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SEISMIC PERFORMANCE OF ROCK BLOCK STRUCTURES WITH OBSERVATIONS FROM THE OCTOBER 2006 HAWAII EARTHQUAKE

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ABSTRACT

Unreinforced masonry construction using blocks of rock is one of the oldest forms of building, in which blocks are stacked, sometimes being mortared with various cements. Ancient civilizations used locally available rocks and cements to construct rock block columns, walls and edifices for residences, temples, fortifications and infrastructure. Monuments still exist as testaments to the high quality construction by historic cultures, despite the seismic and other potentially damaging geomechanical disturbances that threaten them. Conceptual failure modes under seismic conditions of rock block structures, observed in the field or the laboratory, are presented. A brief review is presented of the damage suffered by the culturally vital Hawaiian Pu'ukoholā and Mailekini Heiaus, rock block temples damaged by the M_w 6.7 and 6.0 earthquakes that shook the island of Hawaii on October 15, 2006.

Keywords: rock block structures, Hawaii earthquakes, earthquake observations, geomechanical failures

INTRODUCTION

Construction of unreinforced masonry is common in various earthquake-prone regions, particularly in developing countries, and rural areas of developed countries. This vulnerable type of construction is susceptible to often devastating damage, as evident from the effects of the 2001 Bhuj, India earthquake (Murty et al. 2002), where 1,200,000 masonry buildings built primarily based on local traditional construction practices, either collapsed or were severely damaged. Buildings constructed with adobe and unreinforced masonry suffered devastating damage in the Bam, Iran 2003 earthquake (Nadim et al. 2004). However, in the 2002 Molise, Italy earthquake post-1850 unreinforced masonry buildings performed worse than medieval and renaissance-age masonry buildings (Decanini et al. 2004) indicating that certain methods and materials of construction used in culturally valuable archaeological and monumental structures may have properties that have resisted significant earthquakes. This paper reviews some aspects of the geomechanical performance of structures assembled as unreinforced masonry using blocks of rock.

SOME COMMON CHARACTERISTICS OF ROCK BLOCK STRUCTURES

A simple grouping of rock block structures can be developed based on the cross-sectional aspect ratio of structures (such as width and thickness to height). **Rock block columns** are relatively slender with height substantially greater than their width and thickness and include towers, pillars, and obelisks. **Rock block walls** such as fences, partitions, ramparts, bulwarks, and retaining walls have width of the order of their height, but smaller than the thickness. **Rock block edifices** have width and thickness similar to, or often substantially greater, than their height and include platforms, ramps, terraced

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embankments, dams, mounds and pyramids. Edifices are often of imposing appearance or size and, if of unique character, may be considered monuments.

The exterior envelopes of rock block edifices or the facing of retaining walls may be composed of artfully fabricated veneers of high-quality rock blocks. The inner cores or backfill may consist of stacked courses of blocks, earth or loose rubble. The contacts between facing blocks and core materials range from dry stacked (no inter-block cement) to partially or fully cemented, although the culturally significant monuments considered in this paper are mortar-free. Facings and interior cores of rock block edifices may be penetrated by openings such as windows, doors, corridors, chambers and stairways, the latter being a feature of monuments such as the pyramids.

SOME SIGNIFICANT CULTURAL ROCK BLOCK STRUCTURES IN SEISMIC REGIONS

A few examples of well-known rock block structures constructed by various civilizations in earthquake- prone areas, which are still in good to excellent condition, are presented in the following sections.

Mycenaean civilization

The ancient Greek Mycenaean civilization, best known for the Trojan War, flourished in Greece between the 17th and 12th Century BC. The civilization abruptly collapsed: military invasion, economic collapse, social disturbance, diseases and earthquakes have all been suggested as causes.

The Mycenaean-type of construction is mostly known for the fortification size of its cities such as Mycenae and Tiryns. Zekkos et al. (2005) summarized the currently preserved Mycenaean rock block infrastructure which includes fortifications, underground shafts (graves), retaining walls, roads/pavements, bridges, hydraulic works, dams/embankments, and tunnels. For example, the fortifications in Tiryns consist of building blocks that are typically 2-3 meters long and more than a meter in thickness and height. The blocks of the walls in all cases are made of locally available material, e.g. limestone rocks in Tiryns, and mostly conglomerate in Mycenae. In Mycenae, three different building techniques are evident in the extant fortifications: a) **Cyclopean masonry** (Figure 1), which is the oldest technique, generally consisting of slightly hewn, large blocks. The stone dimensions are larger on the two wall faces (interior and exterior), with cores composed of smaller stones and soil. b) **Rectangular masonry** that consists of carefully hewn rectangular blocks laid in regular courses (Figure 2). This technique was first used probably in about 1250 BC. In some areas, the rectangular technique was used to construct only the outer side of walls while the interior side was constructed with Cyclopean-type masonry. c) **Polygonal masonry** is generally composed of polygonal shaped blocks carefully fitted together (Figure 1).

Figure 1. Polygonal masonry construction (in the center) used to repair section of Cyclopean masonry (left and right) at Mycenae.

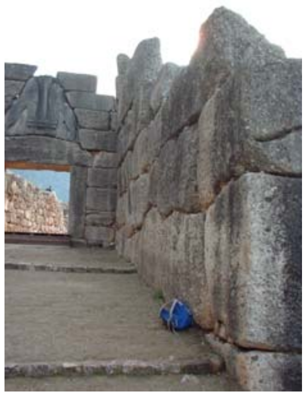

Figure 2. Rectangular masonry adjacent to the Lion's Gate at Mycenae.

Maya and Inca Civilizations

The "classic period" of the **Maya** civilization spanned from the 3rd Century AD to the 10th Century AD. The reasons for the collapse of the Mayan Civilization are not clear and theories include military invasions, social revolutions and natural disasters. The preferred fall directions of stelae indicate that a Magnitude 7.5-7.9 earthquake may have contributed to the collapse of the empire (Kovach, 2007). The Mayan civilization is known for its impressive temples and pyramids. Locally available limestone quarried in the vicinity of the building sites was used in the construction of buildings ranging from pyramids to simple residences. Mortar consisting of pulverized and burnt limestone was sometimes used to augment poor frictional interlocking between the blocks.

The **Inca** civilization arose in the early 13th Century AD and had largely collapsed in the 16th Century AD following the execution of the last Inca Emperor by the Spanish Conquistadors. The Inca civilization expanded into Peru. The seismotectonics of Peru are dominated by the convergence of the Nazca plate and South American plates (Dewey and Silva, 2003). An example of the Inca art of construction is spectacularly evident at Machu Picchu, where the majority of the surviving rock block structures are retaining walls, fortifications and residential construction. Wright and Zegarra (2000) identified at Machu Pichu at least 18 different stone wall types and patterns constructed with different levels of care. The blocks in Machu Picchu are primarily of quarried granite. Mortar, consisting of clay, soil and small stones was used in many of the walls.

Greek and Roman Civilizations

Many examples of rock block construction are preserved from the classic Greek and the Roman civilizations (6th Century BC to 3rd Century AD). The Hellenistic empire established by Alexander the Great was conquered by the Romans and extended from Europe to Asia and Africa. Greek and Roman infrastructure is still preserved in several earthquake-prone areas. A famous Roman rock block structure is Hadrian's Wall, which for 117 km marked the northern border of the Roman Empire in Great Britain (not an earthquake-prone region). The size and type of the materials used in the Wall varied depending on the local geology.

Hawaiian Culture

The islands of Hawaii were populated by seafaring Polynesians who likely emigrated from Tahiti and the other Society Islands in about 1200 AD. Through a heritage developed by centuries of Pacific explorations, the Hawaii pioneers had an intimate understanding of how to survive on previously uninhabited Pacific Islands. Rock (*pōhaku*) was vital in traditional Hawaiian culture and was so important that Hawaiians believed gods could appear as stone (Wong, 2004). Rock was used for tools and weapons; and the early Hawaiians had well-developed skills to construct robust rock block structures. Dry-stack stone masonry (*uhau humu pōhaku*) is still the traditional Hawaiian craft of stacking stones to create interlocked rock structures without the benefit of mortar, although it is nowadays practiced by very few craftsmen (Wong, 2004). The appearance, functionality and stability of Hawaiian rock block construction depended on available materials, the geometry of the structure, the skill of the builder and, the purpose of the structure. With the arrival of Europeans in the late 1700's, mortared rock blocks were increasingly used for construction of churches, commercial buildings and homes.

Traditional Hawaiian rock block structures range from serviceable quality, quickly-erected rock fences and low walls constructed of irregular, relatively light-weight *a'a* clinker (Figure 3) to imposing, high-quality and durable structures crafted from intricately conjoined blocks of massive polygonal basalt (Figure 4).

Large Hawaiian walls typically have large foundation blocks (*niho*) placed at the bottom, or at corners, with smaller blocks placed to form a battered face and tapered cross section (Figure 5 and Figure 6). Wider walls have separated facades with a backfilled core composed of smaller stones *(hākāhāka)* placed in layers or as loose rubble (Greene, 1993; Wong, 2004) .

Figure 3. Rock wall of loosely placed *a'a* clinker blocks.

Figure 4. Rock wall of intricately interlocked massive basalt blocks (Moku'aikaua Church, Kailua-Kona, Hawaii).

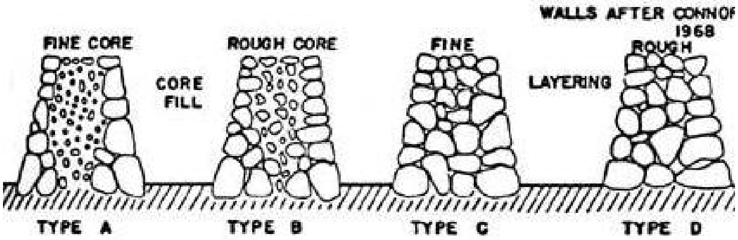

Figure 5. Types of construction for rock block walls. (Greene, 1993; after Kikuchi, 1973).

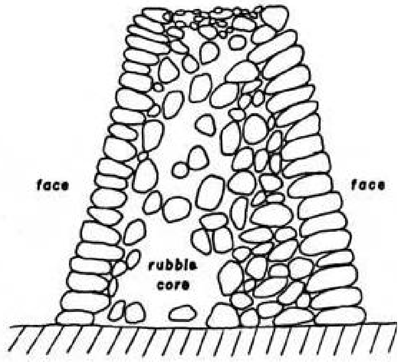

Figure 6. Cross-section through wall at Pu'ukohola Heiau (Green, 1993; after Kikuchi and Cluff, 1969.

Amongst the largest and most imposing rock block edifices in Hawaii are *heiaus*, temples composed of rock block platforms supporting structures used to house priests, sacred items, ritual images, and altars. Heiaus were sacred places; the Hawaiian caste system of *kapu* (taboo) allowed access only to priests and sacred high chiefs: kapu demanded death to common entrants.

The Pu'ukoholā Heiau, located south of Kawaihae on the island of Hawaii (Figure 7) is one of the few surviving relatively intact examples of a finely-constructed rock block edifice and is an important cultural monument in Hawaii. It is still used for Hawaiian ceremonies and only native Hawaiians may enter or walk on it. 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 was built on the brow of the hill above the existing Mailekini Heiau and Kamehameha's compound (Figure 8 and Figure 9).

Pu'ukoholā Heiau is approximately 225 feet by 100 feet (70m by 30m) in plan dimensions. Topographically below the Pu'ukoholā Heiau is the older Mailekini Heiau (Figure 8). The long axes of the heiaus are oriented approximately north-south. The walls, terraces and platforms of the heiaus range from less than 5 feet (1.5 m) to 30 feet (10 m) high (Figure 9). Block sizes range between a few centimeters to more than one meter with most boulders being in the 30 to 60 cm size range.

Figure 7. Mailekini Heiau in middle ground, and Pu'ukoholā Heiau on top of hill.

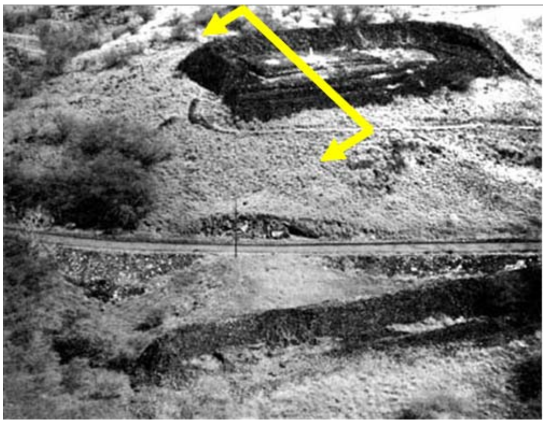

Figure 8. Aerial view of Pu'ukoholā Heiau (top) and Mailekini Heiau (bottom); yellow line shows approximate location of cross section in Figure 9 (after Greene, 1993).

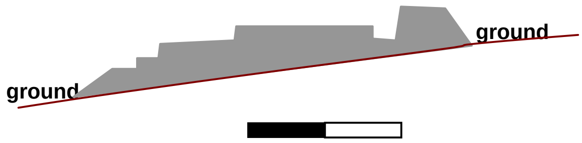

Figure 9. Cross-secti n through u'ukohola Heiau (after Greene, 1993; Kikuchi and Cluff, 1969

The Pu'ukoholā edifice was constructed using local rock for core backfill (Greene, 1993) (Figure 6). Water-rounded cobbles and boulders being "prophetically specified" (Yanoviak, 2003), were stacked to construct the imposing facades. Although rough rock is abundant locally, water-rounded rocks was transported by 20,000 men passing blocks hand-to-hand from the nearest major source of Pololu Valley (Yanoviak, 2003), some 20 miles (30 km) away. Over the years, portions of the heiaus collapsed prompting stabilizations and repairs performed in the 1970's (Greene, 1993). The Heiaus and adjacent cultural assets are administered as a National Historic Site by the United States Federal National Park Service (www.nps.gov/puhe).

Upon abolition of the kapu system in 1819 by Liholiho, (King Kamehameha II) heiaus were abandoned as places of worship; many were subsequently exploited to provide building materials for new structures. Others were destroyed to make way for new developments and commercial agriculture.

SOME FAILURE MODES OF ROCK BLOCK STRUCTURES

Figure 10 show several modes of failure, which have been observed in the laboratory, on sites of culturally significant rock block structures or can be expected for rock block structures subjected to seismic loading. These modes are:

- **A)** Block-on-block sliding of columns: whereas stacked blocks of rocks, that could be for example part of a column of a temple, move relative to each other as a result of seismic excitation and exhibit permanent relative seismic displacement.
- **B)** Bending of a (generally mortared) wall or column during seismic loading as a result of the structural response of the column or the structure that the column supports.
- **C)** Sliding and dislodgement of blocks; that could occur during earthquake loading of the structure that has been exposed to centuries of weathering and erosion.

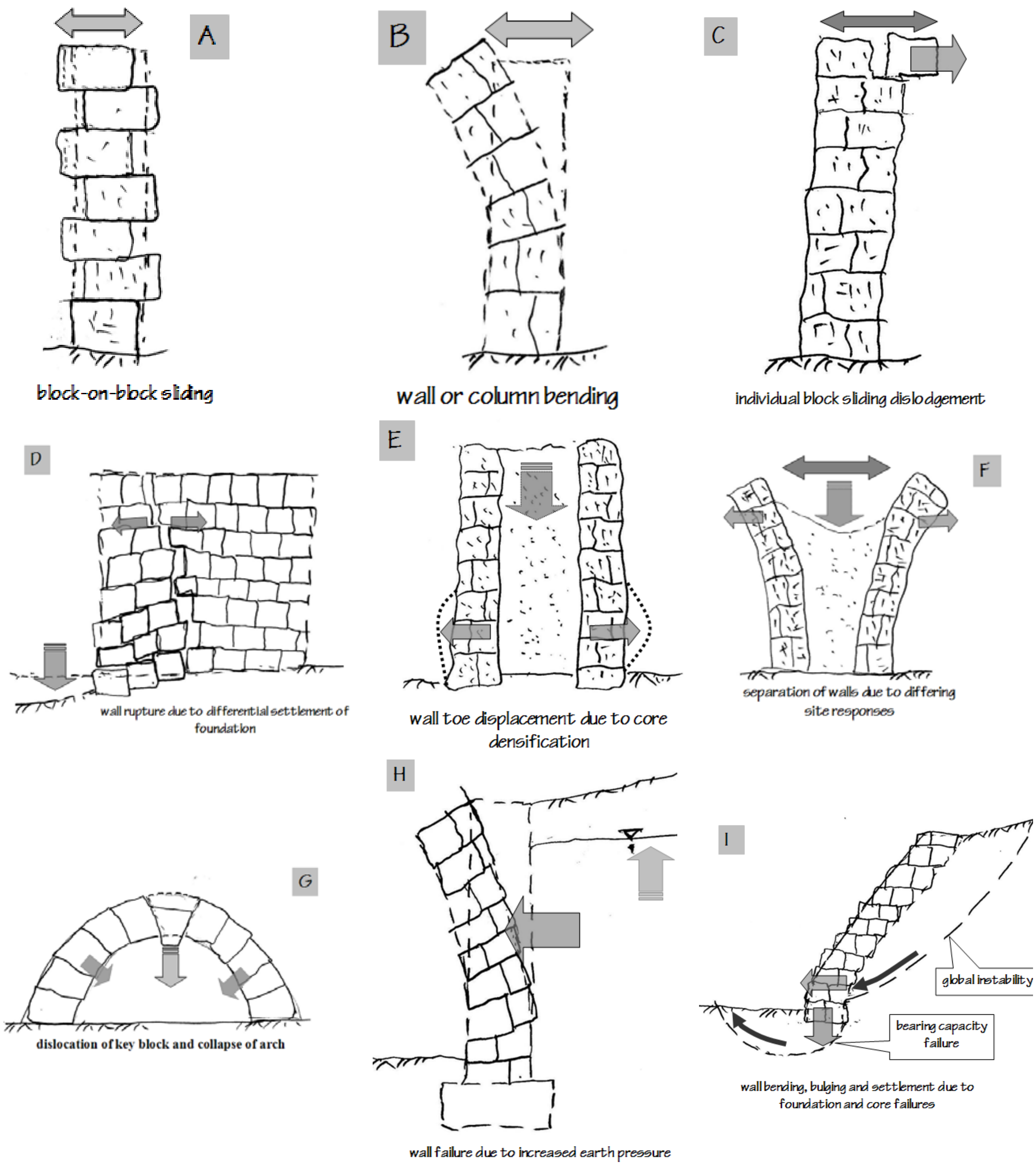

Figure 10. (A-I) Failure modes of rock block structures.

D) Dislocation of walls due to differential settlement of foundation soils, which could take place under static or seismic conditions. An example of this mode for an Inca wall in Machu Pichu is presented by Wright and Zegarra (2000).

E) Loss of strength of loose soil or rubble cores or backfill, and imposition of additional loading on walls; and (**F**) separation of block walls due to differing response of fill and exterior walls; Such modes of failure have been observed in shake table tests performed by Meyer et al. (2007) on brick and stone walls.

G) Loss of arch key block and deformation of arch legs. Such failure modes have been observed on Mycenaean underground burial chambers known as "treasuries".

H) Increase in earth pressures of core or backfill, possibly by the elevation of water.

I) Wall deformation due to global instability such as failure of the core or backfill; or a failure at the toe due to inadequate bearing capacity of the underlying soils.

J) Raveling, bulging and slumping failures of the outer faces of a rock block edifice, such as those observed at the Hawaiian heiaus described subsequently. Face failure may be progressive: the inclination of the bulges increase until they become over-steepened and collapse, thereby inducing collapse of the face above.

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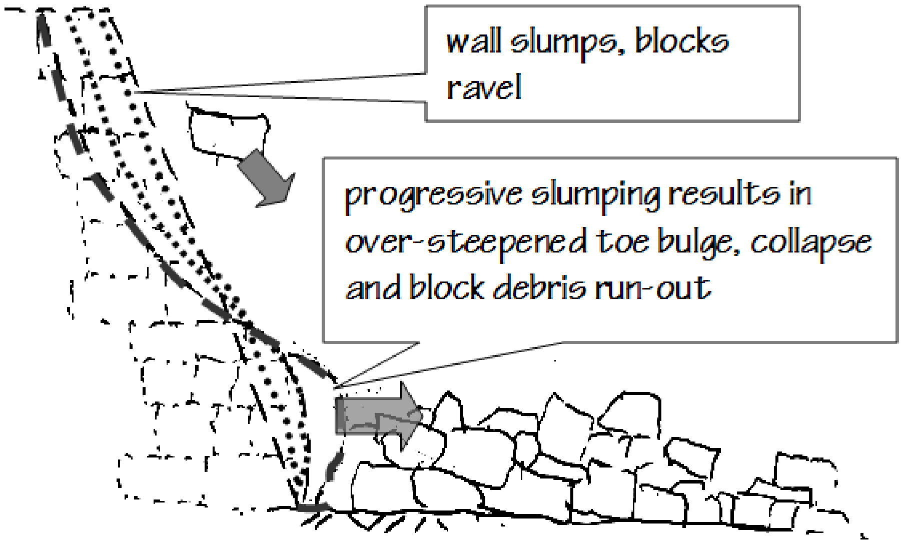

Figure 10J. Raveling, bulging and slumping of the face of a rock block edifice.

There are benefits to considering the apparent similarities between 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 ranging through soil-like to strongly mineralized. Loose rock debris is analogous to talus fans or colluvium.

Considered in geomechanical terms, it can be reasonably expected that rock block edifices may behave under static and dynamic loadings in similar fashion to natural masses of rock and coarse soil. For structures with tightly-packed or layered block arrangements, roughly "circular" failures occur where the failure surfaces negotiate around the boundaries of blocks, with a degree of failure surface roughness dependent on the size of the blocks. For edifices with internal cores composed of loose rubble or soil face slumping or bulging is anticipated. Very steep and high wall faces composed of stacked rocks arranged in columns may topple, much as steeply-jointed slabs of naturally jointed rock topple. Additional analogies between block rock structures and natural rock masses can be conceived.

In some cases, it may be advantageous to perform preliminary geomechanical analysis of rock block edifices using conventional rock mass characterization schemes, which require field estimates of water conditions; intact rock strength: joint orientations, friction angle, spacing, persistence, roughness and surface conditions. These qualities are estimated by an investigating geological engineer or engineering geologist, often without the benefit of much exploration data from penetrative borings or trenches. The need to work with limited observations is also likely a familiar situation for an investigating archaeologist charged with characterizing a rock block structure without the benefit of intrusive explorations.

PERFORMANCE OF ROCK BLOCK STRUCTURES DURING THE OCTOBER 15 2006 HAWAII EARTHQUAKES

The October 2006 earthquakes

The island of Hawaii has suffered several major earthquakes in the last 150 years; some of which have killed hundreds of people, generally because of tsunamis. Another major event shook the island at 7:07:48 a.m. (local time) on Sunday October 15, 2006, when a M_w 6.7 earthquake struck off-shore of the west coast of the island (Figure 11) about 11 km (7 miles) north-northwest of Kalaoa, in Kiholo Bay, Hawaii, some 99 km from Hilo (the second-largest city in the State) and 250 km from Honolulu the capital city, on Oahu) A M_w 6.0 event at 07:14 a.m. and depth of 19 km is considered to have been a separate earthquake. The strongest shaking (MMI VII-VIII) and damage resulting from the two main earthquakes was concentrated on the northern portion of the Island. The felt effects of the earthquake extended to Honolulu, where the International Airport was shut down for several hours.

The earthquakes caused significant damage on the island of Hawaii in the form of failed road cut slopes, landslides, bridges, embankments; rock block retaining walls. Liquefaction and lateral spreading severely damaged the Port of Kawaihae (Medley, 2006; Robertson et al, 2006; and Chock, 2006). Kalahikiola Congregational Church, located at the northern end of the island, suffered almost complete collapse (Figure 12). The church was constructed in 1855 of weakly cemented rock blocks. Although the earthquake damaged many rock block structures, 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 (Medley, 2006). The cumulative damage from the earthquakes exceeded $146 million (Chock, 2006).

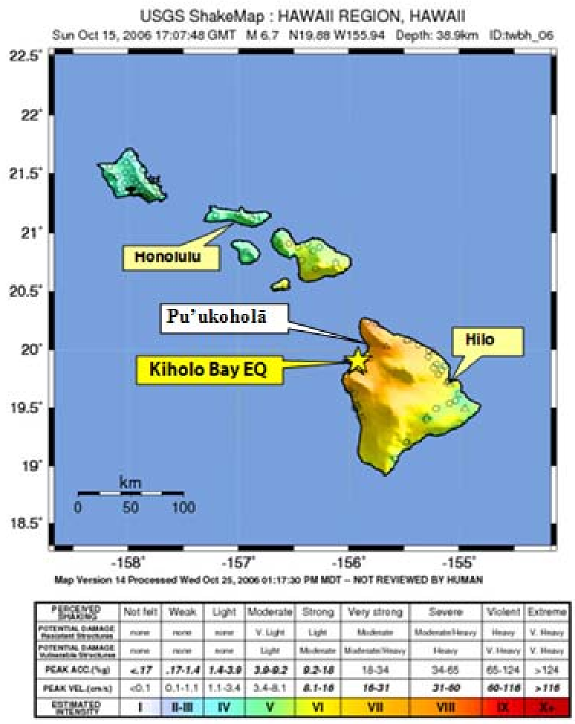

Figure 11. USGS ShakeMap for the M6.7 Kiholo Bay earthquake (after USGS).

Figure 12. Kalāhikiola Church, Hawaii. Weakly cemented rock block walls failed dramatically (Medley, 2006).

Figure 13. Mailekini Heiau, pre- earthquake (photo www.pacificworlds.com/kawaihae).

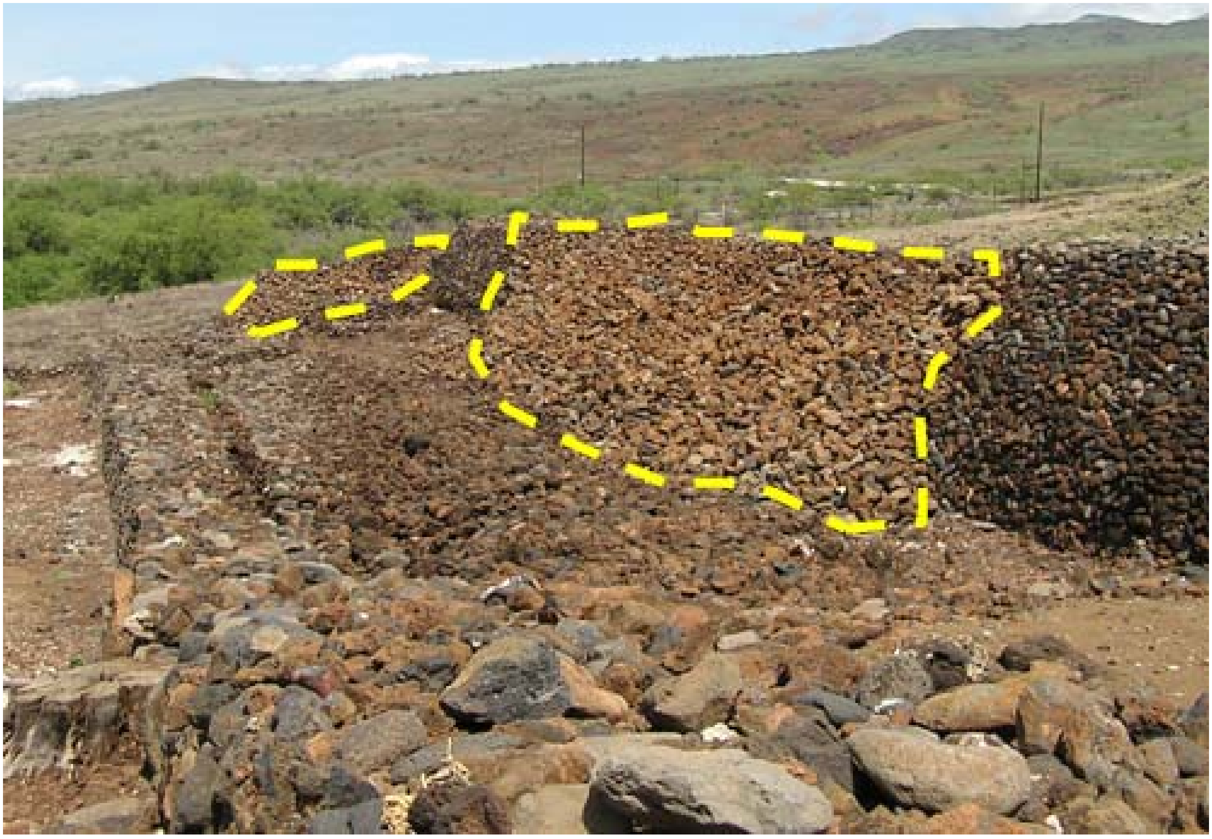

Figure 14. Raveling and slumping of eastern wall of Mailekini Heiau, after earthquake.

Figure 15. Pre-earthquake view of entrance passageway into Pu'ukoholā (Photo www.pacificworlds.com/kawaohae).

Figure 16. Post-earthquake view of collapsed entrance.

Figure 17. Pre-earthquake condition of Pu'ukoholā Outer Wall, from near NE corner (Photo: www.pacificworlds.com/kawaihae).

Figure 18. Post-earthquake photo near NE corner of Pu'ukoholā shows bulging of face of wall (indicated by yellow line).

Performance of Pu'ukoholā and Mailekini Heiaus Rock Block Edifices During the Earthquakes

The Pu'ukoholā and Mailekini Heiaus were both severely damaged by the October 15 2006 earthquakes, the epicenters of which were less than 50 km away (Figure 11). At the Mailekini heiau, much of the interior face of the east wall slumped and raveled (Figure 13 and Figure 14). The worst damage at the Pu'ukoholā Heiau was to high retaining walls bounding the sole access passage (Figure 15 and Figure 16). Many wall bulges were observed at originally steep wall faces (40 to 50 degrees) resulting in further steepening of the wall faces near the bottom of the edifice (Figure 17 and Figure 18), although it is likely that some bulging had occurred before the earthquakes. The bulging suggests that there are future vulnerabilities to increased rock face instability and possible eventual collapses from future earthquakes or creep deformation (Medley, 2006). Some slumps and ravels of the wall faces occurred where the bulges over-steepened and collapsed (Figure 19) apparently in much the same fashion as sketched in Figure 10J. The angle of repose for the slumps was about 30 degrees, with run-outs extending to more than 5 m from the original toe of the walls.

The location of the Heiau on the brow of a hill may have focused seismic shaking, although no details about site response are available. The pre-earthquake geometry of the Pu'ukohola Heiau was apparently surveyed a few years ago with terrestial LiDAR (Light Detection and Ranging) before the earthquake (personal communication with National Park Service staff). As shown in Figure 17, there was apparent wall bulging or steepening of the Heiau walls before the earthquake, but it is unknown how much of this occurred because of, or since, wall renovations in the 1970's A repeat LiDAR survey could form the basis for quantifying earthquake-related deformation, back-analysis and identification of those portions of the edifices vulnerable to further damage in future earthquakes, or due to creep (Medley, 2006).

Figure 19. Pu'ukoholā Heiau. Slump failure due to earthquakes (between dashed lines).

CONCLUSIONS

Construction with unmortared block of rocks is venerable and universal even in seismically active regions. That so many historic and culturally valuable structures have survived is a testament to careful engineering craftsmanship. Finely fitted, massive blocks of rock and well-constructed interior cores and backfill assure the survival of these structures better than poorly constructed unreinforced masonry of modern communities nearby. Modes of failure of rock block structures under seismic loading observed on sites or the laboratory are conceptually presented.

The Pu'ukoholā and Mailekini Heiaus suffered great damage in the M_w 6.7 and 6.0 earthquakes that shook the island of Hawaii on October 15, 2006. The causes of the damage have not been adequately studied, but further analyses should ideally research: ground and structure responses; understanding of the effects of topographic focusing; consideration of the quality of the interior core; review of the nature and quality of previous repairs in the last 200 years; and estimation of the occurrence of prior permanent wall deformations. Since portions of the Heiaus now have potentially hazardous wall geometries, these should be analyzed to assess future potential performance under static and dynamic loading.

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