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Dry Landslide in Sarwodadi Village, Pejawaran Sub-Regency; An Untypical Landslide in Banjarnegara Regency, Central Java Province, Indonesia

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ABSTRAK

Banjarnegara dikenal sebagai kabupaten yang sangat rentan terhadap bencana tanah longsor, dengan lebih dari separuh wilayahnya tergolong memiliki tingkat bahaya tanah longsor yang tinggi hingga sangat tinggi. Gerakan massa di Banjarnegara, khususnya di Sub DAS Merawu, sebagian besar berkategori gerakan luncur. Curah hujan menjadi faktor utama pemicu terjadinya tanah longsor di wilayah ini. Penelitian ini bertujuan untuk membedah penyebab dan mekanisme kejadian longsor unik yang terjadi di Desa Sarwodadi, Kecamatan Pejawaran, Kabupaten Pejawaran, Provinsi Jawa Tengah, pada tanggal 6 Juli 2022 sekitar pukul 22.30. Berbeda dengan kejadian pada umumnya, tanah longsor ini tidak dipicu oleh curah hujan, yang umumnya merupakan penyebab utama terjadinya tanah longsor di Banjarnegara. Dengan menggunakan metodologi tiga tahap yang melibatkan pengumpulan data sekunder, observasi lapangan, dan analisis data, dua kemungkinan penyebab terjadinya tanah longsor dapat diidentifikasi: hilangnya dukungan dari penghalang tegangan (*stress barrier*) dan longsoran massa. Mengingat wilayah tersebut masih merupakan lokasi pertambangan aktif dengan dinamika yang melekat, maka langkah-langkah proaktif sangat penting untuk memitigasi risiko tanah longsor di masa depan. Hal ini penting untuk menjaga keselamatan aktivitas pertambangan lokal, yang merupakan sumber pendapatan utama bagi banyak rumah tangga di Sarwodadi dan sekitarnya. Inisiatif pemetaan dan penilaian komprehensif yang menargetkan wilayah dengan karakteristik geologi serupa dengan yang ada di Sarwodadi harus dilakukan di seluruh Banjarnegara. Upaya-upaya tersebut tidak hanya akan mengurangi terjadinya tanah longsor namun juga meningkatkan kesadaran masyarakat mengenai kejadian tanah longsor yang tidak biasa.

***Kata kunci*:** Banjarnegara, Diorit, Longsor, Curah Hujan, Tidak Umum

ABSTRACT

Banjarnegara is known as a regency highly susceptible to landslides, with over half of its territory classified as having a high to very high level of landslide hazard. Mass movements in Banjarnegara, particularly within the Merawu Sub-watershed, are predominantly categorized as slides. Rainfall stands out as the primary triggering factor for landslides in this region. This study aims to dissect the causes and mechanisms behind a unique landslide event that occurred in Sarwodadi Village, Pejawaran Sub-regency, Pejawaran Regency, Central Java Province, on July 6, 2022, around 10:30 PM. Unlike typical occurrences, this landslide was not propelled by precipitation, which is commonly the principal catalyst for landslides in Banjarnegara. Employing a three-stage methodology involving secondary data collection, field observation, and data analysis, we have identified two potential explanations for the landslide event: the loss of support from the stress barrier and mass sliding. Given that the area remains an active mining site with inherent dynamics, proactive measures are imperative to mitigate the risk of future landslides. This is essential for safeguarding the safety of local mining activities, which constitute the primary source of income for many households in Sarwodadi and its environment. A comprehensive mapping and assessment initiative targeting areas with geological characteristics akin to those in Sarwodadi should be undertaken across Banjarnegara. Such endeavors would not only diminish the occurrence of landslides but also enhance public awareness concerning atypical landslide occurrences.

***Keywords*:** *Banjarnegara, diorite, landslides, precipitation, untypical*

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1. INTRODUCTION

Indonesia is highly susceptible to disasters, particularly hydrometeorological events. Climate change has intensified these disasters by altering the characteristics of rainfall in Indonesia, affecting its intensity, distribution patterns, and seasonality (Susanti & Miardini, 2016). Landslides, a prevalent type of hydrometeorological disaster, are especially common in Banjarnegara Regency, Central Java Province (Agustina et al., 2020; Andaru & Purnama, 2017; Satriagasa et al., 2020; Susanti & Miardini, 2016). Historically, Banjarnegara has experienced numerous landslides with high frequency (Ramadhan et al., 2016; Susanti et al., 2017), resulting in significant fatalities (Susanti et al., 2017; Susanti & Miardini, 2019). Figure 1 illustrates the number of landslide occurrences in Banjarnegara from 2009 to November 23, 2022.

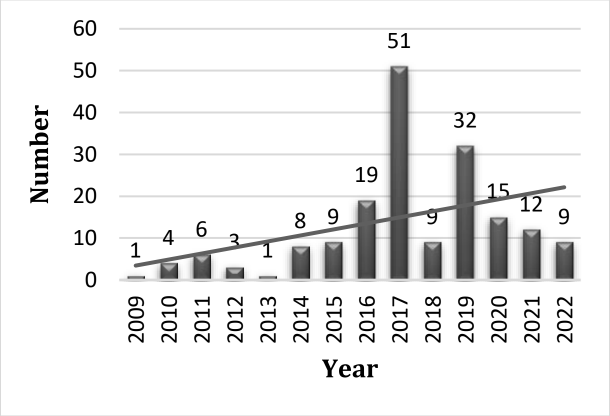

Figure 1. The frequency of Landslides in Banjarnegara Spanning the Period from 2009 to 2022
Source: BNPB (2022)

Banjarnegara Regency is highly susceptible to landslides (U. Nugroho et al., 2017; Prasetya, 2020). Over half of the region is classified as having a high to very high landslide hazard level, while only approximately 24 percent is categorized as having a low to very low hazard level. The sub-districts of Wanayasa, Kalibening, Pejawaran, Pagedongan, and Karangkobar are identified as having very high landslide hazard levels (Susanti & Miardini, 2019).

A landslide is one of six forms of mass movements, which include slide, fall, topple, spread, flow, and combination types. A slide refers to mass movements along a flat sliding plane, often aligned with a discontinuity or weak plane approximately parallel to the slope surface, resulting in translational ground motion (Apriyono, 2009). Landslides occur when rock, debris, or earth slides down and out of a slope. This phenomenon, also known as landslip, slump, slope failure (Anggraini, 2015), or mass wasting (Bayuaji et al., 2016) represents a natural process seeking a new equilibrium due to external disturbances that decrease soil shear strength and increase soil shear stress (Apriyono, 2009). Landslides primarily occur in areas with steep slopes (Satriagasa et al., 2020) or mountainous terrains (Apriyono, 2009). In tropical hilly regions, landslides are often triggered by shear failure along the landslide plane, marking the boundary between soil and parent rock (Susanti & Miardini, 2016).

The failure of materials constituting hill slopes is influenced by a combination of intrinsic and extrinsic factors. Intrinsic parameters are primary, while extrinsic factors—such as natural phenomena—can influence these main factors (Pamungkas & Sartohadi, 201 C.E.). Generally, the factors contributing to landslides include geomorphology (e.g., slope angle), geology (e.g., rock and soil types) (Anggraini, 2015; U. Nugroho et al., 2017; Setiadi, 2013), climate (e.g., precipitation), weathering, overloading (Anggraini, 2015; Setiadi, 2013), water content, vegetation, slope stability (Anggraini, 2015), earthquakes (which induce stresses leading to slope failures), vibrations (from machinery, traffic, explosives, and even lightning) (Setiadi, 2013), gravitational forces (Anggraini, 2015; Bayuaji et al., 2016), land use practices (U. Nugroho et al., 2017), and other triggering factors (Susanti & Miardini, 2019). Complex geological conditions characterized by multi-periodic tectonic movements further increase the risk of landslides (Susanti & Miardini, 2019).

Landslides are natural disasters that frequently occur, particularly during the rainy season. Rainfall can trigger landslides by adding weight to slopes and reducing the shear strength of the soil (Susanti & Miardini, 2016, 2019) (Figure 2). High-intensity rainfall significantly increases the risk of landslides (Satriagasa et al., 2020; Susanti & Miardini, 2019).

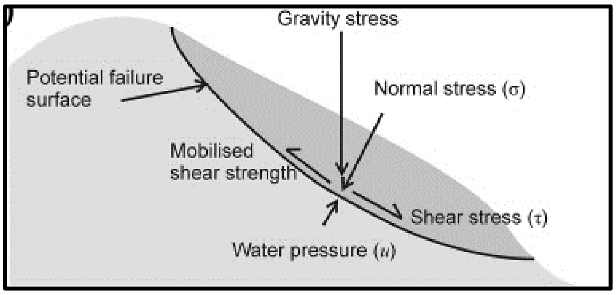

Figure 2. Illustration of Forces in Landslide Mechanism Adopted from McColl (2015)

Landslides typically result from a combination of factors rather than a single cause. Contributing factors include increased slope load, soil cutting at the slope's base, excavation that steepens the slope, rapid changes in water levels in dams or rivers, increased lateral pressure from water, decreased soil shear resistance, and vibrations or earthquakes. Human activities also play a significant role in triggering landslides. Population growth exerts pressure on land for housing, agriculture, industry, and other purposes. Inappropriate land use practices that disregard conservation and environmental sustainability principles can lead to more frequent natural disasters. Activities such as mining, cutting steep slopes for roads and settlements, and other infrastructure developments can trigger landslides (Satriagasa et al., 2020; Susanti & Miardini, 2016).

Based on the type of mass movements, those in Banjarnegara, particularly in the Merawu Sub-watershed, can be categorized as slides. The landslide material in this area is predominantly soil, with landslide depths generally ranging from 5 to less than 20 meters. Most landslides occur in deep red Mediterranean soil and Regosol. The slope aspect does not indicate a dominant influence, although landslides are more common on west-facing slopes compared to other directions (Satriagasa et al., 2020).

Rainfall is the primary trigger for landslides in Banjarnegara (Agustina et al., 2020; Apriyono, 2009; Hidayat & Zahro, 2018; U. Nugroho et al., 2017). Two types of rainfall typically trigger landslides: heavy rainfall of 70 mm to 100 mm per day, and prolonged, less intense rain followed by heavy rain (Hidayat & Zahro, 2018). Continuous rainfall increases soil weight and decreases soil binding capacity, thereby reducing shear strength and destabilizing slopes, which elevates the landslide risk (Apriyono, 2009; Hidayat & Zahro, 2018; U. Nugroho et al., 2017).

When water infiltrates the slip plane, the soil becomes slippery, causing the weathered soil above to move along and out of the slope, resulting in a landslide (Hidayat & Zahro, 2018). An example of this occurred in Kalitlaga Village, where landslides were observed in several locations within a larger block. Here, sandy clay-sized soil masses slid over a claystone slip plane. The claystone at the location becomes water-saturated and slippery during high-intensity rain, causing the soil mass to slide (Apriyono, 2009). Consequently, landslides are more frequent during the rainy season (Agustina et al., 2020).

However, rainfall alone is not the sole cause of landslides. Landslides result from the build-up of high water pressure in the slope, a phenomenon also influenced by the hydraulic, physical, and mechanical properties of the terrain, as well as environmental factors such as slope, vegetation cover, and climatic characteristics (Anggraini, 2015). Soil water content varies with the intensity of rainfall in the area (Mutaqin, 2020).

Data from the National Agency for Disaster Countermeasure - BNPB (2022) supports this. Of the 179 recorded landslides in Banjarnegara from 2009 to November 23, 2022, causes were recorded for 58. Of these, 56 (96.5%) were triggered by rainfall. The remaining two were caused by strong winds and the collapse of a house due to the underlying land, which had been a pool filled with trash and soil, leading to ground subsidence.

Rainfall triggering landslides includes not only the rain at the time of occurrence but also preceding rainfall. Table 1 presents cumulative rainfall data that caused landslides in various locations in Banjarnegara in 2014, 2015, and 2016. The cumulative rainfall triggering landslides for one day ranged from 0 to 126 mm, for three days from 8.7 to 248 mm, and for ten days from 68 to 431 mm (Hidayat & Zahro, 2018).

The rainfall thresholds that can trigger landslides are 56 mm for one-day accumulation, 89 mm for three-day accumulation, and 215 mm for ten-day accumulation (Hidayat & Zahro, 2018). Additionally, according to U. Nugroho, Kusumandari, and Lashari (2017), high-intensity rainfall of 50 mm or more lasting for over six hours can potentially cause landslides, as the water saturates the soil, increasing its weight. Prolonged heavy rainfall, both at the time of and preceding the event, is a significant trigger for landslides (U. Nugroho et al., 2017).

Table 1. Landslide Locations in Banjarnegara and Accumulated Rainfall Triggering Landslides in 2014, 2015, and 2018

Date	Location	Accumulated Rainfall (mm)		
		One-day cumulation	Three-day cumulation	Ten-day cumulation
13/11/2014	Sijeruk, Banjarmangu	4.0	74.0	229.0
29/11/2014	Anjir, Kalitlaga, Pagentan	55.6	58.0	68.0
30/11/2014	Clapar, Madukara	56.0	116.4	205.4
5/12/2014	Paweden, Karangkobar	126.0	159.0	377.0
9/12/2014	Pencil, Wanayasa	30.0	61.2	215.3
11/12/2014	Tunggoro, Sigaluh	125.0	235.0	255.0
12/12/2014	Jemblung, Karangkobar	101.0	248.0	431.0
12/12/2014	Gintung, Binangun, Karangkobar	101.0	248.0	431.0
17/12/2014	Sipete, Madukara	40.0	41.0	312.7
8/2/2015	Sokaraja, Pagentan	15.3	89.0	262.0
4/1/2018	Sirandu, Gununggiana, Wanayasa	41.7	41.7	101.9
4/1/2018	Krangean, Pandansari, Wanayasa	38.9	38.9	91.6
4/1/2018	Paweden, Karangkobar	41.7	41.7	101.9
5/1/2018	Dawuhan, Wanayasa	16.1	57.8	118.0
7/1/2018	Bantar, Wanayasa	0.0	35.4	99.5
8/1/2018	Babadan, Pagentan	24.5	42.8	104.3
31/01/2018	Kayuares Atas, Pagentan	41.6	65.5	134.1
31/01/2018	Kayuares Atas, Pagentan	41.6	65.5	134.1
8/2/2018	Paweden, Karangkobar	7.5	8.7	165.4
10/2/2018	Sawangan, Serogge	0.0	82.2	233.9
22/02/2018	Tempuran, Wanayasa	93.9	151.7	332.0
22/02/2018	Sikelir, Wanayasa	54.6	119.5	227.0

Source: Hidayat and Zahro (2018)

This study aims to analyze the causes and mechanisms of the landslide that occurred in Sarwodadi Village, Pejawaran Sub-regency, Central Java Province, on July 6, 2022, at approximately 10:30 PM. Understanding the causes and mechanisms of landslides is crucial for improving mitigation and adaptation strategies. The findings of this analysis will provide a foundation for developing appropriate landslide mitigation and adaptation measures.

2. METHODS

2.1. Location

The research was conducted in Sarwodadi Village, Pejawaran Sub-regency, Banjarnegara Regency, Central Java, Indonesia, as shown in Figure 3. Banjarnegara is situated between 7º12'-7º31' south latitude and 109º29'-109º45' east longitude, covering a total area of 114,943.5276 hectares, which constitutes 3.29% of Central Java Province's total area (3.25 million hectares). Administratively, Banjarnegara comprises 20 sub-districts, encompassing 266 villages and 12 sub-districts, further divided into 953 hamlets, 1,312 major neighborhood associations (RW), and 5,150 minor neighborhood associations (RT) (Bayuaji et al., 2016; Setiadi, 2013; Susanti et al., 2017; Susanti & Miardini, 2019). Banjarnegara is bordered by Pekalongan and Batang Regencies to the north, Wonosobo Regency to the east, Kebumen Regency to the south, and Banyumas and Purbalingga Regencies to the west (Setiadi, 2013; Susanti et al., 2017). Approximately 60% of Banjarnegara's terrain is mountainous and hilly (Bayuaji et al., 2016). The northern borders feature peaks such as Mount Rogojembangan and Mount Prahu, while the central zone comprises the fertile Serayu Depression zone. The southern zone is part of the Serayu Mountains, characterized by steep relief (Anggraini, 2015; Setiadi, 2013), These geographical and topographical features, along with the complex geological structures, make Banjarnegara highly susceptible to landslides (Anggraini, 2015).

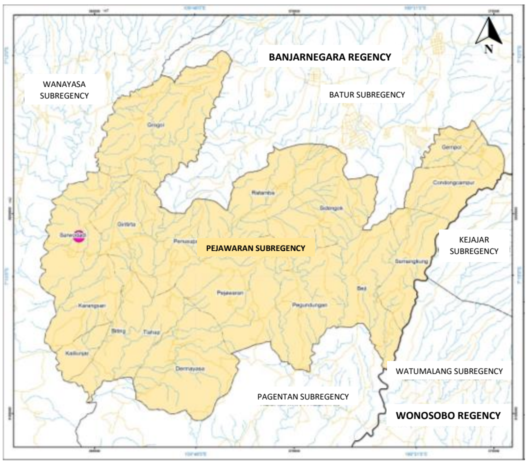

Figure 3. Administration Map of the Study Location

Additionally, a significant portion of Banjarnegara, including Sarwodadi Village in Pejawaran Sub-district, lies within the Merawu Sub-watershed (Satriagasa et al., 2020; Susanti & Miardini, 2016). The Merawu is a sub-watershed of the Serayu watershed, covering a total area of 23,260 hectares. It originates in the Dieng Plateau complex and extends downstream to the Mrican (Jenderal Soedirman) Reservoir (Satriagasa et al., 2020). This sub-watershed is notably prone to landslides (Susanti & Miardini, 2016).

To effectively analyze the research location, this study uses sub-regency level administrative boundaries for mapping. This scale is appropriate for spatial analysis, allowing detailed examination of the topography, geology, soil, meteorology, and land cover features of the study area.

2.2. Data and Tools

This study utilized administrative, geomorphological, geological, soil, meteorological, and land cover data for the research location. These datasets, combined with field observation data, were employed to determine the mechanisms and causes of the landslide. Tools used in this study included a GPS, distance measurer, and digital camera.

2.3. Stages

This study was conducted in three main stages. The first stage involved collecting secondary data, which included administrative, topographical, geomorphological, geological, soil, land cover, and meteorological data specific to the research area. These data sets provided essential tools for analyzing the causes and mechanisms of landslides in the region.

The second stage consisted of field observations, where site investigations were carried out to assess the current conditions of the landslide area. Observations focused on various factors, including the landslide's state, topography, soil characteristics, geomorphology, land cover, drainage channels, and vegetation at the site.

In the final stage, data analysis was conducted with a focus on spatial and chronological aspects, using both the secondary data and field observations. This analytical process aimed to identify and conclude the mechanisms and causes of landslides specifically in Sarwodadi Village. The study methods are illustrated in Figure 4.

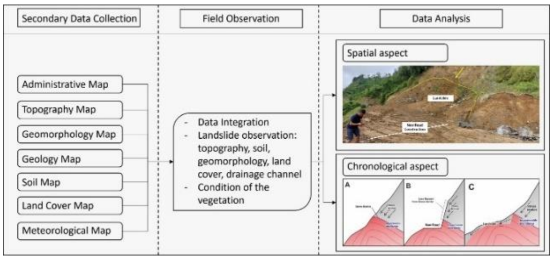

Figure 4. Schematic Method of this Study

3. RESULTS AND DISCUSSION

3.1. Physical Condition

Pejawaran Sub-district is characterized by a hilly terrain with an altitude range of 818-1817 meters above sea level (MASL). The southern region has a lower altitude compared to the northern region. Generally, Pejawaran Sub-district slopes towards the southwest, with steep slopes present around the ivers that traverse the area and in the hilly regions in the northeast. This topographic condition influences the potential of land resources, affecting ease of land cultivation, disaster susceptibility, water resource availability, and the climatic conditions of the region (Figure 5).

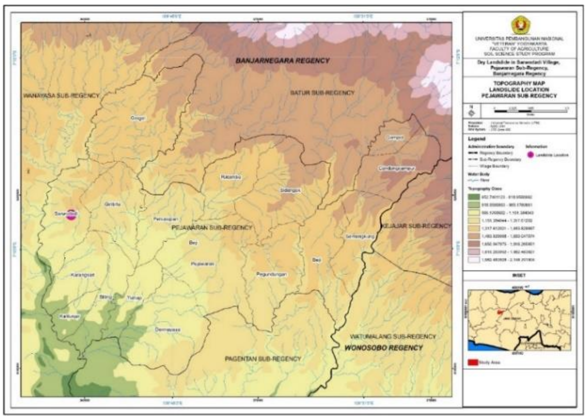

Figure 5. Topographic Map of Pejawaran

The land used in Pejawaran Sub-district is predominantly agricultural, with 74.55% of the total area (4051.91 hectares) classified as dry fields (Figure 6). This is indicative of moderate to high soil productivity, making the region highly suitable for agriculture. As a result, a significant portion of the population is engaged in farming, either as landowners or agricultural laborers. In Sarwodadi Village, a similar land-use pattern is observed, where 56.83% of the land is utilized for dry agriculture, and 27.29% is designated for rainfed rice fields. The remaining land is occupied by settlements, shrubs, and buildings. These patterns underscore the agricultural dependence of the region, with dryland farming being the dominant form of land utilization.

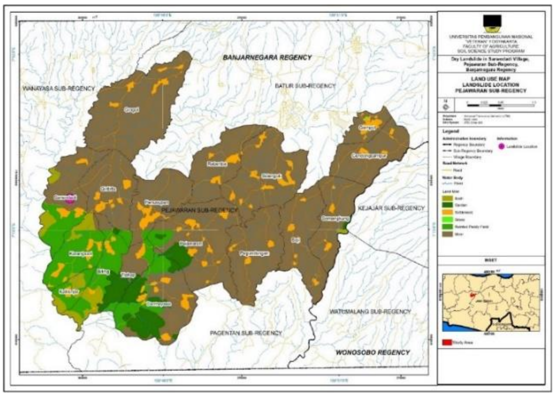

Figure 6. Land Use Map of Pejawaran

The soil composition in Pejawaran Sub-district reflects its geological and volcanic history, primarily consisting of brown andosol and brown regosol, which together cover 84% of the total land area. Andosols, typically formed in volcanic regions, are porous and rich in organic matter, making them suitable for cultivation. They are derived from volcanic ash, tuff, and pumice, which are abundant in this region due to its proximity to volcanic activity (The Editors of Encyclopaedia Britannica, 2000). In contrast, regosols are younger soils with minimal horizon development, well-drained, and composed of medium-textured parent materials (Meek et al., 2008). These soils have a light color, low organic content, and are typically less fertile compared to andosols (FAO, n.d.). The remaining 15% of the area consists of gray humus, alluvial soils, and dark red Mediterranean soil. In Sarwodadi Village, the soil is similarly dominated by brown andosol and brown regosol, aligning with the geological context of the region, which lies atop volcanic rocks from the Jembangan Volcano. This volcanic influence is critical in understanding the unique soil and geological conditions that characterize the region, particularly in relation to landslide susceptibility.

Geologically, the study area comprises two main units: the Diorite unit and the unconsolidated material unit (Figure 7A). The Diorite unit, characterized by a brownish-gray weathered surface and a gray fresh color, displays a phaneritic texture with a porphyritic structure in some areas. This unit also exhibits dominant sheeting-joint structures (Figure 7C), which are the result of intense tectonic activity. The unconsolidated material unit, in contrast, consists of loose sediments that include observable fragments of diorite (Figure 7B), suggesting that this unit was deposited after the diorite had already been exposed. The presence of these sheeting joints within the diorite unit is a significant geological feature, as they form due to compressional tectonics, which are also responsible for the observed anticline structures in the area (Figure 8). Additionally, the fault and fracture systems, observed at various sites during field investigations, further indicate the presence of tectonic activity. These geological characteristics are crucial in assessing the stability of the slopes and understanding the mechanisms that may contribute to landslides in the region (Table 2).

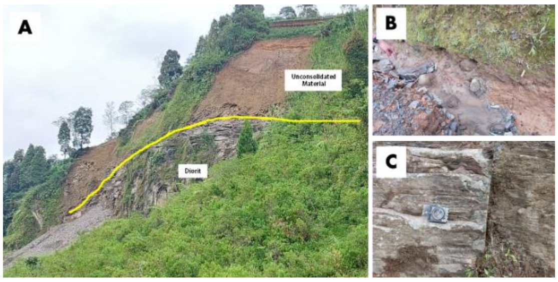

Figure 7. A) Depicts the Stratigraphic Position of the Unconsolidated Unit Overlying the Diorite Unit. (B) Close-up Image of the Unconsolidated Unit Containing Diorite Fragments. (C) Close-up Image of the Fresh Diorite Unit Exhibiting a 'Sheeting-Joint' Structure

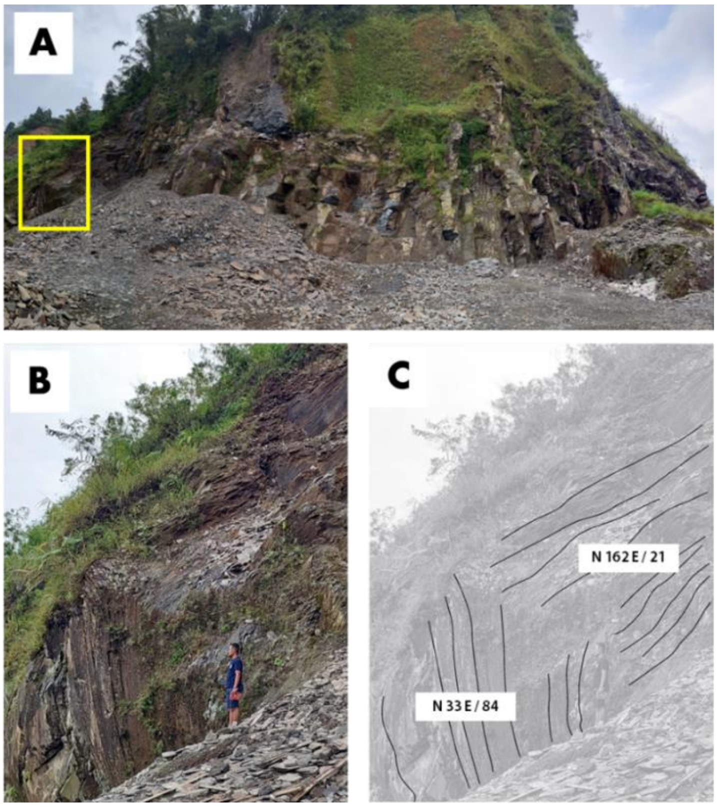

Figure 8. (A) The Image of Observation Site 1 Illustrates the Intensive Fractures and Sheeting Joints within the Diorite Unit. (B) A Detailed Photograph of a Specific Location at Observation Site 1 (Indicated by the Yellow Box in Figure 8A), Showing the Anticline-Fold-Like Feature of the Sheeting Joints. (C) Measurement of the Sheeting-Joint Plane Direction from Figure 8B.

Table 2. The Measurement Data from Six Observation Sites in the Study Area

Site ID	Lat	Long	Strike	Dip	Remarks
1	7°14'19.16"S	109°46'19.29"E	33	84	Joint Plane
			162	21	Joint Plane
			238	43	Fault Plane
2	7°14'20.92"S	109°46'19.48"E	182	44	Joint Plane
3	7°14'22.23"S	109°46'20.54"E	178	59	Joint Plane
4	7°14'22.95"S	109°46'21.70"E	5	35	Joint Plane
5	7°14'25.30"S	109°46'24.77"E	89	34	Joint Plane
6	7°14'26.79"S	109°46'25.28"E	353	74	Sliding Plane
			246	83	Sliding Plane

Precipitation is typically a primary factor in triggering landslides in Banjarnegara, as high rainfall levels increase the soil's water content and reduce its shear strength, leading to slope failures. However, the precipitation levels recorded in the days preceding the landslide event in Sarwodadi Village (Table 3) on July 6, 2022, were insufficient to act as the primary trigger for the landslide. Data from Hidayat & Zahro (2018) indicate that both one-day, three-day, and ten-day cumulative precipitation levels were well below the thresholds commonly associated with landslide occurrences in the region. Therefore, it is unlikely that rainfall alone was the primary cause of the landslide. This suggests that other factors, potentially related to the unique geological conditions or human activities such as land use changes or construction, played a significant role in triggering the event. The absence of sufficient precipitation as a trigger for the landslide in Sarwodadi points to a need for further investigation into the underlying causes, which may include the loss of slope stability due to geological factors or anthropogenic influences.

Table 3. Precipitation Ten Days Prior to the Landslide Event

Date	Precipitation (mm)
June 27, 2022	24.5
June 28, 2022	0
June 29, 2022	0
June 30, 2022	0
July 1, 2022	0
July 2, 2022	0
July 3, 2022	2.5
July 4, 2022	0
July 5, 2022	0
July 6, 2022*	0
One-day accumulation	0
Three-day accumulation	0
Ten-day accumulation	27.0

* The day of the landslide occurrence, at 10.30 PM

WMO ID : 96807
Station Name : Banjarnegara Geophysics Station
Latitude : -7.33300
Longitude : 109.70690
Altitude : 608

Source: (BMKG, 2022)

3.2. Landslide Mechanism and Causes

The landslide that occurred in Sarwodadi Village, Pejawaran Sub-regency, Banjarnegara Regency, on July 6, 2022 (Figure 9), took place at approximately 10:30 PM.

Figure 9. Landslide Condition in Sarwodadi, Pejawaran, Banjarnegara

Unlike typical landslides in Banjarnegara, which are frequently triggered by high-intensity rainfall, this event occurred in the absence of significant precipitation. Based on (Hidayat & Zahro, 2018), the rainfall thresholds in this region required to initiate landslides are 56 mm for one-day accumulation, 89 mm for three-day accumulation, and 215 mm for ten-day accumulation. Additionally, rainfall of at least 50 mm over a six-hour period is known to trigger landslides (U. Nugroho et al., 2017). However, rainfall data at the Sarwodadi site (Table 3) indicate that these thresholds were not met, classifying this event as a "dry landslide," an unusual occurrence in Banjarnegara. This atypical event suggests that other geological and anthropogenic factors were the primary triggers for the landslide.

One of the key geological factors contributing to this landslide was the loss of structural support from a stress barrier due to road construction activities. The site is characterized by a diorite rock formation that is utilized by local miners for ornamental stone, collected manually and transported. To facilitate these activities, a new road was constructed, which required excavation of the diorite unit, leading to a critical loss of slope stability. This loss of support can be attributed to two interrelated processes: the removal of the stress barrier and subsequent mass shear, as illustrated in Figure 10 and 11.

Figure 10. Photo of the Landslide Location at the New Road Construction

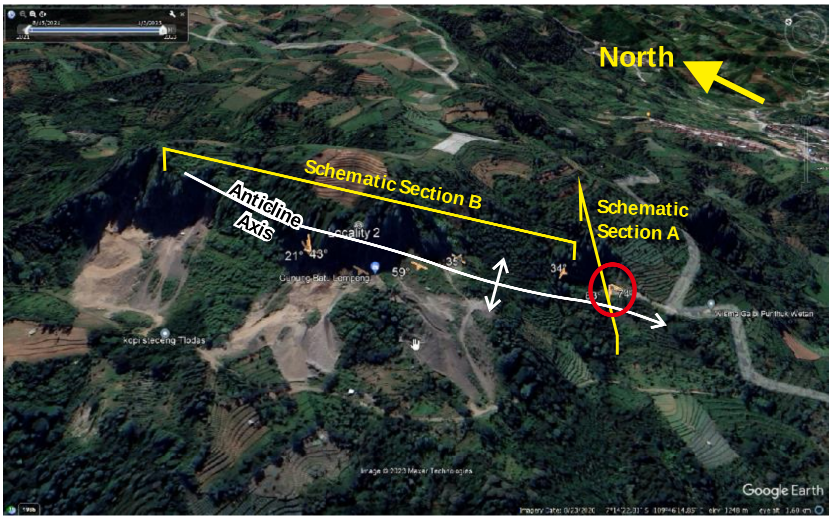

Figure 11. Google Earth Figure Accessed on 10 February 2023. This Figure Illustrates Schematic Section A, Designated for the Conceptual Model Depicted in Figure 12, as Well as Schematic Section B, Allocated for the Conceptual Model Presented in Figure 13. Additionally, the Figure Denotes the Plunging Anticline Axis of the Diorite's Sheeting-Joint, along with the Precise Location of the Landslide Indicated by a Red Circle

The stress barrier comprises two main lithological units: a stable diorite unit at the base, which provides structural support, and an unconsolidated material above it that is inherently less stable. According to Cornforth (2005) and Carson & Kirkby (1972), disruptions to foundational support such as that provided by the diorite rock can significantly increase slope vulnerability to landslides, particularly when the supporting rock layer is weakened through anthropogenic actions like excavation. In the case of Sarwodadi, the road construction activities reduced the integrity of the diorite unit, undermining its role as a stress barrier and initiating the landslide through gravitational forces that acted on the now-destabilized slope (Figure 12).

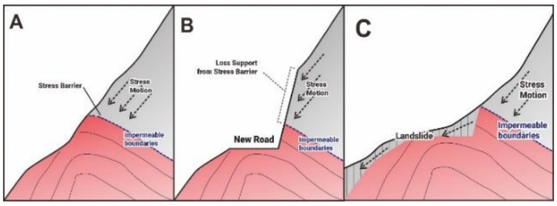

Figure 12. A Conceptual Model to Explain Stress Barrier Loss (this Model Regarding Schematic Section A in figure 4). (A) Condition Before Road Construction, the Diorite Unit (Red Color) Acted as the Supporting Foundation for the Stress Motion of the Unconsolidated Material (Grey Color). It is Ensuring that the Slope Remains Stable. (B) The Condition During Road Construction Cropped the Diorite Unit and Accidentally Made a Loss of Support for the Stress Barrier. (C) The Condition After the Landslide Happened

Mass shear, which further destabilized the slope, was facilitated by the unique structural configuration of the diorite's sheeting joints. These joints form an anticline-like structure with an NE-SW orientation and a southward plunge, creating a natural sliding plane for the unconsolidated material above (Richards & Cowland, 1986). This structure acts as a permeability boundary, with the unconsolidated material displaying higher porosity and permeability compared to the impermeable diorite below (S. Hencher, 2006). When groundwater flows through this boundary, the unconsolidated material can become saturated, reducing its internal stability and increasing the likelihood of mass movement (Figure 13).

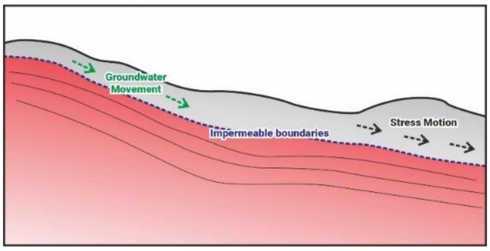

Figure 13. A Conceptual Model to Elucidate the Mechanism of Mass Sliding, focusing on the Schematic Section B Depicted in Figure 11. The Model Illustrates the Flow of Groundwater and Stress Motion, aligning with the Tilt of the Anticline Axis Directed Southward

The phenomenon of mass shear in such conditions has been documented in several studies. For instance, studies by S. Hencher (2006) and Bronnimann (2011) show that in zones where permeable materials overlay less permeable rock, groundwater flow and subsequent saturation of the upper layers create conditions favorable for mass movement, even in the absence of heavy rainfall. Furthermore, stereonet analysis of the Sarwodadi site indicates that the direction of the landslide followed the southwestward tilt of the fold axis, reinforcing the role of geological structure in directing mass shear movement (Figure 14).

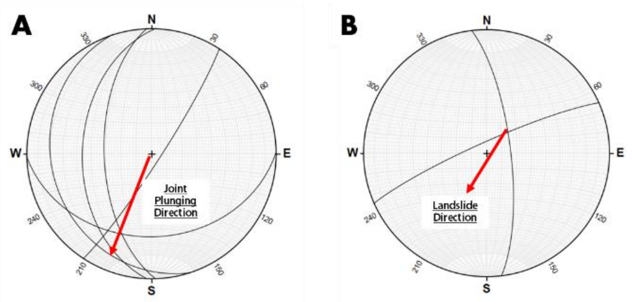

Figure 14. (A) Stereonet Analysis Derived from Measurements of the 'Sheeting-Joint' Plane Reveals the Presence of an Anticline Fold Feature Plunging Southward. (B) Stereonet Analysis Conducted at the Landslide Site Indicates that the Direction of the Landslide aligns with the Orientation Depicted in figure 13A

The findings in Sarwodadi are consistent with prior research on dry landslides influenced by anthropogenic activities and geological structures. Cornforth (2005) notes that landslides can be triggered under dry conditions when anthropogenic disturbances affect foundational rock structures. Similarly, Carson & Kirkby (1972) highlight that geological structures such as anticlines and permeability boundaries are significant contributors to slope instability, particularly when stress barriers are disrupted by human activities.

Groundwater infiltration further contributes to slope instability by percolating through the sheeting joints and increasing the likelihood of mass sliding. As groundwater saturates the unconsolidated material, combined with the southward stress motion along the anticline axis, the conditions facilitate a significant risk for landslide occurrence. The stereonet analysis confirms that the landslide's direction aligns with the orientation of the fold axis (Figure 14), indicating that natural structural features encourage mass movement regardless of rainfall levels. This supports the hypothesis that mass sliding was a key factor in this event, with groundwater infiltration acting as an exacerbating agent.

Table 4. Engineering Options for Stabilizing Slopes in Sheeting Joint Terrain

Option Selection		Common Measures	Recommended Approaches
Passive Protection Measures	Surface Treatment	Hard Covering	Application of shotcrete or geotextile membranes to protect exposed joints and surfaces from weathering. This method is especially effective for shallow slopes (Pease & McKenna, 2002).
		Vegetation	Use of deep-rooted vegetation, especially in regions where slope erosion is accelerated by surface runoff (Lann et al., 2024). Grasses and shrubs may provide only superficial stabilization, while trees with deep root systems can help bind soil layers.
		Fixed Mesh	Installation of reinforced wire mesh over exposed rock faces to prevent loose debris from moving. This technique should be combined with passive drainage to minimize hydrostatic pressure (Maheshwari et al., 2023).
	Retention	Toe Zone Fence	Placement of flexible rockfall barriers at the toe of slopes, reinforced with dynamic anchors to absorb and dissipate energy from small-scale movements (Maheshwari et al., 2023).
		Drape Mesh	Flexible draped mesh over unstable surfaces can allow for controlled sliding of loose material while minimizing hazards to infrastructure below. The drape system should be tensioned with anchors for increased effectiveness (Maheshwari et al., 2023).
		Catch Ditch	Construction of catch ditches to intercept falling debris before it reaches roads or buildings. The ditches should be lined and regularly maintained (Nowak, 2023).
		Catch Bench	Design of stepped benches along the slope to reduce the vertical distance of falling debris, particularly useful in terrains with multiple failure planes. This also serves as an energy dissipation method (Bar et al., 2016).
	On-Slope Fences	Rockfall Barriers	High-strength barriers designed to withstand direct impacts of falling rocks, incorporating elastic elements to maximize energy absorption (Perera & Lam, 2023).
Active Protection Measures	Drainage	Face Channels	Installation of surface drainage channels to divert water away from joints and cracks, preventing water infiltration. Face channels should be constructed in parallel with inclined drains for maximum effectiveness (Johannessen, 2008).
		Crest Channels	Surface drainage channels located at the crest of the slope to capture and direct water away from unstable areas, reducing pore pressure in the slope material (Nettleton et al., 2022).
		Inclined Drains	Drains bored into the slope at a downward angle to intercept and discharge groundwater, reducing pore pressure in the sheeting joints (Cashman & Preene, 2020). In steeper areas, horizontal drains may be required to improve the drainage capacity.
		Vertical Drains	Placement of vertical drains or wells that can relieve high-pressure zones within the joints, reducing the risk of mass shear movement. Vertical wells should be positioned to complement the natural groundwater flow direction (Zhou et al., 2023).
Active Stabilization Measures	Excavation	Cut-back	Re-profiling of the slope to reduce steepness and improve stability. This method is particularly effective when combined with buttressing and drainage systems to manage water flow and soil movement (Popescu & Sasahara, 2009).
	Support	Dowels	Installation of steel dowels to pin rock masses to the underlying stable layers. Dowels should be used in areas with frequent small-scale movements to prevent further opening of joints (Wyllie & Norrish, 1996).
		Cables	Cables anchored into the bedrock to tie unstable rock layers back to the slope, providing additional tension support (Gao et al., 2022). Cables should be pre-tensioned and regularly inspected for wear.
		Rock Bolts	Rock bolts drilled into the slope at key locations to provide tensile reinforcement. This is effective for securing sections of rock mass with limited movements, particularly in the presence of discontinuities (Mohammadi et al., 2017).
		Anchors	Installation of high-capacity ground anchors to stabilize larger masses of rock or soil. Anchors should be installed in conjunction with face treatment and drainage systems (P.J. Sabatini et al., 1999).
		Buttresses	Constructing earth or concrete buttresses at the toe of the slope to resist shear forces and prevent sliding, particularly useful in high-angle slopes or those with weakened rock layers (Ukleja, 2020).

Source: S. R. Hencher et al. (2011) (with modifications)

Groundwater infiltration also impacts mass shear by serving as a weathering agent within the sheeting joints, enlarging voids and weakening the slope's structural integrity. S. Hencher (2006) and S. R. Hencher et al. (2011) describe how infiltrating water can expand joints in weathered rock, increasing the risk of translational movement in unstable areas. As the water pressure within these joints varies across storms, groundwater can generate pressure surges through sheeting joints, a process documented by Richards & Cowland (1986), as well as Banfi et al. (2024), who explain that water surges may lead to delayed mass movement, sometimes occurring even after precipitation has ceased. This phenomenon of irregular pressure dissipation aligns with the conditions observed in Sarwodadi Village, where mass sliding was induced despite the lack of significant rainfall (Figure 15).

A comparison with previous studies supports the understanding that this landslide was primarily influenced by geological and human activity factors. For instance, research by Cornforth (2005) and Kinde et al. (2024) emphasizes that landslides can occur in dry conditions when anthropogenic activities such as excavation disturb the geological equilibrium of the area. Similarly, studies by Carson & Kirkby (1972) highlight that stress barrier loss due to human-induced changes in slope structure can trigger mass shear without significant precipitation. These findings are consistent with the circumstances surrounding the Sarwodadi landslide, where the combination of road construction and natural geological weaknesses contributed to the event.

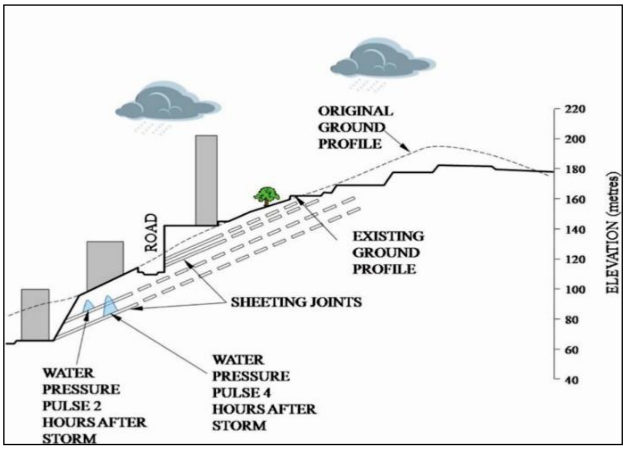

Figure 15. Typical Section Through the Study Area Adopted from Richards & Cowland (1986)

While rainfall is a common trigger for landslides in Banjarnegara, the Sarwodadi landslide was caused by a combination of stress barrier loss due to excavation and mass shear facilitated by the area's unique geological structure. The role of groundwater infiltration in mass shear further complicates the dynamics of slope instability. These findings underscore the need for cautious infrastructure development in geologically sensitive areas, particularly those prone to mass movements. Future studies should continue to explore the interplay between anthropogenic activities and geological factors in landslide-prone regions.

3.3. Engineering Option

Following the landslide incident in this area, community-led engineering measures are imperative to mitigate risks. Drawing from the recommendations outlined by S. R. Hencher et al. (2011), several options aimed at enhancing slope stability are enumerated below (Table 4).

However, given that the area remains an active mining site with its inherent dynamics, certain adjustments are warranted. While the people of Banjarnegara are accustomed to landslides primarily triggered by intense rainfall, the distinct pattern observed in this landslide event, not induced by heavy precipitation, calls for a new perspective on landslides in the region. There is a need for heightened community awareness in Banjarnegara that not all landslides are precipitated by heavy rainfall; unique geological formations, as evidenced in Sarwodadi, Pejawaran, Banjarnegara, can generate distinctive landslides.

Moreover, comprehensive mapping and assessment of areas exhibiting similar geological conditions to Sarwodadi should be conducted across Banjarnegara. This initiative aims to mitigate landslide occurrences and reinforce public awareness regarding unique landslide scenarios.

4. CONCLUSION

This study examined the atypical landslide in Sarwodadi Village, Pejawaran Sub-regency, Banjarnegara, which occurred under dry conditions. The findings indicate that the landslide was not triggered by rainfall, as precipitation levels were below the established thresholds. Instead, the landslide resulted from the loss of support from a stress barrier caused by road construction and mass shear, facilitated by the area's geological structure. These two factors were exacerbated by human activities and groundwater infiltration, contributing to slope instability.

The study highlights the importance of considering both geological and anthropogenic factors in landslide-prone areas. The results underscore the need for responsible infrastructure development to prevent future landslides in similar regions. Limitations of the study include a lack of more detailed hydrogeological data, which could further clarify the role of groundwater infiltration. Future research should focus on integrating more comprehensive geological assessments and exploring mitigation strategies to minimize landslide risks in areas undergoing development.

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