Learning from Earthquakes

Samoa Earthquake and Tsunami of September 29, 2009

Multiple reconnaissance teams traveled to Samoa in October and November 2009, and contributed to the preparation of this report. These included EERI member and structural engineer Steven Baldridge, president of Baldridge & Associates Structural Engineering, and an International Tsunami Survey Team, headed by EERI member Hermann Fritz of Georgia Tech, that covered the entire Samoan archipelago, including the islands of Upolu, Savai'i, Manono, Tutuila, Aunu'u, Ofu and Olosega. Other members of this team were Costas Synolakis and Jose Borrero (University of Southern California), Emile Okal (Northwestern University), Robert Weiss and Patrick Lynett (Texas A&M University), Vasily Titov (NOAA), Bruce Jaffe (USGS), Spyros Foteinis (Technical University of Crete), and I-Chi Chan and Philip L.-F. Liu (Cornell University). A survey team from Geo-engineering Extreme Events Reconnaissance (GEER) included Jennifer Donahue (Geosyntec Consultants) and Michael J. Olsen (Oregon State University).

A separate team was comprised of EERI member Lori Dengler (Humboldt State University), Kate Long (California Emergency Management Agency), Jeff Brandt (California Department of Fish and Game), Heather Lazrus (University of Oklahoma), and Lesley Ewing (California Coastal Commission). This team traveled to Samoa in late October with a team from the American Society of Civil Engineers.

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Introduction

On September 29, 2009, at 17:48:10 UTC (local time: UTC-11), an Mw 8.1 earthquake struck about 200 km south of the main Samoan Islands chain and 75 km east of Tonga’s Niua Group. The earthquake occurred in a region of high seismicity, with 14 large earthquakes in the region since the early 1900s. This is the most significant earthquake on the northern bend of the Tonga trench since 1917 (Okal et al., 2004). The earthquake did not result from subduction of the Pacific plate into the Tonga trench (Figure 1), but rather from normal faulting expressing a lateral tear in the plate as it slides past the northern bend of the plate boundary. Such events are known elsewhere (Grovers and Wortel, 2005), but their recurrence is even more poorly understood than that for great subduction earthquakes.

The ensuing tsunami killed nine people in Tonga, 149 in the independent country of Samoa, and 34 in American Samoa. It was the deadliest tsunami in the Samoa region in living history. The damage in Samoa alone exceeded $150 million. A tsunami warning issued by the Pacific Tsunami Warning Center 16 minutes after the earthquake was too late for many, since the tsunami arrived in 11-15 minutes at some of the hardest hit villages. Fortunately, many Samoans were aware of tsunamis and knew to get to high ground after an earthquake, behavior attributed to education and evacuation exercises initiated throughout the South Pacific over the past decade. Indeed, evacuation exercises had been conducted in Samoa in the preceding year, and many schools in American Samoa practiced monthly evacuation drills.

Tsunami Field Surveys

Eyewitnesses described between one and four main waves, with an initial recession interpreted as a leading depression N-wave (Tadepalli and Synolakis, 1994).
The measured flow depths and run-up heights indicate extreme and significant variation on all main islands. On Tutuila, maximum runup exceeded 17 m at Poloa, near the western tip. Runup decreased somewhat along Tutuila from west to east, reaching 12 m at Fagasa on the central north coast, and 9 m at Tula in the east.

Pago Pago on the central south coast represents an unfortunate example of a town and harbor ideal for protection against storm waves, but vulnerable to tsunami (Fritz and Kalligeris, 2008).

The harbor geometry at Pago Pago amplified the tsunami from just a few meters at the entrance to 8 m at the head, causing inundation and damage more than 500 m inland up the Vaipito River. Similar inundation distances were observed along the river at Leone in southeast Tutuila. An eyewitness described the flooding at Pago Pago as much more violent than during the 1960 Chilean tsunami.

In contrast to Tutuila, which had significant tsunami impact on both north and south coasts, destruction on Samoa’s Islands was confined to the southern coasts. This effect, as well as the location of the highest runup, can be explained by tsunami directivity from the source region that focused wave energy towards the western tip of Tutuila and SE Upolu, and radiated less energy elsewhere. On Upolu, runup reached 14 m at Lepa (Figure 2), while on Savai’i maximum runup exceeded 8 m at Nuu. At nearby Taga, 6 m runup and 200 m of inundation left a boulder deposit field 100 m inland (Figure 3).

**LIDAR**

The use of LIDAR (Light Detection and Ranging) was important to the investigation for multiple reasons. First, it provided a quick way to obtain valuable information before clean-up was done and vegetation grew back. Second, although
no previous data were available, LIDAR provided high-resolution data allowing for much more accurate damage quantification than can be had from traditional methods. Finally, it allowed for models to be available for scientists to study without having to travel to the site.

A Leica ScanStation 2 laser scanner was used by the GEER team for the survey. 360° panoramic overview scans were completed for each setup (Figure 4).

**General Tsunami Damage**

Widespread damage was seen throughout Samoa and American Samoa. The village of Lepa, Samoa (Figure 5) was completely destroyed. From the beachhead inland, there is a small rise in topography, then a ravine, then a steep hillside. Most of the devastation occurred in the ravine, which was littered with debris, houses and cars. Almost 90% of the structures in this area were destroyed.

Of all villages on the island of American Samoa, Poloa sustained the most damage (Figure 6). All structures were destroyed except for the church, which sustained heavy damage to doors, windows and furniture, but only minor structural damage. The sheer cliffs show trim lines up to 17 m. Poloa is located on the western side of Tutuila Island and has a northwestern exposure. At the time of this report, all remaining residents have abandoned Poloa and have moved into the surrounding hills.

**Scour:** Scour around foundations was visible at many locations (Figure 7). It was caused by both the incoming and return waves. Most scour was observed around the foundations of homes, but some was also observed around utility poles.

For most of the buildings, even those with relatively shallow foundations, scour depths did not occur to an extent that contributed to structural failure. Scouring was
most prevalent in the villages Lepa, Alao, Leone, Asili, Poloa, and Tula. The GEER team used both the traditional means of measuring tape and LIDAR to document scour (Figure 8).

Erosion: Substantial erosional damage from the tsunami was observed (Figure 9), and additional erosion and landslides are anticipated with future precipitation because of the vegetation destroyed by the tsunami.

Unfortunately, reference data are not available for overall quantification of the erosion, but by combining LIDAR data from areas of erosion with an approximation of previous topography, it is reasonable to estimate overall quantification of the erosion.

Figure 9. Wave-induced bluff erosion observed in Aufaga, Samoa.

Figure 10 (a) ▲ On Niuatoputapu Island’s north tip: the entire forest was overwhelmed by the tsunami, with stripped and uprooted trees as well as coral boulders.

(b) ▼ The scars on the bark of the tree — at the far right in (a) — indicate 9.4 m flow depth above terrain, 6 m above sea level and 200 m from the beach, with scour of more than 2 m at the roots.

(c) ▼ Tafahi Island looking north from the maximum 22 m runup, with broken branches in the foreground and the destroyed forest along the beach.
Observations in Tonga’s Niua Group

A follow-up expedition from 23 to 28 November surveyed the three main islands of Tonga’s northern-most Niua group. The tsunami impact on this group surprisingly eclipsed the Samoan observations in all aspects, with maximum runup of 22 m on both the east and west coasts of Tafahi Island as well as flow depth of 15 m and inundation of 1 km on Niuatoputapu Island’s east coast. Tafahi represents tsunami impact on a volcanic island characterized by steep hill slopes (typically 1V:5H) and fringing reefs within 100 m of the shoreline.

Niuatoputapu’s flat coastal topography and near-shore fringing reefs allowed for massive inland penetration of the tsunami waves along the south and east coasts. While forests may provide some tsunami attenuation at flow depths below 5 m, the forests on the south coast were completely overwhelmed by local flow depths of up to 10 m above ground (Figure 10).

Fortunately, the coral reefs and tidal flats extending between 1 and 2 km offshore reduced the tsunami impact along the north shore for villages such as Hihifo.

Seven of the nine victims on Niuatoputapu were loaded onto a truck caught by the tsunami while heading back to the high school to pick up the principal, who had already evacuated. An additional Tongan victim at Hihifo returned to his house to close a shop between tsunami waves.

Hence only the keeper of the Palm Tree Island Resort on Hunganga Island, which was totally submerged by tsunami waves, was an unpreventable fatality in the Kingdom of Tonga.

Structural Damage

Many masonry buildings and reinforced concrete columnar open structures known as fales appeared to withstand the forces of the tsunami inundation with only minor structural frame damage. Most of the columnar fales are almost completely open, allowing the tsunami to flow through them (Figure 11).

Many of the low-lying villages have churches near and facing the ocean. The typical construction is a combination of concrete frames and concrete masonry (CMU) infill. There were several examples of the tsunami entering churches through the front door and flowing out the windows along the sides. While doors, windows, and interior furniture were damaged, the structures did not appear to have any distress from the hydrostatic loading. However, the contents of the buildings were either washed from the buildings or strewn about within the structures, resulting in significant financial loss (Figure 12). Some foundations failed due to scouring, but most foundations were found in acceptable conditions.

Figure 11. The damage to the roof of the fale provides evidence of the height of the tsunami. The concrete foundation and columns sustained minor damage.

Figure 12. Damage around and within the church in the village of Poloa, American Samoa.
While most CMU buildings withstood the tsunami, those that were poorly constructed did not fare well (Figure 13). Wood-framed and poorly reinforced masonry buildings in most cases were torn completely from their foundations (Figures 14 and 15).

Several columnar structures with weak reinforcement were severely damaged. There was evidence of damage created by the impact forces of large floating debris such as vehicles, shipping containers and boats.

The structural damage that was observed appeared to be primarily from the tsunami effects and not from strong ground motion during the earthquake.

**Community Impacts**

The interdisciplinary team that visited Samoa and American Samoa in late October had expertise in coastal and port engineering, coastal management, environmental science, anthropology, emergency management, and mitigation. The team focused on identifying the factors that influenced the impacts of the tsunami, and looked at how coastal land use planning and management, emergency planning and response, and culture, education and awareness of tsunami hazards affected outcomes.

**Human Behavior:** All three EERI teams talked with eyewitnesses to the tsunami. Most people were aware of tsunami hazards and had heard that earthquake ground shaking was a natural warning, but many reported evacuating only after watching others do so or once they saw the water withdraw. A number of communities used informal community notification systems such as church and school bells (Figure 16).

Several victims perished during the evacuation while inside cars; this may be attributed to conflicting official statements issued in Samoa on the use of vehicles during a tsunami evacuation.

**Factors that reduced impacts:**

- Time of day: The tsunami occurred early enough in the day that few were at work or on the road, but late enough so that...
everyone was awake. Many people were outside just getting ready to go to work or school and in good positions to see the water drawdown.

- Little earthquake damage: Shaking damage was minimal and did not disrupt roads or structures.
- First significant wave a drawdown
- Availability of high ground: In American Samoa, almost all vulnerable coastal areas were in close proximity to high ground.
- Tsunami awareness: Most people were aware of tsunamis. In American Samoa, September was emergency preparedness month, and a number of projects targeted tsunamis funded through the TsunamiReady program, including showing videos of the 2004 Indian Ocean tsunami. Although aware, many people did not expect it was something that could happen in Samoa. Some schools practiced regular tsunami evacuation drills.
- Altruism: Many people put themselves in harm’s way to save others.
- Rapid cleanup.
- Strong 2-3 story buildings provided vertical evacuation.
- Coastal protection structures generally performed well.
- Village structure provided shelter and high ground: There were no tent cities of evacuees. All villages include both high and low ground and the family ties assured that no one was isolated or left alone.

**Factors that exacerbated impacts:**

- A very large near-source tsunami with first wave arrivals before any official warning could be issued.
- Most people required at least two indications that they were at risk before they evacuated; very few people responded to the ground shaking alone. The most common combination was feeling the earthquake and seeing the water withdraw. Other additional indicators included hearing a bell or siren, or the alerting of neighbors.
- Confusion about where to go.

Tsunami hazard zone signs had been posted in American Samoa but there were no visual signals as to how high was high enough. There were no marked evacuation routes with direction and distance to tsunami safe areas and shelters.

- Many people drove.
- Lack of awareness that there could be more than one wave.
- Embarrassment: young people were aware that ground shak-
Figure 18. The mayor of Amenave had attended a workshop for village mayors on tsunami hazards. When he felt the earthquake, he grabbed his bullhorn and ran through the village notifying people to evacuate.

...ing was a sign of an impending tsunami but were worried that other people would think they were silly if they evacuated.

• Infrastructure that could not resist uplift forces. Bridges were particularly vulnerable to buoyancy forces.

• Barriers to evacuation. A number of communities had difficulty with access to high ground because of rivers or mangrove swamps that isolated coastal areas, landslides, fences, and in one case, pig styes (Figure 17).

Recommendations

• Develop a protocol to assess the vulnerability of coastal villages, including exposure to tsunamis, evacuation procedures, access to evacuation sites on high ground or inland away from the coast, land use (shoreline protection features, vegetation), barriers to evacuation such as rivers and mangrove swamps, and other hazards in the area such as landslides, and hurricanes.

• Chronicle the recovery process over time in terms of rebuilding, use of devastated areas, institutionalizing tsunami warning, evacuation procedures, education and outreach, role of village cultural structures (matai, faifae’au, etc.), and memorials of the event.

• Build on traditional village structure to promote resiliency. Incorporating tsunami safety into village pride may sustain community efforts. Consider the one-year anniversary of the tsunami as an opportunity for villages to develop evacuation routes and practice drills.

• Examine informal warning systems such as bells, private sirens, and bull horns (Figure 18), and develop criteria to support their use for near-source tsunami events.

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References


