 ATC-20 inspections performed by members of the Structural Engineers Association of Hawaii, most of the single family homes that were red-tagged as unsafe were of post and pier construction. Since the posts are resting and are not connected to the foundation, if the relative movement between the 4x4 posts and the supporting foundation exceeds the size of the "tofu block", or successive shaking leads to "walking" of the posts, the building may fall off the foundations. Failure modes observed were posts shaken off the small footing or smaller upper "tofu" pedestal, or where the post had rotated due to inadequate lateral bracing, splitting at the bases of the heavier loaded posts, or overturned footings (Figures 32, 33, and 34). As a result, such homes were vulnerable to lateral sidesway displacement, dropping, and potential collapse of the first floor, and severing of utilities. In some cases, the building collapsed and was totally destroyed, however most of these buildings survived the impact, though rendered unsafe in many cases (Figures 35 and 36). It is possible to reposition the footings under some of the less-damaged residences and effect structural and utility repairs with significant effort. Among damaged homes, the incidence of red- and yellow- tagged conditions was a factor of 2.5 times higher for the elevated post and pier homes than the incidence rate for homes on slab.

Figure 32 Detachment of a Post at the Top and Bottom at a Sloping Hillside Site (Photograph courtesy of Tim Waite)

**Figure 33 Splitting of a Post Base with Lateral Displacement
(Photograph courtesy of Ron Iwamoto)**

**Figure 34 Rotational Instability Mode of Post and Pier “Single” Wall Homes
(Photograph courtesy of Ian Robertson)**

Figure 35 Major damage to a light-wood-framed "single" wall home after collapse of a portion of the post and pier system (Photograph courtesy of Kylie Yamatsuka)

Figure 36 Collapse of the Post and Piers of a Single Wall Home; note lateral displacement from footing (Photograph courtesy of Clifford Lau)

In more recent construction, some designs make use of corner L-shaped walls of reinforced CMU following 1997 recommendations of the Structural Engineers Association of Hawaii and Hawaii State Civil Defense (Figure 37).

Figure 37 An example of an undamaged home with an improved form of elevated floor framing on a hillside utilizing masonry corner walls (Photograph courtesy of Gary Suzuki)

Retaining Walls

Many residences experienced damage to lava rock retaining walls. These walls typically consisted of individual, rough lava rocks stacked dry, or with minimal mortar (Figure 38). The walls were commonly 3 to 5 feet in height, although in some cases taller. In the County of Hawaii, the building code allows walls of up to six feet to be constructed without engineering drawings. Many minimally mortared rock walls failed during the earthquake. Numerous dry-stacked rock walls crumbled in the earthquake (Figures 39 and 40).

Figure 38 Failure of a loosely fitted and mortared lava rock wall causing undermining of single family home; note the beginning of a replacement wall construction in foreground (Photograph courtesy of Glenn Miyasato)

Figure 39 Failed stacked rock retaining wall in Captain Cook, adjacent Hwy 11. (Photograph courtesy of Edward Medley)

Figure 40 Failure of a dry-stacked lava rock wall threatening a neighboring property (also note damaged carport) (Photograph courtesy of Lee Takushi)

Engineered Buildings

As of this date, the County of Hawaii has used the 1991 Uniform Building Code since 1993 to the present (Figure 41). Note that the 1991 UBC placed the island of Hawaii in Zone 3, and this was not corrected until the 1997 UBC. (The County of Hawaii realigned to the Zone 4 designation in mid-1999, but only as an amendment to the 1991 UBC.) Historically, structural (special) construction inspections have been required in Hawaii County only since 1993. The State of Hawaii has no statewide building code, and each of the four counties (Kauai, Honolulu, Maui, and Hawaii) adopts building codes on independent schedules. State building construction follows the county building codes, and so there is the possibility of obsolete seismic provisions being used for public sector work over the years. The other counties of Kauai, Honolulu, and Maui presently use the 1997 Uniform Building Code, and are transitioning to the International Building Code. Earlier in 2006, the County of Hawaii announced the intent to adopt the 2006 International Building Code.

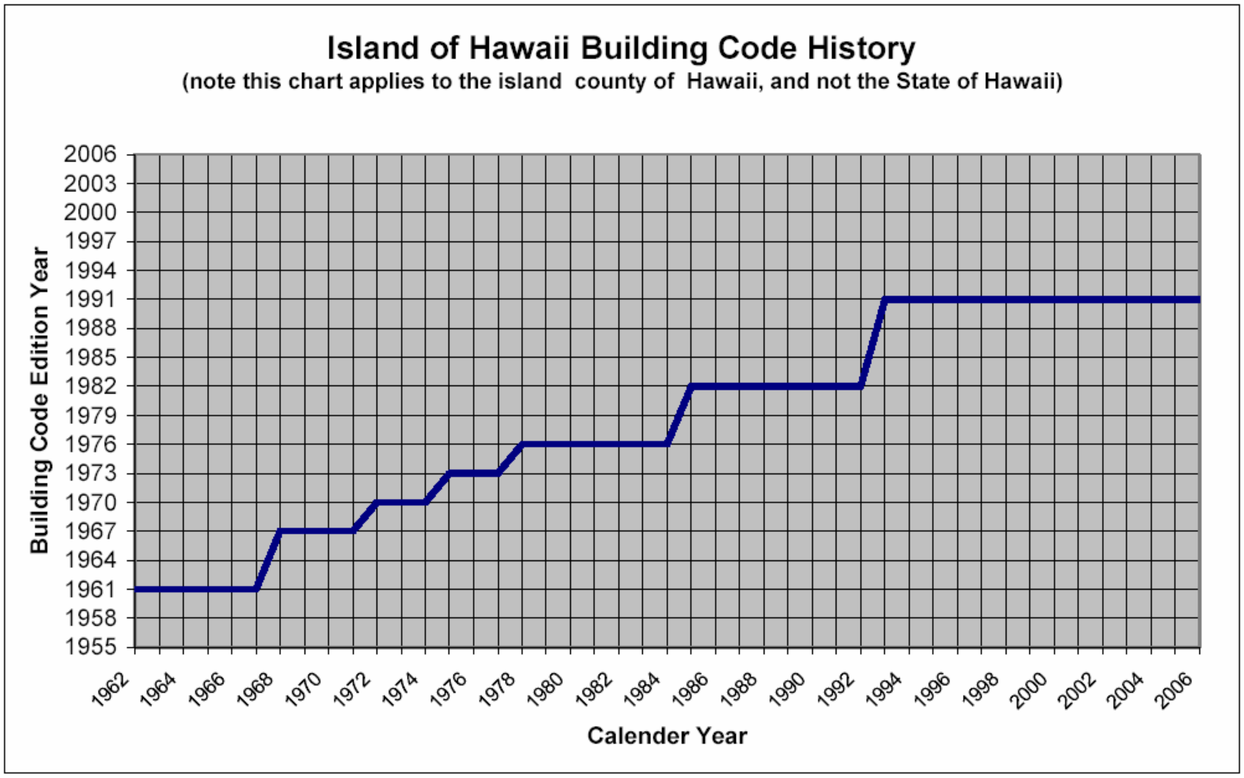


Figure 41 County of Hawaii Building Code History

Hotels and Resorts

The hotels and resorts, as a whole, performed fairly well, and all of them remained in operation. The Mauna Kea Beach Hotel, one of the first major hotels in the north Kona area, suffered the most damage which eventually led to its complete closure for repairs. The Hapuna Prince Beach Resort sustained significant water damage to its ballroom due to broken fire sprinkler heads caused by the movement of unbraced ceilings. The Hilton Waikoloa Resort experienced minor cracks in shear walls of one building and some localized trellis damage. The Sheraton Keauhou had numerous cracks in cementitious plaster finishes and some limited damage to pedestrian bridges and stairs. It was able to provide temporary housing in its ballroom to the long-term-care patients evacuated from the Kona Community Hospital.

Mauna Kea Beach Hotel

The Mauna Kea Beach 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 southern Beachfront Wing of the hotel collapsed as shown in Figure 42. Damage to a balcony below this structure was probably the result of impact from falling debris (Figure 43). 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.

Figure 42 Collapse of concrete trellis frame at Mauna Kea Beach Hotel. (Photograph courtesy of Ian Robertson)

Figure 43 Damage to balcony due to impact from falling debris (Photograph courtesy of Ian Robertson)

In addition to the damaged bay of the low-rise Beachfront Wing, a portion of the top floor of the Main Wing was not occupiable due to severe damage to the steel-framed addition that had inadvertently been built straddling expansion joints of the original structure. Figure 44 and Figure 45 show significant damage to the concrete surrounding two connector plates and the construction joint between a precast exhaust flume and an elevator shear wall of the high-rise northern Main Wing. The U-shaped exhaust flume was added to the south side of the existing shear wall as part of the hotel expansion. 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. Several exterior concrete trellis beam to column joints were also spalled but did not collapse. Other structural damage included cracked and spalled spandrel beams and some cracking at the base of cruciform column/walls. About 60% of the hotel remained in operation until a December 1, 2006 total closure for repairs

Figure 44 Damage to concrete exhaust flume at connector plate – west side. (Photograph by Gary Chock)

Figure 45 Damage to concrete exhaust flume at connector plate – east side. (Photograph by Gary Chock)

Paniolo Club Condominiums, Waikoloa Village

The Paniolo Club condominiums are a cluster of several two-story and three-story buildings built in the mid-1970's. 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 were partially grouted. 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 (Figure 46).

Figure 46 Typical Paniolo Club Condominium Three-Story Building, Waikoloa Village (Photograph by Gary Chock)

A number of localized but severe areas of damage occurred. The CMU at the tops of the gable-ended masonry walls suffered out-of-plane dislodgements, particularly at the roof beam pockets (Figure 47). In some cases portions of the wall fell out onto the grounds or onto the floor of the units. Many of these masonry units were found to be ungrouted and unreinforced (Figure 48). The most severely damaged buildings were red-tagged as unsafe due to the potential collapse hazard of the bearing walls and roof.

Figure 47 Out-of Plane Shear failures at the gable end CMU walls, Paniolo Club, Waikoloa Village (Photographs courtesy of Jeffrey Hanyu)

Figure 48 Dislodged CMU falling debris, Paniolo Club, Waikoloa Village (Photo courtesy of Mike Kasamoto)

In-plane and out-of-plane shear failure was observed at the base of the CMU pier supporting the intermediate stair landings (Figure 49). This wall was found to be grouted at the end cells, but apparently not in most of the main body of the wall. The stair was considered unsafe. Since this was one of the two stairs, the loss of the second fire exiting path of egress resulted in a red tagged status for the entire second and third floors, regardless of whether there was any additional damage to CMU bearing walls supporting the floors of the units. The potential collapse hazard of the gable end bearing walls resulted in a restricted use posting at the ground floor, allowing access to the ground floor for retrieval of possessions.

Figure 49 Exit Stair Support Wall with Spalled End Cells and Lateral Displacement In-Plane and Out-of-Plane (Photograph by Gary Chock)

Bank of Hawaii, Kapaau (Near Hawi*)*

The Bank of Hawaii building is a reinforced concrete structure built in 1909. The reinforced concrete walls of this single-story bank building support timber roof trusses spanning between the side walls. The ends of the roof trusses are pocketed into the concrete side walls. Horizontal cracks developed below the level of these roof truss pockets and diagonal cracks occurred at the buildings corners (Figure 50). This cracking pattern is very consistent for both side walls, which have an identical configuration with a series of five large openings. Lack of adequate diaphragm chord action at the roof level is thought to have allowed significant out-of-plane inelastic warping displacement of the side parapet walls above the openings. The bank is closed due to the falling hazards posed by the walls and the potential loss of support of the roof trusses. It is anticipated that the roof framing and parapets will be demolished and rebuilt to modern standards.

Figure 50 Horizontal and diagonal cracks in concrete walls of Bank of Hawaii in Kapaau, near Hawi (Photograph by Gary Chock)

Healthcare and Emergency Response Facilities

The healthcare facilities were significantly impacted, not by structural concerns, but by damage to their non-structural systems, principally T-bar lighting and ceiling systems and fire sprinkler systems. The large medical centers in the area are the Kona Community Hospital and the North Hawaii Community Hospital. The other two local hospitals, the Kohala Hospital in Kapaau and the Ka'u Hospital in Pahala sustained minor damage, mainly to non-structural elements and contents such as televisions and computer monitors.

Kona Community Hospital

The Kona Community Hospital is a 94-bed hospital (49 acute, 11 psychiatric, and 34 long-term care). Following the earthquake, all patients were evacuated, 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 Kona Community Hospital reported primarily non-structural damage in the form of fallen ceilings, light fixtures and other non-structural elements (Figures 51 and 52). These failures are attributed to the lack of adequate seismic bracing for non-structural components. The ceiling damage at Kona Community Hospital was to older lay-in suspended ceilings without seismic restraints, i.e., wire suspension with no diagonals or compression struts. 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-bars" to this perimeter angle. Ceiling damage was probably due to the ceiling either impacting the wall and locally buckling the T-bars or pulling of the T-bars off the ledger 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, and not hung off of nearby suspension wires, were bent down, also allowing tiles to fall and light fixtures to become dislodged. The attached picture shows both the studs running through and typical damage. Apparently no light fixtures completely fell from the ceiling. In addition to the tiles falling, bent support Ts, and partially dislodged light fixtures, decades of dust that was on the ceiling tiles were deposited over the rooms.

These conditions immediately after the main shock were exacerbated by a second shock 8 minutes later, and a decision was made to evacuate. When power was lost, the emergency generator was started. However, none of the elevators was on emergency power, and the evacuation was implemented down stairways. It was fully operational again approximately two weeks after the earthquake. All construction work had been completed in the facility's three operating rooms. One of these rooms was operational, with the other two still requiring further cleaning. The obstetrics unit was also re-opened and the long-term care patients were returned to the hospital. Structural damage consisted only of minor cracking of reinforced concrete framing.

Figure 51 Fallen Ceiling in the Operating Room, Kona Community Hospital (Photograph courtesy of Glenn Miyasato)

Figure 52 Ceiling Damage in a Medical Records Room at Kona Community Hospital (Photograph courtesy of William Holmes)

Medical Facility in Honoka‘a

The Hale Ho‘ola Hamakua facility provides 48 long-term care or nursing facility beds and two acute beds, in addition providing 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 non-structural 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.

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 no isolated by means of a gap from the surrounding walls. It is worth noting that 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 a 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. The failure of the cladding and soffit system appears to have been caused by an unintended earthquake load path in the structural system. The roof diaphragm consists of steel rod bracing that transfer load to the CMU shear walls on the perimeter of the building. However there is no direct, vertical load path between the roof and the walls, but rather the diaphragm rod bracing extends to the edge of the roof eave, goes down the face of the vertical cladding, and then wraps back to the CMU walls at the soffit level. It appears that the cement plaster and soffit system, being much stiffer than the rod bracing, carried the full seismic load until the connections failed, allowing the lath and plaster to fall. The exterior soffit system over the loading dock driveway, consisting of heavy cement plaster on metal lath, was apparently also unbraced (similar to the interior ceilings) and showed signs of pounding with the structural columns (Figure 53).

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.

Figure 53 Damage to exterior stucco ceilings at Hale Ho`ola Hamakua medical facility in Honoka'a (Photographs courtesy of Ian Robertson)

Schools and Libraries

Damage to the island's schools was estimated to be up to approximately $5 million, with most of the damage at Waikoloa Elementary, Honoka'a Elementary and Kohala Elementary schools. Along with a number of schools in Waimea and Honokaa, the elementary school in Waikoloa suffered considerable non-structural damage. Many classrooms were closed because of an extensive amount of fallen ceilings, light fixtures and other non-structural items. Virtually no structural damage was reported at these schools. The damage to Waikoloa Elementary, less than 10 years old, was primarily to the T-bar ceiling systems and light fixtures. The Honoka'a Elementary, an older school dating to the 1950s, sustained some 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.

Waikoloa Elementary School -- Waikoloa

This school is a modern, multi-building elementary school that was constructed in phases between 1994 and 2000. The buildings are one- and two-story concrete masonry unit (CMU) wall structures, with concrete slab-on-grade first floors and wood truss roofs with unblocked plywood sheathing. The buildings sustained essentially no structural damage, although the buildings appeared to be configured with discontinuous shear walls. The only observed structural damage consisted of some stepped cracking in the transverse CMU walls between classrooms, some cracking in the stairwells and pounding between a concrete bridge and the second story of Building H across a 1-1/2 inch wide seismic joint.

However the school did sustain significant damage to the suspended T-bar ceiling and lighting systems in almost all of the classrooms, the administrative offices and the library. Although the buildings are of recent construction, the ceiling systems were not laterally braced, did not have compression struts to prevent vertical movement, and were no isolated by means of a gap from the surrounding walls. 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. In most locations the light fixtures did have secondary support wires, but the wires were installed in some very unusual and ineffective ways, such as wiring to the corrugated, flexible electrical conduit. The vertical, braided hanger wires for light fixtures in the library snapped, allowing the fixtures to droop. Contents damage was minimal, including bookshelves which did not topple, and books staying on shelving. There was no damage to plumbing or piping.

Honoka'a Elementary School – Honoka'a

Honoka'a Elementary School is located on the northeast cost of the island and appears to have been built in the 1950s. Wind loads appear to have been the principal design consideration. The classrooms had ceilings with acoustical tiles that are glued to the underside of the roof framing, and pendulum light fixtures. The building sustained very little structural and non-structural damage. The structural damage consisted of cracking at the tops of some of the CMU walls were glulam roof girders bear.

Power Outages

Oahu and the entire City of Honolulu was unexpectedly placed in an island-wide power blackout when the earthquake triggered false low hydraulic fluid levels in level switches for the two largest generators at the main generating plant at Kahe on the west coast of Oahu. Nearly at the same time, operators manually shut down two other units representing 12% of the grid's capacity because the earthquake shaking was interpreted instead as turbine malfunction. A few minutes later, the false low fluid alarms caused automatic shutdowns of the two largest generators representing about 23% of the power capacity. With four main generators shutdown (two automatically and two manually) that had produced 35% of the grid's power, there was insufficient capacity of the remaining system to meet demand. This initiated a progressive sequence of manual 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 1225 megawatts had shutdown. HECO has since replaced the mercury switches with dry-contact switches less susceptible to ground shaking that will help mitigate against false triggering of shutdowns.

Power outages impaired public information and media communication efforts on the day of the earthquake. Eighty percent of Hawaii's radio and television stations did not broadcast due to a lack of emergency generators at either the stations or their transmitter sites. Cable Television and internet service were not available due to lack of emergency power. As expected, cellular telephone systems were overloaded. As a result, many residents were cutoff from important information sources, including State government, during the day of the earthquake. Honolulu International Airport was not operational on October 15th because it lacked sufficient emergency power.

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 simply 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 O'ahu could remain vulnerable to an island-wide blackout under similar circumstances in the future.

FEMA Response and Insurance

FEMA has a Pacific Area Office that is located in Honolulu, and representatives of that office were stationed at the State Emergency Operations Center within a few hours of the October 15 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 Hawaii. Government and nonprofit agencies will be eligible for reimbursement of 75 percent of their costs. In the weeks following the earthquake, FEMA and the State successively opened Disaster Recovery Centers in South Kona, Waimea, Honokaa, North Kohala, Hilo, and Na‘alehu. The centers provided information about aid available to residents affected by the Oct. 15 earthquakes. Individuals, households and businesses who registered by December 22, 2006 were eligible for federal loans of up to $200,000 and, for those who don't qualify for loans, grants of up to $25,000. As of mid-December, 2006, Individual Assistance of over $8 million in housing assistance was disbursed, together with about $13 million in loans to homeowners and renters, and over $2 million in loans to businesses. In the course of processing this aid, over 3,000 homes were inspected by FEMA. In Individual Assistance, a total of about $23 million had been approved for about 2,500 families and individuals. Public Assistance was estimated in mid-December to be over $22 million.

Earthquake insurance for homeowners is not generally offered on the island of Hawaii. For example, there are only about 120 homeowners insured for earthquake losses by State Farm in the state, and none of these are on the island of Hawaii. On the other hand, it is very common for homeowners throughout the state to have hurricane insurance, which is normally a requirement of lenders. Much of the damage to single family residences could have been avoided with anchorage and added shear wall retrofits to elevated floors on post and pier foundations. The state has a Loss Mitigation Grant Program for hurricane retrofits, in which homeowners may be eligible for 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., “Hawaii Dam Safety Guidelines: Seismic Analysis & Post-Earthquake Inspections”, Department of Land and Natural Resources, State of Hawaii, Circular C131, April, 2004.

Buchanan-Banks, J.M., “Structural Damage and Ground Failures from the November 16, 1983 Kaoiki Earthquake, Island of Hawaii”, U.S. Geological Survey Professional Paper 1350, Chapter 44, pp. 1187-1220, 1987.

Chock, G., and Sgambelluri, M., “Earthquake Hazards and Estimated Losses in the County of Hawaii”, Department of Defense, State of Hawaii, February, 2005.

Klein, F. W., Frankel, A. D., Mueller, C. S., Wesson, R. L., and Okubo, P. G. “Seismic Hazard in Hawaii: High Rate of Large Earthquakes and Probabilistic Ground-Motion Maps”, by, Bulletin of the Seismological Society of America, Vol. 91, No. 3, pp. 479-498. June, 2001.

Medley, Dr. Edmund W., “Geological Engineering Reconnaissance of Damage Resulting From the October 15, 2006 Earthquakes, Island of Hawaii, Hawaii, USA,” December 15, 2006.

Munson, Clifford G., and Thurber, Clifford H., “Analysis of the attenuation of strong ground motion on the island of Hawaii,” *Bulletin of the Seismological Society of America*; August; v. 87; no. 4; p. 945-960, 1997.

Robertson, I.N., Nicholson, P.G. and Brandes, H.G., “Reconnaissance following the October 15th, 2006 Earthquakes on the Island of Hawai’I”, Research Report UHM/CEE/06-07, University of Hawaii College of Engineering, Department of Civil and Environmental Engineering; 65 pp, October 26, 2006.

URS Group, Inc., “Developing a Hawaii 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., “Isoseismal Maps, Macroseismic Epicenters and Estimated Magnitudes of Historic Earthquakes in the Hawaiian Islands”, U.S.G.S. Bulletin 2006, 93, 1992.