Subsurface Study of Flowslide Liquefaction in Petobo, Palu, Indonesia

by RINI KUSUMAWARDANI

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Abstract A huge flowslide due to liquefaction occurred at Petobo on September 28, 2018. Many building structures were collapsed, tilted, buried, or moved away up to a distance of 800 m or more. Flowslide occurred at slopes of around 3° and the affected area was approximately 1.64 km^2. Magnitude and intensity of earthquake shaking, soil and groundwater conditions etc., would have contributed to the phenomena of the flowslide. Drilling, SPT with hammer energy measurements, laboratory testing on grain-size distributions and groundwater monitoring were performed after the incident. This paper discusses subsurface conditions and the assessment of liquefaction susceptibility. The geometry of ground surface was developed based on topographic survey and DTM data. Results show the materials at Petobo site consist primarily of loose silty sands and sandy silts in the middle and the debris flood areas. At the crown, the soils are mostly gravelly sands or sandy gravels. The groundwater is generally very close to the surface in the middle and the toe areas. The liquefaction susceptibility was assessed by Seed/NCEER method. At BH-1, located near the crown, liquefaction would be more susceptible in layers with depth generally more than 10 m. In the middle areas, BH-2 would likely be liquefied due to the earthquake at depth of less than 10 m. At BH-3, situated near the toe, the liquefaction susceptibility appears low, where only few separated depths are computed with low factors of safety.

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1 Introduction

Soil liquefaction is a phenomenon of saturated sands become liquefied under transient or repeated load. When transient or repeated load is applied, the saturated sand could lose its strength or stiffness and behave like a liquid material. The increase in pore water pressure and decrease in effective strength are the main reasons for strength loss [1, 2]. Liquefaction would cause catastrophic damages to various buildings and infrastructures. Liquefaction is identified through the following phenomena, such as sand boils, lateral spreads, settlement, uplift, sinking, tilting, and buried structures, or even landslides.

During Palu Donggala earthquake (Mw = 7.5) on 28 September 2018, Petobo village, as seen in Fig. 1a, has suffered a dramatic flow slide due to liquefaction [4, 5]. Hundreds of buildings collapsed, tilted, buried, and moved away up to 800 m or more. The flowslide occurred at slopes of around 3°, with affected area of approximately 1.64 km^2 (Fig. 1b).

For determining subsurface conditions in Petobo, the site characterization activities include three boreholes, SPTs (Standard Penetration Test), and grain-size analyses. Figure 1b shows the study area and borehole locations, which are near the Moh. Soeharto road of the site. SPTs were conducted in the boreholes at a depth interval of 1.5 m. Additionally, grain-size as well as physical indices of soils were tested on the split spoon samples. Groundwater levels were measured weekly subsequently after the drilling.

This paper discusses the subsurface soil profile and the speculated of potential slip surface in the Petobo flowslide area. The soil profile was developed based on the boreholes, and liquefaction susceptibility zones were estimated by the Seed/NCEER method [6].

2 Seismicity

Palu city is situated on the island of Sulawesi, which is the capital of Central Sulawesi. Donggala and Sigi regencies border the northern and southern parts of Palu City. The eastern and western regions are bounded by Parigi Moutong and Donggala regencies and by Sigi and Donggala regencies [7].

Palu city is also traversed by Palu-Koro fault (PKF), which is well-known as one of Sulawesi's most active faults. In the past, several earthquakes included the 2018 Palu-Donggala earthquake, had centered on or near this fault (see Fig. 1a). PKF divides the Sulawesi island into Makassar and North Sula regions. The fault length is approximately 500 km, with an estimated slip rate of 34 mm/year [8].

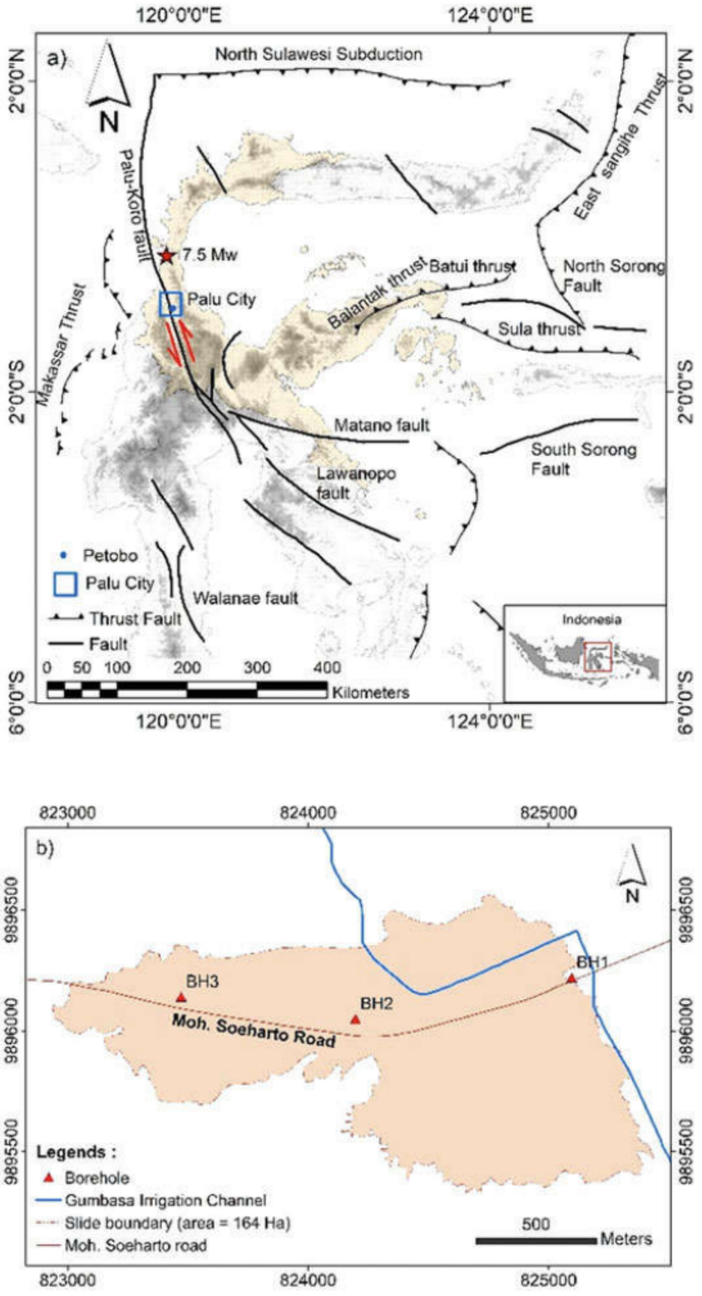

Fig. 1 **a** Regional tectonic map in Sulawesi, Indonesia and surrounding taken from [3]. Red star, blue rectangle and blue dot indicate the epicentre of main shock, locations of Palu city and Petobo village, respectively. **b** Locations of boreholes (BH-1, BH-2, and BH-3) at the Petobo flow slide area

During 2018 Palu-Donggala earthquake, MPSI (Station Mapaga, Sulawesi), located 66 km north of the mainshock, recorded a maximum peak ground acceleration (PGA) of 95.057 gal (0.142 g) in N direction [9]. However, the station of BMKG and JICA, located in Balaroa, recorded a PGA of 333 gal (0.34 g) [10].

3 Site Investigations

3.1 Soil Profile

Three boreholes (BH-1, BH-2, and BH-3) with SPTs were conducted in the slide area along Moh. Soeharto road. The soils were explored to a depth of 20–24 m. Table 1 shows the results of SPT-N and hammer energy ratio (ER) measurements. The SPT-N value and the results of ER varied about 3–71 and 58.3–77.7%, respectively. Results of the soil profiles are shown in Fig. 2.

Table 1 The SPT-N value and Energy measurements

Borehole No	SPT-N	ER (%)	ER average (%)
BH-1	8–71	59–77.7	70.9
BH-2	3–55	63.5–75.6	70.4
BH-3	4–44	58.3–69.7	64.8

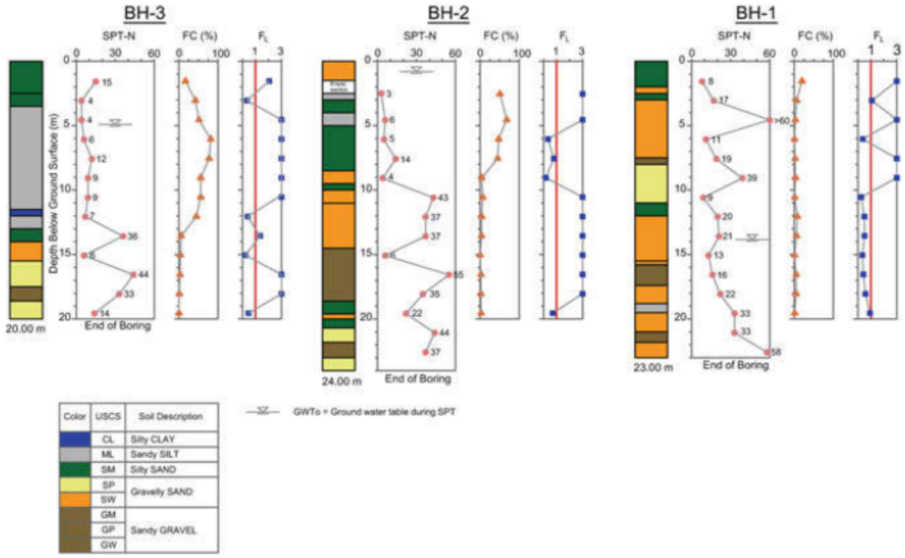

Fig. 2 SPT blow counts, fine contents and the computed safety factor in the boreholes

The soil layer in BH-1 are dominated by sand and gravel. Loose soils with N values of approximately 8−17 have been found at the top 4 m. Below this level, soils become denser with N values between 7−60. Fines content ranges from 1−20%.

The soil layer in BH-2 consists of silt and sand with fines content range of 40−70% for the top 8.5 m. N values vary from 3−14. The soils below 8.5 m are sand and gravel with N values ranged from 22−55.

At BH-3, debris materials were found at the top 2.5 m. Below the debris materials and down to 13 m deep, soils are dominated by loose to medium dense sand and silt with fines content 42−79%. N values vary from 4−12. The soil stratum below 13 m consists of sand and gravel with N values ranged 6−44.

A comparison of SPT blow counts and fines content shows that fines content appears to have a relationship with the N value. At BH-2 and BH-3 with fines content of > 20%, N values would be less than 10. In contrast, BH-1 has a fines content of < 20% and the N values would be more than 10.

3.2 Groundwater Monitoring

Groundwater levels were monitored during drilling and periodically after the drilling for a period started from 18 March 2020 to 24 March 2021.

During drilling, groundwater tables (GWTo) were measured. The groundwater tables at BH-1, BH-2, and BH-3 were−13.83, −0.82, and −4.91 m, respectively, from the ground surface.

As seen in Table 2, the average groundwater level (GWT) after drilling for BH-1, BH-2, and BH-3 are −13.18, −0.05, −3.83 m, respectively. The monitored groundwater levels of the boreholes appeared only minor changes with the values measured during the drilling.

At BH-1, located near Gumbasa irrigation canal, the GWT was found approximately 13−14 m below the ground surface. Although, three weeks after the Petobo flowslide incident, Kiyota et al. [10] observed that the GWT at area near the Gumbasa Irrigation canal was relatively close to the ground. In this case, Gumbasa irrigation canal and paddy fields had affected the GWT at this location before and during the earthquake. The water in irrigation canal and paddy fields would seep into the ground and saturate the soil. However, after the slide, Gumbasa irrigation canal dried out and GWT dropped to currently stable level of approximately 14 m below the ground surface.

Table 2 Results of groundwater table measurements (depth from ground surface)

Borehole no	GWTo (m)	Lowest GWT (m)	Average GWT (m)	Highest GWT (m)
BH-1	−13.83	−12.75	−13.18	−13.63
BH-2	−0.82	+0.34	−0.05	−0.38
BH-3	−4.91	−2.60	−3.83	−4.70

The GWT at BH-2 was < 0.5 m below the ground surface. After sliding, many small ponds and swampy areas were found near the BH-2. Based on the characteristics of surface morphology, the area near BH-2 is judged to locate in the liquefaction flow area.

At BH-3, the groundwater table depth was around 4−5 m. In view of the accumulated debris materials of about 2.5 m, the GWT depth before sliding could be less than 3 m.

3.3 Liquefaction Evaluation

The liquefaction susceptibility has been analyzed using the simplified procedure by Seed/NCEER method [6] and spreadsheet program established by [11]. The liquefaction safety factor (F_L) at any depth is defined as the ratio between cyclic resistant ratio of soils *(CRR)* and cyclic stress ratio due to shaking *(CSR)*, expressed as:

$$F_L = CRR/CSR \tag{1}$$

The CSR is computed with equation as:

$$CSR = 0.65 \frac{a_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} r_d \tag{2}$$

where g is the acceleration due to gravity, r_d is a shear stress reduction factor, σ_{v0} is the total vertical overburden stress and σ_{v0} is the effective vertical overburden stress. By using SPT data for clean sands, *CRR* can be expressed as

$$CRR_{M=7.5} = exp\left(\frac{(N_1)_{60}}{14.1} + \left(\frac{(N_1)_{60}}{126}\right)^2 - \left(\frac{(N_1)_{60}}{23.6}\right)^3 + \left(\frac{(N_1)_{60}}{25.4}\right)^4 - 2.8\right) \tag{3}$$

where $CRR_{M=7.5}$ is the cyclic resistance ratio for a $M_w = 7.5$ earthquake and $(N_1)60$ is the corrected SPT value of clean sand. The *CRR* and *CSR* should be adjusted with magnitude scaling factor (MSF) and overburden correction factor (K_σ).

The groundwater level for *CRR* evaluation uses the groundwater level during drilling (GWTo) as suggested by [12]. For analysis of *CSR*, GWT is assigned for BH-1 by assuming 2 m below the ground surface. In view of a high groundwater table that might have been existing during the earthquake, GWTs in BH-2 and BH-3 are assumed the same level as the ground surface. The peak ground acceleration at the ground surface a_{max} is estimated as 0.30 g and the moment magnitude of Mw Palu-Donggala earthquake of 7.5 is adopted.

The computed safety factors are shown in Fig. 2. At BH-1, the soils with high liquefaction potential are at 6 and 11−18 m. Soil classifications for these depth ranges are SP and SW. The grain-size distributions for samples of BH-1 can be seen in Fig. 3a, indicating the soils in this borehole are almost gravel and sand in size. Our onsite observations in the area around BH-1 did not clearly reveal the symptoms for soil liquefaction. However, numerous cracks and down-dropped ground surface are observable on the surface near to BH-1 area, dividing it into several soil blocks. This phenomenon could be triggered by ground shaking and/or lack of downslope support [14].

In BH-2, liquefaction is estimated to have occurred at a depth of 6−9 m, with soil classifications of SW and SM. As shown in Fig. 3b, the soils in this depth are almost silt and sand, and below 9 m then become sand and gravel. Based on our surface observations, flow liquefaction occurs in the location near BH-2. The SW and SM layers of the borehole are believed to have liquefied and the depth of about 9 m is speculated as the slip surface of this flowslide.

At BH-3, the safety factor of less than 1 occurs at depths of 12−15 m, with soil types of SM, ML, and SP. Observations on the surface of BH-3 are indicative of transported debris mixed with liquefied soils. By comparison with grading curves as shown in Fig. 3c, most of the soils are susceptible to be liquefied. The debris materials include soils, stones, and construction remains.

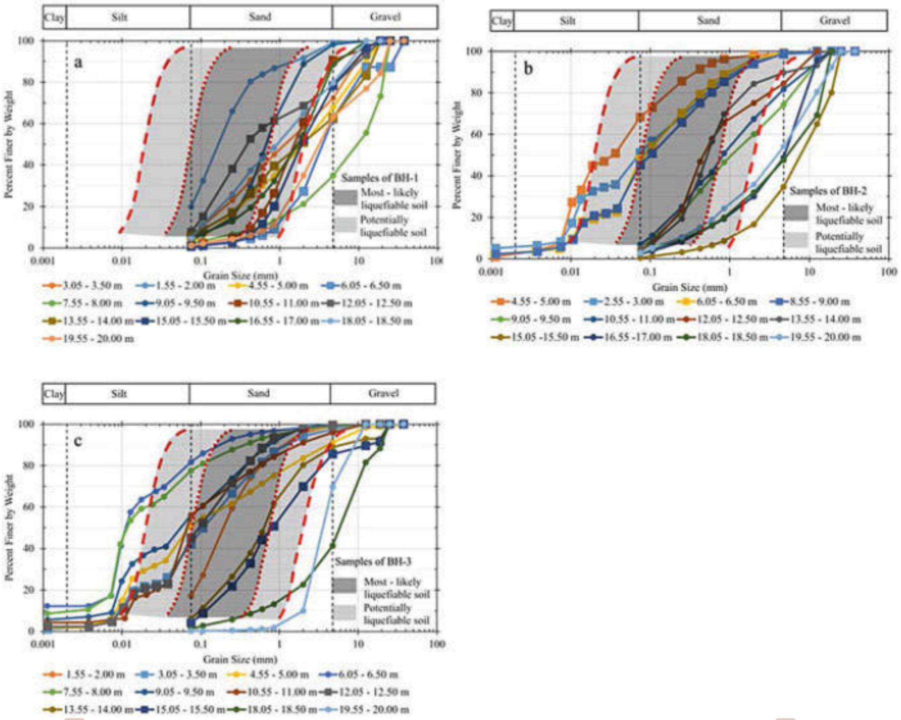

Fig. 3 Grain-size curves of SPT samples as compared with ranges of most-likely susceptible to liquefaction and potentially susceptible to liquefaction [13]

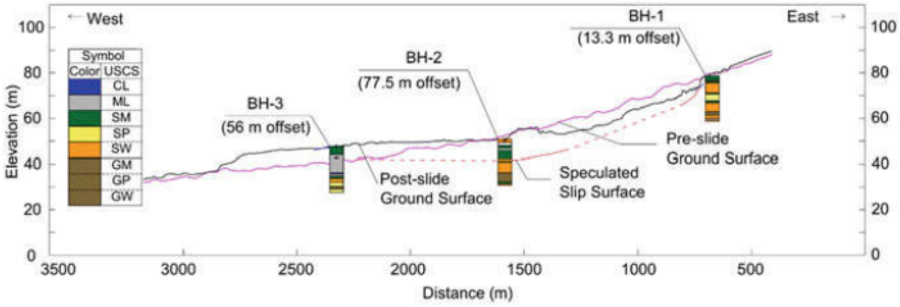

Fig. 4 Soil profile along Moh. Soeharto road. Bold red line and black line indicate post-slide and pre-slide, respectively

Figure 4 shows the soil profile along Moh. Soeharto road revealed after onsite exploration, as well as a potential slip surface estimated in association with the results of liquefaction assessment. The potential slip surface is speculated to locate with a maximum depth of approximately 13 or 10 m, respectively, below the pre-slide or post-slide ground surface.

4 Conclusions

This study aimed to reveal the subsurface conditions in Petobo sliding area. Site investigation, GWT monitoring and laboratory testing have been conducted. The study found sand, silt and gravel existed at the site. Sands and gravels dominate in the crown near irrigation canal. However, sands and silts are more often in middle and toe parts. Groundwater near the crown area would be around 14 m below the ground surface, after the earthquake and without the influence of infiltration by the canal and paddy fields. Moreover, groundwaters at middle and toe parts in the current post-slide period are close to the ground surface. The safety factor against liquefaction has been assessed by using Seed/NCEER method. At BH-1, located near the crown, liquefaction would be more susceptible in layers with depth generally > 10 m. In the middle areas, BH-2 would likely be liquefied due to the earthquake at a depth of < 10 m. At BH-3, situated near the toe, the liquefaction susceptibility would appear low and relatively stable, with only few separated depths computed with low safety factors.

References

1. Prakash S (1981) Soil dynamics. McGraw-Hill Companies, New York
2. Kramer SL (1996) Geotechnical earthquake engineering. Prentice-Hall, Upper Saddle River, New Jersey

3. Cipta A, Robiana R, Griffin JD, Horspool N, Hidayati S, Cummins PR (2016) A probabilistic seismic hazard assessment for Sulawesi. Indonesia. Geological Society, London, Special Publications
4. Irsyam M, Hanifa NR, Sahadewa A, Muntohar AS, Prakoso WA, Harninto DS, Djarwadi D, Ridwan M, Natawidjaja DH, Daryono M, Gunawan E, Meilano I, Pamumpuni A, Rudyanto A, Pramono S, Nazir R (2018) Damages associated with geotechnical problems in 2018 Palu earthquake, Indonesia. In: 20th SEAGC—3rd AGSSEA conference in conjunction with 22nd annual Indonesian national conference on geotechnical engineering, pp 5–14. Jakarta
5. Watkinson IM, Hall R (2019) Impact of communal irrigation on the 2018 Palu earthquake-triggered landslides. Nat Geosci 12:940–945
6. Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian J, Dobry R, Liam Finn WD, Leslie H, Hynes ME, Ishihara K, Koester J, Liao S, Marcuson WF, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, Stokoe KH (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J Geotech Geoenviron Eng 127:817–833
7. BPS (2020) Palu municipality in figures 2020. BPS—statistics of Palu municipality. Palu
8. Walpersdorf A, Vigny C, Subarya C, Manurung P (1998) Monitoring of the palu-Koro fault by GPS. Geophys Res Lett 25:2313–2316
9. BMKG (2018) Ulasan guncangan tanah akibat gempabumi Donggala 28 September 2018. In: BMKG. https://www.bmkg.go.id/berita/?p=ulasan-guncangan-tanah-akibat-gempabumi-utara-donggala-sulteng-28-september-2018&lang=ID&tag=ulasan-guncangan-tanah. Accessed 24 Aug 2019
10. Kiyota T, Furuichi H, Hidayat RF, Tada N, Nawir H (2020) Overview of long-distance flow-slide caused by the 2018 Sulawesi earthquake, Indonesia. Soils Found 60:722–735
11. Chang M (2020) Soil liquefaction analysis spreadsheet program V05
12. Chang M, Chan MS, Huang RC, Upomo TC, Kusumawardani R (2020) Assignment of groundwater table in liquefaction analysis of soils. In: Proceedings of GeoMEast 2020. Giza, p 17
13. Tsuchida H, Hayashi S (1971) Estimation of liquefaction potential of sandy soils. In: Proceedings of the 3rd joint meeting, US–Japan Panel on wind and seismic effects. UJNR, Tokyo, pp 91–109
14. Kusumawardani R, Chang M, Upomo TC, Huang RC, Fansuri MH, Prayitno GA (2021) Understanding of Petobo liquefaction flowslide by 2018.09.28 Palu-Donggala Indonesia earthquake based on site reconnaissance. Landslides 18(9):3163–3182

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