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Earthquake Analysis Using the Probabilistic Seismic Hazard Analysis (PSHA) Method in Palu City

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ABSTRACT

Palu, Indonesia, is a region with high seismic activity due to its location on the active Palu-Koro fault line. This study aims to analyze the probability of earthquakes, the spatial and temporal distribution of earthquake occurrences, and disaster mitigation efforts in anticipation of earthquakes in the region. Earthquake data in Palu City were analyzed based on magnitude, depth, and frequency of occurrence. The results indicate that most earthquakes occur at shallow depths ranging from approximately 10 to 56.8 kilometers, with a dominance of moderate magnitude (5.0–5.7 Mw). Over the past two decades, there has been an increase in the temporal occurrence of earthquakes, with a significant surge in 2018 when a magnitude 7.5 earthquake triggered a tsunami and liquefaction. Probability analysis indicates that earthquakes with high seismicity indices are highly likely to occur within a 10-to 50-year timeframe. The spatial distribution reveals that earthquakes tend to be concentrated around the Palu-Koro fault, the primary source of seismic activity in the region. These findings provide important insights into the seismic patterns of Palu City and can inform community preparedness and disaster mitigation strategy development.

1. INTRODUCTION

Indonesia is a country that is geologically located at the meeting point of three active tectonic plates in the world, namely the Pacific Plate, the Eurasian Plate, and the Indian-Australian Plate (Hamilton, 1979; Bao et al., 2019). The movement of these three plates forms subduction zones or subduction zones that remain active to this day. Additionally, the movement of these three plates is also the source of the creation of faults in Indonesia, both local and regional faults. The existence of these subduction zones and faults can trigger tectonic earthquakes, one of the tangible impacts of tectonic activity being the event in Palu City on September 28, 2018, with a magnitude of 7.4 Mw at a depth of 10 km, centered 26 km north of Donggala, Central Sulawesi (Badan Meteorologi, Klimatologi dan Geofisika & Pusat Studi Geologi, 2018).

One of the active faults in Sulawesi is the Palu-Koro fault, which is an active strike-slip fault stretching approximately 240 km from northern Sulawesi (Palu) to the south (Masamba and Teluk Bone), crossing the Makassar Strait before finally intersecting with the subduction zone in the Sulawesi Sea. This fault has a slip rate of approximately 30-40 mm/year, which is faster than the average global plate movement (Bellier et al., 2001; Pakpahan, Ngadmanto, Rohadi, Widodo, & Susilanto, 2015)

The consequences of these tectonic conditions make Palu City prone to earthquakes and volcanic activity (Jaya, Nishikawa, & Jumadil, 2019). The city is situated along the Palu-Koro Fault, which extends from north to south across Sulawesi. This fault is a zone where the Pacific Plate, the Eurasian Plate, and the India-Australia Plate meet and move against each other (Jayadi et al., 2023). The movement of this fault can cause major earthquakes, such as the one that occurred on September 28, 2018, in the city of Palu, which was followed by a tsunami and liquefaction. Liquefaction is a phenomenon in which saturated soil loses its stability and turns into liquid due to earthquake shocks, which occurred in parts of the city of Palu and its surroundings, causing widespread damage (Jalil, Fathani, Satyarno, & Wilopo, 2021; Kusumawardani et al., 2021)

2. METHOD

This method was first developed by (Cornell, 1968). It was then continued by (Merz, 1973). After that, it was further developed by (McGuire, 1976). This analysis aims to determine the probability of exceeding the earthquake acceleration value in a recurrence period. PSHA is a method used to determine the hazard of earthquakes probabilistically using measurements of the estimated probability of an area or location at a distance (r) from the epicenter experiencing ground motion. This theory assumes that earthquakes with magnitude (m) and distance (r) are random variables . The following equation (1) is used for the PSHA method:

$$f| \mathrm{I} \geq \mathrm{i}|=\int_{\mathrm{r}}\int_{\mathrm{m}}\mathrm{P} \mid \mathrm{I} \geq \mathrm{i} \ |\mathrm{m\ dan\ r}|\mathrm{f_m}\ (\mathrm{m})\mathrm{f_r}(\mathrm{r})\mathrm{dan\ dr} \qquad (1)$$

f_m is probability density function of magnitude, f_r is probability density function of hypocenter distance and P ∣ I ≥i and r is the condition of random probability of intensity (I) exceeding the value (i) at a location due to earthquake magnitude (m) and hypocenter distance (r) To find the probability, the Weibull equation.

The research location is in Palu City and its surroundings. Astronomically, the research location is at 00° 00' 57.6" - 01° 02' 16.8" S and 119° 43' 04.8" - 119° 58' 15.6" E. The earthquake data used in this study was obtained from the United States Geological Survey (USGS) through its official website (https://earthquake.usgs.gov/) (United States Geological Survey, 2024), covering an area within a 100 km radius of Palu City and a time period between 1990 and 2020. The data used were filtered using the criteria of magnitude ≥ 5.0 Mw and depth < 100 km to ensure that only earthquakes with the potential to significantly impact local seismic hazards were analyzed. Based on the selection and validation process, 16 earthquake events that met the criteria were identified and analyzed further, each including information on the time of occurrence, epicenter coordinates, depth, magnitude, and relative location to Palu City. This data was then processed using Microsoft Excel software to perform spatial and basic statistical analysis. Preliminary results show that most earthquakes are distributed north of Palu City, with epicenter distances ranging from 6 km to 99 km, depths between 10 km and 56.8 km, and magnitudes between 5.0 Mw and 7.5 Mw. This distribution pattern indicates the dominance of tectonic activity from the active segments of the Palu-Koro Fault and other geological structures around Palu Bay and the Sulawesi Sea. Table 4.1 below presents the details of the earthquake data used in this study. Table 1 Data obtained from the United States Geological Survey (USGS).

3. RESULTS AND DISCUSSION

Table 4.1 below presents the details of the earthquake data used in this study. Data obtained from the United States Geological Survey

Table 1. Data obtained from the United States Geological Survey

No	Time	Longitude	Latitude	Depth	Mag	MagType	Place
1	1991-07-10 T 06:53:05.100Z	119.946	-0.687	48.5	6.0	Mw	25 km NNE of Palu, Indonesia
2	1998-10-10 T 16:29:08.180Z	119.859	-0.384	33	5.9	Mw	57 km N of Palu, Indonesia
3	1998-10-10 T 16:32:19.490Z	119.84	-0.403	33	6	Mw	55 km N of Palu, Indonesia
4	2000-12-28 T 21:06:54.110Z	119.917	-0.46	33	5.4	Mw	49 km N of Palu, Indonesia
5	2008-08-21 T 21:30:48.000Z	119.731	-0.294	56.8	5	Mw	69 km NNW of Palu, Indonesia
6	2012-02-08 T 08:52:27.160Z	119.951	-0.462	45.1	5.3	Mw	50 km N of Palu, Indonesia
7	2012-03-19 T 05:04:59.640Z	119.927	-0.882	42.8	5.3	Mw	6 km ENE of Palu, Indonesia
8	2014-07-15 T 02:38:00.250Z	1.197.836	-0.3341	52.05	5.2	Mw	64 km N of Palu, Indonesia
9	2018-09-28 T 08:24:58.490Z	1.198.682	-0.3464	10	5.3	Mw	Minahasa, Sulawesi, Indonesia
10	2018-09-28 T 10:02:45.250Z	1.198.462	-0.2559	20	7.5	Mw	72 km N of Palu, Indonesia
11	2018-09-28 T 10:14:20.120Z	1.197.549	-0.0175	10	5.9	Mw	99 km N of Palu, Indonesia
12	2018-09-28 T 10:39:03.190Z	1.198.697	-0.6847	10	5.6	Mw	24 km N of Palu, Indonesia
13	2018-09-28 T 10:47:44.240Z	1.198.689	-0.5499	10	5.4	Mw	39 km N of Palu, Indonesia
14	2018-09-28 T 10:50:25.030Z	1.199.147	-0.7806	10	5.7	Mw	14 km NNE of Palu, Indonesia
15	2018-09-28 T 12:27:33.390Z	1.198.805	-0.4574	10	5.4	Mw	49 km N of Palu, Indonesia
16	2018-10-01 T 23:46:38.980Z	1.198.773	-0.675	10	5.2	Mw	25 km N of Palu, Indonesia

Tables from the USGS provide important information about each earthquake event, including date, time, magnitude, depth and epicenter coordinates (latitude and longitude). Analysis of this data shows that most of the earthquakes that occurred had magnitudes between 4.0 Mw and 6.0 Mw with varying depths, but tended to be shallow (less than 70 km). Shallow earthquakes tend to produce greater surface damage despite their moderate magnitude. This is in line with the characteristics of earthquakes along the Palu-Koro fault, which is known to produce strong and destructive earthquakes such as the one on September 28, 2018.

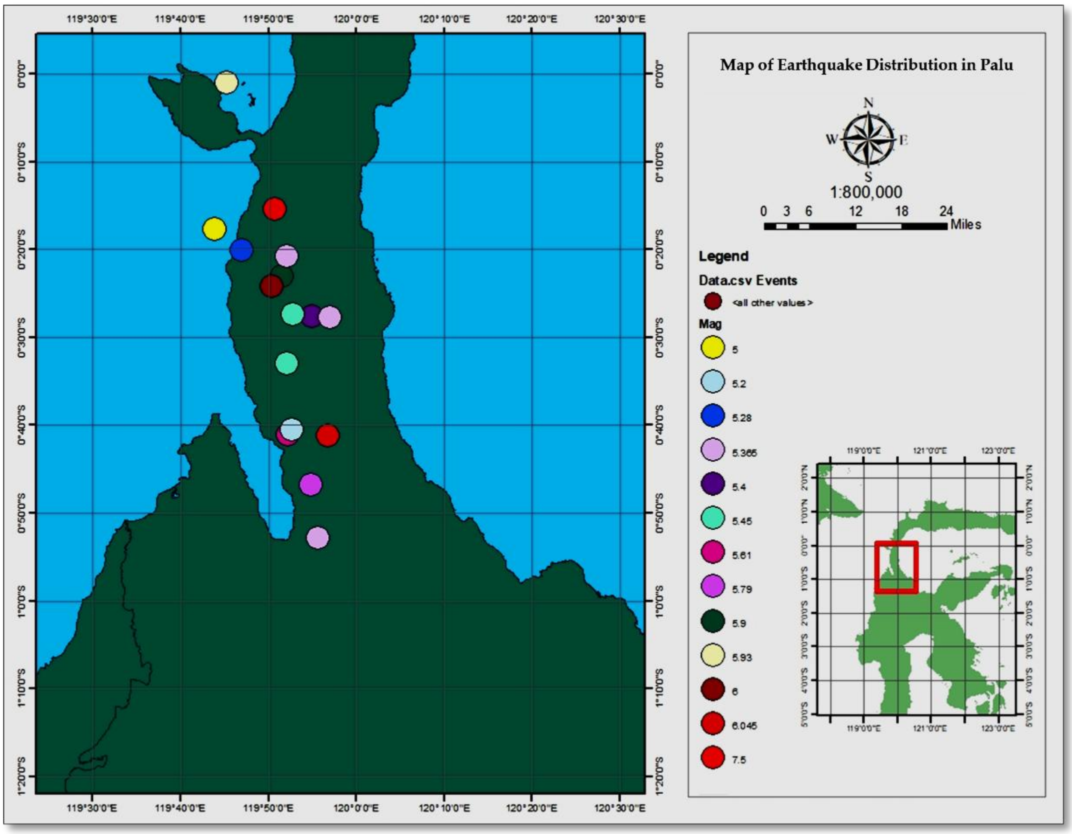

Figure 1. Map of the epicenter of the earthquake in Palu City and its surroundings

Figure 1 shows a map of the earthquake epicentres in Palu City and its surroundings and a table of earthquake data from the United States Geological Survei. Based on the map, the distribution of earthquake epicenters is fairly spread out along the Palu-Koro fault line, which is one of the most significant active faults in the Central Sulawesi region. The color of the dots on the map shows the variation of earthquake magnitude, with intensity ranging from low (light blue) to high (dark red), illustrating that this region experiences quite complex and diverse seismic activity. The epicenter positions, which are generally on land and near fault lines, indicate that earthquakes in this region are more influenced by active shear fault movements.

Based on the longitude and latitude data, this earthquake was centered in an area mostly located north and northeast of Palu, with the epicenter along the Palu-Koro fault line, known as one of the active faults in Indonesia. On the map, shallow earthquakes (around 10 km deep) are concentrated in locations close to land or shallow waters, as seen in the 7.5 Mw earthquake 72 km north of Palu. This earthquake has the potential to trigger a tsunami, as occurred in the 2018 main earthquake. Other locations with smaller magnitudes, such as 5.2 Mw to 5.6 Mw, are scattered around 25 km to 50 km from Palu, forming a pattern of concentrated aftershock activity along the fault.

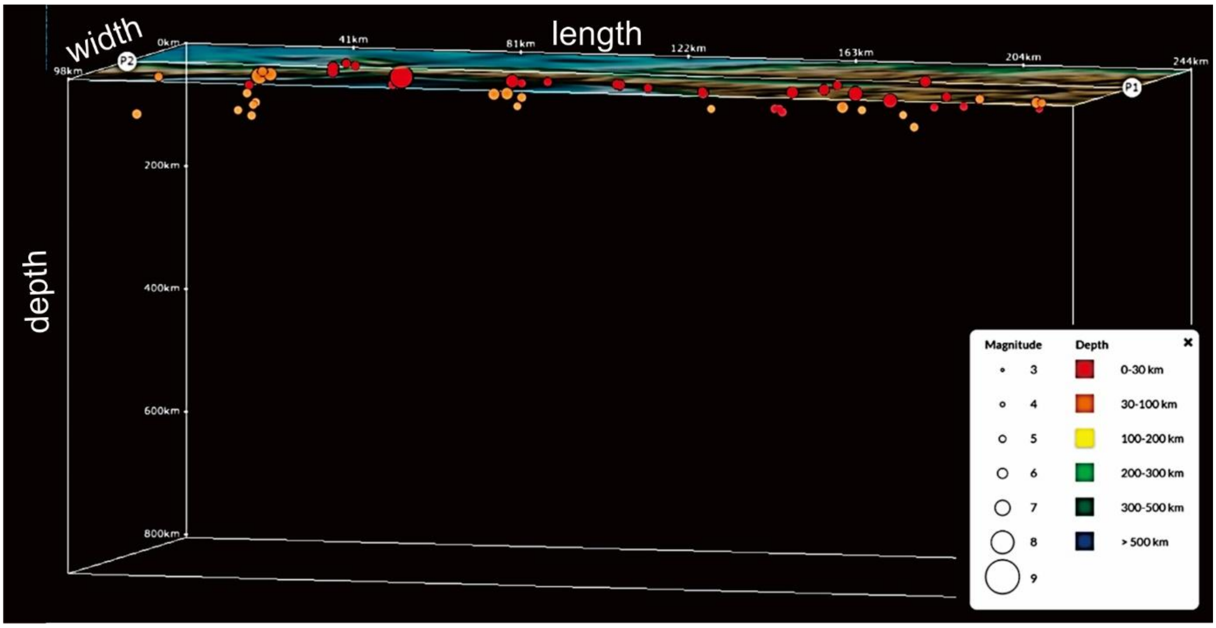

Figure 2. Visualization of earthquake magnitude versus depth in Palu City and its surroundings

Figure 2 visualises the vertical cross-section of seismicity in the earthquake zone, with coordinates extending from point P2 to P1. This line most likely crosses the active zone around the Palu-Koro Fault. This visualisation is critical because it shows how the depth and magnitude of the earthquake hypocenter are distributed vertically and horizontally below the surface.

The horizontal distribution from west to east (P2 to P1) shows that the earthquake centers are concentrated along a horizontal plane near the surface, consistent with the direction of the active strike-slip fault. There are no large earthquakes (blue/green) indicating activity at very deep depths (>200 km), meaning that the subduction zone does not play a significant role in earthquake activity in this part of Central Sulawesi. This is consistent with regional tectonic literature stating that the Palu-Koro fault is a pure strike-slip fault, not a subduction boundary (Bellier et al., 2006; Socquet, Hollingsworth, Pathier, & Bouchon, 2019).

This distribution also indicates segmentation of the fault, where there are several epicenter clusters at certain distances (e.g., approximately 40–120 km and 160–200 km from the starting point). This segmentation is important because it can influence how energy is released during a major earthquake—the earthquake can rupture completely (long rupture) or partially depending on the segmentation.

The distribution of earthquake epicenters shown on the map reveals a linear pattern extending from north to south, parallel to the Palu-Koro Fault. Based on the coordinates in the USGS table and spatial visualization, the epicenter points are located around the city of Palu, Donggala Regency, and extend southward to Sigi Regency and part of Parigi Moutong. In the north, several earthquakes were centered near Palu Bay, an area that is geologically very vulnerable because it is located at the intersection of the coastal zone and the end of an active fault. Coastal areas such as Lere, Talise, and Besusu show high vulnerability to shocks and tsunamis, as evidenced by the 2018 earthquake.

In the south, the epicenters that emerged in Sigi Regency, particularly around Kulawi and South Dolo, indicate that the Palu-Koro fault is not only active in the north but also shows active segmentation into the inland region. The characteristics of this region, which consists of narrow valleys flanked by hills, reinforce the potential for seismic wave amplification and secondary landslides during earthquakes. Several other epicenters also point to the eastern region, near Parigi and Toboli, indicating the possibility of secondary fractures or interactions with minor fault structures that have not yet been fully mapped.

Overall, the correlation between spatial data and administrative area distribution indicates that the most significant earthquake-prone zones in Central Sulawesi include coastal cities (such as Palu and Donggala) and valley areas (such as Sigi and its surroundings). These earthquakes mostly have depths <60 km, indicating their shallow tectonic nature, which is dangerous because their effects are directly felt on the surface. No large earthquakes were found at intermediate depths (>200 km), suggesting that plate subduction does not play a dominant role in local seismicity. The correlation between depth and magnitude is not significant because large earthquakes are located at shallow depths (constant depth), resulting in a correlation approaching zero.

4. CONCLUSION

The Palu region and its surroundings comprise an active seismic zone, dominated by the Palu-Koro Fault, a strike-slip fault that extends from north to south across Sulawesi Island. The distribution of earthquake epicentres shows a strong spatial correlation with this fault line, confirming that earthquakes in this region originate from highly active local tectonic activity. Most earthquakes in this region have shallow depths (<30 km) and moderate to large magnitudes (5.0–7.5 Mw). This indicates that earthquake activity originates from the upper crust (the fragile lithospheric zone), which has the potential to cause significant surface damage. Based on global and historical seismic data analysis, the relationship between magnitude and earthquake depth on the Palu-Koro fault shows a significant pattern, where most large earthquakes occur at a uniform shallow depth, with earthquake depth tending to be constant along the fault. This data supports the notion that large earthquakes in this region are more likely to occur at shallow depths, suggesting that earthquake depth does not have a direct, substantial correlation with magnitude. This is also reflected in previous studies, which indicate that large earthquakes on active faults, such as Palu-Koro, are more likely to occur at consistent and shallow depths.

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