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Liquefaction Disaster Mitigation and Geohydrology Conditions, Lessons from The Palu Earthquake Magnitude 7.4 M_w 28 September 2018

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ABSTRACT: The Palu earthquake with a magnitude of 7.5 M_w occurred on September 28th, 2018 at 18:02 WITA time. Palu-Koro Fault experienced a strike with a mechanism of "strike slip". Earthquake epicentre is located 72 km north of the city of Palu with an earthquake depth of 10 km. This earthquake triggered a tsunami, a shift in the fault (rupture) along The Palu-Koro Fault and its secondary fault, and the occurrence of extensive and massive landslides in the Petobo, Jono Oge, Sibalaya, Balaroa and Lolu villages. One important element in responding to disasters is conducting comprehensive studies related to the phenomena caused by disasters as study material to understand the phenomena that occur, post-disaster handling and disaster mitigation in the future. This report presents the results of a survey of several locations affected by the earthquake in the city of Palu on September 28th, 2018 (6:03 pm local time), such as in the Balaroa and Petobo areas. Studies in the form of groundwater geohydrology analysis with resistivity methods and studies of aged river maps at several locations are reported in this paper.

Keywords: liquifaction, earthquake, resistivity, geohydrology

1 INTRODUCTION

Earthquakes are natural disasters that have a devastating impact and occur suddenly causing damage to infrastructure and the earth's surface and loss of life. Damage to the earth's infrastructure and the surface varies according to earthquake intensity and local geological conditions. The location is close to the epicentre, the damage was immediate and resulted in the destruction of infrastructures such as collapsed buildings, broken bridges and other infrastructure damage. The indirect or secondary damage caused by the earthquake, for example there was a fire, landslides, water pipes and broken gas, electricity supply disruptions, floods, and others.

One important element in responding to disasters is conducting comprehensive studies related to the phenomena caused by disasters as study material to understand the phenomena that occur, post-disaster handling and disaster mitigation in the future. This report presents preliminary results of the monitoring and survey of several earthquake-affected locations in the city of Palu on September 28th, 2018 (6:03 pm local time), such as in the Balaroa, Petobo, Jonoyoge and Sibalaya areas. The study in the form of soil resistivity analysis at several locations is reported in this paper.

2 CONDITION OF AREA STUDY

2.1 *History and Source of The Palu Earthquake*

The Central Sulawesi region is tectonically active as shown in Fig. 1. The damaging history of earthquakes along the Palu-Koro Fault zone occurred in 1907, 1909, 1937 and 2012. Paleoseismology studies have been carried out by Daryono (2016) and it was found that before the earthquake The earth occurred in 1909, 1468, and 1338. Abendanon (1917) concluded that in 1907 the earthquake was followed by a more destructive earthquake 2 years later in 1909. Houses that survived during the 1907 earthquake were mostly destroyed by the 1909 earthquake. Damage occurred along Saluki to the Donggala region. He reported a 7 km large crack with an increase of 1.0 m. Trenching in Onu Village in the Saluki segment shows evidence of a sinistral slip of 1.5 m and a vertical slip of 1.5 m. Daryono (2016) suggests a reasonable repetition interval of 130 years in Palu-Koro.

2.2 *Topographic Conditions of Palu and Sigi Regency with Digital Elevation Model*

The topographic condition of the Palu area is shown by the Digital Elevation Model (DEM) especially in areas experiencing liquefaction; Balaroa (a), Petobo (b), and Jonoage (c) as shown in Fig. 1. Morphology of Palu can be divided into 2 (two) units, namely Plain Morphology in the form of irregular, weak topography, an area with seasonal flooding, base rivers generally increase due to fluvial sedimentation. The morphology is composed by the main material in the form of alluvial rivers and beaches with morphological form in the form of terrain and slope 0-5%. The central area of Palu is dominated by this geomorphological unit. The morphology of denudation and hills in the form of morphology is weak and undulating. The alluvial fan region is included in this morphological unit. The morphology is in the form of smooth relief hills with a slope of 5-15%. In the Palu region, the morphology extends in the East Palu region, North Palu, demarcating the terrain morphology and mountain morphology (Widyaningrum).

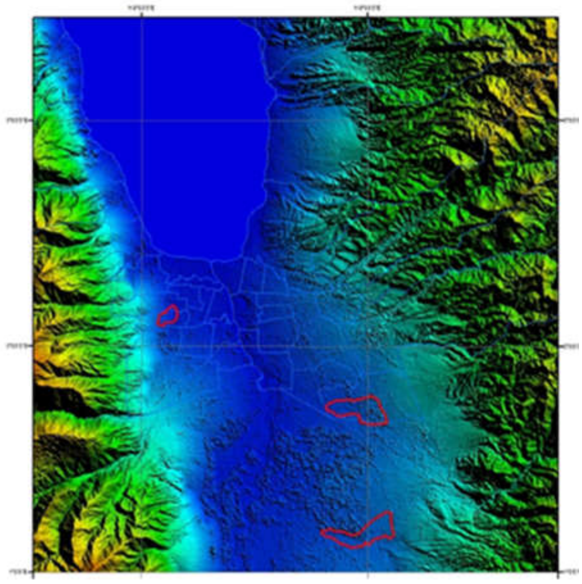

Fig. 1. Digital Elevation Model of Palu City (Source: Geospatial Information Agency (BIG) Website, DEMNAS)

2.3 *Palu's Geological Conditions*

The geological condition of Palu is shown by the Geological Map based on the Palu Geological Regional Sheet, Sulawesi Scale of 1: 250,000 (Rab Sukamto et al., 1973). The study area consists of two rock formations, namely: Alluvium and Coastal Deposits (Q_{ap}) consisting of gravel, sand, mud, and coral limestone. Formed in the environment of rivers, deltas and shallow seas of Holocene age and the Molasa Celebes Sarasin and Seracine Formation (QT_{ms}) consisting of conglomerates, sandstones, mudstone, coral limestones, and Marlies of Pliocene-Pliocene age. Stratigraphically, Palu is composed by three rock groups namely: pre-tertiary rock groups, tertiary rock groups, and quaternary rock groups as described above specifically for the Palu area (Hall, 2010). Pre-tertiary rock groups can be found in the form of marine sedimentary rocks and in the form of metamorphic rocks, both of which are intruded by tertiary granite and granodiorite rocks, and are overlapped not in harmony with the quaternary rock group, which consists of several deposits, namely: river deposits, river deposits, abundant flooding, ancient river channel sedimentation, and alluvium fan deposition. Coastal deposits which can be in the form of beach sand and rock fragments are often found around the Palu bay. Geographically, the plains of Palu were formed because of the process of appointment (graben). Graben process that makes some of the land surfaces raised quite high (forming hills to mountains) as seen along the coast of Palu Bay in the west. Palu Region is characterized by the main form of the valley (graben) where the centre of the city is located in the middle of the valley.

Fig. 2. Geology Condition Map of Palu

The geological structure of this area is based on the results of a study by the Indonesian earthquake map revision team (Irsyam, M. et al., 2010) The active geological structure that passes through Palu is in the form of PKF (Palu-Koro Fault) and MF (Matano Fault) both of which are many active faults found around the Palu valley. The Palu-Koro Fault (PKF) has a North-South direction while some of it has a Southwest-Northeast direction. The active faults that are directed towards North-South are active faults due to the rejuvenation of old structures that can be reactivated, while the faults that are directed Southwest-Northeast are very active structures today. Geologically, the physiography of Palu is related to the structural processes that occur as well as the types of rocks that make up Palu, where the left and right sides of Palu are the main fault lines, namely the Palu-Koro Fault and the area is composed of rocks that are harder than the material making up the valley.

2.4 *Geohydrology of Palu*

The existence of the Palu CAT is closely related to a graben structure in the Palu Basin, the Palu Fault. Administratively Palu CAT is in the Province of Central Sulawesi and covers the area of Palu (as the capital of Central Sulawesi Province), Regency of Donggala, and Sigi. Therefore groundwater in Palu CAT is one of the sources of clean water suppliers for residents in Palu and in some Regencies of Donggala and Sigi. The depth of the free land surface in this alluvial plain is between 1.4 and 2.7 m (Zeffitni, 2013).

2.4.1 *Groundwater Condition Before Earthquake*

Groundwater in the Groundwater Basin of Palu (Palu CAT) is a physical phenomenon that requires spatial analysis. Groundwater in Palu CAT is one of the sources of clean water suppliers for residents in Palu and in some Regencies of Donggala and Sigi. Increase in number of population and development of various sectors such as domestic, industrial, service, agriculture, and other sectors in Palu, directly or indirectly demand provision of clean water sources are increasing. On the other hand, it is faced with the phenomenon of groundwater as a limited resource according to space and time. If this isn't anticipated then degradation of quantity and groundwater quality 8989 will continue to improve. This condition will increase if accompanied by a wrong understanding of the groundwater phenomenon, besides being the impact of human development and activities. Groundwater potential in each hydromorphology and hydrogeology unit is determined by the characteristics of the aquifer in each aquifer system (Zeffitni, 2013).

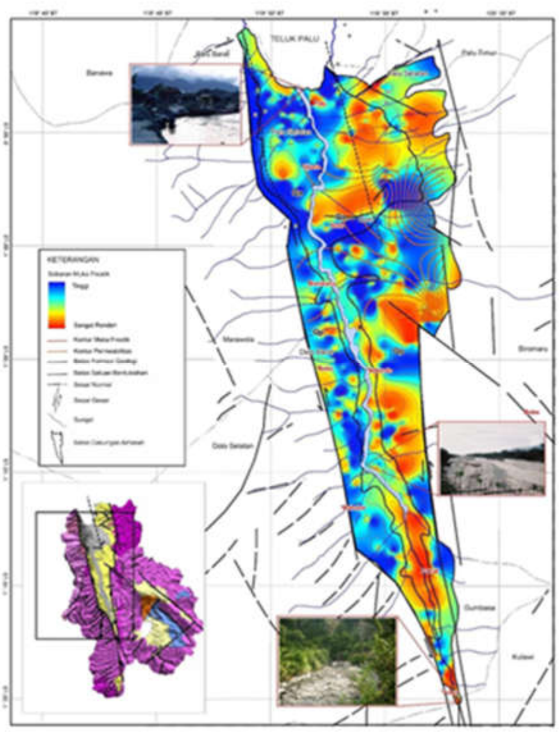

Fig. 3. Map of Hydrogeology of Groundwater Basin at Palu Valley (Zeffitni, 2013)

2.4.2 *Level of Free Groundwater Potential Based on Groundwater Characteristics in Alluvial Plain Hydromorphology Unit*

The characteristics of free groundwater are the basis for estimating groundwater potential determined by parameters: phreatic level, groundwater fluctuation, permeability value, quantity, and groundwater quality. The phreatic level of depth in Palu ranges from shallow to moderate. The shallower phreatic face is 1.38 m interchangeable in the western part of the West Palu District and the phreatic level. While 2.70 m can be found in the eastern part of Gumbasa District. Phreatic face level fluctuations in Palu are generally low (<1.0 m). The lowest phreatic level of facial fluctuations in the western part of the CAT is in the District of West Dolo 0.48 m while the highest in the eastern part of the CAT is in the District of Biromaru 0.85 m.

Permeability value used in this study is the value of free aquifer permeability and based on the results of pumping test data analysis and drilling data of the Public Works Office of Central Sulawesi Province (2000). The distribution of aquifer permeability is generally high with values > 45 m/day or an average of 53.09 m/day. The level of quantitative potential of free groundwater ranges from small to medium. The level of potential small class (<1.0 l/s) only occupies the eastern part of the CAT, namely the District: East Palu, South Palu, and Dolo. The level of potential grade is moderate (1.0-5.0 l/s) turns out to cover the entire western CAT and only 40% in the eastern (Biromaru and Gumbasa). The quality of groundwater in Palu CAT is generally good. The level of potential groundwater is generally in the medium-high class. In the area of East Palu are in the medium-low class because the analysis of the data is only based on the area included in the Palu CAT.

Based on the results of data analysis of free groundwater characteristics, it can be determined the level of free groundwater potential. The potential of free groundwater covers all of the Palu CAT in alluvial plate hydromorphology units. The level of potential of high-grade groundwater in the east is in Biromaru District and in the west is in West Palu and Marawola Districts. The level of groundwater potential is in the eastern part of the Dolo and Gumbasa Districts. In the western part of the distribution in the Districts of South Palu, West Dolo and South Dolo. The level of potential low-grade groundwater is only found in the east, namely in the Districts of East Palu and South Palu.

2.4.3 *Ground Water Condition after Earthquake*

The results of a temporary study conducted by conducting boreholes at several points and direct interviews with people who inhabit the Palu and Sigi Valleys. The groundwater level along the Gumbasa irrigation channel has changed completely, where the face of the ground before the earthquake is very shallow where it is located around 2-4 m in the lower area (west) of the irrigation channel.

For the Palu, groundwater level conditions have not changed much. Where the results of drill holes at several locations and in the wells of residents who inhabit the Palu Valley show that the groundwater level has not changed much.

Many communities reported that people who used deep wells (confined aquifers) experienced a significant increase in water volume after the September 2018 Palu Earthquake. While people who used shallow wells reported that many experienced wells whose pipes were jammed due to being filled with mud and many whose pipes were bent and broken. This is due to the lateral movement of the earthquake and the pressure of the ground pore water that rises to the surface caused by the earthquake carrying material so that it enters the community well pipes. This is also known as a sand boiling process and can cause liquefaction if it occurs massively.

3 LIQUEFACTION DISASTER MITIGATION

Likeness and lateral movement of land right after the 2018 Palu Earthquake, major damage was reported at four locations, namely Balaroa, Petobo, Jono Oge, and South Sibalaya. These areas are located from 1-7.2 km from the Palu-Koro Fault. Although data is still being collected and compiled, it is currently believed that damage at this location is mainly due to liquefaction followed by lateral movements. Liquefaction is a phenomenon in which granular deposits lose strength and stiffness and change from solid to liquid due to increased pore pressure caused by cyclic shocks (Jefferies and Been, 2015). The liquefaction phenomenon is the impact of an earthquake in an area composed of loose sand layers with shallow groundwater levels (< 9.0 m) and is influenced by the intensity, duration, and earthquake shaking and the distance from the epicenter.

According to Youd (1984 and 1992), soil layers that are vulnerable to liquefaction are in relatively limited geological areas. Liquidity usually generally occurs in alluvial fan deposits, alluvial plains, beaches, former lakes and estuaries, liquefaction due to earthquakes can cause four types of soil failure, in the form of:

a. Loss of bearing capacity in flat areas
b. Ground oscillation movements where the surface slope is <0.1%
c. Lateral spreading where the surface slope is between 0.1% and 5.0%
d. Flow type ground motion (flow slide/failure) where the slope of the soil is more than 5%.

3.1 *Sources of Groundwater in Liquefaction Areas*

The presence of confined aquifer that broke resistivity test results, that in the Petobo and Balaroa areas, as well as the Talise area which also experienced local liquefaction it is estimated that recharging groundwater which results in very shallow groundwater is filled by subsurface i.e. from the aged river has experienced siltation due to sedimentation of downstream sand and gravel material, due to the absence of river normalization efforts and material retrieval, causing several rivers in the Palu Valley that led to Palu cities to become shallow. Finally, because of the large housing needs in the Palu town of the watershed, it was made a settlement. Because the type of material available is in the form of sand and gravel which has high porosity, it is estimated that the river water still continue to flow below the surface and participate in recharging groundwater in areas traversed such as in the Petobo liquefaction area on the river Niga, Balaroa area in the aged river flow (see Fig. 4).

The depth of the free groundwater level in this alluvial plain ranges between 1.4 and 2.7 m (Zeffitni, 2013). Thus, the vulnerability of the liquefaction of the City of Palu, Donggala and Sigi is caused by the geological and hydrological conditions of this region. The phenomenon of liquefaction in the Palu plain region is an event that has happened in the past when a large earthquake occurred. The native people of Palu call the phenomenon of liquefaction with the term "Nalodo" which means sinks are sucked up by mud so they avoid these "Nalodo" risk areas. Liquidation effects in the form of oscillation of soil layers also occur in the Sigi Regency, causing damage to buildings and road infrastructure. Thus, the word "Nalodo", in general, refers to the impact of liquefaction in the form of soil mass flow and oscillation movement.

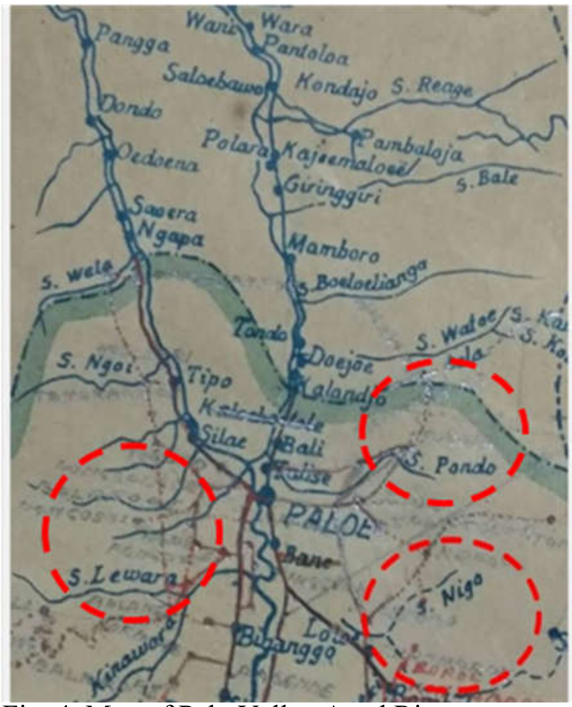

Fig. 4. Map of Palu Valley Aged River

The existence of Gumbasa irrigation in the Palu Valley has existed since the beginning of the 20th century, where the Dutch colonial government tried to improve the living standards of indigenous people and reduce the likelihood of starvation through the construction of a modern tropical irrigation system by building waterways that improved the reliability and productivity of wet rice planting and allowed planting double up. The Gumbasa Canal was completed in 1913 and carried river water that flowed across the eastern slope of a broad valley for more than a century, until it was partially destroyed during the September 28th earthquake (Fig. 5b). The Gumbasa Aqueduct defines the height of the landslide triggered by an earthquake in the eastern Palu Valley. Mapped surface fractures, lumps of sand, and standing water that indicates widespread liquefaction are associated with extensive zones of horizontal displacement below the Gumbasa drain (Fig. 5b). Dryland above waterways shows little deformation and no evidence of liquefaction. The greatest loss of life due to landslides in Palu can be attributed to four landslides that occurred, three of which came from lateral distribution under the Gumbasa Canal (Petobo, Jonoyoge, and Sibalaya), and the fourth in Palu (Balaroa) where waterways were smaller dividing dry land at higher altitudes than failed fertile city land (Fig. 5A, C).

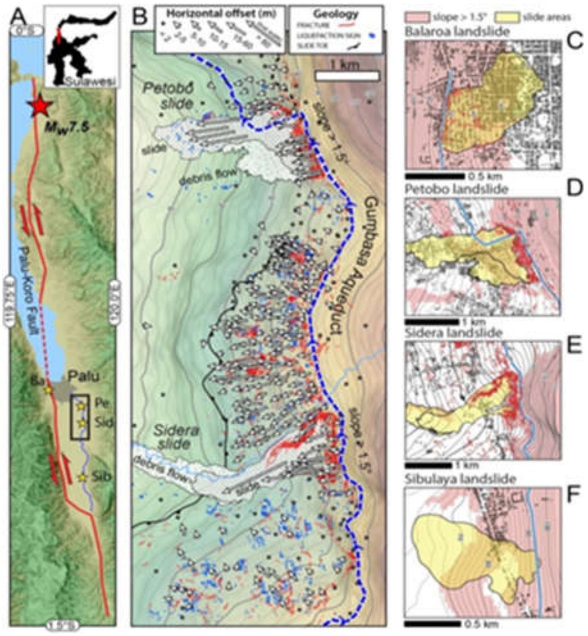

Fig. 5. Map of A Landslide Triggered by An Earthquake in The Palu Valley, Central Sulawesi, Indonesia. (a). Map of The Palu-Koro Fault. (Source: Kyle Bradley et al., 2019)

4 CHARACTERISTICS OF LAND LAYER BASED ON TWO DIMENSIONS (2-D) ELECTRICAL RESISTIVITY TOMOGRAPHY

Electrical resistivity tomography, also known as ERT (electrical resistivity tomography) is widely used to obtain two-dimensional (2-D) and three-dimensional (3-D) subsurface images based on high-resolution resistivity values (Gunther and Rucker, 2012; Ungureanu et al., 2017; Oldenborger et al., 2005). 2-D and 3-D imaging are needed to image subsurface conditions that have complex or irregular geology. In this study a supreme geomative tool was used with a Wenner Schlumberger configuration with 60 electrodes. The spacing of the electrode spacing varies between 4 and 5 m according to the conditions in the field. A total of 4 measurement tracks in the field with details of 2 tracks with 5 m electrode spacing are at the Balaroa location as shown in Fig. 2, and 2 stoves are in the Petobo area (Fig. 4).

The resistivity cross-image was obtained using the RES2DINV program for automatic 2-D inversion of the apparent resistivity obtained in the field. The inversion scheme is based on the least square method with smoothness constraints with quasi-Newton optimization. The optimization of the iteration process is adjusted until the difference between the measurement data in the field (observation) and the calculation model of the apparent resistivity values are as minimal as possibly indicated by the value of the smallest square root or root mean squared (RMS).

4.1 *Balaroa Liquefaction*

Specifically for conditions in the Balaroa area, it can be seen in Fig. 6a (Citra Ikonos satellite acquisition on 3 September 2018), where the area experiencing liquefaction is a slope with a slope of 1-3.8% with an elevation range of 56 m to 18 m and a track length of 988 m (blue track line). This is what supports the mass movement of material. Satellite image of the acquisition on October 2nd, 2018 after liquefaction can be seen in Fig. 6b.

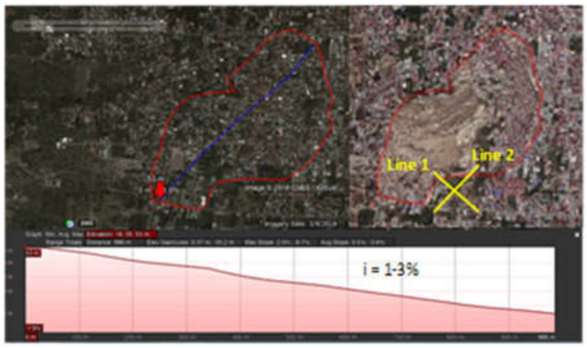

Fig. 6. Balaroa Satellite Imagery (a) Before The Earthquake (b) After The Earthquake and Track 2-D Electrical Resistivity Tomography and Topography Testing

Fig. 7 below shows the resistivity cross-section obtained from iteration 12 with an RMS error value of 1.5%. This resistivity cross-section reaches a depth of 37 m with a value of resistivity range 23.12- 7,922.7 Ωm. Resistivity values of 23.12 - 34.11 Ωm in shallow aquifer layers with depth distribution ranging from 1.5-12 m. In addition, it can also be predicted slip fields marked by resistivity contrast seen at the bottom (between red and yellow). At this location, it was also found the phenomenon of a ruptured aquifer that caused increased water content in the soil layers above. This phenomenon is an indicator of increasing liquefaction potential in this area.

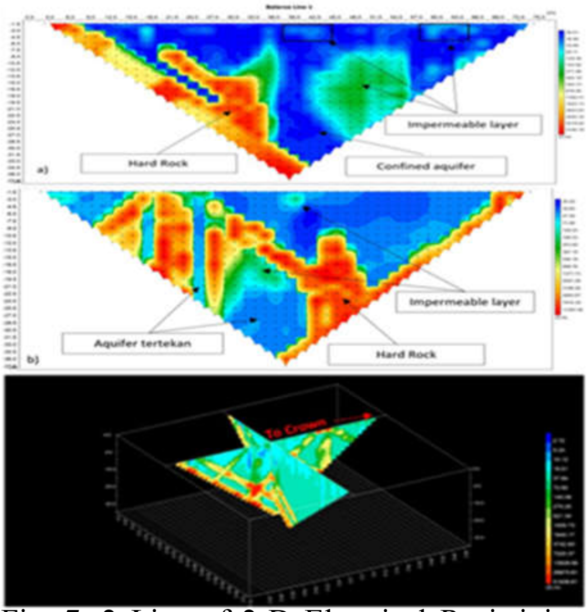

Fig. 7. 2 Line of 2-D Electrical Resistivity Tomography Test at Balaroa

The mechanism of land collapse in the village of Balaroa which is located about 1 km west of the Palu-Koro Fault can be illustrated as shown in Fig. 8a. Where the beginning of the ground movement (crown) is located on Jalan Gunung Gawalise, while the end is located on Jalan Balaroa. The area affected is housing with an area of impact around 34.5 Ha with a circumference of 2.5 km. An aerial view of the damage in Balaroa is presented in Fig. 8d. Direct observations on Jalan Gunung Gawalise where the peak of the landslide began showed that an avalanche took place in the form of a landslide with a slope height after a landslide of around +10 m (Fig. 8b). While the liquid flow (Nalodo) triggered by the earthquake began to appear at a distance of about 60 m from the crown of Fig. 8d, where this liquid flow causes the house in the location to sink and move as far as 300-600 m from the original location.

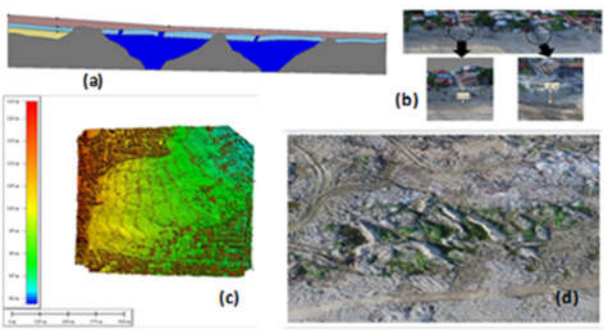

Fig. 8. (a) Model of The Mechanism of The Collapse of Balaroa Liquidation Collapse, (b) Land Slide on The Crown, (c). Digital Elevation Model of Balouroa Contour, (d). Image of Liquefaction Aerial Flow After 15 Days of The Palu Earthquake

4.2 *Petobo Liquefaction*

During the 2018 Palu earthquake, two interesting major events were observed, namely the liquefaction event which was followed by massive lateral spreading. This incident caused the affected villages to be buried and moved (Fig. 9). According to the Center for Groundwater Resources and Environmental Geology, most of the Palu Region has very high liquefaction potential with a liquefaction potential index (LPI)>15 with shallow groundwater level <12 m. However, many aspects of geotechnical engineering after an earthquake are interesting to investigate to find the actual causes and mechanisms that occur. Deeper Investigations and Research are important to support the government in the relocation and reconstruction stages.

Petobo is a residential area that suffered heavy damage due to liquefaction. This area is about 7.2 km east of the Palu-Koro Fault. Although this area has a slightly sloping ground at the surface, the mass movement from the top slope to the bottom is triggered by liquefaction.

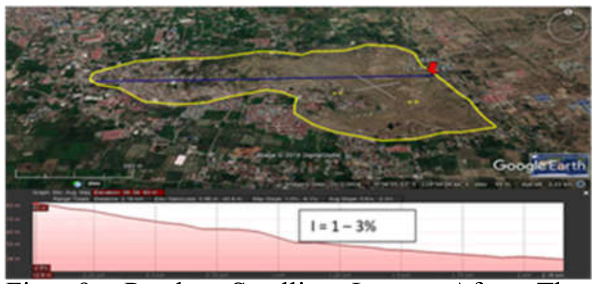

Fig. 9. Petobo Satellite Image After The Earthquake and 2-D Electrical Resistivity Tomography and Topography Test Track

Fig. 10 below shows the resistivity cross-section obtained from iteration 12 with an RMS error value of 1.5%. This resistivity cross-section reaches a depth of 70.4 m with a resistivity range value of 5.61 – 2,387.5 Ωm. Resistivity values of 5.61 - 42.196 Ωm in shallow aquifer layers with depth distribution ranging from 3-12 m. In addition, it can also be predicted slip fields marked by resistivity contrast seen at the bottom (between red and yellow). At this location, it was also found the phenomenon of shallow aquifers that were widespread that caused an increase in the level of soil saturation in the area. The source that causes shallow aquifers can be caused by infiltration from the Gumbasa irrigation channel above, or it could also be the influence of aged river seepage, the Niga River whose dukes once flowed in the Petobo subdistrict, but were closed due to sediment siltation and eventually disappeared due to settlement development. This high level of saturation is an indicator of increasing liquefaction potential in this area.

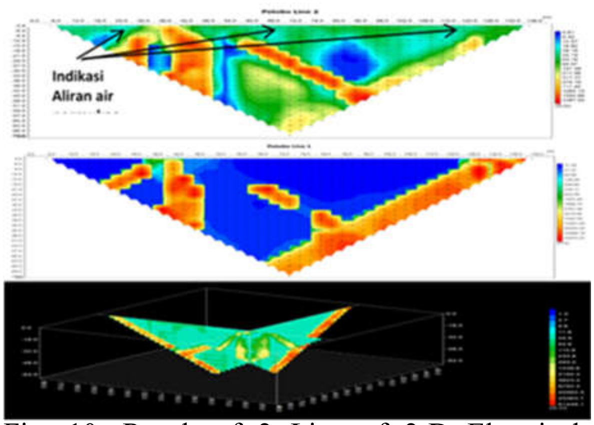

Fig. 10. Result of 2 Line of 2-D Electrical Resistivity Tomography Test

Petobo is a residential area that suffered heavy damage due to liquefaction. This area is about 7.2 km east of the Palu-Koro Fault. Even though this area has a slightly sloping ground at the surface, the mass movement from the top slope to the bottom is triggered by liquefaction. The drainage length is about 2.1 km with a width of about 1.0 km. the total affected area reaches 180 ha of the total area of Petobo around 1,040 ha.

The mechanism of land collapse in the Petobo subdistrict can be described as shown in Fig. 11a. Where the initial ground motion (crown) is located in the western area close to the Gumbasa irrigation primary canal Fig. 10b. while the tip (toe) is located near Dewi Sartika Street. The affected area is housing with a total area of about 180 ha with a total number of affected around 744 houses. An aerial view of the damage at Petobo is presented in Fig. 11c. From direct observation on the crown of the Petobo liquefaction area, where in the crown area there is a lateral movement of land followed by an avalanche with a slope height after a landslide of about +6 m. While the liquefaction flow (Nalodo) triggered by the earthquake began to appear at a distance of about 110 m from the crown of Fig. 11d in a massive sand boiling storm. where debris from the liquefaction flow is expected to go hand in hand when massive sand boils occur. Debris flow is continued by free aquifers that have come out to the surface of the ground.

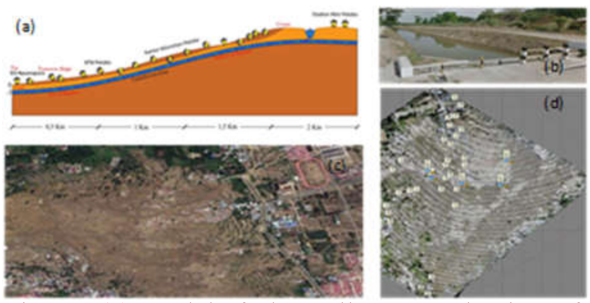

Fig. 11. (a) Model of The Collapse Mechanism of the Petobo Liquidation Collapse, (b) Gumbasa Irrigation Canal Before The Earthquake, (c) Image of Liquefaction Aerial Flow 16 Days After The Earthquake, (d) Aerial Contour Image

5 CONCLUSION

Based on the results of the analysis from this initial survey, several phenomena have been identified at the study location, including:

a. The results of the resistivity test at lane 1 (Balaroa) show the occurrence of the phenomenon of a distressed aquifer that breaks, causing an increase in water content in the soil layers above. This phenomenon is one indicator causing the occurrence of liquefaction in this area. While the resistivity test results in Petobo do not show any broken aquifer, so it can be concluded that the influence of shallow surface water can be derived from infiltration from the Gumbasa irrigation channel or can also come from aged river channels that have been closed due to sedimentation and landfill for settlement land settlement the citizens.
b. Further research needs to be done on groundwater modelling in the Balaroa and Petobo liquefaction areas so that sources and influences of groundwater can be known to contribute to the process; liquefaction in the two regions.

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