Characteristics of landslides induced by an earthquake from a hidden strike-slip active fault in the Cianjur Area of West Java

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Abstract. On November 21, 2022, the Cianjur area in West Java, Indonesia, experienced devastating landslides caused by a magnitude 5.6 earthquake, with the epicenter traced to a hidden active fault approximately 11 kilometers beneath the surface, known as the Cugenang Fault. This study investigates the post-disaster landslides and aims to discover the characteristics of the landslides triggered by this earthquake. The methodology involves literature review, lithology descriptions, landslide slip surface analysis, soil analysis, slope assessment, land cover and land use change examination, landslide orientation evaluation, and distance measurements to the earthquake's epicenter and the Cugenang fault. Drones aided spatial landslide analysis. The study highlights the strong link between intense shaking along the active fault and landslide occurrences. Due to lithological bedding control, these landslides all head southwest and are located 0.35 to 0.67 kilometres from the fault. The residual soil, highly weathered breccia, and possible tuff volcanic deposits, which act as a sliding plane, lie in a similar direction to the slope, creating a vulnerable setting for landslides. The morphology and exposures of the Sarampad and Rawacina landslides showed similar phenomena to liquefaction. Land use changes, including slope cutting without proper stabilization measures, contribute to landslides to a certain degree.

1 Introduction

The unusual earthquake in Cianjur that resulted in collateral landslides has destroyed numerous residential buildings, blocked the national road connecting Puncak to Cianjur, and caused several fatalities, specifically in the Cugenang area. This peculiar event requires more detailed investigations to reveal insight into the earthquake-triggered landslide's unique characteristics.

On a regional scale, Indonesia is geographically located among three prominent tectonic plates and within the Ring of Fire. Indonesia was listed as the third most disaster-prone country globally [1]. Java Island is home to approximately 75% of Indonesia's regions, which are susceptible to disaster [2]. In the past year, Indonesia has experienced a series of seismic events, including an earthquake in Cianjur on November 21, 2022, with 5,6 MW [3]. Cianjur, situated in a region characterized by frequent seismic activity, has encountered several notable seismic events in previous instances [4]. The recent occurrence of the Cianjur earthquake can be related to the active fault that controls by the Eurasian plate because of a shear fault type, which may be associated with the activity of a hidden fault [5]. The data collected from the initial mechanism analysis suggests that the earthquake displays a strike-slip mechanism [6]. The Cugenang fault, characterized by a northward orientation of 347°E and a rightward tilt of 82.8°S from Nagrak Village to Ciherang Village in the northeastern part of the Cianjur region, has been identified as the new primary factor contributing to significant structural damage in the area [7].

The earthquake in Cianjur was characterized as a shallow crustal event and resulted in significant damage [8]. This event impacted 16 of the 32 communities throughout the surrounding area, with approximately 180 out of 360 villages being affected [9]. The infographic of the Cianjur Regency earthquake on December 29, 2022, reveals that 59.889 houses were affected. The number of fatalities resulting from the seismic event has escalated to 600 individuals [10]. Most individuals resided within the geographical boundaries of the Cugenang District, where a total of 400 individuals were identified. A modeling analysis can be applied to investigate the occurrence of deaths resulting from earthquakes and earthquake-induced landslides. Earthquakes associated with landslides generally resulted in more fatalities, indicating a cascading hazard, compared to earthquakes that did not trigger landslides [11]. This is shown in Cianjur earthquake. The geological features of a location have a significant impact on its vulnerability to earthquakes and the subsequent threats they pose [12]. A more detailed study is needed on the landslide occurrence.

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The purpose of this research is to investigate post-disaster landslides and discover the characteristics of the landslides caused by this earthquake.

2 Methodology

The investigation into the characteristics of earthquake-triggered landslides from the active Cugenang fault in Cianjur used a variety of methods. These included reviewing existing literature, gathering data from various sources and media, conducting field surveys and observations, analysing both literature data and findings from field observations, and thoroughly analysing all data and information gathered.

Exploration of available maps and reports was carried out to determine the geological and lithological conditions. Field surveys and descriptions were used to conduct direct observations of lithological conditions such as physical properties, rock weathering conditions, and weathered soil thickness.

Field surveys were also conducted to observe landslide anatomy, slope inclination, land use, land changes that occurred, hydrogeology, landslide orientation, and the distance of landslides from the earthquake's epicentre and active fault. The research was also aided by data collection using Unmanned Aerial Vehicles (UAVs) or drones to assess the spatial condition of the landslide area, length and width.

3 Results

There are four major landslides in Cianjur that will be described as the focal point of this research. These landslides are Cijedil, Cugenang, Sarampad, and Rawacina Landslides. The geology and lithology conditions, earthquake epicenter, and active fault as the triggering factors, landslide characteristics, as well as the discussions and implications of the landslides are described in the following sections.

3.1 Geology and lithology

According to the geological map of Cianjur [13], the landslide area in Cianjur consists of pyroclastic rocks originated from the past Mount Gede volcanic eruptions. These rocks can be categorized into three distinct units: the volcanic breccia unit, volcanic tuff unit, and volcanic lava unit. Approximately 60% of this area is covered by deposits of breccia and lahar, as reported in reference [14]. The Cianjur plain of the Quaternary age comprises tuffaceous sandstones, tuffaceous shales, tuffaceous breccias, and tuffaceous agglomerates. The research region is characterized by a volcanic tuff unit, which encompasses approximately 30% of the total area. The volcanic tuff unit is prominently exposed on slopes and riverbanks, exhibiting significant weathering. The lava unit, accounting for approximately 10% of the total area, comprises Quaternary andesite rock [13].

Fig. 1. Typical yellowish to dark brown residual soil and highly weathered breccia in the landslide area, exposed in the middle of the Cijedil Landslide (top) and in the crown area of Cugenang landslide (bottom).

In the areas of breccia and lahar deposits, small hills or basalt blocks are found locally. Based on field surveys, it was observed that the landslides in Cijedil, Cugenang, Sarampad, and Rawacina occur on the residual soil and weathered rock in the upper layer, with thickness of about 3 meters to 10 meters. The residual soil and the highly weathered breccia layer can be seen in figure 1.

3.2. Earthquake epicenter and a hidden active fault

The November 21, 2022 earthquake in Cianjur, occur at coordinates epicenter of 6.84° S – 107.05° E at a depth of 11 km with a magnitude of 5.6 and this earthquake was orginated from the new active fault known as Cugenang Fault as shown in figure 1 [15]. The Cianjur earthquake epicenter is approximately 17 kilometers (km) away from the Cimandiri Fault. With an average length of the Cimandiri Fault segment of 15 km, the fault that caused the Cianjur Earthquake was most likely separate from the Cimandiri Fault system. As a result, the Cianjur Earthquake resulted from the movement of a new active fault. Unlike the geomorphologically visible Cimandiri Fault, this new fault is not observable, hidden, or covered by young volcanic Quaternary deposits. Figure 2 is showing Cugenang Fault and the landslides sites with their directions.

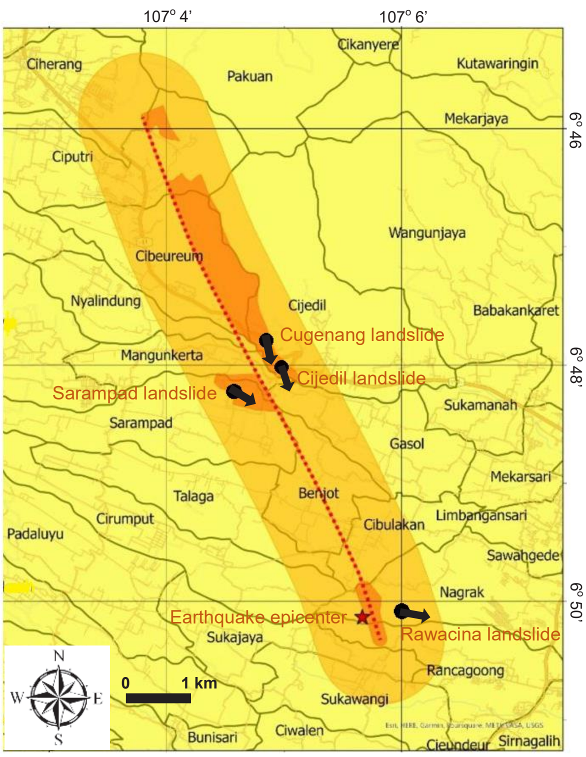

Fig. 2. BMKG-estimated Cugenang fault (dotted line), landslide sites, and landslide directions (modified from BMKG, 2023).

3.3 Landslide characteristics

The Cianjur earthquake caused landslides of varying sizes, from large to small. Due to the burial of materials on the national transportation route from Jakarta to Cianjur in Cugenang, some of these landslides have caused damage and destruction to houses and other structures, as well as the loss of lives. The following describes the characteristics of the four landslides investigated.

3.3.1. Cijedil landslide

The Cijedil landslide occurred at coordinates 107.083194° E and 6.800222° S. At this landslide site, lithology resulting from volcanic breccia weathering is exposed, with the highly weathered breccia lies at the bottom part and dark brown residual soil at the uppermost layer. The exposure at this site shows variations in weathered soil, ranging in colors from dark brown (silty), light brown (sandy), to dark brownish-black (clayey) from upper to bottom, with a thickness of approximately 8 meters. At the base of the landslide, there is a spring, indicating the presence of an impermeable layer beneath the surface. The sliding plane of the landslide is believed to be the result of weathered, impermeable tuff layer. The slope is about 19° and the dip slope is predicted to be in the same direction as the ground surface slope, with the landslide movement direction approximately N165°E.

The landslide morphology exhibits the characteristic horseshoe shape at the crown, with the sliding material reaching the river at the base of the landslide. The distance of the Cijedil landslide from the earthquake's epicenter is 3.96 km, while the estimated distance from the Cugenang Fault is 0.46 km. The landslide area covers 17.536 m^2, with a length of 234.75 – 272.68 meters and a width of 65.98 to 70 meters. Before the landslide incident, the land use in the area was a mixed plantation, and at the base of the landslide, there were slope cuttings for a district road without reinforced on the cut slope.

The landslide occurred due to the earthquake's shaking on the saturated weathered breccia layer, which had an impermeable layer beneath it. During the survey, the post-landslide condition showed that the road construction had reinforced the cut slope area, and the landslide body and crown had been covered with plastic netting and planted with ground cover crops.

Fig. 3. Cijedil landslide showing the crown, main scarp and depletion zone.

3.3.2. Cugenang landslide

The Cugenang landslide occurred at coordinates 107.080219° E 6.79496° S. The exposed lithology on the surface consists of brown residual soil resulting from weathered volcanic rocks, with a thickness of approximately up to 12 meters. The landslide exhibits a distinctive morphology with a sizeable horseshoe-shaped crown, followed by a more miniature horseshoe indicating two primary and one more minor landslide at this location. The sequence of events suggests that the more significant landslide occurred first, followed by the smaller one. The slope is about 20°.

At the base of the sliding terrain, exposed at the bottom of the landslide, there is a moderately weathered volcanic breccia with component sizes ranging up to boulders. The sliding plane of the landslide is estimated to be composed of compact volcanic breccia, of slightly weathered or an impermeable layer derived from tuff rocks.

During the event, the landslide material covered the Puncak - Cianjur national road in Cugenang and reached the river at the base of the landslide. The main landslide direction is approximately N168°E, while the minor is N211°E. The distance from the landslide to the earthquake's epicenter is 4.62 km, and the estimated distance from the Cugenang Fault is 0.35 km. The landslide area covers 29.833 m^2, with a length of 260.94 – 297.66 meters and a width of 94 to 117.57 meters.

Before the occurrence, the area of the landslide was a mixture of gardens and secondary forest vegetation, some of which had been cleared. At the base of the landslide, there were slope cuttings for the national road that had yet to be reinforced before the landslide.

After the landslide, the area has been reinforced with rock gabions along the road edge, and the sliding area has been covered with plastic netting planted with ground cover crops.

Fig. 4. Cugenang landslide showing the distinct horseshoe-shaped of the crown and main scarp and the depletion zone.

3.3.3. Sarampad landslide

The Sarampad landslide occurred at coordinates 6.802749° S and 107.074958° E. The landslide area was relatively gentle, with a slope of about 9 degrees. The landslide crown was on the west side of the road and did not show a clear horseshoe morphology, but there was a 1.5-meter drop in the ground with a sliding direction of N120°E. The exposed surface of the landslide consisted of light brown to yellowish soil with a relatively porous sandy texture. Considering the sand fraction in this soil exposure, the landslide is likely to be a liquefaction event. However, other supporting evidence has yet to be more detailed and investigated.

Fig. 5. Sarampad landslide shows the main scarp, crown, and road rebuilt in the depletion zone.

The sliding plane of the landslide is estimated to be an impermeable layer composed of tuff. The landslide location is within a residential and rice field area, with a road cutting through the housing area, and about 60 meters to the north is a small river. The landslide affected part of the houses and rice fields in the eastern housing area. The distance of this landslide location from the earthquake's epicenter is 4.03 km, while the estimated distance from the Cugenang Fault is 0.43 km. The landslide area covers 6.331 m^2, with a length of 65.75 – 96.25 meters and a width of 60.70 to 63.09 meters. The landslide occurred when water-saturated sandy lithology was above an impermeable layer, possibly composed of tuff, on a gentle slope.

Fig. 6. UAV image of Sarampad landslide showing the gentle slope morphology of the head scarp area.

3.3.4. Rawacina landslide

The Rawacina landslide occurred at coordinates 6.833086° S, 107.095808° E. The landslide occurred on a relatively gentle slope, around 7 degrees, with an undulating morphology in the depletion zone. The exposed lithology is a weathered brown breccia with an estimated thickness of about 3 meters, underlain by an impermeable brownish tuff rock that acts as the sliding surface. The landslide area is covered with shrubs and sparsely planted with garden crops.

The movement direction of the landslide is estimated to be towards N100°E. The distance from the landslide to the earthquake's epicenter is 0.7 km, while the estimated distance from the Cugenang Fault is 0.67 km. The landslide area covers 3.237 m^2, with a length of 92.78 – 103.42 meters and a width of 26.93 to 42.39 meters. This landslide is similar to the one in Sarampad, resulting from the earthquake shaking with a liquefaction effect. However, supporting evidence has yet to be more detailed and investigated.

Fig. 7. Rawacina landslide showing the crown, a gentle slope and the undulating morphology of the depletion zone.

Fig. 8. Light brown tuff layer exposed at the toe side of Rawacina Landslide underneath the completely weathered breccia's light to dark residual soil**.**

3.4 Discussion and implication of the findings on landslides characteristics

The landslides in Cijedil, Cugenang, Sarampad, and Rawacina occurred near the Cugenang Fault at a distance of between 0.35 to 0.67 kilometers. During the annual rainy season, the slope in the area was stable. However, the seismic shaking caused by the earthquake significantly reduced the slope stability, leading to landslides. All four landslides share a similar movement direction, which is relatively southeastward. This similarity indicates a strong lithological control on the occurrence of these landslides.

The lithology of the area consists of volcanic deposits from Mount Gede, with volcanic sediments spreading radially from the eruption center. The sediment flow relatively southeastward during the earlier volcanic sediment deposition in the landslide areas. Hence the sedimentary bedding is relatively in the same direction as the slope direction. These conditions made them susceptible to slope instability, especially where sediment layers of breccia, lahar on top and impermeable tuff deposits at the bottom layer.

Furthermore, the slope cuttings in the Cugenang and Cijedil landslide areas for road lines without proper reinforcement reduce slope stability. Changes in land use from forests to plantations and other purposes also contribute to decreased slope stability in both landslide locations. Human land use activities dominate surface and shallow landslides in the Bogor, Cianjur, and Sukabumi areas of West Java Province [16]. The depth or thickness of the land-sliding soil in Cugenang is about 8 to 12 meters deep whereas in Cijedil is about 5 to 8 meters.

The Sarampad and Rawacina landslides occurred on relatively gentle slopes compared to the steep slopes in Cugenang and Cijedil. The landslides on these gentle slopes also show strong lithological control, where the upper part consists of weathered breccia or lahar with an estimated thickness of about 3 meters, underlain by an impermeable tuff layer. The morphology of the landslides in these two locations resembles the liquefaction phenomena. Compared to the Palu seismic liquefaction-induced landslides that failed along gentle slopes with general slopes <3°, the Sarampad and Rawacina have 7° to 9° slopes [17]. Furthermore, the soil in these two landslides is sandy soil susceptible to liquefaction. These two landslides also occurred due to seismic shaking near the Cugenang Fault.

The Cijedil, Cugenang, Sarampad dan Rawacina landslides incident offers valuable insights into future landslide prevention measures. While landslides are prevalent in Indonesia during the rainy season, they have been relatively uncommon in the area, even during periods of heavy rainfall. However, devastating landslides can be attributed to the intense shaking generated by a hidden active fault. Earthquakes originating from hidden active faults have proven to be a significant disaster risk, leading to a cascade of landslides. Future studies should focus on investigating the occurrence of active faults and the potential for earthquake-induced landslides in other areas. Furthermore, implementing early warning systems for landslides triggered by earthquakes should be considered as a means to mitigate the risk of disasters in this region.

Conclusion

A shallow earthquake along the active Cugenang Fault triggered Cijedil, Cugenang, Sarampad, and Rawacina landslides in Cianjur. The distance of these four landslides to the fault is relatively close, ranging from 0.35 to 0.67 kilometers, indicating intense shaking along the fault that resulted in these landslides. The earthquakes on this fault can potentially cause collateral landslide disasters, even though the area was relatively safe before, despite the annual rainy season cycle that could trigger landslides. The direction of movement for all four landslide locations is similar, towards the southeast, indicating lithological control. The lithological layers consist of residual soil to highly weathered breccia soil at the top, followed by an impermeable layer of tuff or slightly weathered or massive breccia below, with the bedding direction relatively aligned with the slope inclination, serving as the control for all landslide occurrences. The landslides in Sarampad and Rawacina show morphology similar to liquefaction phenomena. Field lithological observations support this evidence, where sandy soil lies on top of clayey tuff soil at the bottom layer. Land use change, including slope cutting without proper slope stabilization measures, contributes to landslides. The findings of this study indicated that the distance of earthquake shaking from the active fault, slope and lithology orientation, and land use change could be used to forecast upcoming landslide disasters in other areas with similar settings. The study also revealed that earthquakes caused by a hidden active fault pose a significant disaster risk, causing a cascade of landslides.

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