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THE MECHANISM OF LANDSLIDE-INDUCED DEBRIS FLOW IN GEOTHERMAL AREA, BUKIT BARISAN MOUNTAINS OF SUMATRA, INDONESIA

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Landslides frequently occur in Indonesia, especially in the geothermal areas located on Sumatra's mountainous island. On April 28, 2016, around 04:30 Western Indonesia Time, a landslide-induced debris flow occurred in Lebong District, Bengkulu Province, Indonesia. The source area of the landslide was located at Beriti Hill on the Bukit Barisan Mountain Range. It resulted in 6 fatalities and damage to infrastructures such as geothermal facilities, roads, water pipes, houses, and bridges. Subsequent landslides and debris flows occurred on April 30, May 2, and 3, 2016. Therefore, this study aims to examine the mechanism and to know the most significant contributing factor to the Beriti Hill landslide. Field investigation, soil sampling, XRD analysis, and Lidar analysis were carried out in the research. Beriti Hill is a geothermal area with many manifestations and is composed of volcanic rocks. Alteration processes produced a thick layer of soil from volcanic rocks. The thick soil dominated by clay minerals and steep slopes is the dominant controlling factor of a landslide, triggered by high rainfall intensity. Increasing water saturation in the landslide material due to high rainfall is the most contributing factor to the developing debris flow from the landslide. Debris flows are recurring events based on the Air Kotok river's stratigraphic data downstream of the landslide area. The debris flow material is toxic due to the low pH from the geothermal process. Therefore, the alluvial fan deposit area from Beriti Hill debris flow is a hazard zone and unsuitable for settlement and agriculture. This research shows that a landslide mechanism in a geothermal area was controlled by clay mineral presence due to the alteration process. The future of landslide risk assessment in the geothermal area can be considered by detailing clay type and their characteristic that significantly contributes to debris flow.

Key words: landslides, geothermal, alteration, rainfall

INTRODUCTION

A landslide is the movement of a mass of rock, earth, or debris down a slope [1]. Landslides are categorized based on the materials and their moving process [2]. The landslide materials can be divided into loess-paleosol and loess-bedrock, which for movement consists of slide, fall, topple, flow, and spall [3]. A landslide occurs due to shear failure along the landslide field, which is the boundary of soil or rock mass movement. Landslides on slopes are caused by changes in the effective stresses, variations of material properties, or geometry changes. Effective stresses can be influenced either directly due to differences in external forces (earthquake, human activity) or indirectly through water pore pressure from rainfall [4-5]. Degradation processes can cause variations in slope material properties from weathering and chemical reactions [6].

Several internal factors contributing to landslides are slopes (geomorphic), geologic, and hydrologic conditions [7]. Landslides are usually triggered by external factors such as earthquakes, heavy rainfall, or strong vibration, but sudden events can occur without any of these factors occurring [8-9]. Earth movements depend on the moving material, topography, and water content [8]. Landslides

and debris flows are common phenomena in mountainous areas and are triggered by earthquakes and rainfall [10-11]. The movement of soil or rock mass on the slope can occur due to the interaction of several conditions, including morphology, geology, geological structure, hydrogeology, and land use [12]. These conditions influence each other and form slope conditions that have a tendency or potential to move. Even though the slope is already susceptible to collapse, if there is no trigger from rain, earthquake, or human activity, a landslide will not occur. Some researchers have carried out studies to understand landslide occurrence mechanism [13,14]. The ancient landslide in Breckenridge, Quebec, Canada is a "flake" type failure occurred in sensitive clay and triggered by earthquake [13] and the Wulipo landslide which was transformed into debris flow and occurred in the Upper Cretaceous Guankou formation with siltstone and mudstone interbedded, was triggered by heavy rainfall [14]. The current study investigated slope failure mechanism in geothermal areas to understand the triggering mechanism and also to look into the type of the minerals of the areas.

Geothermal areas are specific areas characterized by

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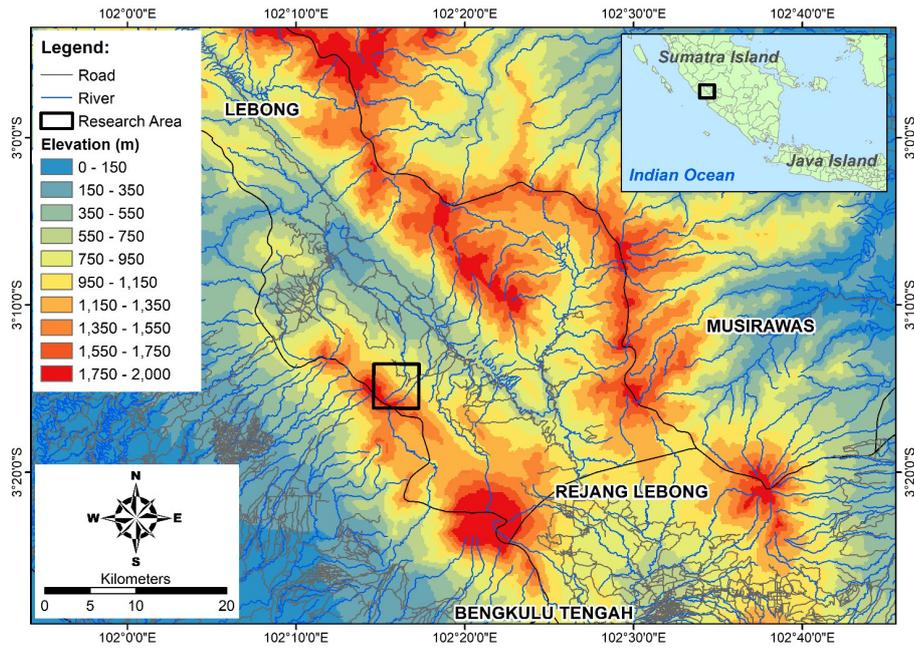


Figure 1: Landslide location at Beriti Hill in Lebong District, Bengkulu Province

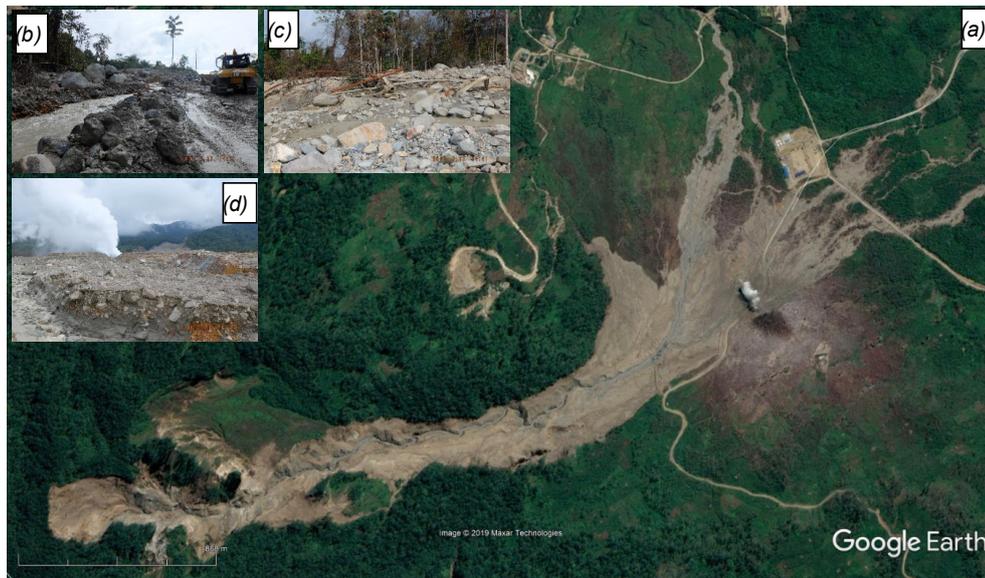


Figure 2: (a) Google Earth Image on 28-09-2016 after the landslide [19]; (b) road damage; (c) water pipe damage; (d) geothermal wellhead damage

a very thick soil layer, and most of them are located in the mountain area. The thick soil is dominated by clay minerals from alteration products [15]. Therefore, it is very easy to collapse due to rainfall or earthquake, or a combination of both. The sliding surface's potential in the geothermal area consists of a clay layer dominated by the mineral of halloysite and metahalloysite [16]. Besides, montmorillonite clay minerals in the geothermal area also contribute to the landslide due to their swelling potential [17]. A significant landslide in the altered hydrothermal area is mostly related to argillic alteration when medium to small landslides mainly occur in prophylic alteration [18].

Landslides frequently occur in Indonesia due to complex geology, topographic, and tectonic conditions. An island in Indonesia that often experiences landslides is Sumatra. This island is composed of the Bukit Barisan

mountain range that extends from northwest to south-east, forming valleys and hills. On April 28, 2016, at around 04:30 Western Indonesia Time, a landslide-induced debris flow occurred in Lebong District, Bengkulu Province, Indonesia, as shown in Figure 1. The landslide was originated from Beriti Hill. The crown of the landslide was located in Beriti Hill caldera at $3^{\circ}15'11,5''S$ and $102^{\circ}14'40,9''E$, about 2.5km from a geothermal facility. It resulted in 6 fatalities and damage to infrastructures such as geothermal facilities, roads, water pipes, houses, and bridges, as shown in Figure 2. Subsequent landslides-induced debris flows occurred on April 30, May 2, and 3, 2016. This research studies the mechanism and factors that triggered landslide-induced debris flow in Beriti Hill. It also examines the geological condition in the Beriti Hill area and the impact of the debris flows.

METHODOLOGY

The research was conducted by field investigation, soil sampling, XRD analysis, and light detection and ranging (LiDAR) analysis. A field investigation was undertaken to identify the deposited materials' rock layer and types in the sources zone, transported zone, and deposited zone. Nine soil samples were taken from the field, which each zone had three samples to identify their mineral composition using XRD from Rigaku. The soil samples were taken from the middle of each layer at a depth of 30-50cm based on the field outcrop. The XRD analysis for soil samples was carried out with oriented clay mineral aggregates [20]. The sample was prepared by air-drying and removing organic materials with 30% H₂O₂ solution, and then it was ground to get appropriate particle size by hand grinder using agate mortar. They were then ethylene glycol (EG) solvation and heated at 550°C for 1 hour before detected by the XRD equipment. The position and the intensity of peaks in a diffraction pattern from the XRD result were compared to the international center for diffraction database to identify the mineral type. Besides, undisturbed soil samples were collected from the depositional zone to determine their physical and mechanical properties according to ASTM standards. The pH measurement was conducted both in the material and seepage water by pH meter from Hanna instruments. The pH meter was calibrated in compliance with the manual of the device before it was used in the

field. The landslide material volume was calculated by comparing the topography data before and after the landslide occurrence and multiplying it with the depositional area using a geographical information system (GIS) [21]. The topography models were developed by digital elevation model (DEM) from LiDAR data. Rainfall data were collected from the nearest rain gauge of Kepahiang Meteorological Station around 10km from Beriti Hill [22] and JAXA Global Rainfall Watch [23]. Earthquake data were collected from USGS open data [24].

GEOLOGY OF THE RESEARCH AREA

Soil mass movements are mostly influenced by morphological conditions, lithology, and geological structures [25]. The landslide sources are coming from the caldera of Beriti Hill. The morphological conditions of the peak of Beriti Hill indicate a volcanic caldera shaped like a bowl with a narrow gap in the northeast as the headstream of the Air Kotok River, as shown in Figure 3. The caldera has a steep slope of more than 40°. The morphology can be divided into three zones, i.e.: (1) the source area of a caldera in the high slope zone; (2) the transport area in the moderate slope zone, which then progresses downstream into the low slope zone; and (3) the depositional area in the slope zone, which has a relatively flat slope, as shown in Figure 3.

Figure 2(a) shows alluvial fans deposit from landslide materials. Alluvial fans are the accumulated sediment that

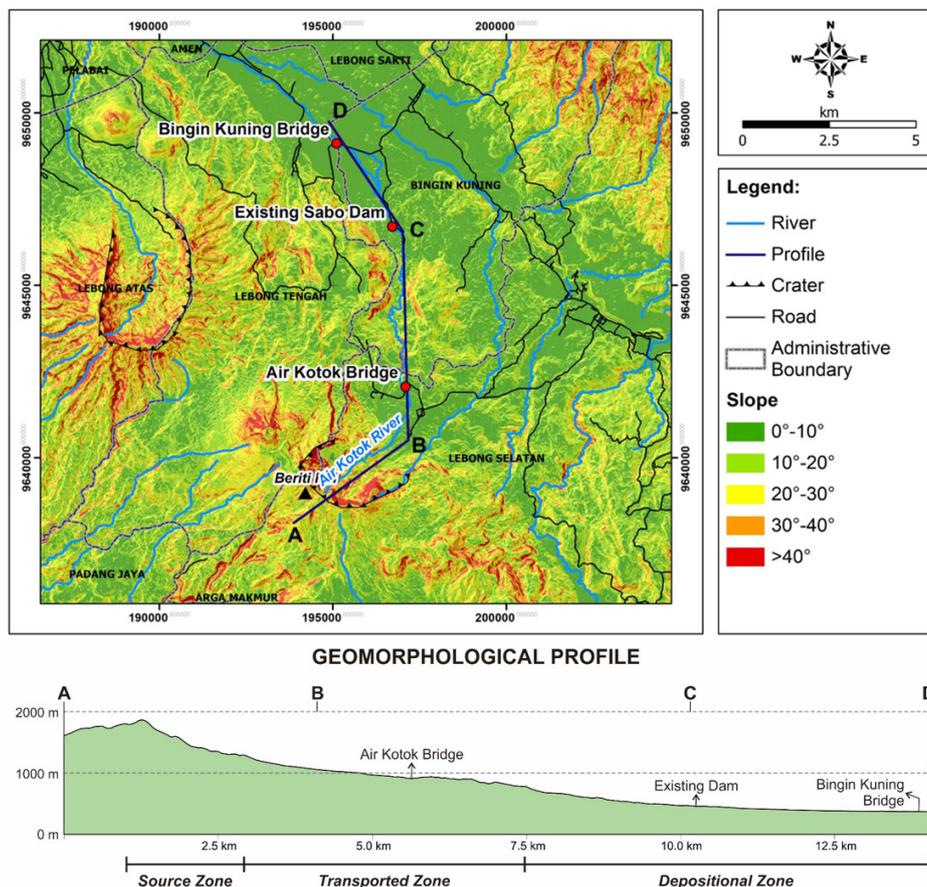


Figure 3: Beriti Hill slope gradient map and its cross-sectional profile

appears at the mouth of a valley/stream from a mountainous region due to debris flows in non-fluvial areas [26]. Most alluvial fan areas look bare, or only covered in grass, while in other places, the areas are overgrown with tall plants/trees. Figure 2(b, c, d) show the distribution of landslide materials from Beriti Hill landslides that destroyed infrastructures, including geothermal wells and access roads.

The rocks of Beriti Hill are the rio-andesite volcano formation and the basaltic andesite volcano formation, as shown in Figure 4 [27]. The rio-andesite formation is composed of rhyolite, dacite, and andesite materials, hybrid tuff, solid tuff, volcanic breccia, and pumice of the Pleistocene age [27]. The basaltic-andesite volcanic formation has a composing lithology of andesitic-basaltic lava, volcanic breccias originating from Daun Hill. This formation is from the Pleistocene-Holocene epochs. Beriti Hill area has many geothermal manifestations around the caldera, such as fumaroles, hot springs, and steaming ground. Therefore, most soil and water in this area have acidic conditions.

Beriti Hill is part of the Bukit Barisan Mountain Range that stretches along Sumatra Island. The geological structure in Beriti Hill is influenced by a regional fault called the Semangko Fault that stretches along the island of Sumatra (NW-SE). Along the Semangko Fault Zone, several active and dormant volcanoes were found [28-29]. The geological structure in Beriti Hill shows the main directions are northwest-southeast with a relatively long dimension and northeast-west with a shorter dimension that intersects with the main structure. The Semangko Fault is a dextral fault that causes minor faults with vary-

ing directions. The discontinuity structure is a weak area that reduces the carrying capacity of rocks. This weak zone is the way of hydrothermal solution from inside the earth, which accelerates the rock alteration rate. Based on the digital elevation model (DEM) image data created from LiDAR and previous data [15, 25], geological structures can be identified. The geological structure is of various directions: northeast-southwest (NE-SW), north-south (N-S), and northwest-southeast (NW-SE), as shown in Figure 4. The high geological structure density at the source areas is an indication that there are many geological structures in the area.

The Beriti Hill is prone to earthquakes because of its active sides of Sundaland in Sumatra, formed from the subduction results between the Indo-Australian Plate and the Eurasian Plate. This subduction process formed the Sumatran Fault Zone with a dextral fault type and formed an oblique pattern resulting from the tectonic strain. This subduction process also produced active faults in the same direction as the Sumatra Fault Zone, northwest-southeast. With such tectonic conditions, the study area is an active earthquake zone. The Sumatra Region Earthquake Source Map shows that the study area is close to the Musi Fault's active earthquake source, as shown in Figure 5 [30]. This fault is one of the faults located in the Sumatra Fault Zone that extends northwest-southeast. The Musi Fault has a strike-slip mechanism with a 13.5mm/year slip-rate and a maximum magnitude of 7.2. In addition, the study area is also close to other earthquake sources, such as the Ketaun Fault in the north-east and the Manna Fault in the south. The two faults also have a strike-slip mechanism. The

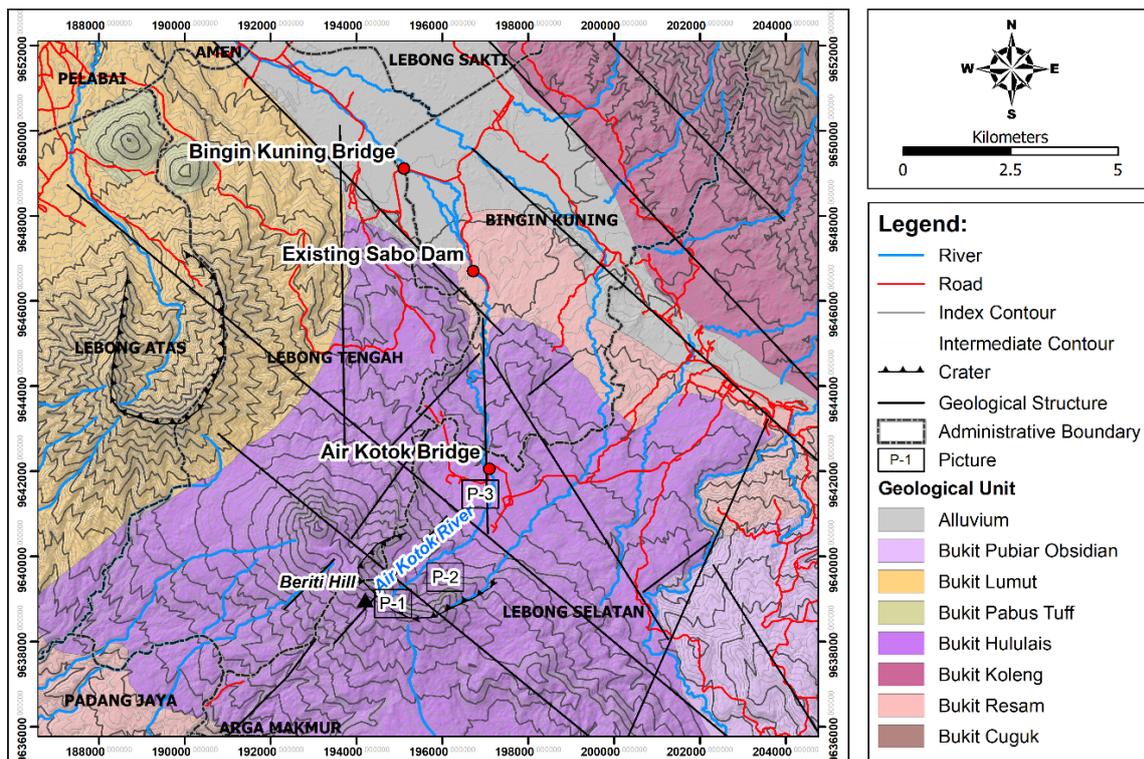


Figure 4: Geological map of Beriti Hill and its surrounding area [27]

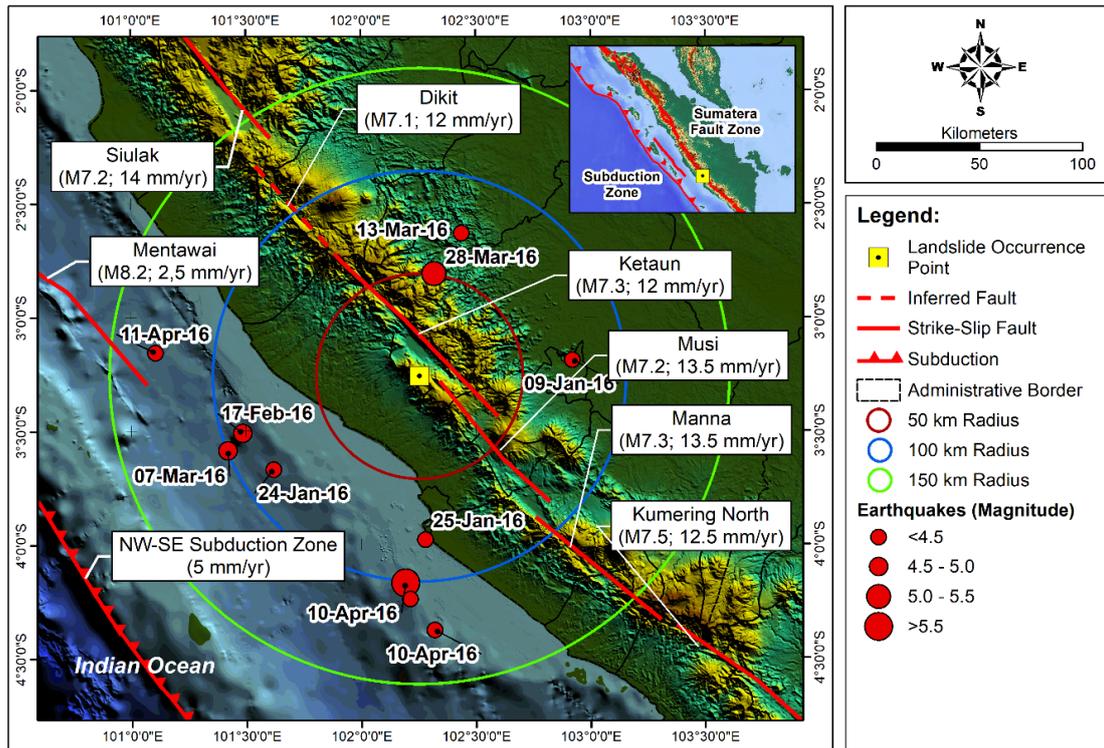


Figure 5: Map of earthquake sources and earthquake epicenters in March-April 2016 [24,30]

Ketaun fault and Manna fault have a maximum magnitude of 7.3 with a 12 mm/year slip rate and 13.5 mm/year, respectively [30].

RESULT AND DISCUSSION

Landslide controlling factors

The caldera slope (source zone) comprises volcanic rocks consisting of andesite, volcanic breccia, and tuff breccia, as shown in Figure 6(a). The rocks underwent hydrothermal alterations associated directly with fumarole areas where water can accumulate or areas with low groundwater levels [15]. Table 1 shows the XRD result from the soil sample in the source, transport, and depositional zones. The source area's dominant mineral is kaolinite, cristobalite, halloysite, and tridymite, as shown in Figure 6a. Therefore, the source area has an argillic alteration [31]. The thickness of the soil layer from the alteration process is more than 10 meters. The soil has high acidity with a pH value of around 3.5, while the pH

of seepage water is 2.7. The stratigraphy of the transport zone shows the upper layer is not a well-compacted coluvial deposit followed by the intersection of andesite and andesite breccia lava, as shown in Figure 6(b). The upper and middle layers consist of chlorite, mix illite/smectite, mix chlorite/smectite, and tridymite categorized as prophylic alteration [29]. The lower layer consists of halloysite, cristobalite, quartz that indicate argillic alteration. The headstream on the Air Kotok River cliff shows that the lowest rock in the outcrop is a volcanic breccia with a thickness of about 1.8m and is indicated as a product of debris flows, as shown in Figure 6(c). The volcanic breccia matrix consists of smectite, halloysite, mix chlorite/smectite, tridymite, and cristobalite. This clay minerals composition is similar to the material in the landslides' source zone. The middle layer is alternating sandstone and sandstone-gravel about 1.4m thick, which is the river flow sediment product. The upper layer is a volcanic breccia with a thickness of about 2.8m.

Table 1: XRD result from each zone

Source zone (P-1)	Upper	Kaolinite, cristobalite
	Middle	Kaolinite, cristobalite
	Lower	Halloysite, tridymite
Transport zone (P-2)	Upper	Chlorite, Mix illite/smectite, Mix chlorite/smectite, Smectite, tridymite
	Middle	Mix chlorite/smectite, tridymite
	Lower	Halloysite, cristobalite, quartz
Depositional zone (P-3)	Upper	Halloysite, cristobalite, smectite
	Middle	Smectite, Mix chlorite/smectite, tridymite
	Lower	Smectite, Mix chlorite/smectite, cristobalite

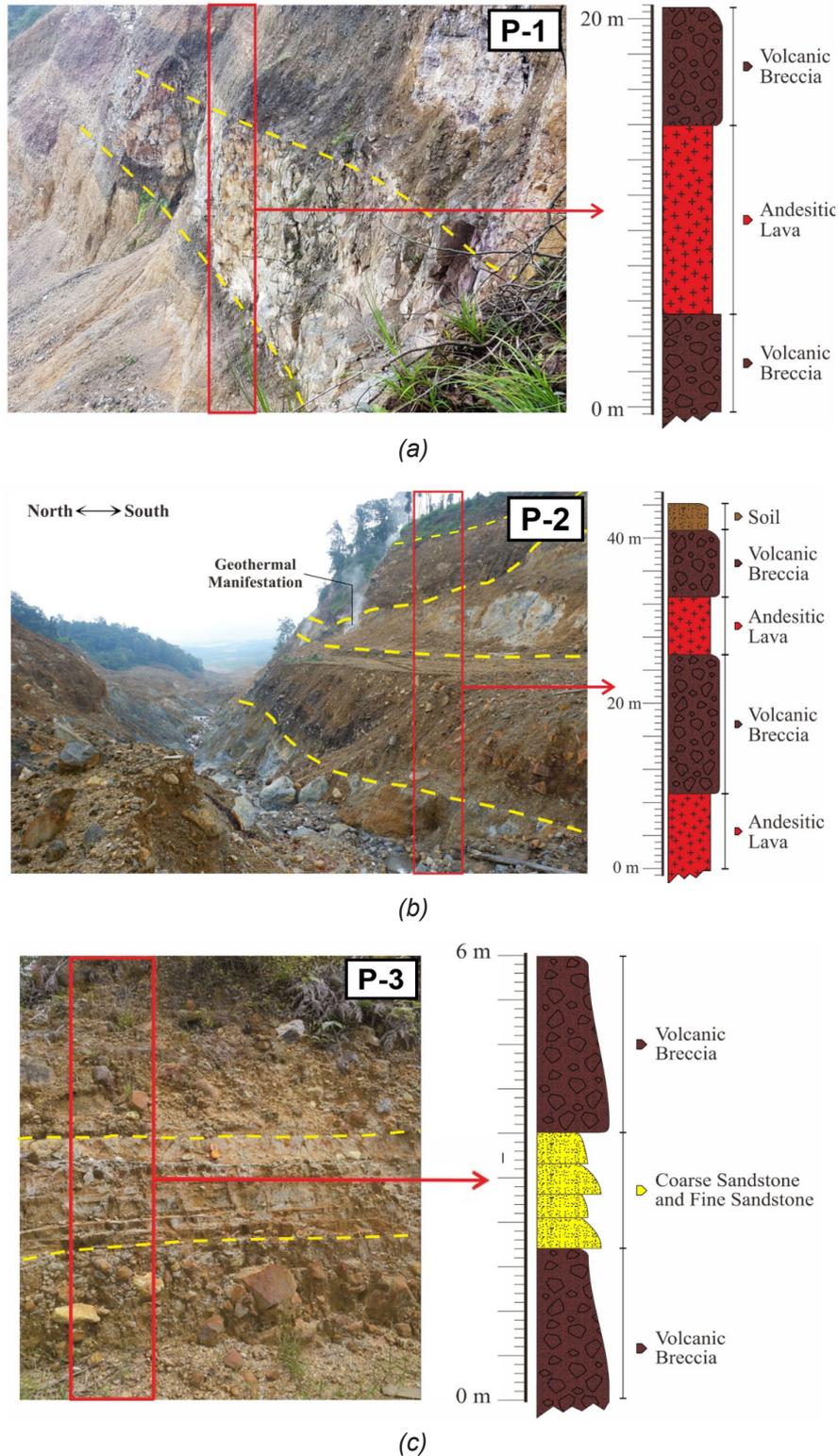


Figure 6: (a) Stratigraphy of the caldera wall of Beriti Hill (source zone), (b) Stratigraphy in the middle of the transport zone, (c) Stratigraphy on the depositional zone (the Air Kotok River cliff)

Alluvial fans are composed of lumps of rock, silty sand, and organic clay. The layer of silty sand sits above the inorganic clay layer. The thickness of the clay-sand layer varies between 1 and 4 meters. The top layer has densities from loose to solid. The cohesion obtained from the direct shear test ranges between 3 and 22 kPa. Based on the visual criteria, the inorganic silt layer can be divided into yellowish and reddish silt, 38.49% of which

passed through the number 200 sieve. According to the USCS (Unified Soil Classification System), this soil is clayey sand. Furthermore, the soil has a liquid limit (LL) and plasticity index (PI) values of 55.44% and 17.37%, respectively. Based on these values, the soil can be classified as SC, clayey sand with a mixture of medium to high sand-clay plasticity.

Factors triggering landslide

Based on the historical data on earthquakes recorded at the U.S. Geological Survey [20], the earthquake that has the most significant impact in Beriti Hill (3°24'16,13"; 102°27'83,14") and its surroundings is the earthquake that occurred on April 22, 1997, with a magnitude of 5.9 Mw. The earthquakes that occurred during January-April 2016 in the study area were shallow; on April 10-11, 2016, earthquakes with a magnitude of 4-5 Mw occurred. The earthquakes' epicenter points in the study area are generally on land with a depth of 150 km. The earthquake activity data before the landslide occurred, as shown in Figure 7. Beriti Hill has a peak ground acceleration (PGA) value of 0.6-0.8 g, referring to the peak ground acceleration map in the bedrock for a probability exceeding 10% in 50 years [30]. The PGA value is equivalent to the force/energy exposed to the building during short-term ground shocks. An earthquake with a minimum of a horizontal ground acceleration value of 0.28 can trigger a sensitive clay layer [13]. The vibrations caused by this earthquake can trigger mass movements [32]. These vibrations cause liquefaction of slope-forming materials, especially in water-saturated material. The liquefaction process causes the land's strength and carrying capacity to decrease rapidly [33]. Water entering the material, making up the slope due to this process, can increase the slope's loading, which then triggers mass movements. Therefore, the earthquake with a high PGA value contributes to the landslide process in this area.

Generally, rainfall is one of the primary landslide triggers, especially in tropical high-precipitation regions [34-36]. Indonesia has a tropical climate with high rainfall intensity. Heavy or moderate rain that lasts a long time is very instrumental in triggering soil/rock movement. Rainwater that seeps into the soil on slopes can increase water saturation in the soil. Therefore, water pressure can stretch the bond between the soil and the soil mass transported by the slope's water flow, making the slope unstable and causing landslide or debris-flow activity. The rainfall data from the Kepahiang Meteorological Station, around 10 km from Beriti Hill [20], shows that the rainfall in the area of study during the landslides in April 2016 had a very high value, reaching 546 mm/month. This rainfall value is higher than the rainfall in the previous months, which ranged from 200-300 mm/month. Besides, detailed data from JAXA Global Rainfall Watch [21] shows the rainfall in Beriti Hill on the day before the landslide occurred reached 58.41mm/day, and at the time of the incident, it was 46.51 mm/day, as shown in Figure 7. Then, subsequent landslides occurred on April 30, May 2, and May 3, during which rainfalls were 20.93, 52.71, and 20.81 mm/day. Heavy rain causes the rocks on Beriti Hill to be more unstable and easy to move for landslides. A landslide can be transformed become debris flow due to heavy continuous rainfall in the mudstone-sandstone mixed stratum [14].

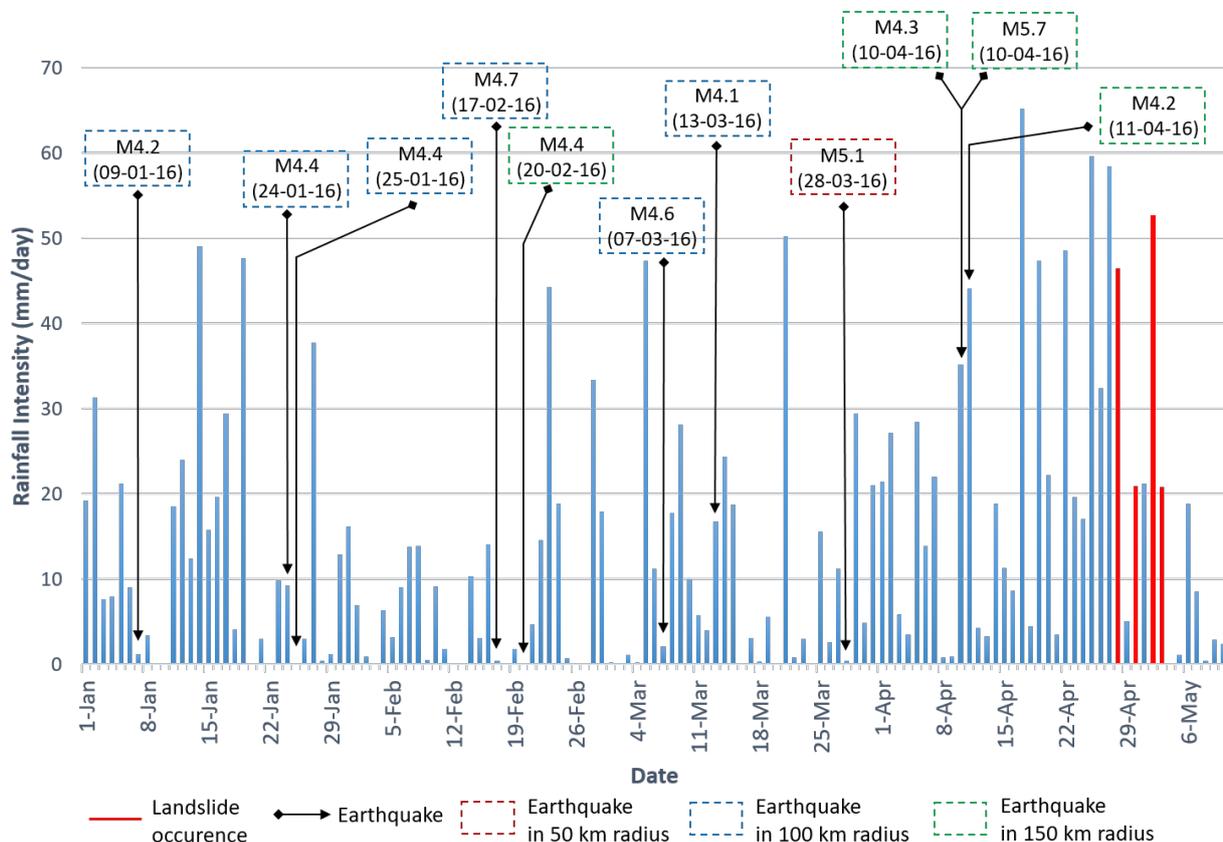


Figure 7: Daily rainfall and significant earthquake from January to May 2016 at Beriti Hill [23, 24]

Discussion

The wall slope of Beriti Hill caldera as a source area has a steep slope of more than 40° . With the steepness of this slope, the site is very vulnerable to landslides. This caldera has a gap in the north-east part that forms a narrow and steep valley. Northeastward, the slope is less steep upstream of the Air Kotok river. There is alluvial fan sediment morphology at the end of the slope. The characteristics of rocks around the caldera that experienced intensive geological structures caused the hydrothermal solution to flow upwards through the weak zone. This hydrothermal process is marked by fumaroles and hot springs, which resulted in rock alteration and produced very thick soil deposits accompanied by rock chunks. The sliding surface of the landslide consisted of clay minerals such as halloysite, cristoballite, and quartz. The weathering or alteration process will also reduce the soil/rock slope's strength, causing landslides, especially during heavy rains [37-39].

An earthquake occurring within a 50 km radius on March 28, 2016, with a magnitude of 5.1 on the Richter scale and three successive earthquakes on April 10-14, 2020, did not trigger immediate landslides, as shown in Figure 7. It indicates the effect of earthquakes on landslides in Beriti Hill is lower compared to that of rainfall.

A landslide occurred on April 28, 2020, with daily rainfall reaching 46.51mm/day, lower than April 17, which reached 65.19mm/day. It shows that the occurrence of landslides is not triggered by daily rainfall but is more influenced by antecedent rainfall. Most landslides are triggered by 10-day rain with total rainfall of more than 88.35mm [40], while the rainfall in Beriti Hill in the last ten days before the landslide reached 355.21mm. Previous research also supported that more than 61mm a day or three-day rain with a cumulative intensity of more than 91mm will trigger landslides in Indonesia [41].

Continuous rain caused some water to be retained at the top of the hill and formed high saturation in the soil, causing infiltration where water entered soil pores to the point of contact with the bedrock. When the load on the slope increased, the slope's stability was disrupted, and a landslide occurred. Landslide material in the form of andesite boulder fragments and weathered volcanic breccias material slid down along the 2.5 km and damaged the geothermal facilities. The movement of material from the caldera wall also eroded the cliff wall of the valley passed by, so it produced deeper valleys upstream, adding to the landslide material as shown in Figure 6(b). The debris flow slides' material volume reached 4,300,000 m³ based on topographic contour maps from LiDAR before and after the landslide. The debris flow material buried all agricultural areas downstream, as shown in Figure 2(a). The material had a high acidity that makes all the vegetation dead. It takes a long time to make the pH of the soil neutral. Therefore, it is necessary to put topsoil from other areas with high fertility for the reforestation process or add lime in the debris materials to increase

the pH. Dense vegetation is essential to minimize debris flow impact distribution in the future of landslides, especially the transported zone.

Landslides-induced debris flow in Beriti Hill and surrounding areas are recurring events. The Air Kotok River's stratigraphic data shows evidence of this process that consists of a repetition of volcanic rock breccia layers with sandstones, as shown in Figure 6(c). In debris flow events, large material (volcanic breccia materials) will be deposited, while sand materials will be deposited under normal conditions. Also, Google Earth photos show an alluvial fan in the Air Kotok River channel's slope in the bend section. Grass dominates the alluvial fan sedimentation area, which differs from other places, as shown in Figure 2.(a). It shows that this area was once buried by landslide materials, which caused large plants/perennials to die/disappear. The current distribution of debris-flow deposits in the alluvial fan shows the same pattern as before, as shown in Figure 2.(a)

CONCLUSIONS

The geothermal area is prone to landslides since the alteration process produces a thick soil layer dominated by clay minerals. Besides, most of the geothermal areas are located in mountainous areas with steep slopes, dense geological structures, and high rainfall intensity. The landslide in Beriti Hill occurred due to the collapse of the mass block of soil and rock, controlled by the thick soil layer conditions due to the alteration process, and supported by steep slopes (more than 40°). The landslide occurred after prolonged rain, not soon after an earthquake. It seems that antecedent rainfall has more contributed than the earthquake to trigger the landslide in Beriti Hill. The cumulative rain was occurring within ten days before the landslide is 355.21 mm. Landslides were recurring events based on the Air Kotok River wall's stratigraphic records and the alluvial fan deposits' morphology downstream. Therefore, the Air Kotok River area, especially the alluvial fan deposit, is a debris flow hazard area and is not suitable for a residential area and agriculture. The debris flow material is toxic for vegetation due to its acidity. It is necessary to build a dam in the transported zone and increase the Air Kotok River's volume to mitigate the landslide in the future. Besides, it needs installing early-warning sensors around Beriti Hill caldera to monitor soil/rock movement, including rain gauge, extensometer, and tiltmeter.

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