Damages Associated with Geotechnical Problems in 2018 Palu Earthquake, Indonesia

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1. INTRODUCTION

The Palu earthquake occurred on Friday afternoon, 28 September 2018, at 18:02:44 local time (Central Indonesia Time, WITA) with moment magnitude (Mw) of 7.4, centered 26 km north of Donggala, Central Sulawesi (Figure 1). The earthquake has caused strong shaking, resulted in a tsunami that hit Palu city and disastrous liquefaction occurrences, particularly in Petobo and Balaroa areas. Figure 2 shows the intensity map by the Meteorological, Climatological and Geophysical Agency (BMKG). BMKG automated modeling indicates intensity of VI-VIII in Palu city and Donggala regency, Central Sulawesi. Two-day following the earthquake, BMKG updated the intensity to IX-X (i.e. extensive damage) based on modeling, data instrument, and macro-seismic survey of 30 September 2018. The Palu – Koro fault zone is believed to be the source of the Palu earthquake 2018 (Mw 7.4), as observed from its epicenter location and hypocenter depth, and aftershock distribution (Figure 1).

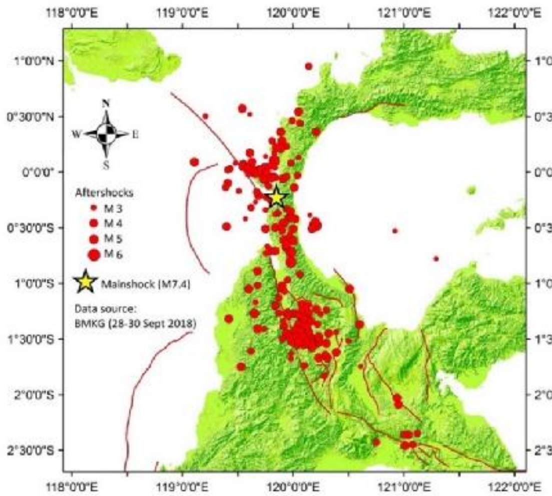

Figure 1 Epicenters of the Palu earthquake 2018 (Mw7.4) and the aftershock distributions (red dots) along Palu – Koro fault in Central Sulawesi (PuSGeN, 2018)

This natural disaster caused many losses of lives and other material damages. The National Agency for Disaster Management (BNPB) on 9 October 2018 reported that this earthquake has caused 2.037 casualties, 671 missing people, and 152 buried bodies. Total of 4.084 people are heavily injured, 74.044 evacuees, and 67.310 houses are estimated to be damaged. Although the most damaged area is in Palu city, these reported numbers are also compiled from other areas, such as Donggala, Sigi, Parigi Mountong, and Pasangkayu, West Sulawesi.

The National Center for Earthquake Studies (PuSGeN) and the Indonesia Association of Geotechnical Engineering (HATTI) deployed a team to conduct field survey assessing impact of Palu Earthquake, from 8 to 15 October 2018. This paper presents findings of field surveys with emphasis on geotechnical impact and fault rupture offset observed in the field.

2. SEISMOTECTONIC OF SULAWESI

Sulawesi is located in the Sunda block adjacent with three plates; the Australia plates, Philippines plate and Pacific plate, known as triple junction. This triple junction results in a complex tectonic in Sulawesi, accommodated by strike slip faulting and thrust faulting. In 2017, PuSGeN considered 50 active-fault segments in Sulawesi and the North Sulawesi Megathrust in the north of Sulawesi (Figure 3). Similar tectonic condition in Sulawesi was also previously reported by Irsyam, et. al., 2010.

The seismicity in Sulawesi is influenced by the subduction along the North Sulawesi Megathrust (Figure 3). The WBZ from the slab in North Sulawesi extends to a depth of about 180 km. The major structures in Central Sulawesi is the Palu – Koro fault system, which extends NNW-SSE direction and cuts Sulawesi apart more than 300 km, from the North Sulawesi trench pass through Palu bay, southward turn to the SE connect to the Matano and Lawanopo faults and further eastward, both faults join to Tolo trench.

Sulawesi moves north-west, suggesting a strong impact from the Australia plate (Figure 4). Velocities in the northern and southern part of Palu – Koro show different magnitude, indicating the activity of Palu – Koro fault zone. To the west of northeast Sulawesi, the island moves westward, indicating an impact from the Pacific plate. The Palu – Koro fault is a sinistral strike-slip fault (horizontal fault striking) in a north-south direction, crossing Palu city. The maximum slip-rate of Palu – Koro fault is 58 mm/year based on geological study by interpretation of geological offset, such as river offset (Daryono, 2016). Recent GPS study also suggests that the slip-rate of Palu – Koro fault is about 40 mm/year.

Central Sulawesi region is tectonically active as shown in Figure 5. Historical destructive earthquakes along Palu – Koro fault zone occurred in 1907, 1909, 1937 dan 2012. Paleoseismologi study has been conducted by Daryono (2016) and obtained that previous earthquakes occurred in 1909, 1468 and 1338. Abendanon (1917) concluded that the 1907 earthquake was followed by a more destructive earthquake 2 years later in 1909. Houses that survived during the 1907 earthquake were mostly destroyed by the 1909 earthquake. The damages run along Saluki up to Donggala region. He reported a large cracking of 7 km with uplift of 1.0 m. Trenching in Onu village on Saluki segment showed evidence of sinistral slip of 1.5 m and vertical slip of 1.5 m. Daryono (2016) suggested a plausible recurrence interval of 130 years in Palu – Koro. During 2017, two main earthquakes were recorded along the fault.

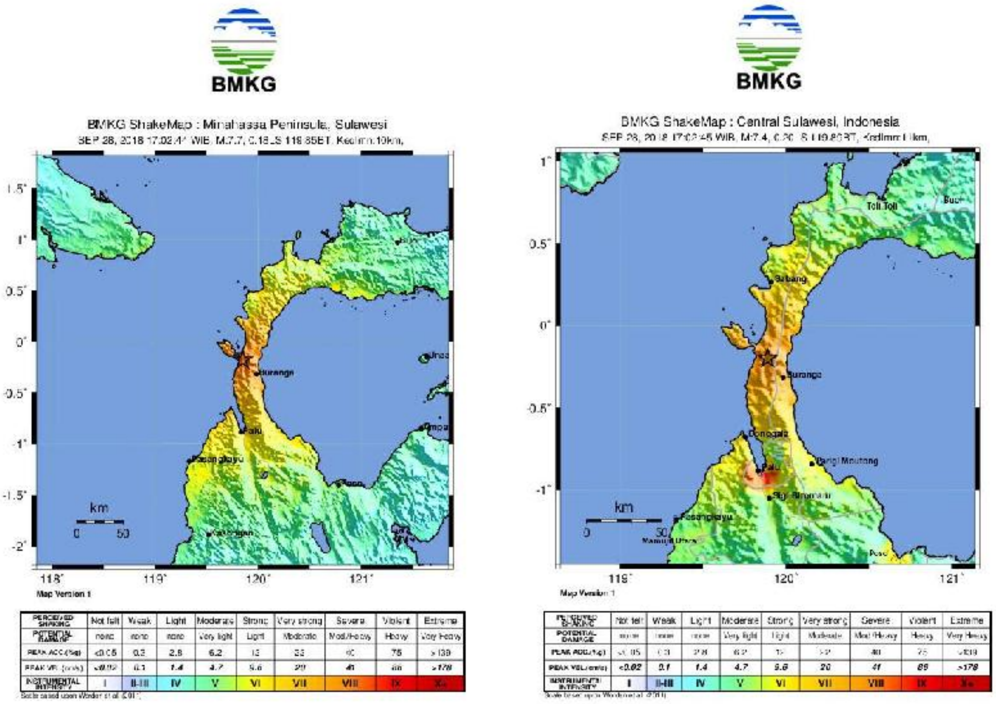

Figure 2 Location of the main shock of the earthquake on 28 September 2018 and its shakemap (BMKG, 2018). Left is the automatic shakemap first generated by BMKG on 28 September 2018, Right is the corrected shakemap based on modeling, data instrument and macroseismic survey as of 30 September 2018

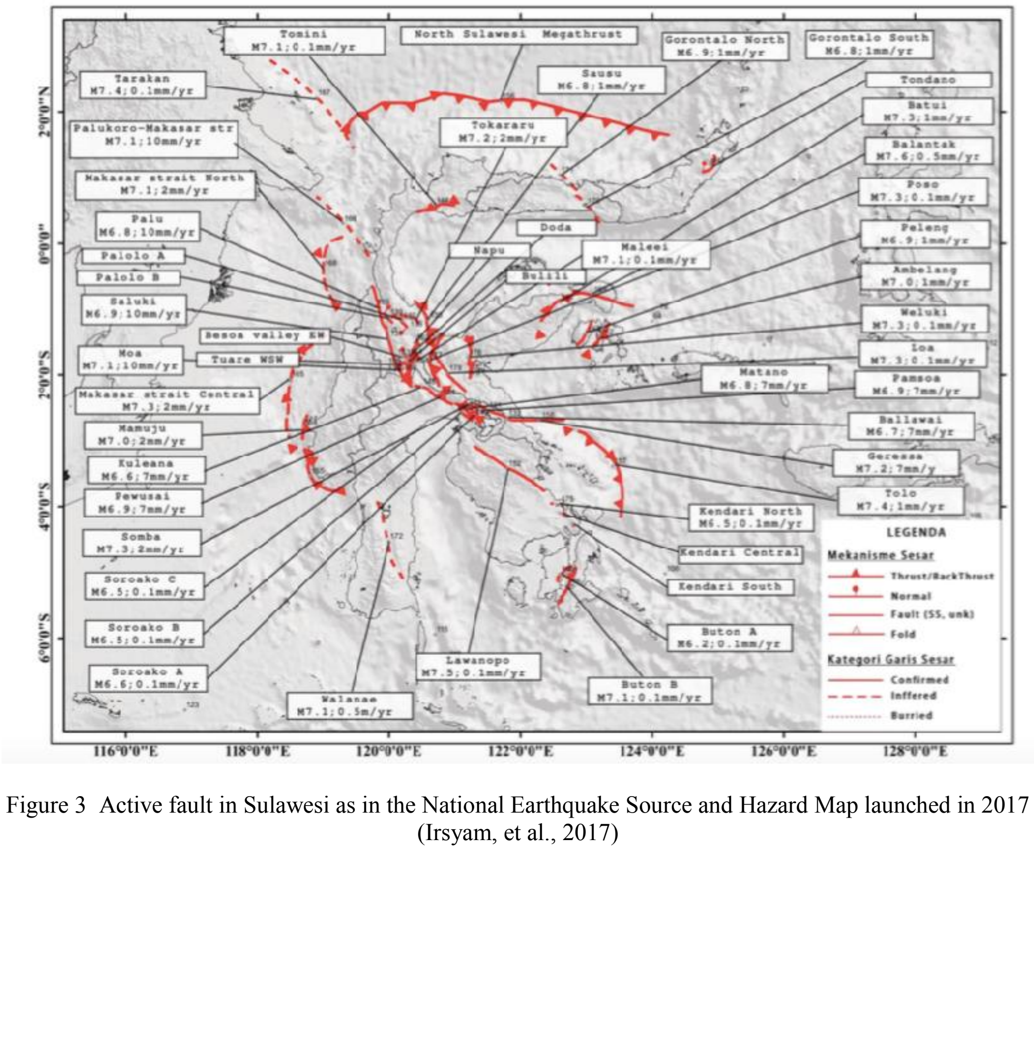

Figure 3 Active fault in Sulawesi as in the National Earthquake Source and Hazard Map launched in 2017 (Irsyam, et al., 2017)

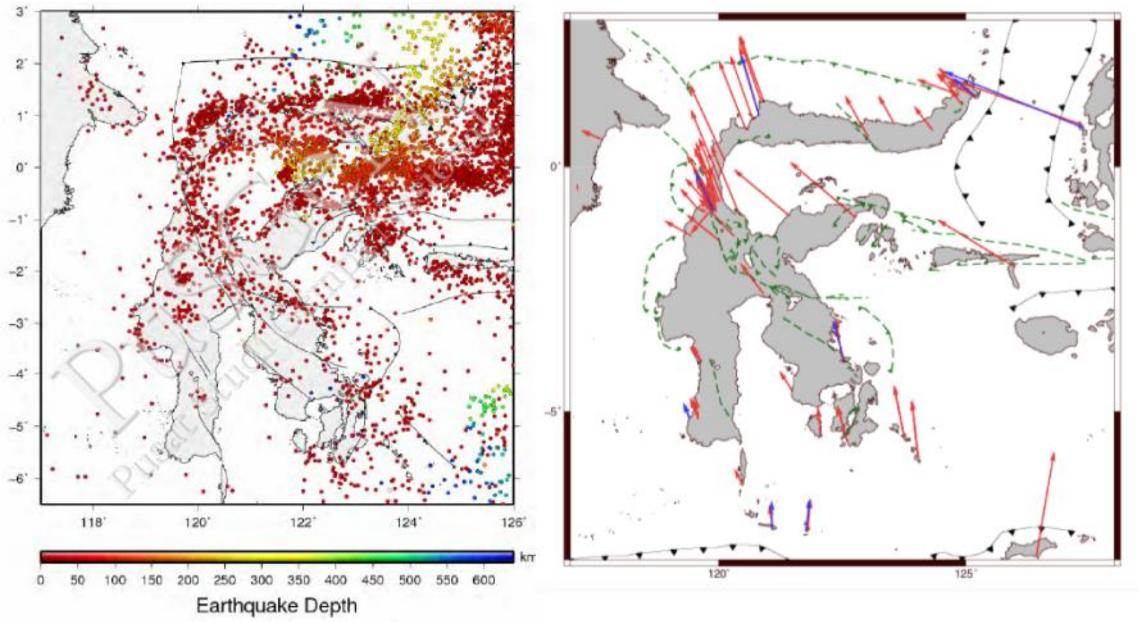

Figure 4 Left: Seismicity of the Sulawesi for Mw ≥ 4,5, right: tectonic and deformation pattern derived from GPS data in Sulawesi (Irsyam, et.al., 2017)

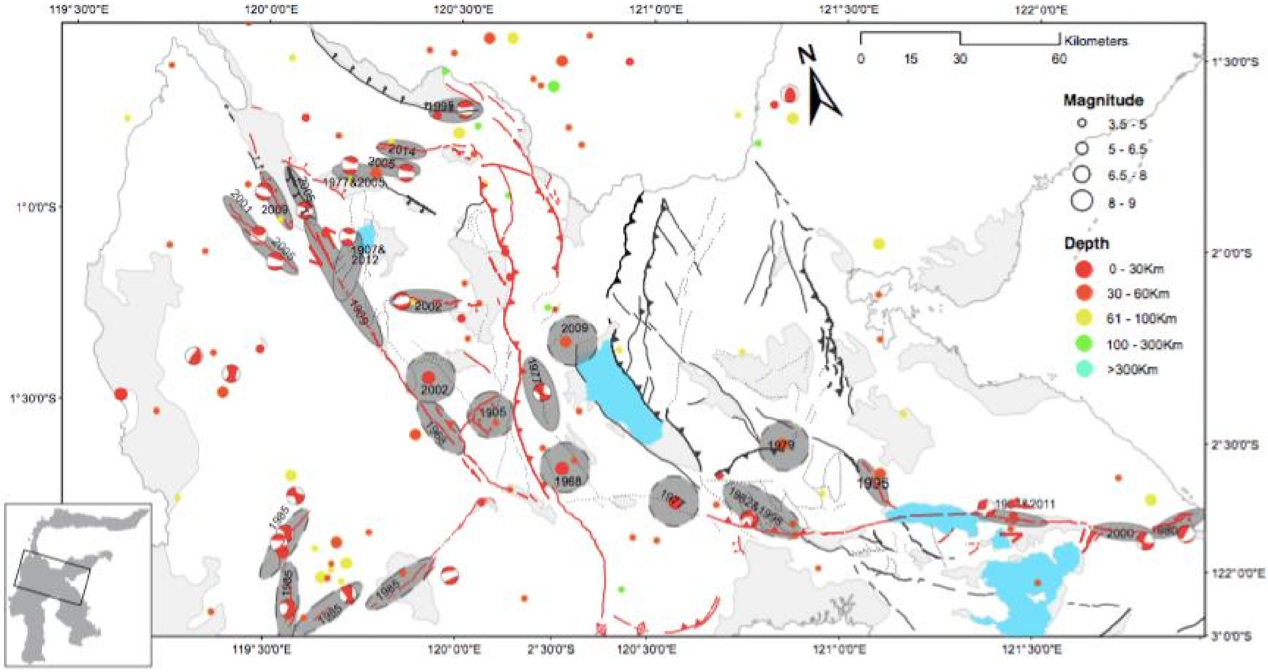

Figure 5 Historical Earthquake in Central Sulawesi (Daryono, 2016). Focal mechanism from CMT catalogue

3. GEOLOGY SETTING AND SUBSURFACE CHARACTERISTIC

The geology of Palu area is shown in Figure 6. Evolution of Neogene kinematics along the Palu – Koro fault was confirmed based on microtectonics approach, i.e., sinistral strike-slip due to east-west compression, radial extensions caused by telescoping vertical movement of Neogene granitoid, and then left lateral with normal component displacement due to north-south extension/east-west compression which actually is still active. Palu depression area is filled by mostly clay, silt, and sand deposits as alluvial deposit. The composition of gravel is granitic fragment to the northwest. West escarpment to the north consists of granite and granodiorite units, and to the south consists of schist-phyllitic units. East escarpment consists of molasses (Pramuwijoyo et al., 1997).

The morphology of Palu area consists of plains, denudation, and hills. Plains area is irregular and weak topography. This area is formed by fluvial sedimentation. Based on regional geology, Palu area consists of alluvium deposits and beach deposit (Qap)) that are Holocene. The unit is composed of gravel, sand, mud, and coral limestone.

This unit is formed in shallow river, delta, and sea environments. As this unit is a young sediment, the arranged layer has not undergone the whole process of lithification or cementation process (Soekamto, 1995).

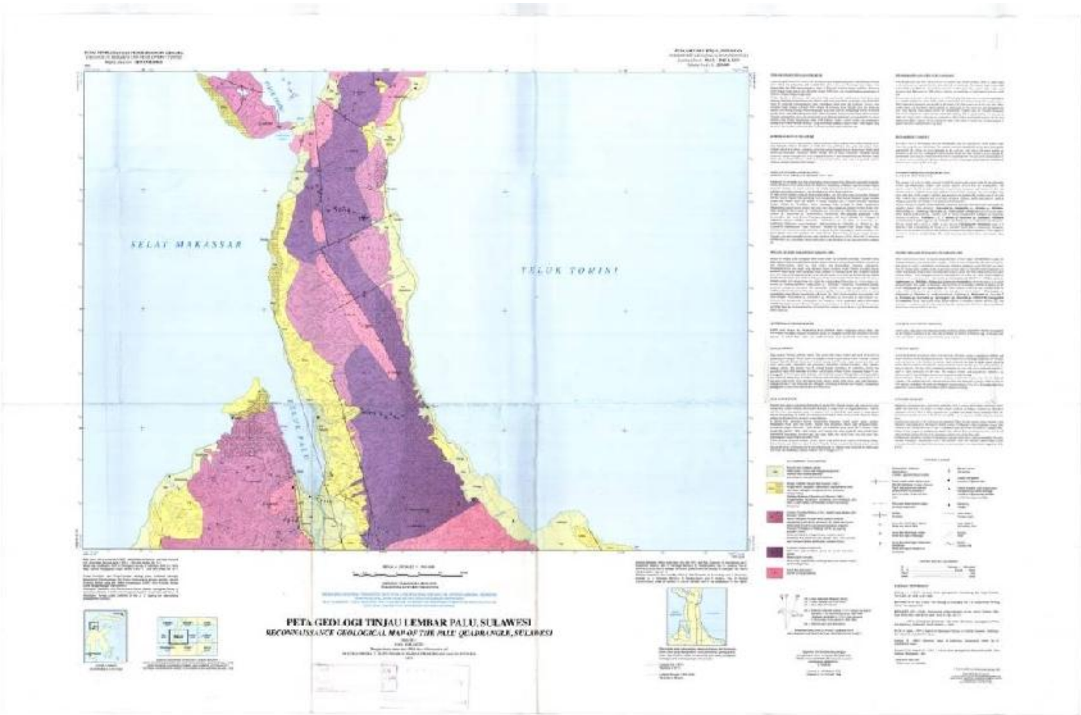

Figure 6 Geology Map of Palu, Sulawesi (source: Geological Agency of Indonesia)

4. SURFACE DEFORMATION DUE TO PALU EARTHQUKAE 2018

Surface deformation due to Palu Earthquake 2018 was detected by ALOS-2 Satellite from JAXA, which was analyzed by the Geospatial Information Authority of Japan (GIS), by comparing interferometry analysis of 21 August 2018 data and 2 October 2018 data. The INSAR data suggests uplift in Donggala area, and subsidence Palu city, in the eastern part of the fault. The surface deformation was also detected by USGS/NASA Landsat-8 imagery of 16 September 2018 and 2 October 2018, which was analyzed and mapped by Austin Elliott, COMET, University of Oxford. Data analysis from landsat image suggest a maximum coseismic surface deformation of 5 meter, in direction consistent with the sinistral slip characteristic of Palu – Koro fault, in Palu city. This surface deformation pattern was verified in the field survey.

The field survey conducted on 8 to 15 Octobers 2018 by Natawidjaja, Daryono, Gunawan, Meilano, and Pamumpuni observed rupture horizontal offset as large as 4-6 meters and vertical offset up to 30-50 cm running through Palu city from south to north (Figure 7-8). The rupture went into the sea in the Palu bay, and is observed again on the ground in Labuan Salumbone, Tawaeli, Donggala, Central Sulawesi, with a much smaller offset of less than 1 meter. The offset of the rupture of Palu Earthquake was then mapped according to field observation as shown in Figure 7.

Figure 7 Offset Rupture 4,8 m at desa Donggala Kodi, Ulujadi, Palu city, Central Sulawesi

Figure 8 Offset Rupture desa Bomba, Marawola, Sigi regency, Central Sulawesi

5. GROUND MOTION

The ground motion of the Palu earthquake was recorded in 2 BMKG stations, namely in Poso (PMCI) and in Sabang (MPSI) (Figure 9), while 1 station in Palu was reported broken due to the foreshock earthquake that occurred 2 hours before the mainshock 7.4.

6. REPORTED BUILDING and INFRASTRUCTURE DAMAGE

Building and infrastructure damages were reported just after the 7.4 earthquake. Examples of building and infrastructure damages are shown in Figure 10.

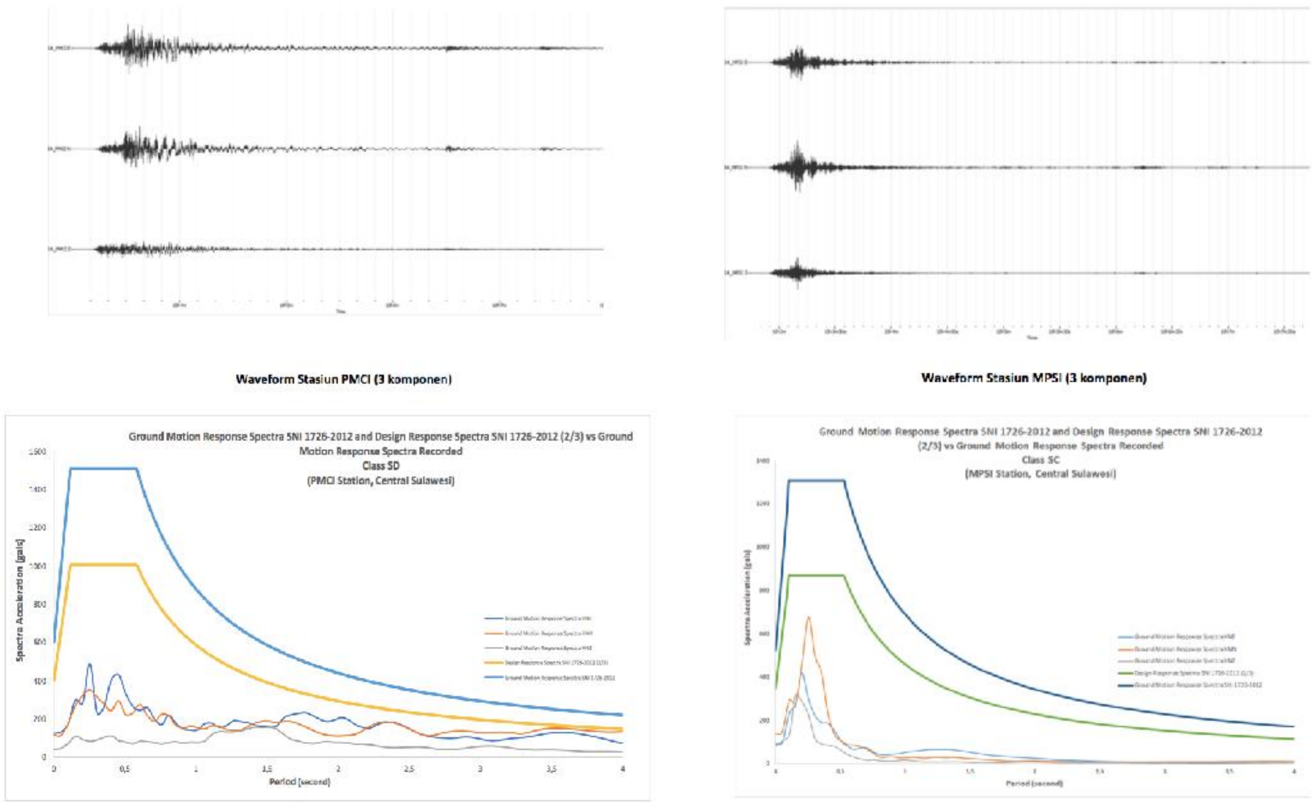

Figure 9 Ground motion and response spectra recorded in Poso (PMCI) and in Sabang (MPSI) by BMKG

Figure 10 Building and bridge damages induced by earthquake in Palu

7. GEOTECHNICAL IMPACT

During Palu earthquake 2018, two major interesting phenomena occurrences were observed, namely liquefaction induced ground failure and massive lateral spreading. These incidents resulted in the affected villages to be buried as well as shifted (Figure 11). The following sections describe liquefaction and lateral spreading in the affected area in more detail.

According to the Center for Groundwater Resources and Environmental Geology, most Palu area has a very high potential of liquefaction with a liquefaction potential index (LPI) > 15 with a shallow ground water level of about < 12 m. However, many geotechnical aspects after the earthquake are interesting to be investigated in order to find the actual cause and mechanism as well as to learn any other relevant lessons. The investigations that are currently conducted are important to support the government for housing relocation and reconstruction phase.

Irsyam and Sahadewa have conducted a preliminary field survey to the liquefaction potential of Palu city and surrounding area. The survey indicated that soil type was dominated by sand and silt. As reported by local people, water table depth was shallow before the earthquake. Combining the impacts of soil type and elevation of ground water table, it can be concluded that the area is susceptible to liquefaction. The lateral spreading and mass failure at the Balaroa dan Petobo are possible triggered by the liquefaction since those villages were covered by saturated loose sand and silty sand deposit.

7.1. Ground Cracking

Ground cracking were found along road near the coastline and mountainous areas after the earthquake. At the mountainous road, ground failure was identified. It is believed that the damages were initially created by the mainshock and became worse with the following aftershock. In particular, the aftershock exacerbated ground deformations and destroyed foundations, suggesting the possibility of the progressive ground failure.

Ground cracking was also observed at runway in Palu main airport, which is located nearby Petobo area (Figure 12). It was informed that the typical top soil layer is clayey and silty soils. The ground water table is relatively deep. Thus far, this situation only generated a minor damage in the air strip, while in the other areas, more severe damages were observed.

7.2. Liquefaction and Lateral Spreading

Just after Palu earthquake 2018, major damages are reported in four locations, namely Balaroa, Petobo, Jono Oge, and Sibalaya Selatan. These areas are located from 1 km to 7.2 km from Palu – Koro fault. Although, data is still being collected and compiled, it is currently believed that damages in these locations are mainly attributed to liquefaction and lateral spreading. Liquefaction is a phenomenon in which saturated loose sand is converted into a liquid-like material and loosing shear strength during an earthquake.

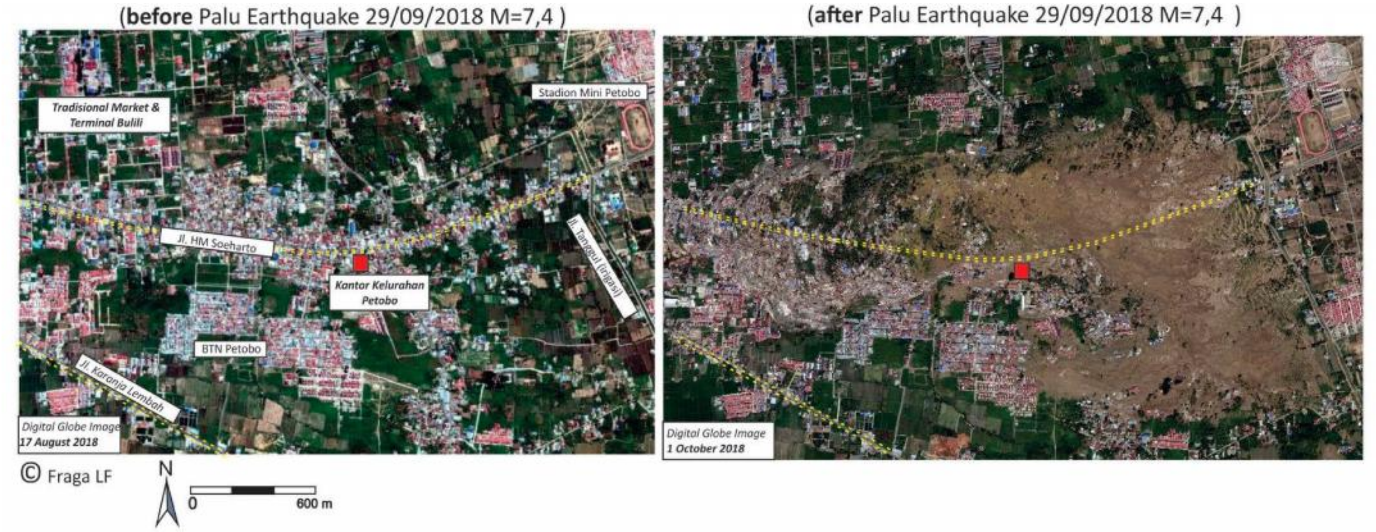

Figure 11 Liquefaction induced lateral spreading in Petobo village (Digital Globe)

Figure 12 Longitudinal Cracks on the Palu airstrip

For certain condition, liquefaction can result in lateral spreading where a large horizontal surface deformation is experienced by large ground blocks above the liquefied layer. Commonly, this lateral spreading occurs in relatively gentle slope surface. Lateral spreading is considered as one of the major contributors on the failure of the structures and buildings in the urban areas with high seismicity.

7.2.1. Balaroa

Soil failure in Balaroa area is located about 1 km to the west of Palu – Koro fault. The crown of soil movement is located in Jalan Gunung Gawalise, whereas the toe is located in Balaroa village. The affected area is mainly residential housing comprising of 34.5 Ha with perimeter of 2.5 km. Aerial view of damages in Balaroa is presented in Figure 13. Field observation at Jalan Gunung Gawalise where the crown is located showed that slope failure may also be attributed to rotational land slide.

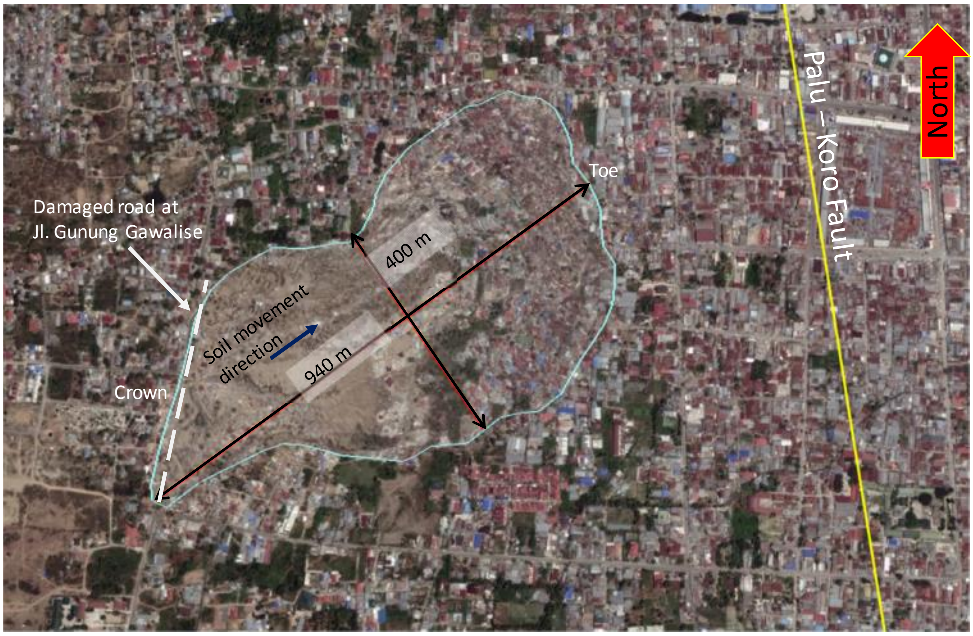

Figure 13 Estimated soil failure affected area in Balaroa

7.2.2. Petobo

Petobo, a populated residential area was severely damaged due to liquefaction. This area is about 7.2 km to the east of Palu – Koro fault. Although this area has slight inclined ground surface, the occurrence of mass movement to downslope was triggered by liquefaction (Figure 14).

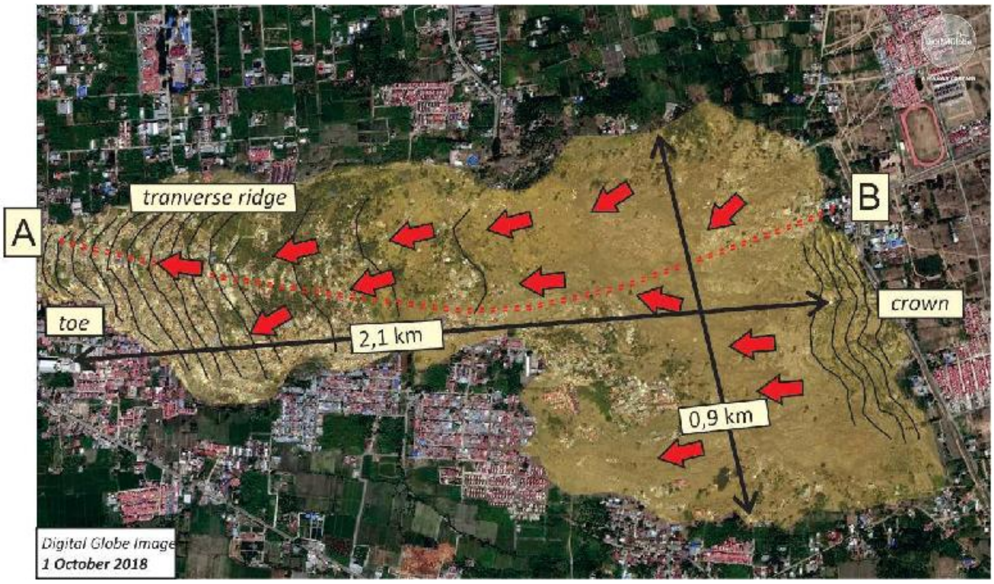

Figure 14 Liquefaction on the residential at Petobo
(Digital Globe)

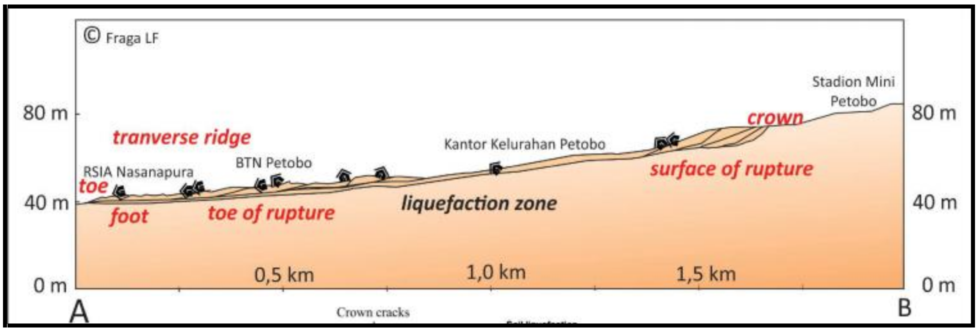

Figure 15 The illustration of mass movement due to liquefaction in Petobo village
(Fraga LF)

7.2.3. Jono Oge

Massive soil failure in Jono Oge village is located about 6.7 km to the east of Palu – Koro fault. The crown of soil movement is located in the east nearby a water channel, whereas the toe is located in the west (Figure 16). In general, north boundary of the affected area is bounded by a river. The affected area is estimated about 185 Ha with a perimeter of 8 km and is mainly comprised of corn farm, residential housing, and roadway. Practically, damaged roadway area turned into a large corn farm which initially is located nearby the crown. It should be noted that the roadway leading to this damaged roadway section and the surrounding area are also heavily affected by the earthquake. Damages in a gas station located about 1 km north to the damaged roadway section is shown in Figure 17.

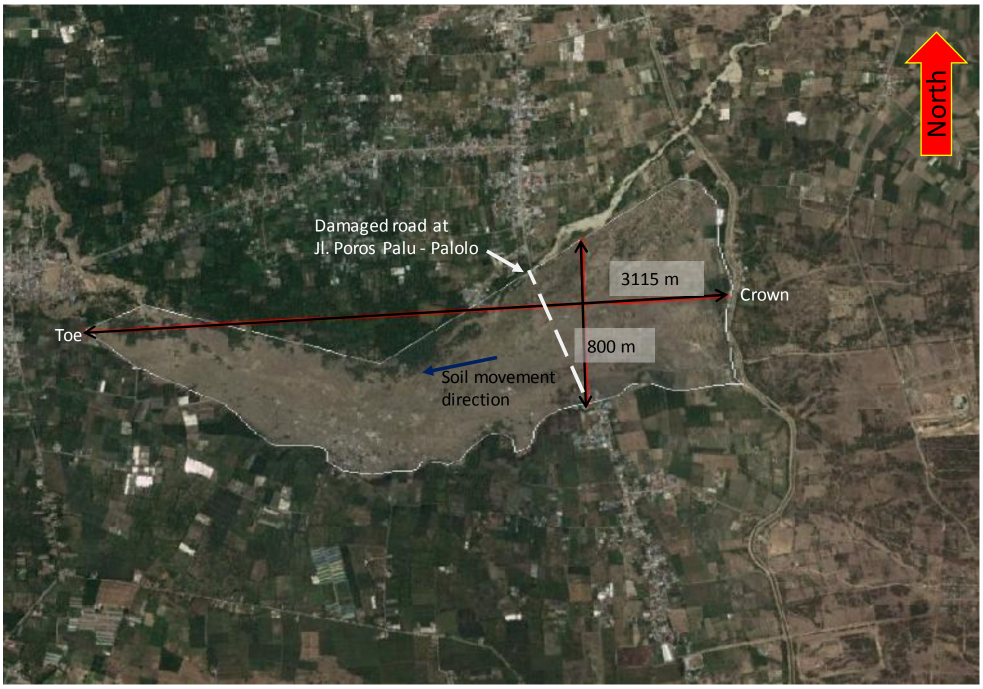

Figure 16 Estimated soil failure affected area in Jono Oge

Figure 17 A damaged gas station in Jono Oge

7.2.4. Sibaya Selatan

Soil failure in Sibalaya Selatan village is located about 3.6 km to the east of Palu – Koro fault. The crown of soil movement in this location is located in the east nearby a sluice gate, whereas the toe is located in the west (Figure 18). The affected area is estimated about 29 Ha with a perimeter of 2.2 km and is mainly comprised of paddy farm, residential housing, and roadway. Figure 19 shows the impact of Palu Earthquake 2018 of translated housing and football field in Sibalaya Selatan village.

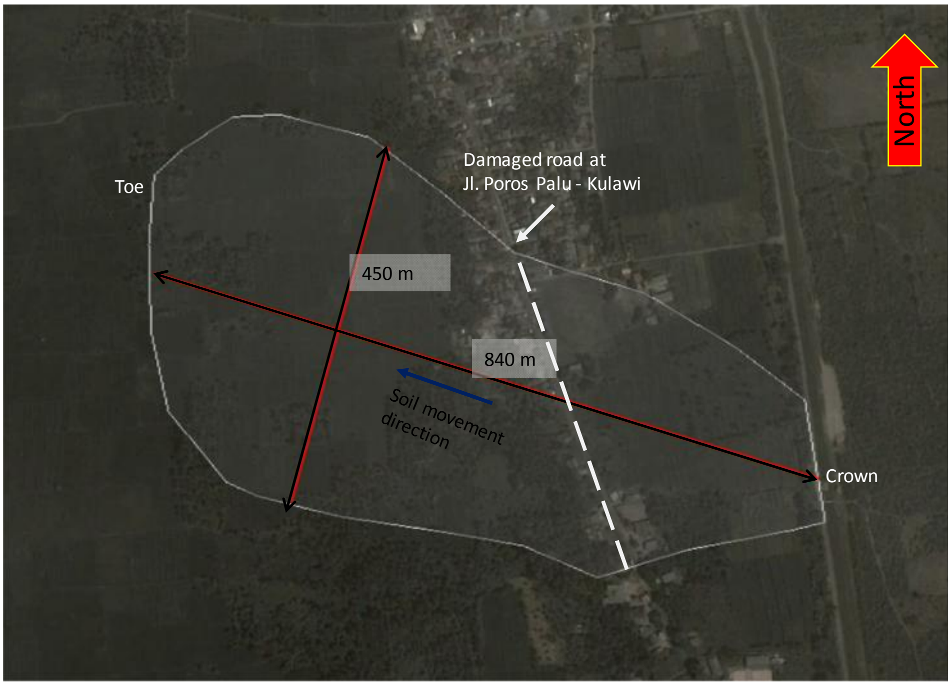

Figure 18 Estimated soil failure affected area in Sibalaya Selatan

Figure 19 Translated housing and football field in Sibalaya Selatan after Palu Earthquake 2018

8. CONCLUSION

PUSGEN and HATTI have conducted a field survey to preliminary investigate the earthquake rupture offset and geotechnical impact of the Palu Earthquake 2018. The rupture offset was found as large as 4-6 meters sinistral offset and about half meter vertical offset. The geotechnical aspects observed after the earthquake are mainly related to liquefaction and lateral spreading. In Palu earthquake, liquefaction resulted in lateral spreading where large horizontal surface deformation is experienced by large ground blocks above the liquefied layer. This lateral spreading was observed in relatively gentle slope surface.

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