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Geoenvironmental Disasters

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Geotechnical damage in the 2018 Sulawesi earthquake, Indonesia

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Abstract

Background: On September 28th, 2018, at 18:02 local time (10:02 UTC), a strong earthquake of magnitude *Mw* = 7.5 struck Central Sulawesi Province, Indonesia. The epicenter was located at 0.256° south latitude and 119.846° east longitude, around 77 km from Palu city, and 20 km below the ground surface. To understand the damage caused by the earthquake, and find a solution to mitigate the geo-disasters in Indonesia, a preliminary investigation on the 2018 Sulawesi earthquake was conducted from 16 to 20 November 2018. This quick report focuses on ground displacements induced by fault movement and large-scale ground flow.

Results: During the survey, there is some geotechnical damage were found, such as ground displacement induced by fault movement, liquefaction, landslides, and large-scale ground flow in some certain areas. Large ground displacement was found in some particular areas, such as Kedondong, Pipa Air, Pangeran Diponegoro and Cemara streets in Palu city. The earthquake also triggered large-scale ground flow in some different sites, such as Balaroa and Petobo districts in Palu city and Jono Oge and Sibalaya Villages.

Conclusions: The locations of large ground displacements appeared at surface coincide well with the estimated fault line. Therefore the large ground displacements were seems to be induced by the fault movement. Large ground flow caused severe damage to not only human but also houses and buildings. The mechanism of the large ground flow should be clarified in near future.

Keywords: The 2018Sulawesi earthquake, Large ground flow, Surface faulting

Background

On September 28th, 2018, at 18:02 local time (10:02 UTC), a strong earthquake of magnitude *Mw* = 7.5 struck Central Sulawesi Province, Indonesia. Figure 1 shows the location of the epicenter. The epicenter was located at 0.256° south latitude and 119.846° east longitude, around 77 km from Palu city, and 20 km below the ground surface. This event was preceded by several foreshocks, the largest recorded as *Mw* = 6.1 and occurred at 14:59 local time (06:59 UTC), 3 hours earlier of the main shock. Figure 1 also shows MMI estimated by USGS. According to this figure, MMI=IX is estimated at Palu city and higher intensity is along the estimated fault line (see Fig. 3). The casualties were approximately 2256 persons, more than 1000 persons missing, and around 10,000 persons injured in three most affected regions which are Palu city, Donggala and Sigi villages.

To understand the damage caused by the earthquake, and find a solution to mitigate the geo-disasters in Indonesia, a preliminary investigation on the 2018 Sulawesi earthquake was conducted from 16 to 20 November 2018. During the survey, some geotechnical damages were found, such as ground displacement induced by fault movement, liquefaction, landslides, and large-scale ground flow in some certain areas. This quick report focuses on ground displacements induced by fault movement and large-scale ground flow.

Methodologies and findings

Large ground displacements induced by fault movement

Large ground displacements were found in some particular areas, such as Kedondong, Pipa Air, Pangeran Diponegoro and Cemara streets in Palu city. Figure 2 indicates the locations of the large ground displacement

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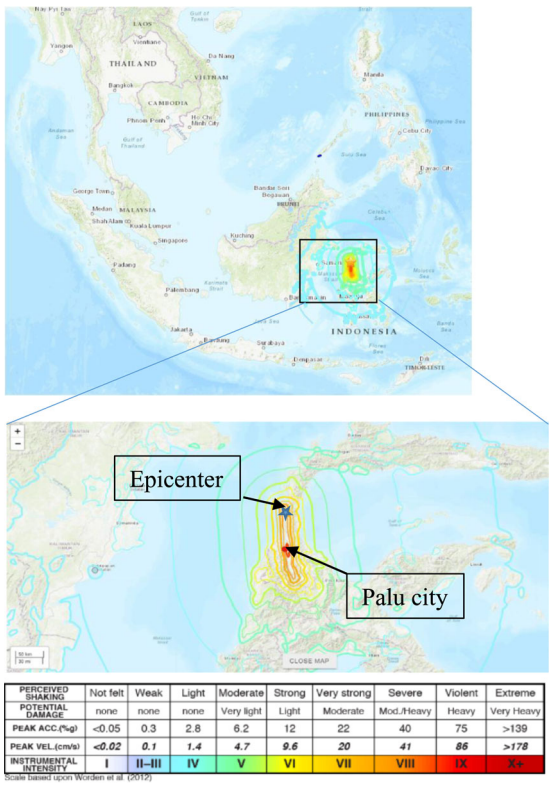

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Fig. 1 Intensity distribution map with location of the epicenter

found in Palu city. These large ground displacements agree with the fault movement of left lateral slip. Figure 3 shows the fault line at surface estimated by USGS (n.d.). The epicenters of aftershocks were also indicated in this figure. The legend in this figure indicates the estimated

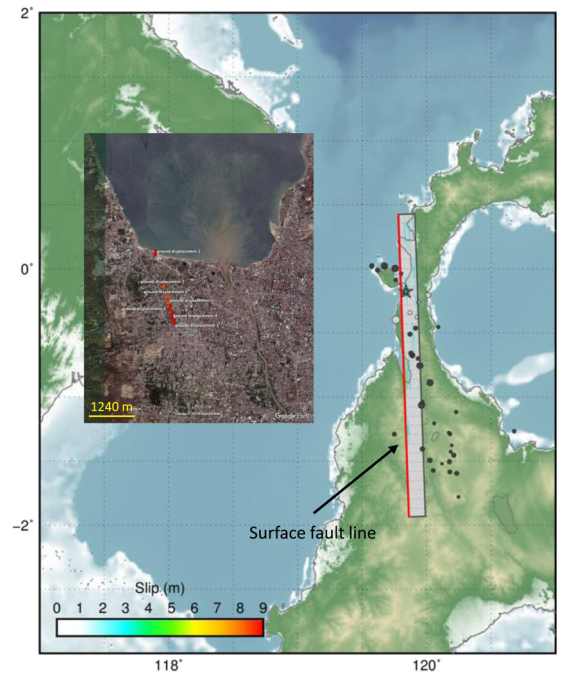

Fig. 3 Fault line at surface estimated by USGS (n.d.)

slip of the fault itself by USGS. According to this figure, the locations of large ground displacements appeared at surface coincide well with the estimated fault line. Therefore, the large ground displacements seem to be induced by the fault movement.

Figures 4, 5, 6 and 7 show the ground displacement triggered by the fault movement in Pangeran Diponegoro, Cemara, Kedondong and Pipa Air, streets, respectively. Before the earthquake, these four roads were

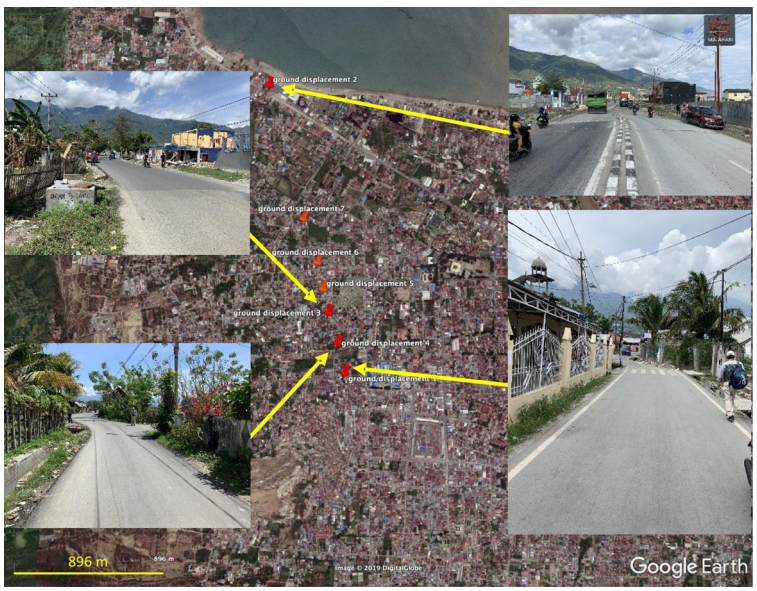

Fig. 2 Ground displacement induced by fault movement in Palu city

Fig. 4 Large ground displacement of 2.7m at Pangeran Diponegoro street in Palu city

straight. After the earthquake, fault movement triggered the occurrence of lateral ground displacement and bent the four roads mentioned above. The horizontal displacements of the four roads are 2.7 m of Pangeran Diponegoro street, 3.8 m of Cemara street, 4.5 m of Kedondong street and 5.0 m of Pipa Air street, respectively.

Large scale ground flow

The earthquake triggered large-scale ground flow in some different sites, such as Balaroa and Petobo districts in Palu city and Jono Oge and Sibalaya Villages. The locations large ground flow of Balaroa and Petobo districts in Palu city and Jono Oge village, and the direction of the ground flow are illustrated in Fig. 8 by using Google Earth. Table 1 lists the areas and average slopes before the earthquake of each site of large ground flow estimated by using a function of Google Earth. A satellite photograph of Sibalaya village after the earthquake could not be obtained, so the area of large ground flow cannot be estimated. Average ground slope of Sibalaya village

Fig. 5 Large ground displacement of 3.8m at Cemara street in Palu city

Fig. 6 Large ground displacement of 4.5m at Kedondong street in Palu city

before the earthquake is about 3.1%. The ground slope before the earthquake was not so large. The cause of this phenomenon was reported as soil liquefaction in the local media. Authors agree that the soil liquefaction caused the large-scale ground flows but the mechanism should be clarified by using many geotechnical data in near future.

Balaroa district in Palu city

Figure 9 shows a satellite photograph by Google Earth and some photographs of damage in Balaroa district in Palu city. The direction of the large ground flow is shown by a yellow arrow in this figure. The ground flow occurred from south-west ot north-east. Large ground settlemnts and large tension cracks appeared at the upper side of the flow and collasped houses were piled up and many houses were buried in the flowed soil at the lower side. Balaroa district is a densely populated area. This district was reclaimed from a swamp in 1978

Fig. 7 Large ground displacement of 5.0m at Pipa Air street in Palu city

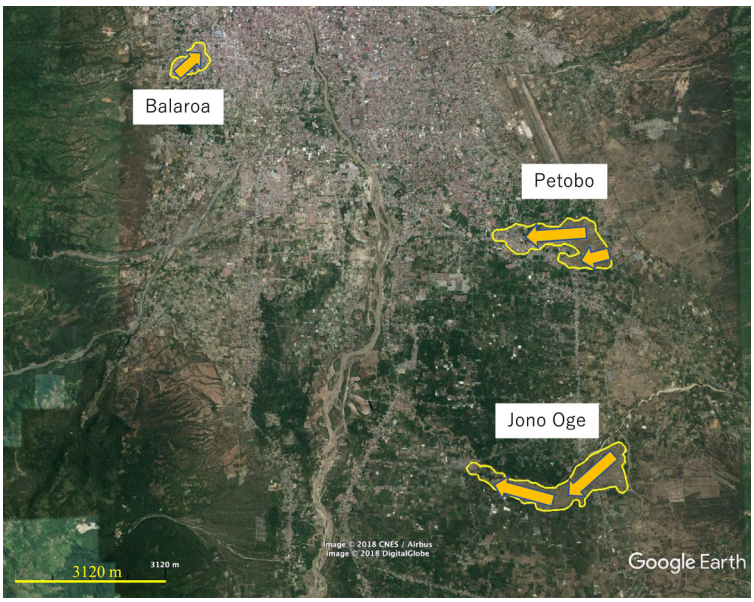

Fig. 8 Locations of large ground flow of Balaroa and Petobo districts in Palu city and Jono Oge village and the direction of the ground flow

to 1979, then the district was used for residential houses from 1980. Therefore, the underground water level is high. Six hundred people were died of the more than 2000 inhabitants, while more are still missing. The area affected in Balaroa district was around 380,000m^2. Balaroa housing complex almost disappeared due to the ground flow. It is reported that around 1700 houses were buried due to lateral ground movement.

Petobo district in Palu city

Figure 10 shows a satellite photograph by Google Earth and some photographs of damage in Petobo district in Palu city. The direction of the large scale ground flow is also shown by a yellow arrow in this figure. The ground flow occurred from east to west here. The affected area was used for residential houses before the event. Similar to Balaroa district, more than 700 houses were severely destroyed by the ground flow and hundreds of people died here. The area affected in Petobo district was much larger than Balaroa, which is around 150,000m^2.

Table 1 Areas and average slope before the earthquake of each site of large ground flow

Site	Area of ground flow (m^2)	Average slope (%)
Balaroa	380,000	3.8
Petobo	1,500,000	2.1
J ono Oge	1,800,000	1.9

Jono Oge village

Figure 11 shows a satellite photograph by Google Earth and some photographs of damage in Jono Oge village. The direction of the large scale ground flow is also shown by a yellow arrow in this figure. The ground flow occurred from east to west. Lateral ground flow occurred as well with the affected area around 180,000m^2 in Jono Oge village. Most of this area was used for rice field before the event. In this area, at least 34 high school students who joined a bible camp were killed, but it is suspected that many others are dead.

Sibalaya Village

Figure 12 shows a satellite photograph by Google Earth before the earthquake and some photographs of damage in Sibalaya village. The direction of the large scale ground flow is also shown by a yellow arrow in this figure. Sibalaya village is located about 40 km south of Palu city. A satellite photograph of Sibalaya village after the earthquake could not be obtained yet. Most of this area was also used for rice field before the event. In this area, only three people were dead due to building collapse. Figure 13 shows the photograph of Sibalaya village taken by a drone after the event. The road and houses moved laterally up to about 350 m. Figure 14 shows the same house before and after the event. What made this phenomenon extraordinary is that the moving road and some houses only experienced minor damage. The mechanism of the large ground flow should be clarified in near future.

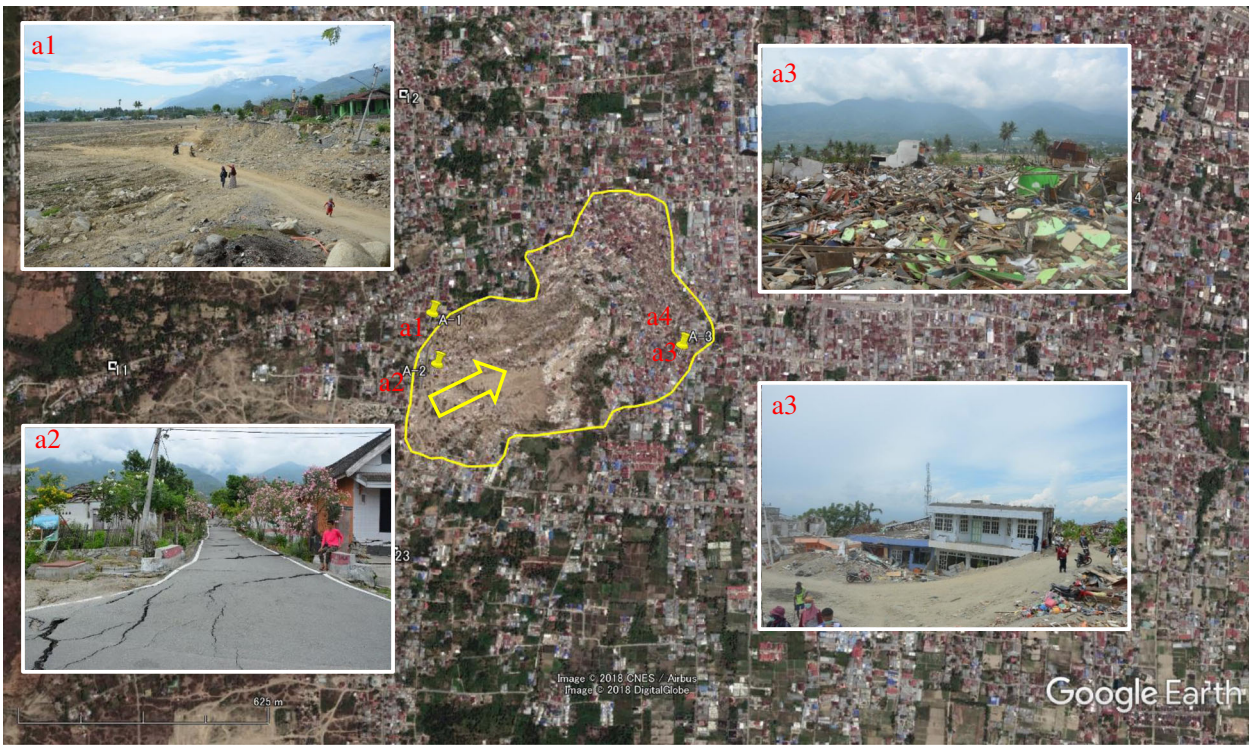

Fig. 9 Satellite photo by Google Earth and some photos of damage in Balaroa district in Palu city

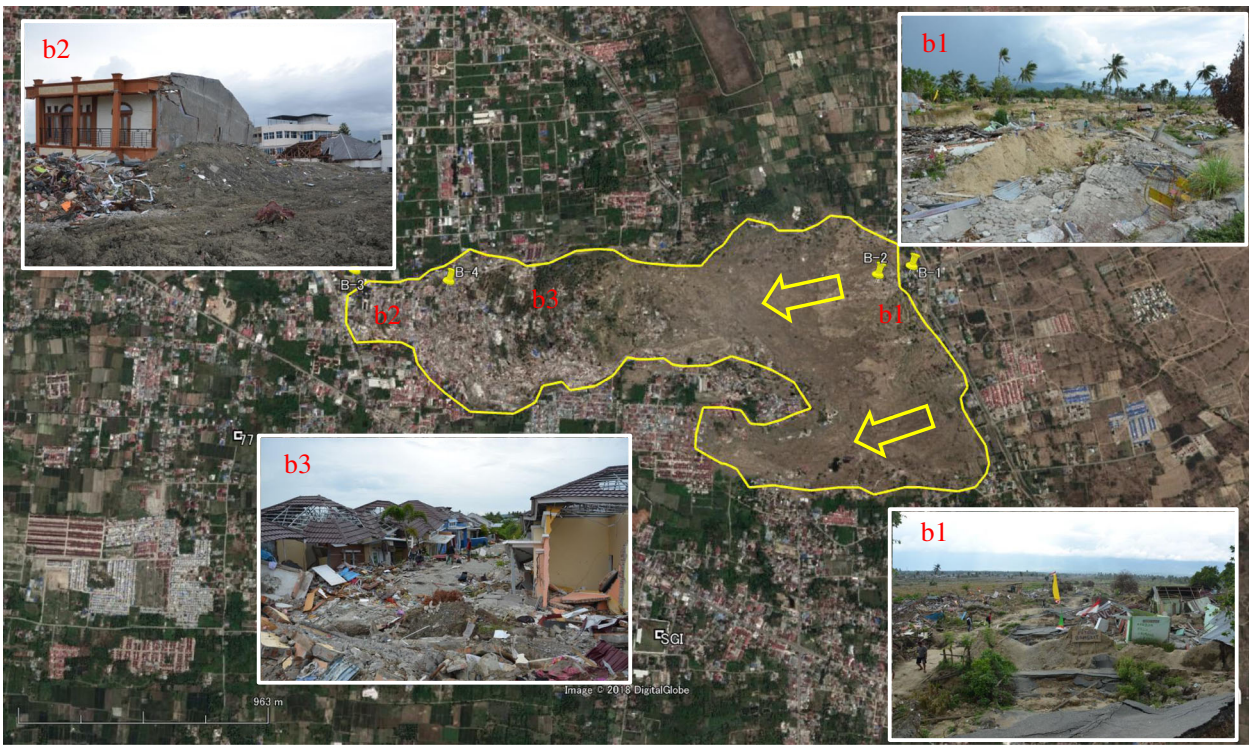

Fig. 10 Satellite photo by Google Earth and some photos of damage in Petobo district in Palu city

Fig. 11 Satellite photo by Google Earth and some photos of damage in Jono Oge village

Conclusion

The field investigation on the damage induced by the 2018 Sulawesi earthquake, Indonesia was conducted from 16 to 20 November 2018 to understand the damage caused by the earthquake, and find a solution to mitigate the geo-disasters. Large ground displacement was found in some particular areas, such as Kedondong, Pipa Air, Pangeran Diponegoro and Cemara streets in Palu city. The locations of large ground displacements appeared at surface coincide well with the estimated fault line. Therefore, the large ground displacements seem to be induced by the fault movement. The earthquake also triggered large-scale ground flow in some different sites, such as Balaroa and Petobo districts in Palu city and Jono Oge and Sibalaya Villages. The ground slope before the earthquake was not so large. However affected areas were so large and the distance of flow was also large. Therefore, the large ground flow caused severe damage to not only houses and building but also human. We should collect geological and geotechnical information and the mechanism of the large ground flow should be clarified in near future.

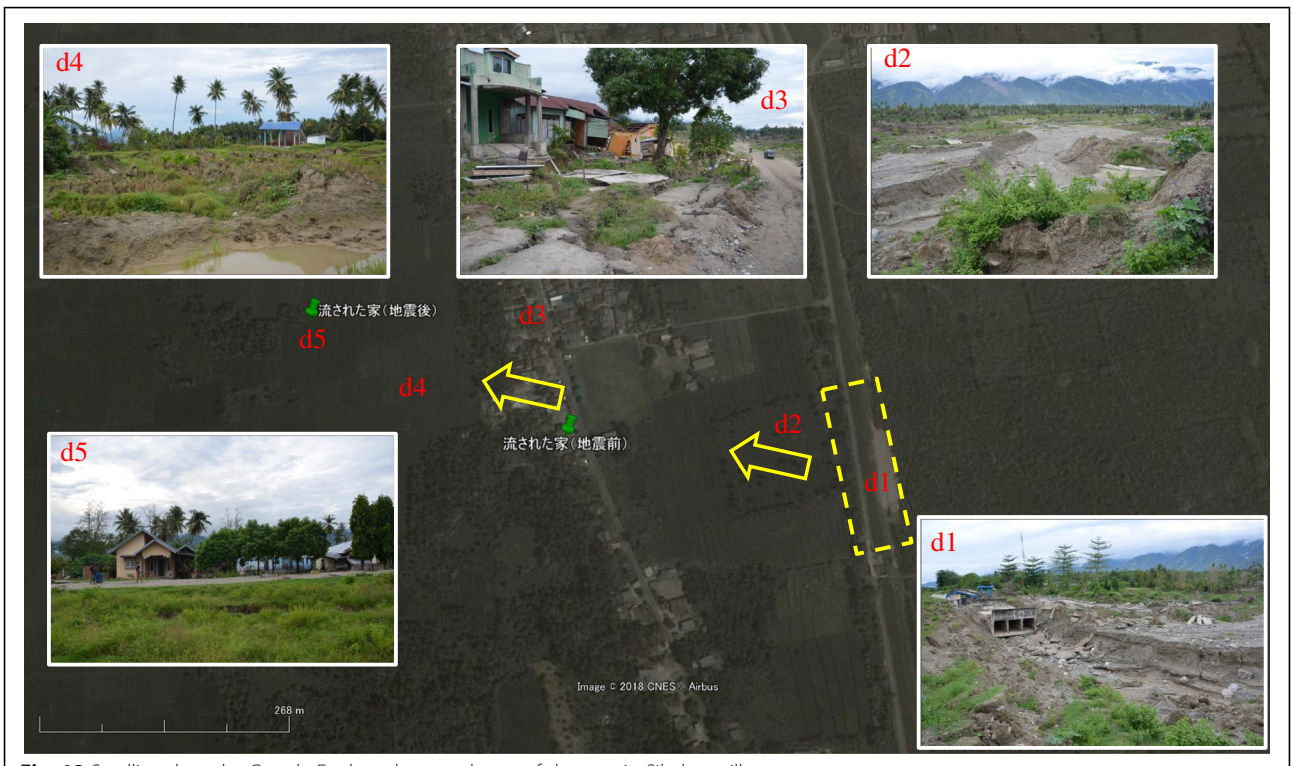

Fig. 12 Satellite photo by Google Earth and some photos of damage in Sibalaya village

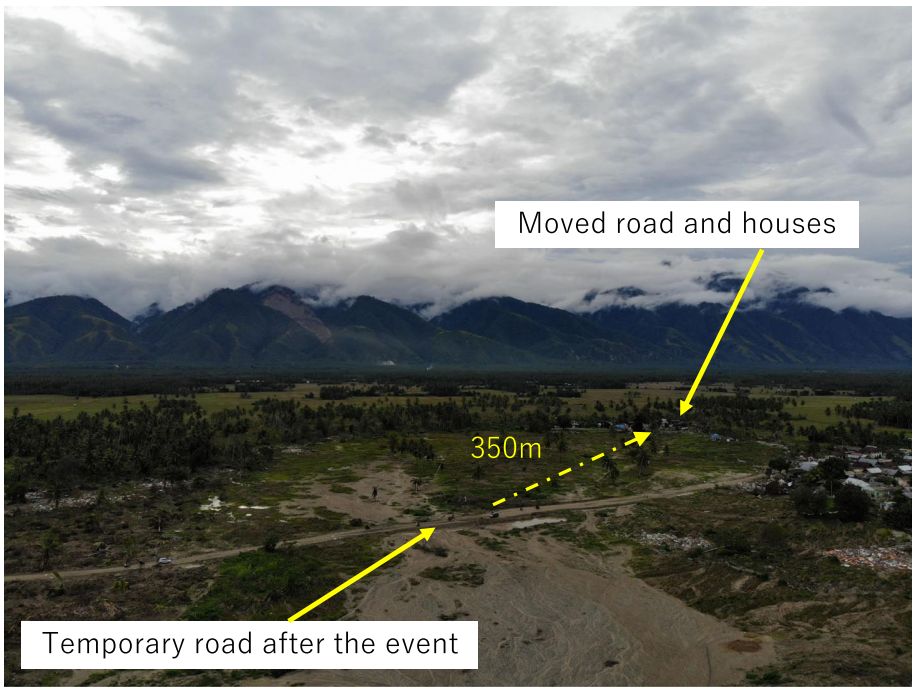

Fig. 13 Photo of Sibalaya village taken by a drone after Earthquake

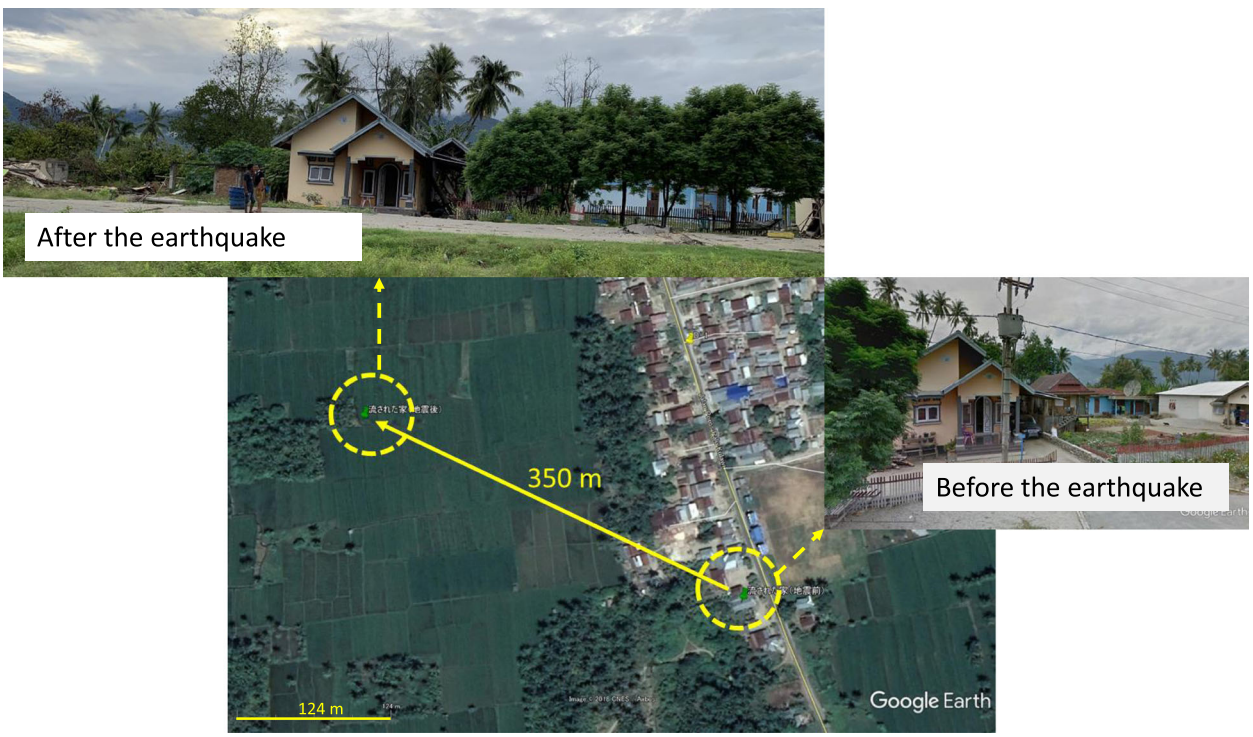

Fig. 14 Location of the moved house in Sibalaya village

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Authors' contributions
MM, HS, MY, YO, KK, ISO, M and I participated in the field investigation. MM, HS MY and YO drafted the manuscript. All authors have read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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