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An Overview Study of Flowslide Liquefaction in Petobo, Palu, Indonesia

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An Overview Study of Flowslide Liquefaction in Petobo, Palu, Indonesia

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Abstract. A magnitude (Mw) 7.5 Palu-Donggala earthquake struck Palu, Indonesia on Friday, 28 September 2018 at 18:02:44 Central Indonesia Time (GMT+8). The earthquake resulted in tsunami and flowslide liquefaction. Balaroa, Petobo, Jono Oge and South Sibalaya were affected areas of flowslide liquefaction. Area of Petobo flowslide liquefaction had the largest impact as compared to other locations. This paper emphasizes on the observations on the ground surface when liquefaction occurred in Petobo. Interviews with the survivors and living witnesses, displacement vectors with reference to buildings, observations of soil conditions and groundwater levels as well as descriptions of conditions pre- and post-slide, are conducted in these observations. In addition, several data consisting of Satellite Imagery, DEM (Digital Elevation Model), regional geology and some photographs taken at the site are also discussed. Results show the slope of the area of flowslide liquefaction ranges from 1^o to 2^o. Besides earthquake shaking, soil types and groundwater tables are believed to have had contributions to the flowslide liquefaction. Loose silty medium to fine sands are found in the flowslide areas. Based on interviews, witnesses indicated the liquefaction occurred in about few seconds after the initiation of shaking. The ground then became like muddy flow and buildings started to move or sink. After flowslide, large swampy areas had appeared and the soft ground took several weeks to become hardened again.

1. Introduction

Liquefaction is a condition where a saturated cohesionless medium to fine-grained soil losses its strength or stiffness and behaves like a liquid caused by monotonic, transient or repeated load usually due to earthquake shaking. The increase in pore water pressure is the main reason for the loss of soil strength [1-3]. Liquefaction may cause serious structure damages, landslides, earth dam failures, ground settlements, and others [3-4].

A magnitude (M_W) 7.5 Palu-Donggala earthquake struck Palu, Indonesia on Friday, 28 September 2018, at 18:02:44 Central Indonesia Time (GMT+8) [5]. The epicenter of earthquake was located at 0.18° south latitude and 119.85° east longitude, around 26 km north of Donggala, Central Sulawesi, and 10 km deep below the ground surface [6]. At 14:59:59, three hours before mainshock, a large foreshock registered as M_W 6.1 hit Palu, Indonesia, with the epicenter 5 km deep below the ground surface. This foreshock was located at 0.41° south latitude and 119.77° east longitude [5]. Locations of the earthquake epicenters are shown in Figure 1.

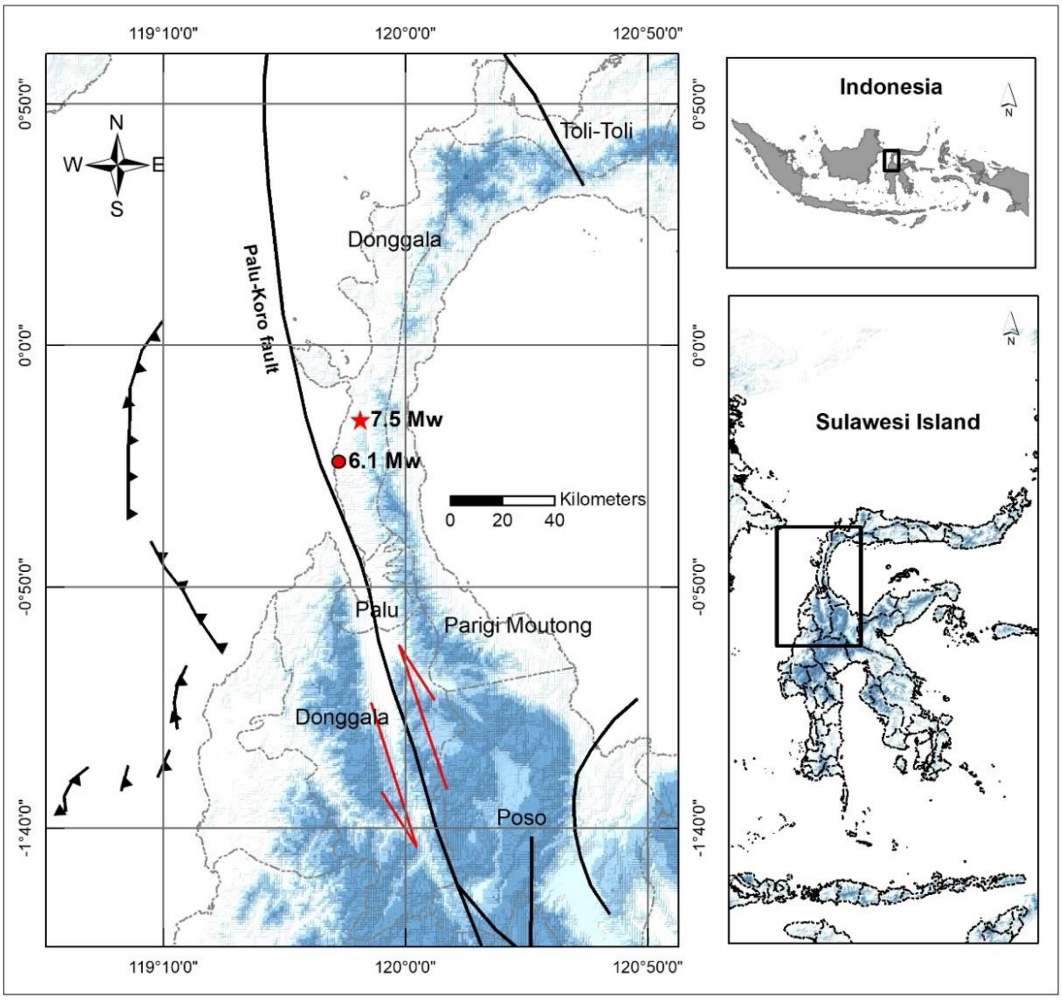

Figure 1. Locations of M_w 7.5 mainshock (red star) and the largest M_w 6.1 foreshock (red dot). The main active fault taken and redraw from [7].

Immediately after the main shock of Palu-Donggala earthquake, extensive slides induced by liquefaction of soils hit several locations of inland and tsunamis struck along the bay of Palu [8-10]. More than 4000 people died or missing, and around 170,000 people evacuated in Palu city, Donggala and Sigi villages [11]. The locations of extensive slide were in the areas of Balaroa, Petobo, Jono Oge and South Sibalaya. The largest sliding area was in Jono Oge. However, Petobo area had suffered the greatest impact from the slide. Figure 2 presents the slide locations in Balaroa, Petobo, Jono Oge and South Sibalaya.

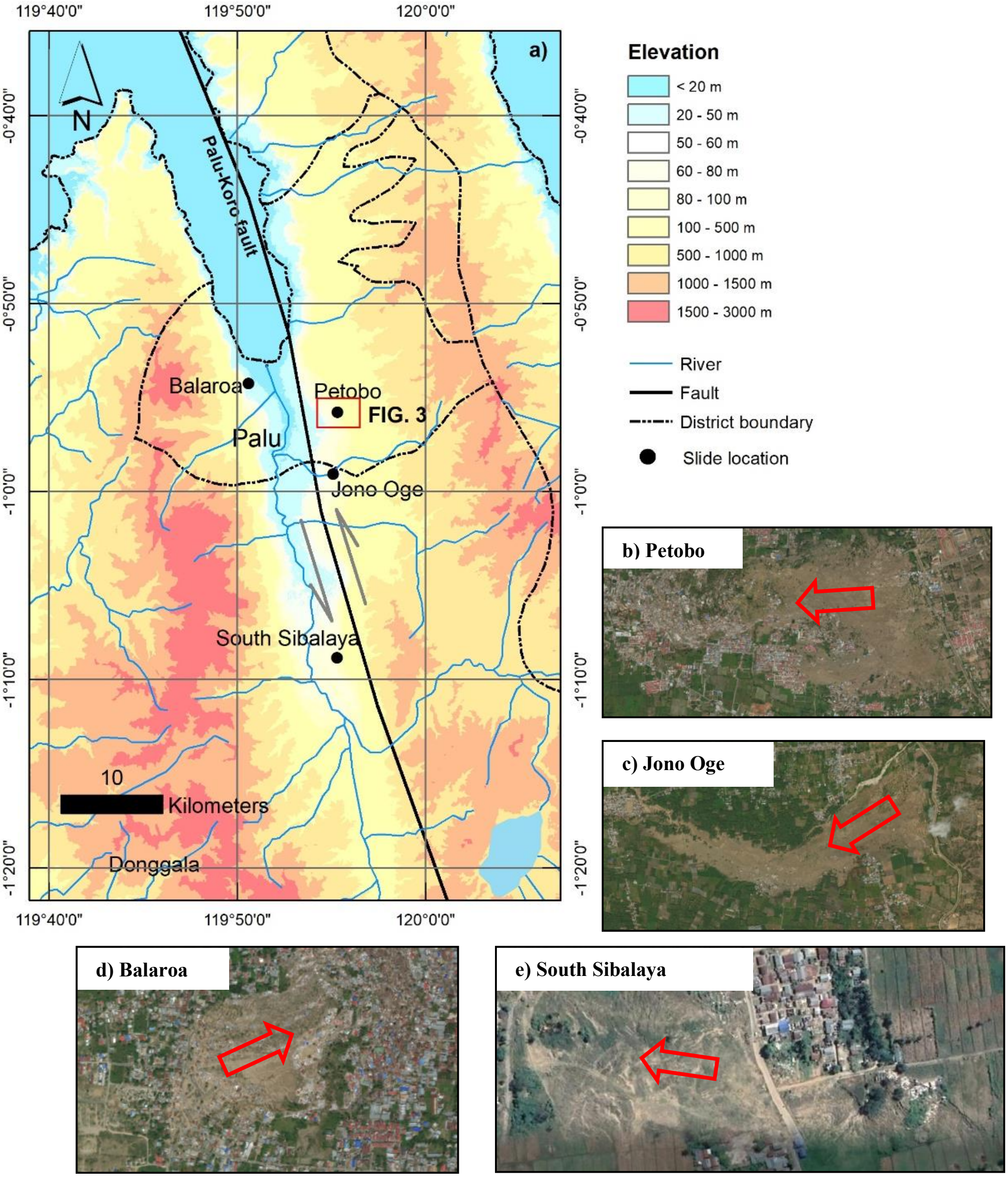

Figure 2. Slide locations of Balaroa, Petobo, Jono Oge and South Sibalaya. The main active fault taken and redraw from [7]. The satellite photo of Balaroa, Petobo, Jono Oge and South Sibalaya taken from Digitalglobe 2 October 2018.

To understand the mechanisms and damages in Petobo slide area, interviews with survivors and living witnesses, as well as surface observations, including soil conditions, building displacements, groundwater levels, etc., have been conducted. Additional data consisting of satellite imagery, DEM (Digital Elevation Model), regional geology and some Google photos of the site are also discussed.

2. Descriptions of study area

2.1. Location

The study area, as shown in Figure 3, is located in Petobo village, southern part of Palu city, Central Sulawesi, Indonesia. Palu city is the capital of Central Sulawesi. The figure indicates the area affected by the sliding is 164 Ha, which covers approximately the entire village of Petobo.

The lengths of sliding along the south and north boundaries are about 1.2 km and 2.2 km, respectively. In addition, the widths of sliding on the east and west sides are around 1.3 km and 0.65 km, respectively. At the east part, the sliding area is bordered by 9 m wide Gumbasa irrigation canal. Rice paddy fields served by irrigation canal are located to the west of the canal. Resident area is mostly located in the middle part from east to the west along Moh. Soeharto road. Approximately 744 buildings were completely demolished and buried [12]. The international airport of Palu city situated approximately 0.5 km to the north of the study area.

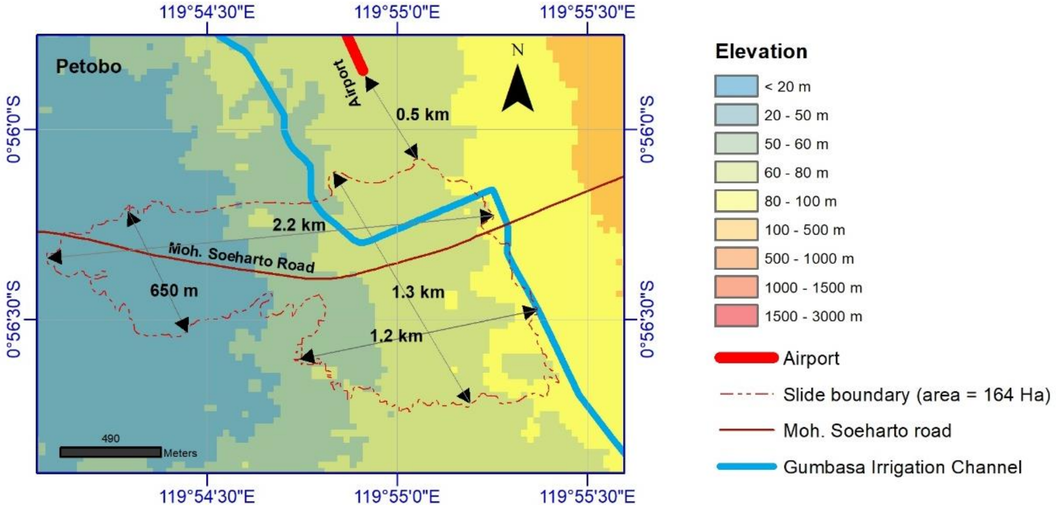

Figure 3. Location of Petobo Slide

2.2. Geology

The geological condition in Palu consists of two rock formations, namely celebes molasse of sarasin and sarasin (QTms) and alluvium and coastal deposits (Qap) [13]. Celebes molasse of sarasin and sarasin is of middle Miocene age and a deposition of shallow sea. Alluvium and coastal deposit is of Holocene age. Formation QTms consists of weakly consolidated conglomerate, sandstone, mudstone, coral limestone and marl. Gravel, sand, mud and coral limestone are included in the formation. The entire area of Petobo slide is in Formation Qap, where gravel, sand and mud can be found in the area. Figure 4 shows geological map in Palu and Petobo area.

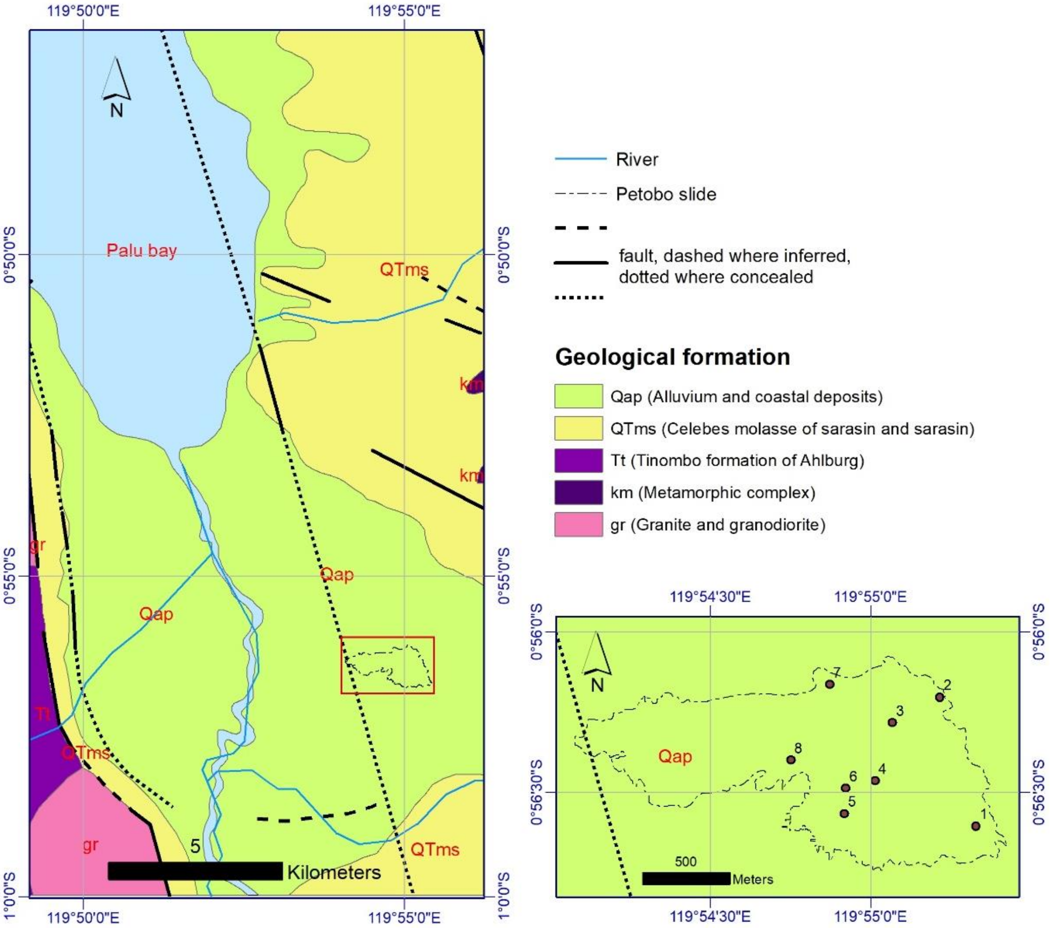

Figure 4. Geological map in Palu and Petobo [12]

In Palu city, [14] indicated the sand, silt and clay of Formation Qap are at various depths between 1-7.2 m. [15] investigated using portable dynamic cone penetration tests in Petobo area. They found that the converted SPT-N values are lower than 10 at the site with depths less than 6.5 m, indicating the sandy soils should be loose to very loose. Based on our surface mapping, the sandy soils of the site are generally loose to medium dense. Figure 5 shows the photographs of onsite soils taken in Petobo area, with locations indicated in Figure 4.

2.3. *Seismicity*

Sulawesi island is situated at the junction of Eurasia, Indo-Australian and Pacific plates [16-17]. Palu-Koro Fault (PKF) is one of the most active faults in Sulawesi. Several earthquakes had centered on or near this fault in the past [16],[18-19]. The source of 2018 Palu-Donggala earthquake was due to the Palu-Koro fault zone [9], [20-21.

PKF is a left-lateral strike slip in a direction mainly towards north-south [19]. Figure 6 shows that PKF cuts along Palu city and divides the Sulawesi Island into Makassar and North Sula regions. The fault length is about 500 km [22], with a slip rate estimated 34 mm/year [23].

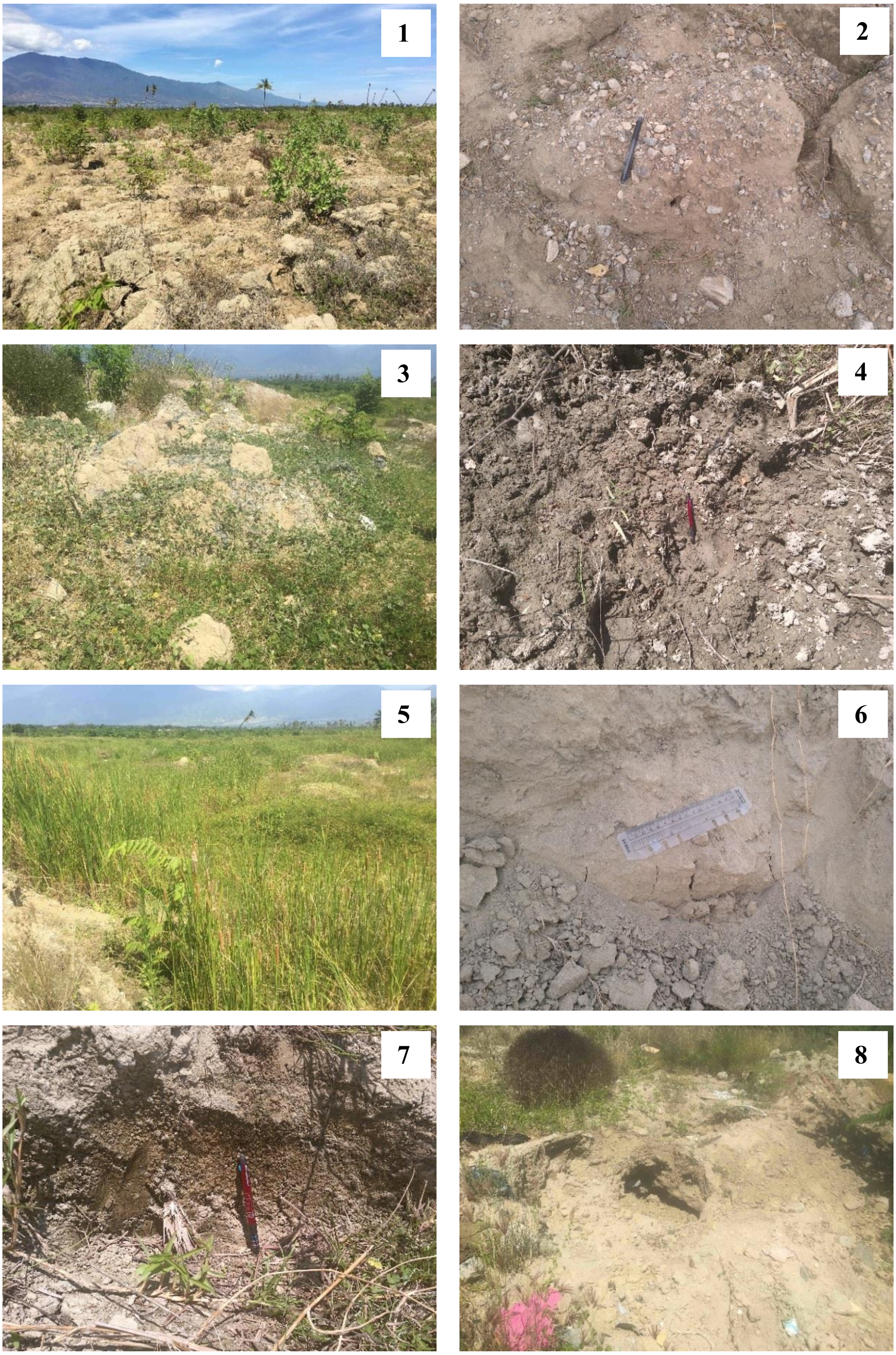

Figure 5. Soil conditions in Petobo slide area

There are 25 seismological stations in Sulawesi with recorded data of the 2018 Palu-Donggala earthquake (Figure 6). The nearest station to the epicenter is MPSI, with a location of 0.3374° north latitude and 119.898° east longitude, and an epicenter distance of 57.36 km. Table 1 indicates the recorded peak ground accelerations of Palu-Donggala earthquake at the BMKG stations. For MPSI station, the components of the peak ground acceleration are 95.057 gal (0.096 g), 138.871 gal (0.142 g) and 84.377 gal (0.086 g), respectively, in Z, N and E directions [24].

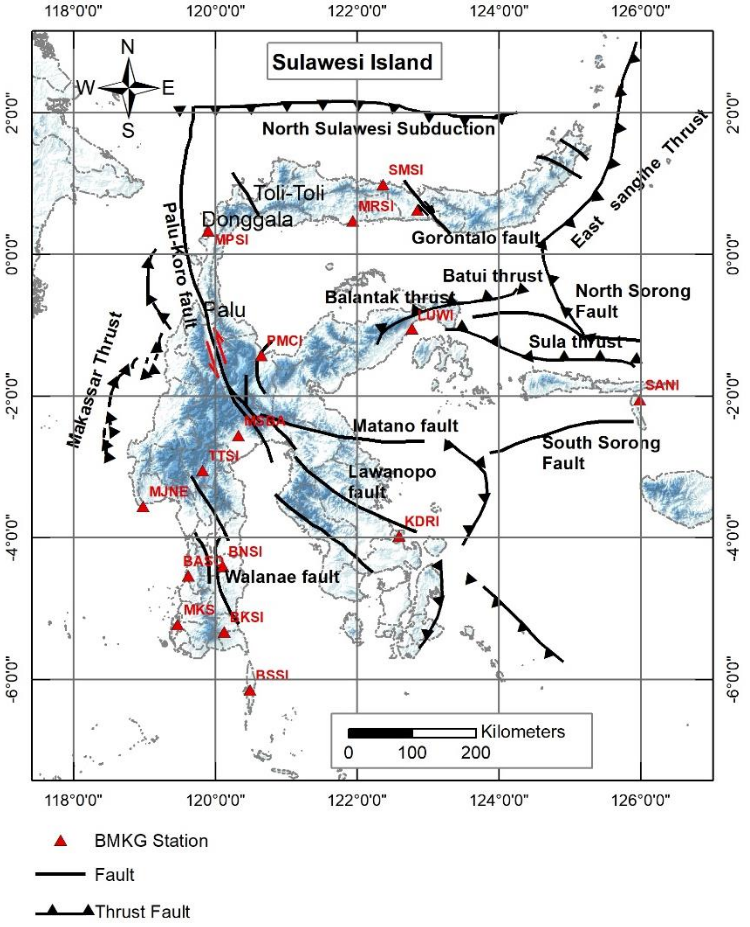

Figure 6. Locations of main active faults and BMKG stations in Sulawesi [7], [24]

2.4. Groundwater

Petobo sliding area is situated in an alluvium and coastal formation (Qap). [14] found that the soils of the formation are permeable with groundwater levels varied between 0.5-16 m in depth. In Petobo, the groundwater level of the area had been affected by the infiltration of the water from irrigation canal and paddy fields [9], [25-26]. The canal and paddy fields were without lining. Consequently, water could freely seep into the ground and increase localized groundwater tables. [15] suggested that the slide induced by liquefaction in Petobo would probably be related to the pressures from the confined aquifers. Their post-slide investigations revealed the groundwater levels of the area ranged 0.85-1.1 m deep from the ground.

Table 1. Recorded peak ground accelerations of 2018 Palu-Donggala earthquake at BMKG stations [24]

No	Station	Latitude (km)	Longitude (km)	Z (gal)	N (gal)	E (gal)
1	BASO	-4.530	119.620	4.297	4.542	3.802
2	BGKI	-1.250	116.910	3.430	2.965	1.700
3	BKB	-1.107	116.905	2.062	0	1.074
4	BKSI	-5.322	120.122	1.718	1.233	0.914
5	BMNI	-8.488	117.413	0.447	0.322	0.447
6	BNSI	-4.401	120.106	9.289	8.959	6.094
7	BSSI	-6.143	120.490	1.541	1.195	0.791
8	DBNI	-8.502	118.312	1.340	0.839	0.579
9	EDFI	-8.750	121.690	0.135	0.128	0.118
10	GMCI	0.630	122.850	14.264	14.466	7.110
11	KDRI	-3.970	122.590	1.471	1.479	0.735
12	LUWI	-1.042	122.772	8.081	-	7.086
13	MJNE	-3.550	118.980	32.824	36.969	14.390
14	MKS	-5.218	119.469	8.832	6.406	5.630
15	MMRI	-8.636	122.238	0.215	-	0.186
16	MPSI	0.337	119.898	95.057	138.871	84.377
17	MRSI	0.477	121.941	4.963	4.000	2.524
18	MSBA	-2.555	120.324	25.798	15.809	5.562
19	NLAI	-3.239	127.100	0.483	0.463	0.462
20	PMCI	-1.420	120.650	124.956	115.983	40.964
21	SANI	-2.048	125.988	0.309	-	0.198
22	SMSI	0.989	122.365	2.504	2.378	1.676
23	SUHA	4.998	119.572	0.799	0.824	0.448
24	SUPA	4.998	119.572	1.379	1.352	0.429
25	TTSI	-3.045	119.819	19.028	19.167	13.800

3. Results and Discussions

3.1. Witness Interviews

According to witness interviews, two major earthquake shakings had occurred on the same day. The first shock hit around 3 pm of local time (GMT+8) and the second (main shock) occurred at 6.00 pm of local time (GMT+8). The interviewers characterized the major shock as lasting 10 seconds to 1 minute and beginning with vertical (U-D) vibrations and ending with horizontal (N-S) shakings. Immediately following the shaking, the ground began to shift, and buildings as well as trees began to float, tilt, or sink. During the floating with the sliding mass, truck-like sounds were heard continuously, and sulfur odors were detected. Most likely, the odors originated from liquefied gas utilized in common residences.

During the sliding, the ground was flowing in a wavelike motion, with vertical amplitude about 1.5~2 m and a moving distance of about 15 m in around 20 seconds per cycle, which was equivalent to a horizontal speed around 0.75 m/s. The ground surface was muddy, wet and soft. If people tended to walk, they could be sinking to around the knees or 40 cm in depth. However, some witnesses claimed that the ground became soft and that the telephone pole, which stood 6-9 meters tall, could sink to the ground. At the time of sliding, witnesses saw muds came from the ground, or sand boiling. The sand boils mixed with "black" waters, which are extruded around 50 cm to 2 m and 2–5 m above the ground surface in the northeastern and southeastern portions of the sliding region, respectively. Furthermore, some witnesses had moved downslope along with the sliding mass, a distance of about 0.4 km from their original location. Generally, few weeks after the sliding occurred, the soils had become harder again.

3.2. Onsite Images

The pre-sliding satellite image, as shown in Figure 7(a), was taken from Digitalglobe on 18 June 2018 with a resolution of 30 cm. Figure 7(b) shows the post-sliding satellite image, also from Digitalglobe, taken on 2 October 2018 with the same resolution, which was acquired in 4 days after the event. Figure 7(a) shows the houses used to be densely populated along Moh. Soeharto road prior to the slide. While in Figure 7(b), the houses were disappeared and displaced after the slide, with deposition debris found on the west part of the area (yellow rectangle). Some unaffected residential houses, however, could be seen in the southern part of the site (Figure 7(b)).

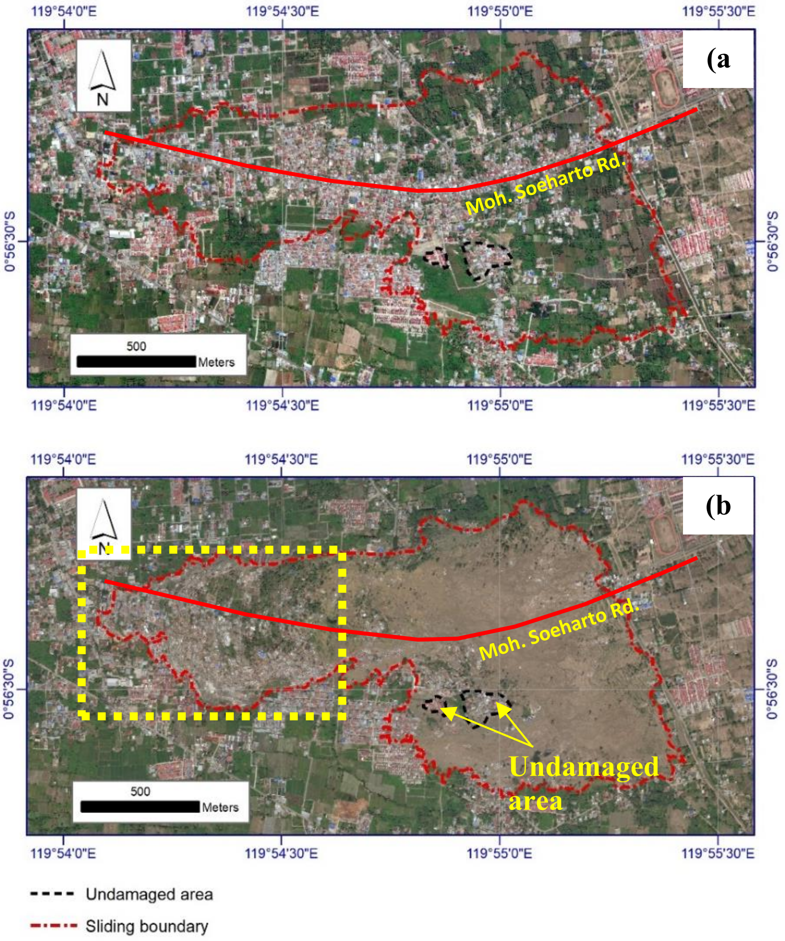

Figure 7. Comparison of satellite images from Digitalglobe: (a) before sliding on 18 June 2018 and (b) after sliding on 2 October 2018

Photographs of onsite images before and after sliding were compared in several locations. The post-slide photos were taken close to the border of the sliding area, such as roads, irrigation canals and houses, during our reconnaissance in January and February of 2020. The pre-slide photos were obtained from Google street view. Figure 8 illustrates the comparisons of images before and after the sliding.

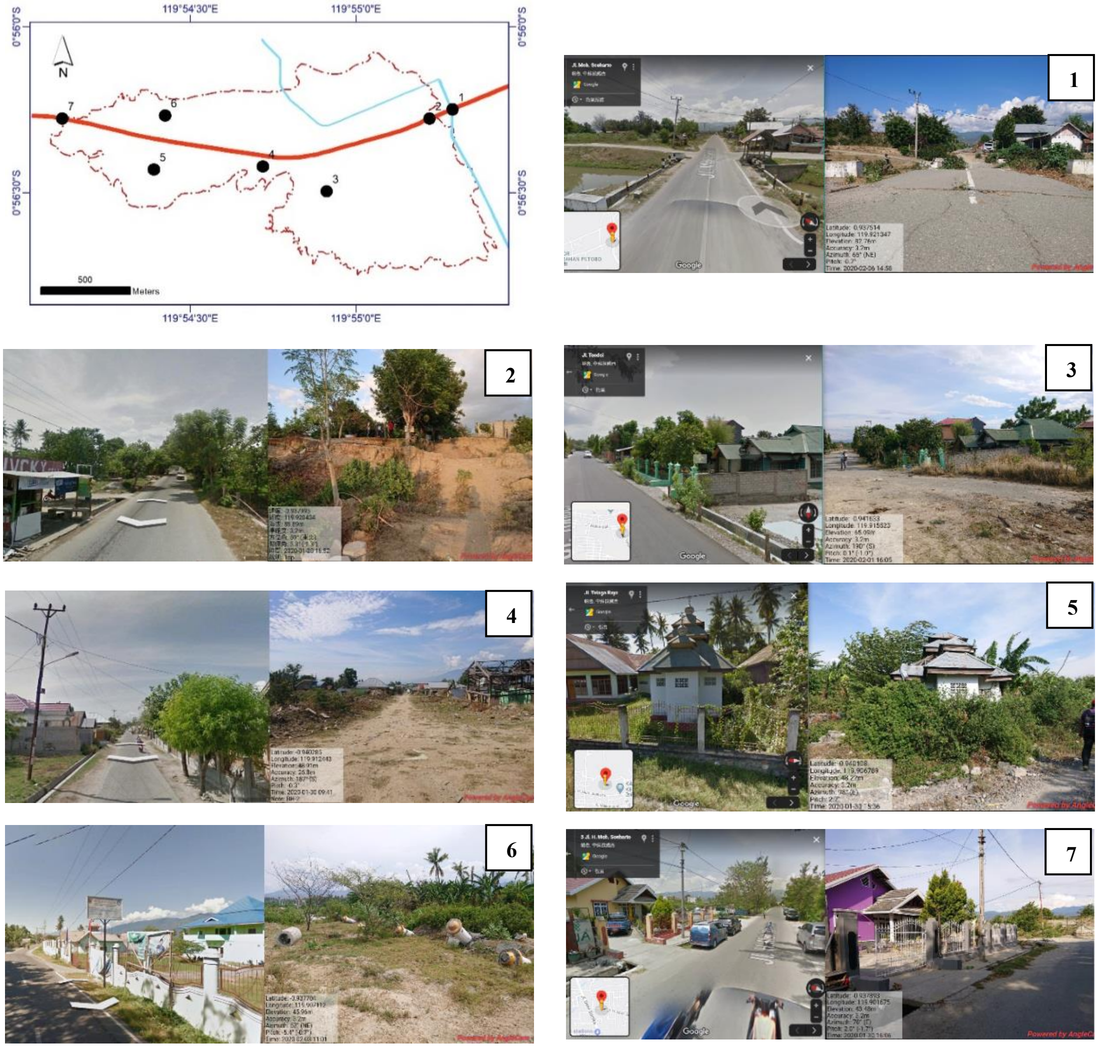

Figure 8. Comparison of onsite images before and after sliding.

Locations 1 and 2 are in the area of the headscarp, adjacent to the Gumbasa irrigation canal on the eastern part of the sliding boundary. As seen, surface cracking and ground slipping are clearly visible. Locations 3 and 4 are in the southern part of the area, where the residential buildings had been hit by the debris flow (a mixture of construction materials and soils). Locations 5 and 6 are close to the lower-middle part of the area where the mosque and school fence had been encountered and ripped away by the debris flow. Location 7 is at the toe boundary of the slide, and the houses in this area were relatively intact and unaffected by the sliding.

3.3. *Surface Topography*

Digital Elevation Model (DEM) before and after sliding was obtained from the Indonesian Agency of Geospatial Information and Centre of Data and Technology Information Ministry of Public Works of Indonesia. Based on DEM data, the longitudinal profiles before and after sliding along Moh. Soeharto road as well as a three-dimensional (3D) post-slide view are developed.

Figure 9 indicates the changes in elevation before and after sliding for the cross section along Moh. Soeharto road, as well as some photos showing morphological features observed at the site. To the east or beyond headscarp, the elevation change was negligible. In the middle portion, however, the elevation dropped around 10 m, while the west portion of the sliding area the elevation mounted about 6 m. Figure 10 presents a 3D view of sliding with arrows showing the direction of movement at several locations of the sliding mass. Generally, the ground had moved from east to west, resulted in significant losses of soil materials on the eastern part that were transported and deposited on the western portion of the sliding area.

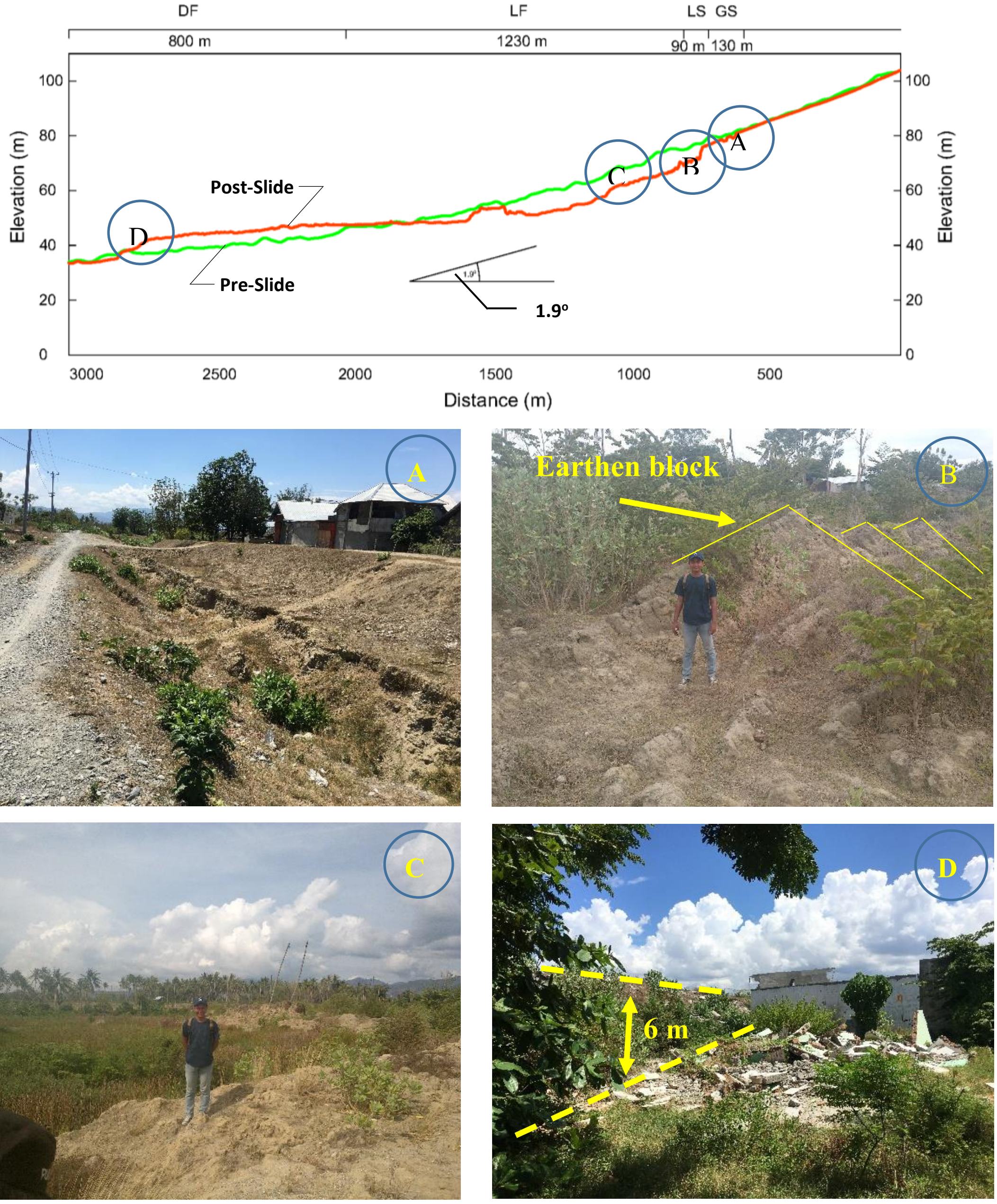

Figure 9. Before and after sliding profiles along Moh. Soeharto Road and morphological features observed at the site

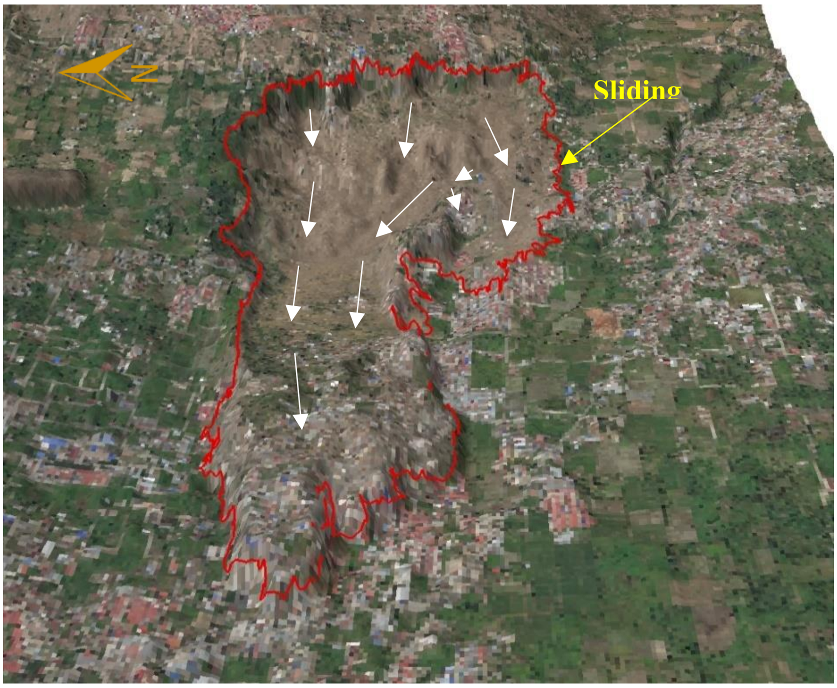

Figure 10. Post-slide 3D topography of Petobo area with arrows showing directions of movement.

3.4. *Displacement Vectors*

Vectors of displacement were measured by several ways including manually tracking the objects in satellite photos before and after sliding, information provided by witnesses, and measurements of on-site objects with reference to pre-slide positions from Google street view. Displacement vectors in Figure 11 are divided into three categories, with the magnitude of displacement of more than 100 m, 20-100 m and less than 20 m. As can be seen, the area with displacement of less than 20 m occurred mainly along the crown and toe boundaries; while significant displacements of more than 100 m were observed in the large middle portion of site.

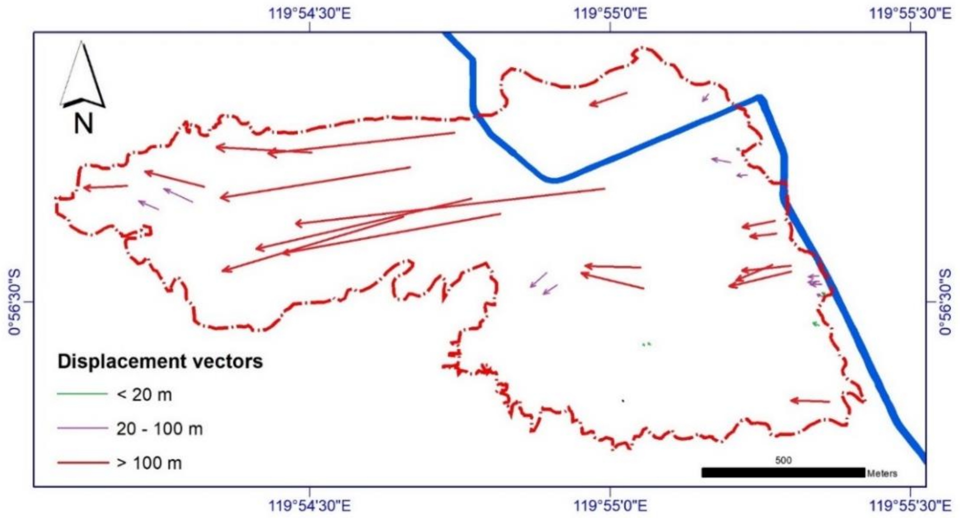

Figure 11. Displacement vectors of sliding in Petobo area.

4. Morphological Zones of Petobo Slide

According to failure phenomena observed at Petobo site, we divide the sliding area into 4 morphological zones, as indicated in the cross-sections and associated photos of Figure 9, with each zone characterized by unique features which reflect potential mechanisms of the sliding. These zones may include: ground slip (GS), lateral spread (LS), liquefaction flow (LF) and debris flow (DF). The characteristics for each of the morphological zones are further described as follows:

(a) Ground Slip – Scarps or cracks can be seen on the ground's surface, as shown in Figure 9(A), dividing the ground into many earthen blocks. The area is found adjacent Gumbasa canal to the western border of the sliding zone.

(b) Lateral Spread – As shown in Figure 9(B), surface ground phenomenons of lateral spread may consist of a series of sequential cracks or earthen ridges with damaged and lowered ground on the side. The cyclic motions and spreading of liquefied soils may result in the destruction, tilting, or distortion (elongation) of structures on the ground. The width of the lateral spreading zone along the Moh. Soeharto road segment is approximately 90 meters. The lateral spread zone is adjacent to the ground slip zone to the west.

(c) Liquefaction Flow – As shown in Figure 9(C), during earthquake shaking, pore water pressures would be built up to a limit such that soils would lose their strengths. Ground becomes a muddy flow. Houses and features on the ground would be sinking, tilting or moving for a large distance. The significant proportion of the zone of liquefaction flow is distributed in the middle part of the sliding area.

(d) Debris Flow – As shown in Figure 9(D), earthen materials of liquefaction flow mixed with construction debris ride over the existing ground. The existing ground elevation would be mounted. The debris flow zone is situated in the western portion of the slide. The debris deposit could reach around 6 m in height above the existing ground, and the length of transported debris flow could be as large as 700 m.

5. Conclusions

The paper herein discusses preliminary study of site reconnaissance at Petobo site where significant liquefaction induced flowslides were observed during the 2018 Palu-Donggala earthquake. Some findings of this study can be summarized as the following:

- The 2018 Palu-Donggala earthquake has caused several significant slides induced by liquefaction. At Petobo site, sliding caused up to 700 houses to sink, damages or tilts. The area of slide is about 164 hectares with a longitudinal length of 2.2 km and a lateral width of 1.2 km.
- Irrigation canal (Gumbasa) and paddy fields had affected the groundwater levels at Petobo site. Groundwater depths in the sliding area were measured to be 0.85-1.1 m in depth from the ground surface after sliding.
- According to witness interviews, the sliding had occurred immediately after the earthquake. The soils became soft and liquefied. There were several meters-high sand boils sprouting from the ground.
- Comparisons of data before and after sliding from DEM, satellite images, onsite mapping and photographs, the morphology of the Petobo sliding area could be classified into several zones. Four zones are identified with each of which characterized by unique morphological features. These zones include: ground slip (GS), lateral spread (LS), liquefaction flow (LF) and debris flow (DF). The liquefaction flow zone has been the widest in size and the largest in lateral displacement.

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