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Understanding of Petobo liquefaction flowslide by 2018.09.28 Palu-Donggala Indonesia earthquake based on site reconnaissance

Abstract The Palu-Donggala earthquake struck Palu city of Sulawesi island, Indonesia, on 28 September 2018. A large-scale liquefaction phenomena occurred in some areas which caused massive fatalities and destructions. The most severe liquefaction incident during the earthquake followed by flowslides occurred in Petobo district of the city. The affected area due to Petobo flowslide liquefaction was approximately 1.64 km^2. The damages were severe because of densely populated area with estimated more than 3300 houses collapsed and nearly 2000 fatalities. The slide materials transformed into debris and flowed on the low-relief ground of about 2% with a slide distance of more than 800 m. A site reconnaissance of Petobo flowslide was conducted in early 2020, which covered surface observations and documentations before and after the flowslide, interpretations of geological characteristics, summary of witness interviews, analyses of ground displacement and changes in surface elevation and slope due to the flowslide. The results reveal insights as to the failure mechanism of the Petobo flowslide. Based on the observed phenomena on the surface, the Petobo flowslide area could generally be divided into four types of morphology, namely, ground slide (GS), liquefaction spread (LS), liquefaction flow (LF) and debris flood (DF). The GS and LS were considered to be the initiation zones, then the slide materials spread down and formed LF zone. In this area, the soils became wet and muddy as triggered by liquefaction. The liquefied materials then transported into DF zone where densely populated areas in lower elevation of the site were hit.

Keywords Liquefaction flowslide · Site reconnaissance · Morphological characterisation · 2018 Palu earthquake

Introduction

On 28 September 2018, the Petobo flowslide due to liquefaction was triggered by a massive earthquake of magnitude 7.5. The epicentre was located at 0.256 southern latitude and 119.846 eastern longitude, 70 km northeast of Palu city, in central part of Sulawesi island, and a focal depth of 20 km (Cummins 2019; USGS 2020; GEER team et al. 2019). Hours before the mainshock, several earthquakes also hit Palu city. The largest foreshock registered as Mw 6.1 was occurred 3 h before the mainshock which was triggered by Palu-Koro horizontal movement fault activity. The active strike-slip of Palu-Koro fault was initiated by progressive migration of faulting activity to a more easterly normal fault to the intra basin strike slip fault (Jaya et al. 2019; Patria and Putra 2020). Due to this, active strike-slip also created a series of aftershocks with a maximum one of magnitude of Mw 5.8. Earthquake epicentres can be seen in Fig. 1. The mainshock and the largest foreshock of this earthquake series are signed as red star and red dot.

The Petobo flowslide induced by liquefaction was recorded as one of the catastrophic liquefaction events in Indonesia with enormous size. At the same time, other flowslide locations were Balaroa, Jono Oge and South Sibalaya. The flowslides had caused a significant loss or missing of lives. Moreover, many buildings and infrastructures were severely damaged (Bradley et al. 2019; Hidayat et al. 2020).

As seen in Fig. 2, Petobo flowslide is located in Palu City, approximately 0.5 km south of Mutiara SIS Al-Jufrie airport. The flowslide area is around 164 Ha, with lengths along the north and south portions of the slide are 2.2 km and 1.2 km, respectively. The widths extended on along the east and west portions of the slide are 1.3 km and 650 m, respectively.

However, many geotechnical aspects still remained after the earthquake, which are relevant to be investigated to find out the causes and mechanism of the slide as well as lessons to be learned. Consequently, a reconnaissance was conducted in Petobo flowslide area to document the surface conditions before and after the earthquake.

This paper presents our onsite observations with respect to the classification of morphological zones and the possible mechanism of the flowslide. The paper also summarises our surface observations and compares with available satellite photos and DEM data provided by Centre of Data and Information Technology (2020) Ministry of Public Works and Public Housing of the Republic of Indonesia. Geological characteristics, ground displacements and documentations of variations before and after earthquake, as well as witness interviews are also discussed.

Study site

Geological condition

The geology condition of Palu and the surrounding area is shown in Fig. 3. The history of Palu geology has revealed the Palu-Koro fault is one of active faults in Indonesia as indicated by the appearance of multi-tectonic movements. Daryono (2016) confirms that micro tectonic movements have frequently occurred along this fault, i.e. sinistral strike-slips due to east-west compression and north-south extension, or east-west compressions due to normal component of displacement with left lateral.

The Palu-Koro fault in Palu Valley has experienced an evolution with age for two distinct alluvial fan units, i.e. old alluvial fans and young alluvial fans (Bellier et al. 1999). The Petobo flowslide area is situated on the old alluvium fan deposit formation (Qf2) and the alluvial, flood and old river channel deposit formation (Qal) of the Palu river valley. The alluvial and flood deposit consists of mostly

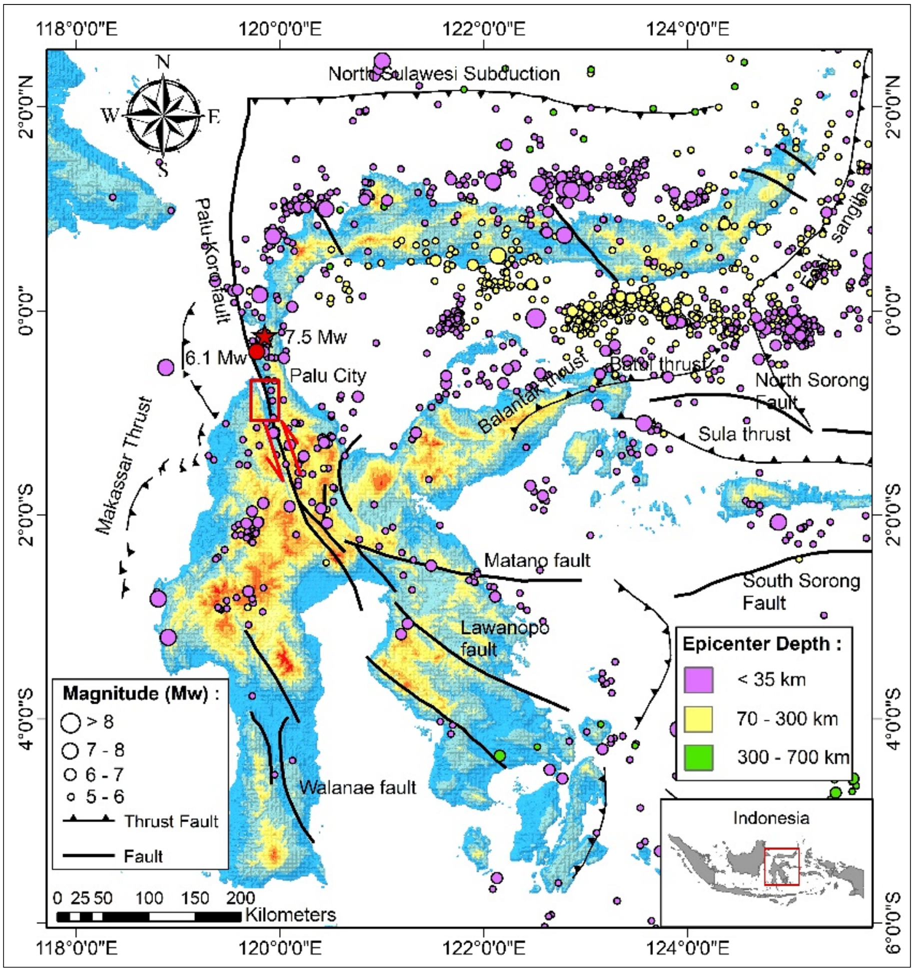

Fig. 1 Regional tectonic map in Sulawesi and surrounding. The size and coloured dots indicate as magnitude and epicentre of earthquakes taken from USGS catalogue 1900–2019. The red rectangle is the location of Palu City. The locations of largest foreshock and mainshock of 2018.09.28 Palu Earthquake are shown as red dot and red star, respectively. Credit: Base map adapted from GADM, base digital elevation model derived from CGIAR SRTM 30-second grid. Bold lines and toothed lines are faults and thrust faults, respectively, taken from Cipta et al. (2016)

sand, silt and clay (Pyi et al. 2015). Furthermore, the alluvial fan deposit is typically composed by gravel-sand transitions and it often exhibits similar gravelly soils with a narrow particle size distribution. Due to poor particle gradations, the soil contains a series of voids where water easily fulfils the voids and saturates the soil (Litwin et al. 2014). During the 2018 Palu earthquake, a strike slip fault was ruptured at north west of Palu Valley and initiated the deformation in the surface. It could be observed by the appearance of a series of ridges uplifted associated with transpression deformation. Furthermore, along the eastern part of old alluvial fans appeared fault scarps which represent normal faulting activity (Patria and Putra 2020).

Seismic history

Sulawesi island is located in the Sundablock adjacent with three tectonic plates: Pacific, Australia and Philippine plates, which is also known as a triple junction (Kadarusman et al. 2011; Bellier et al. 2001; Watkinson and Hall 2017; Socquet et al. 2019). Since this triple junction causes a complex tectonic system in Sulawesi, including strike-slip and thrust faults, earthquakes are frequent (Patria and Putra 2020; Nugraha and Hall 2018). The Indonesia National earthquake source and hazard map reveals nearly 50 active fault segments are detected in Sulawesi as well as the North Sulawesi Megathrust in the north of Sulawesi (Irsyam et al. 2020). The subduction along the North Sulawesi Megathrust generates seismicity in Sulawesi which is significantly high (Jaya et al. 2019; PusGen 2018). The Palu-Koro fault as mentioned is a significant seismic system in Central Sulawesi, which extends from north-west to south-east across Sulawesi for more than 300 km long. The fault starts from North Sulawesi trench, passing through Palu Bay, turning southwards to south-east, then connecting to Matano and Lawanopo faults. Both faults join further eastwards to Tolo trench (Bellier et al. 2006; Socquet et al. 2006; Watkinson and Hall 2019).

Figure 1 illustrates tectonic activities in Central Sulawesi region. Historical destructive earthquakes of more than Mw 5 along Palu-Koro fault zone repeatedly occurred with epicentres located either offshore or inland as shown by purple dots. One of the earthquakes along Palu-Koro fault was described by Abendanon (1917), indicating the 1907 earthquake was followed by a more damaging earthquake 2 years later. Abendanon reported that the 1909 earthquake had almost destroyed the

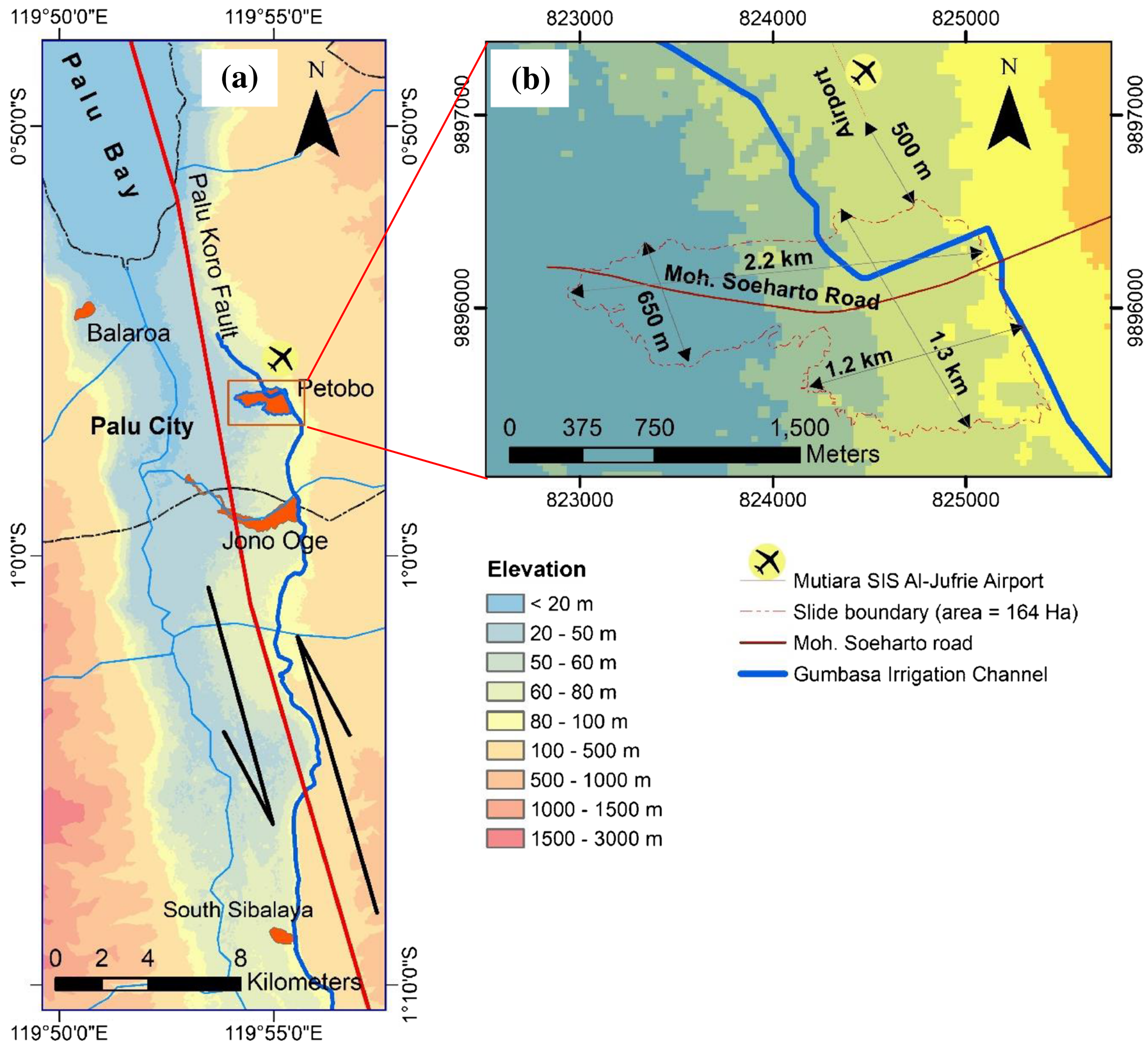

Fig. 2 (a) Flowslide locations after Palu-Donggala earthquake of 2018.09.28. (b) Dimensions of Petobo flowslide. Credit: Base map adapted from GADM, base digital elevation model derived from JAXA's ALOS Global Digital Surface Model 30 m × 30 m resolution

houses that survived during the 1907 earthquake. The damages spread along from Saluki up to Donggala regions. It was noticed the appearance of a surface cracking of 7 km long with an uplift of 1 m. Evidence of a vertical slip of 1.5 m and a sinistral slip of 1.5 m were also observed after a trench excavation in Onu Village along Saluki segment.

Kiyota et al. (2020) reported the measured shaking data of the 2018 Palu-Donggala earthquake consisted of two horizontal components (EW and NS) and a vertical motion (UD). The resultant peak horizontal vector acceleration (PGA) of 333 gal (0.34 g) was recorded during the earthquake. The predominant frequency of motion was measured in between 0.2 and 0.6 Hz, which revealed the intense shaking of the small frequency range may well have been responsible for the severe geotechnical damages.

Liquefaction susceptibility

Regional geology of Palu area is composed of alluvium and flood deposits. Risna (2012) reported a preliminary study of liquefaction potential in Palu and the surrounding. Several cone penetration tests were conducted on the site to obtain the characteristic of soils. The field testing revealed, for mostly of the alluvium and debris deposits, the soil layers generally consist of sands on the top, silt in the middle and clay at the bottom. Grey sands are generally loose, poorly graded, good porosity and permeability, with a thickness of 1–7.2 m. Silts are normally found under the sands with a consistency of soft to firm, medium plasticity, and a thickness of 0.2–0.7 m. The clays are brown to dark brown, soft to firm, and highly plastic, with a thickness varied between 0.1 and 2.7 m. Weathered soils underneath in this formation are generally grey sands, loose, well-graded, good porosity and permeability, with a thickness of about 3.5 m. In this area, the depth of groundwater level is less than 12 m. The alteration of soil behaviour in each soil layer could occur when experienced by seismic wave. When the seismic wave propagated from the bedrock through the saturated sand soil layers, it led to the decreasing of effective soil stress. A susceptibility of liquefaction could be reached when pore water pressure equals to initial effective stress. In Palu city and surroundings, a suspect area with a high risk of liquefaction occurrence is in the alluvium deposit. Details of liquefaction

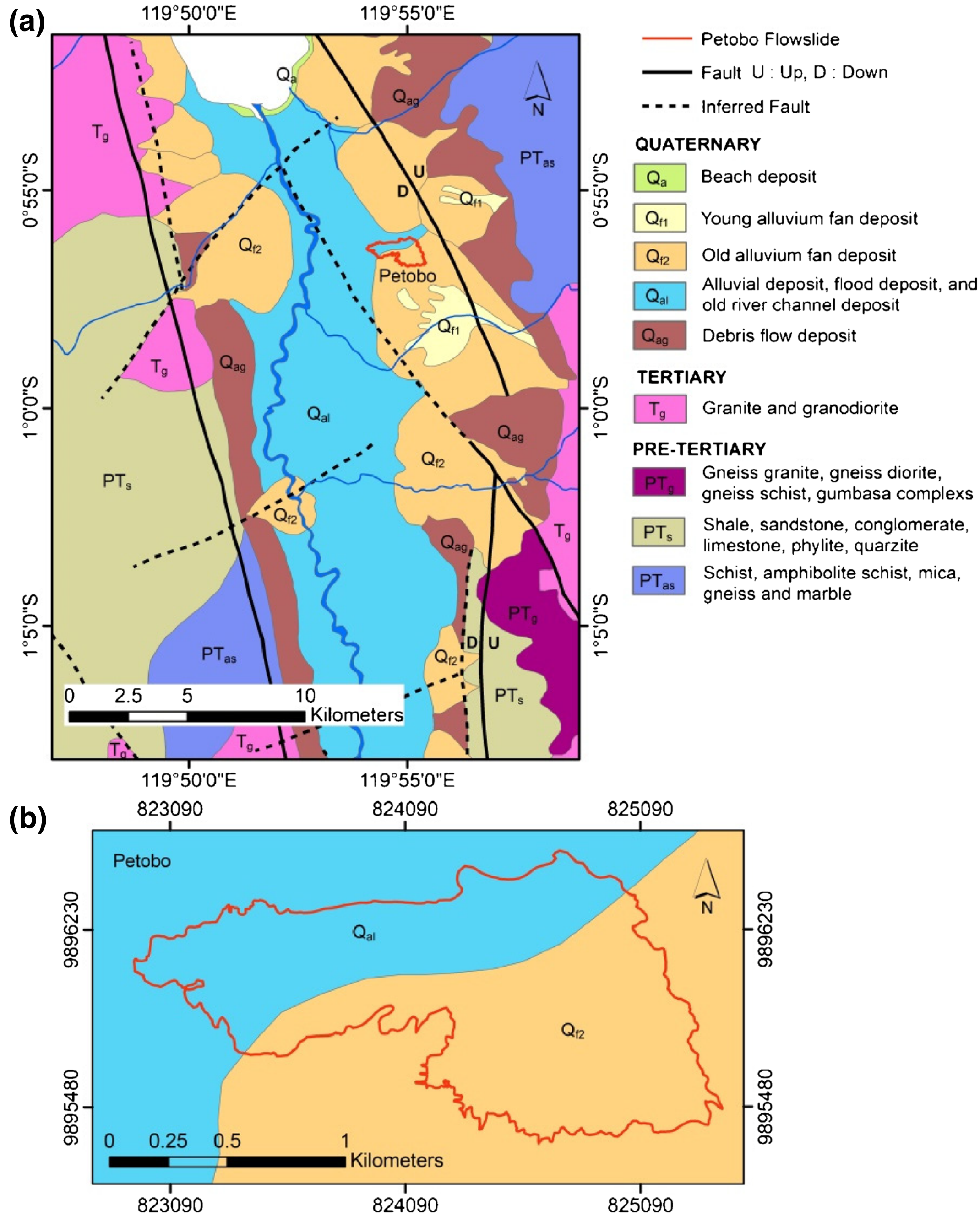

Fig. 3 (a) Geological map of Palu and surroundings (Hanifa 2018) consists of surficial deposits in Quaternary, Tertiary and Pre-Tertiary periods. The study area is identified by the red line. (b) Location of the study area is composed dominantly by the old alluvium fan deposit and the alluvial, flood and old river channel deposits

susceptibility and groundwater level in Palu and surrounding can be seen in Fig. 4.

Results

Eyewitness review

The information from the witnesses and survivors is very important to understand the condition of failure at the time of earthquake shaking. During site reconnaissance, we tried to compile documentations with interviews of local people who survived in the flowslide. The locations where each of the witnesses was during the earthquake can be seen in Fig. 5. Details of the interview contents are shown in Table 1.

Table 1 summarises the findings through interviews with the witnesses and survivors of the flowslides. As seen, the wed paddy fields, distributing around eastern portion of sliding area, and the Gumbasa irrigation canal, with many places unlined and filled with water, would locally raise the groundwater level and lead to adverse effects on triggering liquefaction of the ground during earthquake; a situation as mentioned in other literatures (Bradley et al. 2019; Cummins 2019; GEER team et al. 2019).

As regards earthquake shaking, the interviewers had expressed different viewpoints on the timing of sliding. The witnesses B, G and L, located near the eastern boundary of the sliding area during earthquake, felt the ground started to move in around 10 s or less after the shaking. Witness D, who was at the mid-south of sliding area during the shaking, felt the ground started to move in about 20 s after the shaking. Witness F, who was located to the north boundary in the middle portion of the sliding area, felt, however, the sliding started in approximately 60 s after the shaking. Although there might have been involved to some degree the uncertainty of personal intuitions, the individual perceptions on the slide initiation would appear to indicate the sliding might have had started in sequence during and after the shaking, with most likely scenario by starting from eastern boundary, proceeding to southeast, then towards north portion of the sliding area.

The witness interviews also revealed the information on the form and velocity of the sliding. Generally, the witnesses (G, K, L and M) who located near the eastern portion of the sliding area indicated the sliding was in a wavy form. Since these people were sitting near the eastern boundary, one would expect that they had been experiencing a severe spreading of the ground due to liquefaction of underneath soils by the shaking, and the back and forth moving actions of the spreading would likely be the reason for how they felt. Witnesses F, G and L had also described in different ways how fast the slide was moving. It could be estimated based on their statements that the sliding they had experienced were approximately in a velocity of 2.5~5 km/h, or equivalently a speed of walking to jagging.

With respect to liquefaction phenomena, most of the interviewers observed the ground extruded by dark muddy water, resemblance to mortar, which was warm and with an erupted height up to around 2 m and 5 m, in the NE and SE portions, respectively, of the sliding area. Few big eruptions of sands were also observed near the central portion, approximately along Moh. Soeharto road of the sliding area, with eruptions up to a coconut tree high. For post-slide observations of the ground, most interviewers indicated the ground was very wet and soft, and some places were ponded with water up to 1 m. It took months for the ponded lands to be gradually retreated. In fact, when the research team of this study visited the site in early 2020, several locations in the middle portion of the sliding area were still ponded with water. Those waters were believed to have been formed as a result of extruded pore water due to severe liquefactions of the ground by the shaking.

Land-use changes

The earthquake caused land-use changes in Petobo area. Figure 6 illustrates the land-use changes at different periods. As shown in Fig. 6 a, the eastern and southern parts of the Petobo flowslide area before earthquake were mostly paddy fields, while residential area was densely populated in the western and middle parts. A main

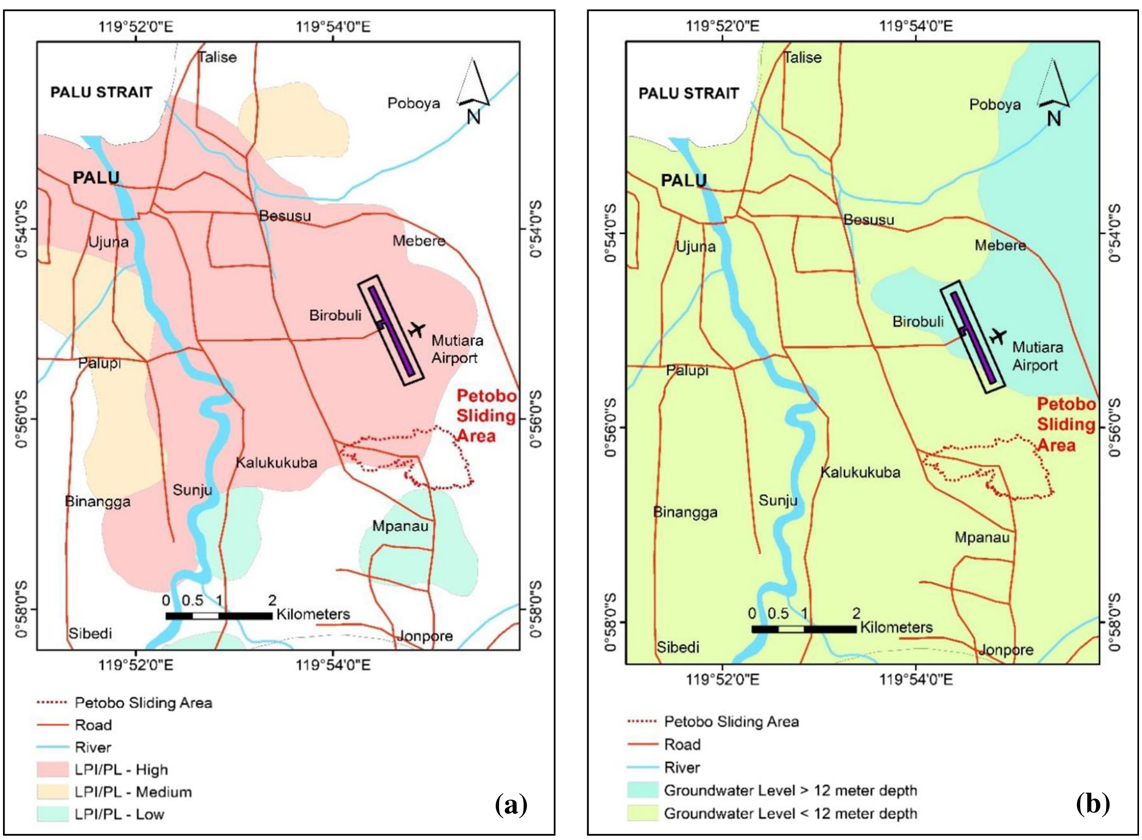

Fig. 4 **a** The map of liquefaction susceptibility in Palu and surrounding with three levels of potential of liquefaction. Palu city is identified to have a high possibility of liquefaction occurrence in particular to the east of Palu river. One of triggering factors contributed to liquefaction occurrence is the shallow depth of groundwater. **b** The map of groundwater level in Palu and surrounding reported by Risna (2012) which can be divided into two zones with different depths of groundwater level

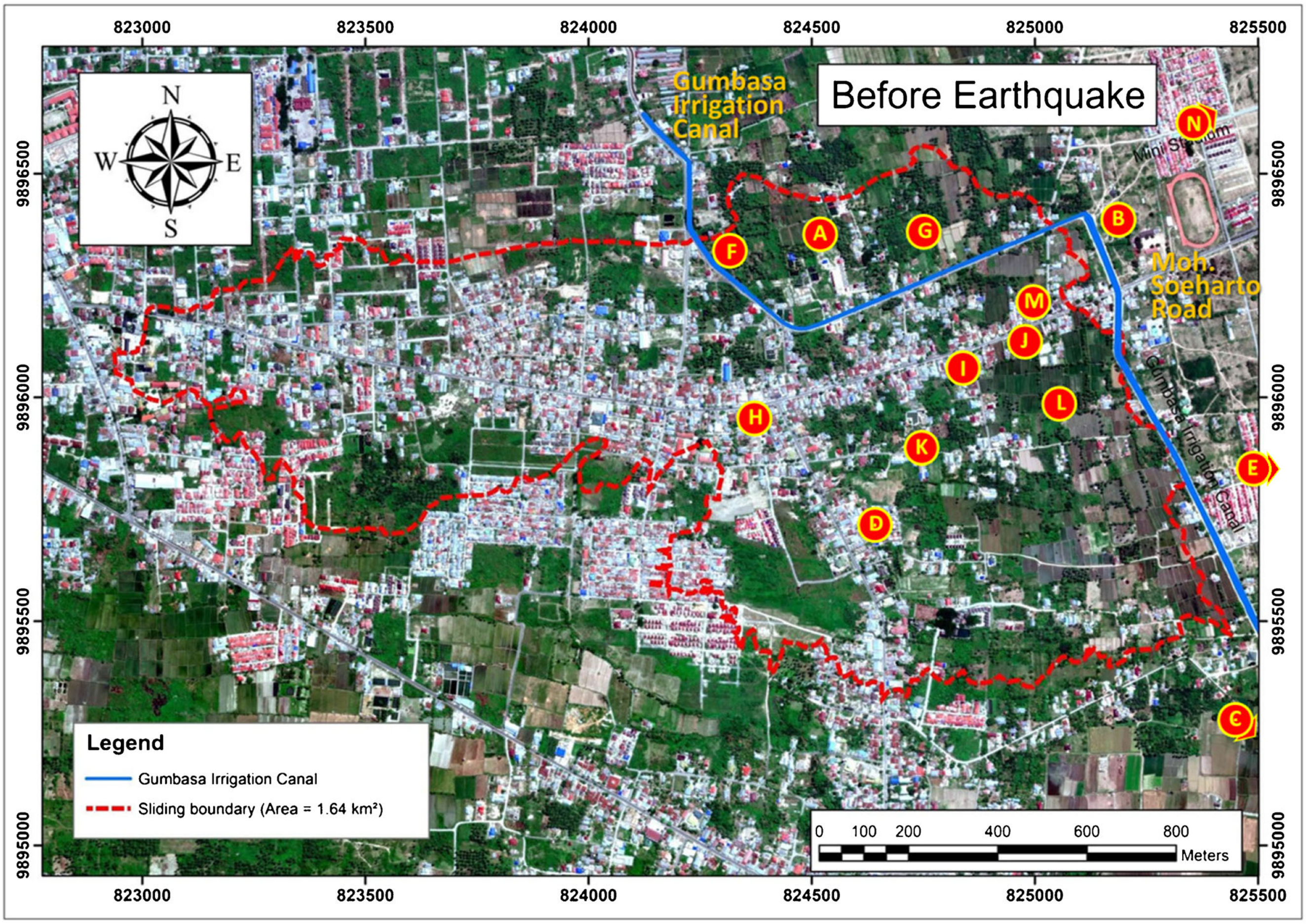

Fig. 5 Locations where interviewed witnesses were in the Petobo area during 2018.09.28 Palu-Donggala earthquake. Based photo is taken from Google Earth satellite image of 2018.08.17

road of Moh. Soeharto passed across the flowslide zone from east to west. The earthquake shaking obviously destructed the eastern part of site and swept away everything, such as people, properties and houses, westwards. Figure 6 b indicates the area hit by liquefaction flowslide was covered by debris on the surface in brown colour. Figure 6 c shows the condition of the site 1 year after the disaster. As can be seen, the area was almost preserved, as confirmed by our team during site investigation, where no reconstruction was noticed and the damaged infrastructures could be observed as an accumulation of ruined debris in the western part of flowslide area.

Variations of surface objects

The affected area at Petobo due to flowslide liquefaction is about 164 ha. The street maps of the site before and after the sliding can be seen in Fig. 7. The Gumbasa irrigation canal was originally running along the eastern boundary from south to north, then turned westwards and passed across the NE portion of the site (Fig. 7a). As mentioned, the flowslide liquefaction was initiated from the east portion near Gumbasa irrigation canal, and flowed away from their original locations towards west. Maximum travelling distance of the flowslide had reached more than 800 m.

In the middle of the site, our team visited an area where Witness G had indicated big eruptions of sands from the ground during the sliding (Fig. 8). We noticed the ground surface was rugged and piled with sands, suggesting severe liquefaction outflows or eruptions might have occurred during the earthquake shaking. In the southern part, we found an undamaged area (Fig. 7b), where houses and people were not hit directly but surrounded by the flowslides.

Google earth images prior to earthquake are compared with the results of our onsite observations for some key features at the site. Figure 9 indicates locations of the key features and Fig. 10 is the photo pairs of features for the comparison of variations before and after the earthquake.

Photos 1 and 2 show the Gumbasa irrigation canal located along the eastern boundary of the sliding area. As seen, the canal was unlined and full with water prior to the earthquake. However, the earthquake had triggered slippages of the ground, causing cracks and drainage of the canal. Photos 3 and 4 are for surface features at east side and northeast corner of the sliding area. As indicated, the ground had been seriously distorted and displaced, apparently the result of liquefaction spreading during the earthquake.

Photos 5–8 show four key features originally situated in the middle and western portions of the area. As seen in Fig. 9, these features had been displaced towards west with a distance of 250~700 m. Some of the features would appear to be structurally sound (Photo 6, mosque); however, some of them had been severe

Table 1 Summary of interviews with eyewitness and survivors of 2018 Petobo flowslide incident

Findings related to paddy fields and the irrigation canal
•Rice planting normally involved 2 harvests per year. •Paddy fields were constantly wet (filled with water) between February and May and between August and November. •During wet paddy, the fields were normally filled with water to a height of about 30–50 cm and for fish raising (e.g. tilapia). •The paddy fields were constantly watered from the irrigation canal (IC; Gumbasa) and its tributaries; however, individual households had their own pumps for drinking water (note: more populations were clustered along the EW main road (Jl. Moh. Soeharto), and supposedly these areas would have had lower groundwater levels due to the pumping). •The IC, in most places were unlined, was full of water at the time of earthquake.
Findings related to the earthquake shaking
•Two severe shakings occurred on the same day; one (pre-shock) at about 3 pm and the other (main shock) at about 6 pm. •The main shock by severe shaking for about 10 s~1 min, with firstly vertical (U-D) vibrations then horizontal (N-S) shakings. •Witness L felt the shaking started with vertical vibrations for about 2 s, then followed by severe horizontal shaking.
Findings related to the sliding
•The ground moved subsequently soon after (few seconds ~ 20 s) the shaking started. •During the moving of the ground, houses and trees were floating, tilting or sinking. •During the sliding, a continuous “truck-like” sound was heard, and a “sulphur” smell was noticed (note: probably due to liquid gas used by general households in dinner time). •Witness K indicated while she was trapped and sunk in the mud, she felt the ground being lifted up and down, in a wavy form. The soil blocks separated by a gap also moved relatively in lateral direction, which caused the gap closing and opening periodically. •Witness D indicated during the flowslides, the debris hit the houses where his in-law and other neighbours resided, and formed in two flow branches that surrounded the north and south sides of the housing area. •Witness I noticed the ground was moving firstly towards SW direction, and then the debris flow from the SE part of the sliding area moved towards NW direction. •Witness F observed the ground with a moving distance of 100 m would take about 2 min (note: ~3 km/h). •Witness G noticed the ground moved in a wavy form, with estimated vertical amplitude of 1.5~2 m and a travelling distance of about 15 m in around 20 s per cycle (i.e., horizontal speed ~2.7 km/h). •Witness L indicated the ground sliding was initiated sooner after the shaking started, and the sliding lasted for around 1 minute for a travel distance of about 75 m of his house (note: for a sliding distance of 75 m in 1 min, the sliding speed would have been around 4.5 km/h). •Witness F found one of his relative’s houses, sitting in the middle of the area, had moved ~120 m (from E to W). •Witness J indicated she was moved to downslope location during the sliding, a distance of around 400 m away from her original place (i.e., her parents’ house; along the main road to the E-portion of the sliding area). •Witness L indicated his house (to the east side of the sliding area) had been moved laterally by ~75 m, and raised up to a telephone pole height (i.e. ~6 m). •Witness M indicated she was sitting on a piece of pavement and floated with a sliding mass, in the east portion of the sliding area, with a moving distance of around 300 m during this incident.
Findings related to the liquefaction and sand boils
•Many places of the ground were observed with erupted gases (smoke?) and “dark” water with soils (sand boils). Some people were sunk into the ground or holes where sand boiled. •Water with bubbles extruded from the ground was warm (~35 °C). •Sand boils, in a form of sandy soils with “dark” water, extruded above the ground surface to a height of around 0.5~2 m and 2~5 m, respectively, in approximately the NE and SE portions of the sliding area. •Witness G noticed 2~3 places with big eruptions of sands, with a height up to about a coconut tree (15~20 m). One of the big eruptions was at a location close to the village office (Kantor Kelurahan Petobo) in the middle of the sliding area.
Findings related to the ground conditions
•The ground surface was wet, muddy and soft, like a “mortar”, and would be sinking if walk. •Witness J indicated the ground became muddy and soft that she sank into the ground to her knees (~30–40 cm). •Witness K indicated while she was sinking in the mud (in a gap between soil blocks), she felt the ground was rotating (or floating?). The mud and water in the gap between blocks were warm (~35 °C?), and felt like a “mortar”. •Witness I indicated the ground was flooded by “warm” water to a height of 0.5~1 m, in the middle of the Petobo site, after the shaking/sliding. About 2 months later, the flooding was gradually retreated. •Witness K noticed the paddy fields were not fully wet prior to the earthquake. But after the earthquake, the paddy fields were full of water to a height of 20~30 cm.
Findings related to others
•Several deep pump wells, with depths of around 130 m and located beyond the E-boundary of the Petobo slide, were installed by the government for municipal usage of the temporary housing for the affected households. Some of these wells were found with hot water from the ground, which are generally in alignment with the direction towards the sliding area.

damaged or torn (Photos 7 and 8, residential buildings). The phenomena would suggest the ground had been liquefied as a result of earthquake shaking and flowed, with driving forces and low resistance, for a large distance.

Photos 9–12 illustrate three surface features sitting around the western peripheral of the sliding area and one feature located near the previously mentioned undamaged area (Fig. 7b) to the southern portion of Petobo site. As shown in these

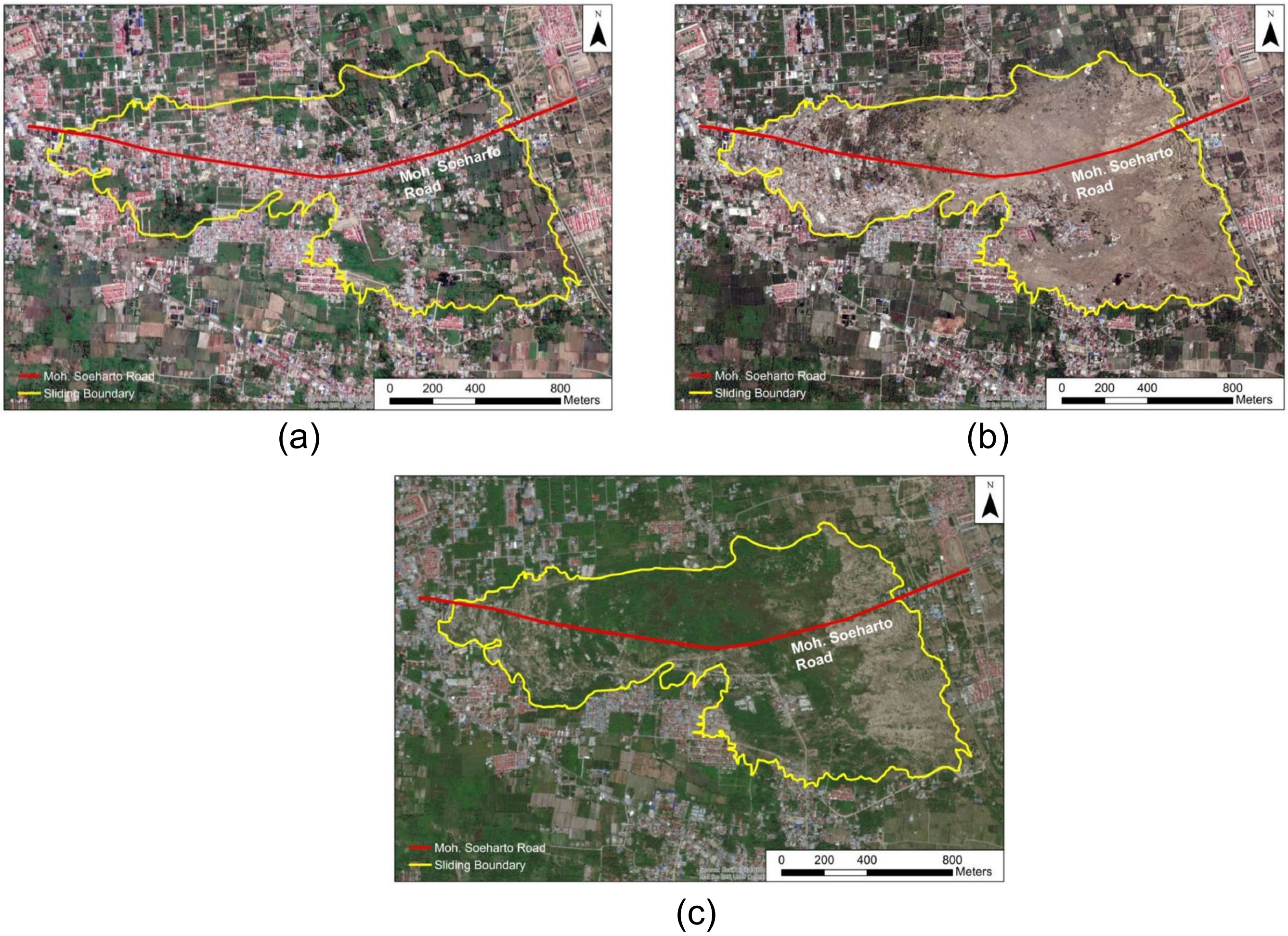

Fig. 6 Site conditions before and after earthquake are documented at three different times taken from Google Earth. **a** Before the slide on 2018.08.17, the site could be seen with dense population. **b** Four days after the slide on 2018.10.02. **c** Recent image on 2019.11.06

photos, the sliding debris had deposited and piled up on the ground to a height of 3~6 m, as compared with the adjacent unaffected area.

During onsite investigation, the authors found several locations in the middle portion of the sliding area were inundated with swamps and presented with artesian waters (Fig. 11). It is evidenced that these the ground water levels at locations should be very high, and presumably the results due to previously severe liquefaction events.

Ground displacements due to sliding

Displacements of the ground are identified based on our onsite investigation as well as Google Earth satellite images before and after the earthquake. Figure 12 shows the displacement vectors of surface objects of Petobo site. As seen, for the eastern portion of the area, the ground slid approximately up to 200 m. However, the ground moved much longer with distances of 500~1000 m and <400 m, respectively, in the middle and western portions of the sliding area.

Elevation and slope changes after earthquake

The flowslide liquefaction contributed to the changes in soil elevation in Petobo area. Figure 13 a describes the elevation changes due to the earthquake. Figure 13 b illustrates the grading of ground surface after the slide. In the eastern part of the site, the elevation dropped in the range of 5~8 m and the slope grade changed intensively up to 20° due to the shaking. The slope grading should have been affected by lateral spreading of the ground. In the middle part of the site, the elevation changes could be divided into two sub-areas. The sub-area near the said lateral spreading zone, the elevation changes dropped more than 7 m and the surface grade was relatively flat at about 2°–4°. It appeared to be the result of liquefaction flow that occurred after the cease of lateral spreading or seismic shaking. The other sub-area further to the west, the elevation gradually changed to raise 1~4 m, with surface grading remained the same as 2°–4°. In the western part of the site, the ground surface was generally lifted up by 4~10 m. The surface grading became rougher again as due to the compression and accumulation of the debris flow from the upstream side.

Discussions

Impact of Gumbasa irrigation canal

Gumbasa irrigation canal was constructed by the Dutch colonial government in 1910s. In the beginning, the canal was a simple dike

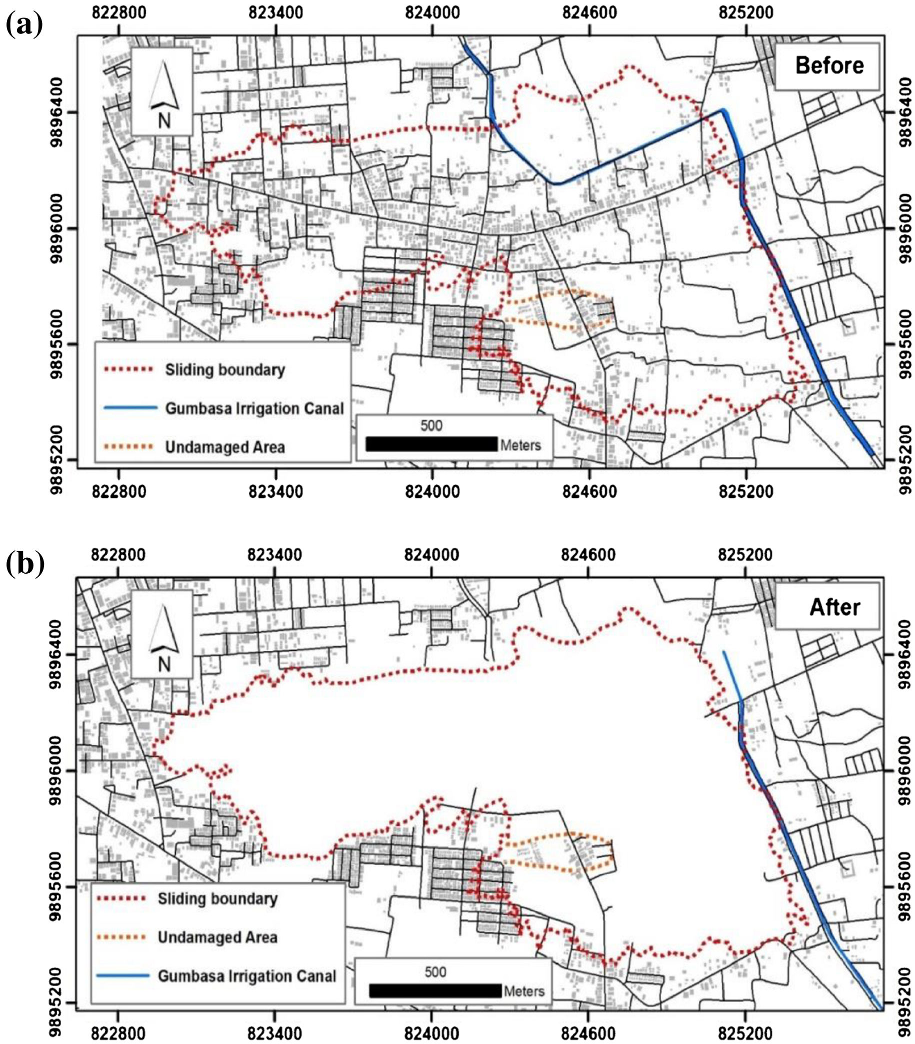

Fig. 7 The site condition before and after the earthquake. **a** Condition before earthquake where Gumbasa irrigation canal passed across the flowslide area. **b** Situation after the earthquake where Gumbasa irrigation canal in the NE portion of the sliding was swept away and an undamaged area was found in the southern part of the sliding area

for municipal purposes instead of agriculture irrigation. In order to increase agricultural productivity, Gumbasa irrigation canal had been reconstructed for the farmlands and inhabitants of the neighbourhood. Nowadays, Gumbasa irrigation canal with a total length of 36 km is the primary water source for paddy fields and other agriculture activities in the Palu valley.

As indicated by local residents and in Google Earth images, Gumbasa irrigation canal was constantly filled with water before the earthquake (Photos 1 and 2; Fig. 10) and the paddy fields were also inundated with water for about 8-month plantation time annually, which are based on our site reconnaissance as summarised in Table 1. During the plantation, the paddy fields

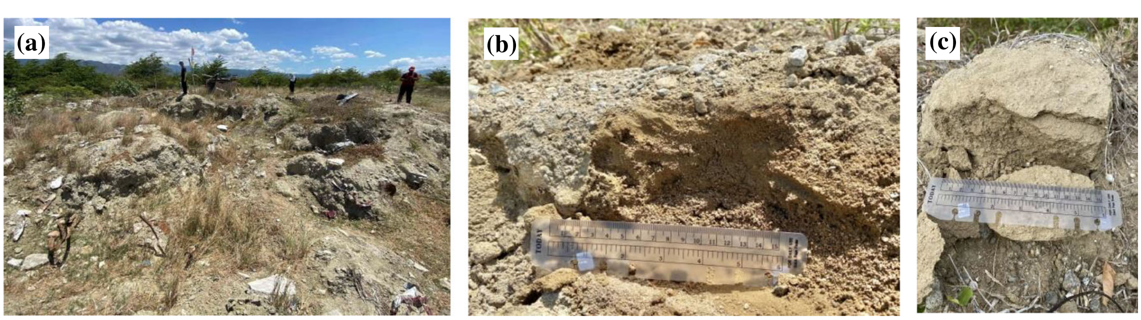

Fig. 8 **a**. A site with big eruptions of sands during earthquake based on the interviews with Witnesses G and H. The location was near District Office of Petobo (Kantor Kelurahan Petobo). **b**, **c** Exposed sands as evidences of soil liquefaction

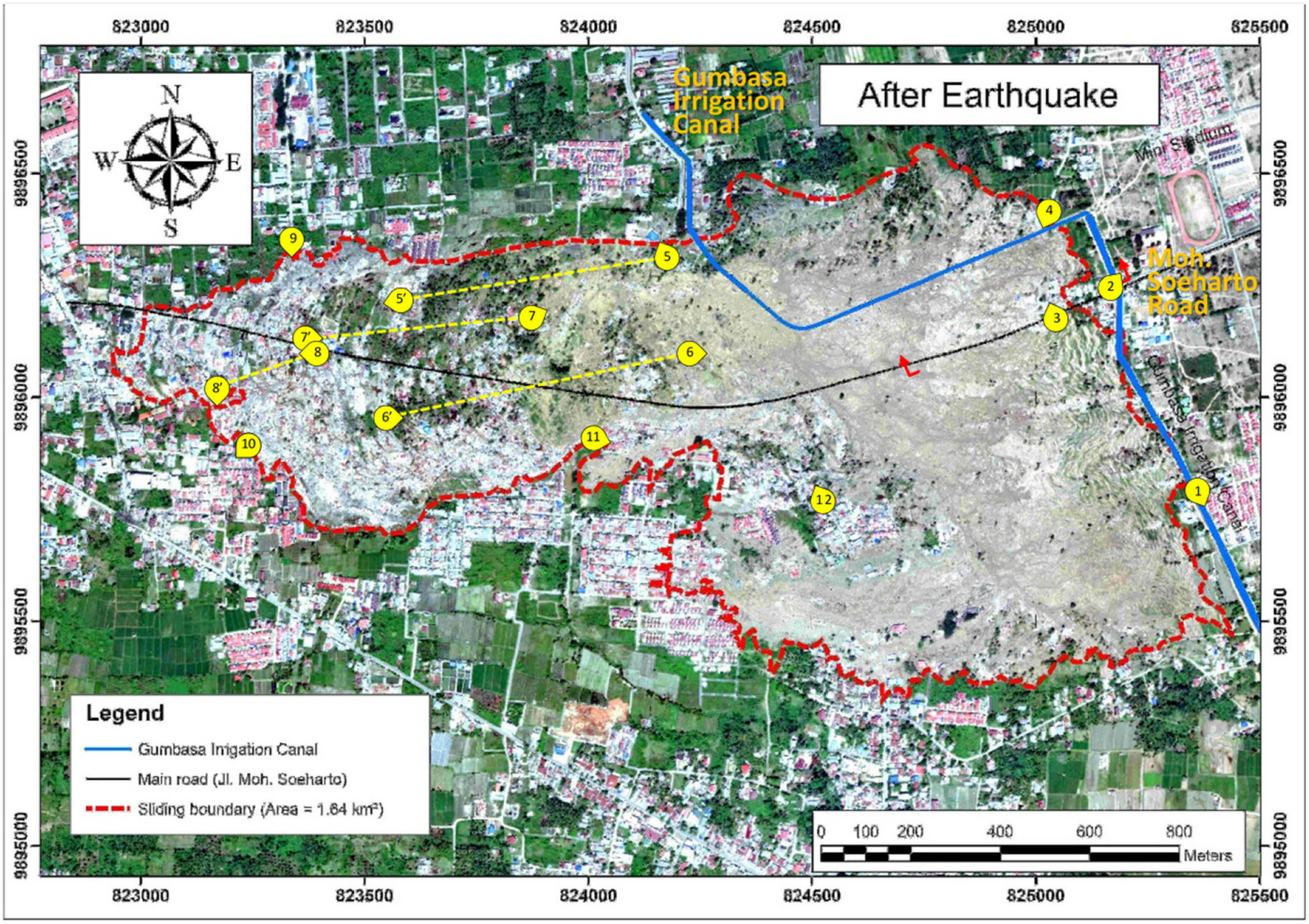

Fig. 9 Locations of key features at Petobo site for pre- and post-slide comparison, with also the location of mapped section along Moh. Soeharto road discussed in the later part of this paper. The base photo is taken from Google Earth satellite image of 2018.10.02

would be submerged at least by water about 30–50 cm above the soil surface for plantation purposes. Furthermore, the intensive irrigation systems to paddy fields from Gumbasa canal would constantly supply the local ground water tables under the paddy fields. In our opinion, the rainfall would appear to not really affect the increase of ground water table under the paddy fields as reference to Fig. 14, which clearly indicates the absence of rain a week before the flowslide occurred.

In view of mostly unlined Gumbasa irrigation canal along eastern boundary of Petobo area and a long plantation period of wet paddy fields, the underground soils were easily saturated causing localised raised ground water tables. The localised high groundwater tables in downstream side of Gumbasa canal and under the paddy fields to the eastern portion of the Petobo site would have had a significant contribution to the severe liquefaction phenomena observed onsite during the earthquake.

It was noticed during our site visit where northern section of the irrigation canal had been completely swept away during the slide. It was also observed a different type of failure along the east periphery of Gumbasa irrigation canal where a big head scrap was formed. These areas would appear to be the uppermost portion of Petobo slide as we could see a series of tensile cracking parallel to the prominent scarp along with the irrigation canal.

The disappeared water from the canal during the earthquake would have played an important role on ground failure. We notice scarps or longitudinal cracks in the unlined canal would have facilitated the conveyance of water into the downstream liquefiable sandy layers and maintained high pore pressures in the layers generated by the shaking. Hence, the downstream slopes could have been sliding for some durations and with large distances.

Observed morphological features along Moh. Soeharto road

The research team had conducted a detailed mapping on the surface along the east section of Moh. Soeharto road, to examine phenomena of the ground that would help the characterisation of morphological features and zonation of the site as well as our understanding on the initiation and process of sliding due to liquefaction of this earthquake incident. The mapping was started approximately 10 m east of Gumbasa irrigation canal and headed westwards along the road with a distance of about 520 m, accounted for roughly 1/4 of the length of Moh. Soeharto road that passed longitudinally (from east to west) across the sliding area. Figure 15 illustrates results of the mapping and Fig. 16 shows associated photos taken along the road with the numbers marked on the mapped sketch. Location of the mapped section is indicated in Fig. 9 and Fig. 19.

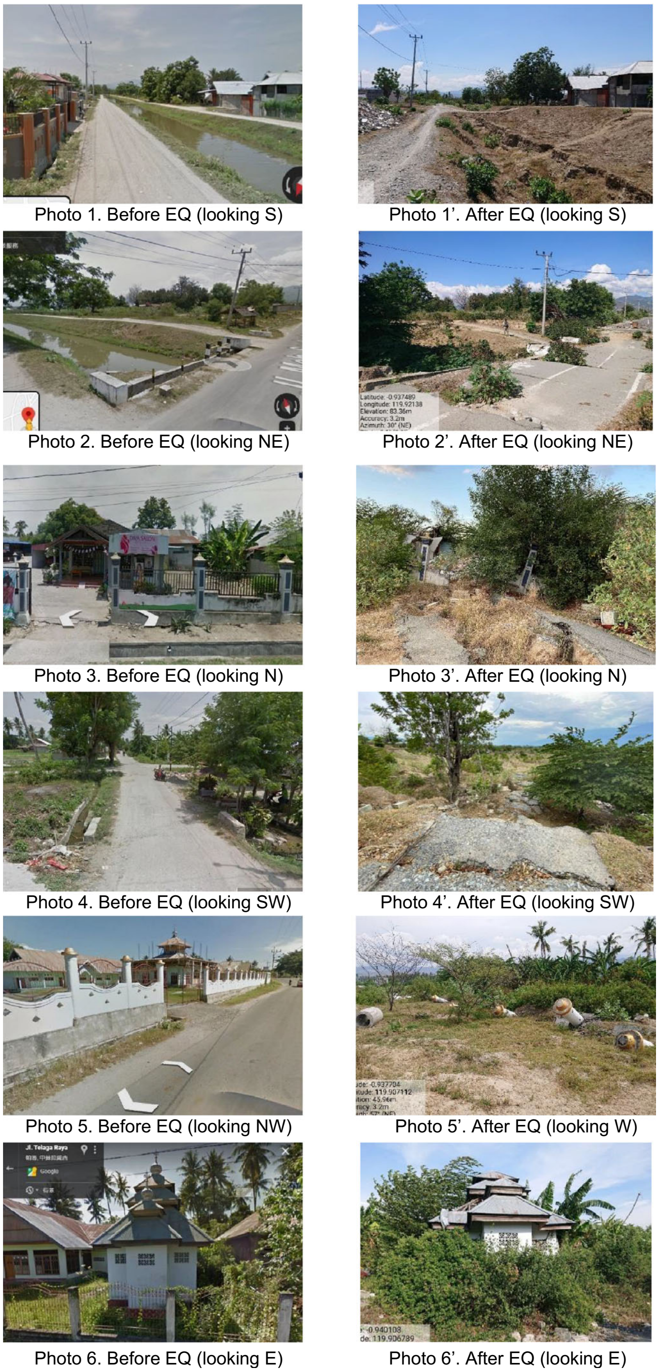

Fig. 10 Photo pairs showing some key features at Petobo site before and after the earthquake. Pre-earthquake photos are captured from Google street view. Locations of the photo pairs are indicated in the previous figure

Fig. 10 (continued)

To the east of starting point (Mileage 0), the pavement of Moh. Soeharto road was almost intact (Photo 1; Fig. 16). However, several fractures and slippages were observed to the west and along the road up to a mileage of about 30 m (Photos 2–4; Fig. 16). The surface cracking became scarce until a mileage of 130 m (Photos 5 and 6; Fig. 16). Then a serious slippage was apparent with a head scarp of 3 m high (Photos 7–10; Fig. 16), an indication where the slide had initiated. In the subsequent mapping range with Mileages 130–290 m, the ground elevations subsided approximately 6 m, on which the surface was extremely rugged, fractured and filled with extruded sands (Photos 11–24; Fig. 16).

Within this range of mapping, we noticed several earthen ridges of 1~2 m high, an example shown in Photo 12 (Fig. 16), which were observed periodically for approximately 10~20 m distance apart. This phenomenon would appear to be in relation to the testimonies by Witnesses G, K, L and M, who had indicated a wavy form of ground sliding, with vertical amplitudes of 1.5~2 m and travelling distances of around 15 m (Table 1). In view of the locations of witnesses during the earthquake, we expect these peoples might have been experiencing a liquefaction spreading

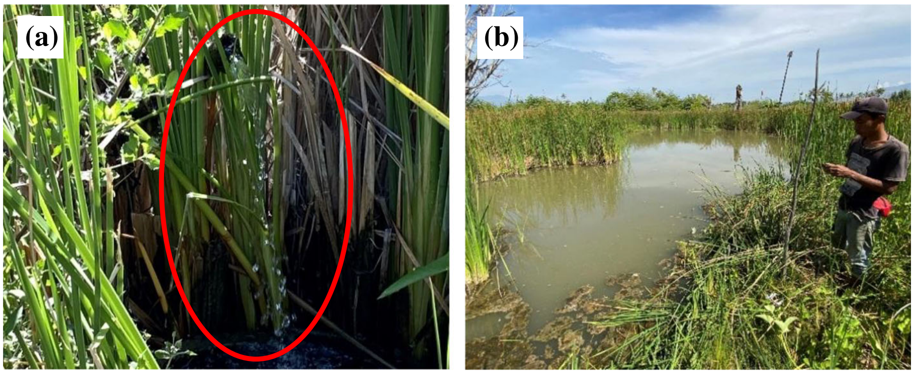

Fig. 11 **a** The presence of artesian waters in the flowslide area. **b** A swamp with ponded water in the middle part of the sliding area

during the earthquake shaking. Photos 18, 20–23 (Fig. 16) are indicative of tearing, tilting and settling of houses and water pipes as a result of the spreading of the ground.

In the subsequent mapping range with Mileages 290~492 m, the ground elevations once again dropped by additional 2~4 m. However, the surface appeared to be less rugged, more gentle, and more abundant with extruded sands on the ground (Photo 25; Fig. 16). The observed phenomena in this mapping range would suggest the ground might have liquefied significantly during the shaking and flowed further to the west (lower lands) after the earthquake. Photos 26 and 27 (Fig. 16) show the forefront of the liquefaction flow.

For the lands further to the west of Mileage 492 m, the ground elevation decreased substantially by 6 m or more. The ground

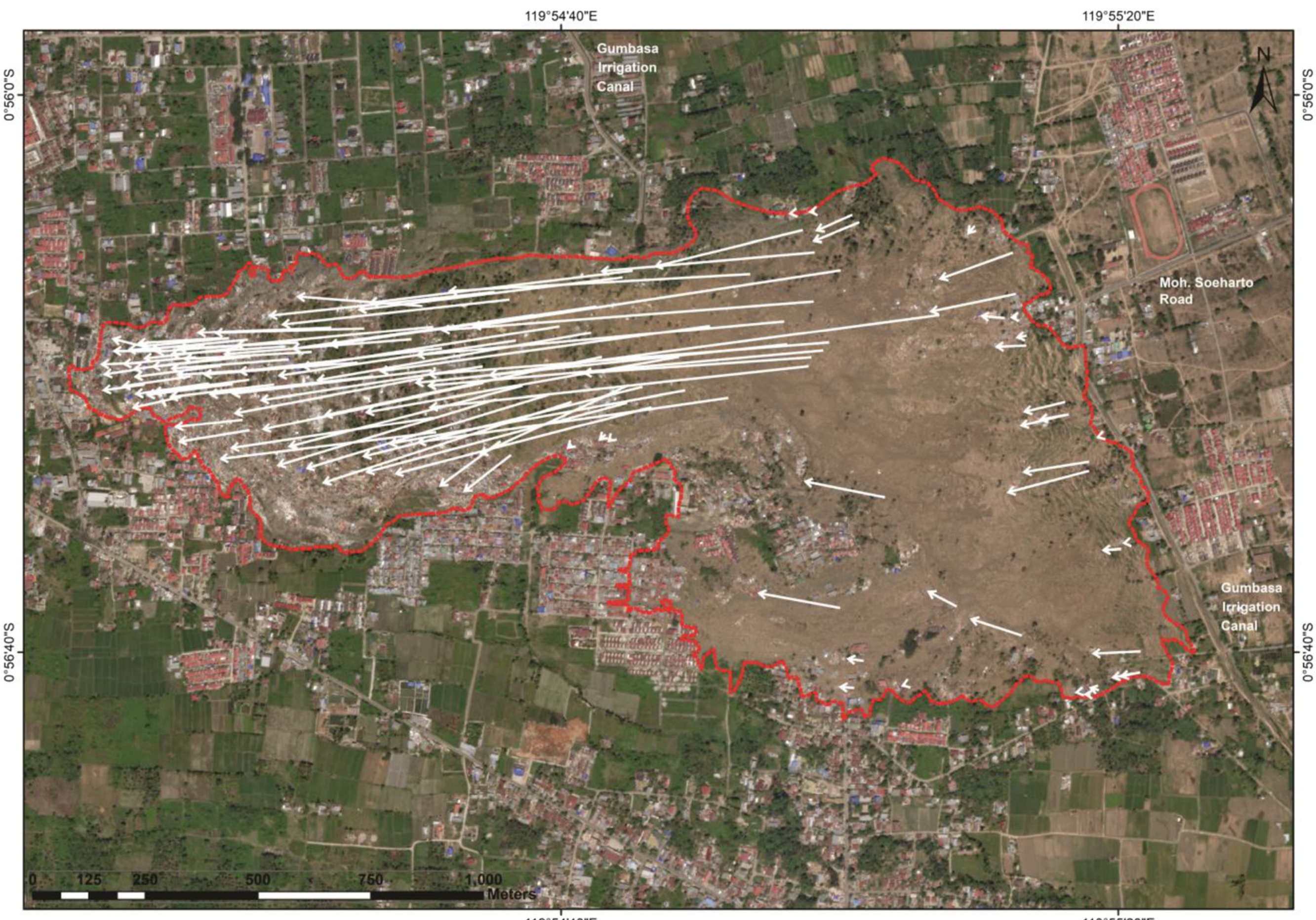

Fig. 12 Displacement vectors of surface objects identified by onsite investigation as well as based on Google Earth satellite images before the after the earthquake. The white arrows are the direction of displacements. Base photo is taken from Google Earth satellite image of 2019.05.23

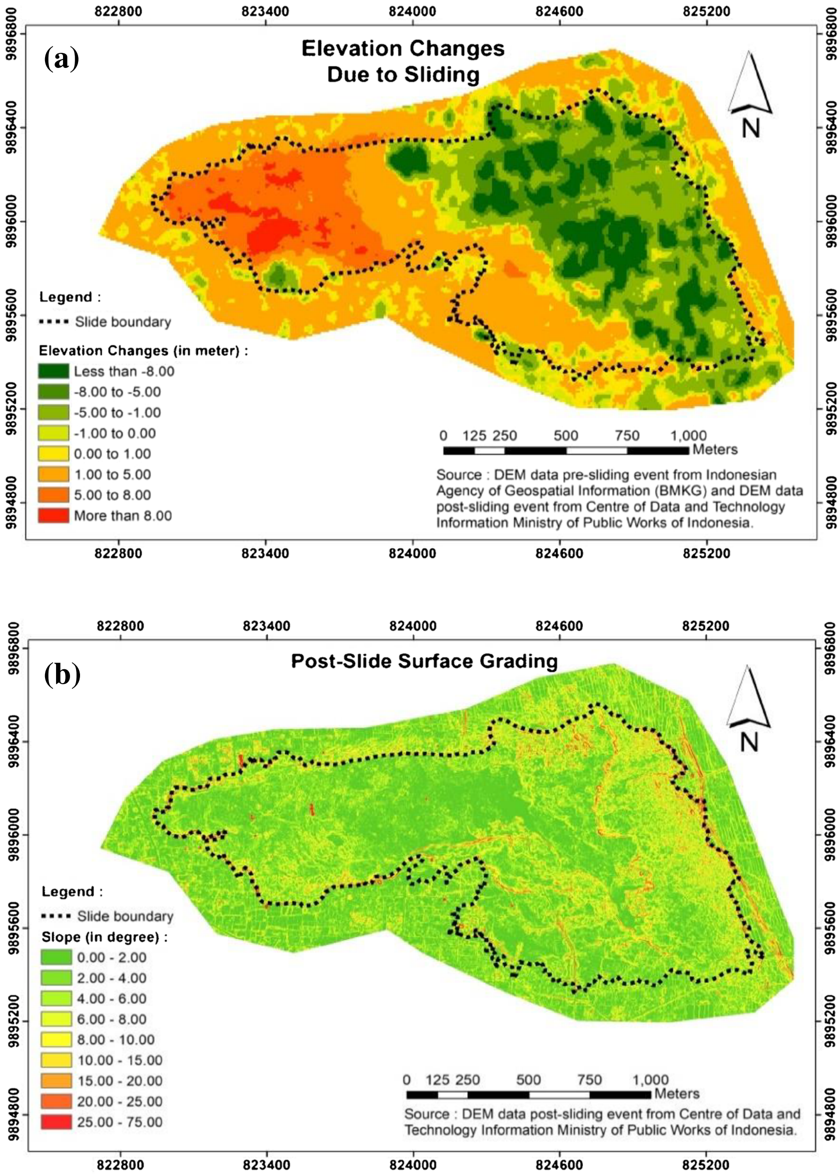

Fig. 13 **a** The elevation changes due to sliding. **b** The grading of ground surface after the earthquake. The elevation changes varied approximately between −8 and 8 m. In the eastern part, the elevation dropped down more than 8 m (green colour) and in the western part raised more than 8 m (red colour). Before the earthquake the surface grading in the study area was gentle, with an angle of about 2°. After the earthquake, however, the surface grading changed locally, with an inclination of up to 25° in eastern part. In the middle part, the ground surface was generally flat, but then became rougher again to the western part of the flowslide area

became more flat, but wet, swampy and full of aquatic plants that had prevented the research team to approach further. Photos 28–32 (Fig. 16) show distant views of the lower lands. As seen, the ground was exposed with sands, water ponds and aquatic plants. These areas were also suggested a separate stage of liquefaction flow that followed subsequently the previous flow stage as identified in Mileages 290~492 m.

Morphological zonation of Petobo sliding area

Based on results of mapping on Moh. Soeharto road, the observed surface features could be classified into several morphological types. These morphological features might have been in relation to the initiation and the progress of sliding in Petobo during the earthquake. To be consistent with the terminologies commonly adopted in geotechnical engineering as indicated by Hungr et al. (2014), we propose four types of morphological features for this study, as depicted in the schematic illustration shown in Fig. 17. The associated definitions of the morphological features are addressed below.

Ground slide “Ground slide” (GS) is a phenomenon of failure by the slippage of coherent earthen materials, as identified between Mileages 0~130 m of the mapped section (Fig. 15) and illustrated in Fig. 17. Generally, cracks or scarps are visible on the surface, which

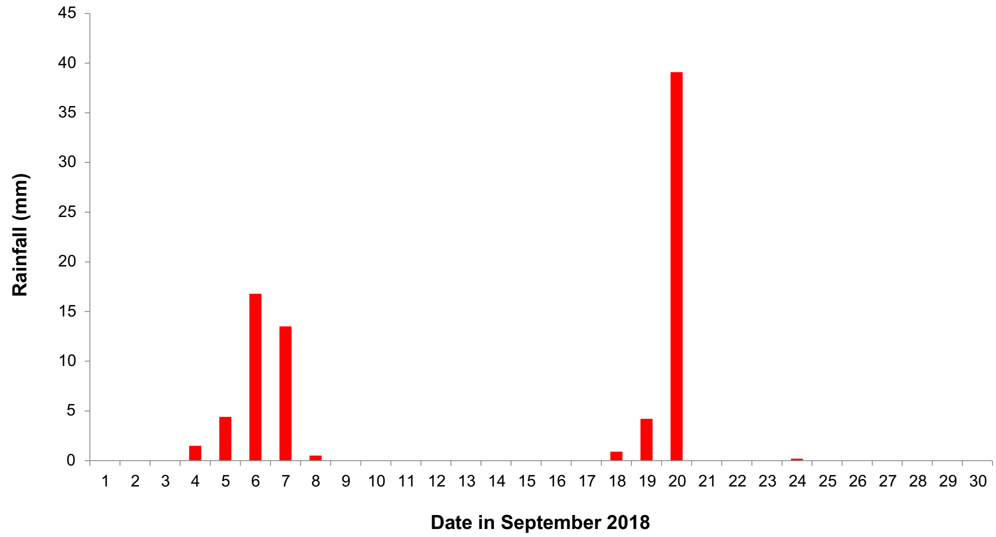

Fig. 14 Daily rainfall intensity during September 2018 in study area which clearly indicates the absence of rain a week before the flowslide occurred (Meteorological, Climatological and Geophysical Agency 2021)

divide the ground into several chunky earthen blocks. Ground slides may be triggered by a sudden increase in the inertia of ground, such as earthquake shaking, and/or due to a decrease or loss of the downslope supports, such as a cut at slope toe. The sliding/slip surfaces are basically passing through the intact earthen mass, which is not liquefied during the ground shaking.

Liquefaction spread "Liquefaction spread" (LS) is a phenomenon of failure by the laterally cyclic spreading of earthen crust due to underneath liquefied soils in the process of shaking, as appeared in the mapped section between Mileages 130~290 m (Fig. 15) and in Fig. 17. Surface manifestations of liquefaction spread may include a series of linear cracks or earthen peaks (ridges) with broken and lowered ground sideways (i.e., horst and graben terrain). Surface structures may be destroyed, tilted or distorted (elongated) as a result of the cyclic movements and spreading of earthen crust. Extruded liquefied sands may be found on the ground in areas of cracking and peaking. Liquefaction spreads are triggered by the liquefaction of underneath soils. Due to cyclic nature of shaking, the earthen crust will move back and forth laterally, resulting in a gradual spreading, and a lowering height as well, in a direction with less lateral restraints.

Liquefaction flow "Liquefaction flow" (LF) is a phenomenon of failure by the monotonic sliding or flowing of fully liquefied earthen materials, occurring primarily after the earthquake shaking, as depicted in Mileages 290~492 m and beyond of the mapped section (Fig. 15) and in Fig. 17. The ground surface of liquefaction flows is usually uneven and bumpy with extensive exposures of liquefied sands. Structures on the liquefied surface may sink (buried), tilt or float with the flow for a large distance. Liquefaction flows usually occur in an inclined ground in which the earthen materials are fully saturated and liquefied due to ground shaking. As a result of the gravity and/or additional driving forces from upper sides of the slope, such as by ground slips or liquefaction spreads, the liquefied earthen materials may start flowing downslope following the shaking. Liquefaction flow may proceed in stages, as shown in Fig. 17, depending on the viscosity of liquefied earthen materials, the degree of liquefaction that sliding mass can sustain, the history of shaking, and the geometry of ground and sliding surfaces, etc.

Debris Flood "Debris flood" (DF) is a phenomenon of failure, similar to "liquefaction flow", by the monotonic sliding or flowing of liquefied earthen materials mixed with construction debris. However, the debris flood is different with the aspect that the existing ground of flood area is generally non-liquefied (i.e., stable) but covered with liquefied soils and debris from the upstream side (Fig. 17). The flowing earthen soils mixed with construction debris are massive and mighty, and are destructive for the structures on the existing ground. Surface manifestations of the debris flood are characterised by the irregular surface of liquefied earthen materials and debris, the destroyed existing and transported structures and the elevated ground surface as opposed to the adjacent areas unaffected by the flooding. Causes of debris floods are similar to those of liquefaction flows. The earthen materials on upstream side first fully liquefy during earthquake shaking, then flow downslope by gravity following the shaking.

The characterised morphological features can generally be visualised through the bird's-eye views of drone photos by Soralump (2018). As shown in Fig. 18 a, a ground slide (GS) zone is found along Moh. Soeharto road adjacent to the east boundary of Petobo slide, where cracks and slips are visible on the surface and divide the ground into several earthen blocks. Figure 18 b indicates the zones of liquefaction spread (LS), liquefaction flow (LF) and debris flood (DF) on the south-eastern portion of the sliding area. Liquefaction spread is signified by a series of curvilinear features on the ground, as a result of cyclic spreading during shaking. The liquefaction flow emerges next to the downstream side of the spread zone, with relatively smoother ground surface, due to monotonic flow after the shaking. Debris flood would be the liquefied soils that flow over and inundate the existing ground, as seen in the far side of the photo (Fig. 18b), where the surroundings of a small area with existing houses had been destroyed and buried in the debris.

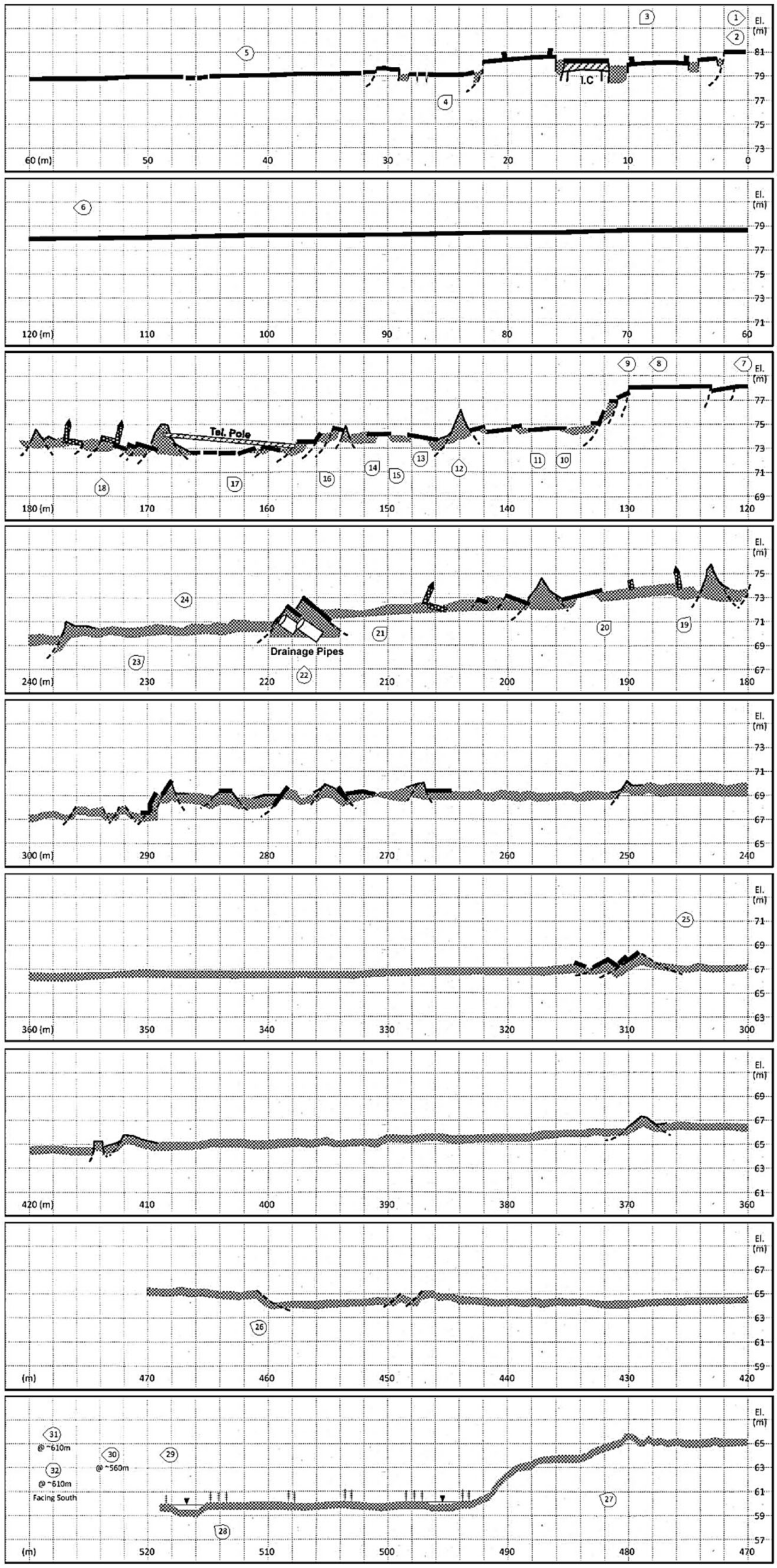

Fig. 15 Mapping of east section of Moh. Soeharto road in Petobo sliding area

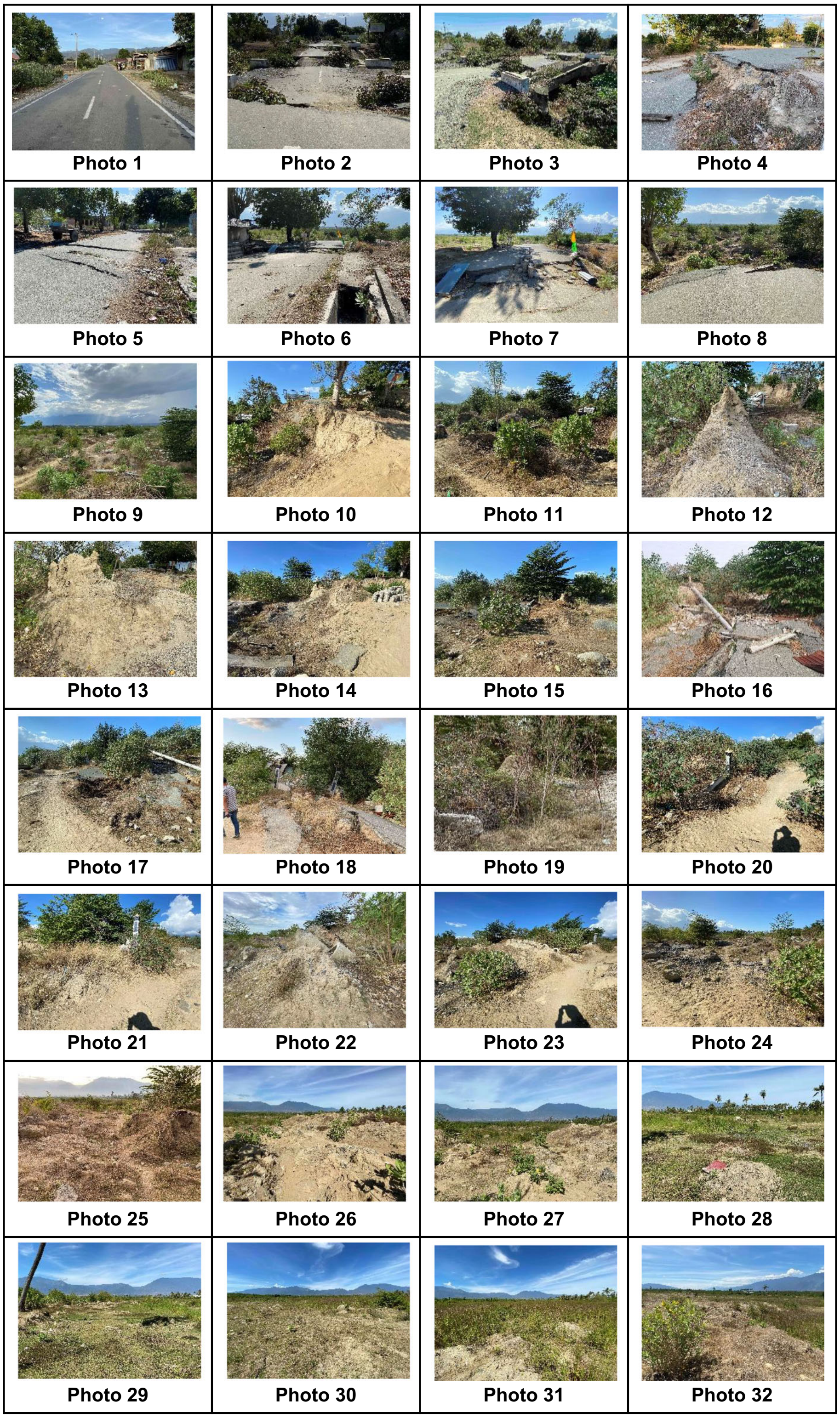

Fig. 16 Associated photos as indicated in the mapping sketch along Moh. Soeharto road to the east of Petobo sliding area

The characterised and defined morphological features, mainly based upon the mapping along Moh. Soeharto road, are further applied for the zonation of entire sliding area in Petobo, and the results are shown in Figs. 19 and 20. As seen in Fig. 19, the ground slide (GS) falls in a narrow zone approximately along Gumbasa irrigation canal and in adjacent to the eastern boundary of the sliding area. Photos 1 and 2 of Fig. 20 show representative features (i.e. cracks and slides) of the ground slide surface. Liquefaction spread (LS) zone is neighbouring to the west of GS zone, with a width of about 300 m in east-west direction. Photos 3 and 4 of Fig.

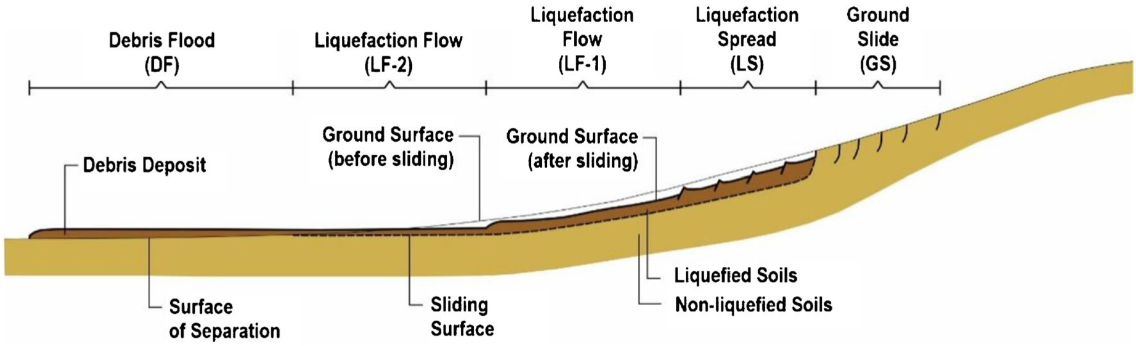

Fig. 17 Schematic illustration of types of morphological zonation observed in Petobo sliding area due to 2018 Palu-Donggala earthquake

20 indicate the linear pattern of earthen ridges and cracks observed on the spreading ground.

Liquefaction flow (LF) zones are further to the west of the LS zone. As seen in Photos 5 and 6 of Fig. 20, the liquefaction flow surface is generally uneven and bumpy with extensive exposures of liquefied sands. During onsite investigation, we observed the liquefaction flow area could be subdivided into several small zones or stages, as depicted in Fig. 19. It is speculated that the causes might have been due to the changes in viscosity of liquefied soils during slide, the reoccurrence of post-shakings to the site or some other reasons yet to be found.

Debris flood (DF) zones are bordered to the west of LF zones, near the toes to the west and south of the sliding area (Fig. 19). The ground surface of DF zones was covered by the liquefied soils and construction debris from the upstream side, and raised up its elevation up to about 8 m from the existing ground. Photos 7–12 of Fig. 20 show the debris deposits on the east and south strands of the slide, with a mixed composition of liquefied soils and construction remains, as well as elevated grounds as compared with the adjacent buildings unaffected by the debris flooding.

Concluding remarks

This paper discusses results of onsite reconnaissance of Petobo liquefaction flowslide area due to 2018.9.28, M_w7.5, Palu-Donggala Indonesia earthquake, with emphases on the characterisation of morphological features observed on the ground and the implication of potential sliding mechanism of the failure. Major findings of this study are summarised below:

(1) Based on comparisons of topography and surface features before and after the earthquake, the Petobo flowslide had occurred on the ground of low relief (~2°) and slid generally from east to west direction. The area of sliding is approximately 1.64 km^2 in size, with a longitudinal distance of about 2.2 km and a lateral width of about 1.3 km.

(2) The eastern portion of the sliding area, bordered Gumbasa irrigation cannel and a EW width of around 300 m, had slid with a distance of <200 m and subsided by 5~8 m. The middle portion of the sliding area, a EW width of around 1100 m, had slid with a distance of 500~1000 m. The ground surface of this portion had changed by settling >7 m in the east side to raising 1~4 m in the west side. The western portion of the sliding area, a EW width of around 800 m, had slid with a distance of <400 m and raised by 4~10 m.

(3) Interviews with onsite witnesses revealed the initiation of sliding might have had started in sequence during and after the shaking, with most likely scenario by starting from eastern boundary, proceeding to southeast, then towards north portion of the sliding area. The witnesses situated in the eastern portion of the area at the time of earthquake had indicated a wavy form of sliding, which is speculated as these people had been experiencing a severe liquefaction spreading during the shaking. Based on their observations on the ground movement, we estimate the sliding velocity of the ground might have been in the range of 2.5~5 km/h, or equivalently a speed of walking or jagging.

(4) Witnesses interviewed had indicated the phenomena of soil liquefaction during and after the shaking. Sand boils were

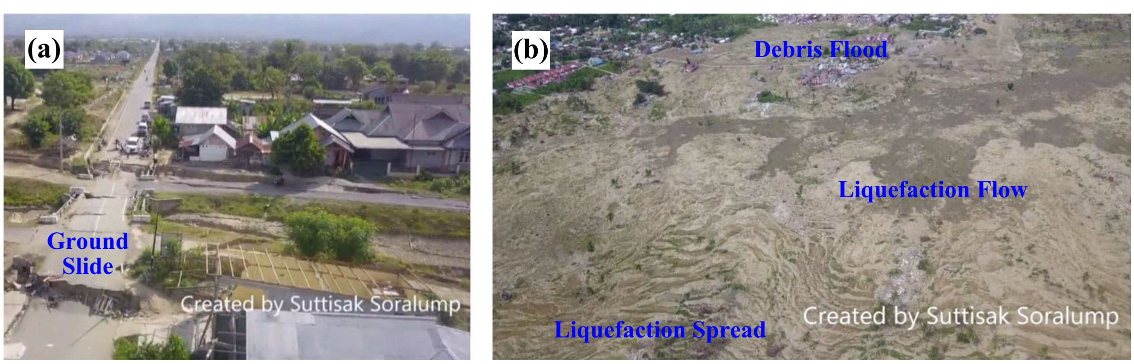

Fig. 18 Morphological features observed from the snapshots of drone videos by Soralump (2018). **a** Photo of the ground slide feature along Moh. Soeharto road to the east boundary of Petobo slide (facing east). **b** Photo of the features of liquefaction spread, liquefaction flow and debris flood on the south-eastern portion of Petobo slide (facing west)

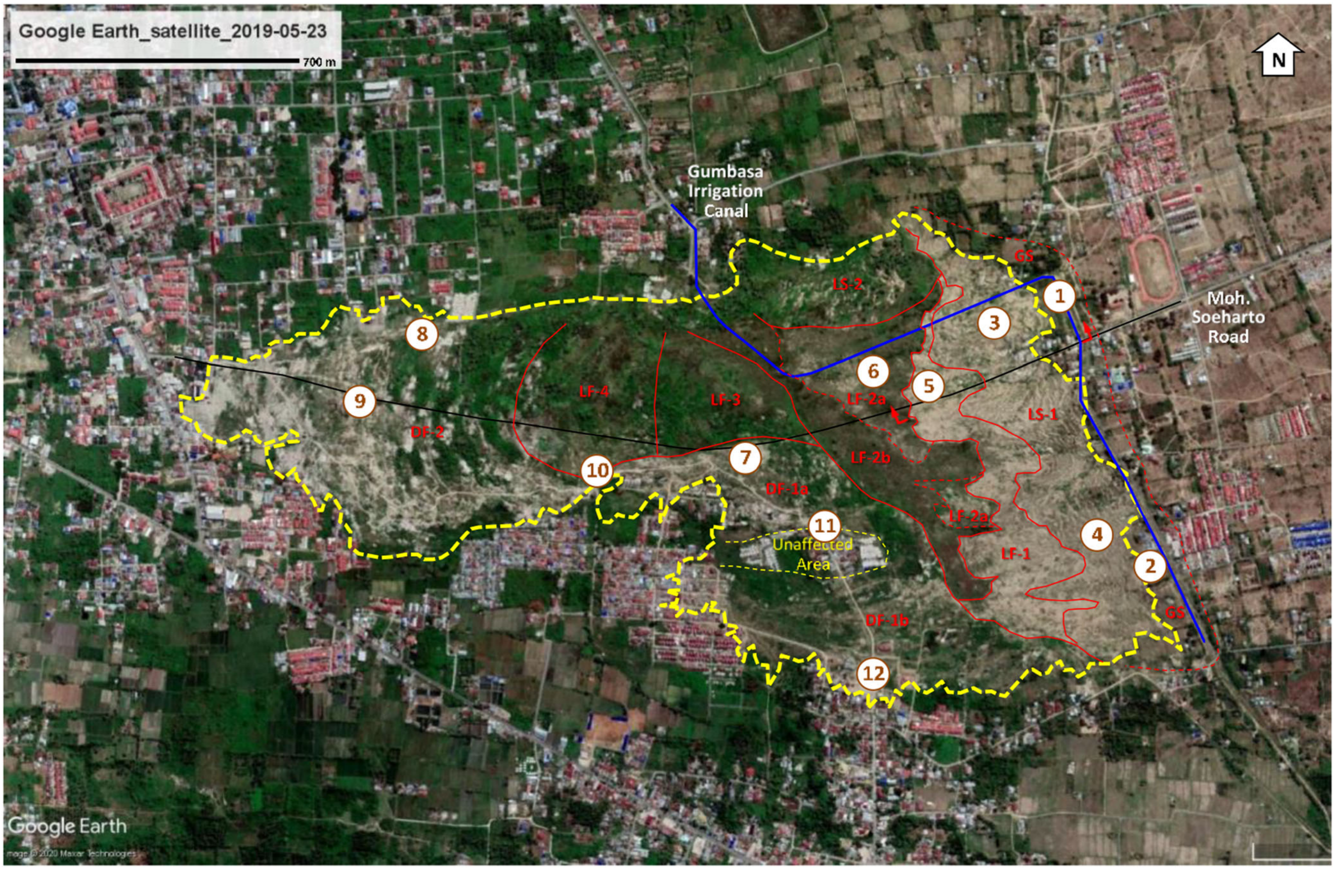

Fig. 19 Zonation of morphological features at Petobo sliding area, with locations of photos of representative morphologic features showing in the subsequent figure, as well as the location of mapped section along Moh. Soeharto road

Fig. 20 Photos of associated morphological features identified on Petobo sliding area, with locations indicated on the previous figure of morphological zonation

observed in a lot of places with eruption heights of up to about 2 m and 5 m, respectively, in the NE and SE portions of the sliding area. After the sliding, the ground was wet and soft, and in some places ponded with water of 1 m high. It took months for the ponded lands to be gradually retreated.

(5) The morphological features of the ground have been carefully mapped along the east section of Moh. Soeharto road, which passes from east to west across the sliding area. Four morphological features are characterised and defined, including ground slide (GS), liquefaction spread (LS), liquefaction flow (LF) and debris flood (DF). These morphological features might have in relation to the initiation and the progress of sliding in Petobo during and after the earthquake.

(6) Ground slide (GS) occurs by slippages in coherent earthen materials which are not liquefied during the shaking. Liquefaction spread (LS) is caused by laterally cyclic spreading of earthen crust as a result of liquefaction of underneath soils in the process of shaking. A curvilinear pattern of a series of earthen ridges would appear the signature of the spreading. Liquefaction flow (LF) is due to monotonic sliding or flowing of fully liquefied soils occurred primarily after the shaking. The ground surface is usually uneven and bumpy, with extensive exposures of liquefied soils. Debris flood (DF) is similar to LF by the monotonic sliding or flowing of liquefied soils and mixed with construction debris. The debris flood is different, however, with the aspect that the existing ground of DF is generally non-liquefied but covered by liquefied materials from upstream side, which would destruct the existing buildings, mix with construction debris, and pile up on the existing ground.

(7) Based on categorised features, the Petobo sliding area could be divided into several morphological zones. The GS falls in a narrow zone approximately along Gumbasa canal in adjacent to the eastern boundary of the sliding area. The LS zone is neighbouring to the west of GS zone, with an EW width of about 300 m. The LF zone is further to the west of LS zone, which expends around 1100 m from east to west and can be subdivided into several small zones. These small zones or stages might have been due to the changes in viscosity of liquefied flow, the reoccurrence of post-shocks to the site or some other reasons yet to be found. The DF zones are bordered to the west or south of LF zones. The EW width for the DF zone in the toe area is around 800 m.

(8) The unlined Gumbasa irrigation canal and the widespread paddy fields in the eastern portion of the sliding would have been causative to the significant liquefaction flowslide in Petobo. Due to a prolonged infiltration of irrigation water, the groundwater levels under these areas would be locally raised and increase liquefaction and flowslide potential.

(9) In view of observations of onsite morphological features and interviews of witnesses of the slide, causes of the flowslide might have been due to the following: (a) the onsite silty sand and sandy silt of the alluvial fan, flood and river deposits that were prone to liquefaction as shaking; (b) highly raised groundwater levels near the crest and the eastern portion of the Petobo area (as a result of unlined Gumbasa canal and wet paddy fields) that increased liquefaction susceptibility of these areas; and (c) strong shaking by the severe M_w7.5 earthquake occurred along Palu-Koro fault that triggered the liquefaction of the ground. The process of the flowslide would appear to be initiated by the extensive liquefaction of sandy soils underneath the crust of LS zone and the soils in the LF zones as a result of the strong shaking. Due to the spreading, the earthen crust in LS zone would gradually be elongated and lowered, which would further trigger the slippages in GS zone and gradually drive the slide or flow in the LF zones, during and after the shaking. With the advances of liquefaction flow, the flowing debris would encounter and inundate the ground without liquefaction, and would become the DF zone.

(10) The above speculations on the causes and mechanism of the slide are based on our onsite observations and witness interviews, which remained uncertain and further verifications would be needed. It would be suggested to conduct thorough subsurface investigations and laboratory testing, as well as physical modelling or numerical simulations, etc. to confirm the findings and speculations of the current study.

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Author contribution

R. K. and M. C. conceived this research and designed the study; T. C. U., R. H., M. H. F. and G. A. P. participated in the field investigations and interpretations of the data; R. K. and M. C. wrote the paper and participated in the associated revisions. All authors read and approved the final manuscript.

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Data availability

The authors declare that the data supporting the findings of this study are available within the article, except for the supporting Lidar data from Centre of Data and Information Technology, Ministry of Public Works and Public Housing of the Republic of Indonesia which are not publicly available. The data for this project are confidential, but may be obtained with use agreements with the Centre of Data and Information Technology, Ministry of Public Works and Public Housing of the Republic of Indonesia.

Code availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Competing interests The authors declare no competing interests.

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