Review of the 2018 Palu Tsunami: Disaster Behavior and Reflections on Disaster Management

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The 2018 Palu $M_w 7.5$ earthquake and tsunami attracted geophysicists’ attention for its strike slip focal mechanism and magnitude. We inspected the details of this disaster and discussed its particularity and possible causations. The submarine landslide and special terrain conditions could have contributed to the unusual size of the tsunami. The early warning system and the post disaster response is also reviewed. Efficient social warnings and broadcast systems along with good maintenance is essential. We also found that enhancing publics scientific literacy is the most important way to reduce disaster damage and casualties. Moreover, social conditions and rebuilding difficulties post tsunami are related as reference resources for future disaster management strategies.

Key words: Palu tsunami; Disaster loss; Tsunami early warning; Disaster management

INTRODUCTION

The latest report by the United Nations Office for Disaster Risk Reduction shows that the number of natural disasters worldwide is rapidly increasing. Occurring around the world, natural disasters affect human life, cause great economic losses and cause great damage to the environment. According to the report, natural disasters have killed 1.3 million people and injured or displaced 4.4 billion people in the past 20 years (Pascaline W. et al., 2018). Of all those

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disasters, the first killer is the earthquake and the tsunami it triggered, causing 740,000 deaths. The most recent tsunami was the Palu tsunami.

On September 28, 2018, a deadly tsunami swept Palu, the capital city of central Sulawesi, Indonesia, following the $M=7.5$ earthquake. The Palu tsunami devastated this 1.5 million people island and left the city in ruins. According to the Indonesian National Disaster Agency announcement, 2,256 people had been killed, 4,488 were seriously injured and 1,075 were lost in Palu and nearby cities, making this earthquake and tsunami the deadliest disaster since the 2006 Yogyakarta earthquake in Indonesia. Due to its huge casualties and large amount of damage, the Palu tsunami attracted the attention of the international community again after the destructive Sumatra-Andaman tsunami in 2004 (Lay T. et al., 2005) and Fukushima tsunami in 2011 (Mori N. et al., 2011). Coincidentally, the 2004 Sumatra-Andaman tsunami also attacked Indonesia, resulting in a casualty of nearly 170,000 people. Given the amount of devastation, it worth considering what tsunamis are and what we should do when facing a tsunami.

According to the statistics from the National Disaster Mitigation Agency of Indonesia, the earthquake and tsunami caused severe destruction in Palu, Sigi and Donggala. Estimates from October 22, 2018 show that 1,703 people had been killed in Palu, the worst-hit area, with 1,549 injured and 832 missing. Sigi and Donggala are among the major casualty areas with 366 and 171 deceased, respectively. There were also reports on missing persons and casualties in nearby regencies. This disaster also resulted in more than 2,000,000 people displaced from their homes and over 10,000 people injured in Central Sulawesi in total, among which 4,612 are seriously injured. This disaster resulted in economic losses of Rp 13.82 trillion (US $911 million or 6.33 billion yuan (RMB)), which consisted of Rp 1.99 trillion in lost income and Rp 11.83 trillion in physical damage. The residential sector received serious damage. This tsunami, with its height reaching an estimated maximum of 4m to 7m, destroyed almost all the buildings along the Palu Bay. About 70,000 houses and hundreds of workshops, schools and shops were severely damaged. The earthquake also caused soil liquefaction in areas that the tsunami never reached, leading to mudflows in Petobo, a sub-district in southern Palu and one rural village Balaroa. This village almost disappeared as the ground collapsed and most of the houses became submerged, and 600 out of its 2,000 inhabitants are known to have died.

This disaster also paralyzed public infrastructure and traffic systems. A mosque and a major section of the Antapura Hospital were destroyed in Palu. Dozens of people were trapped by the collapse of many hotels and shops, among which was Palu’s Tatura Mall, one of the oldest local shopping centers. The airport runway and some buildings were damaged during the earthquake, forcing the airport to close. The tsunami also caused major structural damage to ports in Pantoloan Harbor and Ogoamas Harbor. The Kuning Ponulele Bridge, which is one of Palu’s iconic buildings also collapsed. Some of the main roads connecting Palu to other cities were blocked and cut off, and access to affected areas has been challenging due to rubble and landslides. The earthquake and ensuing tsunami also affected the telecommunications systems. Official media reported that more than 500 wireless communication towers were damaged, leaving the disaster area without contact after the disaster.

Although Indonesia established an early warning system for destructive tsunamis after the 2004 Indian Ocean tsunami, they still suffered a high number of casualties. It seems that the warning system didn’t play its supposed role. This tsunami caused by an $M7.5$ earthquake also surprised geologists as the earthquake had a strike-slip focal mechanism and a relatively small magnitude. These facts along with the enormous life and economic loses left us many questions about our current knowledge about tsunamis. In this article, we will first discuss why this tsunami is so special from tectonic aspect, and then analyze the possible role of the local topography in the disaster. We will also evaluate the function of the tsunami warning system so that new insights
about tsunami generation and hazard mitigation can be obtained. The tsunami triggered hazards and the rebuilding difficulties of Palu will also be discussed.

1 UNEXPECTED TSUNAMI INDUCED BY A STRIKE-SLIP EARTHQUAKE

As mentioned earlier, the 2018 Palu tsunami was an extremely destructive tsunami that attacked Indonesia in recent years. Located in the circum-Pacific Rim seismic belt area, also called the Pacific Ring of Fire, Indonesia is an earthquake-prone country, which sees approximately one significant volcanic eruption and one major earthquake every year. Earthquakes and volcanic eruption can trigger tsunamis, which makes the Indonesian archipelago one of the most threatened areas of tsunami hazards. Though a large tsunami can occur once every five years, the 2018 Palu tsunami caught geophysicists by surprise.

The English word “tsunami” comes from Japanese, which means the wave in a harbor (Yang Huating, 1987). As the name suggests, a tsunami is an oceanic traveling wave with super-large wavelength and periods generated by sudden changes in the submarine topography. There are several causes to generate a tsunami, such as earthquakes and volcanic eruptions that cause vertical land motion underwater, seabed mudslides, and landslides. When it propagates towards the shallower water area near the coast, the wave amplitude rises sharply, and can sometimes reach 20m–30m or more, suddenly forming a “water wall”, instantaneously invading coastal land and sweeping down everything along its path (Charlier R. H., 2010). The tsunami has terrible energy and can cause considerable damage.

Almost all of the great tsunamis are caused by thrust earthquakes that happen at the subduction zone and convergent plate boundaries, where the plates compress each other and the stress accumulates to cause tremendous and rapid vertical land displacement. In addition, an earthquake that triggers a significant tsunami must have enough energy, in other words, it should be a giant earthquake. For example, the earthquake that caused the 2004 Sumatra-Andaman tsunami has a magnitude of $M_w 9.3$ and the earthquake that caused the 2011 Fukushima tsunami has a magnitude of $M_w 9.0$. But the 2018 Palu earthquake doesn't match either of these cases.

The focal mechanism solution shows that the Palu earthquake's mainshock fault was a strike-slip fault. The United States Geological Survey (USGS) determined that the principal source parameters of the mainshock is as follows; the original time was September 28, 2018, 10:02:43, GMT time and 18:02 local time; epicenter located in 0.178°S, 119.840°E. The focal mechanism solution shows that the Palu tsunami has a focal depth of 10.0km. The position and the mechanism solution are showed in Fig.1.

Although there were tsunamis generated by strike slip earthquakes in record, this type of tsunami is usually much smaller than subduction zone generated tsunamis. Because most subduction zone earthquakes are thrust earthquakes, a fault dip of a minor angle and the plates travel along the dip while vertical motion is present. Therefore subduction zone earthquakes can cause enough vertical land motion at the seabed to trigger a significant tsunami (Fukao Y., 1979; Satake K. et al., 1999). Conversely, in most instances, the dip of a strike slip fault is roughly 90°, which means the two plates of the fault move horizontally. This type of movement leads to none or slight vertical land motion at the surface of both plates and results in less displacement of water than a thrust fault would. Accordingly, a strike-slip earthquake rarely generates a tsunami. Only a few strike slip earthquakes have generated tsunami, but that is with small run-up elevation. For example, the 1999 $M7.4$ Izmit earthquake in Turkey generated a small tsunami with a maximum run-up elevation of about 2m (Altinok Y. et al., 1999). This earthquake was located at the North Anatolian fault, which is a strike slip fault.

Another reason why the Palu tsunami is special is that the magnitude of the generating
earthquake is relatively small. According to the earthquake catalog, there was a sequence of foreshocks before the mainshock. The biggest foreshock had a magnitude of $M_w 6.1$ at 15:00 local time. The mainshock was felt as far as Samarinda and Malaysia, and strong shaking was reported in Palu and Donggala, but the magnitude of the mainshock is only $M_w 7.5$. Following the mainshock, 14 of $M > 5.0$ aftershocks in the first 24 hours occurred around the epicenter. This data demonstrates that the Palu earthquake is not so giant. The empirical relationship between tsunami height and earthquake magnitude is shown in Table 1. It is generally believed that although destructive tsunami events caused by earthquakes which magnitudes are $7.0 - 8.0$ have occurred in history, they are relatively rare.

**Table 1** Empirical relationship between earthquake magnitude and tsunami height

<table>
<thead>
<tr>
<th>Earthquake magnitude ($M$)</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
<th>8.5</th>
<th>8.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsunami height (m)</td>
<td>&lt;0.3</td>
<td>0.5–0.7</td>
<td>1.0–1.5</td>
<td>2–3</td>
<td>4–6</td>
<td>16–24</td>
<td>&gt;24</td>
</tr>
</tbody>
</table>

It remains a mystery that why a relatively light, strike slip earthquake caused a big tsunami. The Palu tsunami reminds us to reconsider the possibility of devastating tsunami generation, and to reconstruct the knowledge and prediction system for the future. Some experts believe that submarine landslides might contribute to the Palu tsunami. The soft sediment of the Palu Bay collapsed during the earthquake and caused the submarine landslides. Extensive landslides have been observed in the surrounding mountains, along the valley floor in Palu and the shoreline. This provides a clue that these landslides might also happen in submarine conditions, and these underwater landslides contributed to the size of the tsunami indirectly. This conjecture needs to be verified by the geological survey data of the Palu Bay.
2 DESTRUCTIVE TSUNAMI Magnified by Special Terrain Conditions

A tsunami is the result of the combined effects of submarine traveling waves and surface elevation changes. When the tsunami propagates in the deep sea area, the height of the waves remains at a minor value. Observation shows that even the wave height of the 2004 Sumatra-Andaman tsunami in the center of the Indian Ocean is about 0.6m, however the wave length is about 500km (Lay T. et al., 2005; Alongi D. M., 2008). Therefore, the tsunami is quite flat in the deep sea area. As the depth of the sea decreases, the height of the tsunami increases and finally forms a huge wave on the coast. Similarly, land topography can affect the development of tsunamis, too. When tsunami traveling in the vast sea area arrives at narrow land surrounded by mountains, masses of water accumulates in smaller and smaller spaces. As a result, the height of the tsunami increases, making the tsunami magnified, which may be another reason why the Palu tsunami was so great. A similar situation occurred in the 2016 Fukushima tsunami in Japan, where the tsunami run-up height was enlarged almost 2 times due to coastal topography (Suppasri A. et al., 2017).

![Fig.2 The topography of the Palu bay](image)

An extremely long and narrow topography in the Palu bay (From U.S. Geological Survey ShakeMap)

The Sulawesi Island is the 11th largest island in the world, with a total land area of 174,600km². It is located between central Indonesia and southern Philippines, where the Eurasian plate, Oceania plate and Pacific plate converge. It is a part of the volcano-island arc of the Western Pacific (Fitch T. J., 1972; Carlile J.C. et al., 1990). The shape of Sulawesi Island is very special, similar to a large K letter, with four peninsulas. The epicenter of the M7.5 earthquake was located on the lateral back of the K, close to the city of Palu. The coast is steep and tortuous with a total length of 5,478km. The central part of the island is a steep mountain while the coastal plain is relatively narrow. Sedimentary strata and volcanic rock strata in this area constitute the southern margin of the North Sulawesi area structure.

The administrative region of Sulawesi is divided into six provinces West Sulawesi, North Sulawesi, Central Sulawesi, South Sulawesi, South-East Sulawesi and Corontalo. Palu, the central city of Sulawesi, lies on a narrow bay about 10km long and 2km wide in the Central Sulawesi Province, on the NNW-SSE Trend Palu-Koro strike-slip fault which is between the Makasa Strait and the Tomini Bay (Bellier O. et al., 2001; Socquet A. et al., 2006; Watkinson I. M. et al., 2017). The topography is so narrow and slender due to the sheltered location between the ridges on both sides that this area is favorable for weather like typhoons.

The Bay is blocked by shorelines on both sides, forming a wave shadow zone in the bay,
which reduces the energy of waves and tides. But if a tsunami attacks this area, this pocket-shaped terrain will magnify the destructive force of the waves when it rushes toward the city, due to the strengthening effect, similar to the Qiantang River Tide in China (Lin Bingyao et al., 2002). This is because after the tsunami spreads to the bay, affected by the sea water depth, the wave height increases and reaches the maximum at the end of the bay. Indonesian officials confirm that about 20 minutes after the earthquake, the tsunami reached Palu. The tsunami reached 5m when it attacked Palu, and rose as high as 6m. The special terrain caused severe damage to the island of Palu by the tsunami.

3 TRAGIC TSUNAMI WITHOUT SUPPOSED EFFECTIVE FORECASTING

Scientific research on tsunamis is to enable people to foresee and mitigate the hazard that tsunamis can cause. Past experience shows that it is important to establish effective detecting and broadcasting systems to provide real-time accurate tsunami forecasts and warnings for residents and public utilities (Yang Huating, 1987). Following the M7.5 earthquake, a tsunami alert was issued for nearby Makassar Strait, but was canceled half an hour later. This unsuccessful warning provides us a painful lesson about tsunami warning theory and methods. The tsunami warning work is not new, but should be a more mature routine social security work. The failure in Palu leaves us with at least three questions to think about.

Firstly, we should broaden the theory about destructive tsunami generation. As referred to in this article, the Palu earthquake was a mild strike slip earthquake that is not likely to cause a significant tsunami according to previous theories. Giant earthquakes with rapid vertical displacement is a key factor for a tsunami. The necessary conditions for issuing a tsunami warning by the Pacific Warning Center are as follows: the focal depth of seabed earthquakes is less than 60km, and the magnitude of the earthquake is bigger than 7.8. These guidelines could explain why the warning was called off too early for the Palu tsunami. Strike slip earthquake caused tsunamis in special geographical environments should be considered in the future.

There are two types of tsunamis. One is the offshore tsunami, also known as a local tsunami, where the submarine earthquake occurred within hundreds of kilometers or less from the coast. The travel time for the tsunami to reach the coast is very short (a few minutes or tens of minutes). It is difficult to defend. The other type is the oceanic tsunami, which spreads from or even across the ocean and causes a great damage even thousands of kilometers away (Xu Qihao, 2007). The oceanic tsunami takes hours to arrive at the coast, leaving enough time for a warning. In an oceanic tsunami situation, a warning system consisting of a network of tidal gauges that measure sea level and land-based station that detects earthquake activity is enough to give accurate tsunami warnings. But this system wouldn’t have worked for the Palu tsunami, which was a type of local tsunami. The reaction time is too short and a local earthquake would destroy the equipment. A more suitable complementary warning model is urgently needed for local tsunamis.

Secondly, an efficient and well-run social emergency management system is essential. This demands a set of advanced detection and warning equipment, good routine maintenance and a reliable official-to-public communication system. After the huge 2004 Indian Ocean tsunami, Indonesia established a new early warning system to prevent such widespread destruction from happening again. This system consists of 22 buoys deployed in Palu Bay. These buoys connected to undersea sensors can monitor tiny changes in pressure and issue a warning. The key to whether such a system could work is the location of the tsunami source and location of these buoys. First, the system must be on the path of the tsunami so that it can detect the tsunami before it reaches the people at risk. Also, sufficient reactive time is needed to broadcast the warning message to the public and for people to take appropriate measures. However, this system was offline during this
Fig. 3 Illustration of deep ocean assessment and report system of tsunami (From dart.org)

catastrophe due to unsolved equipment upgrade problems and none of the buoys have been working since 2012. But even if they were working properly, this system would not have helped in Palu because it was subjected to a local tsunami. There was also a problem with the message broadcast. The Indonesian government issued a tsunami warning via text message, but many residents didn’t receive it as the earthquake wrecked many mobile signal towers. Similarly, damage to power lines prevented sirens from working.

Thirdly, public safety awareness and safety training must attract enough attention. For a local tsunami, the ground shaking should be the most direct warning for people who live in or travel to a coastal region that is susceptible to tsunamis. There is no need for sirens or any other notification. The government must systematically train residents in their ability to respond to natural disasters, and let them know what to do if they are in a disaster damaged area. Society as a whole, especially the organizer of public events must have a good sense of public security and must take responsibility for public safety. When the Palu tsunami was raging on Sulawesi Island, an annual festival called Palu Nomoni Festival was held along the coast of Palu. Even when officials did send warnings via telephone and television, tsunami alarms were not paid enough attention by festival attendees. The festival continued and some people were still strolling on the beach when the tsunami struck.

Still using Indonesia as an example, its National Tsunami Warning Center issued a tsunami alert on April 11, 2012, when a M8.6 earthquake attacked Banda Aceh. But the local response to the alert does not bode well for future disasters. The government department failed to adopt effective disaster coping strategies for the city. The entire city was in chaos. Instead of getting to high ground, many people chose to go home or to pick their kids up at school. The roads were choked and people were trapped in their cars. Surprisingly, the officers responsible for operating the tsunami sirens fled, and the city’s tsunami shelters were locked. Fortunately, this earthquake didn’t generate a tsunami, otherwise the consequences would be unimaginable. Even these wake-up calls revealed the lack of organization during tsunami in Indonesia, public safety awareness
and security training has not received sufficient attention, which has partially led to huge losses in Palu six years later.

4 THE PAINFUL TSUNAMI CAUSED CHAOS AND RECONSTRUCTION DIFFICULTIES

The tsunami paralyzed Palu and nearby areas, leaving social order in chaos. Society returned to partial functionality several days later, but rebuilding difficulties caused by solid liquefaction remained a thorny problem.

![Fig.4 The remains of Ponulele Bridge](image)

The Kuning Ponulele Bridge, the iconic bridge of Palu and also the first arch bridge in Indonesia destroyed (From Sopa Images)

After the earthquake and tsunami in Indonesia, the main road to Palu was cut off, and the main airport was closed after the tsunami. More than 350,000 people were affected by the disaster. Rescue efforts were hampered by the lack of heavy machinery, disruption of transport routes, large-scale damage and the initial reluctance of the Indonesian government to accept foreign aid. According to some reports, hundreds of Palu residents rushed into supermarkets and gas stations to scramble for foods and fuel on September 30, 2018. At a supermarket in downtown Palu, locals emptied the supermarket with plastic garbage bags and baskets filled with daily necessities such as biscuits, potato chips, diapers, gas cans and toilet paper. Daily Mail reported that the Indonesian government confirmed that on October 2, 2018, two days after the quake, the police had tolerated desperate survivors taking food and water from stores, which could be compensated by the government. But dozens of people who stole computers and cash had been arrested.

On October 3, 2018, the food supply began to recover, stealing was forbidden and community enforcement was strengthened. According to the Associated Press, Indonesia's National Disaster Management Bureau disclosed that 92 people were arrested for robbery the next day. Local television reported that those people were convicted of looting of cargo including oil, tires, tiles and some agricultural equipment. Those people are mainly from Palu and the surrounding areas affected by the disaster. The Indonesian police force also said it would strengthen security patrols to ensure order in Palu, the largest city in the disaster area. On October 5, 2018, Indonesia held its seventh news conference, saying that some shops in the main market in Palu had begun to reopen under the protection of armed military police and economic activity was gradually resuming. However, due to the shortage of supplies, commodity prices rose considerably. Until the afternoon of October 8, 2018, the head of Indonesia's Disaster Relief Agency confirmed that a total of 101 suspected robbers were arrested in the disaster area, and 12 suspected of fabricating earthquake rumors in social media were arrested in different places.

Parts of Central Sulawesi were hit by major mudflows following the earthquake as a result of
solid liquefaction. Petobo sub-district and the village of Balaroa were the hardest hit area areas. Both of them are some distance from the coast. The severe mudflow destroyed residential areas and left many dead. On October 11, 2018, the Indonesian National Disaster Response Agency (BNPB) pointed out that an estimated of about 5,000 people were missing in these two places and 20 thousand houses were destroyed. A spokesman for the BNPB also said it was difficult for authorities to know the exact number because liquefied soil following the strong earthquake in the two areas swallowed a large number of houses into liquid land, making it a challenge to locate bodies from rocks and debris. As time went by, the chances of finding survivors diminished greatly. The government was assessing the feasibility of turning several earthquake areas into mass graves.

![Image](image_url)

**Fig.5** A destroyed Community in Palu, Indonesia, on October 3, 2018

Hundreds of buildings were destroyed by liquefaction, which causes soil to lose its ability to support structures (From The New York Times)

Soil liquefaction occurs when a saturated or partially saturated soil substantially loses strength and stiffness in response to an applied stress, such as shaking during an earthquake. The phenomenon is most often observed in saturated, loose (low density or uncompacted), sandy soils. Solid liquefaction would result in a significant decline in the bearing capacity of the foundation, so that the ground buildings sink in the flowing sand and cause great damage (Karamitros D. K. et al., 2013). Generally, the phenomenon of sandblasting and water emitting after an earthquake are also the result of liquefaction in sandy soil buried in the ground. Solid liquefaction is the product of strong earthquakes. As the earthquake magnitude increases, the scope of the liquefaction becomes larger. There are some traditional treatment measures for liquefaction including the vibration consolidation method, drainage method and soil replacement method. However, when the sand liquefaction area is too large, it will also bring severe challenges to construction and dramatically increase the cost.

5 CONCLUSIONS

The Palu earthquake and tsunami resulted in serious losses both in life and economically. A devastating tsunami generated by a mild strike slip type earthquake has led us to rethink the necessary conditions for the development of a tsunami. Disaster warning and mitigation require a more general tsunami model that is highly adaptable to local tsunamis. Under special terrain situations, a smaller earthquake that caused a giant tsunami is a new issue for geophysicists. Lessons can be learned from Indonesia that an efficient social warning and broadcast system is essential along with good maintenance. It is an important task to raise public awareness of and
ability to deal with disasters. Moreover, the post-tsunami social situation and reconstruction difficulties are reviewed as a reference resources for future disaster management strategies.

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