Onsite Observations of Petobo Liquefaction Area due to 2018.9.28 Palu-Donggala, Indonesia Earthquake

Galih A Prayitno[1, *], Muhsiung Chang[2], Togani C Upomo[3], Renchung Huang[4], Rini Kusumawardani[5]

[1, *] Master Student, Dept. of Civil and Construction Engrg., Nat'l Yunlin Univ. of Sci. & Tech. (YunTech), ROC (M10816021@yuntech.edu.tw)
[2]Professor, Dept. of Civil and Construction Engrg., Nat'l Yunlin Univ. of Sci. & Tech. (YunTech), ROC
[3]PhD Student, Graduate School of Engrg. Sci. & Tech., Nat'l Yunlin Univ. of Sci. & Tech. (YunTech), ROC
[4]Project Manager, Dept. of Civil and Construction Engrg., Nat'l Yunlin Univ. of Sci. & Tech. (YunTech), ROC
[5]Associate Professor, Dept. of Civil Engrg., Universitas Negeri Semarang (UNNES), Semarang Central Java, Indonesia

ABSTRACT

Liquefaction-induced flowslides occurred in several places of Palu City, in the Central Sulawesi of Indonesia, due to Palu-Donggala earthquake with a magnitude (M_w) 7.5 on September 28, 2018. One of the landslides was in Petobo Village, which is close to Mutiara SIS Al-Jufrie Airport of the city. Petobo landslide, with an area of approximately 1.64 km^2, has caused most fatalities among other areas affected by this earthquake. To have a better understanding of the flowslide, onsite observations through witness interviews, drone photos and site mapping have been conducted in the early of 2020. Additional information from satellite images and Google Street views are also compared with the onsite observations. The study reveals that Petobo landslide could possibly be divided into four types of morphology. Ground slip (GS) is due to a sudden loss of support and results in cracks and soil blocks. Lateral spread (LS) is characterized by a series of parallel cracks and earthen ridges as a result of lateral spreading and shaking. Liquefaction flow (LF) occurs in the liquefied ground after the shaking. The gravitational driving shears, if sufficient large enough, would move the liquefied ground for a large distance. Debris flow (DF) is similar to LF, with the difference that the existing ground is not liquefied but deposited with debris from the upstream side.

Keywords: Soil liquefaction, ground slip, lateral spread, debris flow, onsite observations.

1 Introduction

The M_w 7.5 Palu-Donggala earthquake occur on Friday afternoon 28 September 2018, at 18:02 local time (10:02 UTC). The location of epicenter was around 77 km from Palu city, Central Sulawesi at 0.256° south latitude and 119.846° east longitude and with the hypocenter 11 km in depth (Fig. 1). This earthquake triggered by the active strike-slip of Palu-Koro fault, which passes immediately northwest of the urban center in Palu city. The active strike-slip created series of foreshock with the largest magnitude (M_w 6.1) occurred 3 hours before the mainshock and a series of aftershocks with a maximum magnitude of M_w 5.8. The earthquake resulted in the collapse of buildings and public facilities, also generated tsunami waves that destroyed Palu City coastal areas. Several locations in Palu City and Sigi Regency occurred landslides where thousands of buildings sank in relatively flat areas. As a result, 2,101 people died, 4,438 people were injured, 1,309 people were missing.

A saturated cohesionless soil deposit would be vulnerable to soil liquefaction in the case of strong ground shaking. Excess pore pressures increase when rapid loading occurs under undrained conditions. The combinations of water infiltrations and seismic shaking was obviously the causes of liquefaction in loose sand (Ishihara et al. 1990). This phenomenon was the main triggering factor of landslide in sandy soil deposits. After 1964 Niigata Earthquake (Japan) and 1964 Great Alaskan Earthquake (America), soil liquefaction has been studied extensively throughout the world (Huang et al. 2014).

A preliminary investigation was conducted from 19 January to 17 February 2020 to get a better understanding about the liquefaction induced flowslides. The contents of the investigation included collections of information on the field through witness interviews, satellite photos and site mapping. This paper summarizes the observations of the preliminary damage survey of liquefaction-induced landslides in Petobo due to the Palu-Donggala earthquake. A discussion of morphological zonation of the liquefaction-induced landslide is also presented.

2 Liquefaction Case Histories

The generation of excess pore pressure under undrained loading condition is a hallmark of liquefaction phenomena (Kramer 1996). Flow liquefaction can occur when shear stress is greater than the shear strength of the soil in its liquefied state. Loose sandy deposits with high groundwater levels would generally be the subject with high liquefaction potential (Towhata 2008).

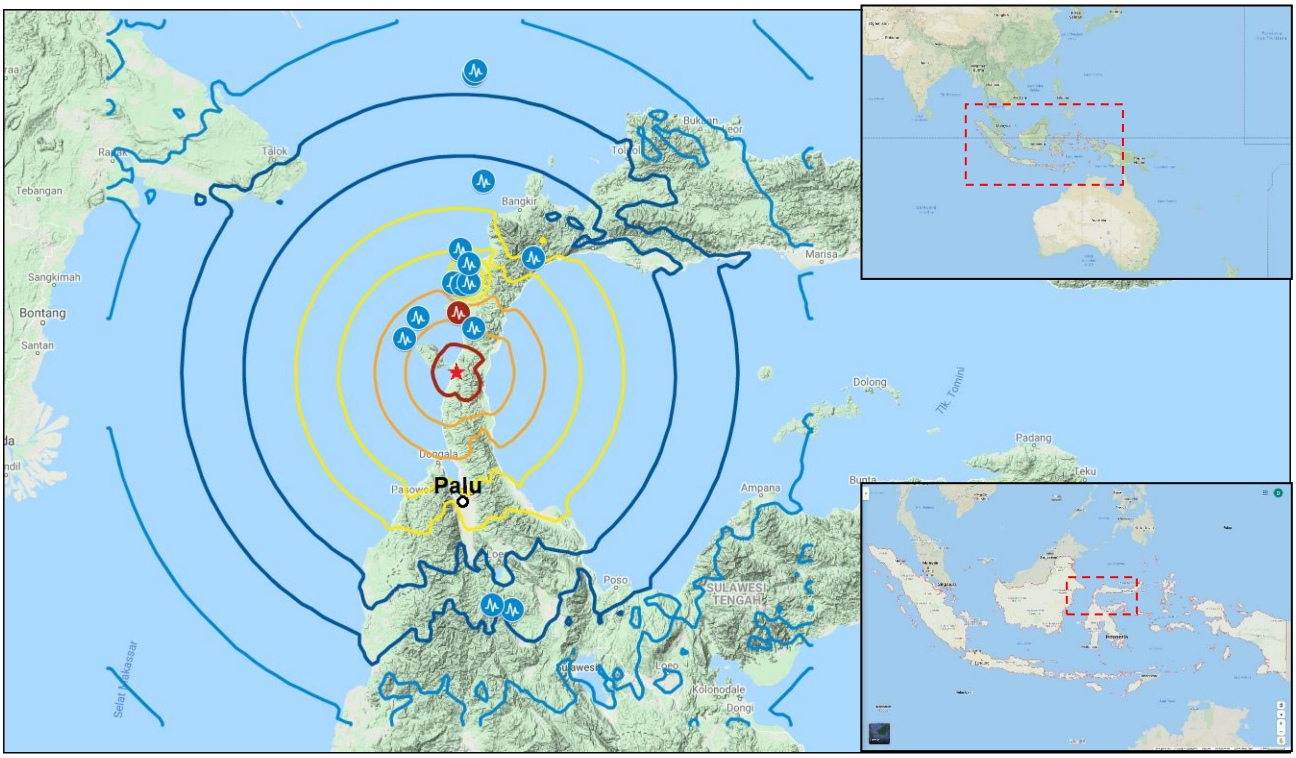

Fig. 1 Epicenter of Palu-Donggala Earthquake on September 28, 2018

In 1964, Niigata earthquake (M_s = 7.5) of Japan and Good Friday earthquake (M_w = 9.2) of Alaska signified examples of massive damages due to liquefaction, such as failures of slopes, bridges and building foundations, and flotations of buried structures (Kramer 1996). On the North Island of New Zealand, called the Bay of Plenty, soil liquefactions followed by lateral spreading were found shortly after the M_L 6.3 Edgecumbe earthquake of 1987. Soil liquefaction and lateral spreading had resulted severe damages with losses of around NZ$10 million for flood control and drainage schemes, including utility lifelines, public facilities and infrastructures (Pender and Robertson 1987).

The road embankment at Gomyoko Bridge, Hachirogata Lake, Akita, distorted during the 1983 Nihonkai-Chubu earthquake. The dike sank and laterally displaced to the side, which was a result of the loss of bearing capacity of soils beneath the foundation. Many cracks were found on the road pavement in the longitudinal direction of the embankment, indicating the embankment had elongated laterally in the direction of the slope (Asada 1998).

On February 27, 2010, at 3:34 local time, a large earthquake with M_w 8.8 struck south-central Chile. After extensive field investigations and reviews of local newspapers, several sites affected by liquefaction were identified. As a result, more than 170 locations were recognized with clear evidences of liquefaction, which covered an area with a length of approximately 1000 km. Examples of damages caused by lateral spreading on gentle natural slopes commonly consist of superficial soil blocks which are broken, moving downward and “floating” on top of the liquefied layer (Verdugo et al. 2015).

In Noshiro City, lateral movements of liquefied gentle slopes have been studied, based on air photos after the 1983 Nihonkai-Chubu Earthquake. Although the slope gradient was merely 1–2%, lateral movements had reached at a maximum of 4 m, in downslope directions. The slope movements had related to the gravity (Hamada et al. 1986a; 1986b).

3 Petobo Liquefaction Flowslide

Sulawesi island, Indonesia, is located within a very complex geological structure that comprises of the converging sea plates of Eurasia, Indo-Australian and the Philippines (Kadarusman 2011). Presently, Central Sulawesi has several active faults, one of them is Palu-Koro fault, which crosses Palu city limits the Eurasian (Bellier et al. 2001). Fig. 2 shows that this fault crosses along Palu city with left-lateral strike slip in a direction mainly towards north-south. As the result, Palu-Koro Fault has divided the Sulawesi Island into regions of South Sulawesi and North Sulawesi.

More than 260 earthquakes with magnitudes greater than 5 have occurred in Sulawesi island since 2008 according to the United State Geological Survey (USGS).

The Palu-Koro fault is believed to have triggered major earthquakes in Palu city area, with an estimated slip rate of 34 mm/year (Walpersdorf et al. 1998).

After the main shock of Palu-Donggala earthquake, extensive slides induced by liquefaction of soils initiated and hit several locations, as well as tsunamis smashed along the bay of Palu (BNPB 2018a; Irsyam et al. 2018). Four massive liquefaction-induced landslides occurred in different locations around Palu City, such as Balaroa and Petobo villages in Palu city and also Jono Oge and Sibalaya villages in Sigi district (Fig. 2). The largest area affected by the landslide is in Jono Oge (2.1 km^2) and the smallest area with 0.4 km2 is in Balaroa. For Petobo and Sibalaya Selatan, the areas are 1.64 km^2 and 0.52 km^2, respectively, affected by the landslides. However, Petobo had suffered the most severe effects by the slide. Fig. 2 presents the slide locations in Balaroa, Petobo, Jono Oge and Sibalaya Selatan.

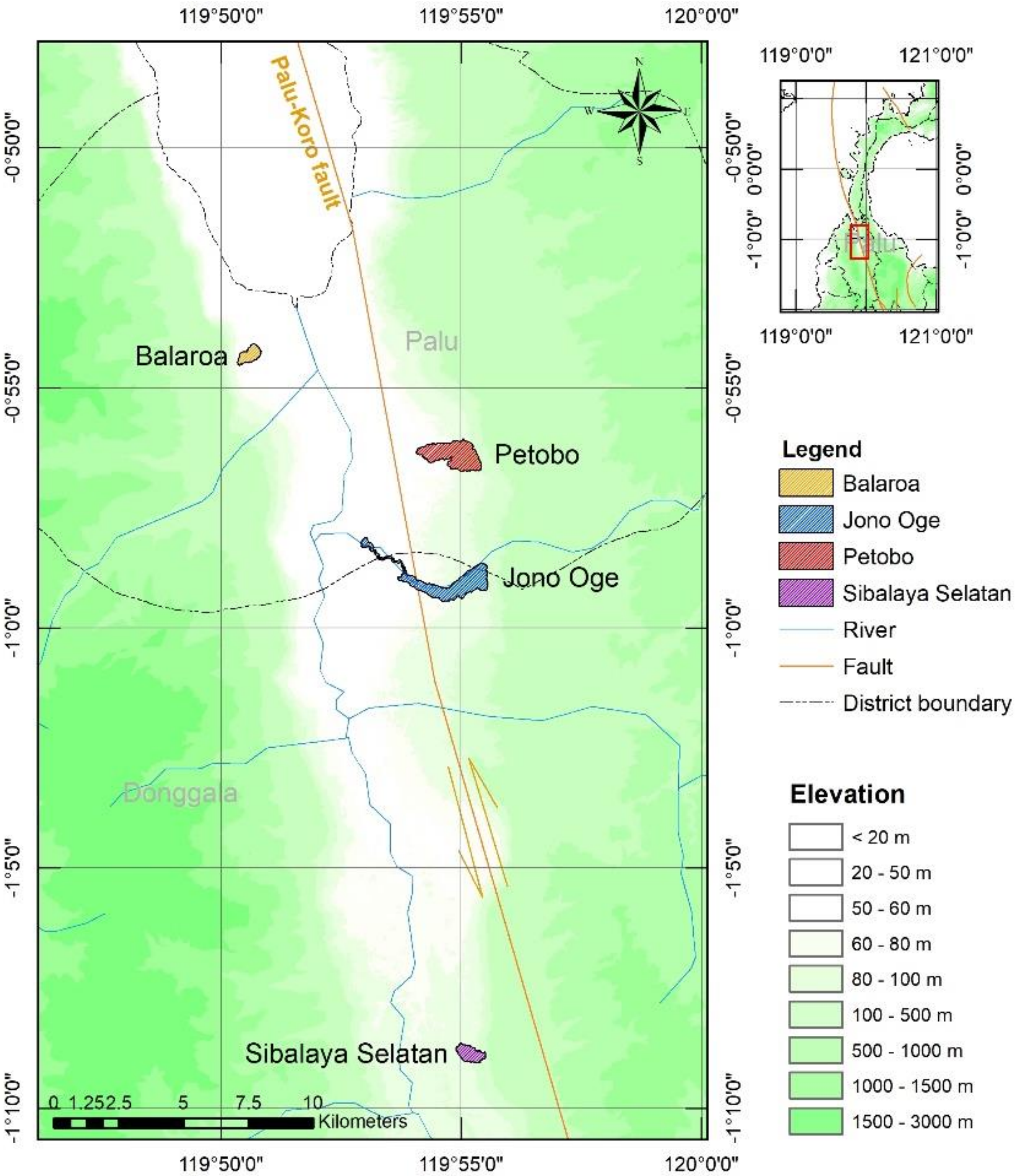

Fig. 2 Locations of liquefaction-induced landslides

Petobo is a densely populated area with a total population of 7094, according to the 2018 Central Statistics Agency. Petobo village is administratively located in Palu Selatan District, and is about 0.5 km south of Sis Al-Jufri International Airport of Palu City.

Post-earthquake surveying and evaluation of the flow failures identified the areas that had affected by landslide. At present study, the investigation methods used to collect information of the Petobo landslide mainly include visual observation and mapping. Additional information from satellite images and Google Street Views are also adopted in this study.

Fig. 3 presents the satellite photos captured from Google Earth for the Petobo landslide area in its pre-slide (date picture taken: 18 June 2018) and post-slide (date picture taken: 2 October 2018) time periods. The boundaries of the area affected by landslides are marked with yellow lines. The black dashed lines represent the areas that had not been affected by the landslide, where some houses were not damaged and remained intact.

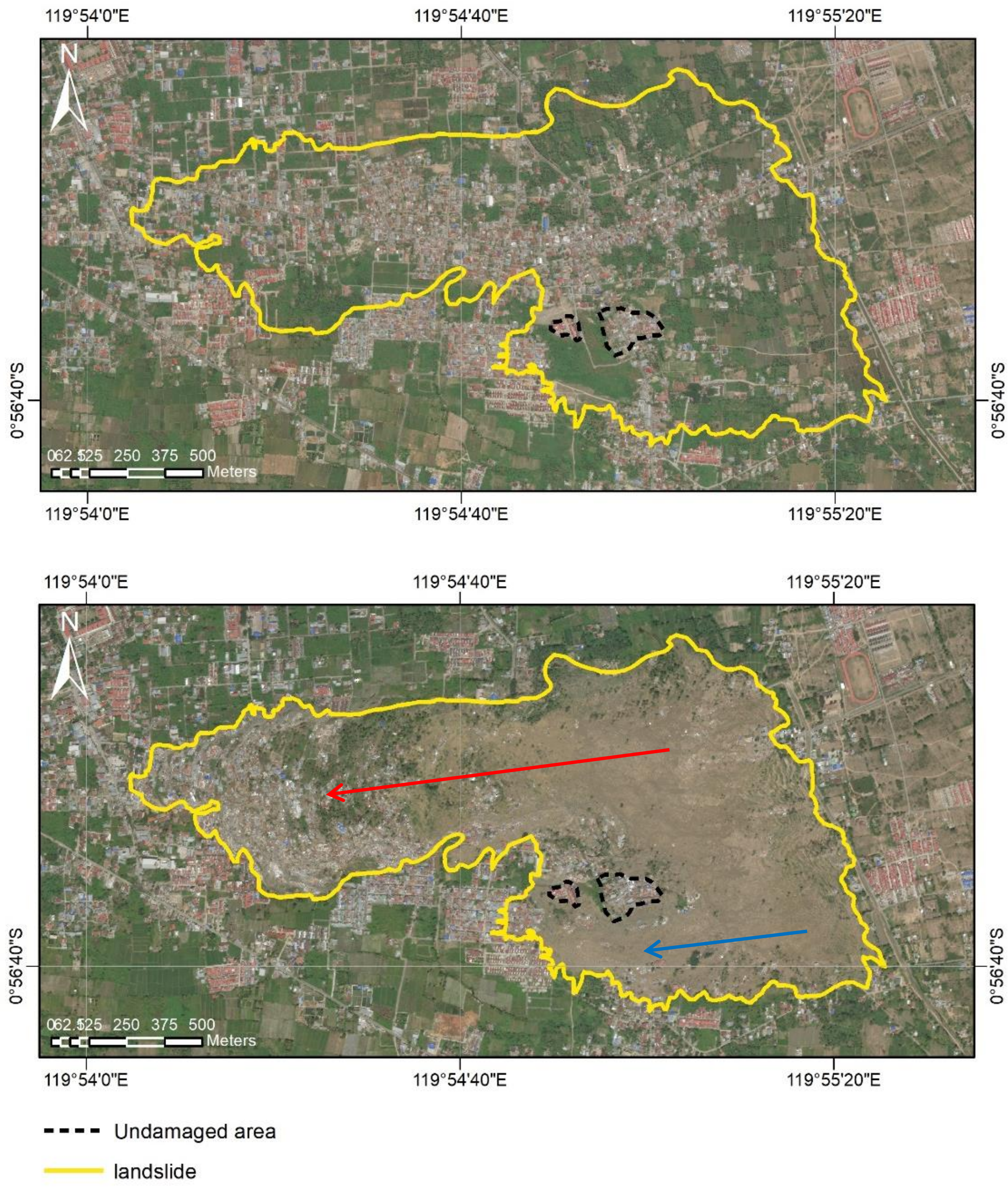

Fig. 3 Pre-slide and post-slide satellite images of liquefaction-induced landslide in Petobo

Approximately 1920 buildings were reported collapsed and affected by the mass movements, with the majority being residential houses (BNPB 2018). Based on the pre-slide image in Fig. 3, the middle and western part of the sliding area were residential with a large number of buildings. Fig. 3 also shown that the eastern portion of the sliding area was primarily paddy fields.

Petobo liquefaction flowslide generally moved from east to west. The major slide in the northern part of the sliding area had moved approximately up to 1 km along Jl. Moh Soeharto (the EW main road of the site). The slide in southern part of the area was generally shorter, about 0.5 km or less. In Fig. 3, the red arrow shows general direction of sliding of the northern part, while the blue arrow indicates the direction of sliding of the southern part. Among the landslides triggered by earthquakes, the flow-like long-runout landslides, with large-volume and high-speed, are generally considered most destructive (Huang 2014). The surface grading of the ground before the sliding was very gentle, with an average inclination of 2–3% (Hidayat 2019).

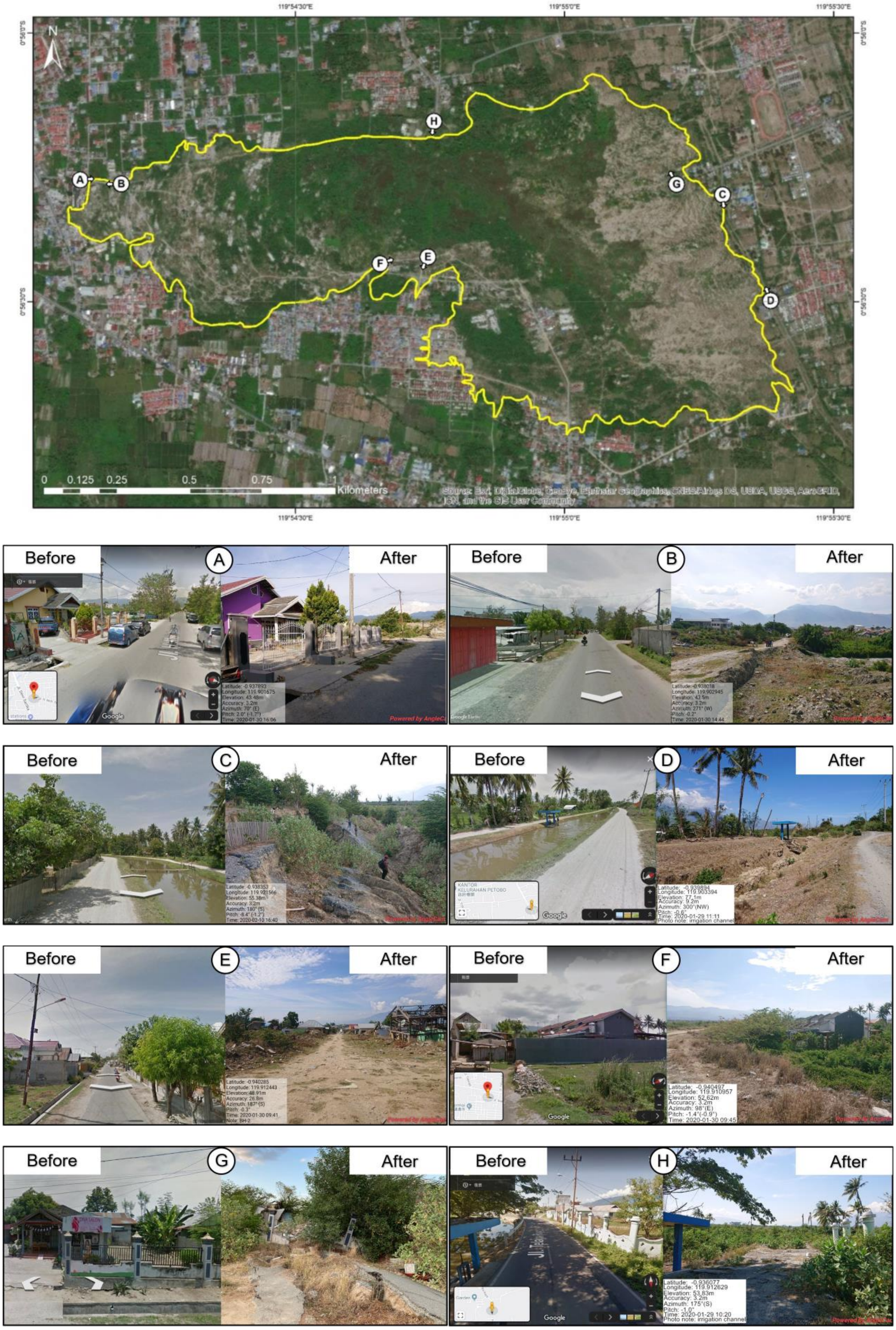

Fig. 4 Location map and photographs of feature before and after earthquake

4 Discussions

4.1 Onsite Observations

To identify damages caused by the landslide, field observations were implemented. Fig. 4 shows the post-slide satellite images taken on 11 June 2019. The white dots in the image are the post-slide locations of features indicated in Figs. 4A-4H. The arrows along with the white dots indicate the direction of viewing or shooting. The photograph pairs for features before and after the sliding were taken along the sliding boundary. Conditions of post-slide features are compared with those of pre-slide images using Google Street View. To ensure the correctness, coordinates of the shooting location and camera angle had to be confirmed.

Figs. 4A and 4B were taken from eastern part of the slide area near the toe. Fig. 4A shows the roads that had been cut off due to the debris. This picture was taken from outside of the boundary line facing to the east direction. It was remarkable that the buildings outside the slide area were merely unaffected. From the opposite side, Fig. 4B was taken facing west direction. It can be seen from the picture that the red building and the road had completely buried by the thick soils deposited after the flow.

The unique feature to the eastern part of Petobo landslide area is the irrigation channel (Gumbasa canal) that bordered the eastern boundary of the site. Figs. 4C and 4D were taken from eastern part of the sliding area. Fig. 4C shows the irrigation channel that had slip away toward downslope direction. Several crack along the irrigation channel in Fig. 4D could be seen and the blue water gate only suffered minor movements. These two pairs of pictures clarified that the water in the irrigation channel had disappeared after the earthquake.

Fig. 4E shows the damage of a road and several building that had already covered by the debris due to the landslide This road which was originally asphalted has changed into a dust road made by local people after they removed the debris materials. It is one of the access roads used by the local people leading to the landslide area, which is now already covered with vegetation. They also usually bring their livestock (cows and goats) to the landslide area. Fig. 4F shows the ground surface level increased almost as high as half of the building. The houses shown in the photo are no longer inhabited. These two figures were taken in the southern boundary.

Fig. 4G shows a comparison of the pre-slide and post-slide conditions of a house. The fence and the road suffered severe cracks and tilts. Fig. 4H shows a road that lay between the irrigation channel on the left and the Islamic School on the right. The irrigation channel could not be seen with only the blue water gate left in the figure. Some part of the Islamic School buildings in the south had been moved away by the slide further to the west. From the post-slide picture, only portions of the fence remained in the original place.

4.2 Morphological Features

The failure phenomena or morphological features observed in the Petobo sliding area could be summarized and defined as follows:

Ground Slip (GS)

“Ground Slip” is a failure phenomenon caused by slippages in soil materials. Several soil blocks divided by cracks or scraps usually can be observed at the ground surface (Figs. 5A and 5B). Ground slips can be triggered by a sudden increase in ground inertia, such as an earthquake shaking, and/or a drop or loss of a downhill support, such as a slope toe cut. The slip surface practically passes through the intact soil mass which does not liquefy during the ground shaking.

Lateral Spread (LS)

“Lateral Spread” is a failure phenomenon due to cyclic lateral spreading of liquefied soil materials during earthquake shaking. The surface appearance of lateral spreading may include a series of linear fractures or earthen peaks (ridges) with broken and lowered ground sideways (Figs. 5C and 5D). Surface structures can be destroyed, bent, or damaged by cyclic motions and the spreading of liquefied soils. Extruded liquefied sands are found on the ground in areas of cracking and peaking (Fig. 6). Lateral spreads are due to liquefaction of the soil. Due to the cyclical nature of shaking, the liquefied soils move back and forth laterally, leading to a gradual spreading and a decrease in the height of the liquefied mass.

Liquefaction Flow (LF)

"Liquefaction Flow" is a failure phenomenon due to the monotonic sliding or flowing of fully liquefied earthen materials, which occurs mainly after the earthquake. The ground surface of the liquefaction flows generally uneven and bumpy with extensive exposures of liquefied sands (Figs. 5E and 5F). Structures on the liquefied surface can sink, tilt or flow with sliding over a long distance. Liquefaction flows generally occur in sloping ground in which earthen materials are completely saturated and liquefied due to ground shaking. Due to the gravity and/or additional driving forces from the upper side of the slope, such as by ground slip or lateral spreads, the liquefied soil materials can start flowing downslope right after the ground shaking. The liquefaction flow can be accomplished in stages, depending on the viscosity of the liquefied soil materials, the degree of liquefaction that sliding mass can carry, the geometry of the ground and sliding surface, etc.

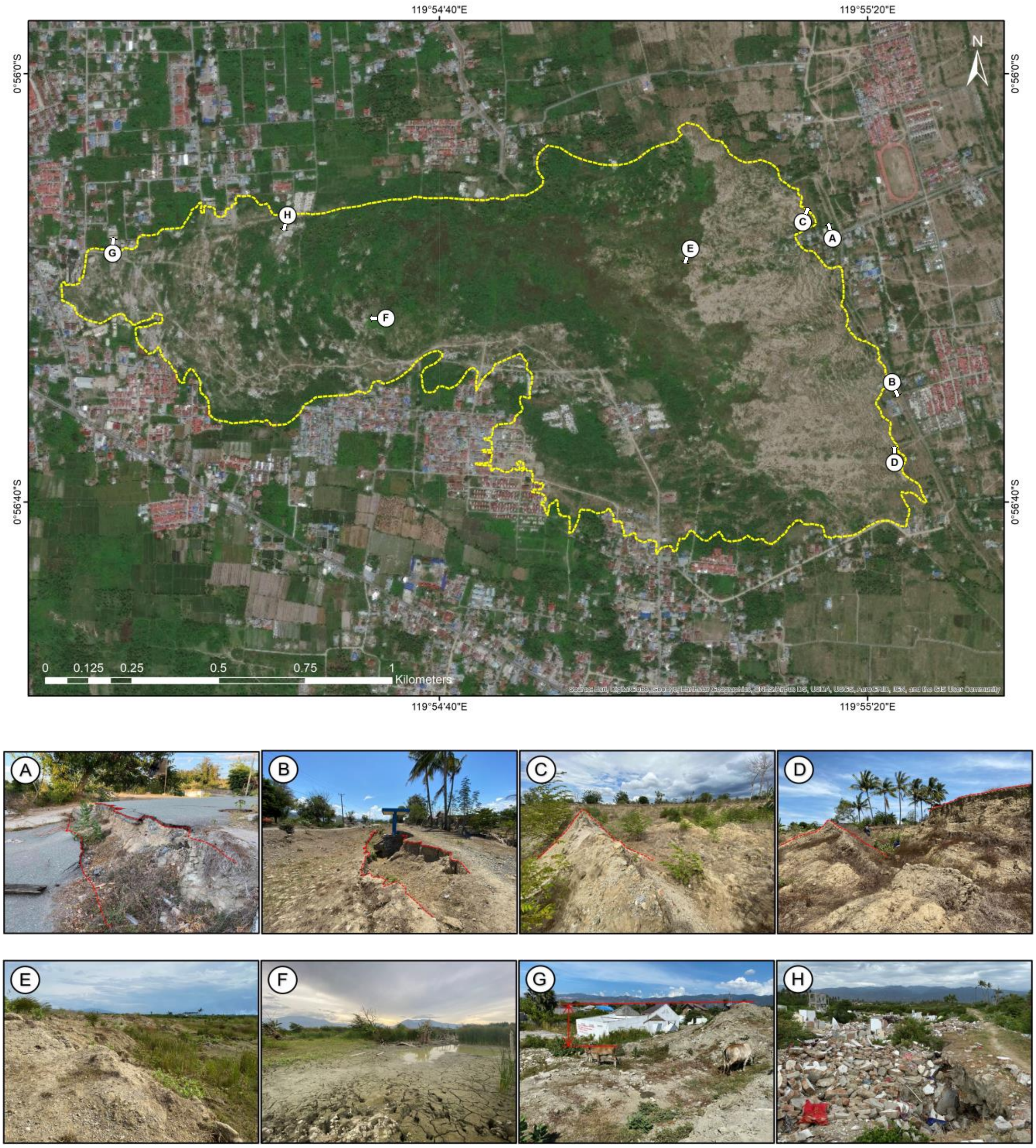

Fig. 5 Morphological features observed at the site

Debris Flow (DF)

"Debris Flow" is a failure phenomenon similar to the "Liquefaction Flow", an overflowing of liquefied earthen materials mixed with construction debris. However, the debris flow is different with the aspect that the existing ground of debris flow area is generally non-liquefied but covered with liquefied soils and debris from the upstream side. The liquefied soils with mixed debris are whacking and destructive for structures on the existing ground. Surface manifestations of the debris flow are characterized by the irregular surface of liquefied soil materials and debris, the destroyed existing and transported structures, and the elevated ground surface as opposed to the adjacent areas unaffected by the debris flows, etc. (Figs. 5G and 5H). The causes of debris flow are similar to those of liquefaction flow. When an earthquake is shaking, the soil on the upstream side is completely liquefied, dragged by gravity, and then flowing downward.

Fig. 6 Extruded sands in areas of lateral spread (LS)

5 Conclusions

The study herein discusses the field observations conducted in Petobo on the liquefaction-induced landslides due to the 2018 Palu-Donggala earthquake of Indonesia. Major findings of this study are found as follows:

a. Liquefaction-induced landslide in Petobo had been the most severe than the other three locations (Balaroa, Jono Oge, and Sibalaya Selatan), with approximately 1920 buildings collapsed and affected by the mass movement;
b. Based on site investigations and satellite images, the northern part of sliding area had moved from east to west with a distance of up to about 1 km, while the minor slide on the southern part moved approximately 0.5 km or less;
c. This study reveals the morphological features of Petobo slide could possibly be defined into four types. Ground slip (GS) is triggered by a sudden loss of downslope support and is characterized by cracks and soil blocks. Lateral spread (LS) is due to cyclic motions and soil liquefaction. As a result of lateral spreading, a series of parallel cracks or earthen ridges is apparent on the surface. Liquefaction flow (LF) is caused by a monotonic movement of liquefied soils after earthquake shaking. Due to a persistent gravitational shear and negligible shear resistance of the liquefied soils, the liquefaction flow can move for a large distance. Debris flow (DF) is similar to the liquefaction flow, with the only difference that the existing ground does not liquefy during the shaking but is deposited by the liquefied soils and construction debris from the upstream side.

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