Geological Engineering Reconnaissance of Damage Caused by the October 15, 2006 Hawaii Earthquakes

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ABSTRACT: *Two strong earthquakes shook the Island of Hawaii, Hawaii on the morning of October 15, 2006. Peak Ground Accelerations reached 1.2g, and earthquake felt intensity of MMI VIII. Earthquake damage of public and private property totaled about $200 million, with no fatalities. Geological engineering reconnaissance of earthquake damage resulting from the earthquakes focused on the apparent relationships between the observed geology and the damage. Some roadway embankments failed causing temporary closure of Island highways. Landslides were common at steep coastal cliffs. Liquefaction and lateral spreading occurred in coralline fill at Kawaihae Harbor. There were extensive road cut failures, in which the performance of road cuts in soil slopes was generally better than that of rock slopes. Where a'a clinker underlay massive a'a basalt blocks in road cut slopes, the loose clinker dislodged thereby undermining the blocks, and causing failures that blocked important roads. There was serious damage to stacked rock edifices such as the Hawaiian ritual temples of Pu'ukoholā and Mailekini. There are some parallels between the geomechanical behavior of clinker rock masses and the behavior of stacked rock structures: slope angle, slope height, particle size and nature and proportion of inter-particle contacts govern the seismic performance for both.*

KEYWORDS: Geological Engineering, Hawaii, Earthquake Damage, Rock Mass, Basalts, Rock Block Structures

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

ONLINE DATABASE: Geographically positioned supplemental photos

INTRODUCTION

A geological engineering reconnaissance was performed to observe damage resulting from the October 15, 2006 earthquakes that strongly shook the Island of Hawai'i, in the State of Hawaii, USA. The principal observations reported in this paper are related to the failure of road cut slopes, landslides, and the failure of stacked rock structures. Since fuller detail of the failure of buildings, bridge structures and approaches has been presented by Robertson et al. (2006) and Chock (2006), only a few observations of damage to these features are presented here.

Most paved highways on the island were traveled at least once during the reconnaissance and about 40 stops were made for observations (Figure 1 and Table 1). The latitude and longitude coordinates of each stop were recorded using a hand-held GPS receiver. Table 1 lists the locations of the stops, their coordinates, and other information. Several locations known to have been damaged by the earthquakes (e.g. Waimea area dams and the Palolo Valley Lookout) were not visited due to a lack of formal permissions. However, entry was granted by the National Park Service to observe the perimeters of the badly damaged stacked rock edifices of the Pu'ukoholā and Mailekini heiaus, located immediately south of Kawaihae.

Some photographs were taken in stereo (two photographs taken with considerable overlap) to facilitate subsequent analysis and exposition in 3-D (dimensions) as described by Medley (2007). Examples of 3-D stereo images are provided here where they offer more information. Stereo images are shown as side-by-side stereographs, requiring stereo glasses such as those used for air photo analysis; and as red-cyan anaglyphs, which require red/cyan anaglyph glasses from 3-D stereo photography suppliers (Medley, 2007).

This paper was initially presented as a report (Medley, 2006) prepared for the Geo-Engineering Earthquake Reconnaissance

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(GEER) Association and Earthquake Engineering Research Institute (EERI) to augment contributions by Robertson et al. (2006) and Chock (2006).

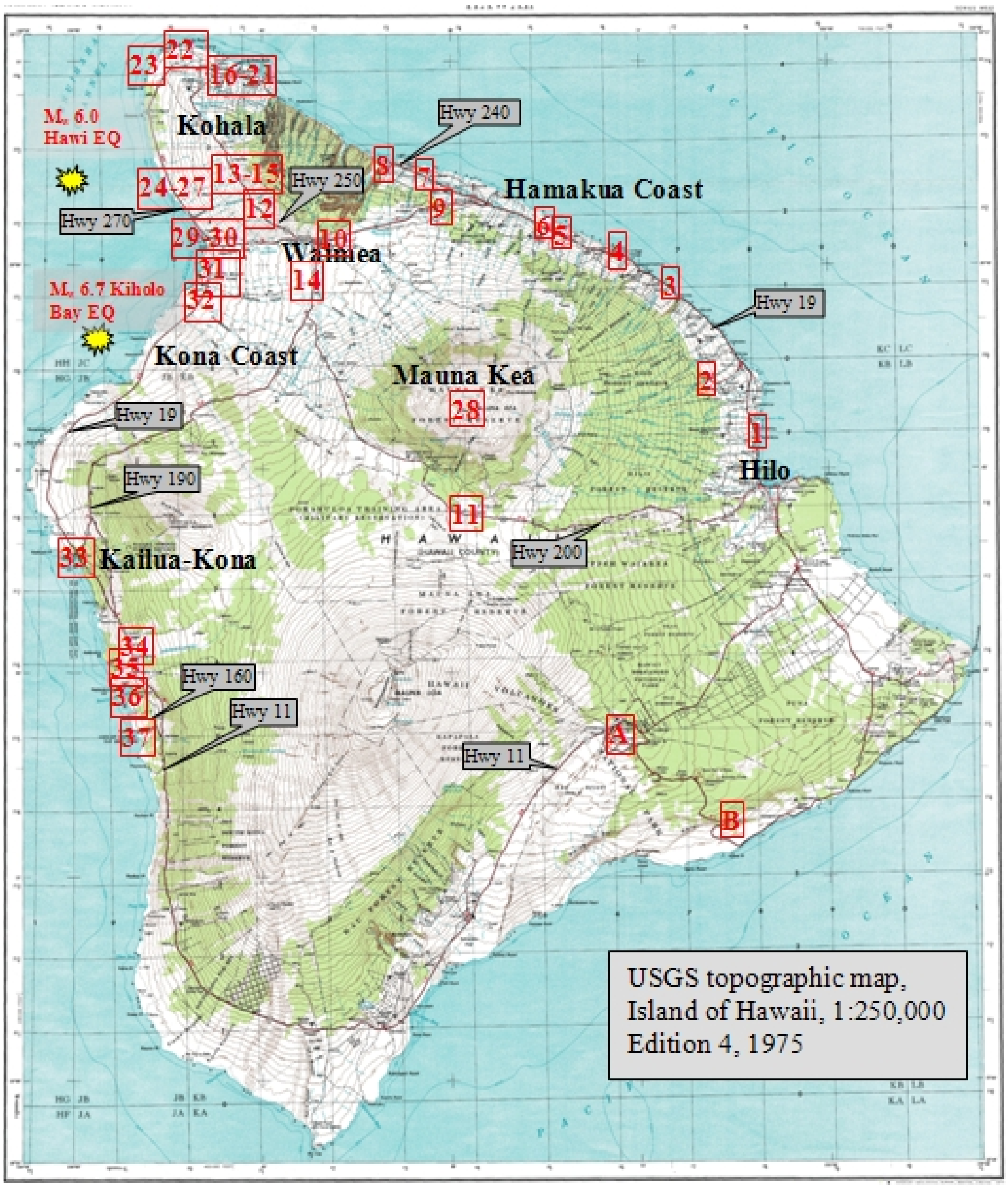


Figure 1. Locations of M_w6.7 Kiholo Bay and M_w6.0 Mahukona (Hawi) earthquakes of October 15, 2006. Also shown are the numbered locations of observation stations and route numbers of Highways referred to in text and Table 1.

Table 1. Reconnaissance Locations and Observations
(locations positioned in the International Journal of Geoengineering Case Histories geographic database)

Sta.	Location	Lat. (N degs)	Long. (W degs)	Feature	Comments
A	Hawaiian Volcano Observatory - Volcanoes Nat. Park	19.4203	-155.2880	Seismograph record of Kihilo Bay EQ	Advised by Park personnel that no damage other than minor rock falls or trails; no damage at Observatory.
B	Volcanoes Nat. Park: Chain of Craters Road	19.3149	-155.1285	Pāhoehoe sequences exposed in high road cut	In Aug 2006: observed almost vertical cuts in pāhoehoe sequences; assume no significant EQ failures according to Park personnel
1	Onomea Scenic Drive	19.8059	-155.0919	Road cut slide	Typical of many slides any seen along Scenic Drive, traffic coned.
2a	Pepe’ekeo Sugar Mill	19.8439	-155.0854	Sugar mill stack	(Stack fell at Kapa’au). Stack standing,; nearby Lighthouse too.
2	Akaka Falls State Park	19.9540	-155.1549	Fresh scars at Falls	Scars due to landslides caused by EQ? EQ caused trees to topple, which damaged railings at Park.
3	S. of Kepehu Camp	19.9571	-155.1971	Road cut slides	Slides within pre-existing slide bounds; 3-5 foot thick slides; soil failed over weathered rock.
4a	Laupāhoehoe Harbor “Tidal Wave Memorial” Park.	19.9920	-155.2406	Site of 1946 fatal tsunami	No damage observed at Park.
4	Near Ōōkala, old road beneath Hwy 11 bridge	20.009	-155.2867	Road cut slides	Soil slope failed across road? Top 1/3 of slope.
5	Near Kūka’iau, Hwy 11, MP 32	20.0273	-155.3394	Road cut slides	Several small slides not contained by pre-existing netting??
6	Near Pa’auilo, MP 35, Hwy 11	20.0328	-155.3545	Embankment at bridge abutments	Fill at south approach to bridge failed; half of roadway fell into stream
7	Near Kupalena, Hwy 240, Honoka’a-Waipi’o road	20.1067	-155.5373	Lava tube	Little rock fall within cave despite 10m wide roof span, 5 m high roof and abundant fractured rock exposed at cave surfaces.
8	Waipi’o valley access road	20.1165	-155.5875	Rock fall	Sole rock fall seen on very steep 4x4 access road, high road cut slope.
9	Honoka’a-Waimea, Hwy 19	20.0711	-155.4942	Rock fall	Active rockfall clearance; tree roots in rock fractures.
10	East side Waimea, Hwy 19	20.0456	-155.5866	Landslides (?)	Unknown if these fresh scarps are result of EQ: many observed.
11	Saddle Road (Hwy 200) near intersection w/	19.6931	-155.4929	Rock wall (intact)	Intact rock walls built of loosly stacked a’a clinker blocks, across extensive a’a

Sta.	Location	Lat. (N degs)	Long. (W degs)	Feature	Comments
	Mauna Kea Road				clinker lava surface.
12	Scenic Lookout Kohala Mt. Road (Hwy 250)	20.0704	-155.7599	Views of Waimea-Kona coast-Kohala coast	Much of the coast was impacted by EQs.
13	Near Scenic Lookout, Kohala Mt. Road (Hwy 250)	20.0719	-155.7608	Road cut (intact)	Little evidence of slope failures: massive cut, >100 feet (30 m) high in volcanic ash/tuff.
14	Kohala Mt. Rd. (Hwy 250)	20.0807	-155.7632	Road cut failure	Typical of many road cuts observed along the highway, in mixed a'a clinker/massive basalt.
15	Hwy 250, Mile Post 9.34, bridge over Kawaihae Uka; for > 100 m north of bridge	20.0902 to 20.0910	-155.7675 to -155.7689	Embankment failure (north of bridge)	Failures at top of road embankments, adjacent and north of bridge on down slope side of road; conspicuous scarps and extension of tops of slope; narrow to no roadside shoulder (bridge/road was temporarily closed after EQs).
16	Hwy 270 east of Kapa'au	20.2288	-155.7892	Soil cut failures	Detrimental effects of tree roots in soil failures; slide surfaces often revealed tree roots
17	Hwy 270 east of Kapa'au	20.2206	-155.7539	Soil cut failures	Detrimental effects of tree roots in soil failures.
18	Hwy 270 Makapala area	20.2089	-155.7388	Rock cut failures, embankment failure	Road cut failure of fractured/well broken angular basalt underlain by residual soil/ Soil has prominent baked zone at contact with overlying rock; and abundant core stones. Failures occurred in upper rock. On opposite side road, significant slope cracking ans slope failure scarps at top of high, steep embankment.
18a	Hwy 270 Makapala area, Waiapuka Gulch bridge	20.2083	-155.7390	Intact bridge adjacent road cut/embankment failures	No evidence of distress at bridge though abutment approach fill has tensions cracks.
19	Kēōkea Beach Park	20.2276	-155.7453	Sea Cliff failures	Large blocks of cliff top slid down cliff faces, includes block to west at headland of Kēōkea Bay.
19a	Kēōkea Beach Park	20.2272	-155.7456	Pavilion failure	Structure "red tagged" as unsafe. Cracked pavilion

Sta.	Location	Lat. (N degs)	Long. (W degs)	Feature	Comments
					columns.
20	Hwy 270 Mile Post 27.3, Bridge 407	20.2204	-155.7483	Bridge failure	Thrust road pavement; abutment fill problems; bridge damage includes widening (?) of old cracks.
21a	Kapa'au; King Kamehameha statue	20.2306	-155.7985	Structure Intact	No apparent distress to famous statue.
21	Kapa'au; Kalāhikiola Church (1855)	20.2227	-155.7946	Structure failure	Ungrouted rock in weakly cemented stacked rock walls failed; extensive damage
22	Road to Upolu Airport	20.2609	-155.8556	Structures intact	9 of 16 windmills working and Silos still standing. Any windmills damaged?
23	Ala Kahaki trail between Honoipu Landing and Parking area at Puakea Point	20.2437	-155.889	Sea cliff failures	Cracks in cliff top; failures in weathered clinker; failures of rock structure below asphalt parking lot at rock walls.
23a	Lapakahi Heritage Park	20.1743	-155.8995	Structures intact	According to docent: no distress to historic Hawaiian village except minor wall failures; no damage observed.
24	Mile Post 8 Hwy 270, south of entrance Kohala Ranch Estates	20.0743	-155.8561	Rock cut failures, embankment failure?	Raod cut failures in mixed a'a clinker/massive basalt. Also possible embankment failure.
25	Hwy 270 north of Kawaihae, near entrance Kohala Estates	20.0653	-155.8482	Rock cut failures	Extensive road cut failures, some retreat of road cut crest toward structure??
26	Honokoa Gulch bridge, Hwy 270 Mile Post 4.98	20.0515	-155.8393	Bridge failure	Bridge distress ocean side; minor failure of approach fill south side.
27	Kawaihae Small Boat Harbor	20.0394	-155.8311	Lateral spreading, liquefaction, boils	Much evidence of liquefaction and lateral spreading.
28	Mauna Kea Keck Observatory	19.8260	-155.4747	Structure damage,	Some damage observed to stucco at Keck Observatory; none obvious at adjacent high crib retaining wall.
29	Pu'ukoholā Heiau, National Monument, south of Kawaihae	20.0281	-155.8231	Failures of stacked rock block edifices	Overview of Pu'ukoholā and Mailekini heiaus from Kamehameha Royal compound
29-1	Pu'ukoholā heiau south side	20.0273	-155.8213	Stacked rock block slopes	South side relatively intact
29-2	Pu'ukoholā heiau: east side, NE corner	20.0279	-155.8213	Failures of stacked rock block slopes	East side and NE corner, major bulging, slumping and raveling failures

Sta.	Location	Lat. (N degs)	Long. (W degs)	Feature	Comments
29-3	Pu'ukoholā north side	20.0279	-155.8216	Failures of stacked rock block slopes	North side; most damage is to collapsed access stairs; see pre-EQ photo: http://www.pacificworlds.com/kawaihae/native/images/heiau3.jpg
29-4	Pu'ukoholā heiau west side heiau, SW and NW corners	20.0276	-155.8217	Failures of stacked rock block slopes	West side, SW and NW corners: slumping and bulging failures
29b (east)	Mailekini Heiau, Kawaihae, east side	20.0276	-155.8219	Failures of stacked rock block slopes	East wall exterior shows some bulging and slumping;
29b (west)	Mailekini Heiau west face, SW corner	20.0283 to 20.0275	-155.8222 to -155.8224	Failures of stacked rock block edifice	NW corner, west side and interior face east wall: extensive slumping failures. See pre-EQ appearance at: http://www.pacificworlds.com/kawaihae/native/images/mailekn3.jpg
30	Spencer Beach Park, south of Kawaihae	20.0245	-155.8226	Deformed cemented stacked rock block wall	Bent free-standing rock wall; formed from two panels of grouted rock blocks. Bending and block missing near base: evidence of recent EQ damage? No other deformed walls seen, but no other wall are free standing.
31	Mauna Kea Hotel South side	20.0040	-155.8237	Structure damage	Extensive EQ damage at south end of building; hotel subsequently closed. Terrain flat.
32	Hwy 19, Queen Ka'ahumanu Hwy	19.9570	-155.8260	Road cut failure	Cut slopes to 90 degrees. Failures typical of raveling a'a clinker; undermined massive blocks failed into highway
33a	Hulihe'e Palace, Kailua Kona	19.6393	-155.9944	Structure failure	Cracks at exterior; could not access property.
33b	Moku'aikua Church, Kailua- Kona	19.6397	-155.9942	Structural failure of cemented rock walls; and intact stone boundary walls	Cracks at exterior, recently repaired; grouted rock masonry; intact rock boundary walls in Hawaiian rock wall style. Intricate arrangements of blocks of walls provide intimate block-to-block contacts.
34	Kealakekua, Hwy 11	19.5306	-155.9253	Rock wall failure	Failed wall adjacent private property.

Sta.	Location	Lat. (N degs)	Long. (W degs)	Feature	Comments
35	Captain Cook, Hwy 11	19.5006	-155.9200	Rock wall failures	Failed walls adjacent private property: typical of the few seen.
36	Napo'opo'o Beach Park	19.4753	-155.9196	Sea cliff failure	Views of failures (in poor light) spawned from old landslide scarp (Pali Kapu o Keōua, head of Alika landslide; 100k to 105k yBP). See view of landslide occurring: http://www.flickr.com/photos/konaboy/270510964/
37	Hwy 160, near City of Refuge	19.4229	-155.8996	Intact slopes	Intact slopes in pāhoehoe; rock wall under construction.

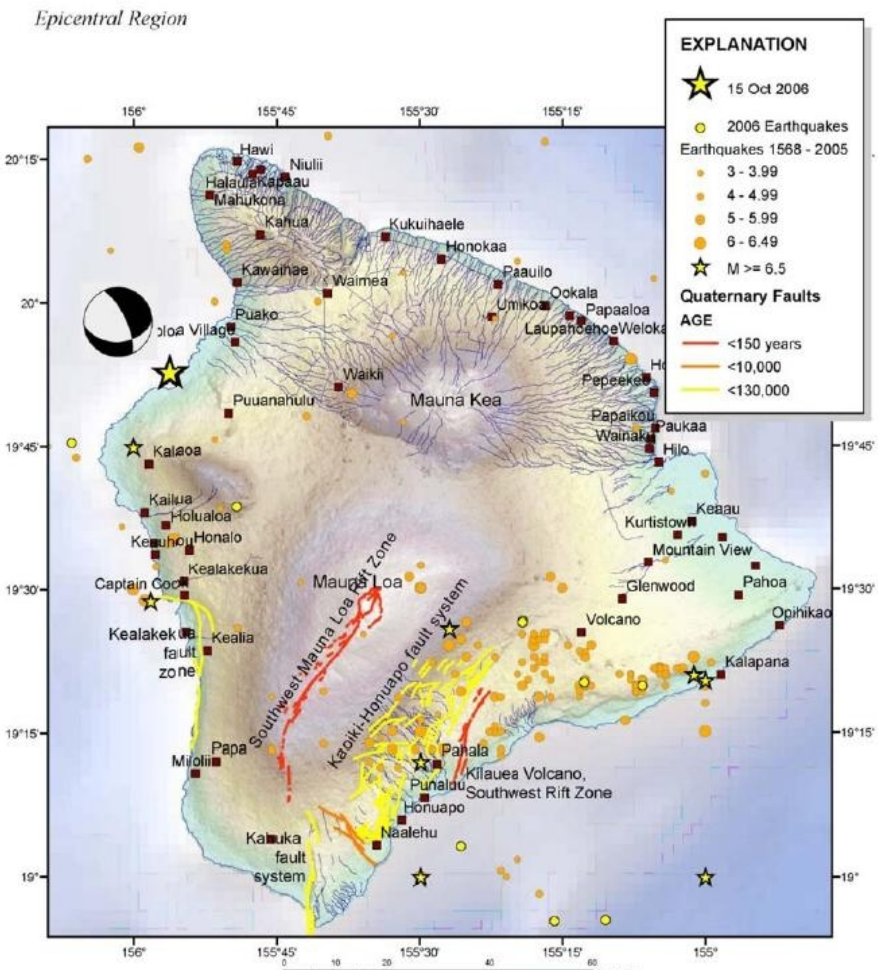


Figure 2. The Island of Hawai'i: locations of towns, volcanoes, principal historical earthquakes, major faults and Kiholo Bay M_w6.7 earthquake of October 15, 2006. (Chock, 2006; after USGS).

GENERAL SEISMICITY OF THE ISLAND OF HAWAII

Even when not directly related to eruptions, most Hawaiian earthquakes are broadly related to volcanic activity (USGS, 2006a). Being less than about 1 to 2 million years old, Hawai'i (Figure 1) is the youngest island in the Hawaiian chain, and is still growing, erupted lavas originating from a deep magma source beneath the crust (USGS, 2006a). The island is formed from the merging of basalt rocks produced by the island's five volcanoes: Kohala, at the north, being the oldest and Kilauea, at the south, being the youngest. Kilauea is the source of current eruptions at the southwest portion of the island. The other three volcanoes are Hualalai, Mauna Kea, and Mauna Loa (Figure 2).

Historically, the largest earthquakes in Hawai'i have occurred at shallow depths (approximately 10 km), beneath the flanks of active volcanoes (Figure 2), as magma moves prior to or during volcanic eruptions. However, non-volcanic earthquakes, such as the October 15 events, release longer term lithospheric stresses accumulated in the crust by the gradual loading of the volcanic edifices (Chock, 2006; USGS 2006a).

The ground shaking hazard of the Island of Hawai'i ranks among the highest in the United States and earthquakes on the on the island are relatively common. The largest earthquake on record occurred in 1868, had a magnitude of 7.9 and occurred near the south coast. It produced a tsunami that drowned 46 people and caused numerous landslides that resulted in 31 deaths (USGS, 2006a). A magnitude 6.9 earthquake on August 21, 1951 damaged scores of homes on the Kona coast (Figure 1) and caused numerous damaging landslides (USGS, 2006a).

CHARACTERISTICS OF OCTOBER 15 2006 EARTHQUAKES

At 7:07:48 a.m. (local time) on Sunday October 15, 2006 an M_w 6.7 earthquake struck off-shore of the west coast of the island of Hawai'i. The earthquake originated at N19.878°, W155.935°s and a focal depth of about 39 km (24 miles) (USGS, 2006a), and generated strong motions for about 20 seconds (Chock, 2006). The epicenter was about 11 km (7 miles) north-northwest of Kalaoa, in Kiholo Bay (Figure 1, Figure 2, Figure 3), 99 km (62 miles) from Hilo and 250 km (155 miles) from Honolulu (Figure 3). The Kiholo Bay earthquake occurred on a normal fault (Chock, 2006).

Numerous aftershocks occurred, including a M_w 6.0 event at 07:14 a.m. at N20.129°, W155.983° and a focal depth of 19 km (12 miles), referred to as the separate "Hawi" earthquake (Figure 1, Figure 3 and Figure 4) by Robertson et al (2006) and as the "Mahukona" earthquake by Chock et al, 2006 (their Figure 1). The latter earthquake generated strong motions for about 15 seconds. According to Chock (2006) the difference in depths and epicenters suggest that the Kiholo Bay and Mahukona events were seismically separate.

According to Chock (2006) strong motion (SM) data from 12 dialup sensors (Figure 4), operated by the USGS National Strong Motion Project (NSMP), were transmitted to a USGS server in Menlo Park, California, operated by the Advanced National Seismic System (ANSS), but were not incorporated into any USGS automated event processing. Data from three recently installed ANSS SM stations on Hawai'i 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 Accelerations (PGA) for the 12 SM stations on Hawaii are shown on Figure 4. (The PGAs and other seismic parameters are listed in Table 1 of Chock (2006) for the Kiholo Bay earthquake and Table 2 of Chock (2006) for the Mahukona earthquake). Figure 5 illustrates example ground accelerations at the Waimea Fire Station SM instrument (Figure 4) for the Kiholo Bay and Mahukona earthquakes.

Soil type conditions vary at SM sites on the island, which has rock close to or at the ground surface. However, there is relatively thick soil development along the Hamakua Coast, the side of the island with most windward exposure and subject to frequent and heavy tropical rainfalls. Soil is also well developed in the northeast part of the Kohala area on the oldest, thus most weathered, Hawai'i rocks. There are also scattered areas underlain by thick deposits of volcanic ash. The soil-covered areas would tend to amplify the earthquake shaking, depending on the intensity (Figure 4). For example, Waimea Fire Station (PGA 1.2g) is located in an area of volcanic ash deposits Soil Type SD (Figure 4) which has been observed to double the ground accelerations (Buchanan-Banks, 1987, URS, 2006). The Kealakekua Kona Hospital (PGA 0.52g) and Honokaa Police Station (PGA 0.65g) SM instrument sites are also underlain by Soil Type SD, as also evident in Figure 4. But a lower PGA of 0.27g was recorded at the Kailua-Kona Police station SM site, closer to the Kiholo Bay earthquake epicenter than the Kealakekua SM site, but on the stiffer SB Soil Type (Figure 4).

As shown on Figure 6, the strongest shaking (MMI VII-VIII) and damages resulting from the October 15 earthquakes was concentrated on the western Kona Coast, the northern Kohala region, and the northeastern Hamakua Coast, north of Hilo, (Figure 1 and Figure 2). The felt effects of the smaller Mahukona earthquake (aka Hawi earthquake by Robertson et al, 2006) were reported to be "...as severe as, or even worse, than those of the Kiholo Bay event" (Robertson et al, 2006), possibly due to the shallower focal depth (Chock, 2006).

Shaking from the Kiholo Bay earthquake (Figure 6) and subsequent shocks were felt elsewhere in the State and damage was reported at the eastern end of the island of Maui, located northwest of Hawai'i. The earthquake effects also included loss of electrical power on Maui and Oahu. The cumulative damage attributed to the earthquakes was estimated by Chock (2006) to be about $190 million in December 2006.

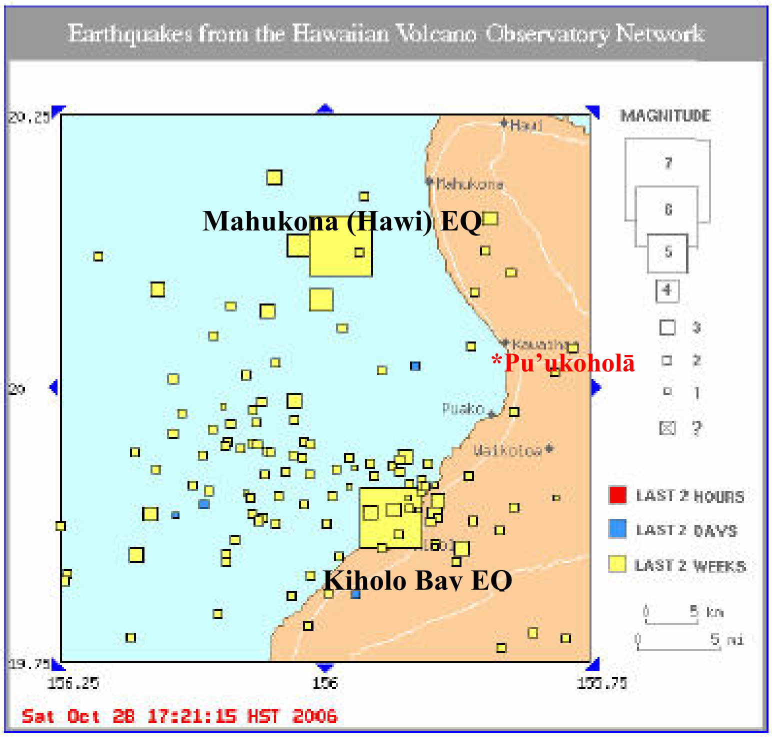


Figure 3. Locations of Kiholo Bay M_w6.7 and Mahukona (Hawi) M_w6.0 earthquakes of October 15, 2006 (after Chock, 2006; after USGS-Hawaiian Volcano Observatory) and location of Pu'ukoholā heiau (and Mailekine heiau) south of Kawaihae.

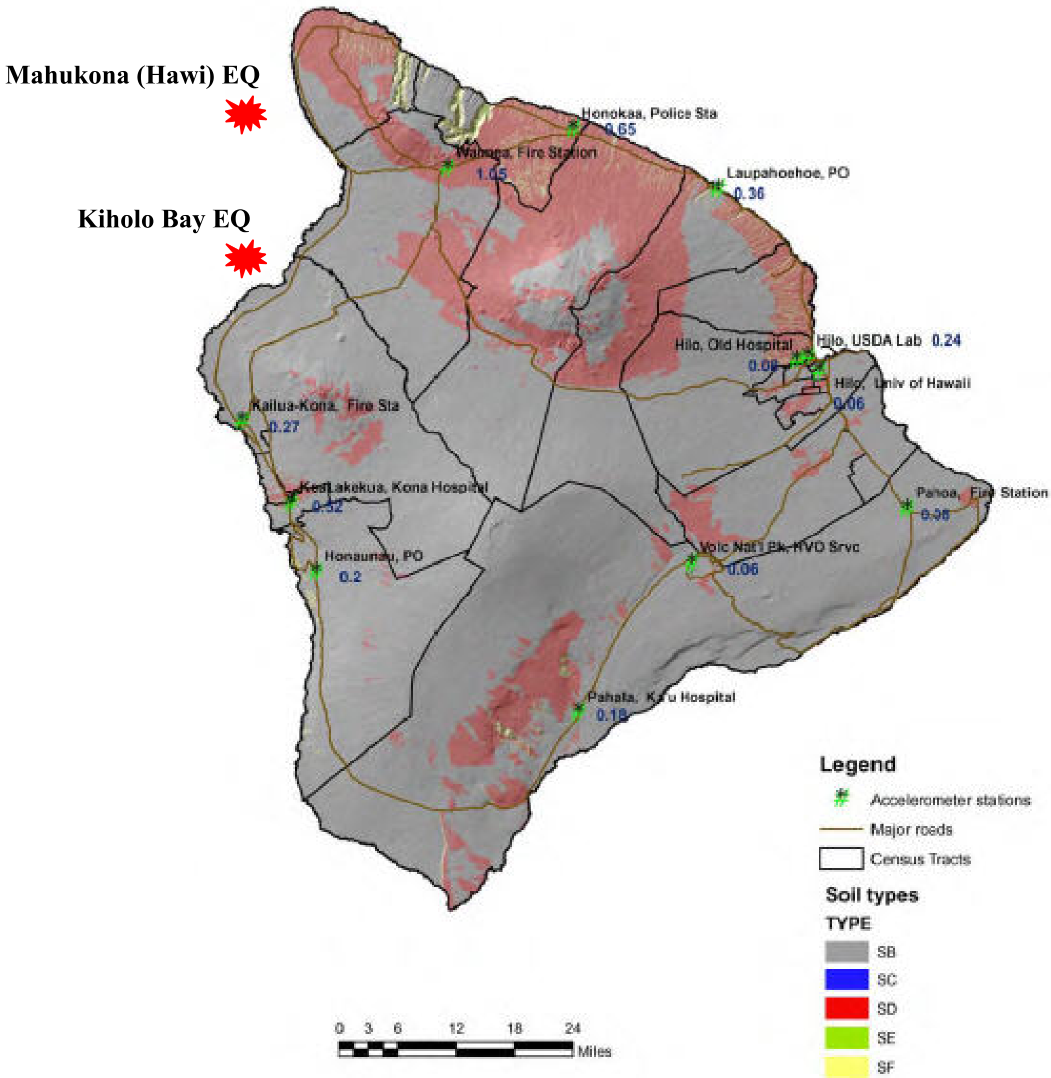


Figure 4. Locations of Kiholo Bay and Mahukona earthquakes and locations of dial-up strong motion instruments on Island of Hawai'i; shows also the Peak Ground Accelerations (blue text) for Kiholo Bay earthquake. The Uniform Building Code (UBC, 1997) Soil Profile Types are as presented by Chock (2006) (after URS, 2006) based on a compilation of soil boring data and geologic maps. Gray (SB) is Rock with V_s 760 m/s to 1,500 m/s; red (SD) is Stiff Soil V_s<180 to 360 m/s; and green (SE) and yellow (SF) are weaker soils.

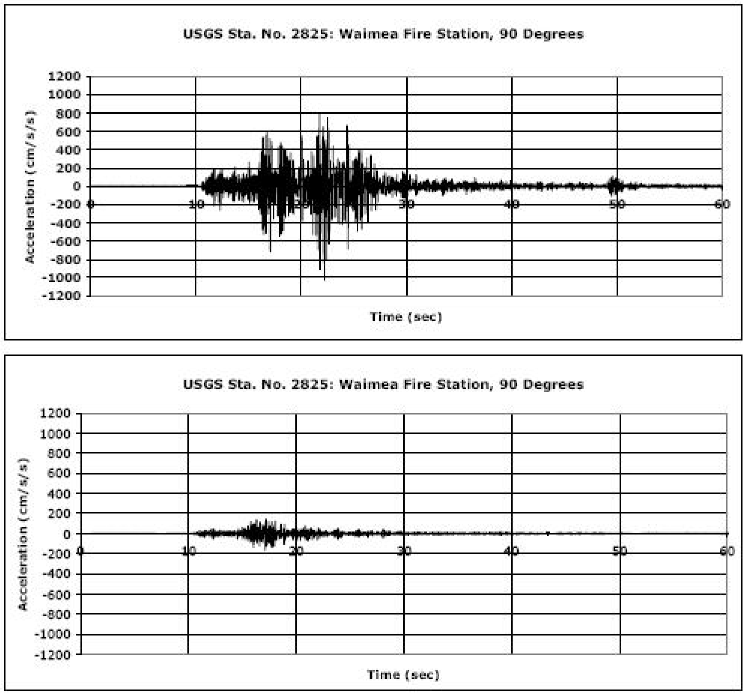
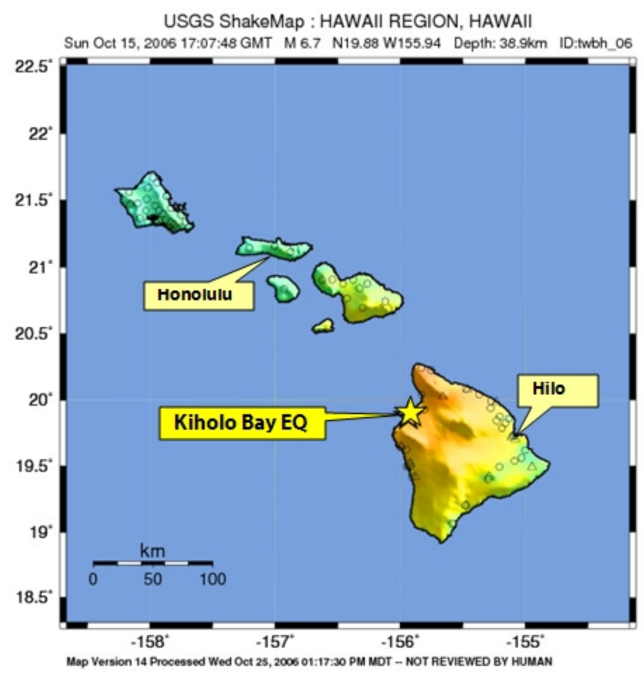


Figure 5. Ground accelerations recorded at (top) Waimea Fire Station during the M_w 6.7 Kiholo Bay and (bottom) M_w 6.0 Mahukona (Hawi) earthquakes (Robertson et al, 2006).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
POTENTIAL DAMAGE Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
ESTIMATED INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6. USGS ShakeMap for the M_w6.7 Kiholo Bay earthquake (after USGS, 2006b).

FAILED ROCK ROAD CUT SLOPES

Most of the reconnaissance was performed along Island highways (Figure 1) between six to nine days after the earthquake, and after most of the more disruptive road cut slides had been cleared. However, despite the greater proportion of highway alignments being within cuts, there were relatively few significantly failed road cuts.

In general, slope cuts are steep in Hawai'i: even in soils, the slopes exceed 45 degrees inclination (Figure 7 and Figure 8) and many almost vertical slopes were observed in deep cuts. Based on the reconnaissance, there appeared to be strong relationships between slope heights, geology and the occurrence of failures. That rock falls from road cuts are apparently common on the Island as was evident by the many highway signs warning of "Rock Fall".

Generally, Hawaiian basalts are either a'a or pāhoehoe. (In the Hawaiian language, the word aa is correctly spelt a'a, and pronounced "ah-ah", with the apostrophe being a glottal stop, or slight pause. Accented letters in Hawaiian words, such as the "ā" in pāhoehoe, are stressed.)

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 and boulders in size (Figure 9). A'a clinker commonly surrounds discontinuous and contorted massive inclusions of irregularly fractured, extremely strong basalt (Figure 1 and Figure 11). Road cuts tend to be very steep, and generally require blasting, which induces mechanically-induced fractures in the massive rock inclusions additional to the natural discontinuities

There is a considerable difference in the mechanical properties of the a'a clinker and massive basalt. During the earthquakes, loose a'a clinker raveled, removing support from the overlying massive blocks, some of which failed during the earthquakes as shown by Figures 9 through Figure 17 (includes 3-D stereo versions). It was the large and heavy blocks, rather than the soil-like clinker, that represented the greater hazard to traffic, and required greater effort to move. Consequently, where heavy equipment was not immediately available, fallen large rock blocks obstructed roads for longer periods than the finer debris.

Figure 7. Hwy 270, Station 18, near Kēōkea Bay Beach Park access road. Highway was blocked by rock falls after the earthquakes.

The other major form of basalt in Hawai'i is pāhoehoe, often known as "ropey lava" (Figure 18). Being less viscous than a'a lava, pāhoehoe flows tend to be thinner. With smoother or inter-flow contact surfaces, there is also considerably less clinker and a greater proportion of massive rock. Hence, road cuts in pāhoehoe are generally more stable than those in a'a sequences (Figure 19 and Figure 20), although relatively few road cuts in pāhoehoe sequences as fresh as those illustrated were observed. Rockfall from cuts in obvious pāhoehoe sequences were relatively isolated blocks of rock.

At Location 13 on Hwy 250, (Milepost 8, Kohala Mountain Road) a very high and steep road cut appeared to have sustained little to no distress during the earthquake (Figure 21). The rock is a pyroclastic assemblage of welded volcanic ash and other volcanic debris (Figure 22).

Lava tubes are common in pāhoehoe. One lava tube beside Highway 240 (Figure 23) showed little apparent disruption of wall and roof rock mass, despite a span of about 10 m, height of to 3 m and the fractured rock exposed at the cave surfaces. The degree of rock mass failures in caves and tunnels due to the earthquake is unknown. The vulnerability of tunnels to rockfall during large earthquakes is an important lifeline issue given that Statewide, many water supply routes occupy tunnels. Water supply to the Waipio area was interrupted by collapse of a major ditch in the Kohala area, according to news reports.

Figure 8. Failed rock cut: massive a'a block undermined by raveled a'a clinker (Chock, 2006; after Robertson et al, 2006).

Figure 9. Location 11, Saddle Road (Hwy 200). Lava flow of a'a clinker and dry stacked wall of clinker composed of a'a blocks.

Figure 10. Location 32, road cut at Hwy 11. Massive basalt in a'a flow.

Figure 11. Location 32, Hwy 11. Failure of massive basalt blocks overlying weaker rock (weathered a'a clinker and baked zone).

Figure 12. Location 2, near Kohala Ranch Estates, Hwy 270. View from road of excavation in mixed massive a'a and clinker. See stereo 3-D photographs of Figure 13 and Figure 14.

Figure 13. Location 25, near Kohala Ranch Estates, Hwy 270. 3-D stereo pair version of Figure 12. Road cut in mixed massive a'a and clinker.

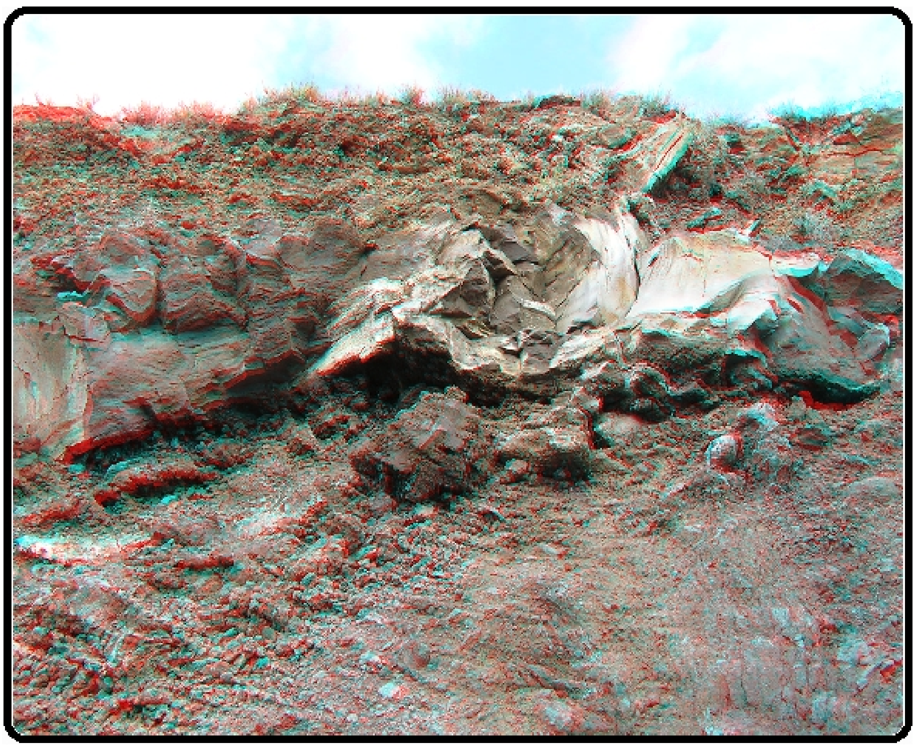


Figure 14. Location 2, near Kohala Ranch Estates, Hwy 270. Anaglyph 3-D image version of Figure 12. Road cut in mixed massive a'a and clinker.

Figure 15. Location 25, Hwy 270 north of Kawaihae. Cantilevered block of massive a'a basalt, undermined by clinker that raveled during the earthquakes. See 3-D stereo images of Figure 16 and Figure 17.

Figure 16. Location 25, Hwy 270 north of Kawaihae. 3-D stereo pair version of Figure 15. Cantilevered block of massive a'a basalt, undermined by clinker that raveled during the earthquakes.

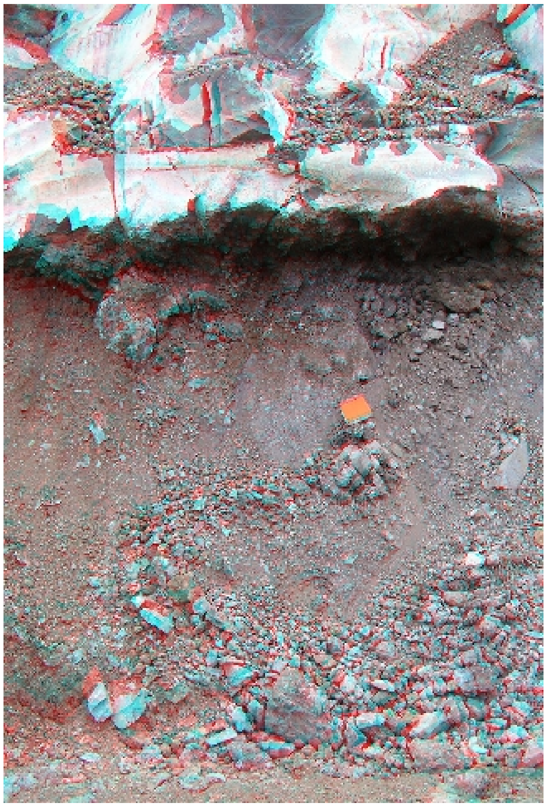


Figure 17. Location 25, Hwy 270 north of Kawaihae. 3-D anaglyph stereo version of Figure 12. Cantilevered block of massive a'a basalt, undermined by clinker that raveled during the earthquakes.

Figure 18. Vicinity Location B, Hawaii Volcanoes National Park. Pāhoehoe basalt (ropey lava).

Figure 19. Location B, Hawaii Volcanoes National Park. Stacked sequence of pāhoehoe lava flows with lava tubes (small dark cave openings in cut).

Figure 20. Location 37, Hwy 160. Pāhoehoe in road cut.

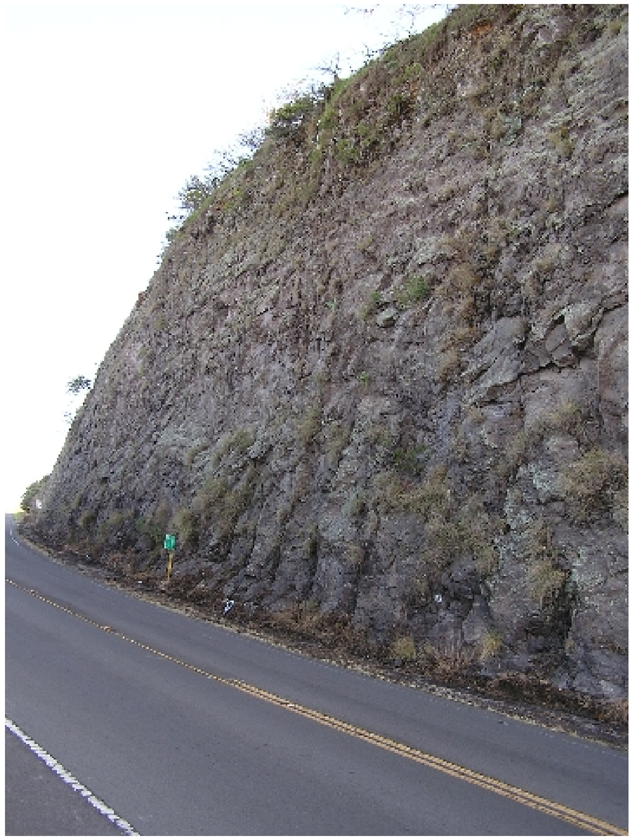


Figure 21. Location 13, Milepost 8, Hwy 250. Stable steep and high road cut.

Figure 22. Location 13, Milepost 8, Hwy 250. Road cut in a pyroclastic assemblage of ash and other volcanic debris.

Figure 23. Location 7, Hwy 240, near Kapulena, north of Honokaa. Lava tube with apparently little rock fall from roof and walls.

FAILED SOIL ROAD CUT SLOPES

Soil development on the island of Hawai'i is most apparent at the older northern end of the island (Kohala region) and along the wetter eastern side (Hamakua Coast) (Figure 4). For the purposes of this paper, and using a commonly understood definition, "soil" is the material that can be excavated by conventional earthwork equipment. Accordingly, moderately to completely weathered rock is considered soil, a range which includes residual soil and saprolites, which to varying degrees preserve a rock-like appearance and the legacy of the original rock mass discontinuities. Such soils thus have the worst qualities of both geo-materials: the weakness of soil and the built-in potential failure surfaces resulting from weathered rock discontinuity surfaces.

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 (Figure 11 and Figure 24), in a fashion similar to that above described for a'a/massive basalt sequences.

Many small slides of soil were observed during the reconnaissance, although the majority of these were generally of a few cubic meters in volume only. It is unknown what proportions of the observed failures were directly related to the earthquakes; subsequent common, and frequently heavy, tropical rainfall; and, the combination of these factors. Many road cut soil slides were observed to have occurred within larger and older failure features. As indicated above, soil slopes were generally inclined as steeply as rock cuts, greater than 45 degrees (Figure 25).

Composite slopes, where soil overlay rock or weathered rock, generally showed failure of the soil only (Figure 26). Where the soil/rock profile varied laterally at road cuts, failures predominated in the soil sections.

Weathered rock was often found to have failed along fractures occupied by tree roots. Where slopes had been stable long enough for tree roots to take hold in fractures, sections of the slopes peeled off to expose the roots (Figure 27, and Figure

28). The waving of trees due to prolonged shaking may also have contributed lateral loading to the failed veneers. However, within less weathered rock the presence of tree roots within joints was less effective (Figure 29).

Moderately to highly weathered rocks, in which hard blocks of rock are surrounded by weaker soil (Figure 24 and Figure 26); or rock masses composed of massive blocks of basalt within a'a clinker matrix (Figure 11) are complex geological mixtures. As described by Medley (1994), such rock/soil mixtures have a block-in-matrix rock ("bimrock") fabric when the blocks are larger than about 5 percent of a characteristic dimension indicating the scale of engineering interest (such as the height of a road cut) and have an appreciable volumetric proportion. The seismic response of a slope composed of blocks of rock surrounded by weaker matrix is as yet poorly understood, despite the common and worldwide occurrence of road cuts in rock/soil mixtures. Further research is warranted.

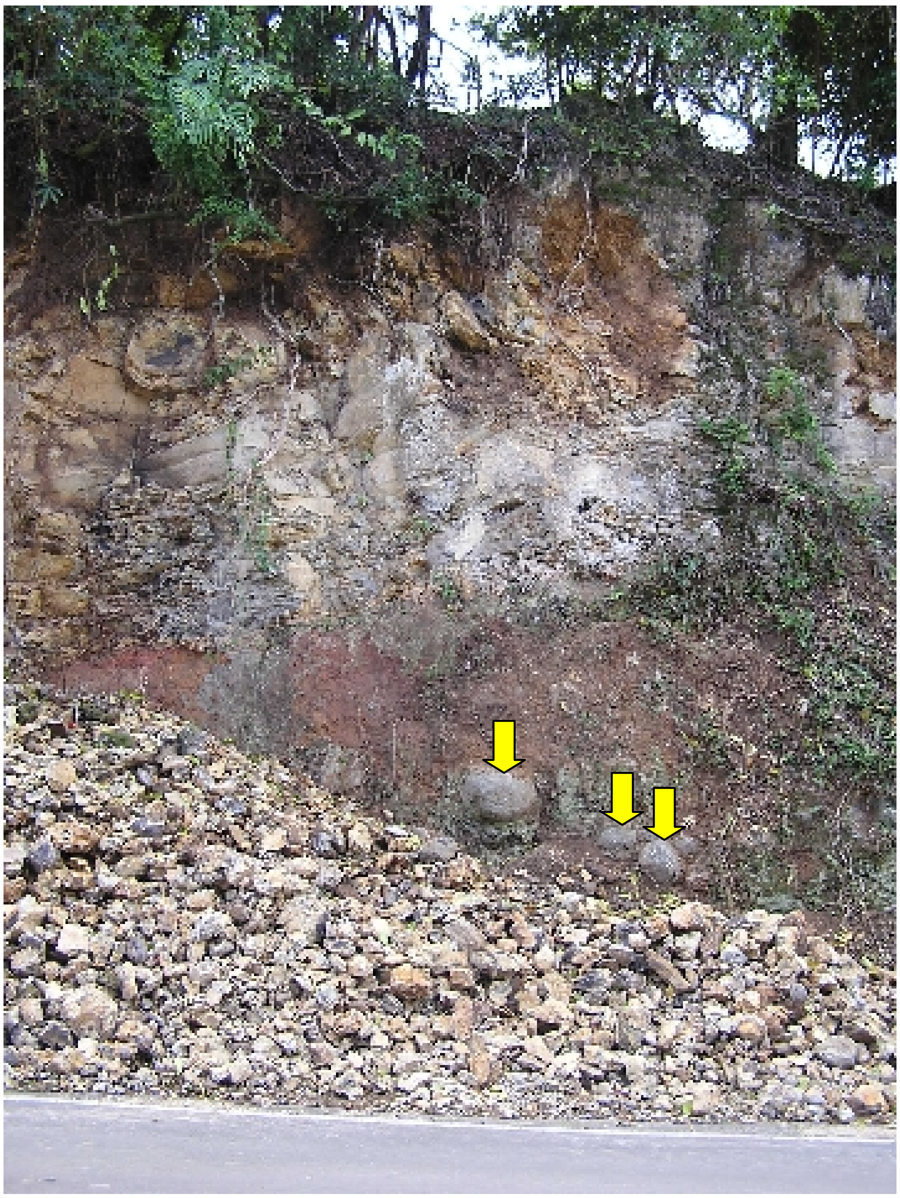


Figure 24. Location 18, Hwy 270 at Makapala. Failure (pile of rock fragments at front) of stronger rock underlain by baked zone soil, with weathered corestone boulders (arrowed).

Figure 25. Location 4, old Hwy 11 near Ōōkala, Modern Hwy 11 viaduct above. As evident from red stains in road, soil failed onto and across across Road (arrows) from very steep road cut; typical of many such slides along this road.

Figure 26. Location 4: old Hwy 11 near Ōōkala. Failure of soil above rock. Note inclusions of corestone rocks within soil.

Figure 27. Location 16, Near Kapa'au (Kohala), Hwy 270. Tree roots (arrowed) within relict rock mass fractures degraded the stability of road cuts in soil.

Figure 28. Location 9, Hwy 19 near Honoka'a. Weathered rock. Fractures occupied by tree roots, as shown in insert.

Figure 29. Location 9, Hwy 19 near Honoka'a. Wide fracture likely not caused by earthquake- note debris and tree root.

LANDSLIDES

Landslides occurred along the northern Hamakua coast and at the eastern end of Maui as illustrated by Chock (2006). Rockfalls and landslides in remote inland valleys and ravines blocked or destroyed many sections of critical aqueducts serving northern Hawai'i which is a key agricultural and ranching area. Because of the abundance of steep and high slopes, high rainfall conditions, weak soils and weathered rock, there were likely many landslides in the Kohala and Hamakua areas of Hawai'i initiated by the earthquakes, but few were observed during the reconnaissance.

Apparently recent slides were observed on the cliff face of the Akaka Falls (Figure 30). Other earthquake effects at the State Park property were apparently limited to fallen trees and damaged hand railings.

At Waipi'o Valley, the coastal cliffs show evidence of older landslides which have deposited debris that is at least 35 years old (Figure 31) since the debris is obvious in the aerial photograph referred to in the caption of Figure 185 of MacDonald and Abbott (1970). Prominent large scars on the cliffs (Figure 31) are likely not due to the earthquake since at the time of the reconnaissance, the water at the toe of the cliff was not muddy. The alignment of the failed cliffs in Figure 31 suggests an ancient mega-landslide head scarp or a fault scarp, although the faceted spurs may also be due to erosion.

At K*ēō*kea Bay, the pavilion at the K*ēō*kea Beach Park was red-tagged because of structural damage caused by the earthquakes. Adjacent to the Park, previous cliff-top trees had slid to the shore down freshly scarred cliff faces (Figure 32 and Figure 33), and muddy near-shore waters were obvious indicators of recent slides resulting from the earthquakes (Figures 33).

Closer to the epicenters, the seismic activity resulted in landslides and tension cracks several feet from the cliff top along the trail between Honoipu Landing and Puakea Ranch (Figure 34 and Figure 35).

A dramatic earthquake-triggered landslide occurred at Kealakekua Bay (Figure 36), near the Captain Cook Monument, south of Kailua-Kona from the Pali Kapu o Keōua, a fault trace and the head scarp of the Alika mega-landslide that occurred about 100,000 years ago. The area seaward and landward of the cliffs and shore, including nearby roads and hiking trail, were closed by the State because of unstable ground and the risk of future landslides. Consequently the area was not investigated during the reconnaissance.

Figure 30. Location 2, Akaka Falls, Hamakua Coast. Scars in the cliff face may not be attributable to the earthquakes.

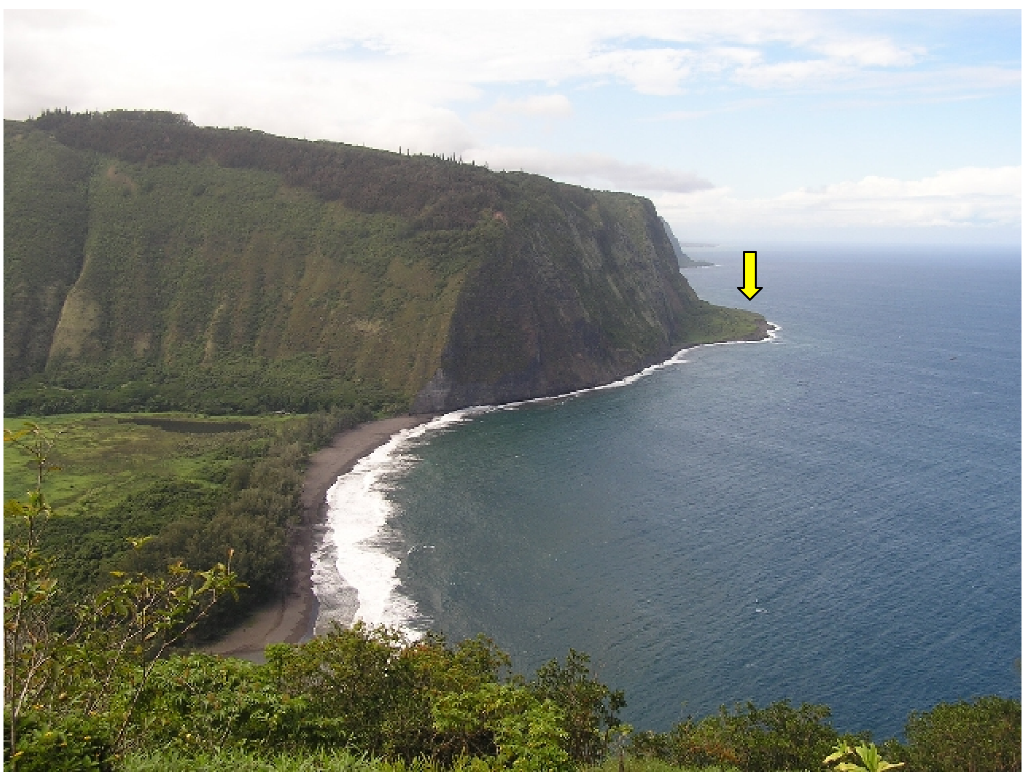


Figure 31. Location 8, Waipi'o Valley cliffs. Debris from an older slide (arrow) intrudes into the sea in the background. Scars in the closer, truncated spur are apparently not a result of the earthquakes since the water is not muddy.

Figure 32. Location 19, Kēōkea Bay. Cliffs failed during the earthquake with displaced trees at base of slope and slide scars.

Figure 33. Headland to the northwest of Location 19, Kēōkea Bay. Cliff top slid into the ocean, indicated by the displaced tree and the mostly submerged toe debris.

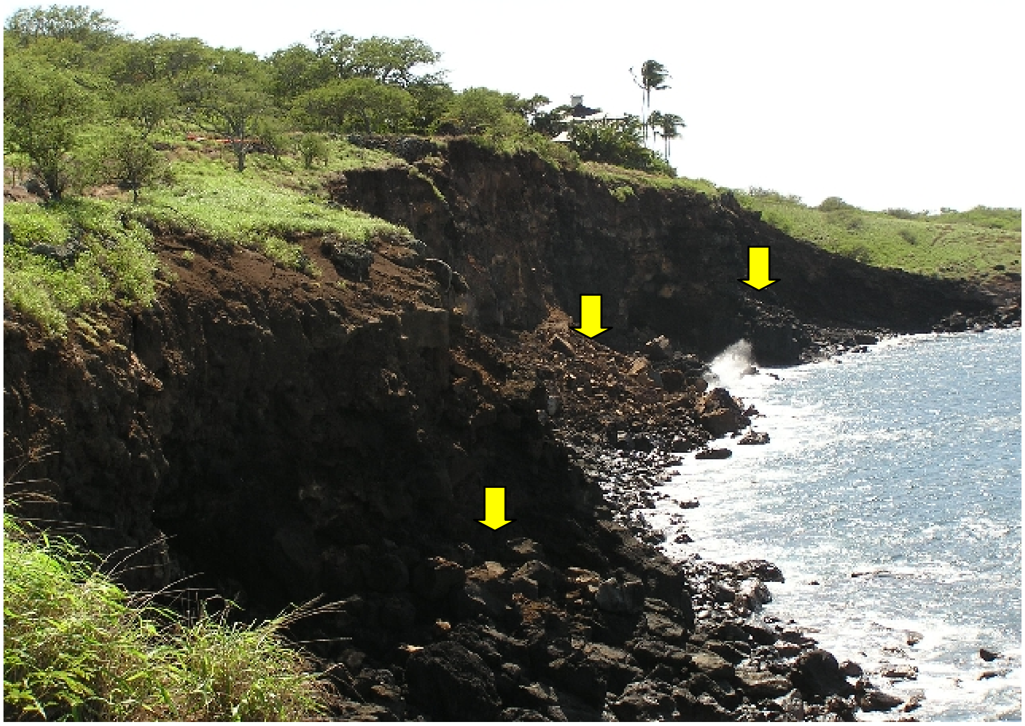


Figure 34. Location 23, failed cliffs (arrowed) south of Honoipu Landing (Ala Kuakini Trail).

Figure 35. Location 23, Ala Kuakini Trail. Tension cracks behind cliff top (arrowed) in foreground.

Figure 36. Location 36, Napo'opo'o, facing the Pali Kapu o Keōua, a fault/mega-landslide scarp.

Figure 37. Location 27, Kawaihae Small Boat Harbor, showing arcuate ground crack resulting from lateral spreading.

LIQUEFACTION AND LATERAL SPREADING

The major commercial Port at Kawaihae Harbor (Figure 2 and Figure 3) is located less than 20 km (12 miles) from both earthquake epicenters and sustained major damage from liquefaction and lateral spreading from the earthquakes, as described by Robertson et al (2006) and Chock (2006). The Harbor was largely constructed from dredged coralline fill in the 1950's and constructed in part to service military operations. The Port consists of two pile-supported concrete wharves, warehouse and administrative buildings, and an asphalt paved shipping container yard.

As reported by Robertson et al. (2006) and Chock (2006), sand boils were observed throughout the Harbor area, indicative of liquefaction of the underlying fill. The resulting lateral spreading of 15 to 30 cm caused up to 15 cm of settlement of the asphalt pavement at the shipping container area and lateral displacement of the pile supported concrete wharf.

Figures 37, Figure 38 and Figure 39 show examples of the lateral spreading, ground fissuring and ejection of liquefied sand resulting from the earthquakes, still evident a week after the event. Eye witnesses reported to the author (and to Robertson et al. 2006) sand and water "squirting" several feet into the air; and "squirting out of the cracks" in the pavement during and following the earthquakes.

Figure 38. Location 27, Kawaihae Small Boat Harbor. Lateral spreading, and damage to dock. Liquefied sand was ejected from the ground crack (white sand).

Figure 39. Location 27, Kawaihae Small Boat Harbor parking lot, adjacent boat yard at south side. Liquefied (white) sand was ejected from wide ground crack during the earthquake shaking.

PERFORMANCE OF STACKED ROCK STRUCTURES

In Hawai'i, dry stacked rock structures built of stone placed without mortar are common, being the heritage of an ancient art (*uhau humu pohaku*) used to craft walls, temples, and platforms. Stacked rock walls, sometimes weakly mortared, are also evident in old churches and more modern structures such as retaining walls and boundary fences. The rocks used in the walls vary between a'a clinker (Figure 40) to segments of columnar jointed basalt (Figure 41).

Although the earthquake damaged many stacked rock structures, the observed effects were inconsistent. The overall impression was that most damage was suffered by tall and/or steep structures close to the earthquake epicenters, and where the contacts between rocks were minimal. As reported by Robertson et al. (2006), dramatic damage occurred at the Kalāhikiola Congregational Church in Kapa'au (Location 21, Figure 1), which was largely constructed of weakly grouted stacked rock (Figure 42). At Spencer Beach Park (Location 30, Figure 1), south of Kawaihae, a tall free-standing grouted stacked rock wall appeared to have accommodated earthquake-related bending deformation (Figure 43). No other walls at the Park showed damage, although none seemed unrestrained like the one pictured.

Failed stacked rock retaining walls were observed in several locations, such as that shown in Figure 44 in Captain Cook (Location 35, Figure 1), on Hwy 11 south of Kailua-Kona. Virtually no stacked rock wall (or road cut) failures were observed on Hwy 11 between Captain Cook and Hilo. Only minor damage to trails was reported at Hawaii Volcanoes National Park (Location A, Figure 1), located more than 90 km (55 miles) from the earthquake epicenters. Cliff failures damaged a dry stacked rock wall structure supporting part of the parking area for shoreline access at the Puakea Ranch residential development in Kohala (Figure 45).

Amongst the largest and most imposing rock block edifices in Hawai'i are *heiaus*, ritual temples composed of rock block platforms supporting structures once used to house priests, sacred items, ritual images, and altars. One of the most important heiaus is that at Pu'ukoholā (Figure 3 and Figure 46) located immediately south of Kawaihae and about 22 km (12 miles) from the epicenters of the earthquakes. Pu'ukoholā is a ritual temple commissioned by the Hawaiian chieftain Kamehameha between 1790 and 1791 in a tribute to the war God Ku'ka'ilimoku, as a religious adjunct to Kamehameha's military and diplomatic efforts to conquer all the islands of Hawaii. The heiau is still used for Hawaiian ceremonies and only native Hawaiians may enter or walk on it: accordingly, the reconnaissance was performed around the perimeters.

Pu'ukoholā heiau is approximately 70 m by 30 m (225 feet by 100 feet) in plan dimensions (Medley and Zekkos, 2007). The long axes of the heiaus are oriented approximately north-south. The heiau was built on the brow of the hill topographically above the older Mailekini heiau and Kamehameha's royal compound (Figure 46 and Figure 47). The walls, terraces and platforms of the heiaus range from less than 1.5 m (5 feet) to 10 m (30 feet) high (Figure 47 and Figure 48) and 1.5 m (5 feet) to more than 12 m (37 feet) wide at the top. Block sizes range between a few centimeters to more than one meter with most boulders being in the 30 cm to 60 cm size range (Figure 48). The edifice was partially constructed with wall facings of water-rounded cobbles and boulders, apparently transported hand-to-hand from Pololū Valley some 32 km (20 miles) away.

The heiaus were badly damaged by the earthquakes. The hill top location of the heiaus may have focused seismic shaking, although no details about site response are available. The worst damage at the Pu'ukoholā Heiau was to high retaining walls bounding the sole access passage (Figure 48 and Figure 49). At the Mailekini heiau, much of the interior face of the east wall slumped and raveled (Figure 50 and Figure 51).

Medley and Zekkos (2007) observed that there are apparent and intriguing similarities between stacked rock block edifices and natural arrangements of rock blocks in rock masses. In-situ blocks in rock masses are bounded by joints, shears, fractures and other discontinuities which range between open apertures or contain infillings that may vary from soil-like to strongly mineralized. In geomechanical terms, it can be reasonably expected that rock block edifices may behave under static and dynamic loadings in similar geomechanical fashion to natural masses of rock and coarse soil.

Figure 40. Location 11, Saddle Road (Hwy 200). Stacked rock wall of a'a clinker.

At the Mailekini and Pu'ukoholā heiaus damage in the form of slumps and ravels of the wall was observed that seemed to roughly match the behaviors described by Medley and Zekkos (2007). Many wall bulges were observed at originally steep wall faces (40 to 50 degree inclinations, Figure 52) resulting in further steepening of the wall faces near the bottom of the edifices (Figure 53; stereo Figure 54 and stereo Figure 55) although it is likely that some bulging had occurred before the earthquakes. Many wall bulges were observed where the slopes approached vertical (Figure 53), which suggests vulnerabilities to increased rock face instability and eventual collapse from future earthquakes or creep deformation. Some slumps and ravels of the wall faces occurred where the bulges over-steepened and collapsed (Figure 56, Figure 57; stereo figure 58 and stereo Figure 59). The slumps apparently occurred in much the same fashion as sketched in Figure 60. The angle of repose for the slumps was about 30 degrees, with run-outs extending to more than 5 m from the original toes of the walls (Figure 52 and Figure 56).

Figure 41. Location 33, Moku'aikaua Church, Kailua-Kona. Finely constructed stacked rock perimeter wall.

Figure 42. Location 21, Kalāhikiola Congregational Church, Kapa'au. Weakly cemented stacked rock walls (inset) failed dramatically.

Figure 43. Location 30, Spencer Beach Park, south of Kawaihae. Apparent earthquake damage of partially mortared rock wall: wall is bent.

Figure 44. Location 35, Captain Cook. Failed stacked rock retaining wall. 3

Figure 45. Location 23. Collapse of dry stacked rock wall supporting paved parking area for shoreline access at Puakea Ranch end of trail to Honoipu Landing, due to cliff failures undermining wall foundation.

Figure 46. Location 29. Mailekini Heiau in middle ground, and Pu'ukoholā Heiau on top of hill.

Figure 47. Location 29. View of part of rear of Mailekini heiau as seen from Pu'ukoholā heiau.

Figure 48. Pre-earthquake view of entrance passageway into Pu'ukoholā (Location 29) (Medley and Zekkos, 2007; original photo from www.pacificworlds.com/kawaihae).

Figure 49. Location 29, Pu'ukoholā heiau, north side: Earthquake caused collapse of access step structure.

Figure 50. Location 29. Pre-earthquake view of Mailekini Heiau (Medley and Zekkos, 2007; original photo from www.pacificworlds.com/kawaihae).

Figure 51. Location 29, Mailekini heiau. Significant raveling and slumping of interior face of the eastern wall (outlined).

Figure 52. Location 29, NE corner Mailekini heiau. In foreground: typical intact face inclined at about 50 degrees. In background, toe of raveled face shown in Figure 56.

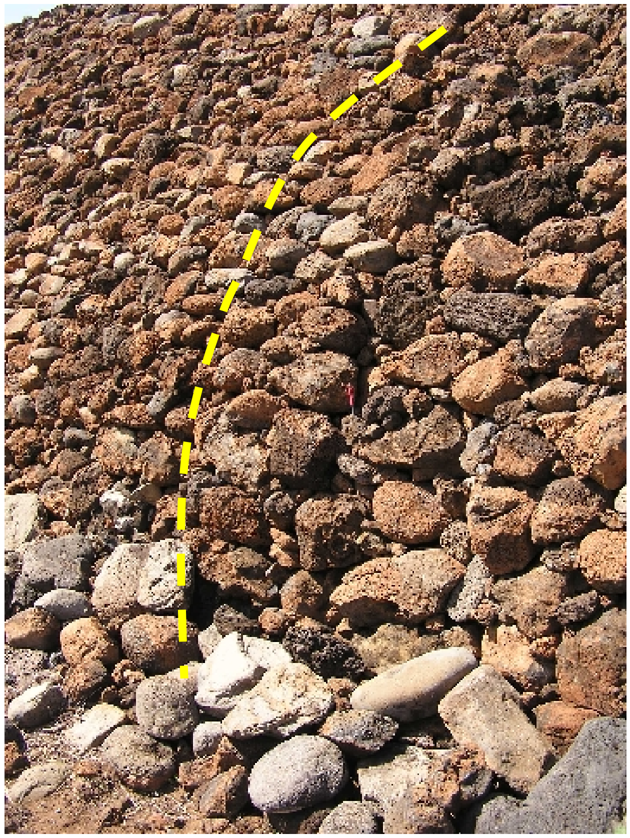


Figure 53. Location 29, NE corner Pu'ukoholā Heiau. Bulging of rock face approaches 90 degree inclination as indicated by yellow line. Bulge is clearly seen in 3-D stereo versions of Figure 54 and Figure 55.

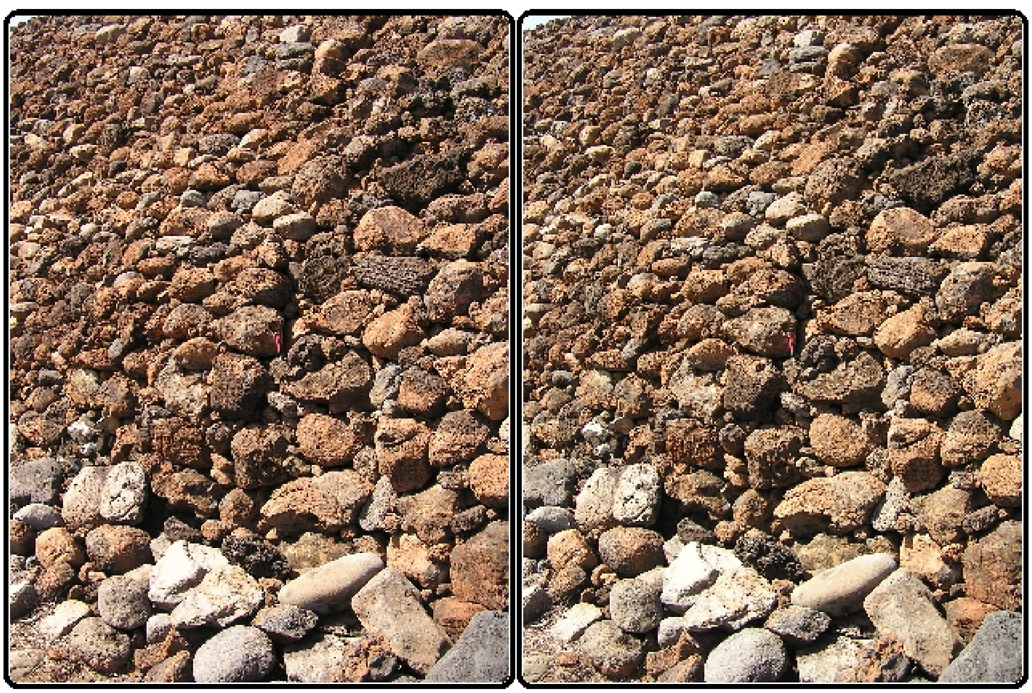


Figure 54. Location 29, bulge at NE corner of Pu'ukoholā heiau. 3-D stereo pair version of Figure 53.

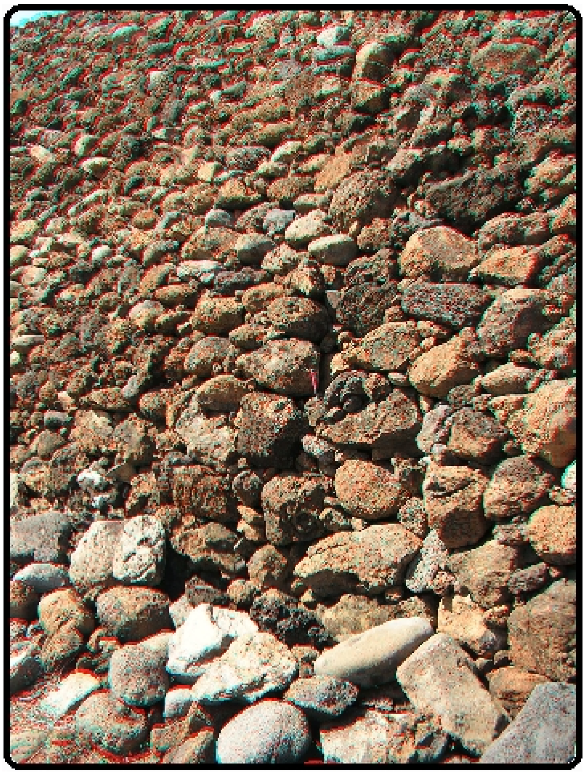


Figure 55. Location 29, bulge at NE corner of Pu'ukoholā heiau.
3-D anaglyph stereo version of Figure 53.

Figure 56. Location 29, Pu'ukoholā heiau, northeast corner. Dashed lines indicate boundary of ravel zone.

Figure 57. Location 29, slump failure in high rock wall of Pu'ukoholā heiau, west side. See 3-D stereo images of Figure 58 and Figure 59.

Figure 58. Location 29, slump failure in high rock wall of Pu'ukoholā heiau, west side. Stereo pair 3-D version of Figure 57.

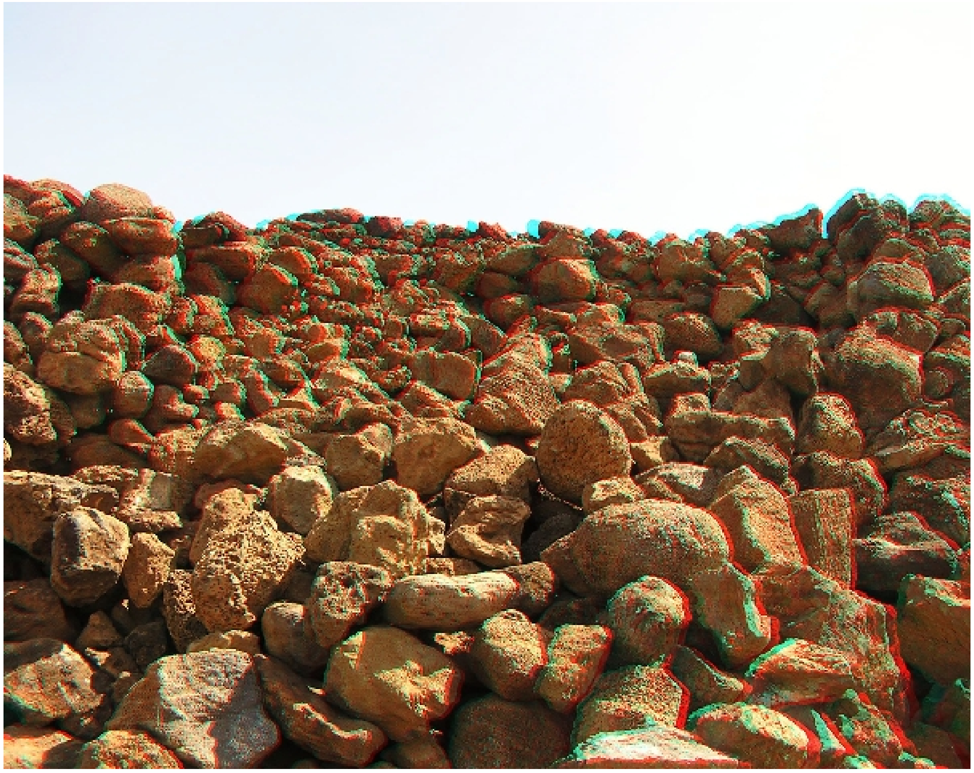


Figure 59. Location 29, slump failure in high rock wall of Pu'ukoholā heiau, west side. 3-D anaglyph stereo version of Figure 57.

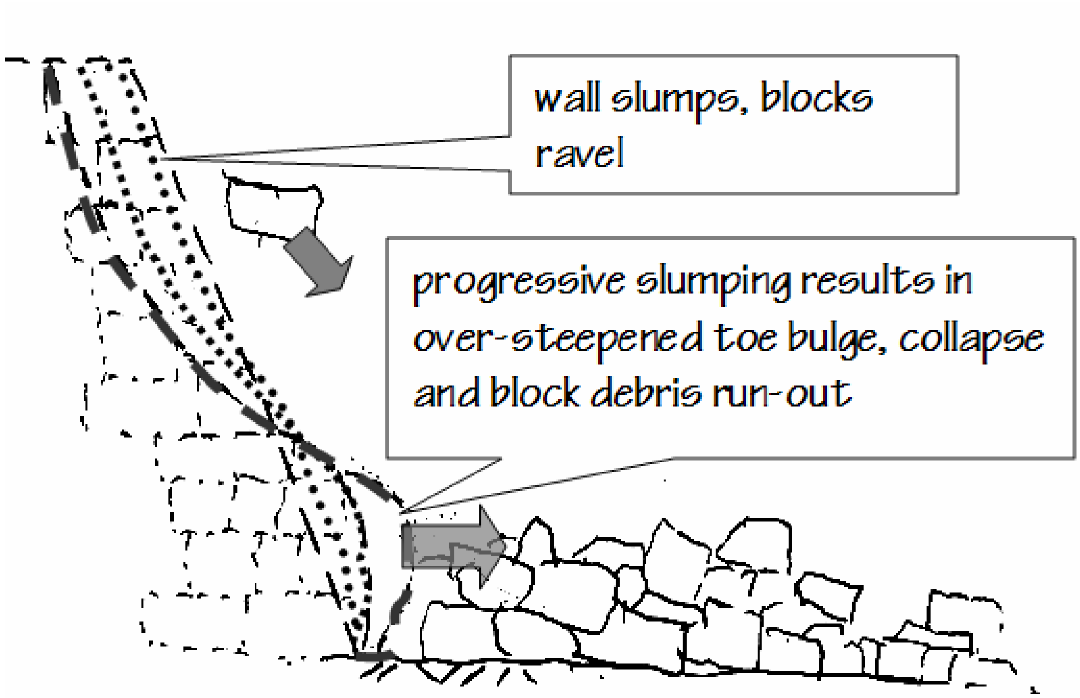


Figure 60. Raveling, bulging and slumping of the face of a rock block edifice (Medley and Zekkos, 2007).

BRIDGE APPROACHES AND EMBANKMENTS

As reported by Chock (2006) and Robertson et al. (2006), damage occurred to dams and irrigation ditches in the Waimea-Kamuela area where recorded peak ground acceleration exceeded 1g and soil depths are greater than at the rocky western coast nearest the epicenter. Some earthen dams built originally for irrigation purposes were reported to have experienced cracks along their crests, or showed evidence of incipient slope failure (Robertson et al, 2006; Chock, 2006). Two dams located above the town of Waimea were emptied after excessive seepage and "water-boils" (piping) was observed five days after the earthquakes (Chock, 2006).

Figure 61. Location 6, Mile Post 35, Hwy 11 near Pa'auilo.
Failure of fill at east side of southern approach to bridge.

Earthquake-related distress occurred at some embankment fills adjacent to bridges, as some of which were also reported by Robertson et al (2006) and Chock (2006):

1. At Mile Post 35 on Hwy 11, near Pa'auilo (location 61), an embankment for the southern approach failed (Figure 61).

2. At Mile Post 9.4 on Hwy 250 (Kohala Mountain Road, location 15), the down slope side embankment failed at several locations over several hundred meters (Figure 62). There is a narrow shoulder for this road, and the bridge itself is single-lane. The road was temporarily closed at this location after the earthquake. Since Hwy 270 was also temporarily closed, there was thus no route open for traffic in or out of Kohala after the earthquakes.

3. At the crest of a steep embankment near Makapala on Hwy 270 (location 18), tension cracks and a head scarp about 0.3 m high were observed (Figure 63). The high embankment was on the down slope side of the road, and had side slopes of greater than 45 degrees.

4. At the bridge located at approximately Mile Post 28, Hwy 270, (location 20) cracks in the road surface appeared to match the locations of the cut/fill transitions of underlying sub-grade (Figure 64). At one location, cracked asphalt concrete pavement was thrust over adjacent pavement (Figure 65). The west bridge abutment headwall had suffered some spalling at apparent pre-existing cracks (Figure 66).

5. At the Mauna Kea Observatories complex at the summit of Mauna Kea (location 28), (about 4,260 m elevation), no apparent distress was observed at the high earthwork embankment adjacent the Keck Observatory building, although recent spalling had occurred at the exterior (Figure 67).

Figure 62. Location 15, north of Mile Post 9.4 Hwy 250. Slump failure of embankment on down slope side of road.

Figure 63. Location 18, Hwy 270 near Makapala, down slope side. Arrow indicates tension cracks and short head scarp 30 cm high at crest of steep and high fill slope.

Figure 64. Location 20, bridge at approximately Mile Post 28, Hwy 270.
Asphalt pavement cracked at approximately the cut/fill transitions of underlying subgrade.

Figure 65. Location 20, bridge at approximately Mile Post 28, Hwy 270.
Thrusting of asphalt concrete pavement.

Figure 66. Location 20, bridge at approximately Mile Post 28, Hwy 270. At SW corner of bridge, looking upward at wooden plank sidewalk above. Fresh spalling of bridge abutment headwall at old, pre-existing cracks.

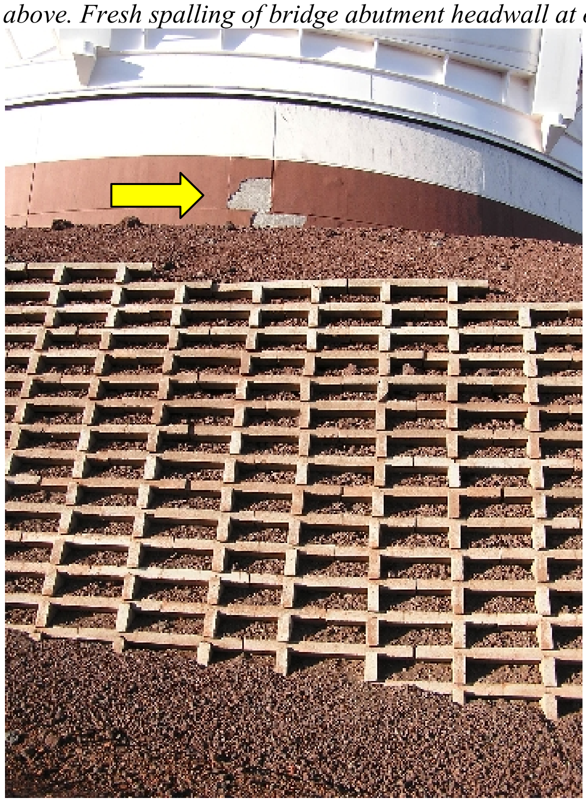


Figure 67. Location 28, Keck Observatory, Mauna Kea summit. No apparent distress to high embankment beside the observatory. Spalled stucco evident at two places on the exterior wall of the building (one arrowed).

CONCLUSIONS

The geological engineering reconnaissance resulted in the following conclusions:

1. The performance of road cuts in soil slopes was generally better than that of rock slopes.

2. The failure of road cut rock slopes was much influenced by the presence of a'a clinker. Where clinker underlay massive basalt blocks, there was a tendency for the loose clinker to translate, rotate and ravel downslope, thereby undermining the blocks. Where the massive blocks could not sustain a critical cantilever, they dislodged as well.

3. There are some parallels between the geomechanical behavior of clinker rock masses and the behavior of stacked rock structures: slope angle, slope height, particle size and nature and proportion of inter-particle contacts govern performance for both. Analysis of failure modes and modeling of vulnerabilities would be ideally suited to discontinuous deformation analysis (DDA) or other discrete element numerical methods commonly used in geological/geotechnical engineering.

4. Although many stacked rock walls likely will be repaired relatively easily, some historical and cultural structures (such as the Pu'ukoholā and Mailekini heiaus) will require detailed, culturally-sensitive and inter-disciplinary assessments of damage and scope of repairs. Initial non-intrusive damage surveys could be performed using LiDAR and/or photogrammetric surveying using terrestrial stereo-photography.

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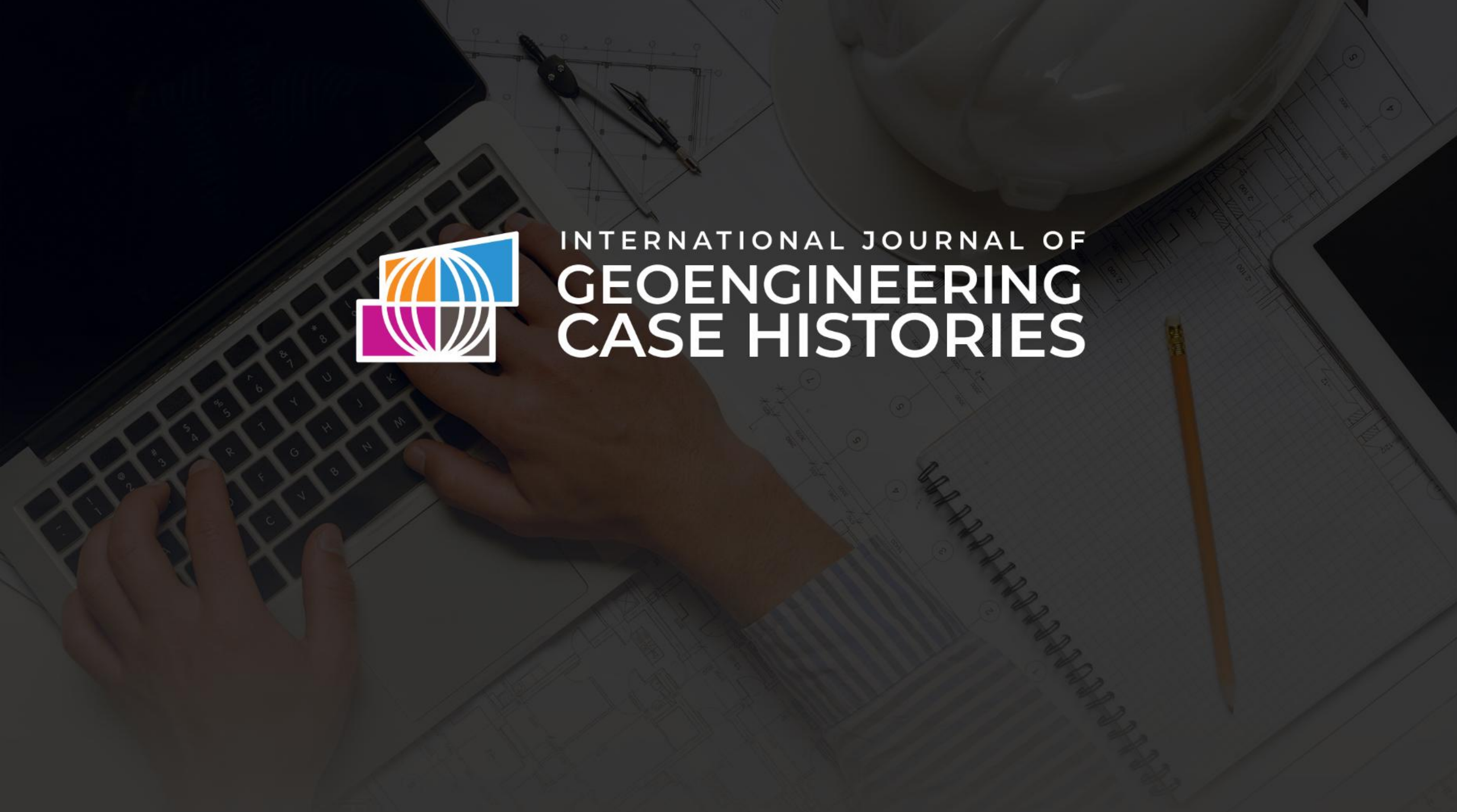

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