

**BUKTI KORESPONDENSI ARTIKEL PADA
JURNAL INTERNASIONAL BEREPUTASI**



Pengusul:

Dr. Rini Kusumawardani, ST, MT, MSc./NIDN: 0021097802

UNIVERSITAS NEGERI SEMARANG

Juni, 2024

Semarang, 04 Juni 2024

Kepada Yth.

Penilaian Usulan PAK

Dengan hormat

Bersama surat ini kami sampaikan proses submit sampai dengan publish Karya Tulis Ilmiah saya ke Landslide Journal. Seluruh proses submission, review dan informasi manuscript decision dengan The Editor Office dilaksanakan melalui <https://www.editorialmanager.com/> milik Springer serta dikirim melalui email. Komunikasi pertama kali dengan The Editor Office pada tanggal 9 Desember 2020. Demikian keterangan ini saya susun dengan sejujur-jujurnya.

Di samping itu, saya bermaksud menyertakan bukti bukti korespondensi proses artikel pada Jurnal Internasional dengan judul "**Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance**", yang dimuat pada *Landslide Journal*, Volume 18 (2021), ISSN (p): 1612-510X, ISSN(e) : 1612-5118, hal : 3163–3182.

Demikian pengantar ini saya sampaikan, agar dapat menjadi periksa. Terima kasih.

Hormat saya,



Dr. Rini Kusumawardani, ST, MT, MSc

Di bawah ini, saya sajikan susunan kronologi bukti korespondensi yang terdiri dari beberapa poin.

| No | Tanggal | Aktivitas |
|----|------------------|--|
| 1 | 9 Desember 2020 | Pembuatan akun |
| 2 | 9 Desember 2020 | Submit draft manuskrip ke dalam sistem |
| 3 | 5 Januari 2021 | Mendapatkan balasan dari The Editor Office Landslide untuk mengubah kategori manuskrip menjadi “recent landslide” |
| 4 | 8 Januari 2021 | Mengirim revisi manuskrip ke-1 melalui sistem |
| 5 | 26 Februari 2021 | Mendapatkan balasan dari The Editor Office Landslide bahwa manuskrip diterima dengan “major revision” untuk memperbaiki manuskrip sesuai saran dari reviewer |
| 6 | 4 April 2022 | Submit 2 nd revised version submission ke sistem Journal Landslide |
| 7 | 13 Mei 2021 | Manuskrip dinyatakan diterima oleh The Editorial Office |

KRONOLOGI KORESPONDENSI PUBLIKASI ARTIKEL PADA JURNAL INTERNASIONAL BEREPUTASI DAN BERFAKTOR DAMPAK

| | | |
|-------------------|---|--|
| Judul | : | Understanding of Petobo liquefaction flowslide by 2018.09.28 Palu-Donggala Indonesia earthquake based on site reconnaissance |
| Jurnal | : | <i>Landslide Journal</i> |
| Volume | : | 18 |
| Tanggal publikasi | : | 06 Juni 2022 |
| ISSN (p) | : | 1612-510X |
| ISSN (e) | : | 1612-5118 |
| Halaman | : | 3163–3182 |
| Penerbit | : | Springer Nature |
| SJR jurnal | : | 1,918 (2021) |
| Quartile | : | Q1 (Scopus) |
| Cite Score | : | 10,6 (2021) |
| Penulis | : | Rini Kusumawardani, Muhsiung Chang, Togani Cahyadi Upomo, Ren-Chung Huang, Muhammad Hamzah Fansuri, Galih Ady Prayitno |

Bukti indexing journal:

Source details

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Landslides

Scopus coverage years: from 2004 to Present

Publisher: Springer Nature

ISSN: 1612-510X E-ISSN: 1612-5118

Subject area: [Earth and Planetary Sciences: Geotechnical Engineering and Engineering Geology](#)

Source type: Journal

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CiteScore 2021

10.6



SJR 2021

1.918



SNIP 2021

2.582



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10.6

$$= \frac{8,131 \text{ Citations to date}}{767 \text{ Documents to date}}$$

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CiteScore rank 2021

Category

Rank Percentile

Earth and Planetary Sciences

Geotechnical Engineering and Engineering Geology

#6/203

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Abstract

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 km². 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

Landslides

Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance

--Manuscript Draft--

| | |
|--|---|
| Manuscript Number: | |
| Full Title: | Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance |
| Article Type: | Regular issue |
| Order of Authors: | Rini Kusumawardani, PhD Muhsiong Chang, PhD Togani Cahyadi Upomo, Master Ren-Chung Huang, PhD Muhammad Hamzah Fansuri, Master Galih Ady Prayitno |
| Corresponding Author: | Rini Kusumawardani, PhD Universitas Negeri Semarang Semarang, Central Java INDONESIA |
| Corresponding Author Secondary Information: | |
| Corresponding Author's Institution: | Universitas Negeri Semarang |
| Corresponding Author's Secondary Institution: | |
| First Author: | Rini Kusumawardani, PhD |
| First Author Secondary Information: | |
| Order of Authors Secondary Information: | |
| Funding Information: | Universitas Negeri Semarang (ID) (31.18.3/UN37/PPK.3.1/2019) Assoc. Prof Rini Kusumawardani |
| Abstract: | <p>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 km². 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.</p> |

Mendapatkan balasan dari The Editor Office Landslide :

COMMENTS FOR THE AUTHOR:

The manuscript was reviewed by the screening editors and found the manuscript be more suitable as a recent landslide than an original paper. Please submit the revised manuscript by simply changing the category as a "recent landslide " if the authors want the manuscript be reviewed for possible publication as a recent landslide article

Decision on your manuscript #LASL-D-20-00781

External

Inbox

Editorial Office <em@editorialmanager.com>

Jan 5, 2021,
1:05 PM

to me

Dear Dr Kusumawardani:

We have received the reports from our advisors on your manuscript, "Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance", which you have submitted to Landslides.

Based on the advice received, your manuscript could be reconsidered for publication should you be prepared to incorporate major revisions.

When preparing your revised manuscript, you are asked to carefully consider the attached reviewer comments below (if there is any) and submit a list of responses to the comments. Your list of responses should be uploaded as a file in addition to your revised manuscript.

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Your username is: kusumawardani

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We would like to request for an editable source file (i.e. Word or LaTeX) of your revised manuscript because our Production Department will be unable to use a PDF or Postscript file format. The system supports the following file formats:

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for figures -
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If you have used LaTeX, please include the STY files.

We look forward to receiving your revised manuscript.

Sincerely yours,

Editorial Board of Landslides

COMMENTS FOR THE AUTHOR:

The manuscript was reviewed by the screening editors and found the manuscript be more suitable as a recent landslide than an original paper. Please submit the revised manuscript by simply changing the category as a "recent landslide " if the authors want the manuscript be reviewed for possible publication as a recent landslide article.

Reviewers' comments (if any):

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Mengirim revisi manuskrip ke-1 melalui system

Acknowledgement of Receipt of #LASL-D-20-00781R1

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Fri, Jan 8,
2021, 7:32 PM

to me

Dear Dr Kusumawardani:

We acknowledge, with thanks, receipt of the revised version of your manuscript, "Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance", submitted to Landslides. The manuscript number is LASL-D-20-00781R1.

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Your username is: kusumawardani

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Best regards,

The Editorial Office
Landslides

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Mendapatkan balasan dari The Editor Office Landslide :

Decision on your manuscript #LASL-D-20-00781R1

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Inbox

Editorial Office <em@editorialmanager.com>

Feb 26, 2021,
1:19 PM

to me

Dear Dr Kusumawardani:

We have received the reports from our advisors on your manuscript, "Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance", which you have submitted to Landslides.

Based on the advice received, your manuscript could be reconsidered for publication should you be prepared to incorporate major revisions.

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for manuscripts - Word, WordPerfect, RTF, TXT, and LaTeX;

for figures -

TIFF, GIF, JPEG, EPS, and PPT.

If you have used LaTeX, please include the STY files.

We look forward to receiving your revised manuscript.

Sincerely yours,

Editorial Board of Landslides

COMMENTS FOR THE AUTHOR:

Editor: Please have the manuscript edited by someone who has an excellent technical writing skill in English. Currently, the manuscript has many editorial errors, specifically on English grammar and syntax. It requires reorganization at many locations. Also, please improve the quality of figures.

Reviewer #1: 1. It is necessary to follow the template from the Landslide journal. The manuscript is more similar to a field report
2. Please add the data of rainfall, model of ground water and water table depth, so the discussion more accurate

Reviewers' comments (if any):

There is additional documentation related to this decision letter. To access the file(s), please click the link below. You may also login to the system and click the 'View Attachments' link in the Action column.

<https://www.editorialmanager.com/lasl/l.asp?i=264386&l=YVEYNKPJ>

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Mengirim revisi manuskrip ke-2 melalui system

Landslides

Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance --Manuscript Draft--

| | | |
|--|---|--------------------------------|
| Manuscript Number: | LASL-D-20-00781R2 | |
| Full Title: | Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance | |
| Article Type: | Regular issue | |
| Section/Category: | Recent Landslides | |
| Order of Authors: | Rini Kusumawardani, PhD Muhsiong Chang, PhD Togani Cahyadi Upomo, Master Ren-Chung Huang, PhD Muhammad Hamzah Fansuri, Master Galih Ady Prayitno | |
| Corresponding Author: | Rini Kusumawardani, PhD Universitas Negeri Semarang Semarang, Central Java INDONESIA | |
| Corresponding Author Secondary Information: | | |
| Corresponding Author's Institution: | Universitas Negeri Semarang | |
| Corresponding Author's Secondary Institution: | | |
| First Author: | Rini Kusumawardani, PhD | |
| First Author Secondary Information: | | |
| Order of Authors Secondary Information: | | |
| Funding Information: | Direktorat Jenderal Pendidikan Tinggi (31.18.3/UN37/PPK.3.1/2021) | Assoc. Prof Rini Kusumawardani |
| Abstract: | <p>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 km². 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.</p> | |

Editor-in-Chief
Kyoji Sassa
Prof. Emeritus
Landslide Journal

December 09, 2020

Dear Prof. Kyoji Sassa,

I would like to submit the manuscript entitled “Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance” by Rini Kusumawardani, Muhsiung Chang, Togani Cahyadi Upomo, Ren-Chung Huang, Muhammad Hamzah Fansuri, Galih Prayitno to be considered for publication as a regular article in the *Landslide Journal*.

In this study, we conducted a site reconnaissance to reveal the understanding of liquefaction flowslide at Petobo area due to 2018.09.28 Palu-Donggala earthquake. The most interesting findings are the types of morphological zonation observed in Petobo sliding area. These morphological features might have been in relation to the initiation and the progress of sliding in Petobo during the earthquake. We believe these findings are valuable to the readers of *Landslide Journal*.

We declare that this manuscript is original and has not been published before and is not currently being considered for publication elsewhere. As corresponding author, I confirm that all authors have read and approved the manuscript and agree with its submission to *Landslide Journal*.

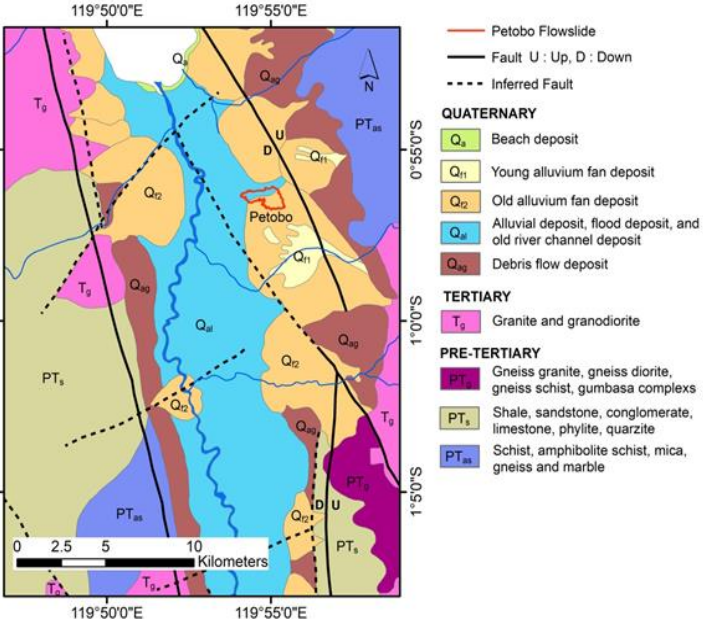
Thank you very much and we look forward to hearing from you.

Sincerely yours,

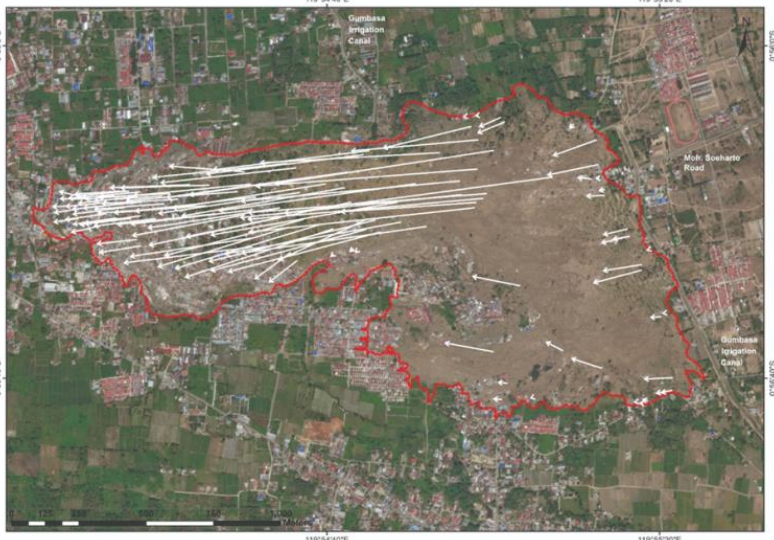
Dr. Rini Kusumawardani

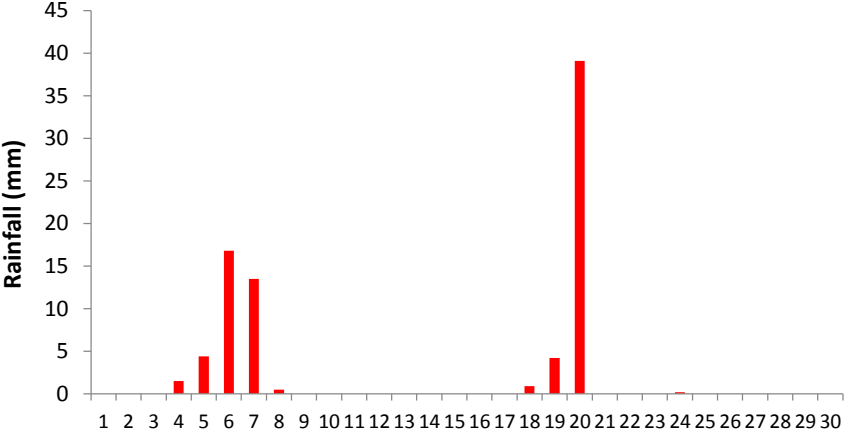
Dept. of Civil Engineering, Universitas Negeri Semarang, Semarang, Indonesia
Kampus UNNES Sekaran, Gunungpati, Semarang, Indonesia, Code Postal 50229
Email : rini.kusumawardani@mail.unnes.ac.id

Table 1. Responses to Comments by Editor

| Item | Reviewer Comment | Author Response (Revised or amended statements in <i>italic</i>) |
|-----------------------------|--|---|
| 1 (page 2 line 23-24) | Keyword please, make it simple | Thank you for your comments. The keyword is made simpler without reducing the meaning. Before the revision, the keywords is "liquefaction flowslide, site reconnaissance, morphological characterization, 2018 Palu-Donggala Indonesia earthquake". After revision, the keyword is " <i>liquefaction flowslide, site reconnaissance, morphological characterization, 2018 Palu earthquake</i> " |
| 2 (page 4 line 8-12) | The authors need to connect the earthquake event to the main Palu-Koro Fault | Thank you for your comment. My revision concerning to your advice as follows, ".....The largest foreshock registered as Mw 6.1 was occurred three hours before the mainshock which was <i>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 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.</i> Earthquake epicenters can be seen in Fig 1. The mainshock and the largest foreshock of this earthquake series are signed as red star and red dot." |
| 3 (page 5 line 51-57) | Need support with reference | Thank you for your advice. In this part, a reference is added for support the research. My revision as follows, ".....The paper also summarizes our surface observations and compares with available satellite photos and DEM data <i>provided by Centre of Data and Information Technology (2020) Ministry of Public Works and Public Housing of the Republic of Indonesia.....</i> " |
| 4 (page 6 line 17) | Symbol U and D need to be clear | Thank you for your suggestion. My revision to symbol U and D as follows,  |

| | | |
|--|--|--|
| <p>5 (page 6 line 54-60 and page 7 line 1-2)</p> | <p>Need to explain related slip field and bedrock components</p> | <p>Thank you for your comments. My revision concerning to your advice as follows, <i>“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 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).”</i></p> |
| <p>6 (page 7 line 51)</p> | <p>Perhaps preferably, the discussion of not only alluvial deposits but the relationship between alluvial deposits and bedrock. perhaps it will show how susceptible liquefaction occurs</p> | <p>Thank you for your comments. My revision concerning to your advice as follows, “...The clays are brown to dark brown, soft to firm, highly plastic, with a thickness varied between 0.1 – 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. A suspect area with a high risk of liquefaction occurrence is in the alluvium deposit. In this area, the depth of groundwater level is less than 12 m. <i>The alteration of soil behaviour in each soil layers could be occurred when experienced by seismic wave. When the seismic wave propagated from the bedrock through the saturated sand soil layers, it lead the decreasing of effective soil stress. A susceptibility of liquefaction could be reached when pore water pressure equal to initial effective stress. In Palu city and surroundings, a suspect area with a high risk of liquefaction occurrence is in the alluvium deposit.</i> Details of liquefaction susceptibility and groundwater level in Palu and surrounding can be seen in Fig. 4.”</p> |

| | | |
|---------------------------------------|---|--|
| <p>7 (Page 19 line 53-54)</p> | <p>Not clear on the figure 12</p> | <p>Thank you for comment The revision for the Figure 12 as follows,</p>  <p>“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. Purple dots are the initial locations and pink dots are the ending positions. The white arrows are the direction of displacements. Base photo is taken from Google Earth satellite image of 2019.05.23.”</p> |
| <p>8 (Page 21 Line 13-24)</p> | <p>Need to connect with rainfall data and water table data. inundated the paddy field must be supported with a reference while the soil of paddy field has specific characteristic different with another soil, especially with a hard pan under the paddy field soil</p> | <p>Thank you for your comments. Concerning to inundated paddy field, we revise the text as follows, “As indicated by local residents and in Google Earth images, Gumbasa irrigation canal was constantly filled with water before the earthquake (Photos 1 & 2; Fig. 10) and the paddy fields were also inundated with water for about 8-months plantation time annually, <i>which are based on our site reconnaissance as summarized in Table 1. During the plantation, the paddy fields 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 which would constantly supply the local ground water tables under the paddy fields. In our opinion the rainfall would appear not really affect the increase of ground water table under the paddy fields as reference to Fig. 14, which clearly indicated the absence of rain a week before the flowslide occurred.</i></p> |

| | | |
|-------------------------------|--|---|
| | |  <p style="text-align: center;">Date in September 2018</p> <p>Fig. 14 Daily rainfall intensity during September 2018 in study area which clearly indicated the absence of rain a week before the flowslide occurred (Meteorological, Climatological and Geophysical Agency 2021).</p> <p style="text-align: center;">In view of mostly unline Gumbasa irrigation.....”</p> |
| 9 (Page 21 line 34-36) | should be clarified with rainfall data, and a stratigraphic cross section to predict how the model groundwater at the study site | Thank you for your comment. In this paragraph, we would like to explain when the Gumbasa canal was broken due to the earthquake, it would have played an important role on the ground failure at Petobo. Because of an intensive irrigation system in this area with gentle slopes, it had caused the liquefaction phenomenon even more severe. |
| 10 (Page 26 line 24-26) | need to combine with the cross section before the liquefaction.....if you have the data | Thank you for your comments. This article summarizes the preliminary study to identify the condition of Petobo area after the liquefaction and slide. The section soil profile before the earthquake would be difficult to find at this stage. |
| 11 (Page 28 line 51-52) | make simple and connect to aims of this study | Thank you for your comment. Our concluding remarks explain the essential phenomena compiled during our site visit investigations and eyewitness interviews. The purpose of elaborations is to give highlights on some important isness that are not described by other related articles. We hope the detailed remarks could contribute more understanding on researches concerning to this liquefaction. |
| 12 (Page 31 line 21-23) | A probabilistic seismic hazard assessment for Sulawesi, Indonesia | Thank you for your comment. The revised version of this reference as follows, “ Cipta A, Robiana R, Griffin JD, Horspool N, Hidayati S, Cummins PR (2016) A probabilistic seismic hazard assessment for Sulawesi, Indonesia. #From: Cummins PR, Meilano I. (eds) Geohazards in Indonesia: earth-Earth science-Science for disaster-Disaster risk-Risk reductionReduction . 441st edn. Geological Society, of London, London, Special Publications, pp 133–152441, http://doi.org/10.1144/SP441.6 ” |

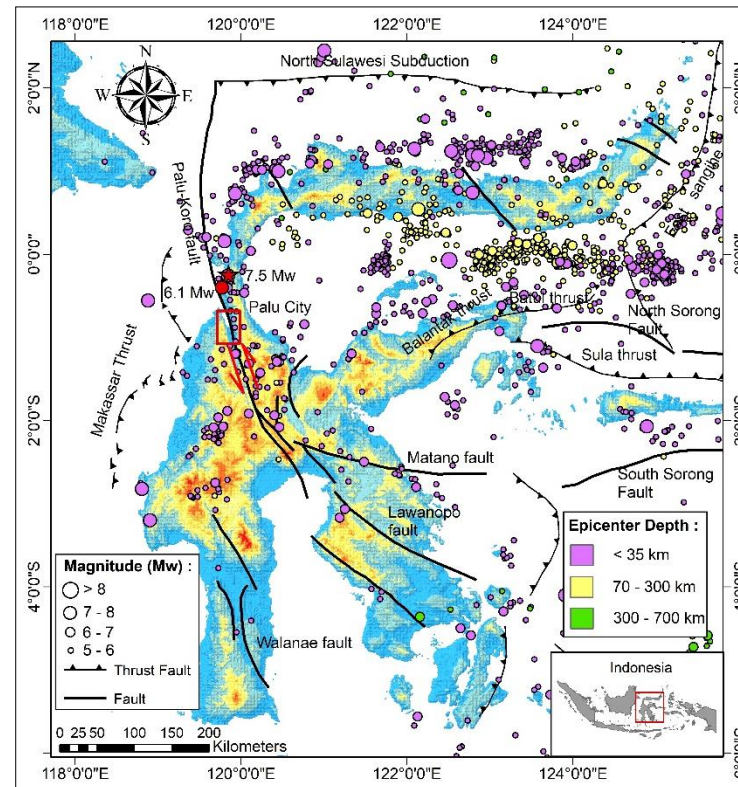


Fig. 1 Regional tectonic map in Sulawesi and surrounding. The size and colored dots indicate as magnitude and epicenter of earthquakes taken from USGS catalogue 1900-2019. Red rectangle is the location of Palu City. The locations of largest foreshock and mainshock of 2018.09.28 Palu-Donggala Earthquake 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).

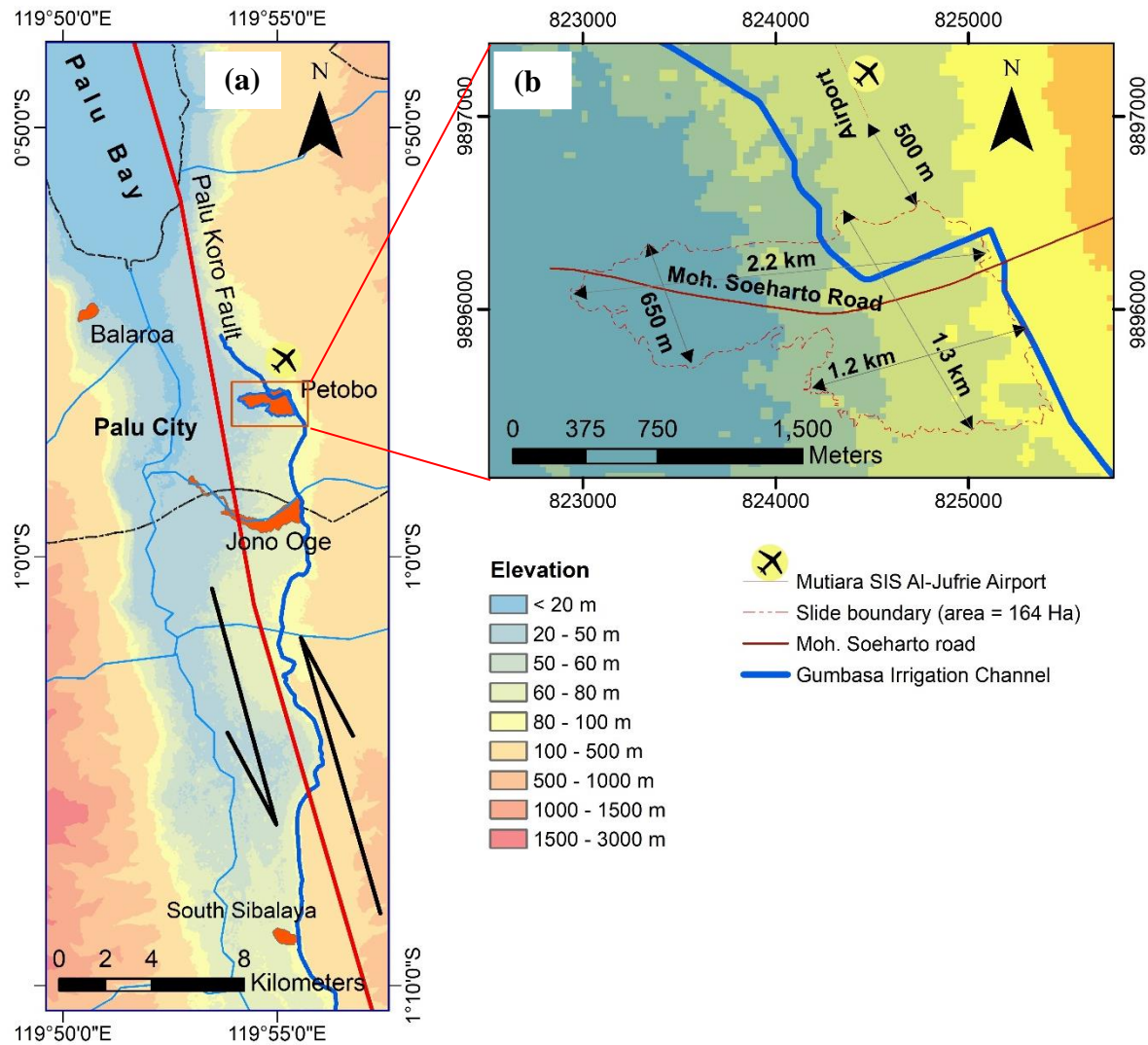


Fig. 2 a Flowslide locations after Palu-Donggala earthquake of 2018.09.28. b Dimensions of Petobo flowslide. Credit: Base map adapted from GADM, base digital elevation model derived from JAXA's ALOS Global Digital Surface Model 30 m x 30 m resolution.

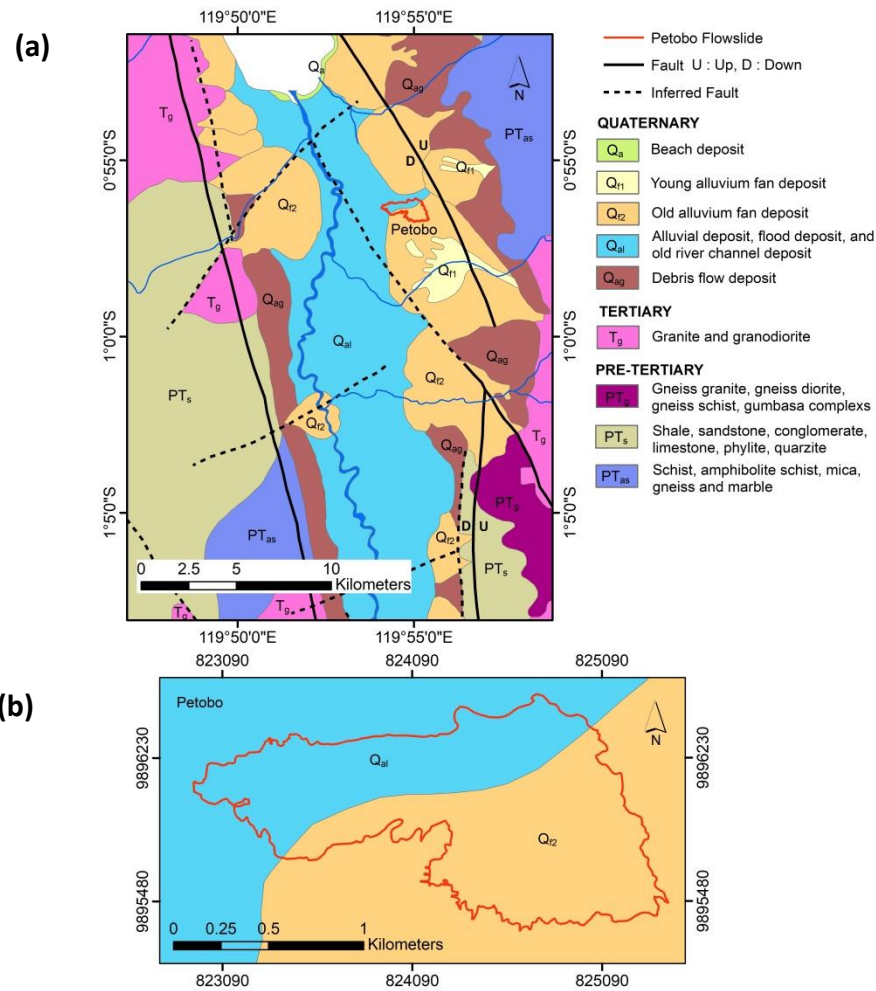


Fig. 3 **a** Geological map of Palu and surroundings (Hanifa 2018) consists of surficial deposits in Quaternary, Tertiary and Pre-Tertiary periods. The study area is identified by the red line. **b** Location of the study area is composed dominantly by the old alluvium fan deposit and the alluvial, flood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

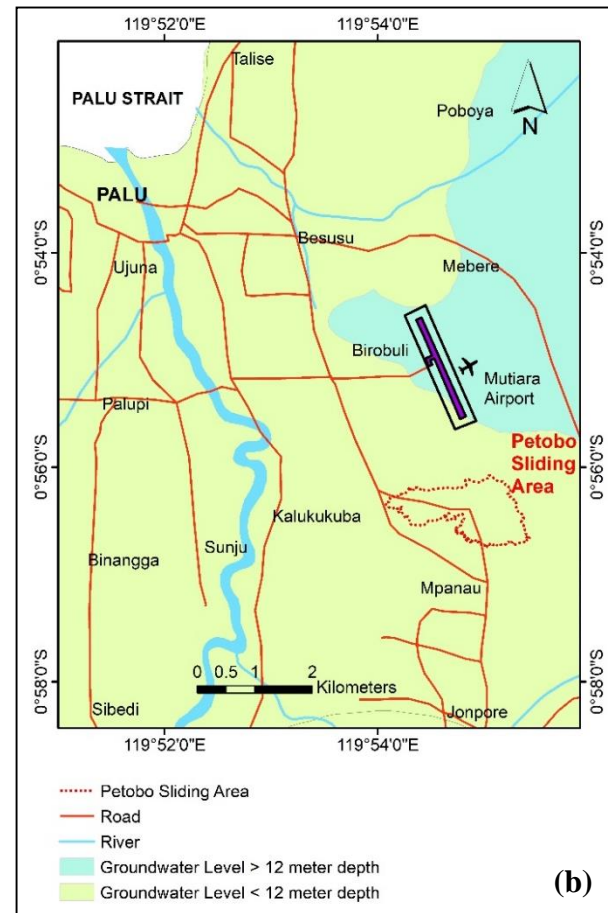
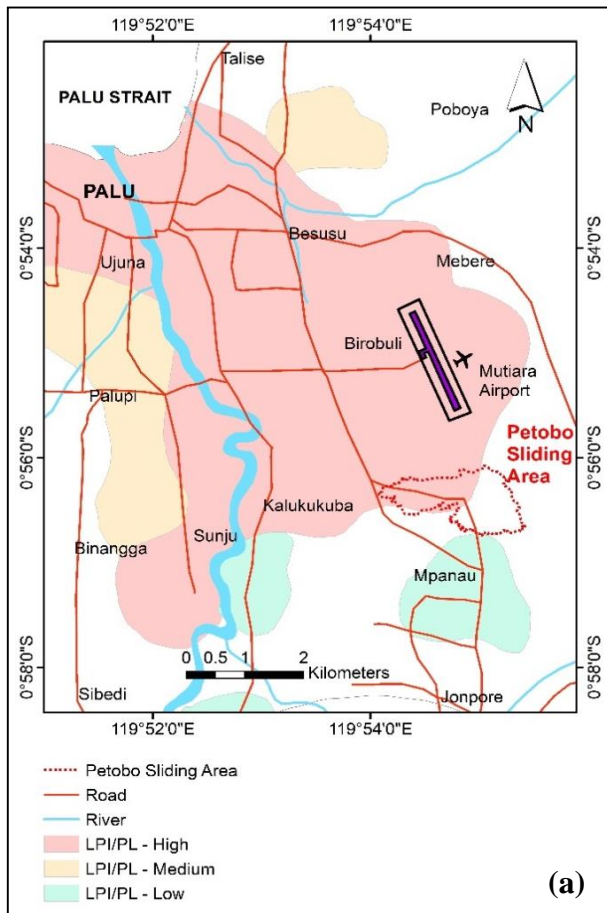


Fig. 4 a The map of liquefaction susceptibility in Palu and surrounding with three levels of potential of liquefaction. Palu city is identified to have a high possibility of liquefaction occurrence in particular to the east of Palu river. One of triggering factors contributed to liquefaction occurrence 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.

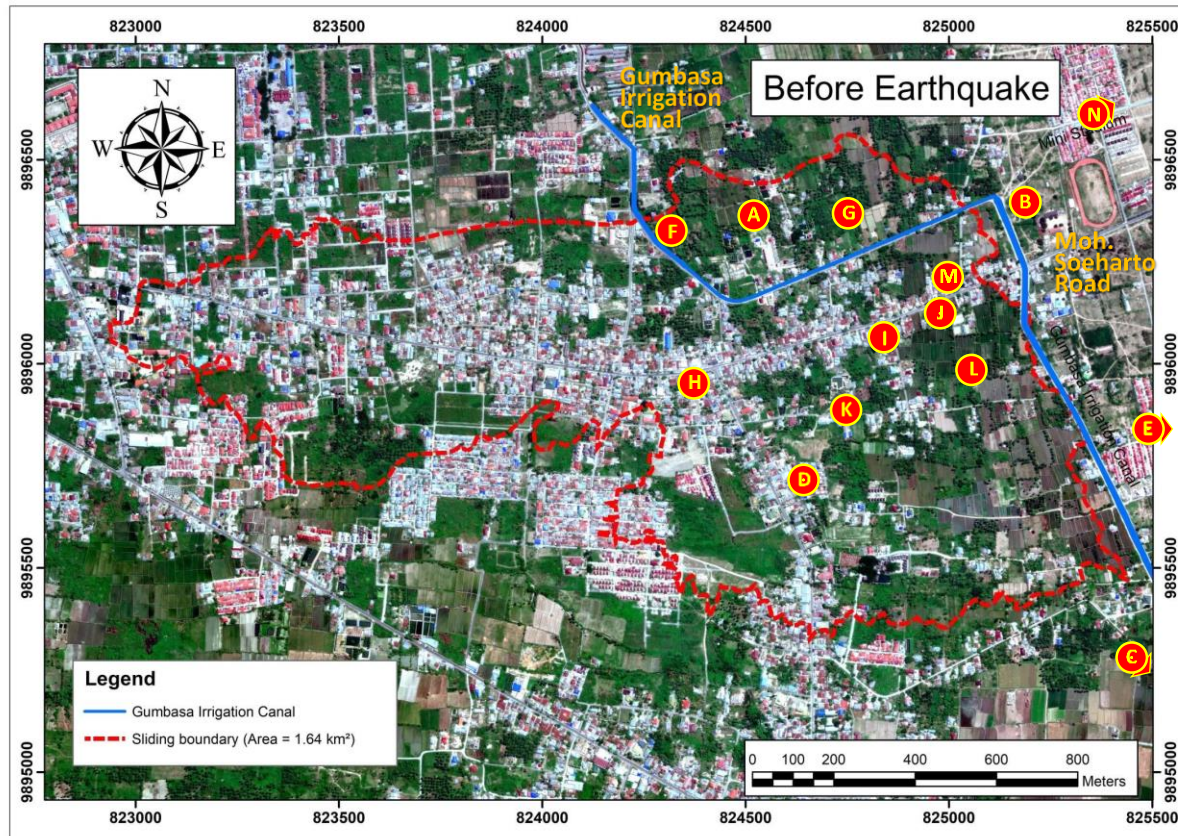
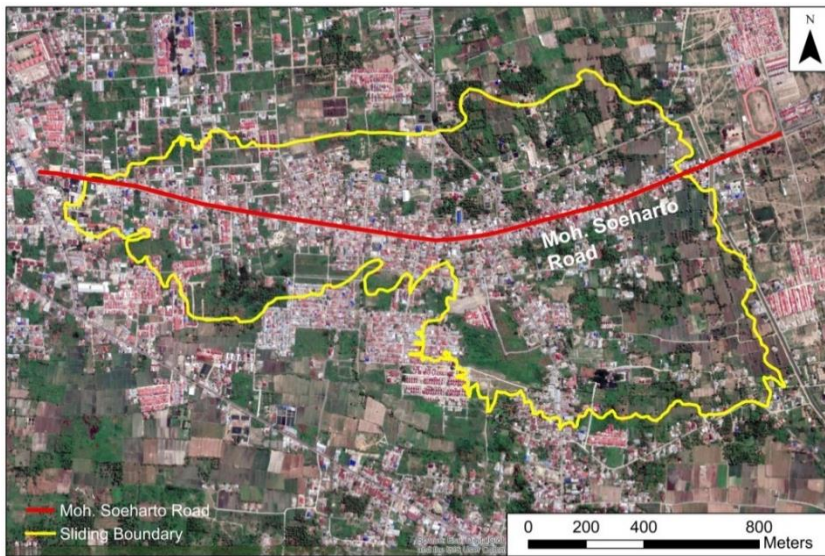
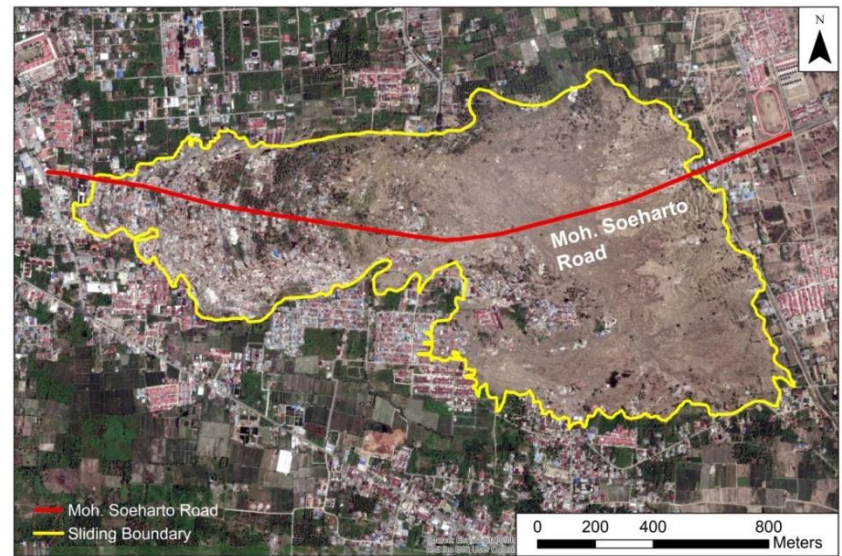


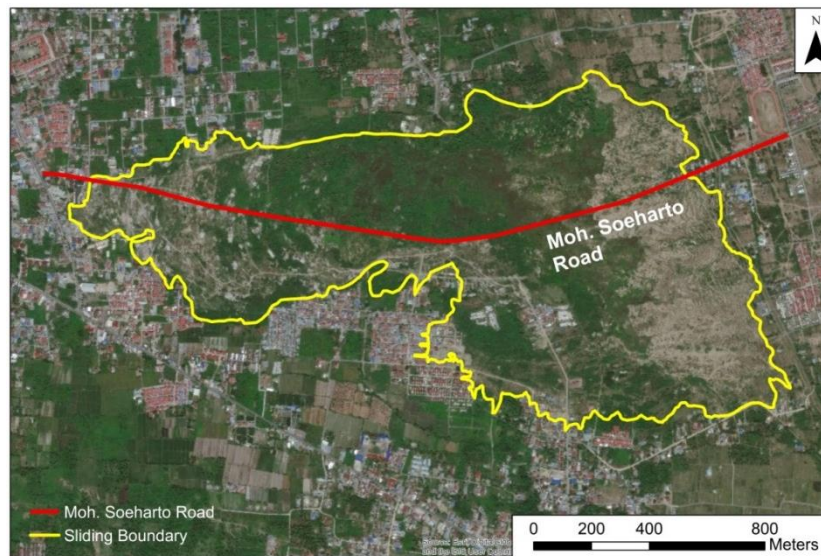
Fig. 5 Locations where interviewed witnesses were in the Petobo area during 2018.09.28 Palu-Donggala earthquake. Based photo is taken from Google Earth satellite image of 2018.08.17.



(a) Pre-slide image on 2018.08.17



(b) Post-slide image on 2018.10.02



(c) Recent image on 2019.11.06

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.

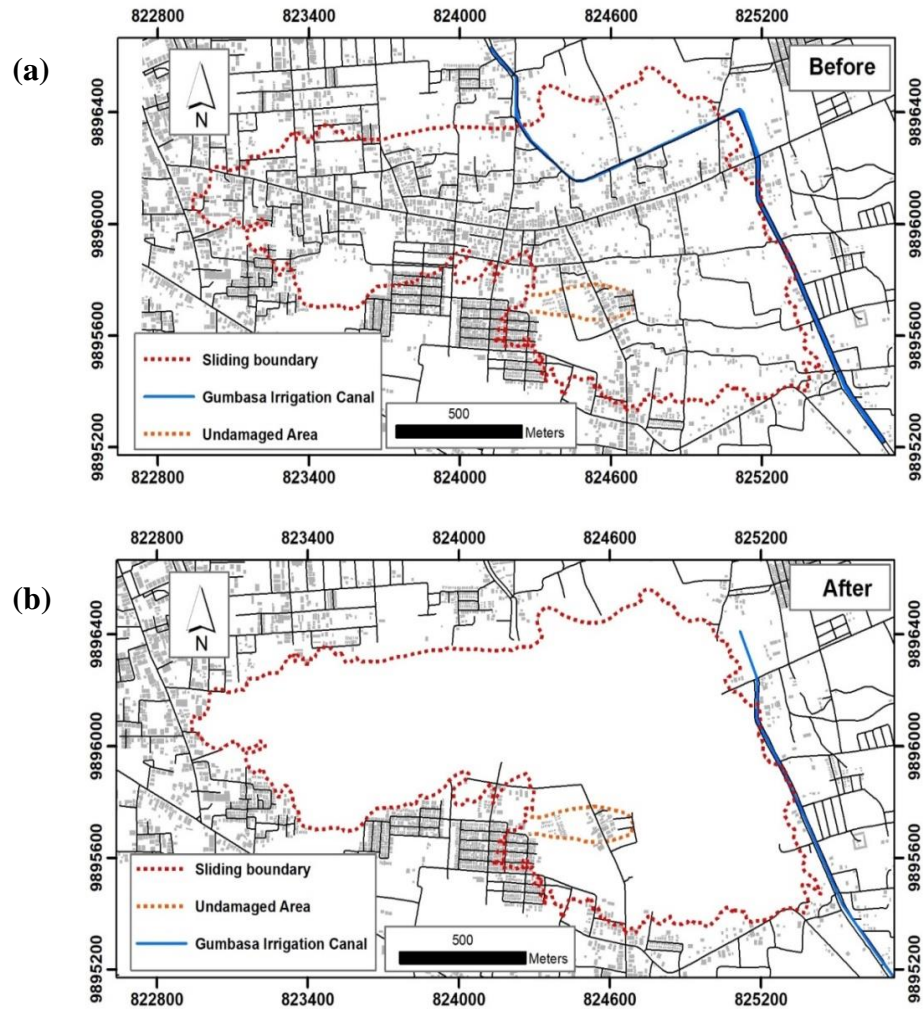


Fig. 7 The site condition before and after the earthquake. **a** Condition before earthquake where Gumbasa irrigation canal passed across the flowslide area. **b** Situation after the earthquake where Gumbasa irrigation canal in the NE portion of the sliding was swept away and an undamaged area was found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



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.

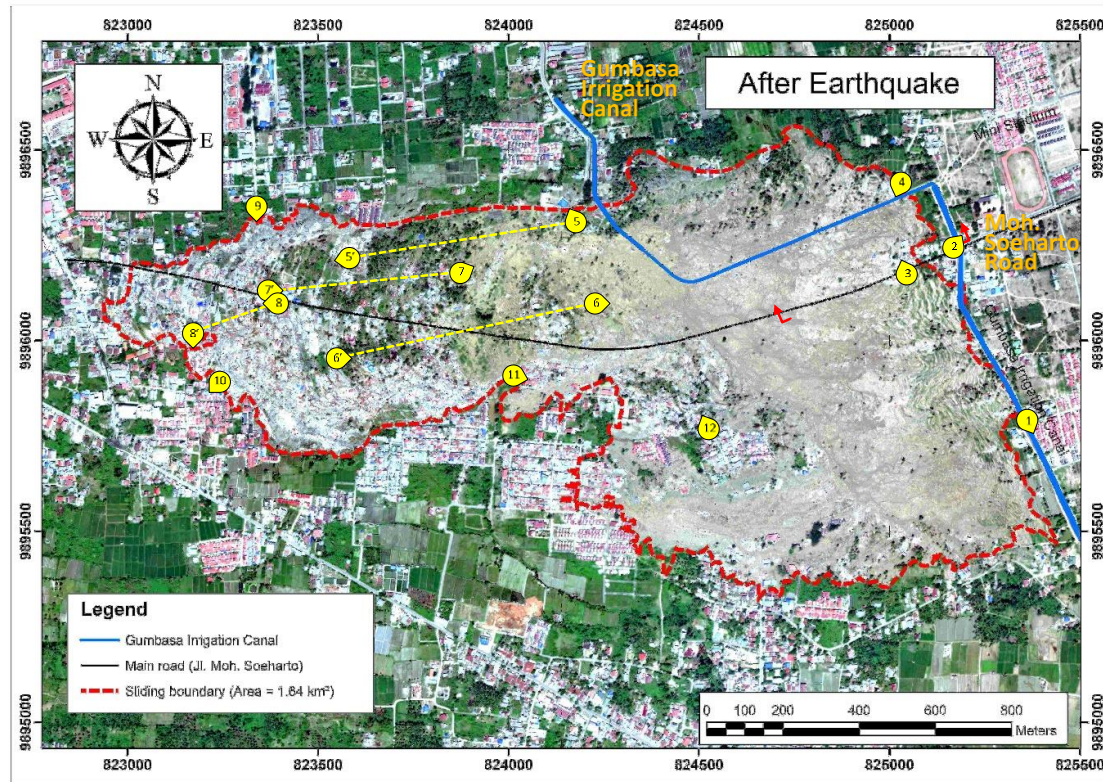


Fig. 9 Locations of key features at Petobo site for pre- and post-slide comparison, with also the location of mapped section along Moh. Soeharto road discussed in the later part of this paper. The base photo is taken from Google Earth satellite image of 2018.10.02.



Photo 1. Before EQ (looking S)



Photo 1'. After EQ (looking S)



Photo 2. Before EQ (looking NE)



Photo 2'. After EQ (looking NE)



Photo 3. Before EQ (looking N)



Photo 3'. After EQ (looking N)



Photo 4. Before EQ (looking SW)



Photo 4'. After EQ (looking SW)



Photo 5. Before EQ (looking NW)



Photo 5'. After EQ (looking W)



Photo 6. Before EQ (looking E)



Photo 6'. After EQ (looking E)



Photo 7. Before EQ (looking E)



Photo 7'. After EQ (looking E)

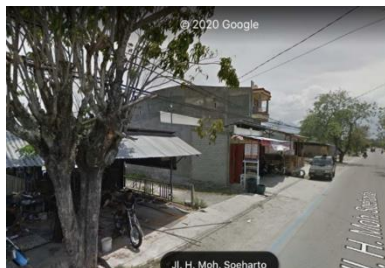


Photo 8. Before EQ (looking W)



Photo 8'. After EQ (looking S)



Photo 9. Before EQ (looking SE)



Photo 9'. After EQ (looking SE)



Photo 10. Before EQ (looking SW)



Photo 10'. After EQ (looking SW)



Photo 11. Before EQ (looking E)

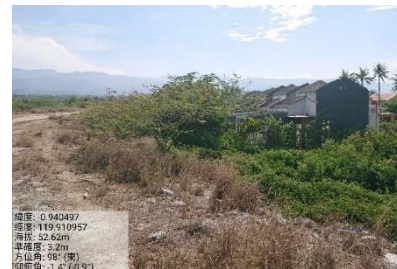


Photo 11'. After EQ (looking E)

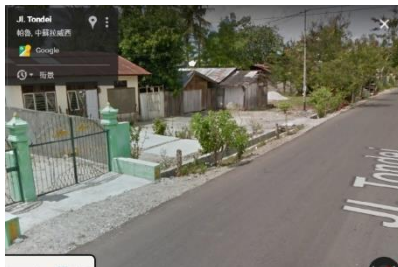


Photo 12. Before EQ (looking NW)



Photo 12'. After EQ (looking NW)

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. 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.

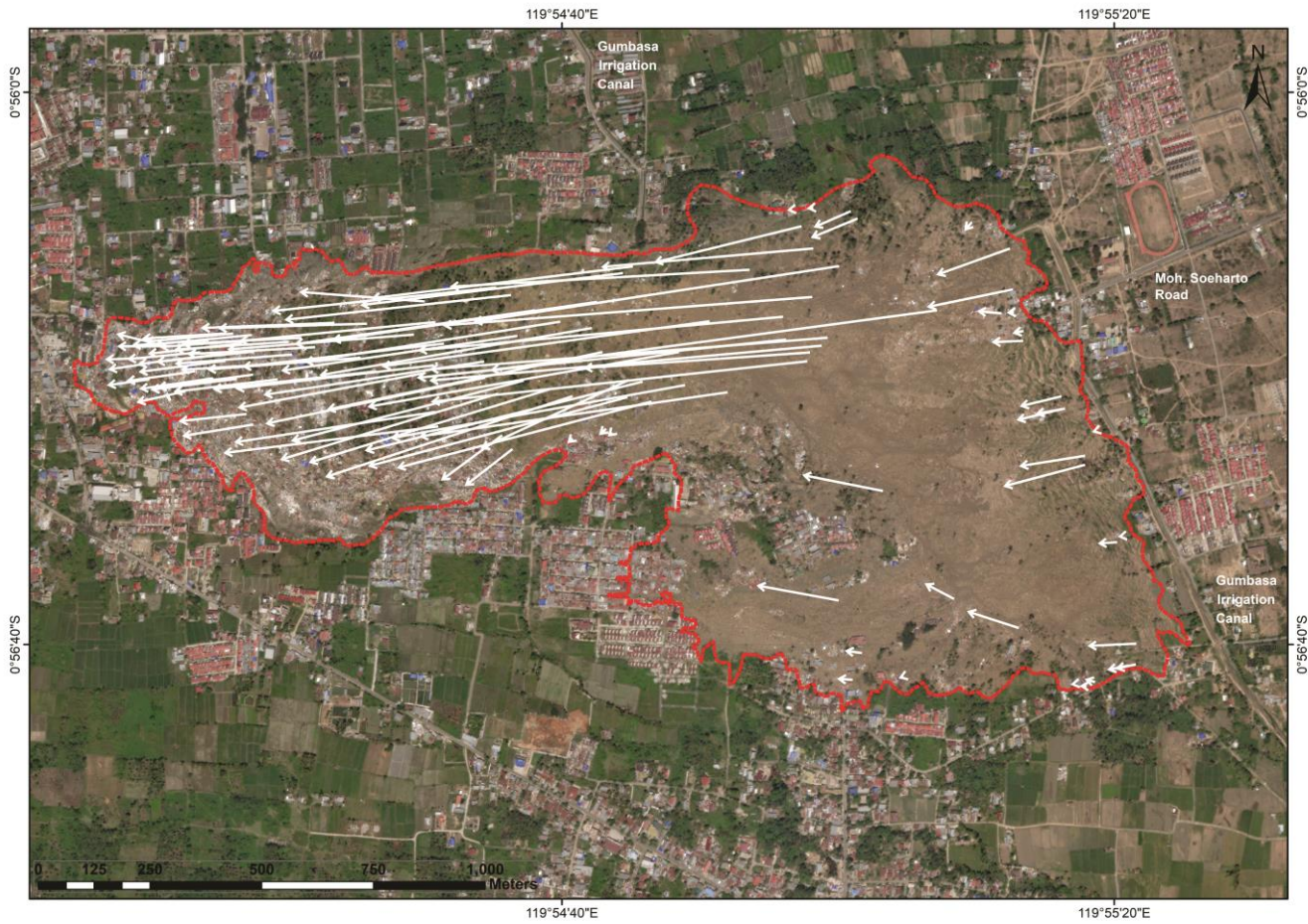


Fig. 12 Displacement vectors of surface objects identified by onsite investigation as well as based on Google Earth satellite images before the after the earthquake. ~~Purple dots are the initial locations and pink dots are the ending positions.~~ The white arrows are the direction of displacements.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

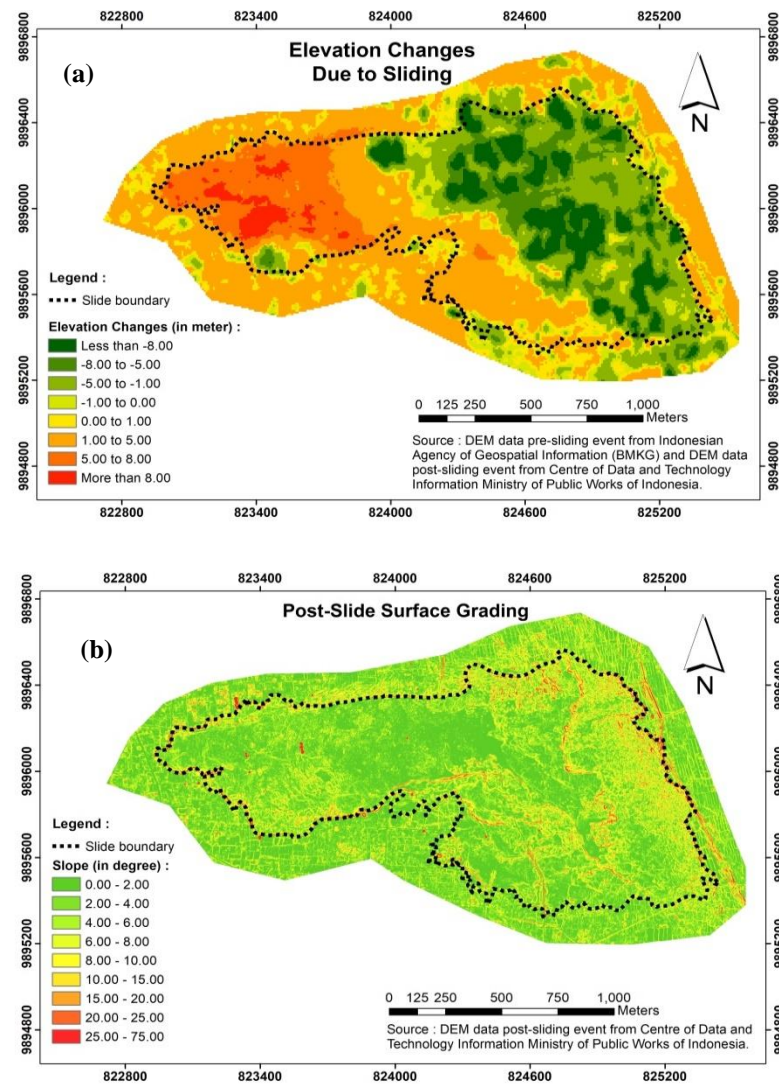


Fig. 13 a The elevation changes due to sliding. **b** The grading of ground surface after the earthquake. The elevation changes varied approximately between -8 m and 8 m. In the eastern part the elevation dropped down more than 8 m (green color) and in the western part raised more than 8 m (red color). 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.

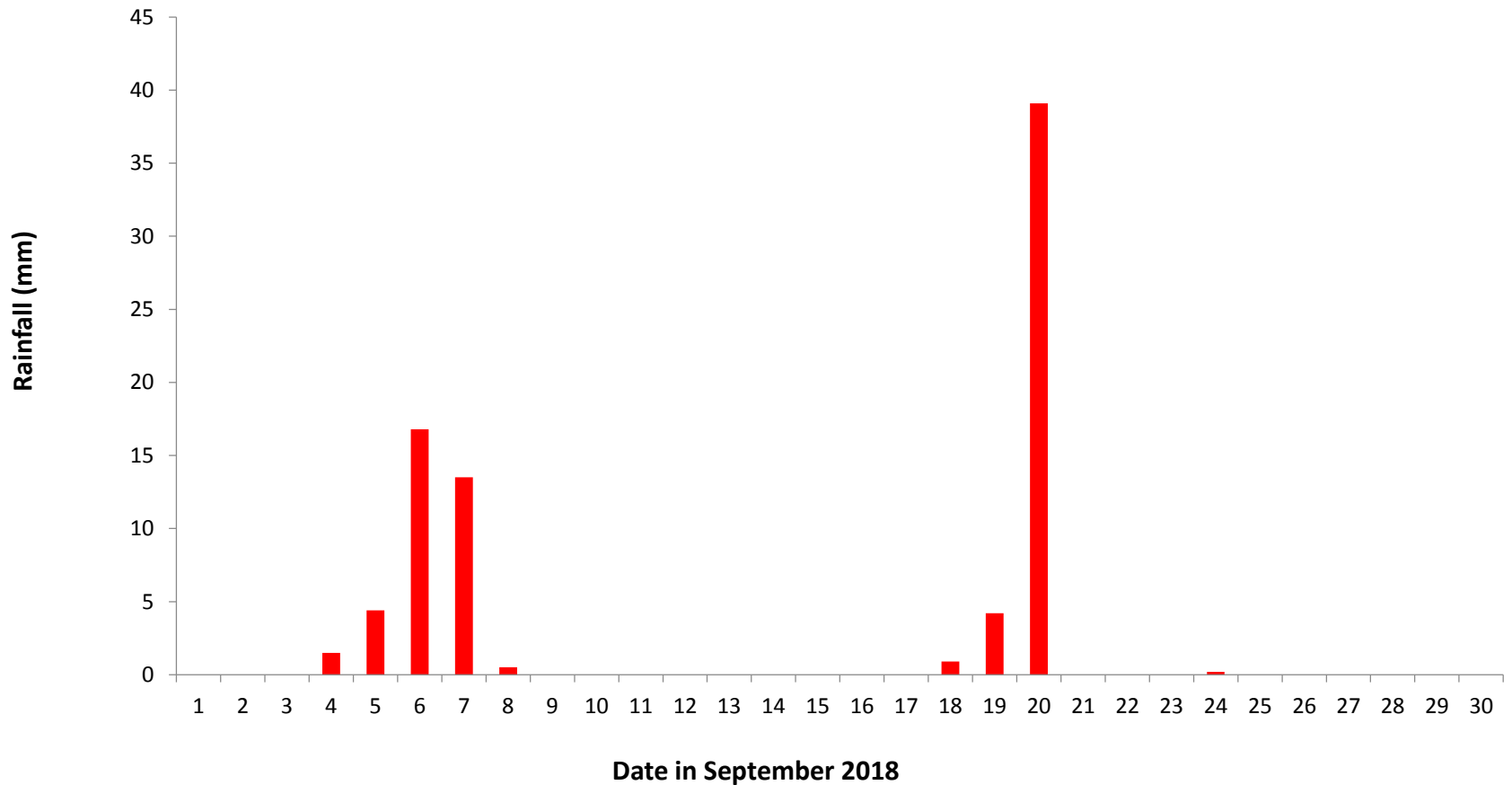


Fig. 14 Daily rainfall intensity during September 2018 in study area which clearly indicates the absence of rain a week before the flowslide occurred (Meteorological, Climatological and Geophysical Agency 2021).

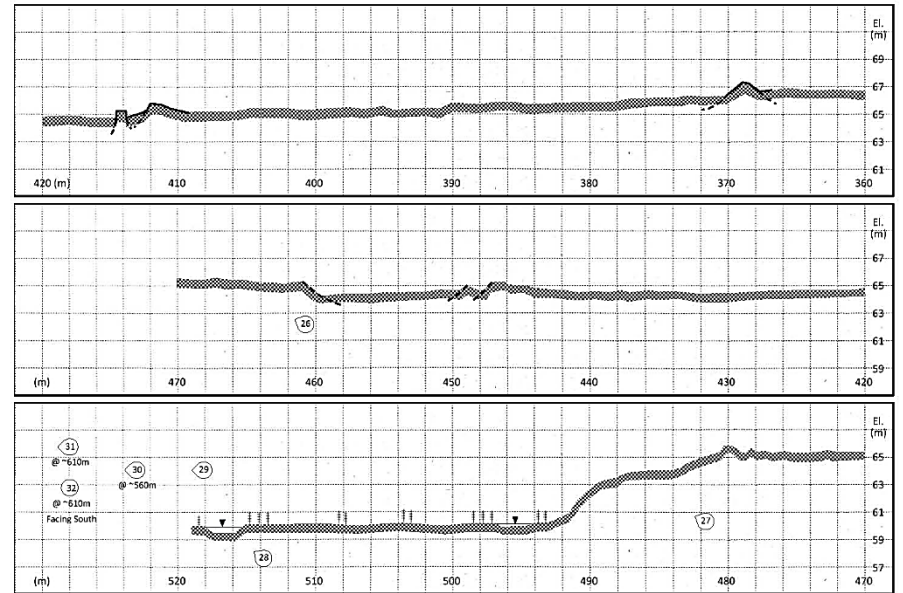
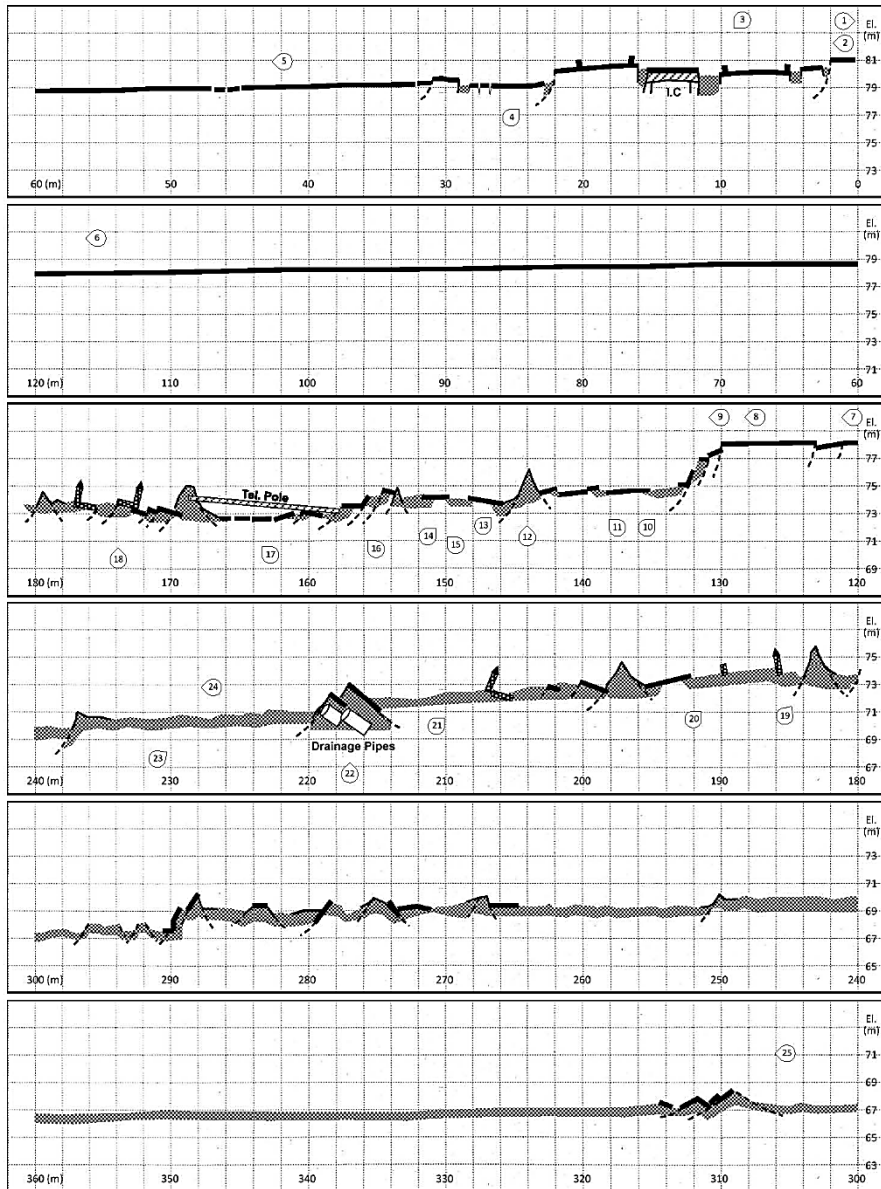


Fig. 15 Mapping of east section of Moh. Soeharto road in Petobo sliding area

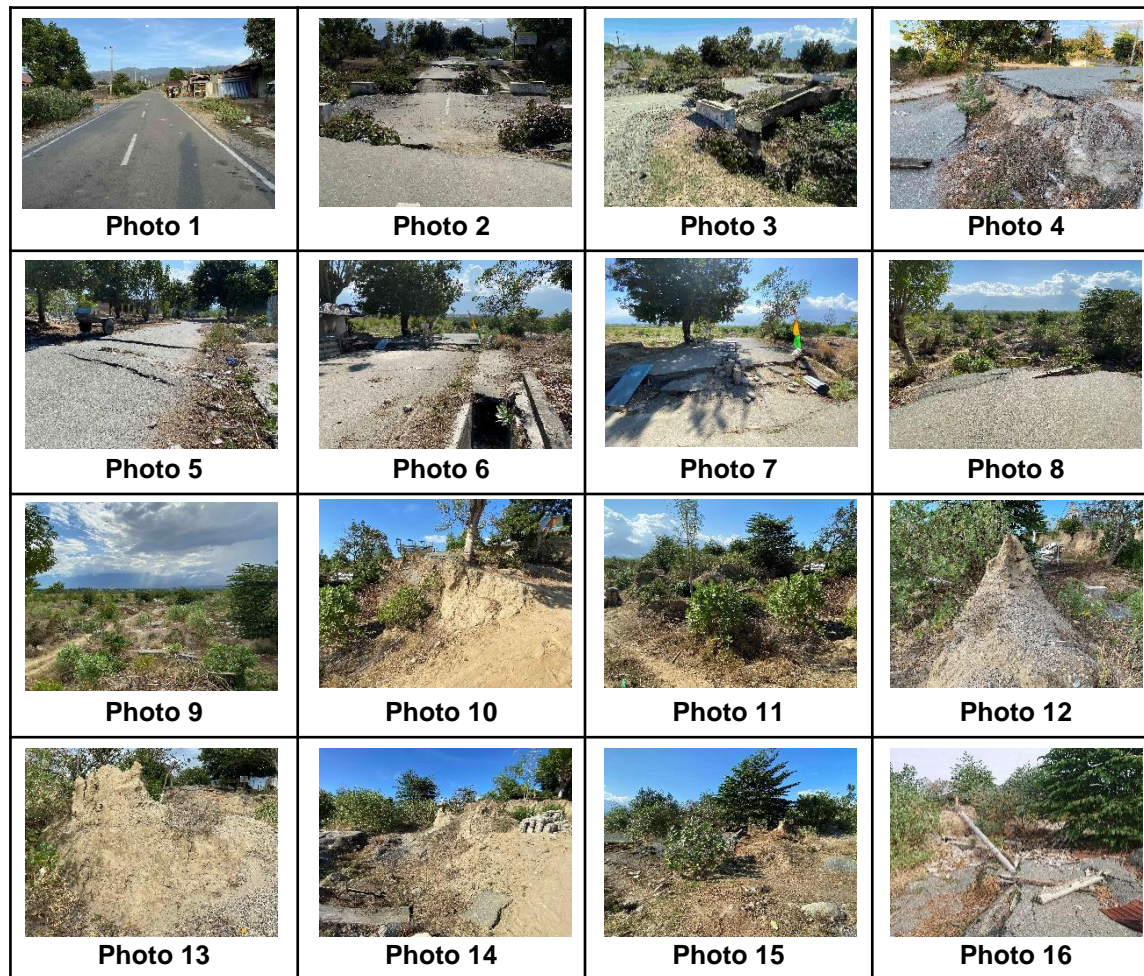


Fig. 16 Associated photos as indicated in the mapping sketch along Moh. Soeharto road to the east of Petobo sliding area.

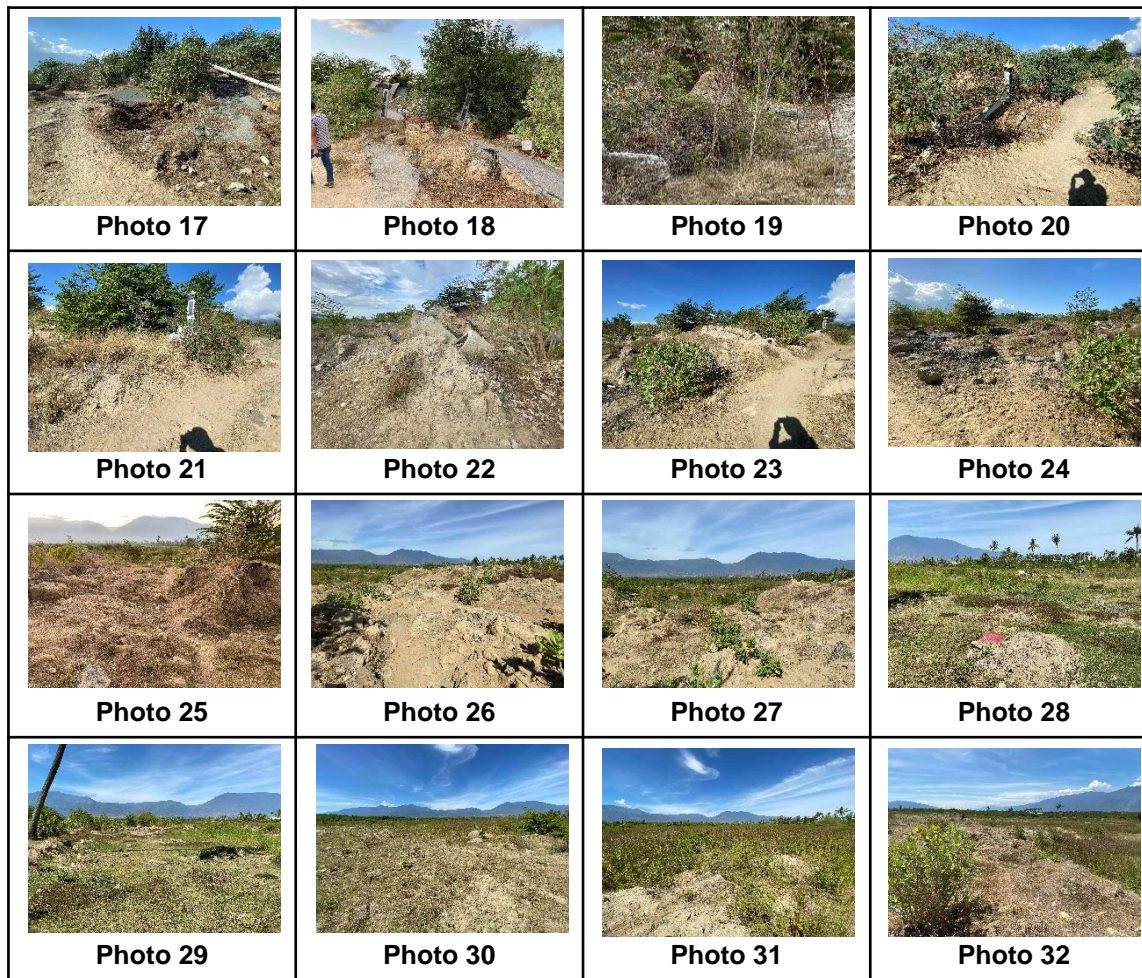


Fig. 16 Associated photos as indicated in the mapping sketch along Moh. Soeharto road to the east of Petobo sliding area.

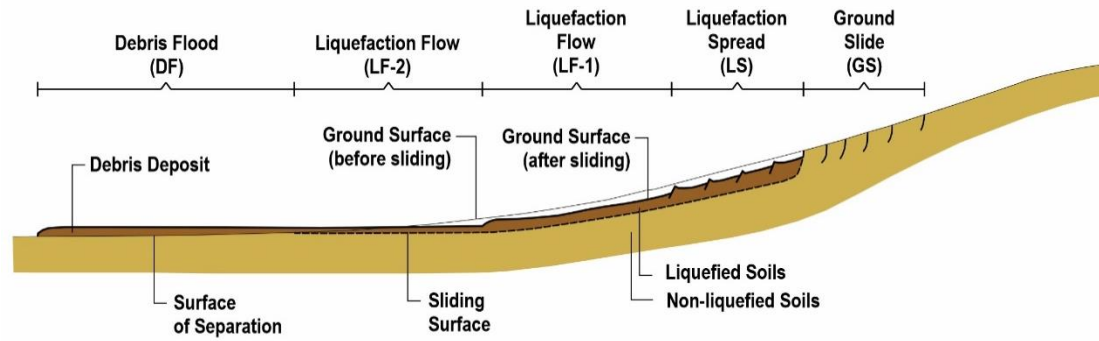


Fig. 17 Schematic illustration of types of morphological zonation observed in Petobo sliding area due to 2018 Palu-Donggala earthquake.

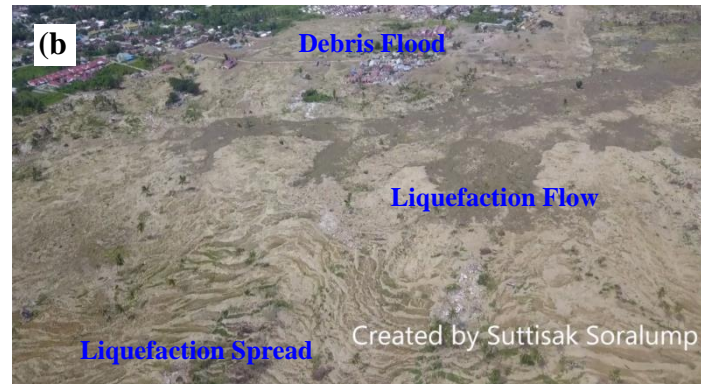


Fig. 18 Morphological features observed from the snapshots of drone videos by Soralump (2018). **a** Photo of the ground slide feature along Moh. Soeharto road to the east boundary of Petobo slide (facing east). **b** Photo of the features of liquefaction spread, liquefaction flow, and debris flood on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

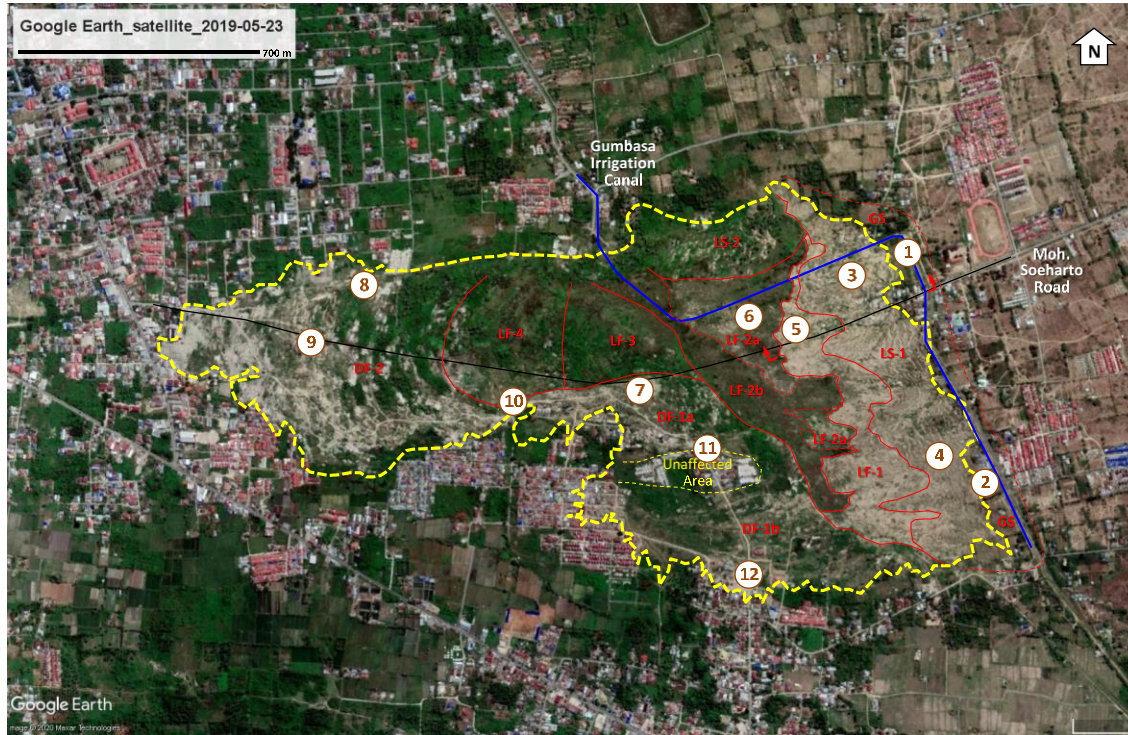


Fig. 19 Zonation of morphological features at Petobo sliding area, with locations of photos of representative morphologic features showing in the subsequent figure, as well as the location of mapped section along Moh. Soeharto road.



Photo 1 (Type: GS)



Photo 2 (Type: GS)



Photo 3 (Type: LS)



Photo 4 (Type: LS)



Photo 5 (Type: LF)



Photo 6 (Type: LF)



Photo 7 (Type: DF/LF)



Photo 8 (Type: DF)



Photo 9 (Type: DF)



Photo 10 (Type: DF)



Photo 11 (Type: DF)



Photo 12 (Type: DF)

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

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

| Findings related to paddy fields and the irrigation canal |
|--|
| <ul style="list-style-type: none"> • 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 30-50cm 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 |
| <ul style="list-style-type: none"> • Two severe shakings occurred on the same day; one (pre-shock) at about 3pm and the other (main shock) at about 6pm. • The main shock by severe shaking for about 10 seconds ~ 1 minute, with firstly vertical (U-D) vibrations then horizontal (N-S) shakings. • Witness L felt the shaking started with vertical vibrations for about 2 seconds, then followed by severe horizontal shaking. |
| Findings related to the sliding |
| <ul style="list-style-type: none"> • The ground moved subsequently soon after (few seconds ~ 20 seconds) 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 toward SW direction, and then the debris flow from the SE part of the sliding area moved toward NW direction. • Witness F observed the ground with a moving distance of 100 m would take about 2 min (note: ~3 km/hr). • 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 seconds per cycle (i.e., horizontal speed ~2.7 km/hr). • 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/hour). • 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 |
| <ul style="list-style-type: none"> • 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-degree 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 |
| <ul style="list-style-type: none"> • 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-degree 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-month 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 |
| <ul style="list-style-type: none"> • Several deep pump wells, with depths of around 130m 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. |

[Click here to view linked References](#)

Understanding of Petobo Liquefaction Flowslide by 2018.09.28 Palu-Donggala Indonesia Earthquake Based on Site Reconnaissance

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1 **Abstract** The Palu-Donggala earthquake struck Palu city of Sulawesi island, Indonesia, on 28
2 September 2018. A large-scale liquefaction phenomena occurred in some areas which caused
3 massive fatalities and destructions. The most severe liquefaction incident during the earthquake
4 followed by flowslides occurred in Petobo district of the city. The affected area due to Petobo
5 flowslide liquefaction was approximately 1.64 km². The damages were severe because of densely
6 populated area with estimated more than 3300 houses collapsed and nearly 2000 fatalities. The
7 slide materials transformed into debris and flowed on the low-relief ground of about 2% with a
8 slide distance of more than 800 m. A site reconnaissance of Petobo flowslide was conducted in
9 early 2020, which covered surface observations and documentations before and after the
10 flowslide, interpretations of geological characteristics, summary of witness interviews, analyses
11 of ground displacement, and changes in surface elevation and slope due to the flowslide. The
12 results reveal insights as to the failure mechanism of the Petobo flowslide. Based on the
13 observed phenomena on the surface, the Petobo flowslide area could generally be divided into
14 four types of morphology, namely, ground slide (GS), liquefaction spread (LS), liquefaction flow
15 (LF), and debris flood (DF). The GS and LS were considered to be the initiation zones, then the
16 slide materials spread down and formed LF zone. In this area, the soils became wet and muddy as
17 triggered by liquefaction. The liquefied materials then transported into DF zone where densely
18 populated areas in lower elevation of the site were hit.
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23 **Keywords:** *liquefaction flowslide, site reconnaissance, morphological characterization,*
24 *2018 Palu-Donggala Indonesia earthquake*
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Declarations

Funding

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Conflict of interest/Competing interest

The authors declare that they have no potential conflict of interest in relation to the study of this paper

Availability of data and material

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.

Authors' contributions

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.

Introduction

On 28 September 2018, the Petobo flowslide due to liquefaction was triggered by a massive earthquake of magnitude 7.5. The epicenter 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 2019). Hours before the mainshock, several earthquakes also hit Palu city. The largest foreshock registered as Mw 6.1 was occurred three hours 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 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 epicenters can be seen in Fig 1. The mainshock and the largest foreshock of this earthquake series are signed as red star and red dot.

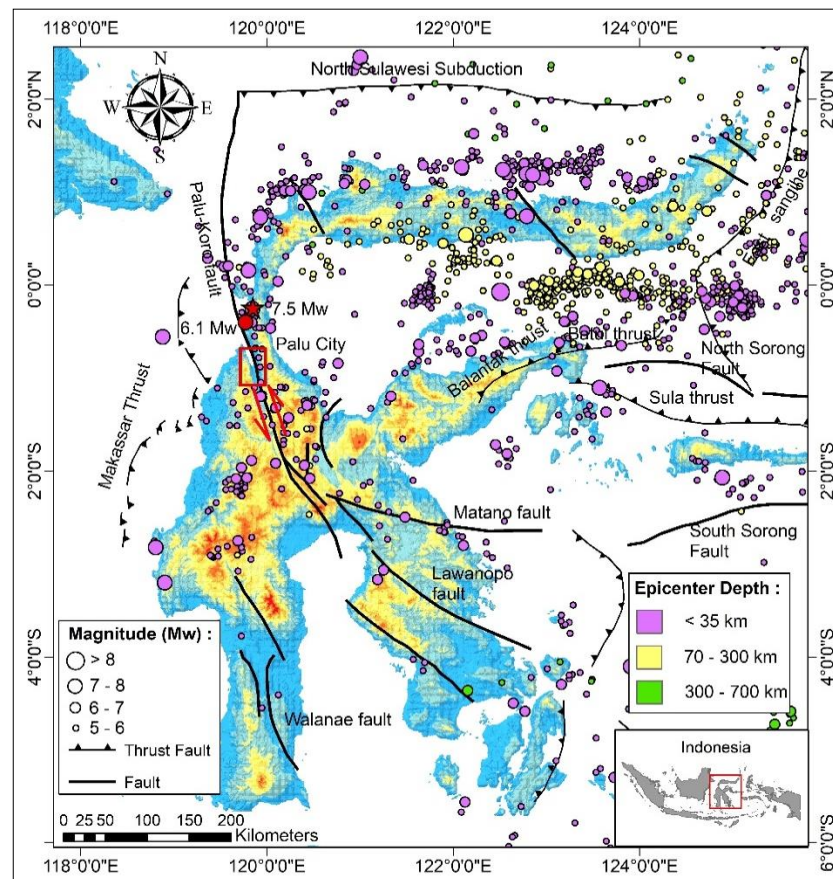
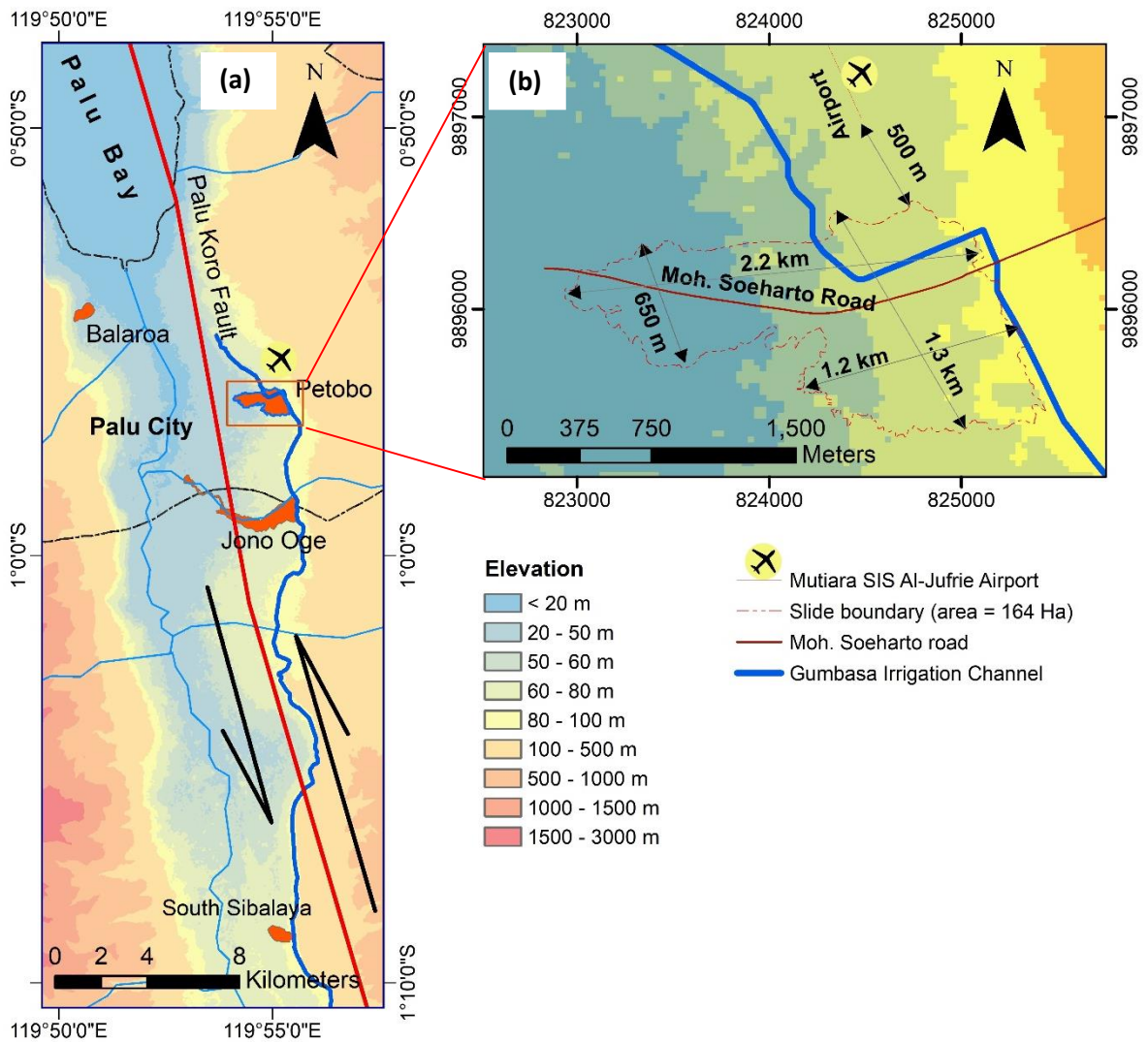


Fig. 1 Regional tectonic map in Sulawesi and surrounding. The size and colored dots indicate as magnitude and epicenter of earthquakes taken from USGS catalogue 1900-2019. Red rectangle is the location of Palu City. The locations of largest foreshock and mainshock of 2018.09.28 Palu Earthquake are shown 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).

1 The Petobo flowslide induced by liquefaction was recorded as one of the catastrophic
 2 liquefaction events in Indonesia with enormous size. At the same time, other flowslide
 3 locations were Balaroa, Jono Oge and South Sibalaya. The flowslides had caused a
 4 significant loss or missing of lives. Moreover, many buildings and infrastructures were
 5 severely damaged (Bradley et al. 2019; Hidayat et al. 2020).
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7 As seen in Fig. 2, Petobo flowslide is located in Palu City, approximately 0.5 km south
 8 of Mutiara SIS Al-Jufrie airport. The flowslide area is around 164 Ha, with lengths along
 9 the north and south portions of the slide are 2.2 km and 1.2 km, respectively. The widths
 10 extended on along the east and west portions of the slide are 1.3 km and 650 m,
 11 respectively.
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 51 **Fig. 2** a Flowslide locations after Palu-Donggala earthquake of 2018.09.28. b Dimensions of Petobo
 52 flowslide. Credit: Base map adapted from GADM, base digital elevation model derived from JAXA's ALOS
 53 Global Digital Surface Model 30 m x 30 m resolution.

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 55 However, many geotechnical aspects still remained after the earthquake, which are
 56 relevant to be investigated to find out the causes and mechanism of the slide as well as
 57 lessons to be learned. Consequently, a reconnaissance was conducted in Petobo
 58 flowslide area to document the surface conditions before and after the earthquake.
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This paper presents our onsite observations with respect to the classification of morphological zones and the possible mechanism of the flowslide. The paper also summarizes 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, 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.

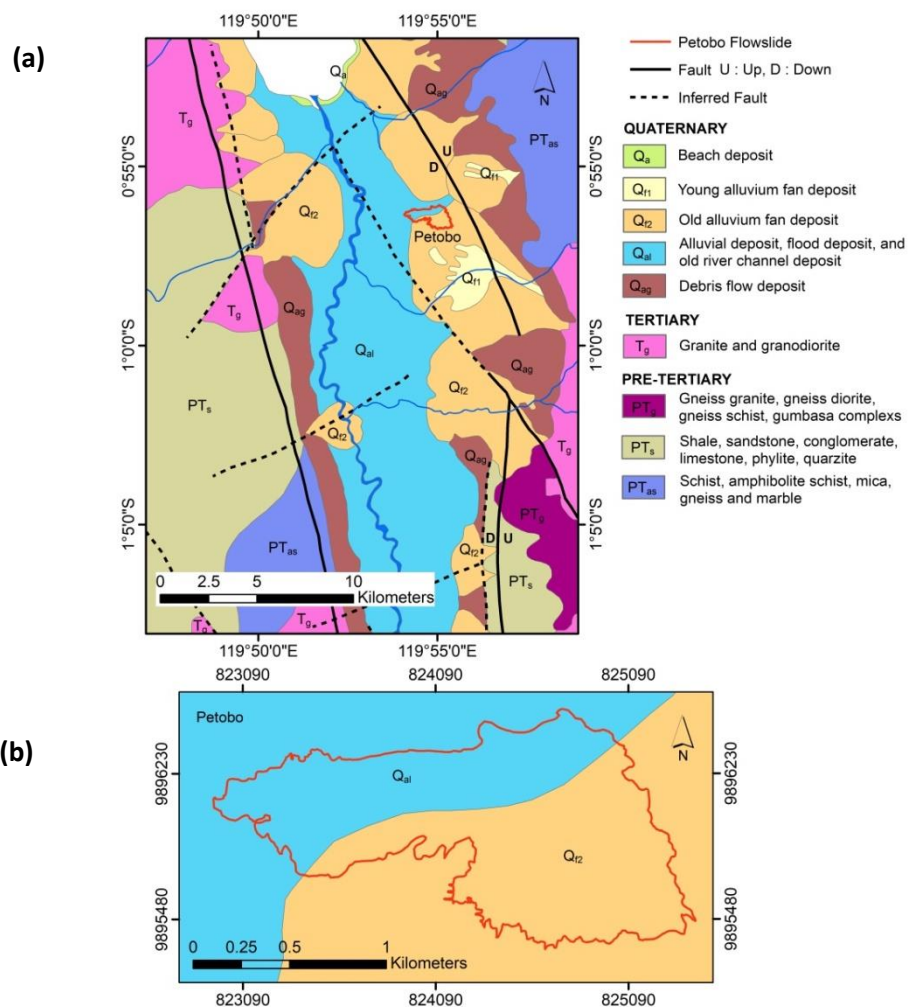


Fig. 3 a Geological map of Palu and surroundings (Hanifa 2018) consists of surficial deposits in Quaternary, Tertiary and Pre-Tertiary periods. The study area is identified by the red line. b Location of the study area is composed dominantly by the old alluvium fan deposit and the alluvial, flood and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

1
2 The Palu-Koro fault in Palu Valley has experienced an evolution with age for two
3 distinct alluvial fan units, i.e., old alluvial fans and young alluvial fans (Bellier et al. 1999).
4 The Petobo flowslide area is situated on the old alluvium fan deposit formation (Qf2)
5 and the alluvial, flood and old river channel deposit formation (Qal) of the Palu river
6 valley. The alluvial and flood deposit consists of mostly sand, silt and clay (Pyi et al.
7 2015). Furthermore, the alluvial fan deposit is typically composed by gravel-sand
8 transitions and it often exhibits similar gravelly soils with a narrow particle size
9 distribution. Due to poor particle gradations, the soil contains a series of voids where
10 water easily fulfils the voids and saturates the soil (Litwin et al. 2014). During the 2018
11 Palu earthquake, a strike slip fault was ruptured at north west of Palu Valley and
12 initiated the deformation in the surface. It could be observed by the appearance of a
13 series of ridges uplifted associated with transpression deformation. Furthermore, along
14 the eastern part of old alluvial fans appeared fault scarps which represent normal
15 faulting activity (Patria et al. 2020).
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21 **Seismic history**

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23 Sulawesi island is located in the Sundablock adjacent with three tectonic plates: Pacific,
24 Australia and Philippine plates, which is also known as a triple junction (Kadarusman et
25 al. 2011; Bellier et al. 2001; Watkinson and Hall 2017; Socquet et al. 2019). Since this
26 triple junction causes a complex tectonic system in Sulawesi, including strike-slip and
27 thrust faults, earthquakes are frequent (Patria and Putra 2020; Nugraha and Hall 2018).
28 The Indonesia National earthquake source and hazard map reveals nearly 50 active fault
29 segments are detected in Sulawesi as well as the North Sulawesi Megathrust in the
30 north of Sulawesi (Irsyam et al. 2020). The subduction along the North Sulawesi
31 Megathrust generates seismicity in Sulawesi which is significantly high (Jaya et al. 2019;
32 PusGen 2018). The Palu-Koro fault as mentioned is a significant seismic system in Central
33 Sulawesi, which extends from north-west to south-east across Sulawesi for more than
34 300 km long. The fault starts from North Sulawesi trench, passing through Palu Bay,
35 turning southwards to south-east, then connecting to Matano and Lawanopo faults.
36 Both faults join further eastwards to Tolo trench (Bellier et al. 2006; Socquet et al. 2006;
37 Watkinson and Hall 2019).
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45 Fig. 1 illustrates tectonic activities in Central Sulawesi region. Historical destructive
46 earthquakes of more than Mw 5 along Palu-Koro fault zone repeatedly occurred with
47 epicenters located either offshore or inland as shown by purple dots. One of the
48 earthquakes along Palu-Koro fault was described by Abendanon (1917), indicating the
49 1907 earthquake was followed by a more damaging earthquake two years later.
50 Abendanon reported that the 1909 earthquake had almost destroyed the houses that
51 survived during the 1907 earthquake. The damages spread along from Saluki up to
52 Donggala regions. It was noticed the appearance of a surface cracking of 7 km long with
53 an uplift of 1 m. Evidence of a vertical slip of 1.5 m and a sinistral slip of 1.5 m were also
54 observed after a trench excavation in Onu Village along Saluki segment.
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58 Kiyota et al. (2020) reported the measured shaking data of the 2018 Palu-Donggala
59 earthquake consisted of two horizontal components (EW and NS) and a vertical motion
60 (UD). The resultant peak horizontal vector acceleration (PGA) of 333 gal (0.34 g) was
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1 recorded during the earthquake. The predominant frequency of motion was measured
2 in between 0.2 to 0.6 Hz, which revealed the intense shaking of the small frequency
3 range may well have been responsible for the severe geotechnical damages.
4

5 **Liquefaction susceptibility**

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7 Regional geology of Palu area is composed of alluvium and flood deposits. Risna (2012)
8 reported a preliminary study of liquefaction potential in Palu and the surrounding.
9 Several cone penetration tests were conducted on the site to obtain the characteristic of
10 soils. The field testing revealed, for mostly of the alluvium and debris deposits, the soil
11 layers generally consist of sands on the top, silt in the middle and clay at the bottom.
12 Grey sands are generally loose, poorly graded, good porosity and permeability, with a
13 thickness of 1 – 7.2 m. Silts are normally found under the sands with a consistency of
14 soft to firm, medium plasticity, and a thickness of 0.2 – 0.7 m. The clays are brown to
15 dark brown, soft to firm, highly plastic, with a thickness varied between 0.1 – 2.7 m.
16 Weathered soils underneath in this formation are generally grey sands, loose, well-
17 graded, good porosity and permeability, with a thickness of about 3.5 m. ~~A suspect area
18 with a high risk of liquefaction occurrence is in the alluvium deposit.~~ In this area, the
19 depth of groundwater level is less than 12 m. The alteration of soil behaviour in each soil
20 layers could be occurred when experienced by seismic wave. When the seismic wave
21 propagated from the bedrock through the saturated sand soil layers, it lead the
22 decreasing of effective soil stress. A susceptibility of liquefaction could be reached when
23 pore water pressure equal to initial effective stress. In Palu city and surroundings, a
24 suspect area with a high risk of liquefaction occurrence is in the alluvium deposit. Details
25 of liquefaction susceptibility and groundwater level in Palu and surrounding can be seen
26 in Fig. 4.
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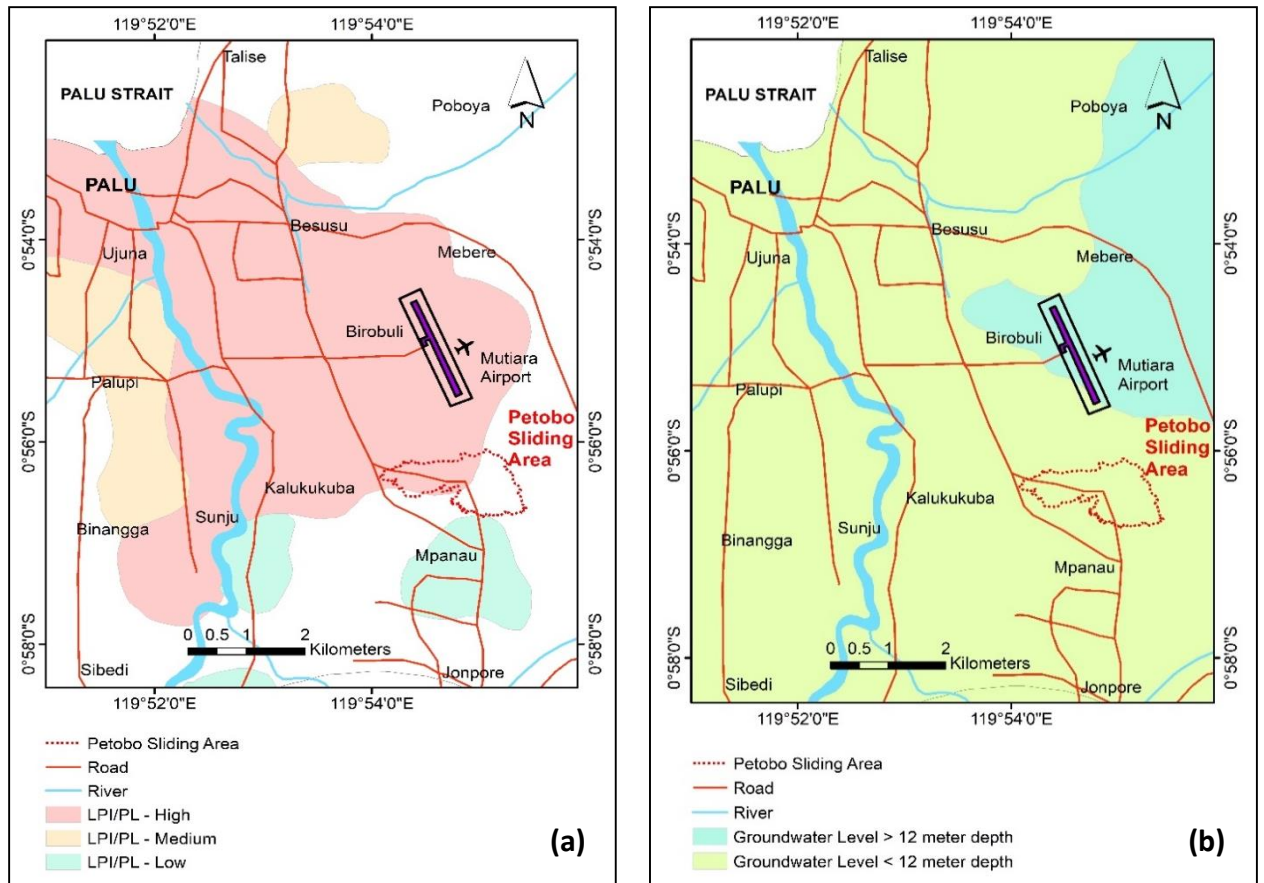


Fig. 4 a The map of liquefaction susceptibility in Palu and surrounding with three levels of potential of liquefaction. Palu city is identified to have a high possibility of liquefaction occurrence in particular to the east of Palu river. One of triggering factors contributed to liquefaction occurrence 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.

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.

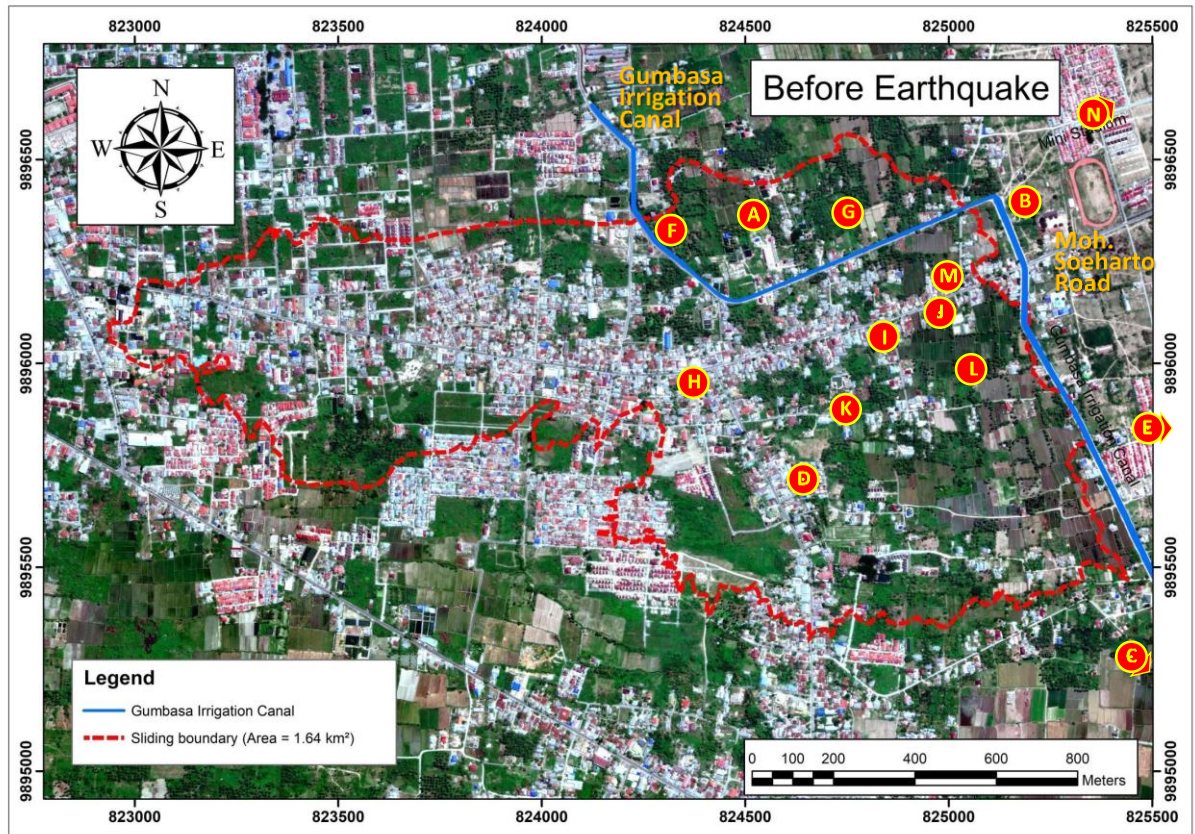


Fig. 5 Locations where interviewed witnesses were in the Petobo area during 2018.09.28 Palu-Donggala earthquake. Based photo is taken from Google Earth satellite image of 2018.08.17.

Table 1 summaries 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 2019).

As regard to 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 seconds 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 seconds 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 seconds after the shaking. Although there might have involved to some degrees 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 toward north portion of the sliding area.

The witness interviews also revealed the information on the form and velocity of the sliding. Generally, for 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

1 severe spreading of the ground due to liquefaction of underneath soils by the shaking,
2 and the back and forth moving actions of the spreading would likely be the reason for
3 how they felt. Witnesses F, G and L had also described in different ways on how fast the
4 slide was moving. It could be estimated based on their statements that the sliding their
5 had experienced were approximately in a velocity of 2.5~5 km/hr, or equivalently a
6 speed of walking to jogging.
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8 With respect to liquefaction phenomena, most of the interviewees observed the
9 ground extruded by dark muddy water, resemblance to mortar, which was warm and
10 with an erupted height up to around 2 m and 5 m, in the NE and SE portions
11 respectively, of the sliding area. Few big eruptions of sands were also observed near the
12 central portion, approximately along Moh. Soeharto road of the sliding area, with
13 eruptions up to a coconut tree high. For post-slide observations of the ground, most
14 interviewees indicated the ground was very wet and soft, and some places were ponded
15 with water up to 1 m. It took months for the ponded lands to be gradually retreated. In
16 fact, when the research team of this study visited the site in early 2020, several locations
17 in the middle portion of the sliding area were still ponded with water. Those waters
18 were believed to have been formed as a result of extruded pore water due to severe
19 liquefactions of the ground by the shaking.
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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 30-50cm 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 3pm and the other (main shock) at about 6pm.
- The main shock by severe shaking for about 10 seconds ~ 1 minute, with firstly vertical (U-D) vibrations then horizontal (N-S) shakings.
- Witness L felt the shaking started with vertical vibrations for about 2 seconds, then followed by severe horizontal shaking.

Findings related to the sliding

- The ground moved subsequently soon after (few seconds ~ 20 seconds) 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 toward SW direction, and then the debris flow from the SE part of the sliding area moved toward NW direction.
- Witness F observed the ground with a moving distance of 100 m would take about 2 min (note: ~3 km/hr).
- 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 seconds per cycle (i.e., horizontal speed ~2.7 km/hr).
- 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/hour).
- 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-degree 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-degree 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-month 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.

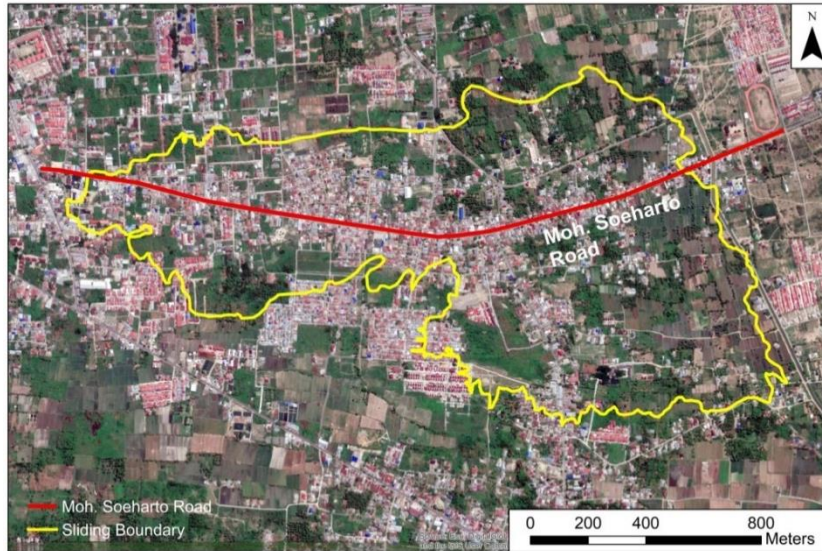
Findings related to others

- Several deep pump wells, with depths of around 130m 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.

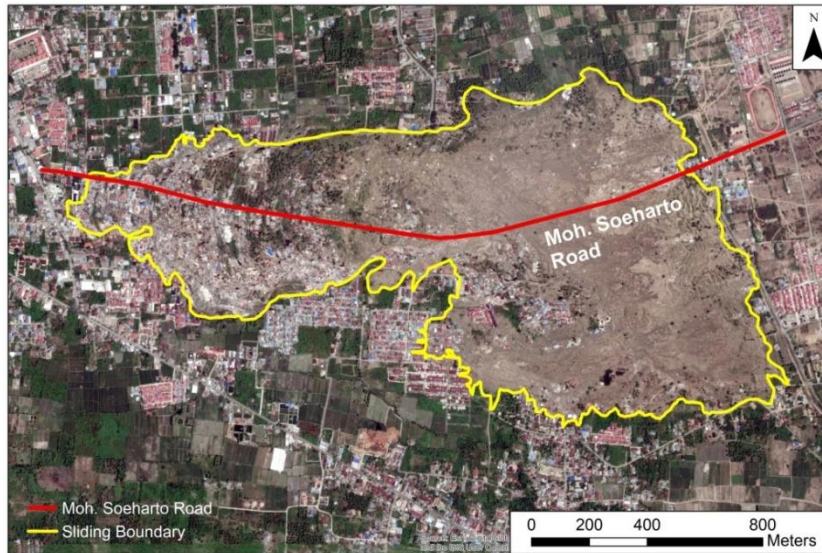
Land-use changes

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2 The earthquake caused land-use changes in Petobo area. Fig. 6 illustrates the land-use
3 changes at different periods. As shown in Fig. 6(a), the eastern and southern parts of the
4 Petobo flowslide area before earthquake were mostly paddy fields, while residential
5 area was densely populated in the western and middle parts. A main road of Moh.
6 Soeharto passed across the flowslide zone from east to west. The earthquake shaking
7 obviously destructed the eastern part of site and swept away everything, such as
8 people, properties and houses, etc., westwards. Fig.6 (b) indicates the area hit by
9 liquefaction flowslide was covered by debris on the surface in brown color. Fig. 6(c)
10 shows the condition of the site one year after the disaster. As can be seen, the area was
11 almost preserved, as confirmed by our team during site investigation, where no
12 reconstruction was noticed and the damaged infrastructures could be observed as an
13 accumulation of ruined debris in the western part of flowslide area.
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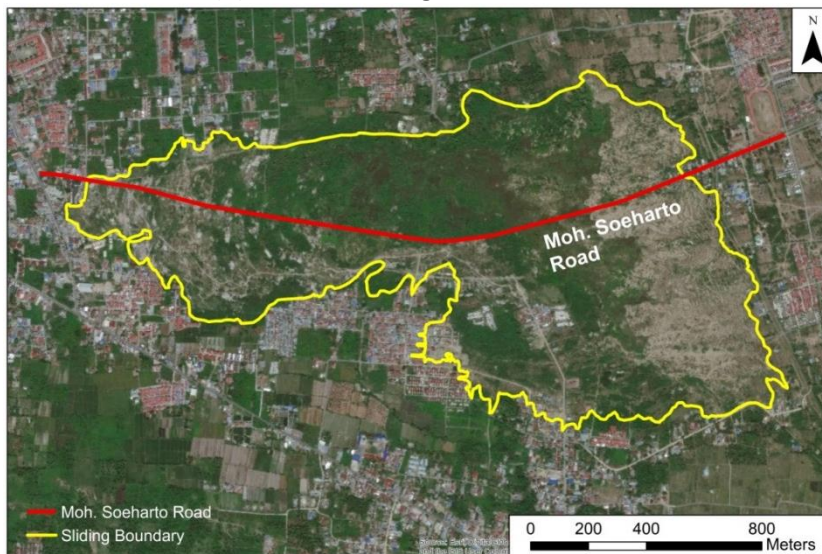
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(a) Pre-slide image on 2018.08.17



(b) Post-slide image on 2018.10.02



(c) Recent image on 2019.11.06

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.

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. 7(a)). 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. 7(b)), where houses and people were not hit directly but surrounded by the flowslides.

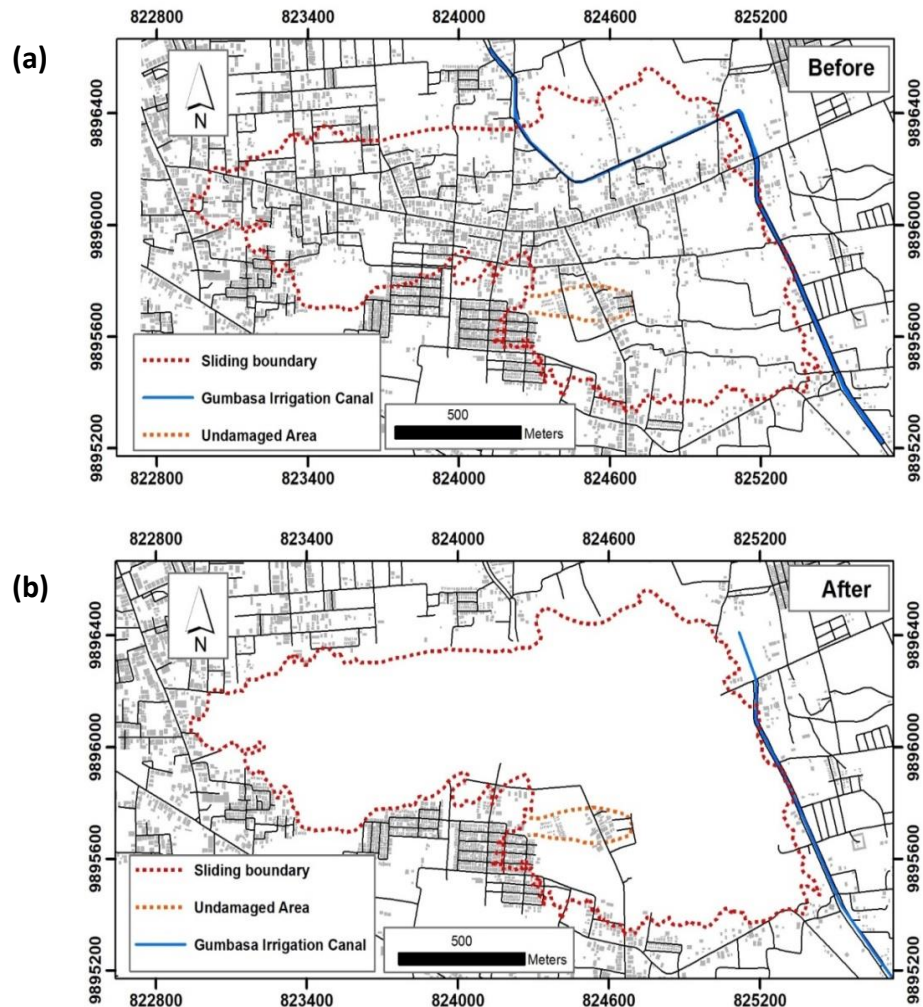


Fig. 7 The site condition before and after the earthquake. **a** Condition before earthquake where Gumbasa irrigation canal passed across the flowslide area. **b** Situation after the earthquake where Gumbasa irrigation canal in the NE portion of the sliding was swept away and an undamaged area was found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

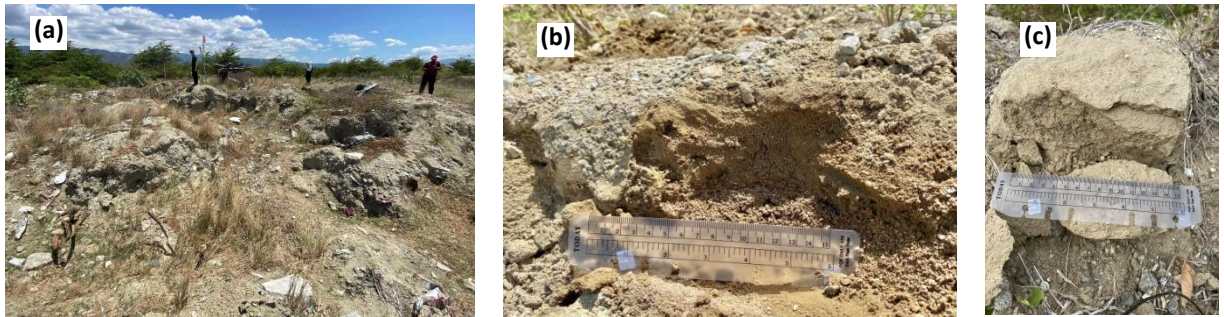


Fig. 8 a. A site with big eruptions of sands during earthquake based on the interviews with Witnesses G and H. The location was near District Office of Petobo (Kantor Kelurahan Petobo). b, c Exposed sands as evidences of soil liquefaction.

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

Photos 1 & 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 & 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 original 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 damaged or torn (Photos 7 & 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. 7(b)) to the southern portion of Petobo site. As shown in these 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.

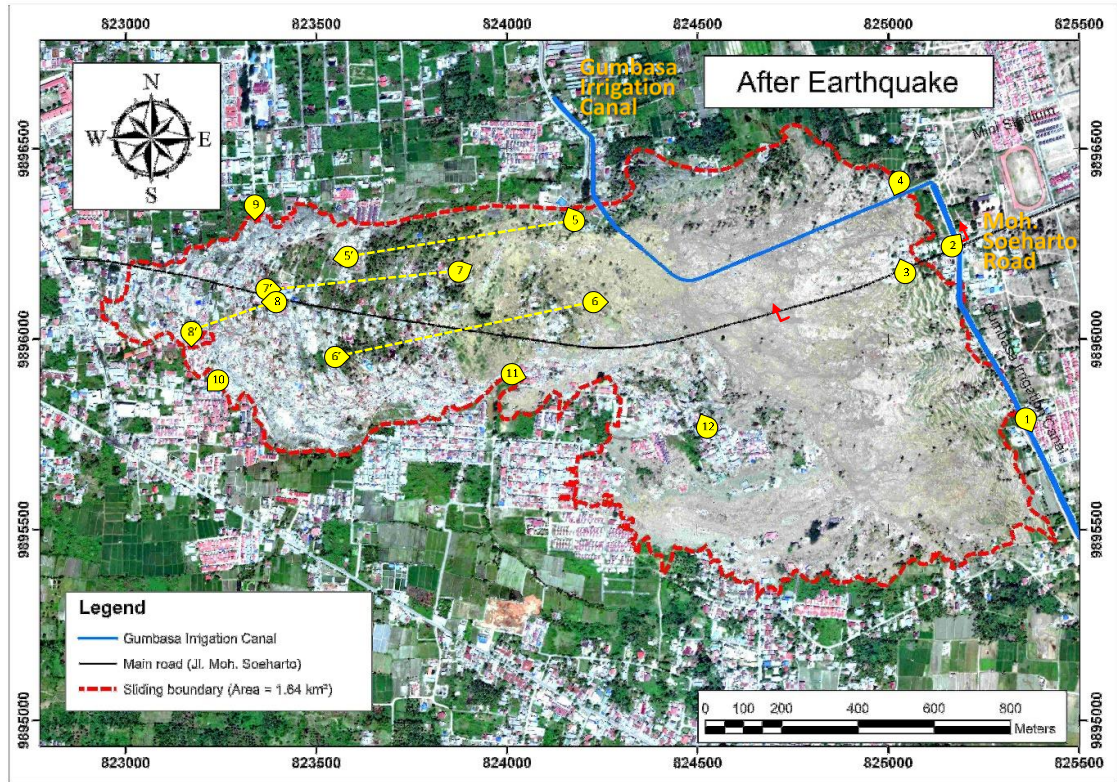


Fig. 9 Locations of key features at Petobo site for pre- and post-slide comparison, with also the location of mapped section along Moh. Soeharto road discussed in the later part of this paper. The base photo is taken from Google Earth satellite image of 2018.10.02.



Photo 1. Before EQ (looking S)



Photo 1'. After EQ (looking S)



Photo 2. Before EQ (looking NE)



Photo 2'. After EQ (looking NE)



Photo 3. Before EQ (looking N)



Photo 3'. After EQ (looking N)



Photo 4. Before EQ (looking SW)



Photo 4'. After EQ (looking SW)



Photo 5. Before EQ (looking NW)



Photo 5'. After EQ (looking W)



Photo 6. Before EQ (looking E)

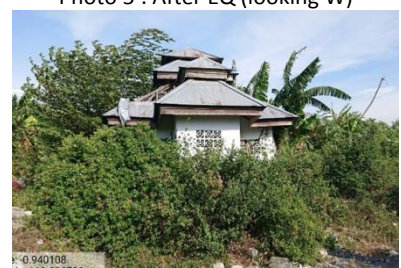


Photo 6'. After EQ (looking E)

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Photo 7. Before EQ (looking E)



Photo 7'. After EQ (looking E)



Photo 8. Before EQ (looking W)



Photo 8'. After EQ (looking S)



Photo 9. Before EQ (looking SE)



Photo 9'. After EQ (looking SE)

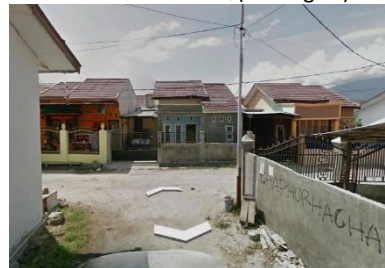


Photo 10. Before EQ (looking SW)



Photo 10'. After EQ (looking SW)



Photo 11. Before EQ (looking E)



Photo 11'. After EQ (looking E)



Photo 12. Before EQ (looking NW)



Photo 12'. After EQ (looking NW)

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.

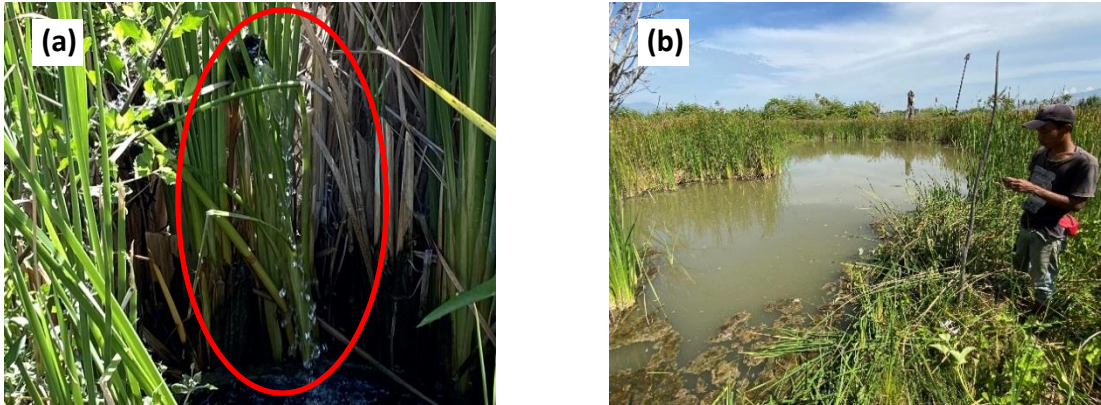


Fig. 11 a The presence of artesian waters in the flowslide area. b A swamp with ponded water in the middle part of the sliding area.

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. Fig. 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.

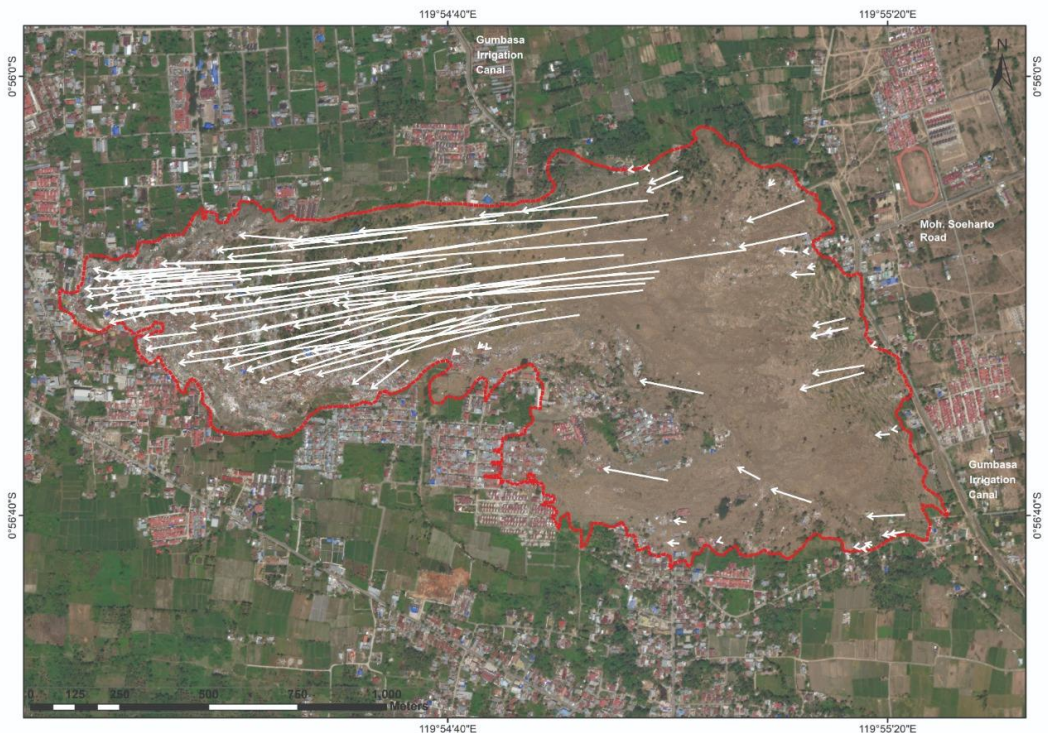


Fig. 12 Displacement vectors of surface objects identified by onsite investigation as well as based on Google Earth satellite images before the after the earthquake. Purple dots are the initial locations and pink dots are the ending positions. The white arrows are the direction of displacements. Base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

Elevation and slope changes after earthquake

The flowslide liquefaction contributed to the changes in soil elevation in Petobo area. Fig. 13(a) describes the elevation changes due to the earthquake. Fig. 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.

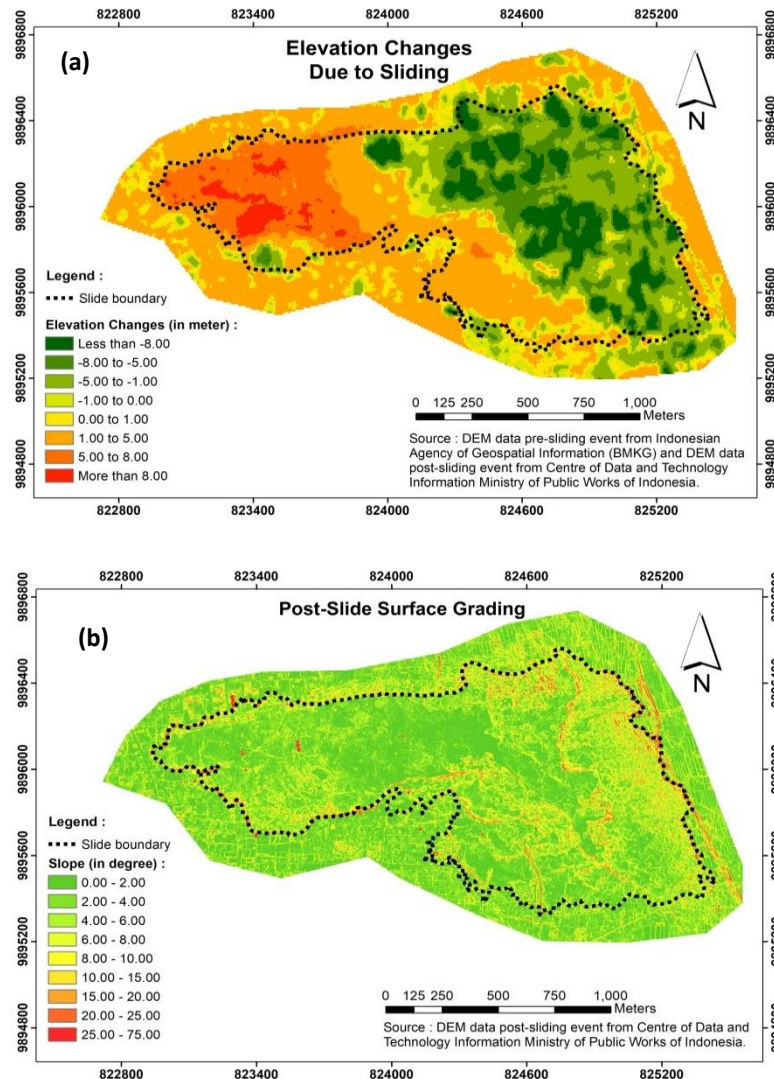


Fig. 13 a The elevation changes due to sliding. b The grading of ground surface after the earthquake. The elevation changes varied approximately between -8 m and 8 m. In the eastern part the elevation dropped down more than 8 m (green color) and in the western part raised

more than 8 m (red color). 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.

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 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 neighborhood. 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 & 2; Fig. 10) and the paddy fields were also inundated with water for about 8-months plantation time annually, which are based on our site reconnaissance as summarized in Table 1. During the plantation, the paddy fields 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 which would constantly supply the local ground water tables under the paddy fields. In our opinion the rainfall would appear 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.

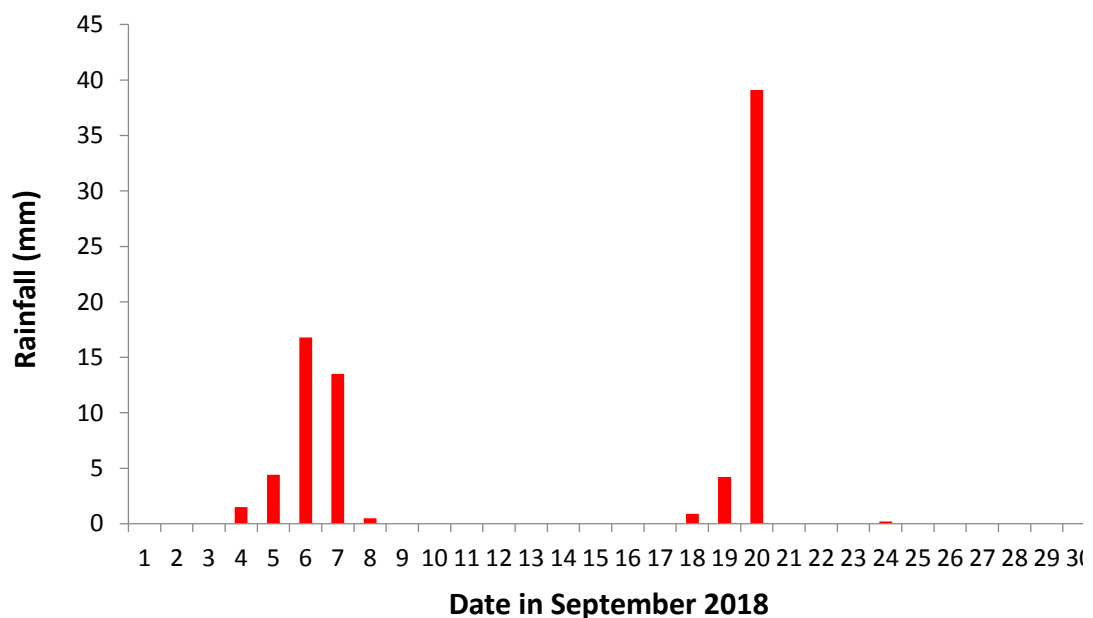


Fig. 14 Daily rainfall intensity during September 2018 in study area which clearly indicates the absence of rain a week before the flowslide occurred (Meteorological, Climatological and Geophysical Agency 2021).

1 In view of mostly unlined Gumbasa irrigation canal along eastern boundary of Petobo
2 area and a long plantation period of wet paddy fields, the underground soils were easily
3 saturated causing localized raised ground water tables. The localized high groundwater
4 tables in downstream side of Gumbasa canal and under the paddy fields to the eastern
5 portion of the Petobo site would have had a significant contribution to the severe
6 liquefaction phenomena observed onsite during the earthquake.
7

8 It was noticed during our site visit where northern section of the irrigation canal had
9 been completely swept away during the slide. It was also observed a different type of
10 failure along the east periphery of Gumbasa irrigation canal where a big head scarp was
11 formed. These areas would appear to be the uppermost portion of Petobo slide as we
12 could be see a series of tensile cracking parallel to the prominent scarp along with the
13 irrigation canal.
14

15 The disappeared water from the canal during the earthquake would have played an
16 important role on ground failure. We notice scarps or longitudinal cracks in the unlined
17 canal would have facilitated the conveyance of water into the downstream liquefiable
18 sandy layers and maintained high pore pressures in the layers generated by the shaking.
19 Hence, the downstream slopes could have been sliding for some durations and with
20 large distances.
21

22 **Observed morphological features along Moh. Soeharto road**

23 The research team had conducted a detailed mapping on the surface along the east
24 section of Moh. Soeharto road, to examine phenomena of the ground that would help
25 the characterization of morphological features and zonation of the site as well as our
26 understanding on the initiation and process of sliding due to liquefaction of this
27 earthquake incident. The mapping was started approximately 10 m east of Gumbasa
28 irrigation canal and headed westwards along the road with a distance of about 520 m,
29 accounted for roughly 1/4 of the length of Moh. Soeharto road that passed
30 longitudinally (from east to west) across the sliding area. Fig. 15 illustrates results of the
31 mapping and Fig. 16 shows associated photos taken along the road with the numbers
32 marked on the mapped sketch. Location of the mapped section is indicated in Fig. 9 and
33 Fig. 19.
34

35 To the east of starting point (Mileage 0), the pavement of Moh. Soeharto road was
36 almost intact (Photo 1; Fig. 16). However, several fractures and slippages were observed
37 to the west and along the road up to a mileage of about 30 m (Photos 2~4; Fig. 16). The
38 surface cracking became scarce until a mileage of 130 m (Photos 5 & 6; Fig. 16). Then a
39 serious slippage was apparent with a head scarp of 3 m high (Photos 7~10; Fig. 16), an
40 indication where the slide had initiated. In the subsequent mapping range with Mileages
41 130-290 m, the ground elevations subsided approximately 6 m, on which the surface
42 was extremely rugged, fractured and filled with extruded sands (Photos 11~24; Fig. 16).
43

44 Within this range of mapping, we noticed several earthen ridges of 1~2 m high, an
45 example shown in Photo 12 (Fig. 16), which were observed periodically for
46 approximately 10~20 m distance apart. This phenomenon would appear to be in relation
47 to the testimonies by Witnesses G, K, L and M, who had indicated a wavy-form of
48 ground sliding, with vertical amplitudes of 1.5~2 m and travelling distances of around 15
49 m (Table 1). In view of the locations of witnesses during the earthquake, we expect
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1 these peoples might have been experiencing a liquefaction spreading during the
2 earthquake shaking. Photos 18, 20~23 (Fig. 16) are indicative of tearing, tilting and
3 settling of houses and water pipes as a result of the spreading of the ground.

4 In the subsequent mapping range with Mileages 290~492 m, the ground elevations
5 once again dropped by additional 2~4 m. However, the surface appeared to be less
6 rugged, more gentle, and more abundant with extruded sands on the ground (Photo 25;
7 Fig. 16). The observed phenomena in this mapping range would suggest the ground
8 might have liquefied significantly during the shaking and flowed further to the west
9 (lower lands) after the earthquake. Photos 26 & 27 (Fig. 16) show the forefront of the
10 liquefaction flow.
11

12 For the lands further to the west of Mileage 492 m, the ground elevation decreased
13 substantially by 6 m or more. The ground became more flat, but wet, swampy and full of
14 aquatic plants that had prevented the research team to approach further. Photos 28~32
15 (Fig. 16) show distant views of the lower lands. As seen, the ground was exposed with
16 sands, water ponds and aquatic plants. These areas were also suggested a separate
17 stage of liquefaction flow that followed subsequently the previous flow stage as
18 identified in Mileages 290~492 m.
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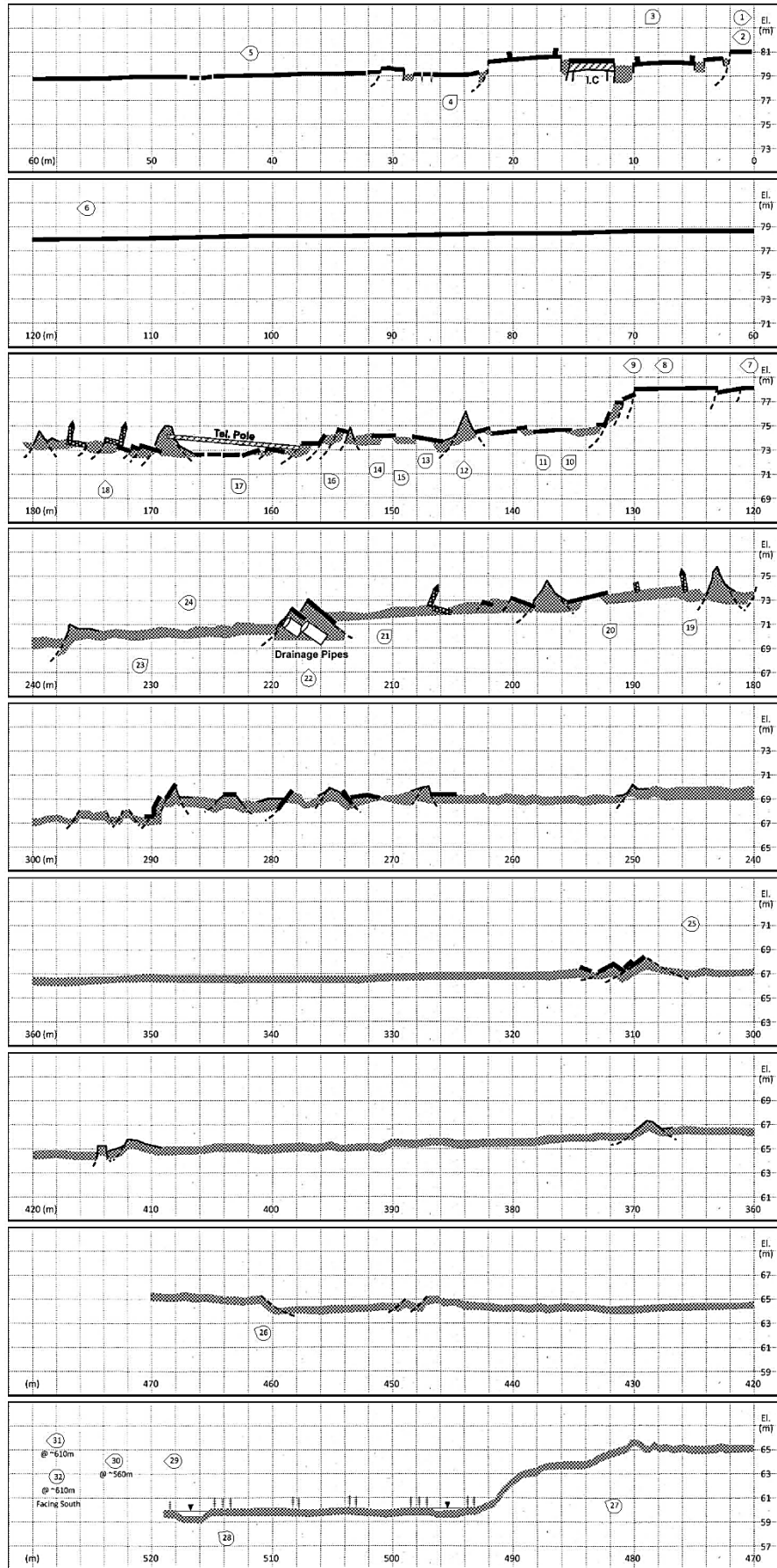


Fig. 15 Mapping of east section of Moh. Soeharto road in Petobo sliding area.

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

Morphological zonation of Petobo sliding area

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2 Based on results of mapping on Moh. Soeharto road, the observed surface features
3 could be classified into several morphological types. These morphological features might
4 have been in relation to the initiation and the progress of sliding in Petobo during the
5 earthquake. To be consistent with the terminologies commonly adopted in geotechnical
6 engineering as indicated by Hungr et al. (2013), we propose four types of morphological
7 features for this study, as depicted in the schematic illustration shown in Fig. 17. The
8 associated definitions of the morphological features are addressed below:
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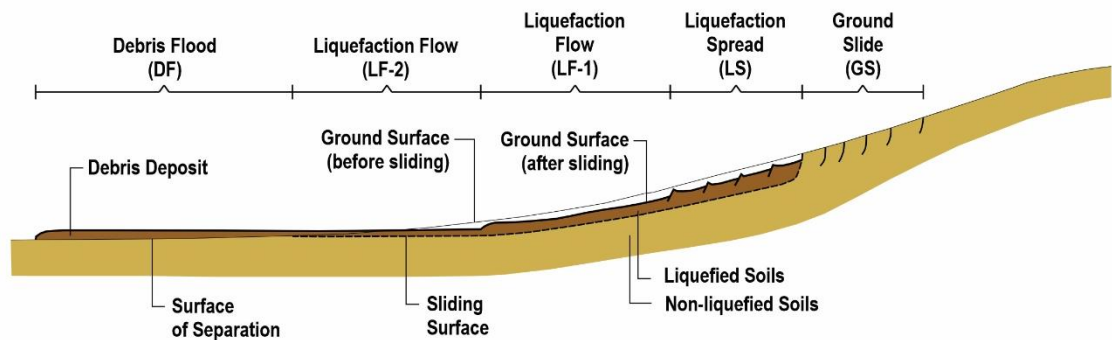
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11 Ground Slide (GS) – “Ground Slide” is a phenomenon of failure by the slippage of
12 coherent earthen materials, as identified between Mileages 0~130 m of the mapped
13 section (Fig. 15) and illustrated in Fig. 17. Generally, cracks or scarps are visible on the
14 surface, which divide the ground into several chunky earthen blocks. Ground slides may
15 be triggered by a sudden increase in the inertia of ground, such as earthquake shaking,
16 and/or due to a decrease or loss of the downslope supports, such as a cut at slope toe.
17 The sliding/slip surfaces are basically passing through the intact earthen mass, which is
18 not liquefied during the ground shaking.
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21 Liquefaction Spread (LS) – “Liquefaction Spread” is a phenomenon of failure by the
22 laterally cyclic spreading of earthen crust due to underneath liquefied soils in the
23 process of shaking, as appeared in the mapped section between Mileages 130~290 m
24 (Fig. 15) and in Fig. 17. Surface manifestations of liquefaction spread may include a
25 series of linear cracks or earthen peaks (ridges) with broken and lowered ground
26 sideways (i.e., horst and graben terrain). Surface structures may be destroyed, tilted or
27 distorted (elongated) as a result of the cyclic movements and spreading of earthen crust.
28 Extruded liquefied sands may be found on the ground in areas of cracking and peaking.
29 Liquefaction spreads are triggered by the liquefaction of underneath soils. Due to cyclic
30 nature of shaking, the earthen crust will move back and forth laterally, resulting in a
31 gradual spreading, and a lowering height as well, in a direction with less lateral
32 restraints.
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35 Liquefaction Flow (LF) – “Liquefaction Flow” is a phenomenon of failure by the
36 monotonic sliding or flowing of fully liquefied earthen materials, occurring primarily
37 after the earthquake shaking, as depicted in Mileages 290~492 m and beyond of the
38 mapped section (Fig. 15) and in Fig. 17. The ground surface of liquefaction flows is
39 usually uneven and bumpy with extensive exposures of liquefied sands. Structures on
40 the liquefied surface may sink (buried), tilt or float with the flow for a large distance.
41 Liquefaction flows usually occur in an inclined ground in which the earthen materials are
42 fully saturated and liquefied due to ground shaking. As a result of the gravity and/or
43 additional driving forces from upper sides of the slope, such as by ground slips or
44 liquefaction spreads, the liquefied earthen materials may start flowing downslope
45 following the shaking. Liquefaction flow may proceed in stages, as shown in Fig. 17,
46 depending on the viscosity of liquefied earthen materials, the degree of liquefaction that
47 sliding mass can sustain, the history of shaking, and the geometry of ground and sliding
48 surfaces, etc.
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51 Debris Flood (DF) – “Debris Flood” is a phenomenon of failure, similar to
52 “Liquefaction Flow”, by the monotonic sliding or flowing of liquefied earthen materials
53 mixed with construction debris. However, the debris flood is different with the aspect
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1 that the existing ground of flood area is generally non-liquefied (i.e., stable) but covered
 2 with liquefied soils and debris from the upstream side (Fig. 17). The flowing earthen soils
 3 mixed with construction debris are massive and mighty, and are destructive for the
 4 structures on the existing ground. Surface manifestations of the debris flood are
 5 characterized by the irregular surface of liquefied earthen materials and debris, the
 6 destroyed existing and transported structures, and the elevated ground surface as
 7 opposed to the adjacent areas unaffected by the flooding. Causes of debris floods are
 8 similar to those of liquefaction flows. The earthen materials on upstream side first fully
 9 liquefy during earthquake shaking, then flow downslope by gravity following the
 10 shaking.
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 27 **Fig. 17** Schematic illustration of types of morphological zonation observed in Petobo sliding area due to
 28 2018 Palu-Donggala earthquake.
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31 The characterized morphological features can generally be visualized through the
 32 bird's eye views of drone photos by Soralump (2018). As shown in Fig. 18(a), a ground
 33 slide (GS) zone is found along Moh. Soeharto road adjacent to the east boundary of
 34 Petobo slide, where cracks and slips are visible on the surface and divide the ground into
 35 several earthen blocks. Fig. 18(b) indicates the zones of liquefaction spread (LS),
 36 liquefaction flow (LF) and debris flood (DF) on the south-eastern portion of the sliding
 37 area. Liquefaction spread is signified by a series of curvilinear features on the ground, as
 38 a result of cyclic spreading during shaking. The liquefaction flow emerges next to the
 39 downstream side of the spread zone, with relatively smoother ground surface, due to
 40 monotonic flow after the shaking. Debris flood would be the liquefied soils that flows
 41 over and inundates the existing ground, as seen in the far side of the photo (Fig. 18(b)),
 42 where the surroundings of a small area with existing houses had been destroyed and
 43 buried in the debris.
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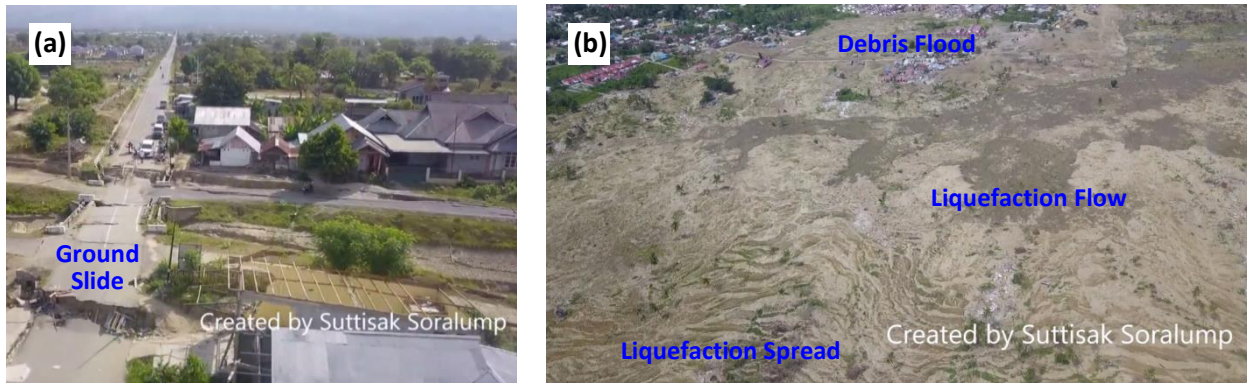


Fig. 18 Morphological features observed from the snapshots of drone videos by Soralump (2018). **a** Photo of the ground slide feature along Moh. Soeharto road to the east boundary of Petobo slide (facing east). **b** Photo of the features of liquefaction spread, liquefaction flow, and debris flood on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

The characterized 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 results shown in Figs. 19 & 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 & 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 & 4 of Fig. 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 & 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.

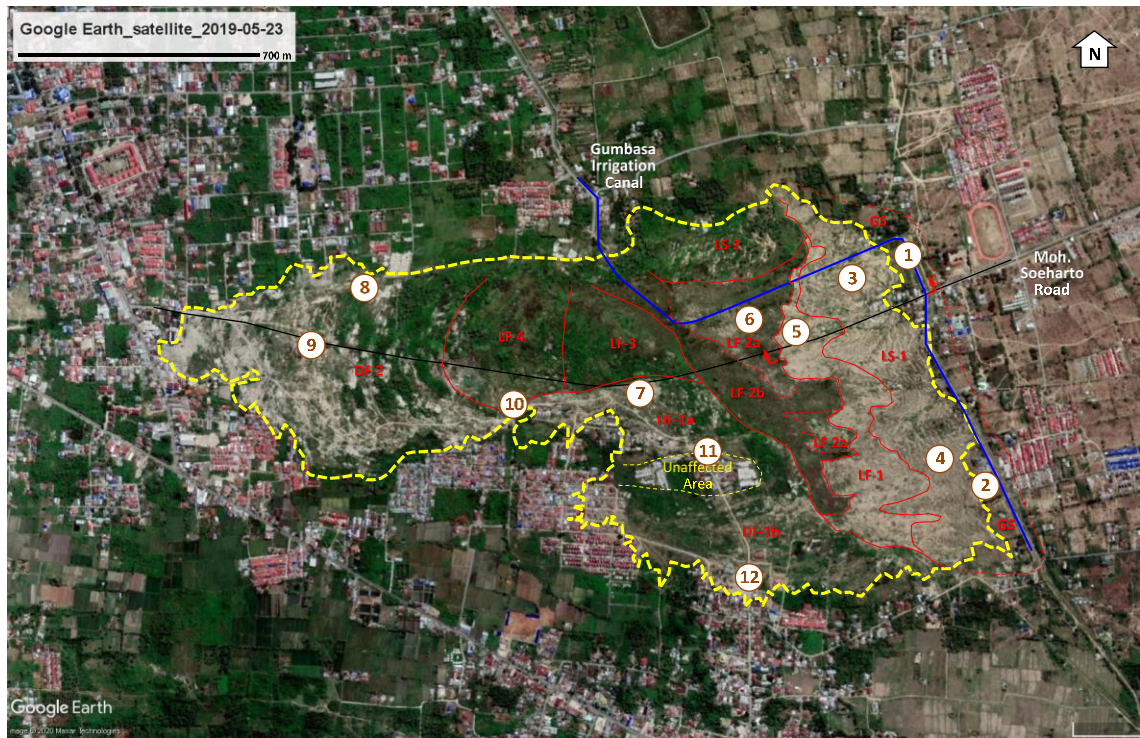


Fig. 19 Zonation of morphological features at Petobo sliding area, with locations of photos of representative morphologic features showing in the subsequent figure, as well as the location of mapped section along Moh. Soeharto road.

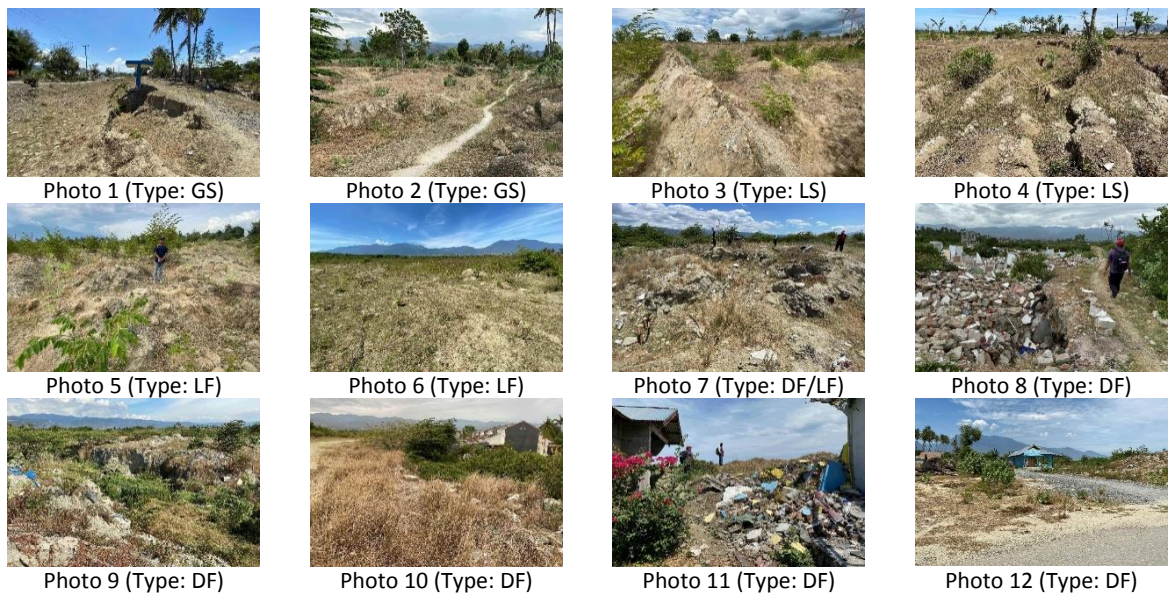


Fig. 20 Photos of associated morphological features identified on Petobo sliding area, with locations indicated on the previous figure of morphological zonation.

Concluding remarks

This paper discusses results of onsite reconnaissance of Petobo liquefaction flowslide area due to 2018.9.28, M_w 7.5, Palu-Donggala Indonesia earthquake, with emphases on the characterization of morphological features observed on the ground and the implication of potential sliding mechanism of the failure. Major findings of this study are summarized below:

1 (1) Based on comparisons of topography and surface features before and after
2 the earthquake, the Petobo flowslide had occurred on the ground of low relief (~2°) and
3 slid generally from east to west direction. The area of sliding is approximately 1.64 km²
4 in size, with a longitudinal distance of about 2.2 km and a lateral width of about 1.3 km.
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6 (2) The eastern portion of the sliding area, bordered Gumbasa irrigation canal
7 and a EW width of around 300 m, had slid with a distance of <200 m and subsided by
8 5~8 m. The middle portion of the sliding area, a EW width of around 1100 m, had slid
9 with a distance of 500~1000 m. The ground surface of this portion had changed by
10 settling >7 m in the east side to raising 1~4 m in the west side. The western portion of
11 the sliding area, a EW width of around 800 m, had slid with a distance of <400 m and
12 raised by 4~10 m.
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16 (3) Interviews with onsite witnesses revealed the initiation of sliding might have
17 had started in sequence during and after the shaking, with most likely scenario by
18 starting from eastern boundary, proceeding to southeast, then towards north portion of
19 the sliding area. The witnesses situated in the eastern portion of the area at the time of
20 earthquake had indicated a wavy-form of sliding, which is speculated as these people
21 had been experiencing a severe liquefaction spreading during the shaking. Based on
22 their observations on the ground movement, we estimate the sliding velocity of the
23 ground might have been in the range of 2.5~5 km/hr, or equivalently a speed of walking
24 or jogging.
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29 (4) Witnesses interviewed had indicated the phenomena of soil liquefaction
30 during and after the shaking. Sand boils were observed in a lot of places with eruption
31 heights of up to about 2 m and 5 m, respectively, in the NE and SE portions of the sliding
32 area. After the sliding, the ground was wet and soft, and in some places ponded with
33 water of 1 m high. It took months for the ponded lands to be gradually retreated.
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37 (5) The morphological features of the ground have been carefully mapped along
38 the east section of Moh. Soeharto road, which passes from east to west across the
39 sliding area. Four morphological features are characterized and defined, including:
40 ground slide (GS), liquefaction spread (LS), liquefaction flow (LF) and debris flood (DF).
41 These morphological features might have in relation to the initiation and the progress of
42 sliding in Petobo during and after the earthquake.
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46 (6) Ground slide (GS) occurs by slippages in coherent earthen materials which
47 are not liquefied during the shaking. Liquefaction spread (LS) is caused by laterally cyclic
48 spreading of earthen crust as a result of liquefaction of underneath soils in the process
49 of shaking. A curvilinear pattern of a series of earthen ridges would appear the signature
50 of the spreading. Liquefaction flow (LF) is due to monotonic sliding or flowing of fully
51 liquefied soils occurred primarily after the shaking. The ground surface is usually uneven
52 and bumpy, with extensive exposures of liquefied soils. Debris flood (DF) is similar to LF
53 by the monotonic sliding or flowing of liquefied soils and mixed with construction debris.
54 The debris flood is different, however, with the aspect that the existing ground of DF is
55 generally non-liquefied but covered by liquefied materials from upstream side, which
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1 would destruct the existing buildings, mix with construction debris, and pile up on the
2 existing ground.

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

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

17 (9) In view of observations of onsite morphological features and interviews of
18 witnesses of the slide, causes of the flowslide might have been due to the following: (a)
19 the onsite silty sand and sandy silt of the alluvial fan, flood and river deposits that were
20 prone to liquefaction as shaking; (b) highly raised groundwater levels near the crest and
21 the eastern portion of the Petobo area (as a result of unlined Gumbasa canal and wet
22 paddy fields) that increased liquefaction susceptibility of these areas; and (c) strong
23 shaking by the severe $M_w 7.5$ earthquake occurred along Palu-Koro fault that triggered
24 the liquefaction of the ground. The process of the flowslide would appear to be initiated
25 by the extensive liquefaction of sandy soils underneath the crust of LS zone and the soils
26 in the LF zones as a result of the strong shaking. Due to the spreading, the earthen crust
27 in LS zone would gradually be elongated and lowered, which would further trigger the
28 slippages in GS zone and gradually drive the slide or flow in the LF zones, during and
29 after the shaking. With the advances of liquefaction flow, the flowing debris would
30 encounter and inundate the ground without liquefaction, and would become the DF
31 zone.

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

37 **Acknowledgement**

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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 km². 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.

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