StEER: Structural Extreme Event Reconnaissance Network

PALU EARTHQUAKE AND TSUNAMI, SULAWESI, INDONESIA
FIELD ASSESSMENT TEAM 1 (FAT-1)
EARLY ACCESS RECONNAISSANCE REPORT (EARR)

Palu Bridge IV which collapsed during the earthquake (Source: Ian Robertson)

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Released: January 15, 2019
NHERI DesignSafe Project ID: PRJ-2128

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Executive Summary

On September 28, 2018, at 17:02 local time (10:02 UTC), a magnitude 7.5 earthquake occurred with an epicenter 78km North of Palu, Sulawesi Island, Indonesia, at a depth of 10 km. The earthquake was caused by movement on a strike-slip fault known as the Palu-Koro Fault. The city of Palu, with a population of 336,000 based on a 2010 census, is located in an alluvial valley at the end of the narrow Palu Bay. Preliminary tsunami modeling reported by CATnews indicates that the bathymetry of the Palu Bay increased the tsunami wave amplitude significantly compared with other coastlines outside of the bay. As of writing this report the death toll is estimated to be over 2200 due to both earthquake and tsunami, with over 1000 still missing. This is approximately 1% of the population of Palu. There were nearly 4500 injured during the event, representing about 1.3% of the population of Palu. Around 75,000 were displaced because of damage to housing due to the earthquake, tsunami and lateral spreading induced by liquefaction. This **Early Access Reconnaissance Report (EARR)** provides an overview of the Palu Earthquake and Tsunami, StEER's event response, and preliminary findings based on the first Field Assessment Team's (FAT-1) collected data.

In general, FAT-1 observed significant damage to a wide cross-section of engineered and non-engineered construction as a result of the earthquake and/or tsunami:

- **Reinforced Concrete Buildings:** A number of multi-story reinforced concrete buildings collapsed during the earthquake, most notably the eight-story Roa-Roa Hotel which resulted in multiple deaths. A reinforced concrete shopping center in Palu experienced partial collapse during the earthquake, and a number of mosques also suffered severe damage or even collapse.
- **Bridges:** The iconic twin steel arch cable-suspended Palu Bridge IV over the mouth of the Palu River collapsed, presumably during the earthquake. The bridge had a total span of 250 meters and the steel box arches were 20 meters tall. A number of other bridges are reportedly damaged, hampering road traffic in and around the city.
- **Port Facilities:** A number of port facilities were damaged either by the earthquake or tsunami, and many ships, barges and boats were washed onshore or out to sea.
- **Lifelines:** Damage to lifelines included extensive road damage due to surface faulting and liquefaction, cracks in the Palu airport runway, and loss of power and telecommunications.
- **Residential Construction:** The tsunami caused considerable damage to light-framed wood structures, while some taller engineered structures survived, protecting those who sought refuge in the upper floors. Extensive lateral spreading due to liquefaction caused by the earthquake also resulted in extensive damage to residential and farm structures in a number of inland areas.

While FAT-1 assessed only selected coastal areas around Palu Bay. Specific recommendations of areas worthy of further investigation are offered at the conclusion of this report.

Introduction

The 7.5 magnitude earthquake and subsequent tsunami that hit Palu and Donggala in Central Sulawesi, Indonesia on Friday, September 28, 2018, killing at least 2,245 people. Some 1075 people are missing and over 10,000 were injured, of whom over 4,000 were serious injuries (Wikipedia, 2018a). Nearly 75,000 were displaced in the three most affected areas: Donggala, Palu City, and Sigi.

StEER's response to the Palu Earthquake and Tsunami had a two-fold objective. The first being the swift capture of perishable data through a coordinated strategy to improve our understanding of the performance of coastal construction under this event. The second viewed this response as an opportunity to prototype the protocols, procedures, policies and workflows that StEER will be developing over the next two years in collaboration with the Natural Hazards Engineering research community, the Natural Hazards Engineering Research Infrastructure (NHERI), and other members of the Extreme Events Reconnaissance Consortium, with emphasis in this instance on protocols for tsunami response.

The first product of the StEER response to the Palu Earthquake and Tsunami was a **Preliminary Virtual Assessment Team (P-VAT) report** released on October 4, 2018 and available on Design Safe:
https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/%2FPRJ-2104.

This **Early Access Reconnaissance Report (EARR)** is the second StEER product, which is intended to:

1. provide an overview of the event, particularly as it relates to the respective impacts of the earthquake and tsunami on structures
2. overview StEER's event strategy in response to this event
3. summarize the activities, methodologies and preliminary findings of the StEER's first Field Assessment Team (FAT-1)
4. Identify potential areas of interest for future field assessment teams and recommendations for future research regarding this event.

It should be emphasized that all results herein are preliminary and based on a high-level assessment of data collected in the field. As such, the data has not yet been processed by the StEER Quality Assurance protocol. Damage discussed herein is based largely on the judgement of the surveyor on the ground.

Note: A number of videos and 3D imagery are referenced in the following pages. If the links cited no longer provide access to these videos/images, readers can access an archived copy at DesignSafe -- follow this link and search for Project Number PRJ-2128 to access the directories of videos and 3D imagery. Please note that the referenced eyewitness videos have been reposted repeatedly on social media; therefore, it is nearly impossible to identify (and acknowledge) the original source of the footage in most cases. A photo/video log is included in the DesignSafe directory providing additional descriptions and sources of these curated assets.

Geophysical Background and Tsunami Generation

On September 28, 2018, at 17:02 local time (10:02 UTC), a magnitude 7.5 earthquake occurred with an epicenter 78 km North of Palu, Sulawesi Island, Indonesia, at a depth of 10 km (Figure 1) (USGS, 2018a). The earthquake was caused by movement on a strike-slip fault known as the Palu-Koro Fault (Figure 2).

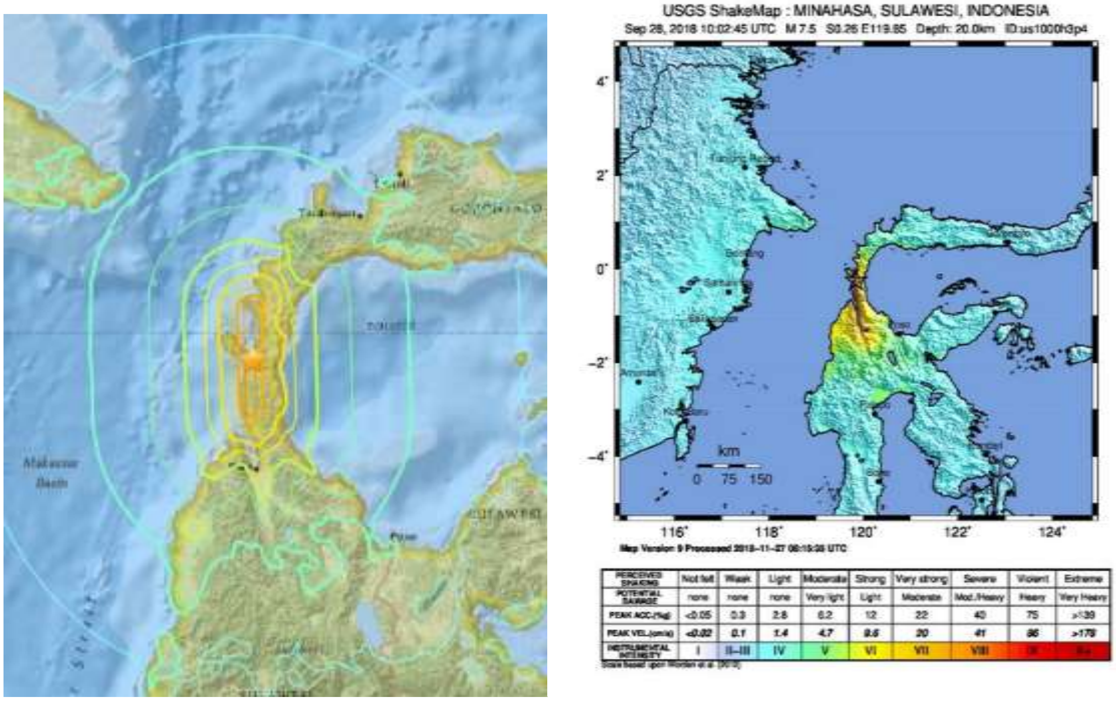


Figure 1: USGS ShakeMap products for Palu, Sulawesi, Indonesia (USGS, 2018a)

Preliminary finite fault results developed by USGS are shown in Figure 3 (USGS, 2018b). The fact that a damaging tsunami was generated by a M7.5 strike-slip earthquake makes this a particularly interesting case. ASCE 7-16 tsunami design zone maps include the effects of strike-slip faults in the Puget Sound area of Washington State, because of potential for similar local-source tsunami generation. Whether or not the tsunami was the result of the earthquake alone or combination of earthquake and submarine landslide will require additional geophysical and geotechnical investigation, as well as numerical tsunami modeling.

A number of Closed Circuit TV (CCTV) and survivor videos captured the earthquake ground shaking. Since the earthquake occurred at sunset, many residents were in mosques for evening prayers. A CCTV video from one of these mosques shows the occupants leaving the mosque as the shaking intensified. The video is available at: https://youtu.be/yBSbUFJDuQE [DesignSafe archived video: Mosque Video].

A dashcam video from a car driving along the coast of Palu bay captured the earthquake shaking. The immediate response of most pedestrians in the area was to head for high ground, indicating the level of awareness of the local community that earthquake shaking could be followed by a tsunami. The video is available at: https://youtu.be/aAPfHEKPxBA [DesignSafe archived video: Video from car].

A closed circuit TV in the town of Wani on the East coast of Palu Bay captured the earthquake shaking starting at 18:02:54 followed by the tsunami wave at 18:06:30 indicating that at that location it took only three and a half minutes for the tsunami waves to arrive. The video is available at: https://youtu.be/oBvx32WgxnY [DesignSafe archived video: CCTV Wani].

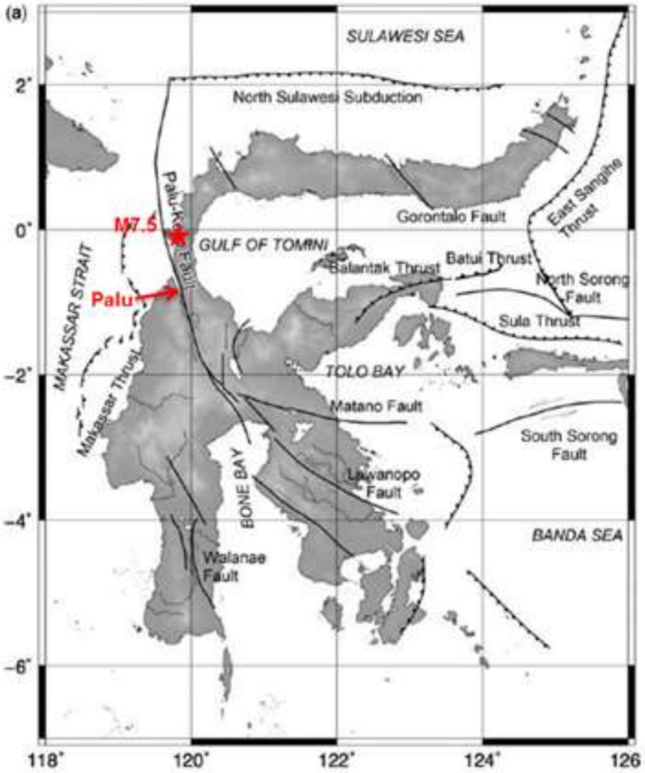
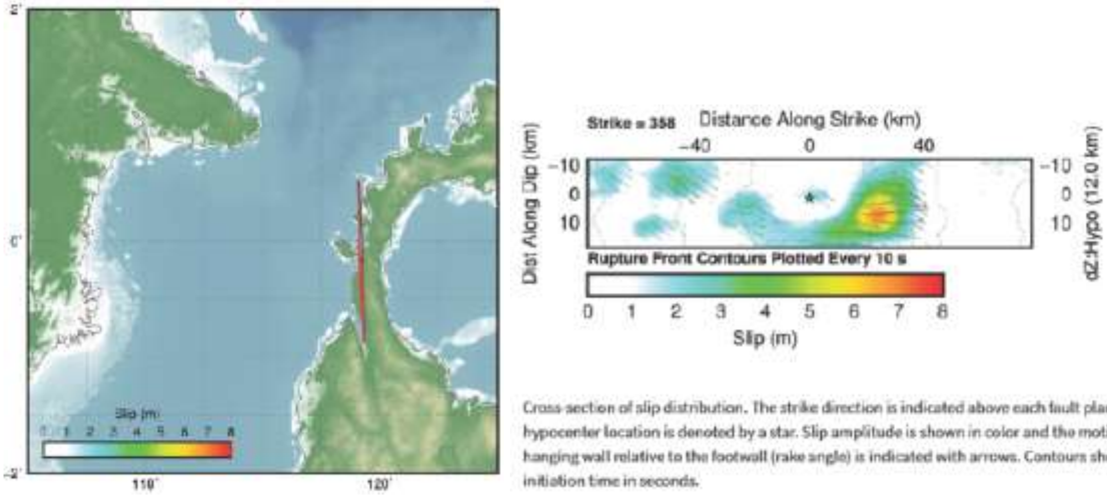
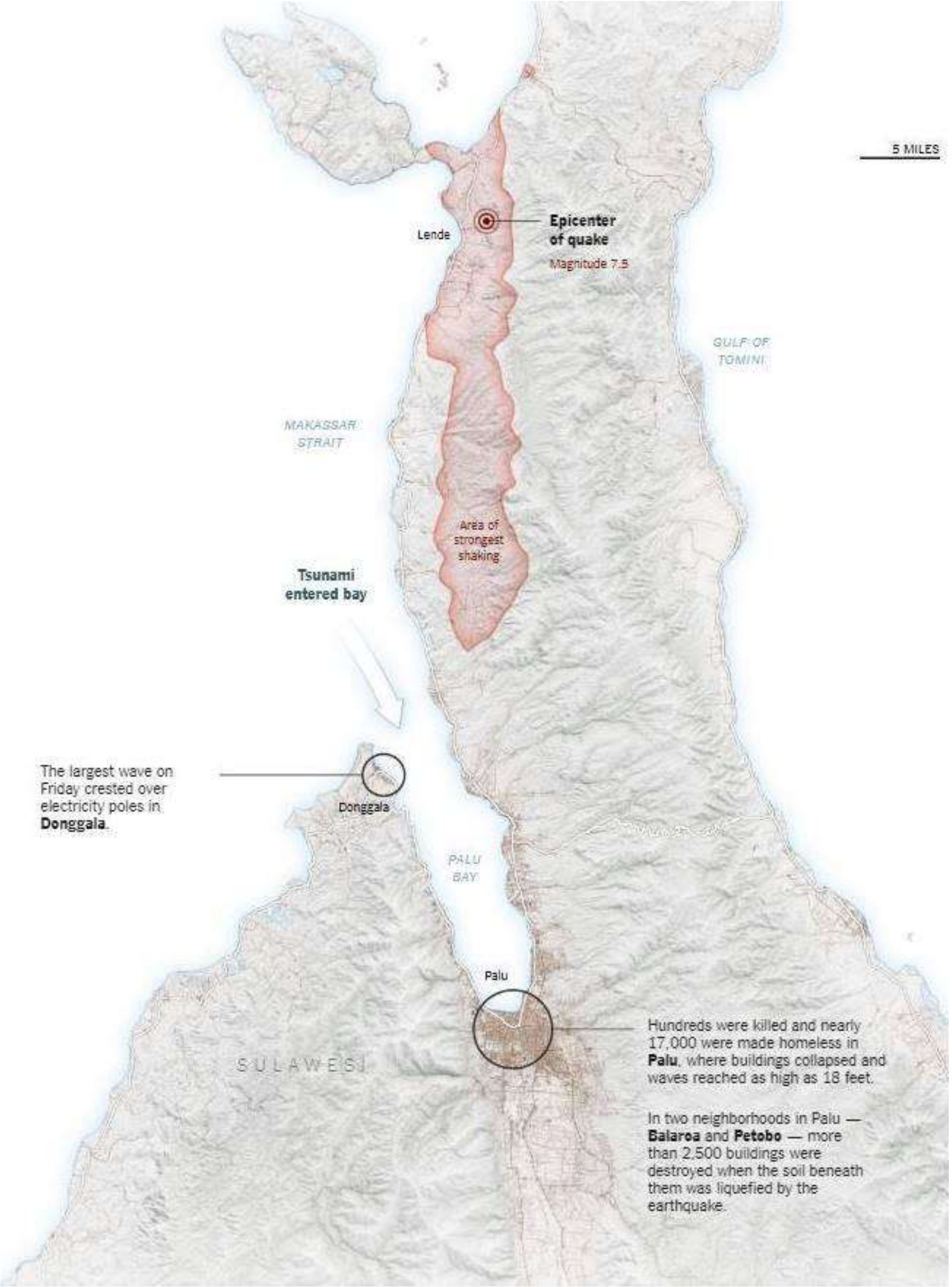


Figure 2: Earthquake location along Palu-Koro Fault (Source: Jascha Polet @CPPGeophysics)



Cross-section of slip distribution. The strike direction is indicated above each fault plane and the hypocenter location is denoted by a star. Slip amplitude is shown in color and the motion direction of the hanging wall relative to the footwall (rake angle) is indicated with arrows. Contours show the rupture initiation time in seconds.

Figure 3: USGS Fault Analysis (USGS, 2018b)



The largest wave on Friday crested over electricity poles in **Donggala**.

Hundreds were killed and nearly 17,000 were made homeless in **Palu**, where buildings collapsed and waves reached as high as 18 feet.

In two neighborhoods in Palu — **Balaroa** and **Petobo** — more than 2,500 buildings were destroyed when the soil beneath them was liquefied by the earthquake.

Figure 4: Graphic showing relative location of the city of Palu, Donggala town and the earthquake epicenter (New York Times, 2018)

The city of Palu, with a population of 336,000 based on a 2010 census (Wikipedia, 2018b), is located in an alluvial valley at the end of the narrow Palu Bay (Figure 4). The town of Donggala is located near the mouth of Palu Bay. Figure 5 shows an aerial view of the relative locations of Donggala and Palu on the shores of Palu Bay. Preliminary tsunami modeling reported by CATnews indicates that the bathymetry of the Palu Bay amplified the tsunami wave significantly compared with other coastlines outside of the bay (Figure 6).

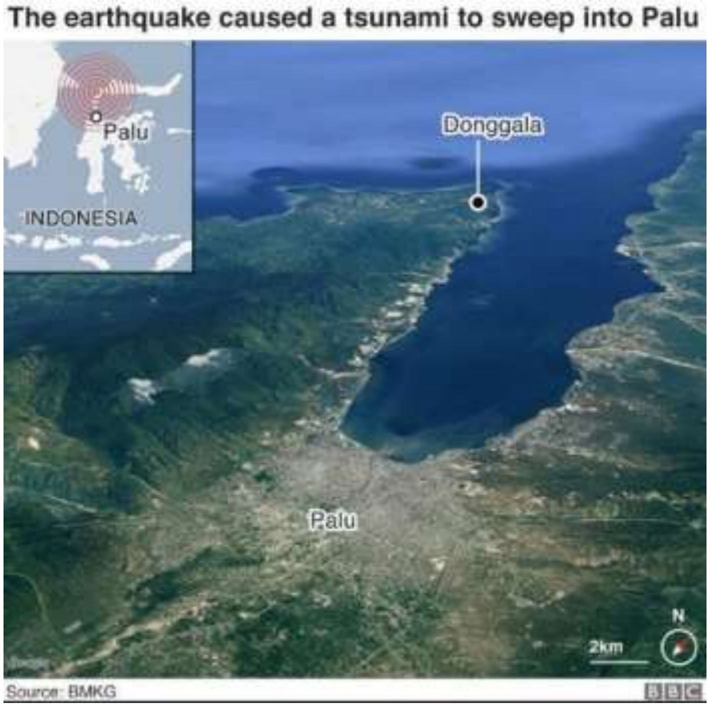


Figure 5: Location of the city of Palu and Donggala town on elongated bay (Source: BMKG/BBC).

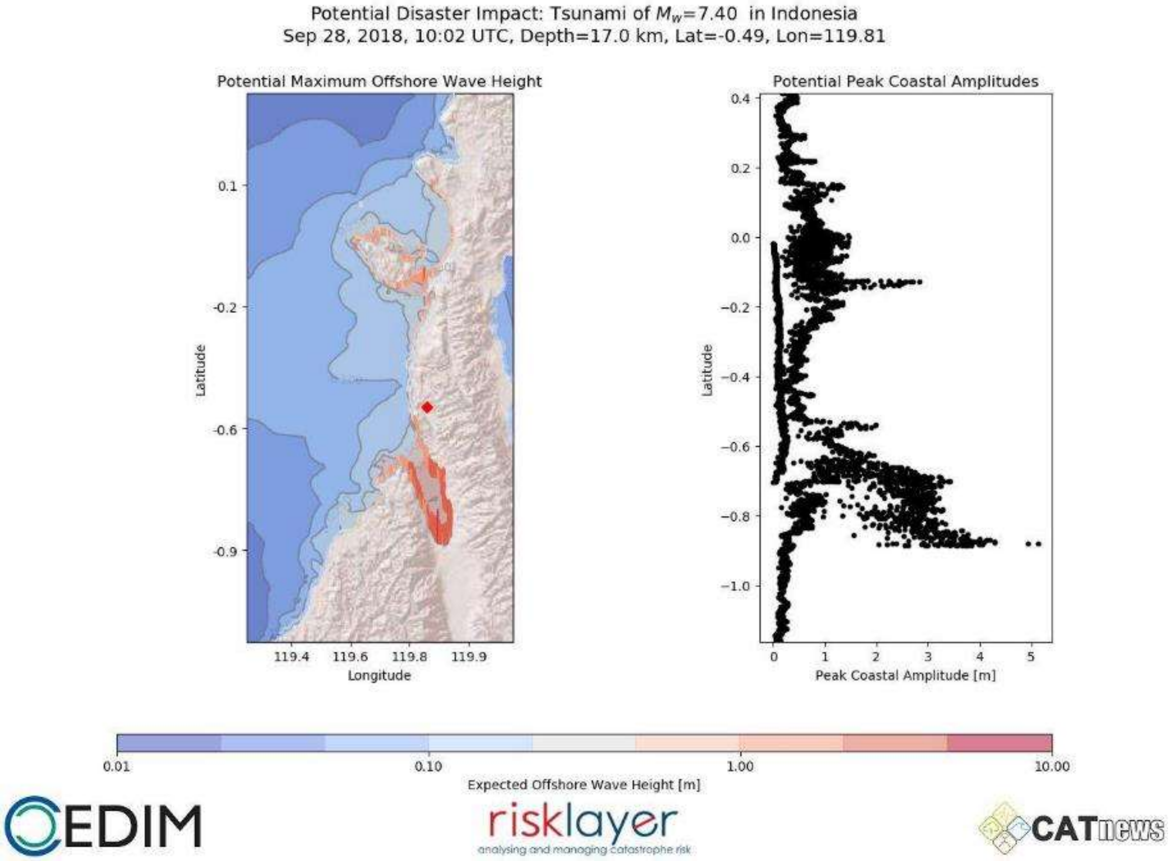


Figure 6: Tsunami wave height model prediction (Source: CATnews, 2018; @CATnewsDE)

Contrary to early assumptions that the tsunami wave entered Palu Bay from the North (as indicated in Figure 4), eye-witness reports, survivor videos and the timing of the arrival of the first waves indicate that the source was more likely in the bay itself. The prevalent theories are that the tsunami waves were generated by a combination of co-seismic slip along the fault plane and submarine landslides around the bay perimeter, and possibly deep inside the bay bathymetry. The potential for co-seismic tsunami generation due to slip along the fault plane is illustrated in Figure 7. Relative movement across the fault is on the order of 5 meters with the right side of the bay moving north by as much as 3 meters. Because of the steep bathymetry at the south end of the bay, this movement could result in significant displacement of the water in the bay.

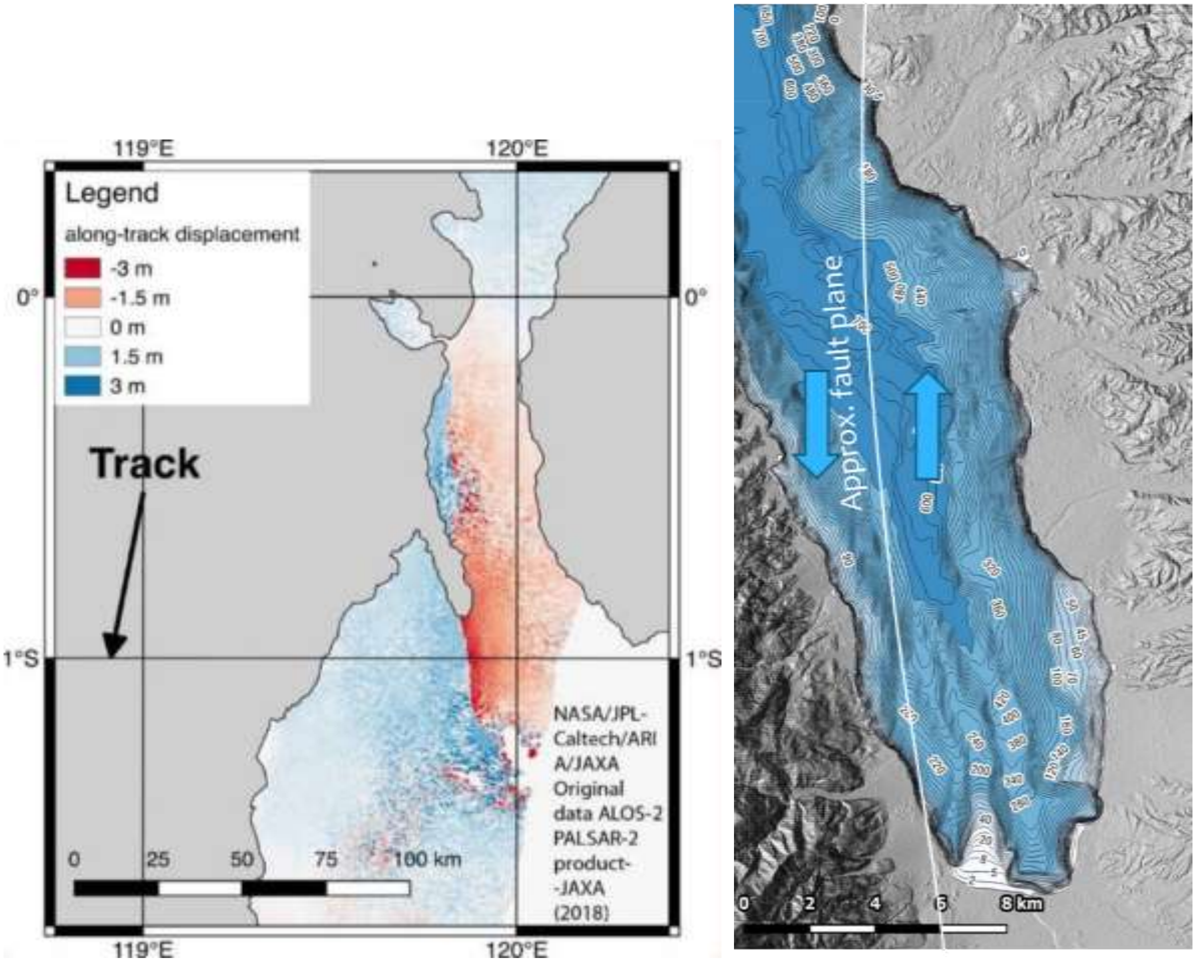


Figure 7: Co-seismic slip along the fault plane based on satellite data (left) (Source: Eric Fielding @EricFielding, NASA/JPL) and superimposed on the bay bathymetry (right) (Source: Sotiris Valkaniotis @SotisValkan and Geospatial Information Agency BIG).

Numerous potential submarine landslides have been identified around the perimeter of Palu Bay. A number of these slides on the West side of the bay are known to have generated tsunami waves based on a 12 second video captured by Batik Airline pilot Ricosetta Mafella as he piloted the last flight out of Palu airport before the earthquake occurred (https://youtu.be/rXvQunKPkDQ) (DesignSafe archived video: Pilot Video). FAT-1 members met with Pilot Mafella to discuss his observations during this flight. He reported that he did not observe any tsunami generation on the East side of the bay, but his flight path was over the East coastline and some of the suspected submarine slides were below and behind his position at the time of taking the video. Other slide locations were identified by comparing before and after earthquake images in Google Earth and other aerial and satellite imagery.

Figure 8 shows thirteen locations where submarine landslides are either confirmed or suspected. The subsequent figures show each of these slide locations in greater detail. Many of the slides occurred at river mouths where loose deposits would have accumulated over time. Some of these coastal deposits were augmented by fill material in order to develop level coastal areas for loading gravel onto barges, particularly along the West side of the bay. This reclaimed land increased the burden on the poorly consolidated river deposits, potentially enhancing the potential for slides. As seen in Figure 7, the bathymetric slope adjacent to both West and East coastlines is relatively steep, increasing the potential energy available for these slides.

Figure 8: Locations of 13 suspected submarine landslides that generated tsunami waves

Figure 9 shows the location of Slide 1 at a river mouth just to the East of the port at Donggala. Judging from the surface area that has dropped away with the slide, it is likely that a considerable volume of material was involved in this slide, with the potential for generating large tsunami waves. However, these waves are oriented predominantly in a Northeast direction, away from Palu Bay.

Figure 9: Google Earth images of the location of Slide 1 in Donggala town (0.667S, 119.746E) before (left) and after (right) the earthquake.

Figure 10 shows an image from the video taken by Pilot Mafella looking towards the West coastline of Palu Bay. The tsunami waves generated by landslides 2, 3 and 4 can be identified.

Figure 10: Still image from the video recorded by pilot Ricosetta Mafella soon after taking off from Palu airport showing tsunami waves radiating from Slides 2, 3 and 4 (Courtesy of Pilot Mafella).

Figure 11 shows before and after Google Earth images of the suspected location of Slide 2, where the coastline has receded as the delta at the end of a small river presumably slid into the bay. Figure 12a and b respectively show the suspected locations of Slides 3 and 4, both at the mouths of rivers. The sedimentary river deposits at Slide 3 had been augmented by gravel fill to create the reclaimed land for a barge loading area. Much of this material fell away with the slide.

Figure 11: Google Earth images of the location of Slide 2 (0.755S, 119.787E) before (left) and after (right) the earthquake.

Figure 13 shows another still image from the video taken by Pilot Mafella. This view of the West side of Palu Bay shows the generation of four separate tsunami waves, presumably from four submarine landslides, numbered from 5 to 8 in the image. Figure 14 and Figure 15 show the suspected locations of these four slides. Slides 5, 6 and 7 appear to be associated with gravel loading docks while Slide 8 is at the mouth of a large river, which was also filled with gravel to form a gravel loading dock.

Between Slides 5 and 6, another survivor video was captured by a worker on one of the tugs adjacent to a gravel barge (https://youtu.be/61ItBglP-YM) (DesignSafe archived video: Tug Video). The video starts looking towards the North where Slide 4 can be seen in the distance. It then spins to the South as Slide 8 occurs (Figure 16). The video then pans around the East side of the bay, but is too far away to capture any tsunami generation on that shoreline. As it pans back to the North, Slide 5 becomes visible beyond the barge (Figure 17). Suddenly the sound of a rockslide draws the videographer's attention back to the South where Slide 6 has just initiated within 50 meters of the tug (Figure 18). The videographer is heard exclaiming “Gempa!” which means “Earthquake”. Numerous dust clouds are visible on the hillside coming from the gravel piles and quarries feeding the gravel trade.

The effects of the tsunami waves were captured by eyewitness videos from at least two other ships in Palu Bay. One ship was on the West coast of the bay at a similar location to the tug boat. It captures the ocean turbulence around the container vessel (https://twitter.com/i/status/1045666942919442432, DesignSafe archived video: Ship 1 Video). The second ship was located adjacent to a pier on the East coast of Palu Bay (Lat: 0.7795S, Long: 119.858E). It shows dramatic sea level fluctuations around the pier and the resulting movement of the ship (https://www.youtube.com/watch?v=9dxb1u_DUHg, DesignSafe archived video: Ship 2 Video).

Figure 12: DigitalGlobe images of the location of (a) Slide 3 (0.801S, 119.806E) and (b) Slide 4 (0.808S, 119.811E), before (left) and after (right) the earthquake.

Figure 13: Still image extracted from the 12 second video recorded by pilot Ricosetta Mafella soon after taking off from Palu airport showing tsunami waves generated by slides 5 through 8 (Courtesy Pilot Mafella).

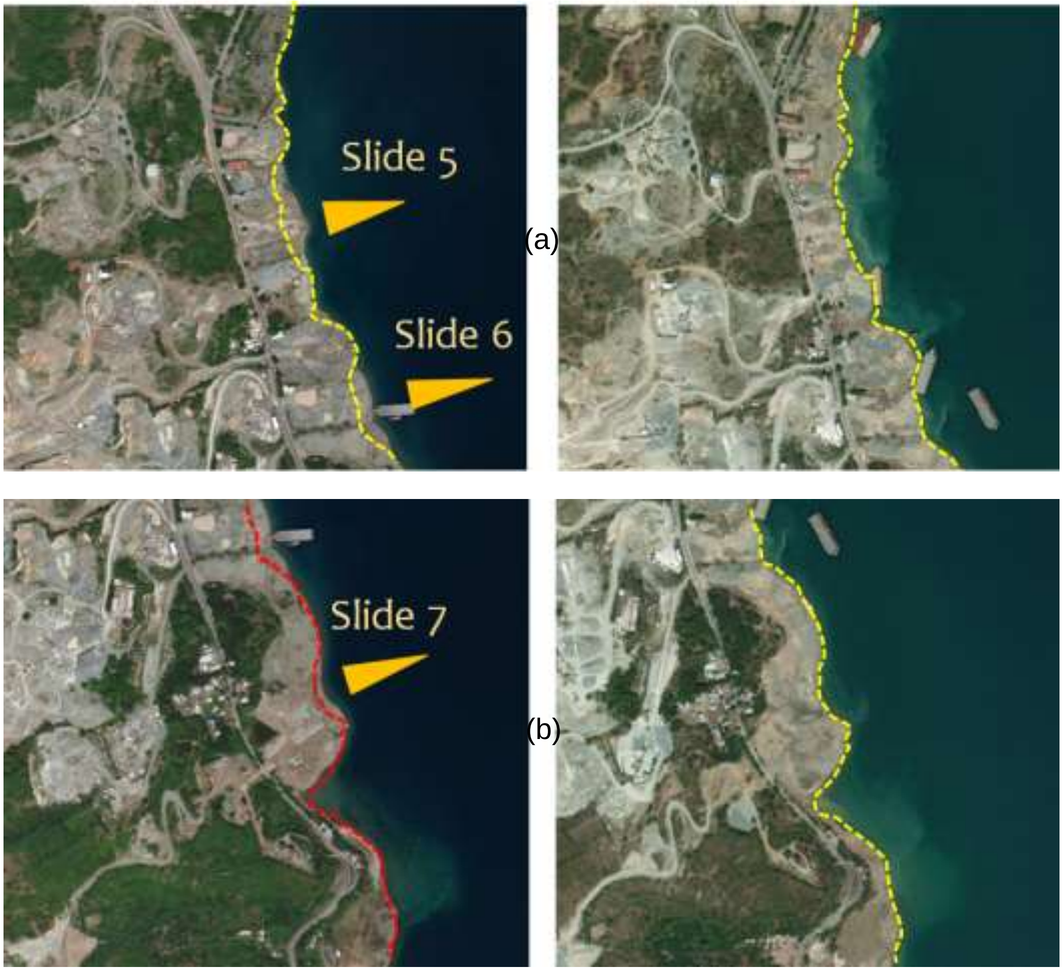


Figure 14: DigitalGlobe images of the location of (a) submarine landslides 5 (0.8282S 119.81175E) and 6 (0.831127S, 119.81279E) and (b) submarine landslide 7 (0.83373S 119.8137E), before (left) and after (right) the earthquake.

Figure 15: DigitalGlobe images location of submarine landslide 8 (0.846S, 119.823E) before (left) and after (right) the earthquake.

Figure 16: Video image from tug looking South at the tsunami wave generated by slide 8.

Figure 17: Video image from tug looking North at the tsunami waves generated by slides 4 and 5.

Figure 18: Video image from tug looking Southwest at the tsunami wave generated by slide 6.

On the South shore of Palu Bay evidence points to at least three landslides. Figure 19 shows the change in shoreline to the West of the Palu River mouth, suspected to be the result of a submarine slide.

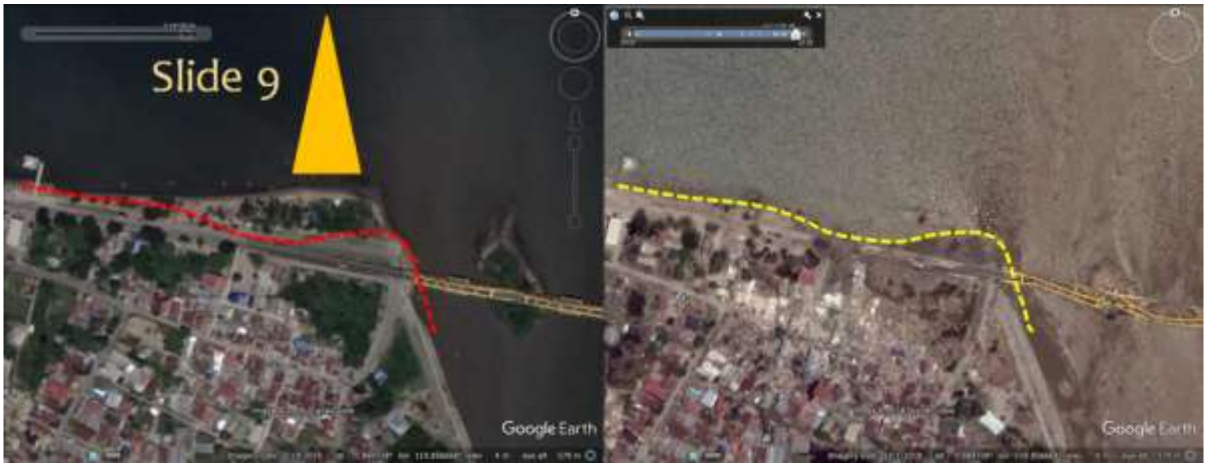


Figure 19: Google Earth images of the location of Slide 9 on the South shore of Palu Bay West of the Palu River mouth (0.88474S, 119.857E) before (left) and after (right) the earthquake.

Figure 20 shows the change in shoreline resulting from a suspected landslide just to the East of the Palu River mouth. Some of this area may have been reclaimed land to create the park area seaward of the coastal highway.

Figure 20: Google Earth images of the location of Slide 10 on the South shore of Palu Bay East of the Palu River mouth (0.8855S, 119.863E) before (left) and after (right) the earthquake.

Figure 21 shows the dramatic shoreline change resulting from another suspected landslide in Talise on the Southeast corner of Palu Bay. This slide is again associated with a river mouth deposit, possibly augmented by fill material to create the coastal esplanade on either side of the river mouth. A portion of the coastal highway and a bridge over the river mouth were lost along with the slide. Figure 22 shows a view looking South along the original alignment of the coastal highway, with the remaining bridge abutment and a leaning house on the far side of the slide crater.

Figure 21: Google Earth images of the location of Slide 11 on the Southeast shore of Palu Bay in Talise (0.879S, 119.871E) before (left) and after (right) the earthquake.

Figure 22: View along original alignment of coastal highway (See Figure 21) that is suspected to have been part of landslide 11 in Talise.

Figure 23 shows evidence of another suspected landslide on the East shore of Palu Bay at the Taipa river mouth and adjacent barge loading area. Similarly, Figure 24 shows suspected Slide 13 at the Labuan River mouth, adjacent to another barge loading area.

Figure 23: Google Earth images of the location of Slide 12 on the East shore of Palu Bay at the mouth of the Taipa River (0.789S, 119.863E) before (left) and after (right) the earthquake.

Figure 24: Google Earth images of the location of Slide 13 on the East shore of Palu Bay at the mouth of the Labuan River (0.688S, 119.823E) before (left) and after (right) the earthquake.

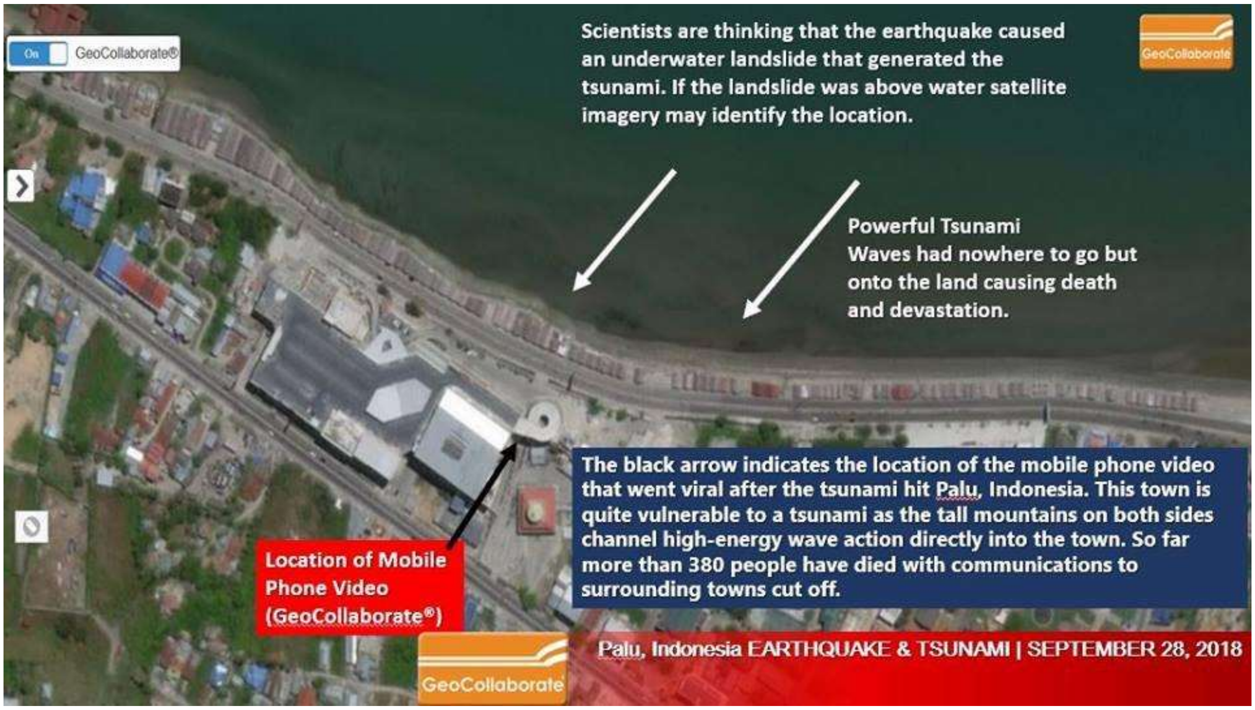
A more detailed analysis of the potential source of the tsunami waves in Palu Bay is currently under review for possible publication (Aránguiz et al., 2019).

A number of survivor videos of the tsunami waves are available online. Figure 25 shows three images extracted from a survivor video of a tsunami wave approaching the Palu shoreline as a broken bore. The nearshore area is already wet, indicating that this was not the first wave in the tsunami sequence. The full video is available at: https://twitter.com/i/status/1045682372623052802 [DesignSafe archived video: Broken Bore Video]. This video was taken from the top level of a circular ramp leading to the roof of a parking structure close to the shoreline (Figure 26).

Other survivor videos of the incoming tsunami waves are available at:

- https://twitter.com/i/status/1046151843888418816 [DesignSafe archived video: Eyewitness 1 Video]
- https://twitter.com/Sutopo_PN/status/1046140234390372352/video/1 [DesignSafe archived video: Eyewitness 2 Video]
- https://twitter.com/i/status/1046021328686534656 [DesignSafe archived video: Eyewitness 3 Video]
- https://twitter.com/cucuadamhawaa/status/1045644563577167872 [DesignSafe archived video: Eyewitness 4 Video]
- https://www.youtube.com/watch?v=ZylSvWAc2_Q [DesignSafe archived video: Eyewitness 5 Video]
- https://www.youtube.com/watch?v=HIaOF-obHJ4 [DesignSafe archived video: Eyewitness 6 Video]

Figure 25: Images from survivor video taken from parking structure spiral ramp as tsunami bore approached the Palu shoreline (Source: https://twitter.com/i/status/1045682372623052802 [DesignSafe archived video: Broken Bore Video]).



Scientists are thinking that the earthquake caused an underwater landslide that generated the tsunami. If the landslide was above water satellite imagery may identify the location.

Powerful Tsunami Waves had nowhere to go but onto the land causing death and devastation.

The black arrow indicates the location of the mobile phone video that went viral after the tsunami hit Palu, Indonesia. This town is quite vulnerable to a tsunami as the tall mountains on both sides channel high-energy wave action directly into the town. So far more than 380 people have died with communications to surrounding towns cut off.

Palu, Indonesia EARTHQUAKE & TSUNAMI | SEPTEMBER 28, 2018

Figure 26: Graphic showing location of survivor taking video of incoming tsunami bore (Source: GeoCollaborate) (0.8837 S, 119.8438 E).

Tsunami Warning and Evacuation

After the 2004 Indian Ocean tsunami, which resulted in over 170,000 deaths in Indonesia alone, considerable effort was directed to developing the country's tsunami early warning system. This included installation of ocean bottom pressure sensors with transmission buoys along the subduction zone to the West and South of the Indonesian island chain, as well as near some of the strike-slip faults between the islands (Figure 27). Based on the location of these buoys, it is unlikely that any of them would have registered a tsunami wave in time to issue a warning for the Palu Bay area, particularly because many of the waves were generated inside Palu Bay either by co-seismic slip or submarine landslides.

The Australian Broadcasting Corporation (ABC, 2018) reported that the number of deaths during this tsunami highlights:

> *"the weaknesses of the existing warning system and low public awareness about how to respond to warnings. A network of 22 buoys connected to seafloor sensors was meant to transmit advance tsunami warnings to the Indonesian meteorology and geophysics agency (BMKG). But Sutopo Purwo Nugroho, spokesman for the National Disaster Mitigation Agency (BNPB), said the detection buoys had not worked since 2012 due to a lack of funding*."

Many of the buoys had been disabled by vandalism, theft or just stopped working due to a lack of funds for maintenance. ABC also reported that:

> *"since the 2004 tsunami, the mantra among disaster officials in Indonesia has been that the earthquake is the tsunami warning and signal for immediate evacuation; [however,] the fact that people were still milling around Palu's*

shoreline when waves were visibly approaching shows the lessons of earlier disasters haven't been absorbed."

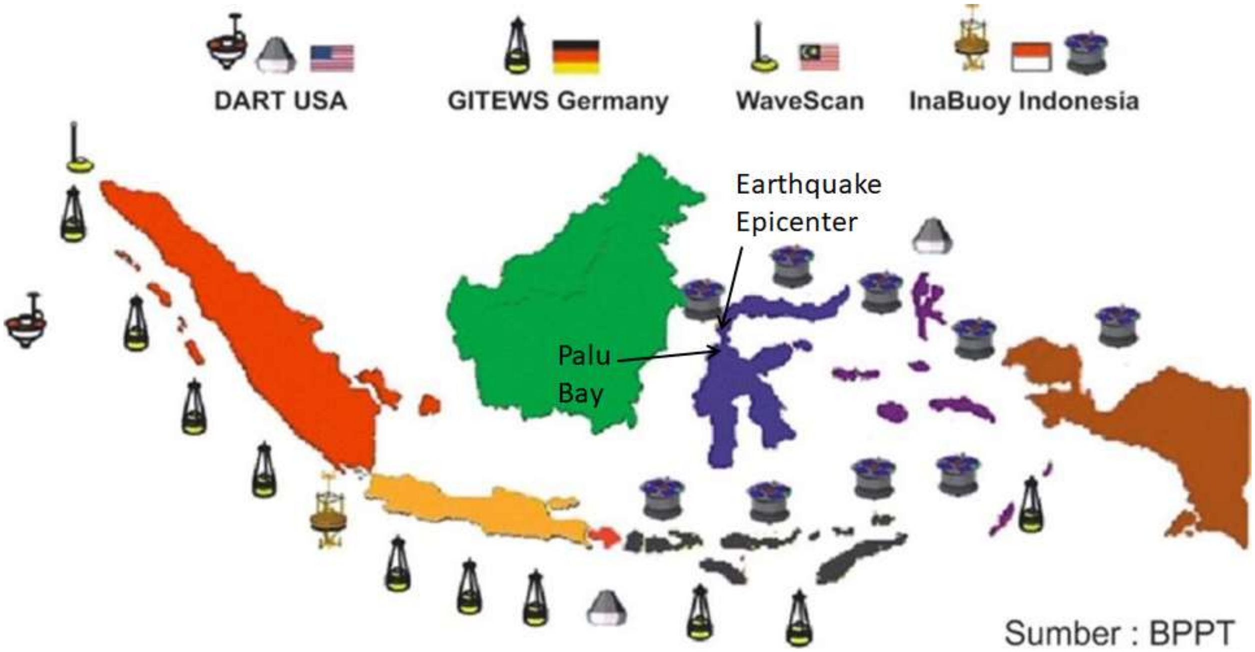


Figure 27: Graphic showing location of tsunami buoys around the Indonesian Islands (Source: BPPT, Indonesian Agency for the Assessment and Application of Technology).

StEER Response Strategy

Following a request from Indonesia, UNESCO's Intergovernmental Oceanographic Commission, in collaboration with Indonesian authorities led by the National Commission of Indonesia for IOC-UNESCO and The Coordinating Ministry for Maritime Affairs, coordinated post-tsunami surveys by International Tsunami Survey Teams (ITST-Palu). This effort was headquartered at the Indian Ocean Tsunami Information Centre (IOTIC) – BMKG Programme Office in Jakarta. ICT helped to ensure that the scientific surveys are well organized, effective and productive. ICT worked to promote sharing of data among filed teams, minimize logistical problems for visitors/hosts, link visiting researchers to Indonesian collaborators and provide a summary report to the Government of Indonesia based on reports from all survey teams. All international researchers planning to undertake post-tsunami field surveys were requested to contact ITST-Palu before planning their missions and to target a recommended window for their work (October 18 to November 30, 2018). All teams were required to work closely with an Indonesian collaborator for the field survey and also to obtain appropriate research/survey permits and visas.

FAT-1 represented the first and only StEER team on the ground and consisted of one StEER expert (Ian Robertson, StEER's Associate Director for Assessment Technologies) embedded within a team of Japanese and Indonesian researchers. FAT-1 collected data from October 27 to 31, 2018 along the entire coastline of Palu Bay. The primary objectives of the mission were to:

1. Deepen the understanding around tsunamis generated by slip-strike faults (a particular concern for the west coast of the US);

2. Document the performance of structures during both the earthquake and tsunami, and particularly the sequential effects of both events;
3. Field validate some of the tsunami loading expressions in ASCE 7-16 based on forensic analysis of damaged and near-collapse structures;
4. Establish which areas should be investigated by others teams or follow up NSF RAPIDs/StEER FATs.

Detailed forensic investigations were generally not achievable within the scope and time limits of FAT-1. Instead, FAT-1 focused on broadly assessing infrastructure performance over large expanse of the impacted area and over a wide range of structural typologies. Follow-up teams are assumed to then focus on specific typologies or regions. While hypothesis-driven research is generally outside of the scope of StEER, data collected by StEER can be used for these purposes in some cases.

The international research team was organized by Professors Shibayama and Esteban of Waseda University, Tokyo, Japan (Figure 28). The primary objectives of the team were to measure tsunami inundation, ascertain the source of the tsunami, and observe damage caused by the earthquake and tsunami. The team received significant logistical and planning assistance from Hendra Achiari, a lecturer at Bandung Institute of Technology in Bandung, West Java, Indonesia. He was assisted in the field by one of his students, Fadel Marzuki, and his brother, Gafur Marzuki, a lecturer at the State Institute for Islamic Studies in Palu, both of whom had grown up in Palu and knew the area well. Names, affiliations and roles of the team are summarized in Table 1.

Figure 28: Palu Survey Team Members: Back row (Left to Right): Jacob Stolle, Tomoyuki Takabatake, Takahito Mikami, Ryota Nakamura, Yuta Nishida. Front Row (Left to Right): Muhamad Fadel Marzuki, Abdul Gafur Marzuki, Hendra Achiari, Tomoya Shibayama, Ian Robertson, Clemens Krautwald, Miguel Esteban.

Table 1. International Team of Collaborators for FAT-1

Name	Position	University	Team Role
Tomoya Shibayama	Professor	Waseda University	Team Leader & Tsunami Inundation Survey
Miguel Esteban	Professor	Waseda University	Bathymetry Survey
Ian Robertson	Professor	University of Hawaii	Structural Damage Survey
Takahito Mikami	Asso. Professor	Tokyo City University	Tsunami Inundation Survey
Tomoyuki Takabatake	Asst. Professor	Waseda University	Tsunami Inundation Survey
Ryota Nakamura	Asst . Professor	Toyohashi University of Technology	Aerial Survey
Yuta Nishida	Graduate Student	Waseda University	Aerial Survey
Jacob Stolle	Graduate Student	University of Ottawa	Structural Damage Survey
Clemens Krautwald	Graduate Student	Technical University of Braunschweig	Structural Damage Survey
Hendra Achiari	Lecturer	Bandung Institute of Technology	Logistical Coordination
Abdul Gafur Marzuki	Lecturer	State Institute for Islamic Studies Palu	Logistical Assistance
Muhamad Fadel Hidayat Marzuki	Graduate Student	Bandung Institute of Technology	Logistical Assistance

The team organized into four distinct survey groups:

i) **Tsunami Inundation Survey:** Professor Shibayama and Associate Professors Takahito Mikami and Tomoyuki Takabatake performed tsunami inundation elevation and runup surveys on all sides of Palu Bay and as far North as the earthquake epicenter.

ii) **Bathymetric Survey:** Professor Esteban rented a speedboat for all three days and performed sonar scans using a GARMIN 585 Plus echosounder of the West and South coastal zones of Palu bay to identify potential submarine landslide evidence.

iii) **Aerial Survey:** Assistant Professor Ryota Nakamura and Yuta Nishida, a graduate student at Waseda University, performed numerous aerial surveys using a DJI Phantom 4 Pro+ quadcopter drone. Aerial surveys covered tsunami inundation regions and individual structures damaged by the earthquake and liquefaction-induced lateral spreading.

iv) **Structural Damage Survey:** Professor Robertson and graduate students Jacob Stolle of the University of Ottawa, Canada and Clemens Krautwald of the Technical University of Braunschweig in Germany performed structural surveys on all sides of Palu bay and at significant earthquake damaged buildings in Palu City.

Apart from the bathymetric survey, each group was accompanied by one of the three Indonesian collaborators. While the groups performed their reconnaissance, the collaborators interviewed local residents who had witnessed the tsunami first hand. During the three days they completed over 200 interviews, collecting useful data about how residents in the tsunami inundation area responded to the event. A copy of the interview form (translated into English) is provided in the Appendix. The survey data are still being analyzed and will be published as soon as they are ready.

Local Codes & Construction Practices

Indonesian Seismic Code

The Indonesian Seismic Code (2012) provides mapped peak ground accelerations (PGA) for the Maximum Considered Earthquake (MCE_G) (Figure 29) and spectral accelerations for short period (S_S) (Figure 30) and 1 second period (S_1) response (Figure 31). The MCE is defined as having a 7% chance of exceedance in 75 years, which represents a return period of about 1000 years.

- The mapped PGA for Palu is 0.8-0.9g (Figure 29). The surrounding areas outside of the alluvial valley have a PGA of 0.6g.
- The 0.2 second short period spectral acceleration is 1.2-1.25g, while surrounding areas outside of the alluvial valley vary from 1.05-1.15g (Figure 30).
- The 1 second period spectral acceleration is 1.0-1.05g for Palu and the surrounding areas (Figure 31).

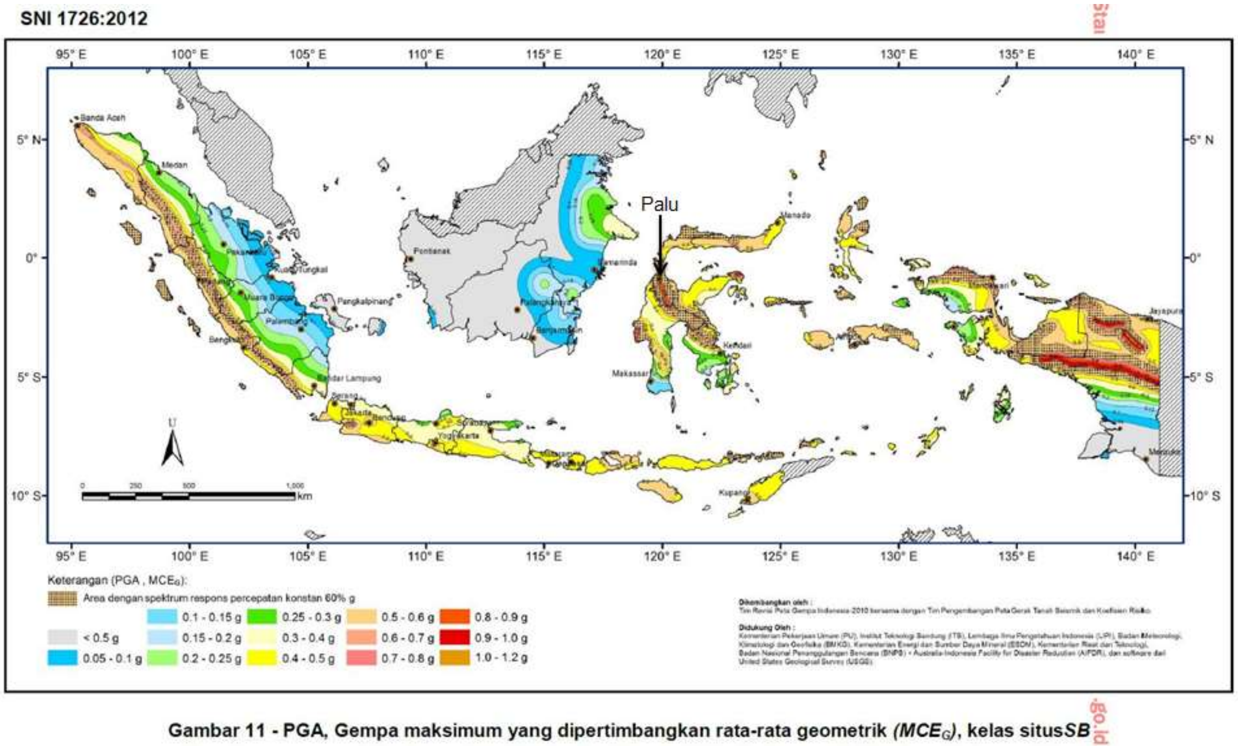
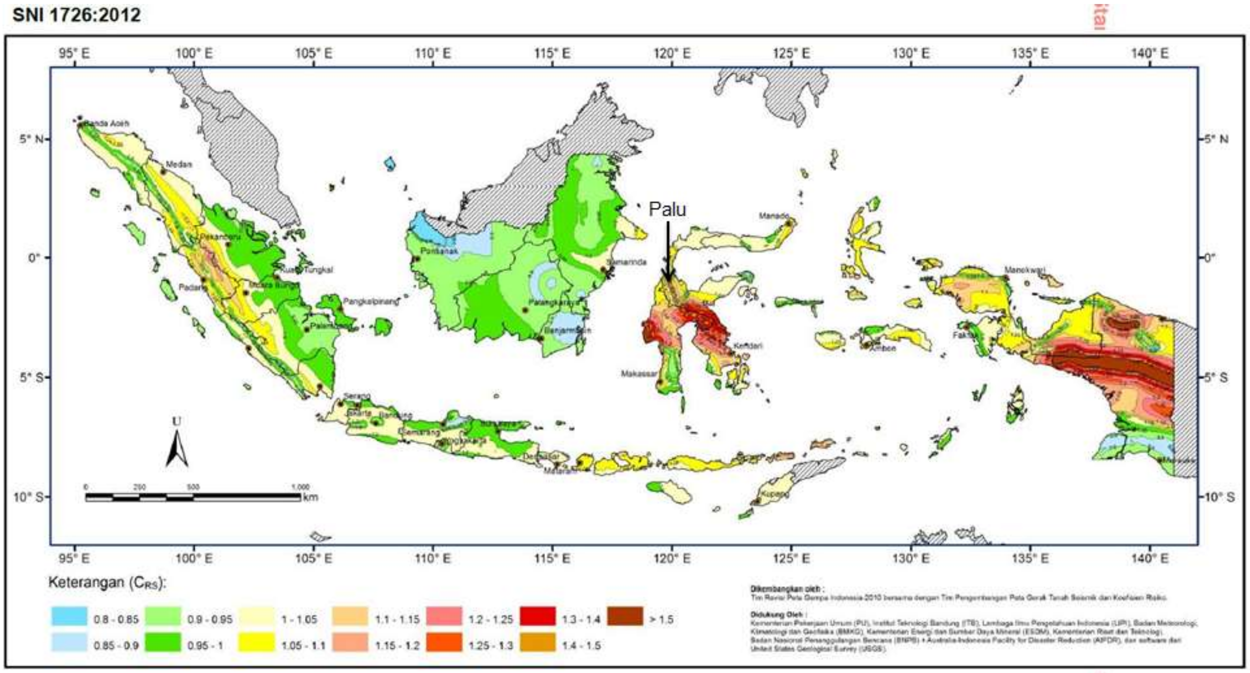
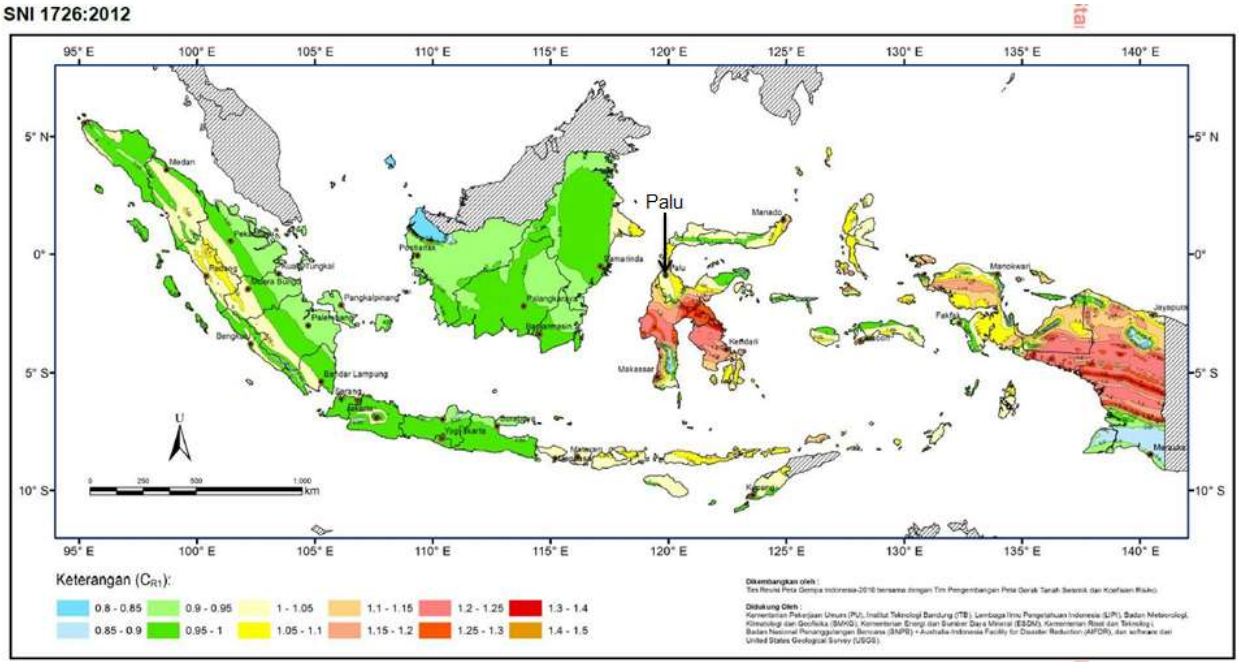


Figure 29: Indonesian Seismic Code map for MCE_G for site class SB (Source: Indonesian Seismic Code (2012)).



Gambar 12 - C_{RS}, **Koefisien risiko terpetakan, perioda respons spektral 0,2 detik**

Figure 30: Indonesian Seismic Code risk coefficient map for 0.2 second spectral response (Source: Indonesian Seismic Code (2012)).



Gambar13 -C_{R1}, **Koefisien risiko terpetakan, perioda respons spektral 1 detik**

Figure 31: Indonesian Seismic Code risk coefficient map for 1 second spectral response (Source: Indonesian Seismic Code (2012)).

Indonesian Concrete Code

The Indonesian code for reinforced concrete construction is modeled on the American Concrete Institute ACI-318 Building Code. Because of the high seismicity in and around Palu, design of reinforced concrete buildings would have included seismic requirements in ACI-318 Chapter 21 applicable to Seismic Design Categories D, E or F. Amongst other requirements, these seismic design provisions include the following:

- Requirements to ensure “strong-column, weak-beam” performance for moment resisting frames.
- Requirements for joint confinement reinforcement at beam-column connections.
- Requirements for enhanced confinement of column members supporting walls that do not continue to the foundation.
- Requirements for shear design of beams and columns to avoid shear failure prior to formation of flexural hinges.

It appears that some of these requirements were not applied consistently, possibly contributing to some of the failures of relatively new reinforced concrete buildings described later in this report.

Prior Earthquake and Tsunami Events

Because of its large geographical expanse and its location on the Pacific Ring of Fire, Indonesia has experienced numerous prior earthquakes and tsunami events. Based on the records of the USGS, Indonesia has had more than 150 earthquakes with magnitude > 7.0 in the period 1901–2017 (Wikipedia, 2018a). These include:

- December 26, 2004: the devastating earthquake and tsunami, which resulted in over 170,000 deaths in Indonesia alone.
- On May 27, 2006: a 6.4 magnitude earthquake at Yogyakarta on Java caused 5,716 deaths and extreme damage.
- July 17, 2006: a 7.7 magnitude earthquake off Java caused a regional tsunami and 668 deaths.
- September 30, 2009: a 7.6 magnitude earthquake off Sumatra Island caused a local tsunami and 1,115 deaths.

Figure 32 shows the locations of major earthquakes affecting Indonesia since the 2004 Indian Ocean tsunami. It also shows locations of some of the more active volcanoes, including Anak Krakatau, which has been erupting since June 2018 and is the probable cause of a tsunami in the Sundra Strait between Sumatra and Java on December 22, 2018 (Robertson, et al., 2018).

Fourteen tsunami events have been recorded on Sulawesi Island between 1820 and 1982, and two events, which were generated along the Palu-Koro fault, produced significant tsunamis in Palu Bay, namely the December 1, 1927 and August 14 1968 events (Prasetya et al., 2001).

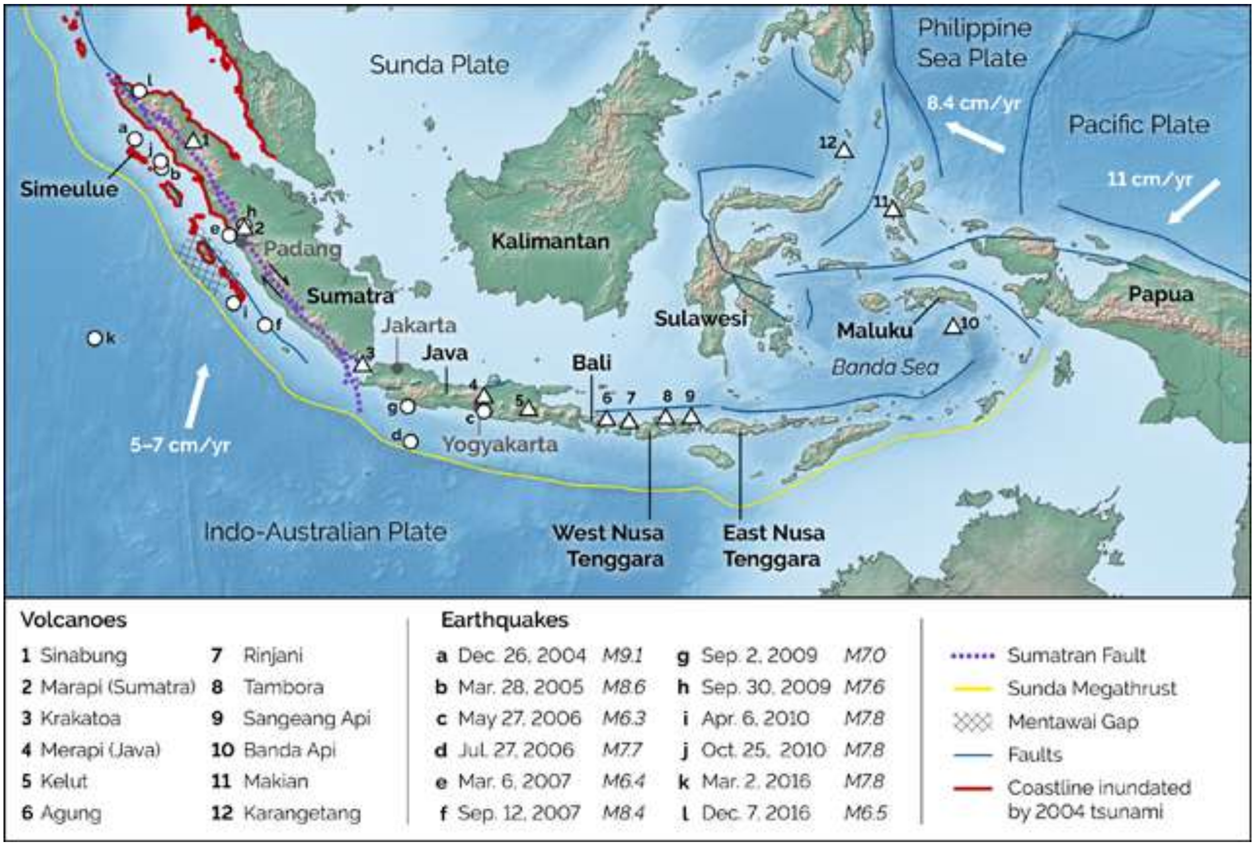


Figure 32: Map showing some of the major earthquakes that have struck Indonesia in recent years, along with the inundation zone of the December 2004 tsunami and a sampling of the country's many active volcanoes. (Earth, 2018; Credit: K. Cantner, AGI.)

Reconnaissance Methodology

The Structural Damage Survey group, consisting of Ian Robertson, Jacob Stolle and Clemens Krautwald, performed two days of tsunami damage reconnaissance along the coastline of Palu Bay, and one day of earthquake reconnaissance in Palu City. The sites selected for particular attention were determined prior to the trip based on available aerial imagery at the time. Subsequent to the survey, additional imagery has highlighted other areas of interest that were not captured during this survey, both because the team was not aware of them and because of the lack of time on the ground to do an exhaustive survey. Some of these missed opportunities were conveyed to subsequent survey teams from Europe and GEER in the hope that they may be able to capture more of the missing data.

Most of the survey was performed by visual inspection of the performance of various structures. If possible, eye-witnesses were interviewed to determine the sequence of damage, particularly in structures subjected to sequential earthquake and tsunami loading.

Seismic and Tsunami Damage Overview

Earthquake ground shaking affected the entire perimeter of Palu Bay. However, the predominant seismic damage was noted in Palu City, which sits on deep alluvial soil layers deposited by the Palu River. Very little evidence of seismic structural damage was observed outside of Palu City. A particularly damaging aspect of this earthquake event was the tremendous extent of lateral spreading attributed to liquefaction. Three neighborhoods in Palu City were almost completely destroyed by lateral spreading, resulting in an estimated loss of over 1000 lives and thousands of homes.

Most of the construction in Palu City consists of light timber-framed residential structures with sheet metal walls and roofing. These seldom experience structural damage during the earthquake. The next most common construction type is unreinforced masonry, where cracking was often observed, with occasional collapse of walls or portions of a structure due to seismic shaking. Taller and more substantial buildings were typically constructed of reinforced concrete frames with unreinforced masonry infill walls. Damage was often observed in the infill walls, with limited structural damage to the concrete frame elements, except in a few notable structures that partially or completely collapsed. A number of these structures are highlighted in the subsequent section on Performance of Engineered Structures.

Tsunami waves were generated both by the co-seismic fault movement and by submarine landslides around the perimeter of Palu Bay. These waves affected the entire coastline of Palu Bay, with some areas experiencing greater tsunami inundation than others. In particular the flat terrain along the Palu City coastline, and the focusing effects of Palu Bay and shallow bathymetry at its South end, resulted in the greatest extent of tsunami damage along the Palu City shoreline. However, areas of significant tsunami damage were also observed along the West and East shores of the bay, while other areas appeared to have very little inundation.

The Palu earthquake and tsunami presented an opportunity to study the sequential loading of structures by earthquake ground shaking followed by tsunami hydrodynamic and debris loading. This sequence of events is of interest to communities in Alaska and the northwest US where large subduction zone earthquakes are likely to be followed within minutes by damaging tsunami waves. However, performing reconnaissance after both events have taken place poses some challenges as to when the observed damage occurred. Fortunately, eye-witnesses were often available to report the extent of earthquake damage before they evacuated. Any additional damage was then attributed to the tsunami waves.

Light timber-framed structures in the inundation zone typically survived the earthquake but were completely destroyed by the tsunami waves (Figure 33). Low-rise reinforced concrete frame structures with unreinforced masonry infill walls also often to survive the earthquake shaking, but suffered wall blowouts due to tsunami hydrodynamic or debris impact loads (Figure 34).

Figure 33: Debris from light framed timber structures along the Palu shoreline (Credit: Jewel Samad/AFP).

Figure 34: Low-rise reinforced concrete frame structures with unreinforced masonry infill wall panels damaged by tsunami loads (Credit: Ian Robertson).

Damage due to Lateral Spreading

The earthquake ground shaking induced liquefaction over three large areas in and around Palu City, namely the Balaroa neighborhood, the Petobo Sub-district and Jono Oge Village (Figure 35). Even though the terrain slope was as low as 1 percent, these areas experienced lateral spreading that extended up to 3.5 kilometers.

A number of eyewitness videos captured these events as they occurred. These videos are available at the following links, or in DesignSafe:

- https://youtu.be/fvdpQKl_xxQ [DesignSafe archived video: CCTV Ground Movement]
- https://twitter.com/Sutopo_PN/status/1046445010231603200/video/1 [DesignSafe archived video: Liquefaction 1 Video]
- https://youtu.be/W8Jvx0OqHzQ [DesignSafe archived video: Liquefaction 2 Video]
- https://youtu.be/1CzdYSC9Z8g [DesignSafe archived video: Liquefaction 3 Video]

Figure 35: Areas of significant liquefaction induced lateral spreading in and around Palu City.

Balaroa

Figure 36 shows before and after Google Earth images of the Balaroa neighborhood where the lateral spreading extended up to 1000 meters on an average slope of 3.4 percent. This densely populated area was almost completely destroyed as the upper soil layers and all of the structures moved downslope to collect as debris at the base of the slide. Figure 37 shows an aerial view of the top end of the slide, while Figure 38 shows the accumulation of building debris at the bottom of the slide. Search and rescue teams attempted to save people trapped in the flow, but it is assumed that a large number are still buried in the slide.

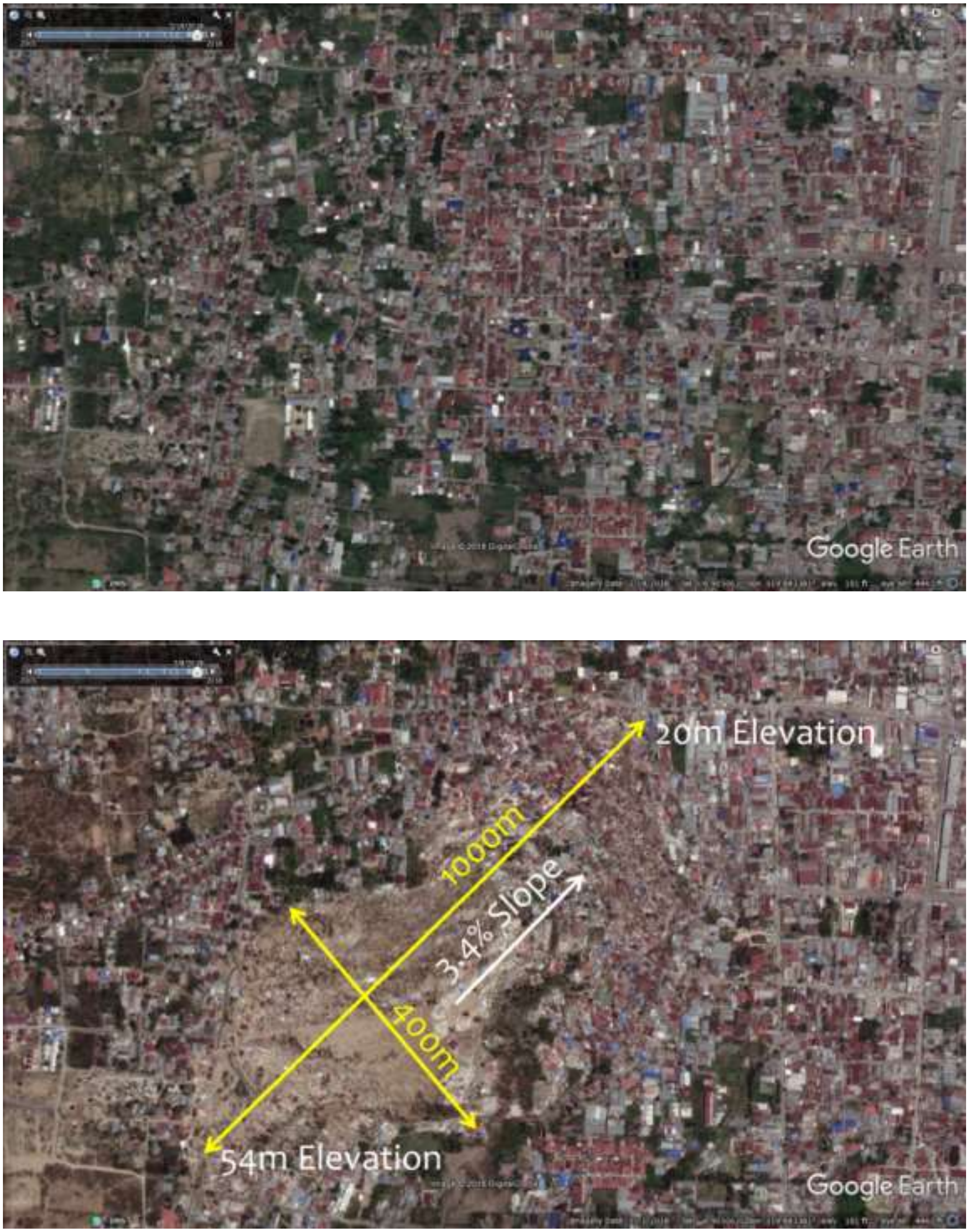


Figure 36: Google Earth image of Balaroa Neighborhood before earthquake (top) and after earthquake (bottom) showing extent of lateral spreading due to liquefaction.

Figure 37: Aerial view of the top end of the Balaroa neighborhood slide (Photo Credit: Jewel Samad/AFP).

Figure 38: Aerial image of accumulated building debris, including a mosque, at the base of the Balaroa neighborhood slide (Photo Credit: Antara Foto/ Hafidz Mubarak A/Reuters).

Petobo Sub-district

Figure 39 shows before and after Google Earth images of the Petobo Sub-district located just south of the Palu airport. Lateral spreading extended up to 2200 meters on terrain with an average slope of only 2 percent.

Figure 39: Google Earth image of Petobo Sub-district before earthquake (top) and after earthquake (bottom) showing extent of lateral spreading due to liquefaction.

An aerial scan of this slide was performed by team members Ryota Nakamura and Yuta Nishida using a DJI Phantom 4 Pro+ quadcopter drone. A portion of the 3-D image generated using "Structure-from-Motion" is shown in Figure 40. The full image is available in DesignSafe (see this project's archived 3D Rendering: Petobo Sub-district). Figure 41 provides a ground-level perspective of the Petobo Sub-district.

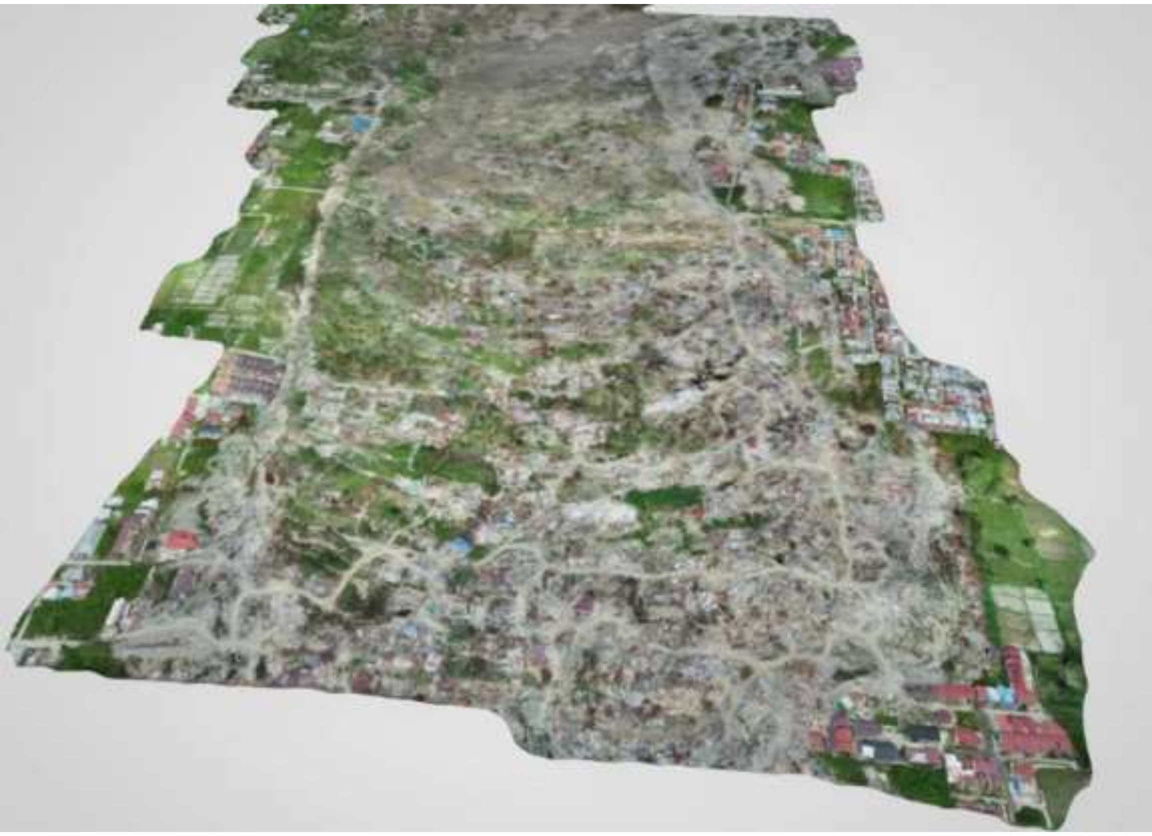


Figure 40: Partial 3-D Image of Petobo Sub-district lateral spreading developed from 3750 drone images using "Structure-from-Motion".

Figure 41: View looking up the Petobo Sub-district slide (left) and a typical timber framed home that traveled with the surface soil during the slide (right).

Jono Oge Village

Figure 42 shows before and after Google Earth images of the Jono Oge Village slide, where lateral spreading extended up to 3500 meters on terrain with an average slope of only 1.2 percent. Although this is a more rural setting, there were still a large number of buildings destroyed in the slide.

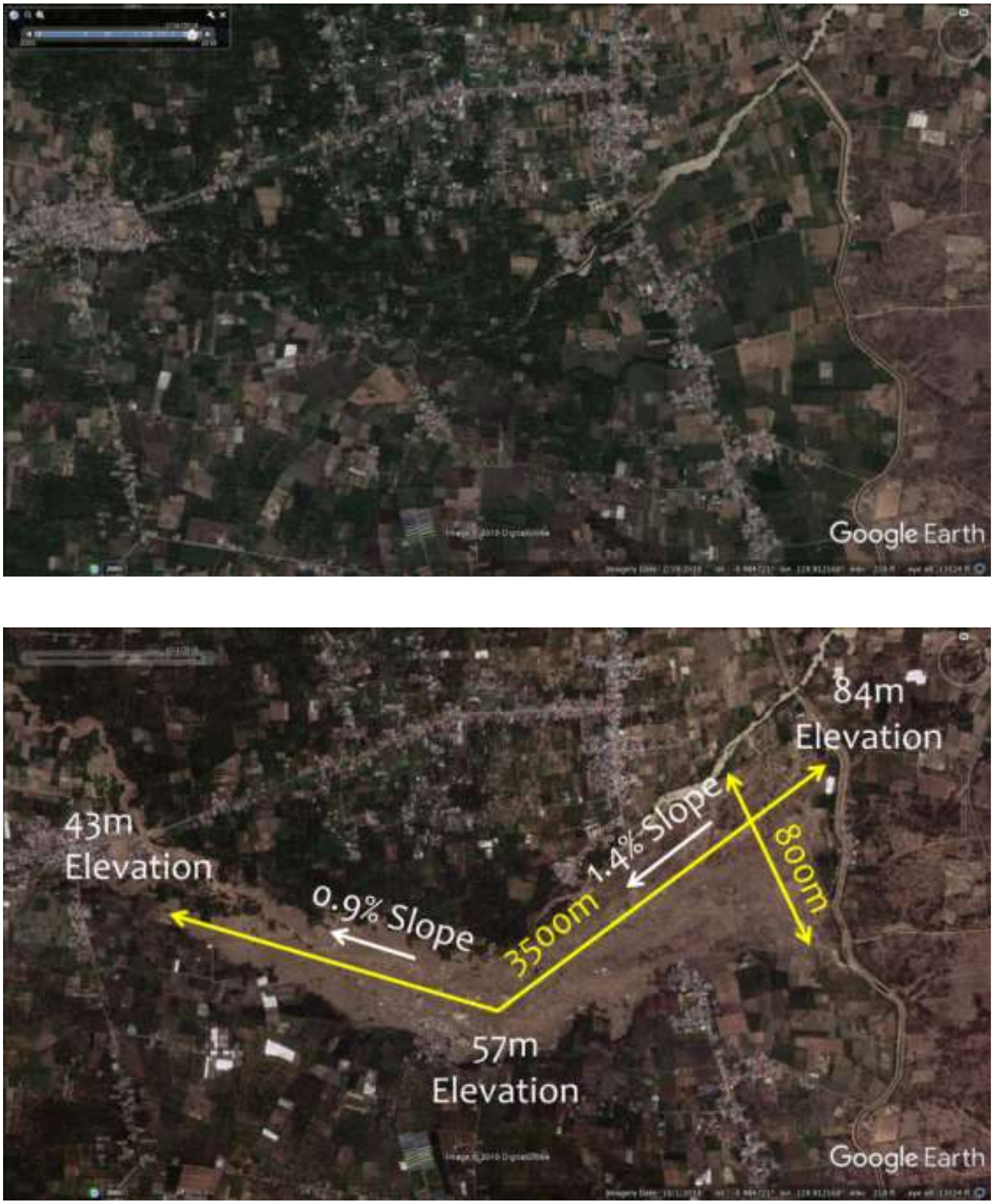


Figure 42: Google Earth image of Jono Oge Village before earthquake (top) and after earthquake showing extent of lateral spreading due to liquefaction (bottom).

Performance of Engineered Structures

The vast majority of buildings in Palu City were either undamaged or only slightly damaged by the earthquake shaking. Light timber framed structures generally survived the ground shaking intact, while some unreinforced masonry structures experienced cracking and occasional wall collapses. Most reinforced concrete or structural steel buildings survived, intact structurally with some cracking of stairs and escalators due to interstory drift and cracking of infill masonry walls.

The authors are not aware of any tsunami design requirements for buildings in Indonesia. As mentioned earlier, the Indonesian Seismic Code peak ground accelerations for Palu indicate that high-seismic design would have been required. The Indonesian concrete building code is based on the ACI 318 code, implying that seismic detailing requirements should have been provided, at least for modern reinforced concrete buildings. However, a limited number of structures that would typically require structural engineering design were severely damaged or completely destroyed during this event. These structures are referred to here as “engineered” structures despite the lack of knowledge about their actual level of engineering for either seismic or tsunami events.

Buildings

A number of multi-story reinforced concrete buildings collapsed during the earthquake. This section highlights some of the more prominent buildings that collapsed due to earthquake shaking. A number of buildings that survived the earthquake and tsunami are also discussed.

Roa Roa Hotel

One of the more dramatic structural failures was the eight-story Roa-Roa Hotel (0.90290 S, 119.86869 E), which collapsed resulting in multiple deaths (Figure 43). Approximately 60 residents were in the hotel at the time of the collapse, but the final number of casualties is unknown. Based on Google Earth historical images, the building was under construction in June 2013, making it only 5 years old at the time of the earthquake. The building’s lateral force resisting system appears to be a reinforced concrete moment frame structure with infill reinforced concrete wall panels on portions of the building perimeter. Details of the framing are evident from Figure 44.

By the time of the FAT site visit, the structure had been demolished in an effort to find survivors. The bases of the columns were inspected and two of the column sizes and reinforcement arrangements were recorded (Figure 45). The concrete in the columns was tested for concrete strength using a Schmidt Impact Hammer (f_c varied from 3500 to 4000 psi). Samples of the reinforcing steel were recovered for testing at the University of Hawaii Structures Laboratory. A single sample from a 21 mm (0.825”) bar produced a yield stress of 70 ksi (483 MPa) and an ultimate stress of 107 ksi (738 MPa). Three tests of 10mm bars gave an average yield stress of 88 ksi (607 MPa) and average ultimate stress of 117 ksi (807 MPa).

An approximate structural layout for columns and walls on the ground floor and the upper floors was developed based on field observations and Google Earth StreetView images (Figure 46). Efforts are underway to obtain structural drawings for this building. It would appear that the transition from wall to individual columns at the ground level on the NE corner of the building could have led to significant torsional effects and considerable displacement demand on those columns. Failure of these columns would explain the collapse of the building towards the North.

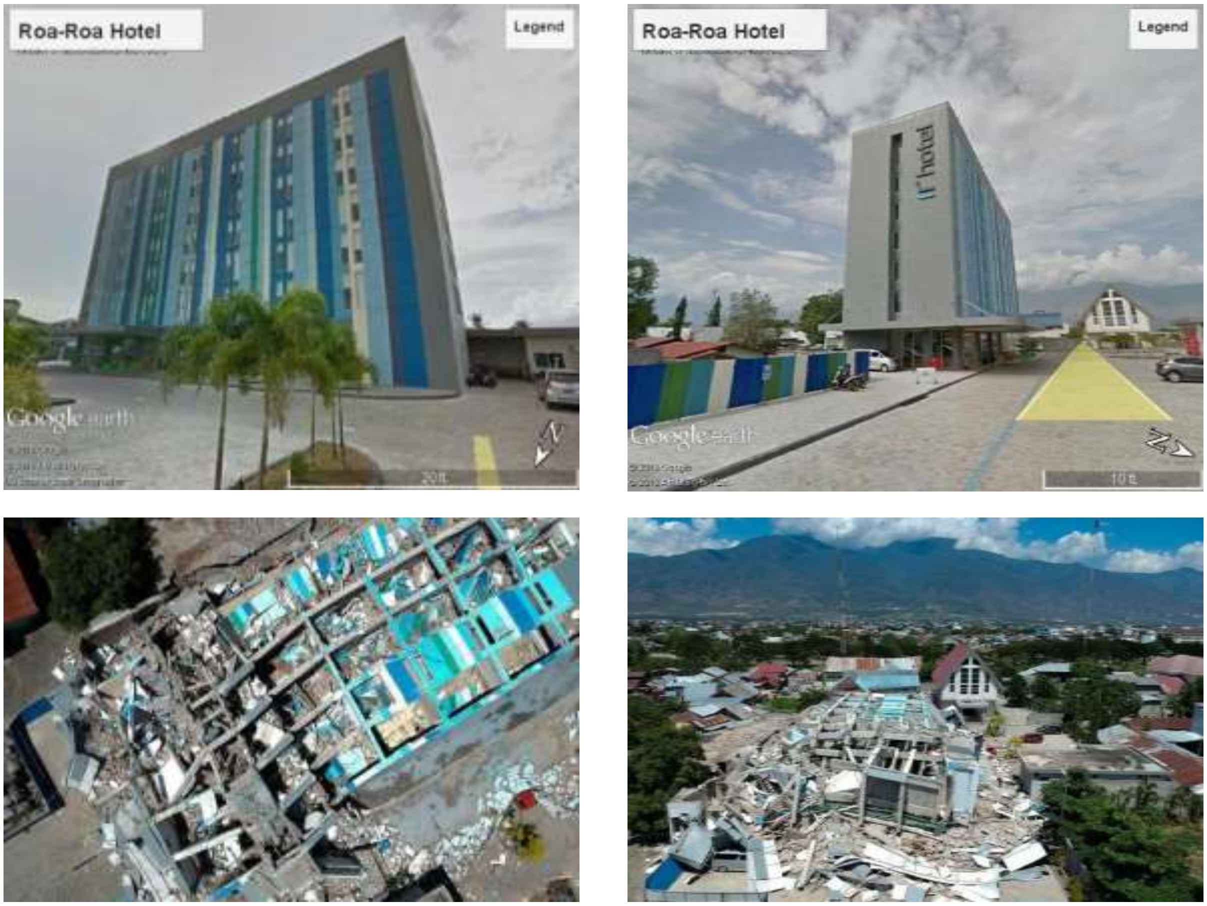


Figure 43: Google Earth Streetview images of Roa-Roa Hotel before the earthquake (top) and collapsed Roa-Roa Hotel after the earthquake (bottom).

Figure 44: Lower levels of Roa-Roa Hotel after collapse during the earthquake.

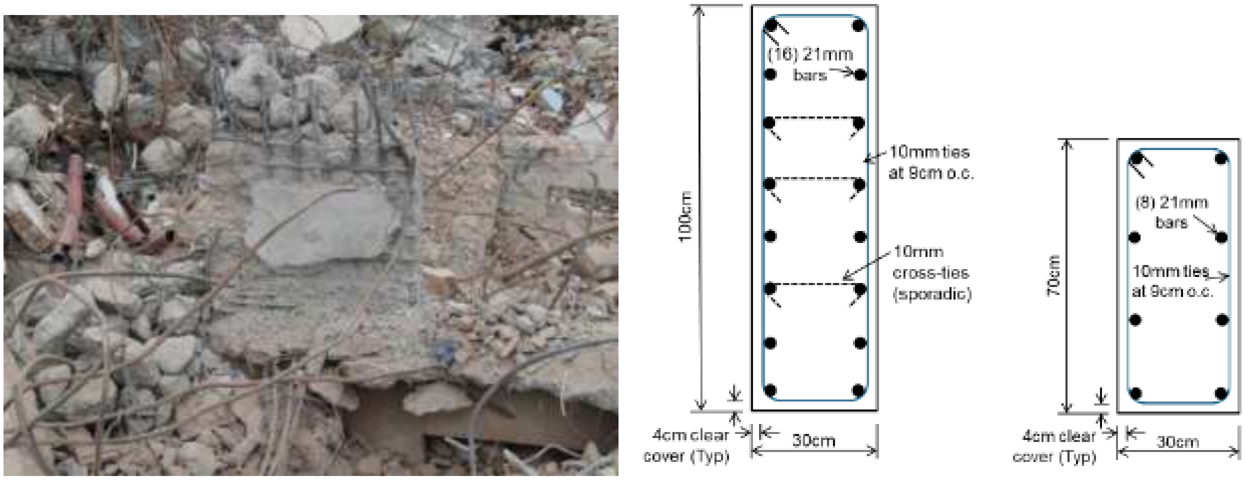


Figure 45: Ground floor columns after demolition of Roa Roa Hotel.

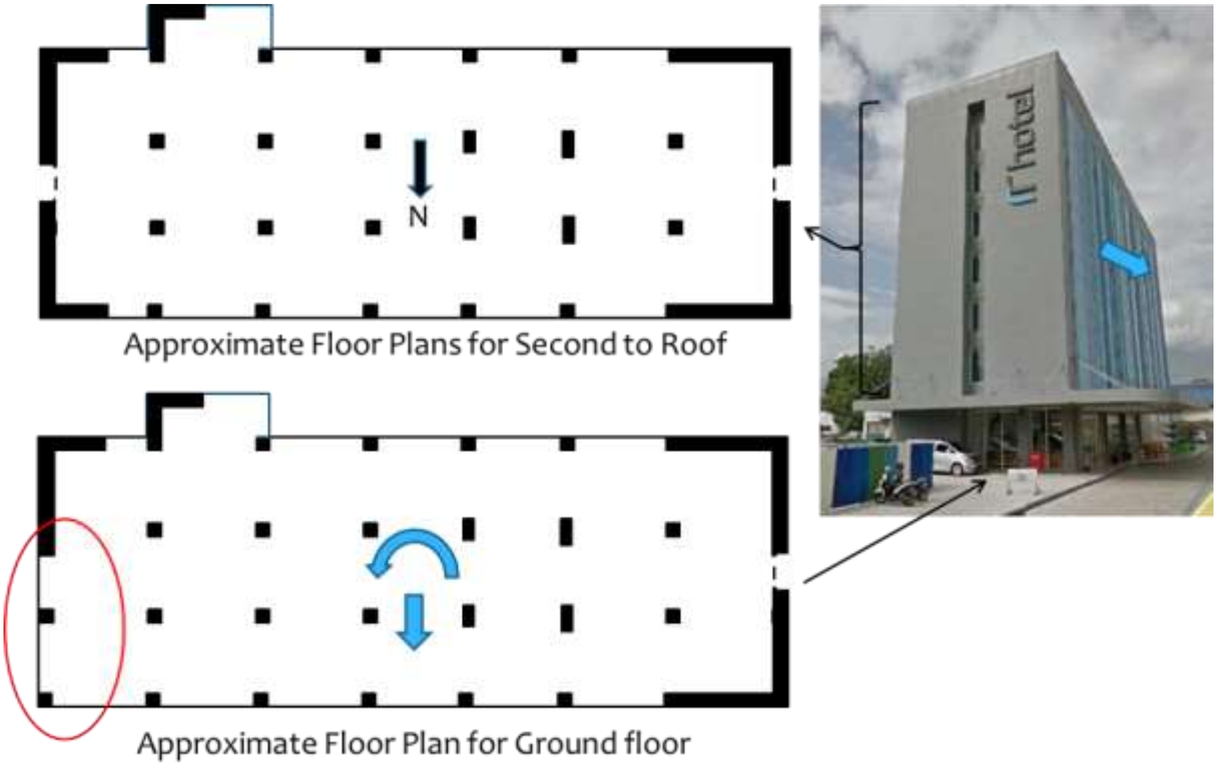


Figure 46: Approximate floor plans and presumed failure mode for Roa Roa Hotel.

Tatura Shopping Mall

The Tatura Shopping Mall (0.908287 S, 119.87627 E) suffered partial collapse during the earthquake. This four-story shopping mall experienced multiple column and beam-column joint failures, resulting in partial collapse of the roof and third floor. Based on Google Earth historical images, the foundations for this building were under construction in March 2005, making the building approximately 13 years old. Figure 47 shows a 3D rendering of the mall generated by “Structure-from-Motion” software Pix4D using 1500 drone images. The DJI Phantom 4 Pro+ quadcopter drone was flown by Yuta Nishida from Waseda University and Ryota Nakamura from Toyohashi University of Technology. The full 3D rendering can be viewed at DesignSafe (see this project's archived 3D Rendering: Tatura Shopping Mall).

Figure 48 shows the West elevation of the damaged structure, with column and joint failures evident. Figure 49 shows a typical exterior and corner beam-column joint where the absence of joint ties probably contributed to the failure. It would also appear that the beams connecting into each joint are stronger than the columns, resulting in an undesirable strong-beam-weak-column condition. Many of the columns also appear to have suffered shear failures, possibly exacerbated by unreinforced masonry infill panels (Figure 50 and Figure 51).

The concrete in the ground floor columns was tested for concrete strength using a Schmidt Impact Hammer (f_c varied from 2500 to 3000 psi). Samples of the reinforcing steel were recovered for testing at the University of Hawaii Structures Laboratory. Two samples of 21mm diameter reinforcing bars produced identical yield stress of 74 ksi (510 MPa) and ultimate stress of 112 ksi (772 MPa). Two samples of 10 mm diameter reinforcing bars used for transverse reinforcement gave an average yield strength of 76 ksi (524 MPa) and ultimate stress of 112 ksi (772 MPa). Efforts are underway to obtain structural drawings for this building.

Figure 47: 3D image of Tatura Shopping Mall generated from 1500 drone images using "Structure-from-Motion"

Figure 48: West elevation of Tatura Shopping Mall showing column and joint failures resulting in collapse of the third level and roof.

Figure 49: Lack of ties in the beam-column joints probably resulted in buckling of column vertical reinforcement and failure of the unconfined concrete in the joints.

Figure 50: Column shear cracking, possibly exacerbated by presence of masonry infills

Figure 51: Partial collapse of two interior columns due to shear or flexural failure in the hinging region. Note the lack of damage in the beams framing into these columns.

Dunia Baru Restaurant

Close to the Tatura Shopping Mall, a three-story restaurant suffered a complete collapse during the earthquake. Figure 52 shows a Google Earth StreetView image of the building prior to the earthquake. Figure 53 shows a 3D rendering of the Dunia Baru restaurant (0.90953 S, 119.87564 E) generated by “Structure-from-Motion” using 577 drone images captured by Yuta Nishida and Ryota Nakamura using a DJI Phantom 4 Pro+ quadcopter drone. The full 3D rendering can be viewed at DesignSafe (see this project’s archived 3D Rendering: Dunia Baru Restaurant). Construction of this building pre-dated the first Google Earth image from March 2005. The beam-column framed concrete structure was reinforced with smooth bars. Figure 54 shows that failure of the columns precipitated collapse of the floors. Lack of damage to the beams indicates the undesirable strong-beam-weak-column condition also noted in the Tatura Shopping Mall structure.

Figure 52: Dunia Baru Restaurant before the earthquake and after the earthquake

Figure 53: 3D image of Dunia Baru Restaurant generated from 577 drone images using "Structure-from-Motion"

Figure 54: Column failures resulting in complete collapse of the three-story Dunia Baru Restaurant

Mercure Hotel Palu

The five-story reinforced concrete frame of the Mercure Hotel on the Palu waterfront (0.8847 S, 119.85 E) experienced a complete collapse of the ground floor and partial collapse of the other floors (Figure 55 and Figure 56). Google Earth historical images show that the hotel was constructed sometime between March 2009 and June 2013. Efforts are underway to obtain structural drawings for this building. The lack of joint reinforcement in the beam-column joints (Figure 57), and the apparent strong-beam-weak-column condition, probably contributed to the partial collapse of this building (Figure 58).

Figure 55: The five story Mercure Hotel experienced a complete collapse of the ground floor.

Figure 56: Ground floor collapse (left) and collapse of all floors for one bay (right) of the Mercure Hotel.

Figure 57: Lack of confinement reinforcement in the beam-column joints may have contributed to the collapse of the Mercure Hotel.

Figure 58: Failed first floor column and damaged joints at second and third floors of Mercure Hotel.

Palu Grand Mall

Palu Grand Mall is a reinforced concrete frame structure on the coastal road along Palu Bay. The building consists of a four-story parking structure attached to the mall building. A circular ramp provides vehicle ingress to and egress from the parking structure (Figure 59 a-b). The mall building also has a vehicular ramp and large staircase to the second level (Figure 59 c-d). This structure survived the earthquake and tsunami without significant structural damage. The tsunami washed through the ground floor level of the structure, destroying much of the non-structural finishes and contents, but without causing structural damage. As a result, the large number of people who sought refuge in this structure by evacuating to the upper floors survived the tsunami.

(a) (b)

(c) (d)

Figure 59: Google StreetView images of Palu Grand Mall (a-b) parking structure and (c-d) ramp and staircase to second level.

Damage to Transportation Infrastructure

This section highlights some of the more significant impacts to transportation infrastructure due to both the earthquake and tsunami. In addition, there were numerous coastal roads that were overwashed by the tsunami, resulting in loss of asphalt paving and damage to the roadway. In a number of landslide areas the coastal road was completely lost as part of the slide.

Palu Airport

As documented in Figure 60, the airport control tower suffered a complete collapse of the roof over the air traffic control center (0.916648 S, 119.906485 E). Unfortunately, because of the need for full 360 degree clear views from traffic control towers, there is often inadequate seismic resistance for the roof framing (Vafaei et al., 2018). After assisting the last Batik Air flight to take off from the Palu Airport, the only controller in the tower, Anthonius Gunawan Agung, realized that the roof of the tower was about to collapse. He jumped from the third floor and unfortunately died later from injuries resulting from the fall.

During the earthquake, significant cracks formed in the only runway (Figure 61). Damage to the terminal building was primarily non-structural in the form of ceiling collapse and cracks in masonry infill panels, but significant damage to an escalator resulted in closure of the second level of the building (Figure 62). Fortunately military planes were able to land and bring supplies within 2 days of the event. The airport was reopened for commercial flights 6 days after the earthquake.

Figure 60: Collapse of the roof of the air traffic control tower at Palu Airport. Structural damage is also evident in walls and columns at the second level of the tower (right).

Figure 61: Earthquake damage to Palu airport runway.

Figure 62: Earthquake damage at Palu airport terminal building: non-structural elements (left) and escalator connecting ground and second floors (right).

Palu Bridge IV

The iconic steel double arch suspension bridge over the mouth of the Palu River was a prominent symbol for the city of Palu (Figure 63). The bridge opened in May 2006 and provided a critical link on the main coastal highway between the West and East sides of Palu Bay. Since its collapse during the earthquake (Figure 64), increased traffic over the remaining Palu Bridges II and III has led to significant congestion. Eyewitness reports confirm that the bridge collapsed during the earthquake before the tsunami waves arrived. The heavy concrete deck suspended from the arches by steel cables may have impacted the base of the arches leading to lateral collapse, or the deck lateral motion may have been sufficient to fail the arches laterally. Samples of the steel plate used to construct the arches were recovered and tested in the Structures Laboratory at the University of Hawaii. The steel plate yield stress was 62 ksi (428 MPa) while the ultimate stress was 83 ksi (572 MPa). Efforts are underway to obtain structural drawings for this bridge.

Figure 63: Palu Bridge IV over the mouth of the Palu River before the earthquake.

Figure 64: Palu Bridge IV after the earthquake and tsunami.

Earthquake Damage to Roadways

Numerous roadways suffered damage during the earthquake (Figure 65). This damage is attributed to liquefaction, fault movement, soil failures, landslides and other geotechnical failures. It is anticipated that a subsequent GEER survey will provide additional information on geotechnical failures.

Figure 65: Road failures due to the earthquake.

Earthquake Damage to Ports and Harbors

Although there is no port or harbor in Palu City, there are a number of ports, harbors and terminals on both East and West sides of Palu Bay (Figure 66). This section will show the effects of the earthquake and tsunami in each of these ports starting at the Port of Donggala and moving counterclockwise around the bay.

Figure 66: Ports, harbors and terminals around Palu Bay.

Figure 67 shows the change in the waterfront adjacent to Donggala Port due to a suspected submarine landslide caused by the earthquake. A portion of a pier and wharf have disappeared with the slide.

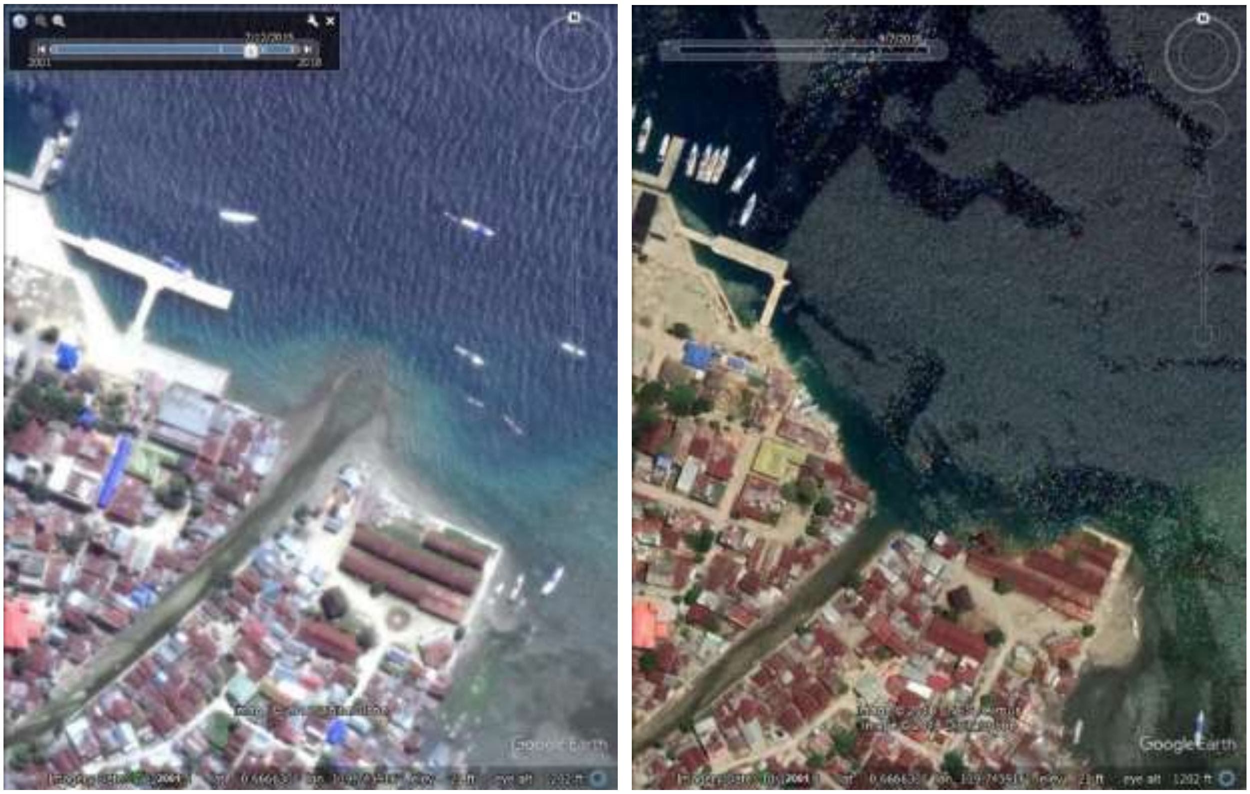


Figure 67: Google Earth images of the Port of Donggala before (left) and after (right) the earthquake and tsunami.

Figure 68 shows a shipping container terminal before and after the earthquake and tsunami. Some of the containers further from the shoreline have experienced minor movement, probably during the earthquake. However, containers closer to the coast have clearly been moved much further, likely due to buoyancy during the tsunami inundation. Based on nearby residential structures, it does not appear that the tsunami inundation was particularly severe at this location, but it takes less than half a meter of inundation to float an empty shipping container. A stack of three empty shipping containers will float in approximately one meter of water. There are also signs of damage to the wharf used to load these containers into ships.

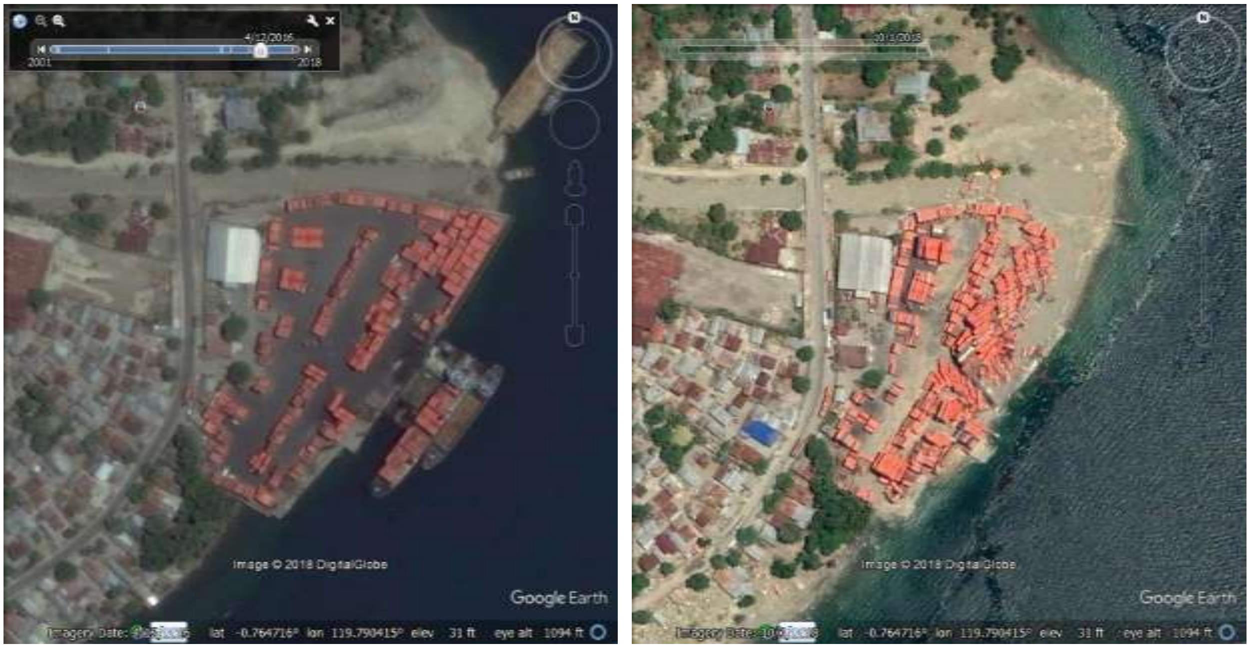


Figure 68: Google Earth Images of Shipping Container Terminal before (left) and after (right) the earthquake and tsunami.

Figure 69 shows before and after images of a Naval Port on the west side of Palu Bay. All ships in this harbor at the time of the tsunami were either washed onshore or severely damaged by impacts with the concrete pier. Figure 70 (left) shows a large naval vessel that broke free from its moorings and washed up onshore adjacent to a damaged building. Evidence of impact from the ship were noted on the side of the building (Figure 71). The second naval ship was secured by a single line during the tsunami, so it continued to pound into the adjacent pier during the tsunami, resulting in significant damage and partial sinking of the ship (Figure 70, right).

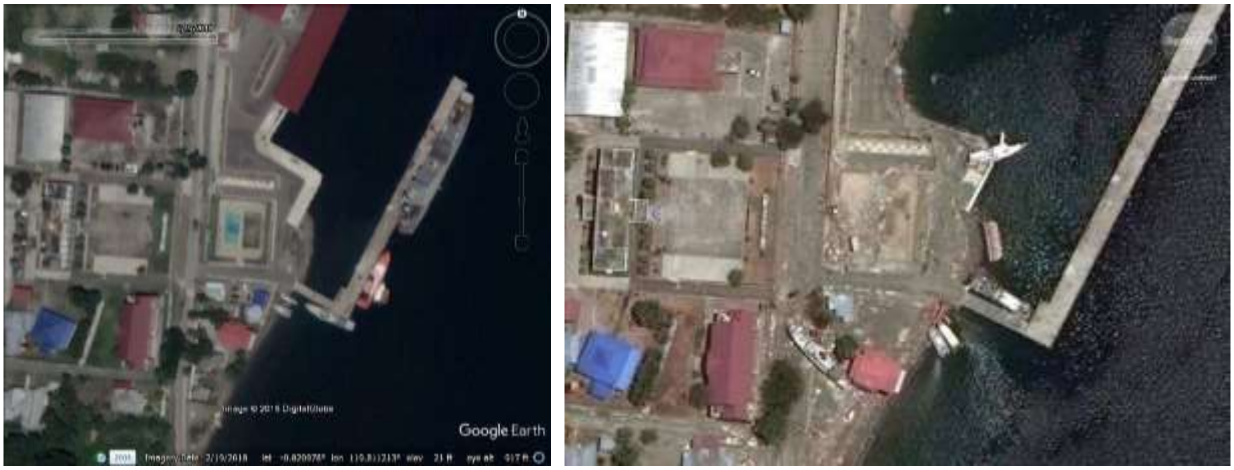


Figure 69: Google Earth image of Watusampu Naval Base before (left) and DigitalGlobe image after (right) the earthquake and tsunami.

Figure 70: Naval ships in Watusampu Naval Base beached (left) and damaged from pounding against piers (right) because of tsunami waves.

Figure 71: Naval ship adjacent to building with evidence of impact damage.

Figure 72 shows before and after images of Mamboro Terminal on the East side of Palu Bay. The tsunami washed two ships onshore and damaged portion of the pier and some of the on-land facilities.

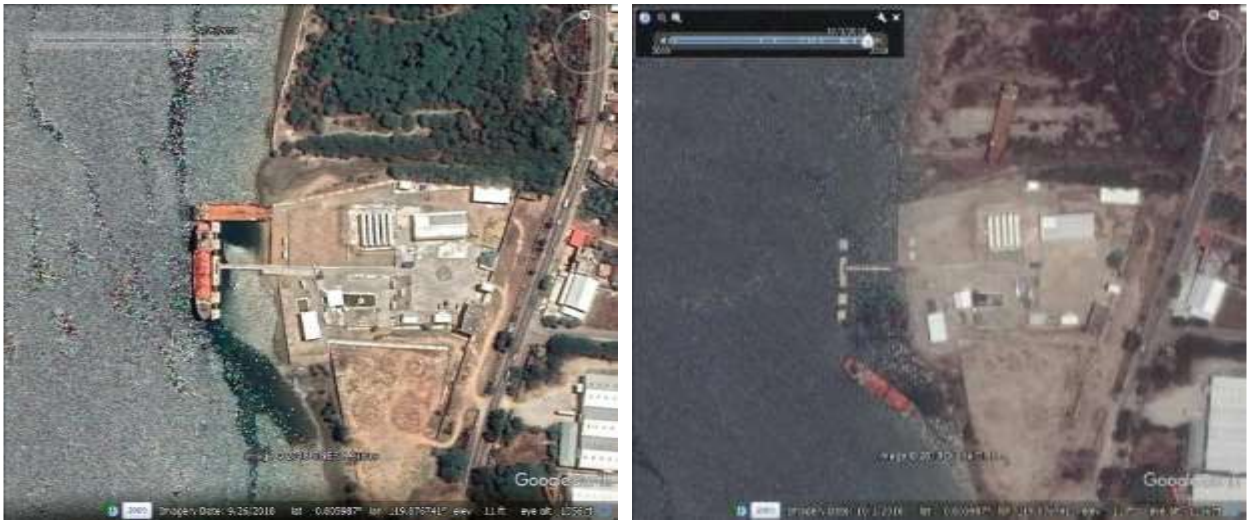


Figure 72: Google Earth images of Mamboro Terminal before (left) and after (right) the earthquake and tsunami.

Figure 73 shows a collapsed gantry crane at the Port of Pantoloan on the East side of Palu Bay. Eyewitness reports and video taken by CCTV confirmed that the crane collapsed during the earthquake shaking. The crane wheels were not restrained against uplift, leading to toppling of the top-heavy structure. Most of the visible damage to the crane occurred when it struck the pier during the fall, including flipping the cantilever gantry over the top of the crane.

Figure 73: Google Earth image of the Port of Pantoloan before the earthquake and tsunami (left) and the collapsed gantry crane after the earthquake (right).

Figure 74 shows before and after images of Wani Port on the East shore of Palu bay. All of the ships docked at the time of the tsunami broke free from their moorings and were washed inland or sank in the port. A large vessel was washed up into a number of buildings on the wharf, resulting in significant impact damage (Figure 75). Other smaller ships also washed into the coastal buildings resulting in impact damage (Figure 76, left), while one of the piers at the port was destroyed by the tsunami, though it might have suffered damage during the earthquake (Figure 76, right).

Figure 74: Google Earth images of Wani Port before (left) and after (right) earthquake and tsunami.

Figure 75: Large and small ships washed aground by tsunami at Wani Port.

Figure 76: Ship impact with buildings (left) and broken pier and sunken ship (right) at Wani Port.

A cement terminal just North of Wani Port suffered both earthquake and tsunami damage. Figure 77 shows Google Earth images before and after the earthquake and tsunami. Eyewitnesses confirmed that the steel-framed cement packaging building collapsed during the earthquake (Figure 78). They also confirmed that one of the two cement silos developed a significant lean after the earthquake (Figure 79, left). They then left the shoreline anticipating a tsunami, and when they returned after the tsunami there had been significant scour below the concrete apron slab surrounding the silo (Figure 79, right). It is likely that foundation settlement during the earthquake caused the silo to lean. Scour below the apron slab would not affect the structural integrity of the silo because the slab-on-grade is not part of the silo foundation system. Figure 80 shows damage to the sheet metal cladding on the pier supporting the conveyor belt that transports cement from ships to the silos. This damage is attributed to hydrodynamic loading during the tsunami.

This combination of earthquake and tsunami damage was common around the coastline. Eyewitness reports or videos were extremely useful for distinguishing what extent of the damage was caused separately by the earthquake and tsunami.

Figure 77: Google Earth images of Cement Terminal before (left) and after (right) the earthquake and tsunami.

Figure 78: Collapse of steel-framed cement packaging building during earthquake.

Figure 79: Leaning cement silo (left) and scour under surrounding concrete apron (right).

Figure 80: Hydrodynamic damage to sheet metal cladding on the pier supporting a conveyor belt for cement transport from ships to the silos.

Damage to Power Infrastructure

The earthquake caused limited damage to the power distribution system in areas outside of the liquefaction and tsunami damaged areas. Numerous power poles and lines were destroyed in the areas affected by liquefaction induced lateral spreading, and also due to hydrodynamic and debris impact loads caused by the tsunami flow in the inundation area. This resulted in power outages to approximately 80 percent of Palu City and the neighboring areas. Ninety generators were shipped from Jakarta to assist during the power outage[1].

Crews were quick to replace downed poles and repair the distribution lines, particularly in the tsunami zone (Figure 81). By the time FAT-1 visited Palu (4 weeks after the earthquake), all power had been restored and cell phone service was available throughout the area surveyed.

Figure 81: Restoration of the power distribution system within days of the earthquake and tsunami.

Economic Recovery

The earthquake and tsunami caused significant disruption to local industries, even if they were not damaged during the event. Loss of power, damaged and blocked roadways and bridges, and worker injury or loss of life hampered restoration of normal services for weeks after the earthquake. For the first week after the event, military planes were used to ship in essential food, water and medical supplies. Businesses in the areas affected by liquefaction-induced lateral spreading were completely destroyed, while those in the tsunami inundation zone typically suffered major non-structural and often structural damage due to the tsunami. These businesses had not recovered by the time of the FAT-1 survey, though the rest of Palu City and neighboring towns appeared to be back to business as usual. Stores were open, street markets were plentiful and goods did not appear to be in short supply (Figure 82).

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[1] https://www.liputan6.com/bisnis/read/3657831/pln-kirim-bantuan-90-genset-ke-palu-untuk-penerangan

Figure 82: Street markets recovered within a week of the earthquake and tsunami.

Temporary Housing

Over 130,000 residents of Palu City and neighboring communities lost their housing as a result of the earthquake, liquefaction and tsunami (Humanitarian Country Team, 2018). Rapid response from national and international non-governmental organizations helped to provide temporary housing for those who could not relocate or move in with friends and relatives (Figure 83). There was a particular urgency to get people housed before the rainy season.

Figure 83: Temporary housing provided by national and international NGOs.

Recommendations for Further Study

FAT-1 primarily focused assessments on coastal areas around Palu Bay. Although the primary focus was on the sequential effects of earthquake shaking followed by tsunami loading, it was not always possible to separate the damage caused by each event. Notable damage due to the earthquake was documented in some detail, though it was not possible to perform a comprehensive earthquake damage survey. Tsunami damage around Palu Bay was surveyed in some detail, but many sites of interest could not be covered in the time available.

Preliminary review of assessments logged by FAT-1 has led to the following recommendations for future study:

I. More comprehensive investigation of earthquake impacts:

1. In the absence of any seismic recordings in Palu City, it would be beneficial to generate an estimate of the ground shaking based on nearby seismic records, where available.
2. A number of relatively modern reinforced concrete buildings and a long-span structural steel arch bridge collapsed or were severely damaged during the earthquake. Obtaining structural drawings for these structures would allow for analysis to determine the most likely causes of damage. Material properties were obtained for many of these structures, allowing for more accurate modeling, if structural drawings are available.
3. No attempt was made during FAT-1 to determine the damage ratio for various types of construction. This would be useful information to inform fragility curves for similar communities during future events.

II. More comprehensive investigation of tsunami impacts:

1. The Structural Damage Survey group recorded various locations where floating debris appeared to have induced at least part of the observed tsunami damage. A paper is currently under review on this topic. Additional research on debris generation, distribution, damming and impact could help to validate or suggest modifications for current ASCE 7-16 standard provisions.
2. The structural group also recorded various locations where scour appeared to have had a damaging effect on structural foundations. Correlations between the scour depth and maximum flow depth at the location could augment the current scour predictions provided by ASCE 7-16.
3. Estimates of tsunami flow velocities determined from damaged structures and video evidence could be used to validate computer models of the tsunami on-land flow.

III. More comprehensive investigation of community response and recovery:

1. Indonesia has a long and painful history of earthquake and tsunami hazards. A study of the community response to this recent event, and the rate of recovery, could help identify areas where disaster preparedness and resilience could be enhanced prior to future damaging events. FAT-1 performed a survey of over 200 tsunami survivors to identify their preparedness for and response to the event. The results of this survey will be published in the near future.
2. A longitudinal study of the recovery of Palu City and neighboring communities will highlight aspects of community preparedness that could enhance resilience to future earthquakes and tsunamis.

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Appendix

Questionnaire Survey on Evacuation Awareness for the 2018 Sulawesi Earthquake and Tsunami

Coastal Engineering Committee, Japan Society of Civil Engineers

[Purpose of the Questionnaire]

On 28 September 2018, an earthquake followed by a tsunami struck Sulawesi. The research team would like to understand the state of tsunami awareness in the area prior to the disaster. For tsunami disaster prevention, information and knowledge for appropriate evacuation as well as accurate forecast are important. The citizens also need to understand the importance of knowledge and to perform evacuation drills for efficient preparation for the disaster. CEC, JSCE is aiming to apply our disaster prevention technologies for reduction of loss and injuries. This questionnaire is not only for your region but for the world-wide tsunami disaster prevention. We request you to kindly fill the questionnaire below. The data generated shall be kept confidential.

A. Demographics

1. Gender: ☐ male ☐ female

2. Age :
☐ 10-19 ☐ 20-29 ☐ 30-39 ☐ 40-49
☐ 50-59 ☐ 60-69 ☐ 70-79 ☐ over 80

3. Industry
☐ Fisheries ☐ Hotel or Food Services ☐ Office ☐ Transportation
☐ Dock Worker ☐ Agriculture or Livestock ☐ Retired ☐ Unemployed
☐ Homemaker ☐Other (specify) ( )

4. Residence (or work address if at work at the time of tsunami) :
Address ( ), City ( )
☐ If at work, please mark the box

5. Distance from the coast to your residence (or office)
☐ - 100m ☐ 100 - 300m ☐ 300 - 500m ☐ 500m - 1km ☐ 1km +
Or GPS coordinates, if available [,]

B. Awareness for tsunamis before the disaster

1. Did you think that a tsunami was a real danger for you? (Choose one)

☐ Yes, I did ☐ No, I didn’t ☐ I had no interest ☐ I didn’t know what tsunami is

2. Were you informed enough about tsunami hazards by the authorities?

☐ Enough ☐ Not enough ☐Tsunami knowledge is part of the local culture
☐ I don’t know

3. Did you assume that you would possibly evacuate for a tsunami? (Choose one)
☐ Yes, I did ☐ Not that much ☐ No, I didn’t at all

4. Have you joined evacuation drills for tsunamis in the past 5 years? (Choose one)
☐ More than once a year ☐ Once in a few years ☐ Just once
☐ No ☐ We didn’t have such drills

C. Early Warning Information

1. How did you get information on the tsunami? (Multiple choices)

☐ TV, Radio ☐ Loudspeaker car ☐ Area loudspeaker ☐Internet
☐ Family, relatives ☐ Neighbours ☐Police and/or firefighters
☐ Deduced by yourself (after feeling earthquake)
☐ Deduced by yourself (after seeing or hearing the sea)
☐ Others (Specify): ____________

2. Was the information useful? (Choose one)
☐ Very useful ☐ A little useful ☐ Confusing ☐ Not needed
☐ Information was wrong

3. Did you get an evacuation order? (Choose one)
☐ Yes, I did ☐ No, I didn’t ☐ I don’t know ☐ Other ( )

D. Earthquake Event

1. Did you experience the earthquake on 28 September 2018?
☐ Yes
☐ No / I don’t know (Why? ____)

2. What types of phenomena did you expect to occur when you felt the ground motion? (multiple answers allowed)
☐ house/building collapse
☐ tsunami
☐ liquefaction
☐ fire
☐ landslides
☐ others (Specify):__________

3. Which of the following were you afraid of during this event? (multiple answers allowed)
☐ house/building collapse
☐ tsunami
☐ liquefaction
☐ fire
☐ landslides
☐ others (Specify):__________

E. Evacuation

1. Did you worry about a tsunami when you felt the earthquake?
☐ Yes, I did ☐ No, I didn’t

2. What did you do when you knew about the tsunami? (Multiple choices)
☐ Just waited ☐ Prepared for evacuation ☐ Collected further information
☐ Contacted family or neighbors ☐ Went to the sea ☐ Other ( )

3. Did you evacuate? (Choose one)
☐ Yes, I did (CONTINUE TO F) ☐ No, I didn’t (GO TO G)

F. For those who did evacuate

1. When did you evacuate? (Choose one)
☐ Right after the earthquake ☐ After you saw the forecast
☐ After you got warning or order ☐ After the first tsunami wave
☐ After the tsunami had subsided ☐ Other ( )

2. In terms of time, how many minutes passed before you decided to evacuate?
☐ 0 – 5 mins ☐ 5 – 15 mins ☐ 15 – 30 mins ☐ more than 30 mins

3. What made you decide to evacuate? (multiple choices allowed)
☐ feeling the ground motion
☐ seeing someone is evacuating
☐ hearing someone is calling for evacuation
☐ seeing an unusual behavior of the sea surface
☐ hearing a loud sound from the sea
☐ seeing directly sea water coming
☐ being caught by sea water
☐ receiving a message from the authorities through TV, radio, sirens, etc.
☐ other (Specify): __________

4. How did you evacuate (Choose one)
☐ Walk ☐ Bicycle ☐ Motorcycle ☐ Car ☐ Other ( )

5. How many minutes did it take for you to reach the evacuation area?
☐ 0 – 5 mins ☐ 5 – 15 mins ☐ 15 – 30 mins ☐ more than 30 mins

6. Was there any difficulty in evacuating?
☐ Yes. Why?
(Multiple choices: ☐ A lot of people are evacuating, ☐ Don’t know what to bring, ☐ Looking for relatives, ☐ There were too many people on the way to safety, ☐ Don’t know where to go,
☐ other: ____)

☐ No. Why? (Optional) (_______________________________________)

7. Where did you evacuate (Choose one)
☐ Shelter Area ☐ Other public facility ☐ Place of other family or relatives
☐ High building ☐ Nearby high ground ☐ Other (_______________)

8. Which place did you evacuate to? (please write the name of the place)
name of the place ___________

G. For those who did not evacuate

1. Why did you not evacuate? (Multiple choices)
Because
☐ I didn’t know how to evacuate
☐ ground was high enough
☐ the tsunami shouldn’t be large
☐ I was out of risk area
☐ I got no evacuation order
☐ I didn’t know the shelter area
☐ It was hard to get to the shelter area
☐ I just didn’t know what to do
☐ I thought I could run away when the tsunami actually arrived
☐ Other（_______________________________________）

H. Post Disaster

1. Did you feel imminent fear for the tsunami after the waves arrived? (Choose one)
☐ Yes, I did very much ☐ Yes, but not that much ☐ No, I didn’t

2. When did you feel it was safe to go back to your house?

☐ Immediately after (0 – 3 hrs)
☐ Within a few hours (3 – 6 hrs)
☐ Within half a day (6 – 12 hrs)
☐ Within a day (12 – 24 hrs)
☐ After a few days (1 – 3 days)
☐ About a week (3 – 7 days)
☐ More than 1 week

3. If you have a similar situation again, will you evacuate? (Choose one)

☐ Yes, I will ☐ No, I won’t

I. About information for tsunami disaster prevention

1. How do you evaluate the tsunami forecast by authorities? (Choose one)
☐ It was rather exact ☐ It was relatively correct
☐ It was incorrect ☐ It was no help
☐ Everybody left area anyway ☐ Other ( )

2. Did you think a tsunami was made of more than one wave? (Choose one)
☐ Yes ☐ No

If more than one, how many waves? (Choose one)
☐ 1 ☐ 2 ☐ 3 ☐ 4 or more

3. Do kids carry out tsunami simulations in schools? (Choose one)
☐ Yes ☐ No

4. If you have any complaint or opinion for the government response for this tsunami event, please describe.

____

____

____

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____

____

Thank you very much!

Acknowledgements

StEER gratefully acknowledges the financial support of the National Science Foundation under Award CMMI-1841667, with deep appreciation for the mentorship provided by Dr. Joy Pauschke. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Special thanks also go to the organizers of this international reconnaissance effort: Professors Shibayama and Esteban of Waseda University, for extending the invitation for StEER participation. This effort would have not been possible without the leadership and careful planning demonstrated by these colleagues. The team is further grateful for the significant logistical and planning assistance from Hendra Achiari of Bandung Institute of Technology in Bandung, West Java, Indonesia and his student (Fadel Marzuki) and brother (Gafur Marzuki, State Institute for Islamic Studies in Palu). Their familiarity with Palu and willingness to support the team's efforts at such a difficult time for their community was vital to the success of the effort.

StEER also appreciates the assistance of the Earthquake Engineering Research Institute (EERI) and its Virtual Earthquake Reconnaissance Team (VERT), facilitated by the early outreach of VERT subcommittee co-chair Erica Fischer, University of Washington, in assembling an event summary in advance of FAT-1's departure.

The sharing of information via Slack was tremendously helpful and much appreciated and benefited greatly from the work of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs. We particularly appreciate the assistance of Tim Cockerill for helping team members get activated on Slack swiftly.

About StEER

The National Science Foundation (NSF) awarded a 2-year EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network. StEER's mission is to deepen the structural natural hazards engineering (NHE) community's capacity for reliable post-event reconnaissance by: (1) promoting community-driven standards, best practices, and training for RAPID field work; (2) coordinating official event responses in collaboration with other stakeholders and reconnaissance groups; and (3) representing structural engineering within the wider extreme events reconnaissance (EER) consortium in geotechnical engineering (GEER) and social sciences (SSEER) to foster greater potentials for truly interdisciplinary reconnaissance. StEER also works closely with the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) RAPID facility and cyberinfrastructure Reconnaissance Portal to more effectively leverage these resources to benefit StEER missions.

StEER relies upon the engagement of the broad NHE community, including creating institutional linkages with dedicated liaisons to existing post-event communities and partnerships with other key stakeholders. While the network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER aspires to build a network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for the two primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible with overseeing the design and operationalization of the network.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, leading StEER's Atlantic/Gulf Regional node and serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Assessment Technologies, guiding StEER's development of a robust approach to damage assessment across the hazards.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data.

StEER's response to the Palu Earthquake and Tsunami (Indonesia) preceded the formation of its official policies, protocols and membership, which are still in active development. All policies, procedures and protocols described in this report should be considered preliminary and will be refined with community input as part of StEER's operationalization in 2018-2019.

StEER Event Report Library

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