StEER: Structural Engineering Extreme Event Reconnaissance Network

PALU EARTHQUAKE AND TSUNAMI, SULAWESI, INDONESIA
PRELIMINARY VIRTUAL ASSESSMENT TEAM (PVAT) REPORT

Collapsed Roa-Roa Hotel in Palu

PVAT Author

Ian N. Robertson, University of Hawaii

Contributing Editors

(in alphabetical order)

Tracy Kijewski-Correa, University of Notre Dame
David Prevatt, University of Florida
David Roueche, Auburn University

Released: October 2, 2018

Table of Contents

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. As of writing this report the death toll is estimated to be over 1200 due to both earthquake and tsunami and expected to rise as the search and rescue efforts continue.

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.

A number of multi-story reinforced concrete buildings collapsed during the earthquake. Most notable was the eight-story Roa-Roa Hotel which collapsed resulting 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.

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.

A number of port facilities were damage either by the earthquake or tsunami, and many ships, barges and boats were washed onshore or out to sea. 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.

The tsunami caused considerable damage to light-framed structures, though 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.

Introduction

StEER's response to the Palu Earthquake and Tsunami (Sulawesi Island, Indonesia) will initially be limited to a Virtual Assessment Team (VAT). The focus of the VAT will be on compiling relevant information about the event from public sources and social media. This Preliminary VAT report is based on information available immediately after the event, and may be followed by a more detailed VAT report. StEER is also seeking collaborators in other teams proposing to visit the disaster zone, and may look for opportunities to join one of more of those teams for field assessments.

The first objective of StEER's response is the swift capture of perishable data to improve our understanding of the performance of constructed facilities during a damaging earthquake followed within minutes by a tsunami. This sequence of events is anticipated along the Northwest US Pacific coast and the Alaskan coastline. Although buildings and structures in these US areas may perform better during the earthquake than those in Sulawesi Island, they are likely to experience similar damage during the subsequent tsunami.

The second objective of this StEER response is to use this international event to exercise 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.

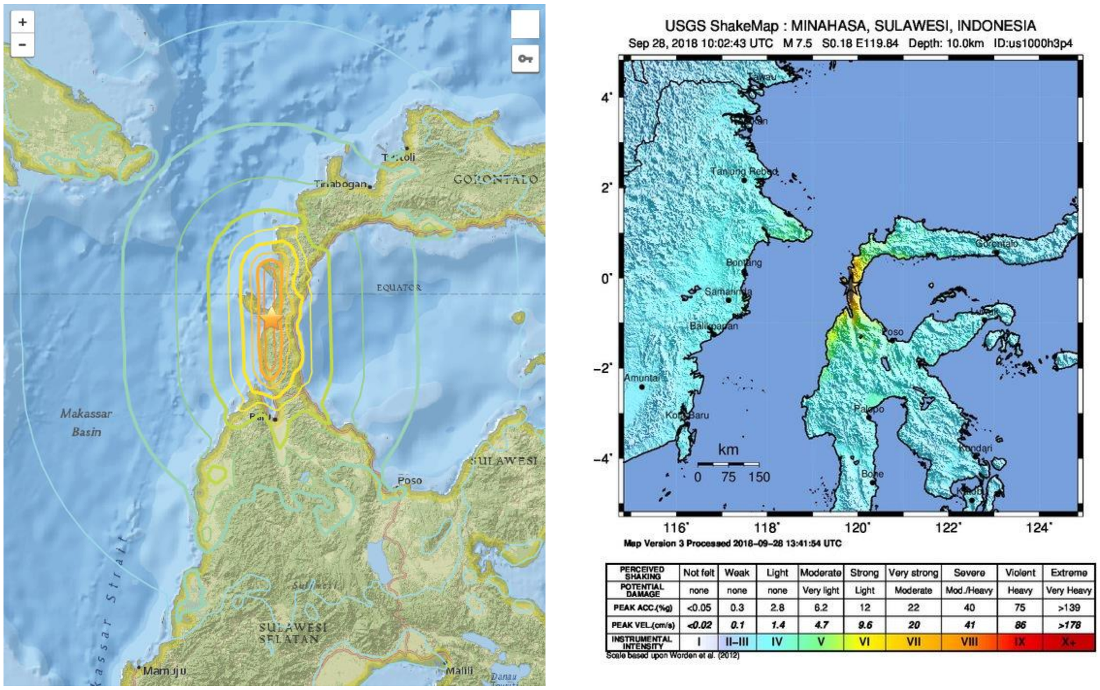
The first product of the StEER response to the Palu Earthquake and Tsunami is this **Preliminary Virtual Assessment Team (PVAT) report**, which is intended to:

1. provide an overview of the Palu Earthquake and Tsunami, particularly relating to sequential earthquake and tsunami effects on coastal structures.
2. overview StEER's event strategy in response to the Palu Earthquake and Tsunami, and
3. summarize the preliminary findings relating to damage caused by both the earthquake and tsunami in Palu and neighboring areas.

It should be emphasized that all results herein are preliminary and based on the rapid assessment of publicly available online data within 3 days of the event. Damage assessments discussed herein are based largely on the judgement of the authors without access to additional aerial imagery and ground-truthing.

Earthquake and Tsunami Details

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 (Figure 1) (USGS, 2018a). The earthquake was caused by movement on a strike-slip fault known as the Palu-Koro Fault (Figure 2). USGS PAGER loss estimates appear to have under predicted the fatalities, possibly because of deaths due to the subsequent tsunami (Figure 3). As of writing this report the death toll is estimated to be over 1200 due to both earthquake and tsunami (NPR, 2018) and expected to rise as the search and rescue efforts continue.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

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

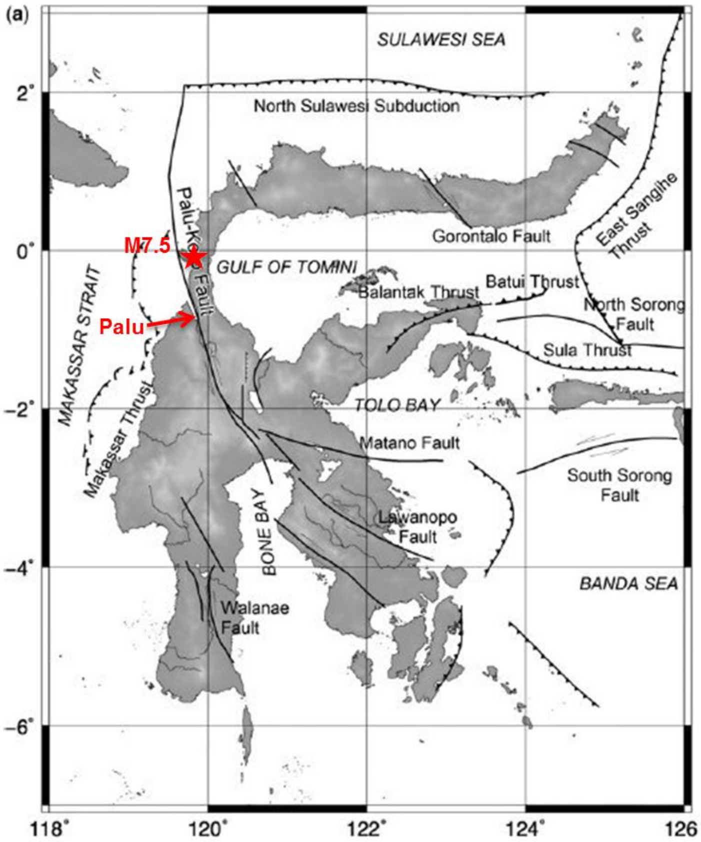
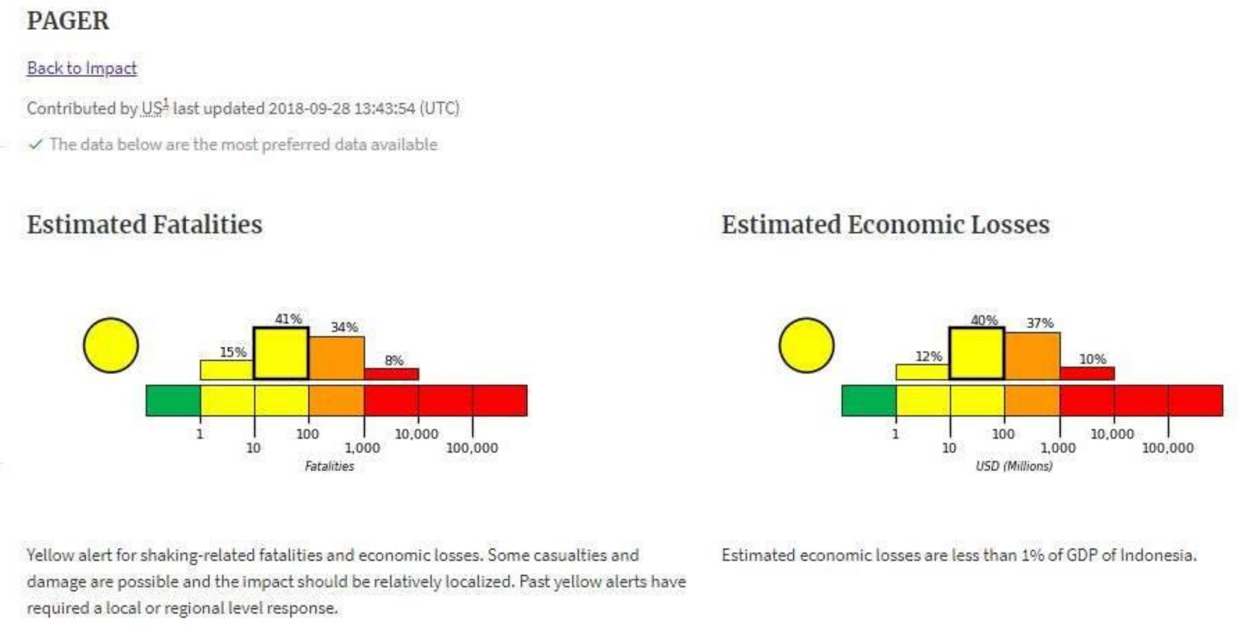


Figure 2: Earthquake location along Palu-Koro Fault



PAGER

Back to Impact

Contributed by US[1] last updated 2018-09-28 13:43:54 (UTC)

✓ The data below are the most preferred data available

Estimated Fatalities

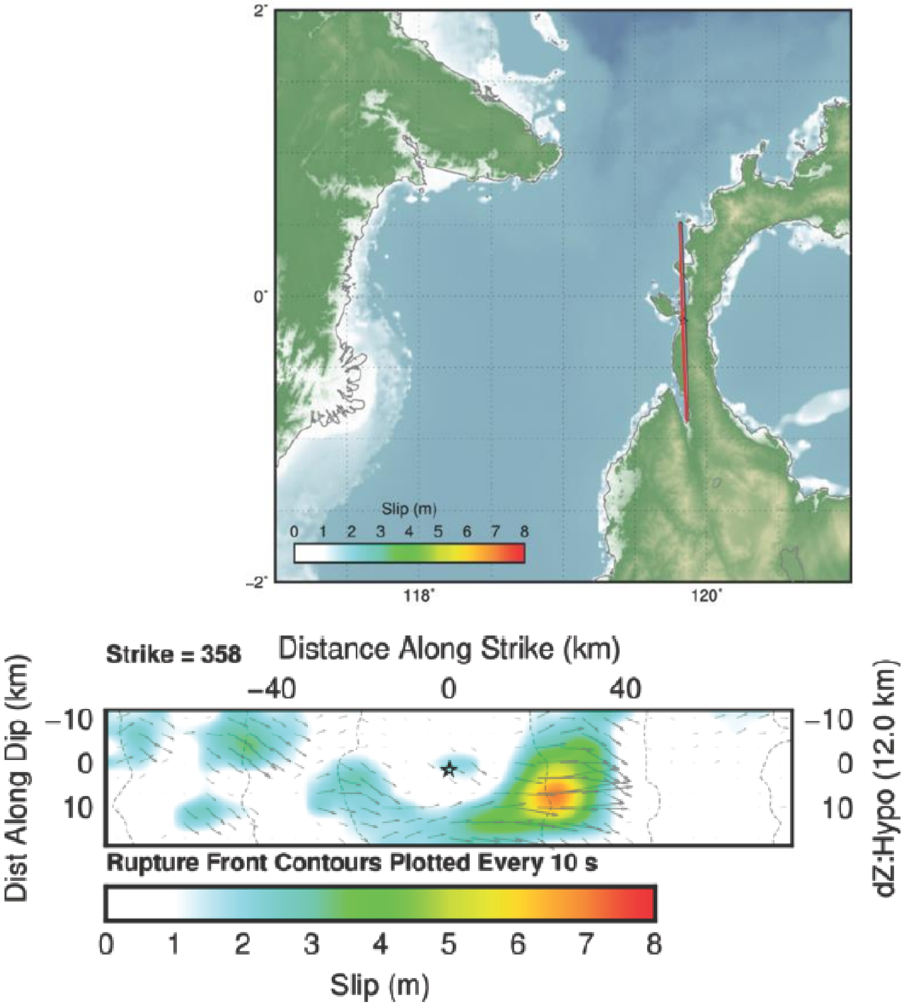
Yellow alert for shaking-related fatalities and economic losses. Some casualties and damage are possible and the impact should be relatively localized. Past yellow alerts have required a local or regional level response.

Estimated Economic Losses

Estimated economic losses are less than 1% of GDP of Indonesia.

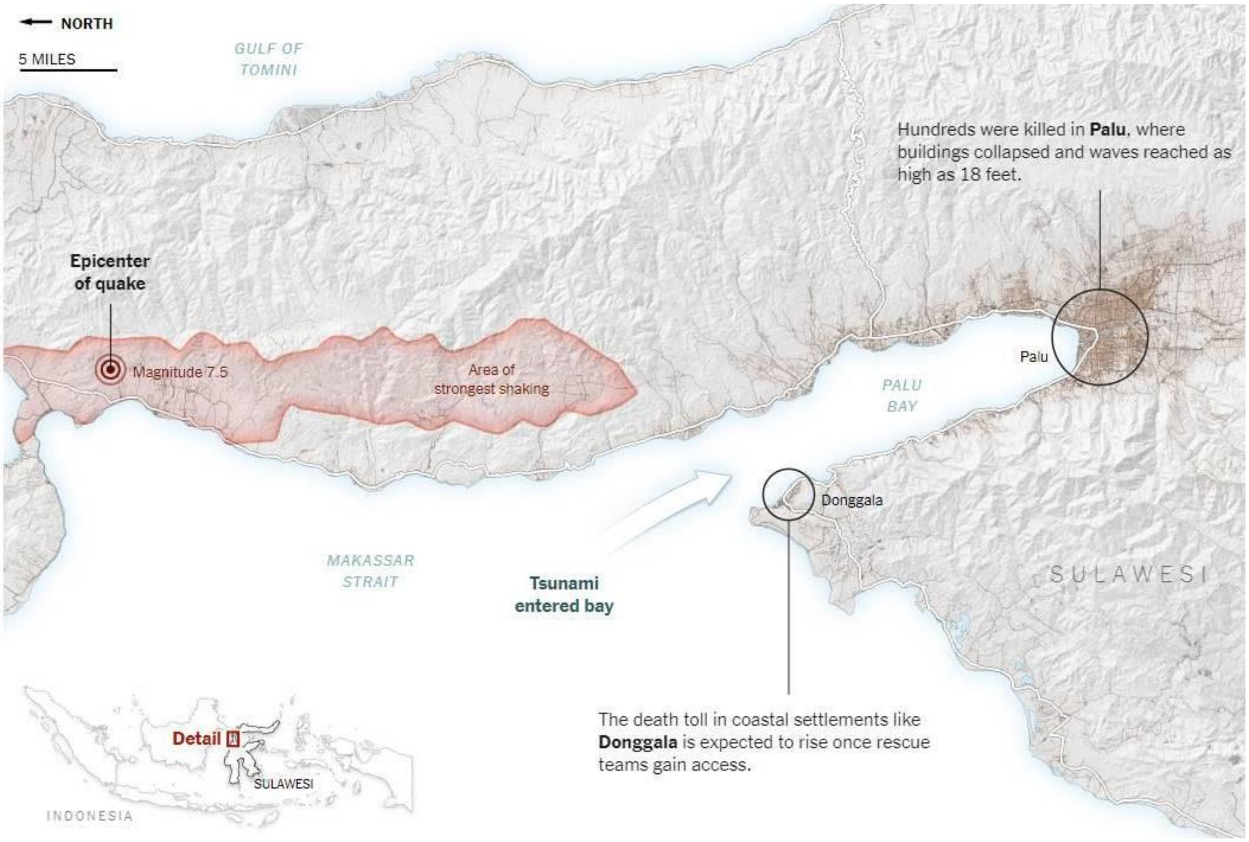
Figure 3: USGS PAGER loss estimates (USGS, 2018a)

Preliminary finite fault results developed by USGS are shown in Figure 4 (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.



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.

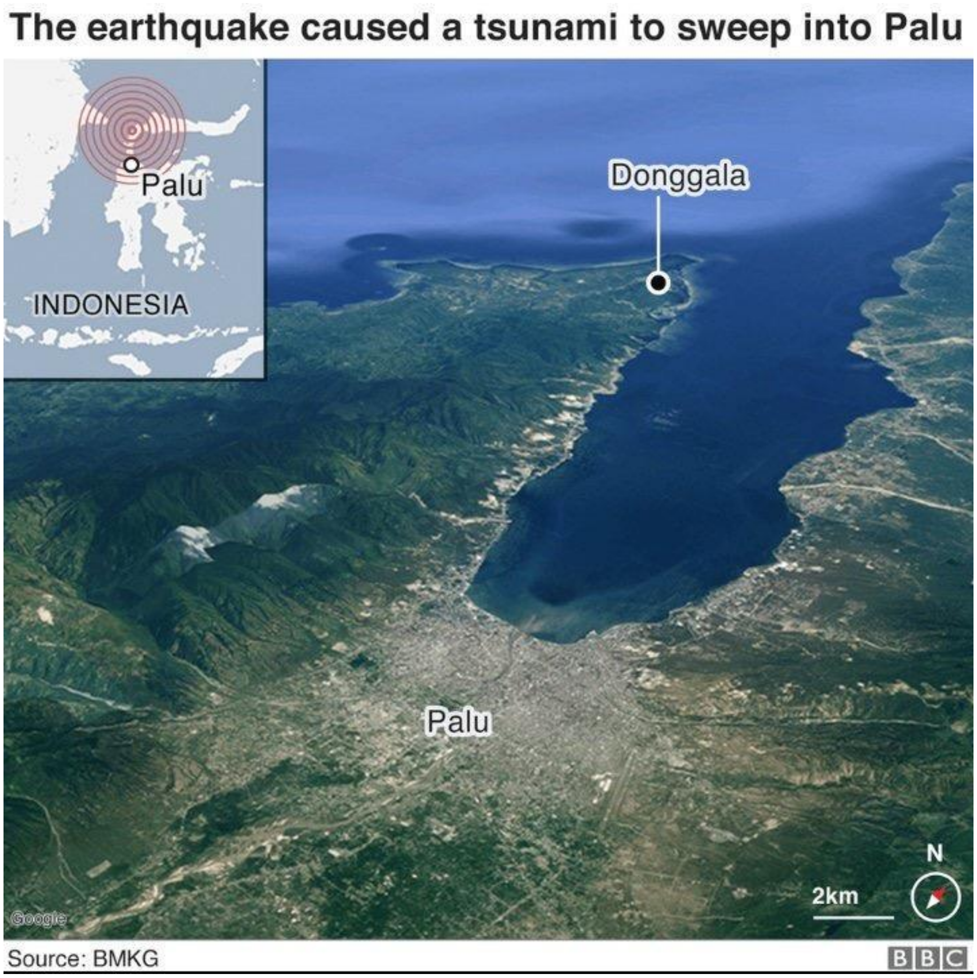
Figure 4: USGS Fault Analysis (USGS, 2018b)



By Derek Watkins and Bedel Saget | Source: U.S. Geological Survey ShakeMap

Figure 5: New York Times Graphic showing relative location of the city of Palu, Donggala town and the earthquake epicenter (NYT, 2018a)

The city of Palu, with a population of 336,000 based on a 2010 census (Wikipedia, 2018a), is located in an alluvial valley at the end of the narrow Palu Bay (Figure 5). The town of Donggala is located near the mouth of the Palu Bay. Figure 6 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 amplitude significantly compared with other coastlines outside of the bay (Figure 7).



The earthquake caused a tsunami to sweep into Palu

Source: BMKG

Figure 6: Location of the city of Palu and Donggala town on elongated bay (Source: BMKG/BBC).

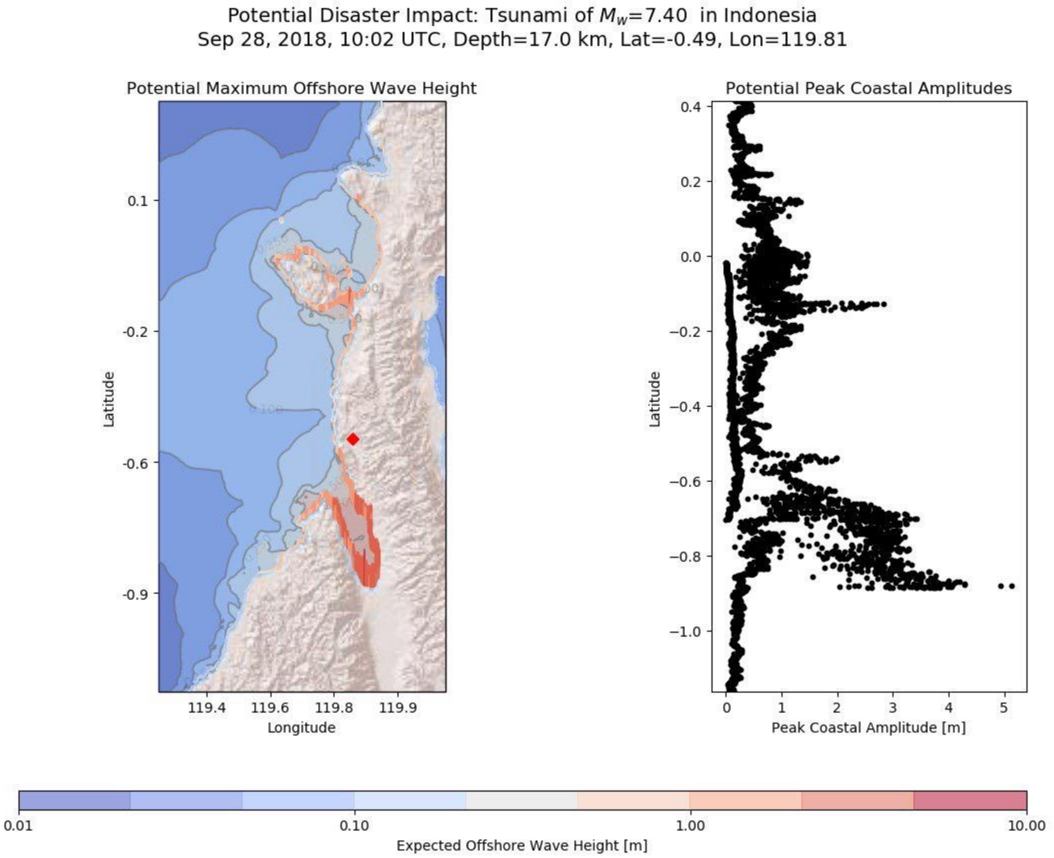


Figure 7: Tsunami wave height model prediction (Source: CATnews, 2018; @CATnewsDE)

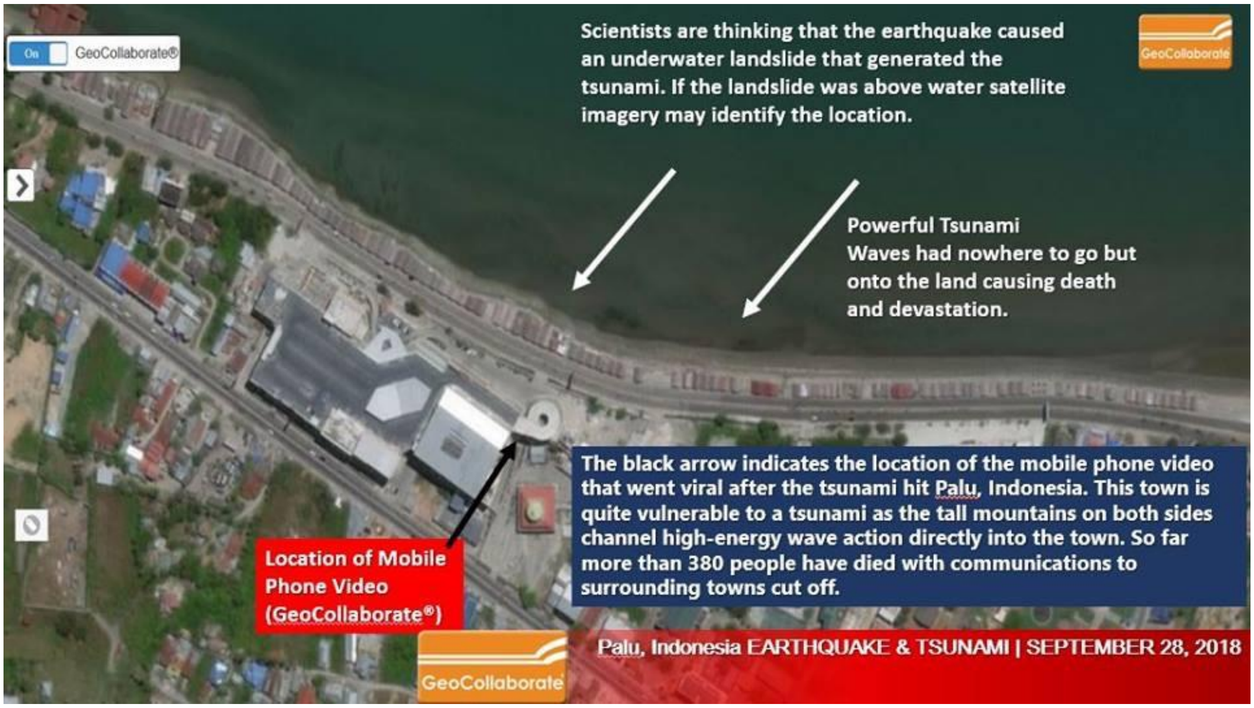
A number of survivor videos are available online. Figure 8 shows three images extracted from a survivor video of a tsunami wave approaching the Palu shoreline as a broken bore. The nearshore area is already wet, indicating that this was not the first wave in the tsunami sequence. The full video is available at: https://twitter.com/i/status/1045682372623052802

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 9).

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

- https://twitter.com/i/status/1046151843888418816
- https://twitter.com/i/status/1046021328686534656
- pic.twitter.com/yFhRH1Saiw
- pic.twitter.com/p5vD9qZ3jO

Figure 8: Images from survivor video taken from parking structure spiral ramp as tsunami bore approached the Palu shoreline (Source: cbsn.ws/2OSf94xpic.twitter.com/mW4qhK9n3X).



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.

Location of Mobile Phone Video (GeoCollaborate®)

Palu, Indonesia EARTHQUAKE & TSUNAMI | SEPTEMBER 28, 2018

Figure 9: Graphic showing location of survivor taking video of incoming tsunami bore (Source: GeoCollaborate) (0.8837 S, 119.8438 E).

Damage to "Engineered" Structures

At the time of writing this PVAT report, the author has limited knowledge of seismic and tsunami design requirements in Sulawesi Island. A number of structures that would typically require structural engineering design were damaged or completely destroyed during this event. These structures are refereed to here as "engineered" structures because of 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 are reported to have collapsed during the earthquake. Most notable was the eight-story Roa-Roa Hotel (0.90290 S, 119.86869 E) which collapsed resulting in multiple deaths (Figure 10 and Figure 11). The building lateral force resisting system appears to be a reinforced concrete moment frame structure (Figure 12 and Figure 13). Details of the beam-column framing are visible in Figure 14.

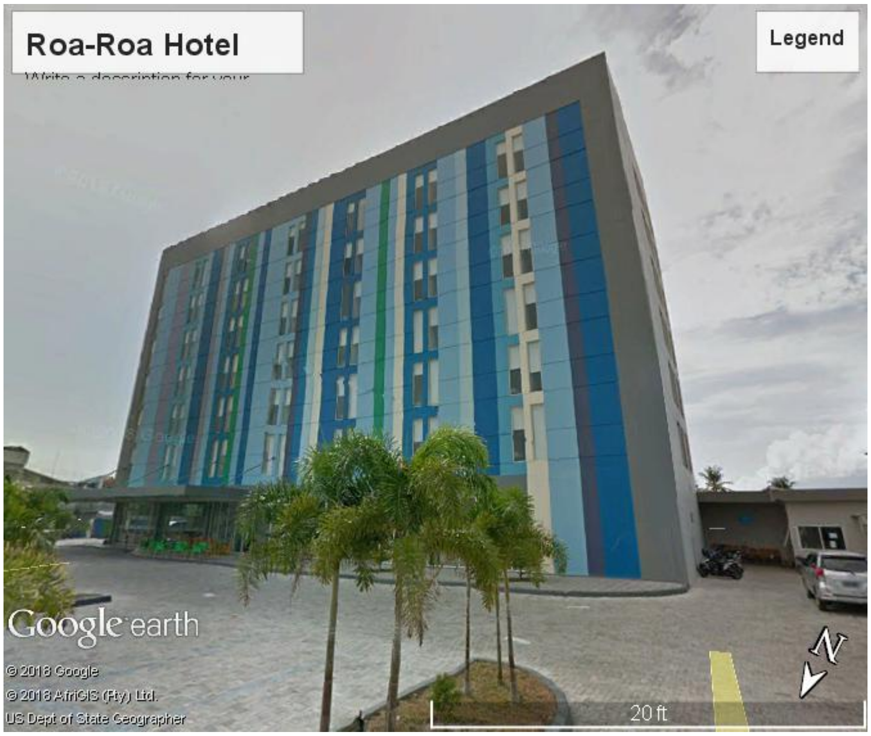


Figure 10: Google Earth Streetview image of Roa-Roa Hotel before the earthquake

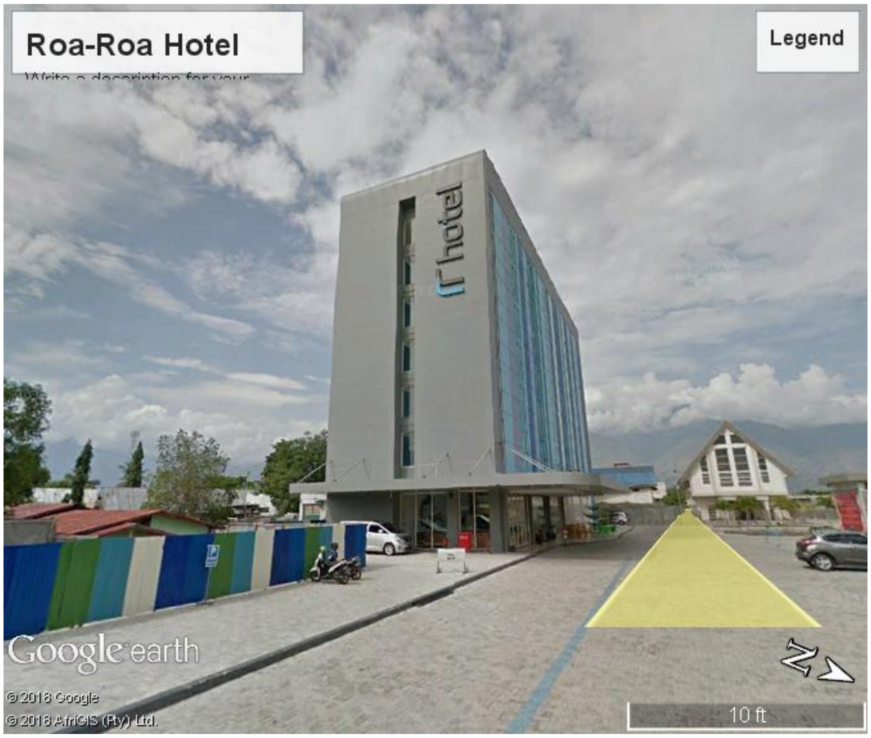


Figure 11: Google Earth Streetview image of Roa-Roa Hotel before the earthquake

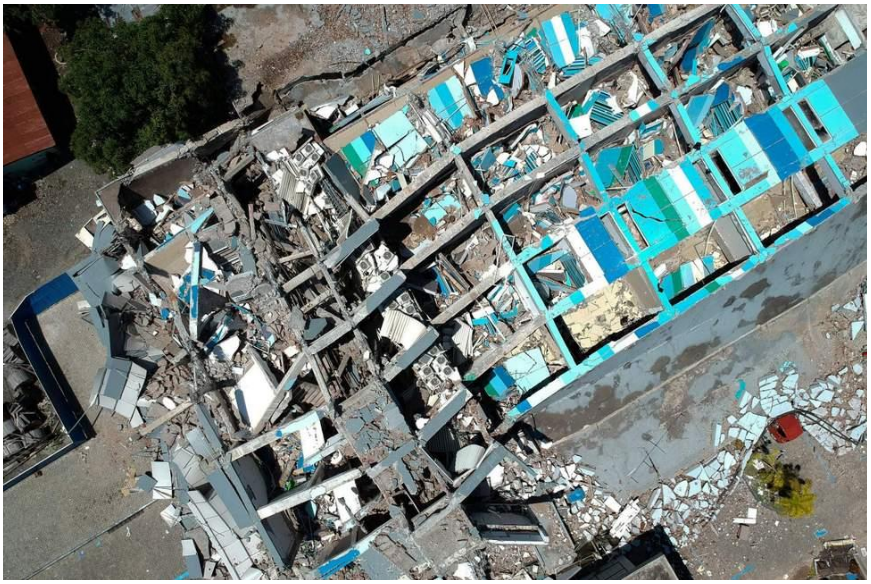


Figure 12: Collapsed Roa-Roa Hotel after earthquake

Figure 13: Collapsed Roa-Roa Hotel after earthquake

Figure 14: Lower levels of Roa-Roa Hotel after collapse due to earthquake

A reinforced concrete shopping center in Palu experienced partial collapse during the earthquake (Figure 15). A number of mosques also suffered severe damage or even collapse (Figure 16 and Figure 17). The Baiturrahman Mosque experienced both the earthquake shaking and the subsequent tsunami. It appears that the partial collapse of the roof dome can be attributed to the earthquake shaking, while the extent of tsunami damage is unknown at this time (Figure 18). The Apung Palu Mosque located on piles slightly off-shore from the Palu coastline suffered severe damage apparently due to significant settlement or damage to the supporting piles (Figure 19). The bridge that provides access to the mosque has collapsed. It is not known whether this damage was the result of the earthquake or tsunami, or a combination of the two.

Figure 15: A reinforced concrete Shopping Center in Palu experienced partial collapse during the earthquake (Photo: AFP/BNPB)

Figure 16: Collapse of mosque (location unknown)

Figure 17: Damage to Baiturrahman Mosque

Figure 18: Baiturrahman Mosque during tsunami inundation

Figure 19: Apung Palu Mosque before (left) and after (right) the earthquake and tsunami. Exact cause of damage not yet established but could be due to earthquake shaking prior to the tsunami, or possibly a combination of both events.

The top level of the Palu Mutiara Sis Al Jufri Airport control tower collapsed during the earthquake (Figure 20 and Figure 21). This is a common occurrence for airport towers because of the large window openings generally required at the control room, and the frequent lack of adequate lateral framing system supporting the roof. One air traffic controller, twenty-one-year-old Anthonius Gunawan Agung, was reportedly on duty in the tower and continued to assist a Batik airplane during take-off, even as the earthquake occurred. He apparently leaped from the control tower just before it collapsed, but died due to injuries suffered in the fall (Times of Isreal, 2018). Damage also occurred in the main terminal building (Figure 22).

Figure 20: Airport Control Tower after earthquake with top level collapse (0.91670 S, 119.90654 E)

Figure 21: Earthquake damage to airport control tower.

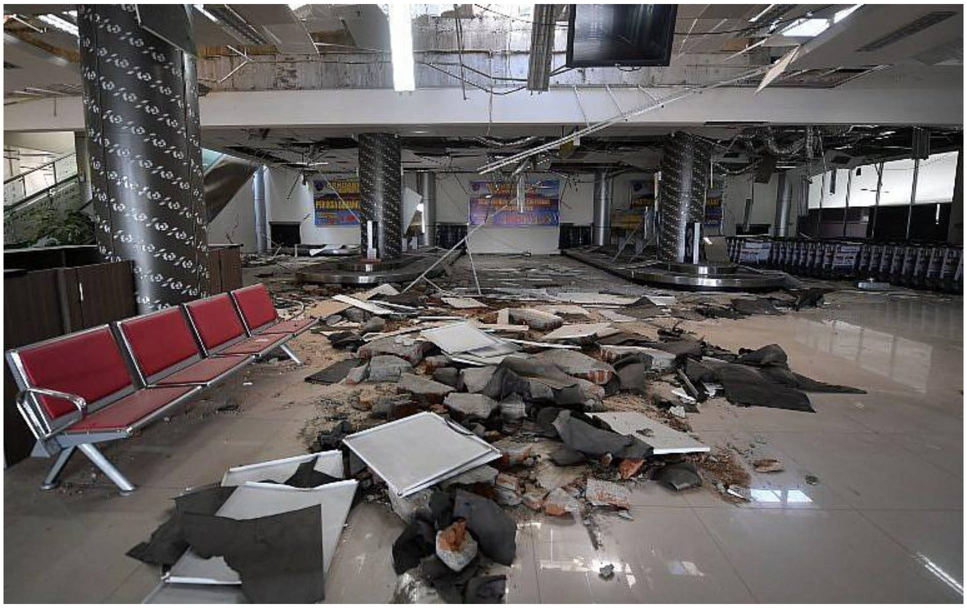


Figure 22: Damage inside airport terminal building (AFP Photo/Adek Berry)

Bridges

The iconic twin steel arch cable-suspended Palu Bridge IV over the mouth of the Palu River (Figure 23 and Figure 24) collapsed, presumably during the earthquake (though this needs to be confirmed) (Figure 25 and Figure 26). 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.

Figure 23: Palu Bridge IV prior to earthquake (Tofan Rozianto) (0.885423 S, 119.85883 E)

Figure 24: Palu Bridge IV before earthquake (Mohamad Affan)

Figure 25: Palu Bridge IV after earthquake and tsunami

Figure 26: Palu Bridge IV after earthquake and tsunami (Photo: Athit Perawogmetha/Reuters)

Port and Industrial Structures

A gantry crane at a port facility to the Northeast of Palu (exact location not yet confirmed) appears to have collapsed during the earthquake, though the exact timing of failure is unknown (Figure 27). Damage is also evident to a port facility further to the North, probably also attributable to earthquake shaking (Figure 28).

Figure 27: Failure of gantry crane (possibly at 0.710899 S, 119.85577 E)

Figure 28: Damage to port facility (0.690718 S, 119.82923 E)

Damage to Lifelines

Roadways

Substantial damage has occurred to roadways in the Palu area (Figure 29, Figure 30 and Figure 31). It appears that some of this damage is due to surface rupture, liquefaction and lateral spreading, while other damage is due to landslides and rockfalls triggered by the earthquake.

Figure 29: Significant damage to roadways due to fault rupture and liquefaction.

Figure 30: Failure of roadway due to landslide induced by the earthquake.

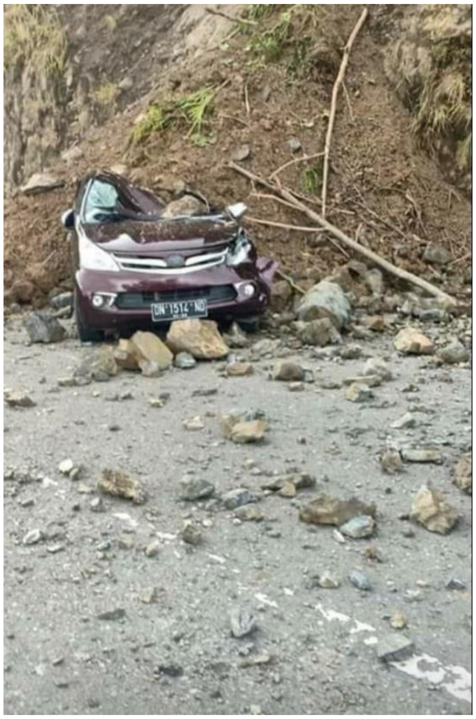


Figure 31: Landslide damage to car and roadway (location unknown)

Airport runway

Similar damage due to earth movement has resulted in large cracks in the asphalt paving on the runway at the Palu Mutiara Sis Al Jufri Airport (Figure 32).

Figure 32: Damage to Palu's Mutiara Sis Al Jufri Airport runway due to ground movement.

Ports and Harbors

A number of ships have been washed onshore by the tsunami (Figure 33 and Figure 34). Other ships and barges broke free of their moorings and were washed out into the bay (Figure 35).

Figure 33: Ship and boats washed onshore by tsunami (Sources: Left image – NYT, 2018c; Right image – phys.org, 2018) (0.69482 S, 119.8403 E)

Figure 34: Ship washed onshore adjacent to Watusampu Naval Base (0.821631 S, 119.81086 E)

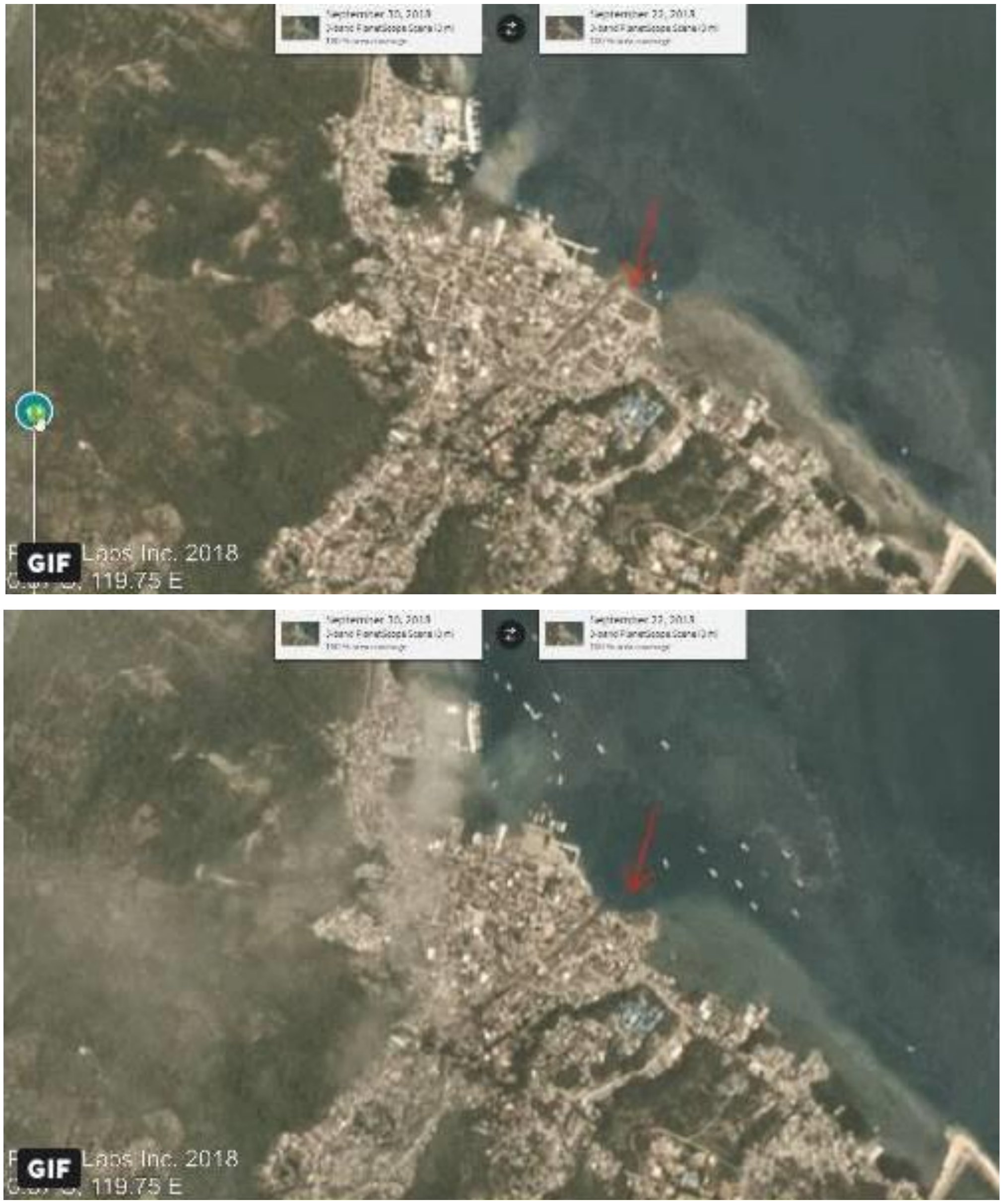


Figure 35: Before (top) and after (bottom) images of ships washed from their moorings by the tsunami. Port damage and erosion evident along coastline. (Source: Murray Ford twitter feed **@mfordNZ)**

Shipping containers stored at the shoreline along the West edge of Palu Bay were only affected at the shoreline (Figure 36). This is likely due to the limited tsunami inundation at this location as evidenced by the lack of damage to adjacent buildings.

Figure 36: Shipping container yard after tsunami (0.76477 S, 119.7905 E)

Power distribution system

Numerous power poles were destroyed during both the earthquake and tsunami. Power was lost to Palu city and had not been reinstated at the time of writing this report. Work is already underway to restore power as quickly as possible (Figure 37 and Figure 38).

Figure 37: Installation of new power distribution poles within days of the earthquake.

Figure 38: Repair of high-voltage transmission lines within days after the earthquake.

Geotechnical Failures

Liquefaction and significant lateral spreading appear to have occurred at a number of locations in Palu (Figure 39). Video evidence of lateral spreading and resulting ground failure and damage to structures can be viewed in the following videos, some of which were posted by Sutopo Purwo Nugroho, Head of Information Data and Public Relation Center, BNPB - National Agency for Disaster Management, Indonesia (Twitter feed: @Sutopo_PN):

- pic.twitter.com/Vf5McUaaSG
- https://twitter.com/jogja_uncover/status/1046031925566091265?s=12
- pic.twitter.com/Qb736P1bA6

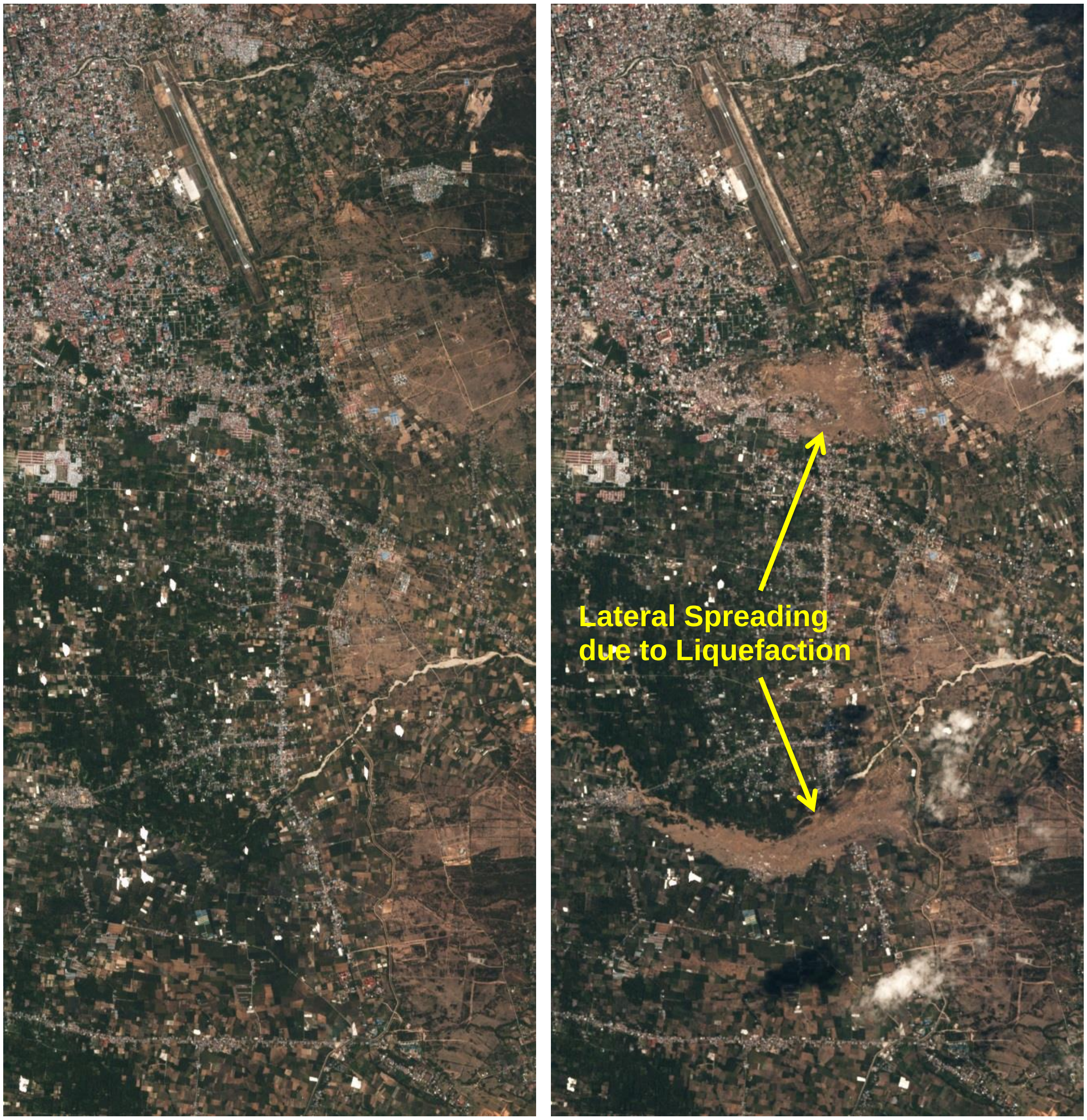


Figure 39: Aerial images of Palu before (left) and after (right) the earthquake. Severe lateral spreading due to liquefaction is evident in two large areas leading to total destruction of buildings and infrastructure in those areas (Source: New York Times, NYT, 2018b)

StEER Response Strategy

StEER has initiated a Virtual Assessment Team (VAT) to collect and process public data relating to the Palu Earthquake and Tsunami. These data will be used to develop a VAT report that will augment this preliminary report. StEER is coordinating with other organizations including GEER, EERI and SEER to determine how best to collect on-site data for this event. Contacts have also been made with earthquake and tsunami researchers in Japan to potentially organize collaborative field assessments.

References

CATnews, 2018: https://twitter.com/CATnewsDE/status/1045717436459307009

NPR, 2018: https://www.npr.org/2018/10/01/653268266/indonesian-tsunami-death-toll-hits-1-200-survivors-desperate-for-aid

NYT, 2018a: https://www.nytimes.com/2018/09/30/world/asia/indonesia-tsunami-science.html

NYT, 2018b: https://www.nytimes.com/interactive/2018/10/01/world/asia/map-tsunami-indonesia.html

NHT, 2018c: https://www.nytimes.com/interactive/2018/10/02/world/asia/indonesia-tsunami-early-warning-system.html

Phys.org, 2018: https://phys.org/news/2018-09-indonesia-tsunami-death-toll-nears.html

Times of Israel, 2018: https://www.timesofisrael.com/indonesian-airport-employee-lauded-as-hero-for-sacrificing-self-to-save-plane/

USGS, 2018a: https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4#executive

USGS, 2018b: https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4#finite-fault

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.

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 each of the 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 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.