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Surface Rupture Damage Effect on the Active Palu-Koro Fault in Palu City, Indonesia

A. Abdullah[1) *], M. D. T. Musa[1)], S. Sandra[1)], A. I. Abdullah[2)], H. Jayadi[2)], D. Rivaldy[2)]

Geophysical Engineering Study Program, Tadulako University, Palu City, Indonesia
Geological Engineering Study Program, Tadulako University, Palu City, Indonesia

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Abstract

The Palu-Koro fault surface rupture, the latest active fault trace, provides valuable geological evidence and a chance to study its geometry, including strike length and damage zone width. Direct measurements indicate a primary north-northwest orientation, ranging from N314oE to N357oE, with a slip value of 2.3 – 5 m. The central part of Palu City experienced the most significant displacement. The surface rupture damage effect on the active Palu City fault spans 11 to 56 m, perpendicular to the fault line, causing substantial damage to buildings, shifting foundations, and altering roads. Liquefaction effects like sand boils, cracks, and stagnant water occurred. No buildings or infrastructure in the damaged zone remain in good condition, categorizing the area as a high-hazard zone. Based on geotechnical engineering and building structure assessments, continuing to construct buildings along the fault path is strongly discouraged.

*) e-mail: abdullahabdmipa62@gmail.com

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1. INTRODUCTION

Active fault lines are susceptible to significant damage during earthquakes, as exemplified by the Mw 7.5 earthquake that struck Palu City and its surroundings in 2018, caused by the displacement of the Palu-Koro fault [1]. Numerous studies have detailed the surface rupture of the Palu-Koro fault line, extending from Sigi Regency to Donggala Regency, encompassing the Palu City bridge [2], [3-5]. Consequently, buildings and residential houses along the fault line suffered damage [6]. The geological hazard posed by the Palu-Koro fault in the region is concerning, especially considering that Palu City served as the capital of Central Sulawesi Province and a hub for economic development in the area. The presence of the Palu-Koro fault within the city's vicinity constitutes a continuous natural hazard, with potential displacements and surface ruptures posing threats at any given time.

This study aims to comprehensively analyze the distribution of the damage zone resulting from the Palu-Koro fault surface rupture in Palu City. The investigation involves understanding the historical hazards associated with the active fault, including its precise location and the width of the fault zone [7]. Consequently, the study aims to develop effective mitigation measures to address surface ruptures caused by active faults. The findings presented in this paper serve as a primary reference for risk reduction strategies in response to the hazards posed by the active Palu-Koro fault. As a result, it offers essential guidelines for development and spatial planning in Palu City, with a particular focus on geological disaster mitigation.

2. RESEARCH METHOD

The path determination of the Palu-Koro fault continuity in Palu City was based on the findings of Abdullah and Abdullah's research [6]. Subsequently, field data was gathered, encompassing the position, strike direction, slip dimensions, fault boundaries, surface conditions, and the impact on infrastructure and residents' homes. The data collection was facilitated using tools such as a global positioning system (GPS), roll meter, compass, and camera. This information was utilized to create a hazard zone map of the fault boundary and to conduct a qualitative analysis of the fault effect and its repercussions.

3. RESULTS

3.1 General Characteristics of Palu-Koro Fault

The Palu-Koro Fault exhibits considerable dimensions, with varying estimates from different sources. Tjia [8] reports its length to be approximately 300 km, while Bellier et al. [9] indicate a length of about ± 218 km. Watkinson and Hall [10], on the other hand, suggest a length of 200 km, expanding to 500 km overall. This fault is categorized as a shear fault zone oriented in a north-northwest-southeast direction. Its south-

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eastern end connects to the Matano fault segment towards the east, and some researchers speculate that a section extends further towards Bone Bay. Conversely, from the Palu Valley towards the northwest, the fault extends into Makassar Strait and intersects the North Sulawesi Trench. Furthermore, based on surface rupture tracks observed following the Mw 7.5 earthquake, the length of the Palu-Koro fault was estimated to be approximately ± 156 kilometers from the south, spanning Sigi Regency through Palu City, and extending northwards to Donggala Regency [6].

The Palu-Koro fault uniquely correlates with the earth's conditions in the Palu, Sigi, and Donggala areas (see Figure 1). Observations from lithology mapping conducted by Sukamto et al. [11] and Sukido et al. [12] reveal that the Palu-Koro fault path is prominently situated between the contact of sedimentary rock formations and igneous or metamorphic complexes. From a tectonic and seismic perspective, the Palu-Koro fault presents the highest risk of seismic activity among all the faults assessed in the triple junction area [10], given the frequent occurrence of earthquake epicenters around this fault. Notably, the Palu-Koro fault is classified as an oblique fault rather than a pure strike-slip fault, as it exhibits a visibly significant fault escarpment (fault scarp) with a dip-slip component [13]. This fault is characterized by steep slopes, featuring triangular ridge facets and tectonic hills. Moreover, the presence of hot springs around the Palu-Koro fault is also evident [6]. These hot springs manifest geothermal activity on the surface, dispersed around Sigi Regency and Donggala Regency. It is well-established that faults and geothermal phenomena share a close correlation, as the presence of gaps resulting from faults can lead to the emergence of hot water on the surface.

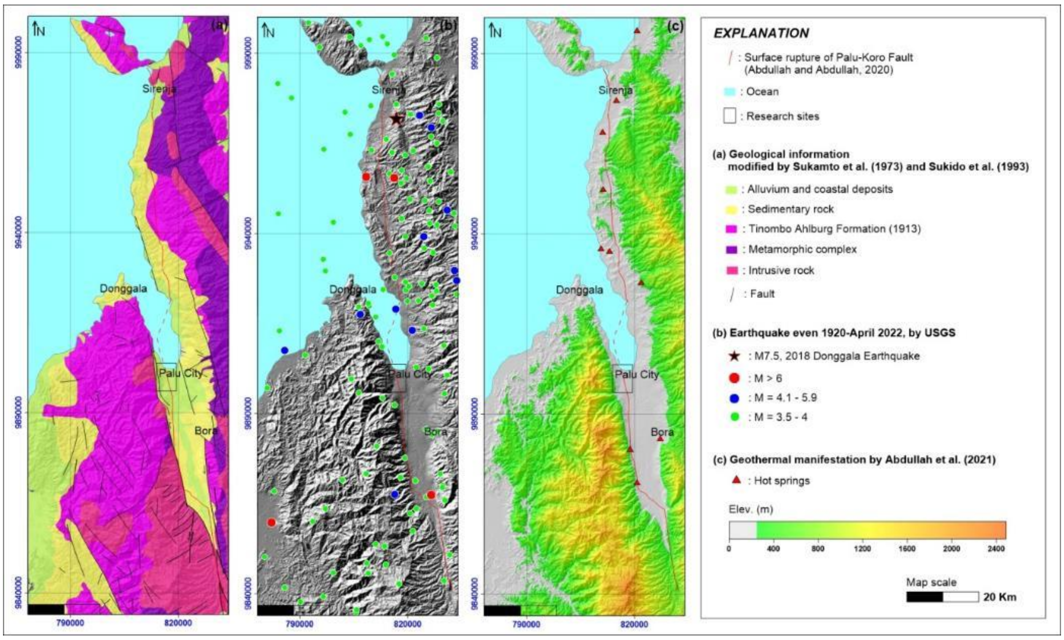

Figure 1 Surface rupture path of the Palu-Koro fault on a) Geological map, b) Earthquake epicenter, c) Topography and distribution of geothermal manifestations

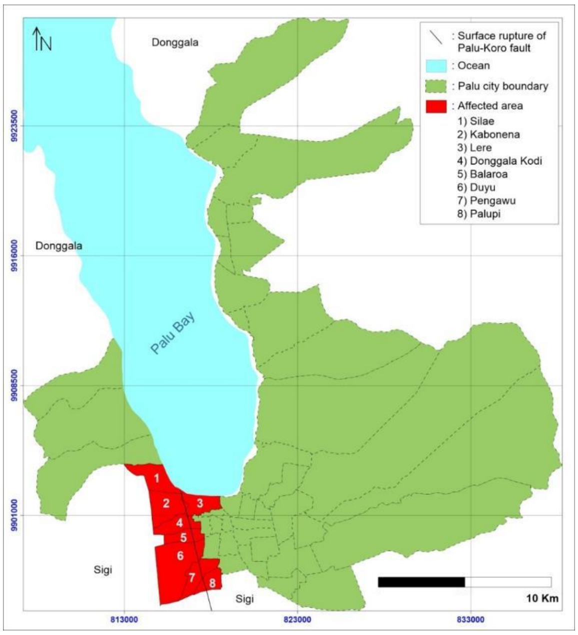

Figure 2 Sub-districts affected by the surface rupture of the Palu-Koro fault in Palu City

3.2 Surface Rupture Hazard of Palu-Koro Fault in Palu City

Many other phenomena have caused disasters, including the Mw 7.5 earthquake in 2018, such as tsunamis, landslides, and liquefaction [4], [5], [14]. It was preceded by a sinistral movement from the Palu-Koro fault. However, without these follow-up phenomena, the Palu-Koro fault would have become a hazard that caused the disaster itself through cracks traces on the surface. Palu City is the area that experienced the greatest displacement; the slip size ranges from 4.5 – 5 m [2], [4]. [5]. The surface rupture length of Palu-Koro fault in Palu City is ± 6 km [6], which has an impact on 7 sub-districts namely Silae, Kabonena, Lere, Donggala Kodi, Balaroa, Duyu, Pengwu, Palupi (see Figure 2).

Surface rupture in Palu City is characterized by a displacement in the eastern block relative to the north and the western block relatively to the south. As a result of this displacement, many buildings, such as mosques, shops, and residents' houses, were damaged. The cracks are right under the building, causing the foundation and pillars to move from their position following the fault movement direction so that buildings that are not sturdy will collapse, and some sturdy buildings will still stand in a damaged or unstable condition (see Figure 3). It can be ascertained that this was not caused by earthquake shocks but due to the surface rupture of the Palu-Koro fault. The buildings on the east and west sides that are not around the fault line effect are relatively undamaged.

Figure 3 Buildings damaged by surface rupture, which are exactly located on the active Palu-Koro fault line

Another damaging impact is that the roads turn to follow the direction of the fault displacement, which becomes the fault plane. Some of the road asphalt conditions were observed sloped upwards, it was assessed as a result of the friction forces buildup (Figure 4).

In several locations it also causes changes in surface shape, the soil seems to undulate, liquefaction effects such as sand boils and many dense cracks (Figure 5). There is also stagnant water which suspected that the water originates from shallow groundwater pushed out through the cracks then rise to the surface (Figure 6). The Palu City residents cannot build permanent buildings, to be used as homes or offices in the active fault zone. Because at any moment, destructive displacement is likely to recur. However, the Palu-Koro fault is considered an active fault, because it is proven that there is a left lateral strike-slip displacement every year at a rate of 34-38 mm/year [15], [16], and can produce large displacements such as the one that caused the Mw 7.5 earthquake in 2018.

Figure 4 The road has meanders, and the road asphalt slopes upwards due to the buildup of frictional forces from displacement faults

Figure 5 Appearance of land shape changes around the fault boundary. The soil looks undulating, there are signs of liquefaction such as sand boils and quite dense cracks

Figure 6 Puddles that are thought to have originated from the subsurface at several locations along the fault line

3.3 Dimensions of the Surface Rupture of Palu-Koro Fault in Palu City

Surface rupture of the Palu-Koro fault is the most recently active fault trace in a fracture line that reveals geological evidence. Based on the evidence that the fault surface rupture had a damaging impact in 2018 on Palu City, it is crucial to study the hazardous character of surface cracks in anticipating the active faults hazard in the future.

After identifying the impact, the dimensions of the damage effect zone around the fault line are measured for 16 possible locations to obtain data on strike, slip, and the width of the fault impact. The fault strike direction is mainly oriented north to northwest between N314oE and N357oE. Then the displacement data is the slip range from 2.3 – 5 m. The most significant displacements are in the central part, Kabonena, Lere, and Donggala Kodi Villages. While the fault boundaries in the northern and central regions are quite broad, the damage is 32 - 56 m, while in the south, it ranges from 11 - 16 m. Thus, the surface rupture damage effect on active faults in Palu City ranges from 11 to 56 m, perpendicular to the fault line or to the west and east sides (see Table 1 and Figure 7).

Many buildings and infrastructure were damaged, there were liquefaction effects and secondary soil cracks in the active Palu-Koro fault damage zone in Palu City. The fault line is being observed for sedimentary landmasses of the Holocene age and as groundwater basins. Some people think earthquakes cause damage, but the surface rupture of faults directly causes significant damage. Detailed investigations may not accurately obtain the width of the rupture zone because trench testing needs to be carried out. However, the impact of surface rupture becomes a reference in assessing the effect and extent of the damage caused. By correlating the width of the damage effect boundary along the fault path, the visualization of the active fault's surface rupture hazard zone in Palu City can be seen in Figure 8 and Figure 9. There are no buildings or other infrastructures in good condition in the fault surface rupture zone. Thus, there is no specific location where geological conditions are resistant to displacement, or building foundations are resistant to soil displacement. So that the danger zone is only made in one class, high hazard states that the impact of the Palu-Koro fault surface rupture has damaging and widespread effects on the fault boundary area.

Table 1 Strike, slip, and border surface rupture data of the Palu-Koro fault in Palu City

No	Village	E	S	Strike (NE)	Slip (m)	Border (m)
1	Silae	119.8414	-0.88333	331	2.3	56
2	Lere	119.8422	-0.88583	343	2.7	54
3	Lere	119.8425	-0.88639	339	3.1	44
4	Kabonena	119.8431	-0.88861	332	3.3	37
5	Kabonena	119.8433	-0.89000	357	3.1	34
6	Lere	119.8442	-0.89306	355	4.3	32
7	Lere	119.8442	-0.89333	318	4.8	35
8	Donggala Kodi	119.8450	-0.89667	314	5	53
9	Donggala Kodi	119.8456	-0.89833	323	4.6	35
10	Balaroa	119.8464	-0.90167	325	2.8	29
11	Balaroa	119.8473	-0.90520	341	3	15
12	Duyu	119.8484	-0.90939	316	2.3	16
13	Pengawu	119.8508	-0.91965	318	3.2	11
14	Pengawu	119.8514	-0.92222	315	3.5	13
15	Palupi	119.8528	-0.92833	332	3.4	12
16	Palupi	119.8534	-0.93014	321	2.4	15

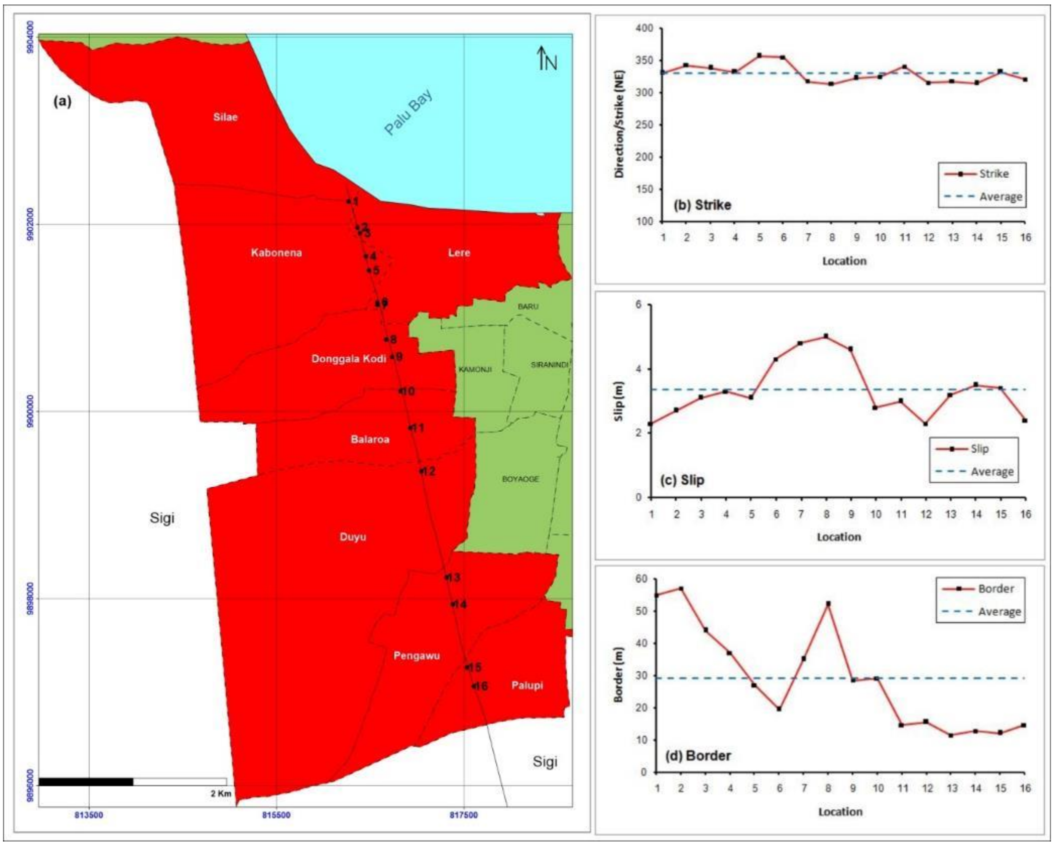

Figure 7 a) Location map of fault dimension measurement on the Palu-Koro fault line in Palu City, b) Strike data graph, c) Slip data graph, d) Fault boundary data graph

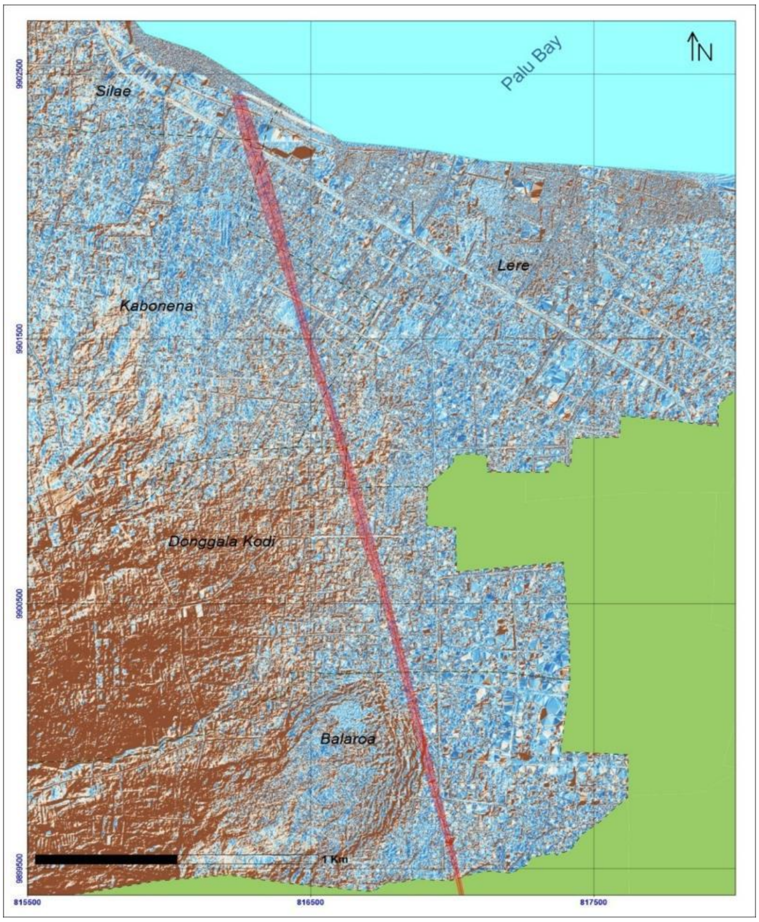

Figure 8 The hazard zone map of active Palu-Koro fault Surface rupture in Silae, Lere, Kabonen, Donggala Kodi, and Balaroa Villages, Palu City

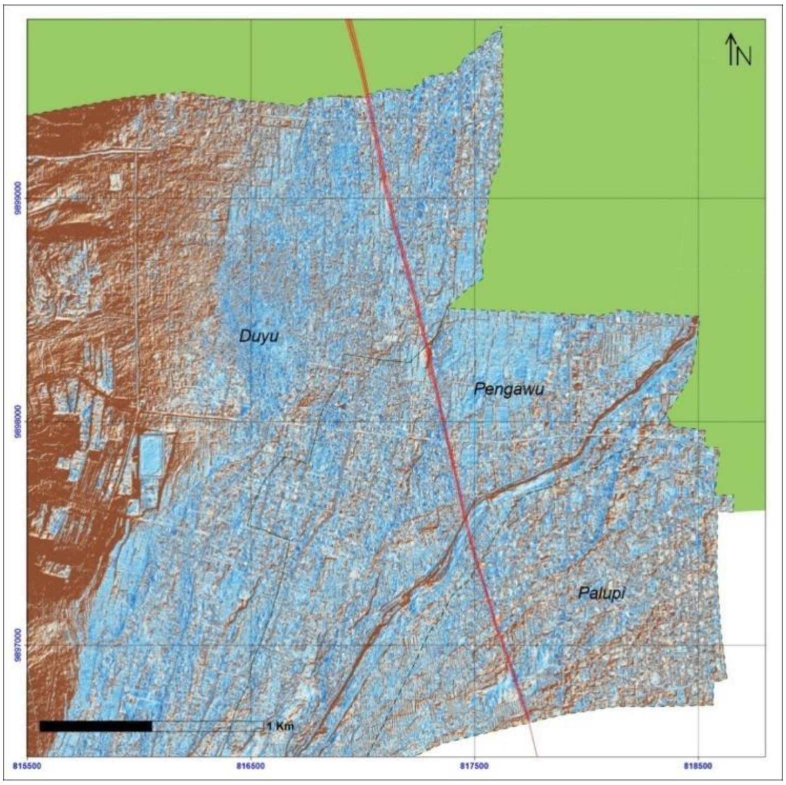

Figure 9 Surface rupture hazard zone of active Palu-Koro fault map in Duyu Village, Pengawu, and Palupi, Palu City

4. CONCLUSION

The occurrence of surface rupture resulting from the Palu-Koro fault in Palu City is a tangible hazard. Numerous efforts have been undertaken to mitigate the risks associated with active faults, primarily through abstaining from utilizing land for residential or commercial purposes along fault lines and their influence zones. Geotechnical and building structures engineering must offer viable solutions to enable continued construction in such areas. However, this should be achieved by adopting temporary building practices and dedicating the land to social facilities, or alternatively, by avoiding the mapped hazard zones altogether to prevent exposure to the surface rupture resulting from active fault hazards.

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