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Research Article

Soil magnetic susceptibility analysis as an indicator of landslide-prone areas in Sanggau Regency, West Kalimantan Province, Indonesia

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Abstract

Sanggau Regency is a highland area that has a rough topography with a relief of undulating hills, causing the potential for landslides. One of the steps to reduce the impact of landslides is to identify the characteristics of landslide-prone areas by conducting magnetic susceptibility analysis in landslide-prone areas. This analysis is a method to identify landslide indicators based on their magnetic properties. This method identifies landslide potential through superparamagnetic grains on the surface soil. The presence of the grain can be known from the frequency-dependent susceptibility χ_{FD}. The study was conducted on 40 soil samples taken at a 20-30 cm depth at Jalan Sabang Merah, Sanggau Regency. The results showed that the average values of low-frequency χ_{LF} and high-frequency χ_{HF} were 5.555 cm^3/g and 5.478 cm^3/g, respectively. A total of 36 soil samples have a χ_{FD} percentage of 0% (containing less than 10% superparamagnetic grains), two soil samples have a χ_{FD} percentage of 3.51% and 6.45%, respectively (containing 10%-75% superparamagnetic grains, and two samples have a χ_{FD} percentage of 10.48%-12.63% (containing more than 75% superparamagnetic grains). The interpretation results show that soil samples with more than 75% superparamagnetic grains indicate landslide-prone areas in the study site; thus, the areas suspected to have a high level of vulnerability are in the northeastern and southwestern parts of the study site.

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Introduction

Natural disasters, as one of the natural phenomena, can occur at any time, causing material and immaterial losses to people's lives. Landslides are categorized as natural disasters, in addition to earthquakes, floods, tsunamis, tornadoes, and others. A landslide is the movement of soil or rock above the surface slope that moves down the slope of the Earth caused by gravity (Liu et al., 2024; Rodríguez et al., 2024). Landslide hazards significantly affect the continuity of human life and always threaten human safety. Landslides in Indonesia have caused significant losses, such as loss of human life and damage to houses, roads, public facilities, and natural ecosystems (Setiawan et al., 2019).

Landslides generally occur when the soil can no longer withstand the mass of the soil layer above it due to additional load on the slope surface and reduced binding force between soil grains (Muhardi and Wahyudi, 2020). In general, landslides are caused by two factors, namely natural factors and human factors. Natural factors can include high rainfall, steep slopes, and rock conditions (Zhang et al., 2024). Natural factors come from nature, such as high rainfall, steep slope conditions, less dense rock conditions, and others (Zhang et al., 2024). Human factors are caused by human activities such as deforestation, settlements on steep slopes, and inappropriate land use that will increase the risk of landslide-prone areas (Paúl et al., 2021).

One of the actions that can be taken to reduce the impact of landslides is to identify the characteristics of landslide-prone areas by conducting magnetic susceptibility analysis in landslide-prone areas (Naldi and Budiman, 2018). This analysis can determine landslide indicators based on their magnetic properties. The physical quantity used in this method is magnetic susceptibility. This method identifies landslide potential through superparamagnetic grains in the surface soil (Ningsih and Irawati, 2021). The presence of the grain can be known from the percentage of frequency-dependent susceptibility χ_{FD}. It is the relative difference between low-frequency susceptibility χ_{LF} and high-frequency χ_{HF} (Boroallo et al., 2023). The higher the χ_{FD} percentage, the more the presence of superparamagnetic grains in the soil (Budiman et al., 2018). Soils containing superparamagnetic grains are fine and easily absorb water. The addition of soil mass due to water makes it easier for the soil to experience landslides if it is on a steep slope.

The potential landslide hazard area in West Kalimantan Province is 5,899,753 ha and is in the high class. The landslide hazard is classified into three hazard classes: low hazard class of 438,456 ha, medium hazard class of 3,378,579 ha, and high hazard class of 2,082,718 ha. Sanggau Regency has a landslide-affected area of 52,476 ha for the low-hazard class, 325,851 ha for the medium-hazard class, and 38,168 ha for the high-hazard class (BNPB, 2021). Sanggau Regency is a highland area with a rough topography, undulating hilly relief, and potential landslides. Sanggau Regency is a hilly and swampy highland area fed by several rivers (BPS, 2024). In addition, high rainfall in Sanggau Regency is a factor that causes landslides. Mapping and direct observation in Sabang Merah, Sanggau Regency, showed a high landslide vulnerability (Perdhana et al., 2023).

This research aimed to map landslide-prone areas in the Sabang Merah area, Bunut Village, Kapuas District, Sanggau Regency, based on soil magnetic susceptibility. The mapping of landslide-prone areas in Sanggau Regency based on parameters affecting landslides based on the Geographic Information System (GIS) shows that the location is dominated by landslide vulnerability levels with moderate to high categories (Subarkah et al., 2024). One of the areas in Sanggau Regency that the government plans to become a residential area in the next few years is the Sabang Merah area. Therefore, a comprehensive preliminary study is needed to manage the area so that it can support and realize the plan. Previous research has identified landslide-prone areas using the resistivity geoelectric method and GIS to map the vulnerability zone in this area (Perdhana et al., 2023). The results showed that landslide occurrence in this location correlates with areas of high vulnerability. Research in the vicinity of this area has also been conducted, using geoelectric methods to identify the slide plane and soil characteristics in Bantai Village, Bonti District, Sanggau Regency (Hendri et al., 2020). The research showed that this area has unstable and mobile soil conditions, especially after heavy rainfall, further exacerbating the risk of landslides.

Managing landslide-prone areas as residential land requires an integrated study to mitigate disaster risks effectively. This study is essential to ensure the safety and sustainability of development in the area. Residential development on such land can potentially increase landslide vulnerability due to land cover change (Fauzan et al., 2020; Senanayake et al., 2020; Fata et al., 2022). Land changes can reduce soil infiltration's ability to absorb water (Perdhana et al., 2024). Therefore, identifying and mapping areas with high landslide risk based on magnetic susceptibility provides essential information for safe and sustainable land use planning. The results of this study can also help determine safer settlement zones in providing engineering recommendations, such as the creation of drainage systems, strengthening of unstable slopes, and selection of appropriate construction designs (Syazwan et al., 2021). In addition, by understanding the soil characteristics in potential settlement areas, governments and developers can implement appropriate conservation measures, reduce further degradation, and ensure that the land is safe for the people who will occupy it. This research significantly contributes to sustainable settlement land management in landslide-prone areas. Identification and mapping of the landslide-prone areas can provide accurate data on high-risk locations. Effective mitigation measures can minimize the impact of landslides in these areas, thus protecting the community and infrastructure from potential losses.

Materials and Methods

Location and time of study

Soil sampling was conducted on 12 August 2023 in an area considered landslide potential, namely on Jalan Sambang Merah, Bunut Village, Sanggau Regency, West Kalimantan, Indonesia. The sampling locations are shown in Figure 1. Magnetic susceptibility measurements on the samples were conducted at the Earth Physics Laboratory, Andalas University, Padang. Analysis and interpretation of measurement results were conducted at the Geophysics and Geographic Information Systems Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Tanjungpura, Pontianak, West Kalimantan, Indonesia.

Equipment and materials

Sampling was conducted at 40 points at a depth of 20-30 cm using a soil drill, with a distance of about 10 m between points. Coordinates and elevation of measurement points were taken using a Garmin 65s

GPS. Magnetic susceptibility measurement using Bartington Magnetic Susceptibility Meter MS2. Mapping to identify potential landslide areas based on magnetic susceptibility distribution using open source software Quantum Gis (QGis) 3.30.

Magnetic susceptibility measurement

Measurement of magnetic susceptibility values in two frequencies was intended to obtain the percentage of frequency-dependent susceptibility χ_{FD} by creating contour maps to identify potential landslide areas. It was obtained from the difference between susceptibility with low frequency χ_{LF} and high frequency χ_{HF}, as shown by Equation (1) (Moghbeli et al., 2021).

$$\chi_{FD} = \frac{|\chi_{LF} - \chi_{HF}|}{\chi_{LF}} \times 100\% \qquad (1)$$

The percentage of frequency-dependent susceptibility χ_{FD} can be used to determine the presence of superparamagnetic grains in the sample. The interpretation of the percentage of frequency-dependent susceptibility χ_{FD} to the presence of superparamagnetic grains is shown in Table 1. The higher the χ_{FD} percentage, the higher the superparamagnetic grain content. The higher χ_{FD} percentage indicates very fine grain particles with a nanomaterial scale (superparamagnetic), while the lower χ_{FD} percentage indicates coarser grain particles (Dearing, 1999).

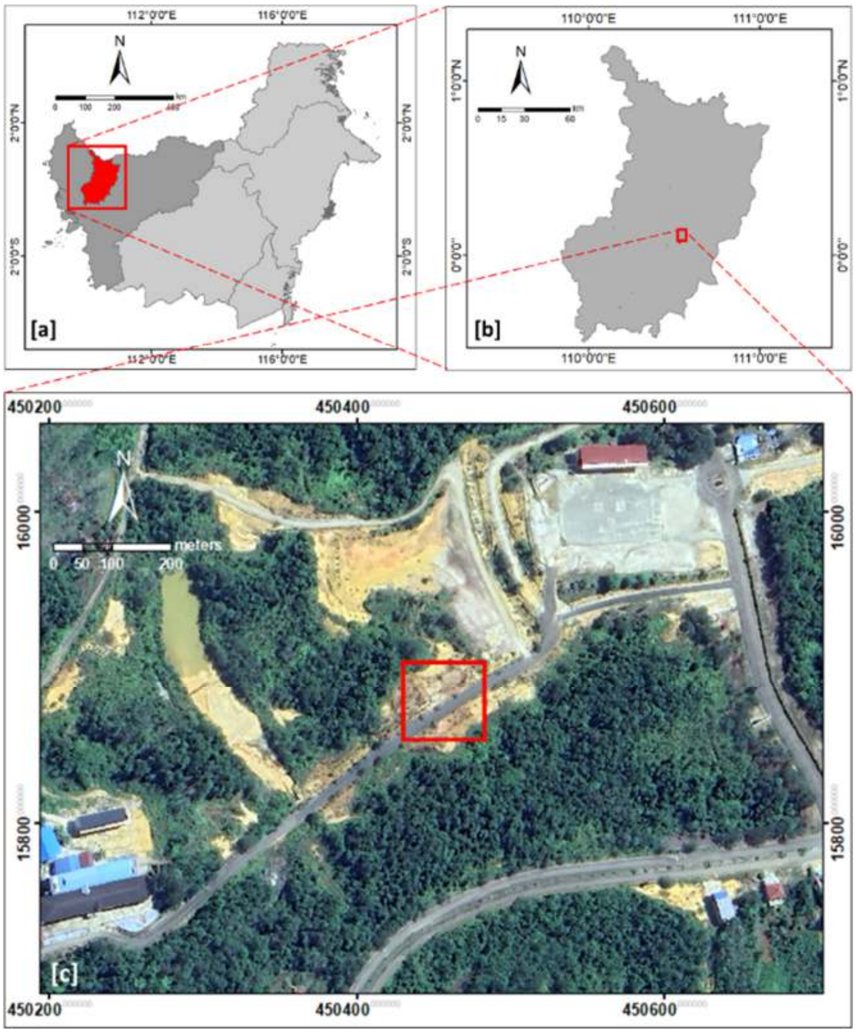


Figure 1. Sampling locations: (a) map of Kalimantan Island, (b) map of Sanggau Regency, and (c) study site at Jalan Sabang Merah, Bunut Village (red box).

Identification of landslide potential areas

Landslide potential is identified through superparamagnetic grains in the surface soil. The presence of these grains can be determined from the percentage of frequency-dependent susceptibility χ_{FD}. This frequency is the relative difference between low-frequency susceptibility χ_{LF} and high-frequency χ_{HF}. The higher the percentage of χ_{FD}, the more superparamagnetic grains are in the soil (Dearing, 1999). Soil containing superparamagnetic grains is fine (grain size 1-30 nm) and quickly absorbs water (Dunlop and Özdemir, 2010; Dhani et al., 2021).

Adding soil mass as landslide material due to the increased water content makes the soil more prone to landslides when located on steep slopes. Soil characteristics in landslide-prone areas can be identified by conducting a magnetic susceptibility analysis in landslide-prone areas (Budiman et al., 2018). This analysis is to identify landslide indicators based on their magnetic properties.

Table 1. Interpretation of χ_{FD} (Dearing, 1999)

χ_{FD} (%)	Description of soil condition	Grain size
<2.00	Contains less than 10% superparamagnetic grains	Coarse-grained
2.00-10.00	Contains superparamagnetic grains between 10% and 75%	Fine and coarse-grained mixtures
10.00-14.00	Contains more than 75% superparamagnetic grains	Fine-grained
>14.00	Rare values, erroneous measurement, anisotropy, weak sample or contamination	

Management of landslide-prone areas

Managing landslide-prone areas in the study site requires an integrated disaster mitigation approach to significantly reduce the risk, especially when the area is planned to be developed as residential land. The steps taken in this mitigation effort include several important considerations, such as topographic characteristics, the number of points identified as landslide zones, and the total area categorized as landslide-prone. In its implementation, mapping the high-risk areas becomes crucial to map the most vulnerable points to land movement. With this mapping in place, mitigation strategies can be developed more effectively, allowing prevention and protection measures to be focused where they are most needed. In addition, this mapping can assist in spatial planning and infrastructure management to suit local geological characteristics.

Results

Sampling was conducted in areas that will be utilized for residential areas suspected to be landslide-prone areas with steep slopes. The measurement points were located on the plateau, with elevations ranging from 118 m above sea level (sample 16) to 141 m above sea level (sample 40). The topographic contour map for each measurement point is shown in Figure 2.

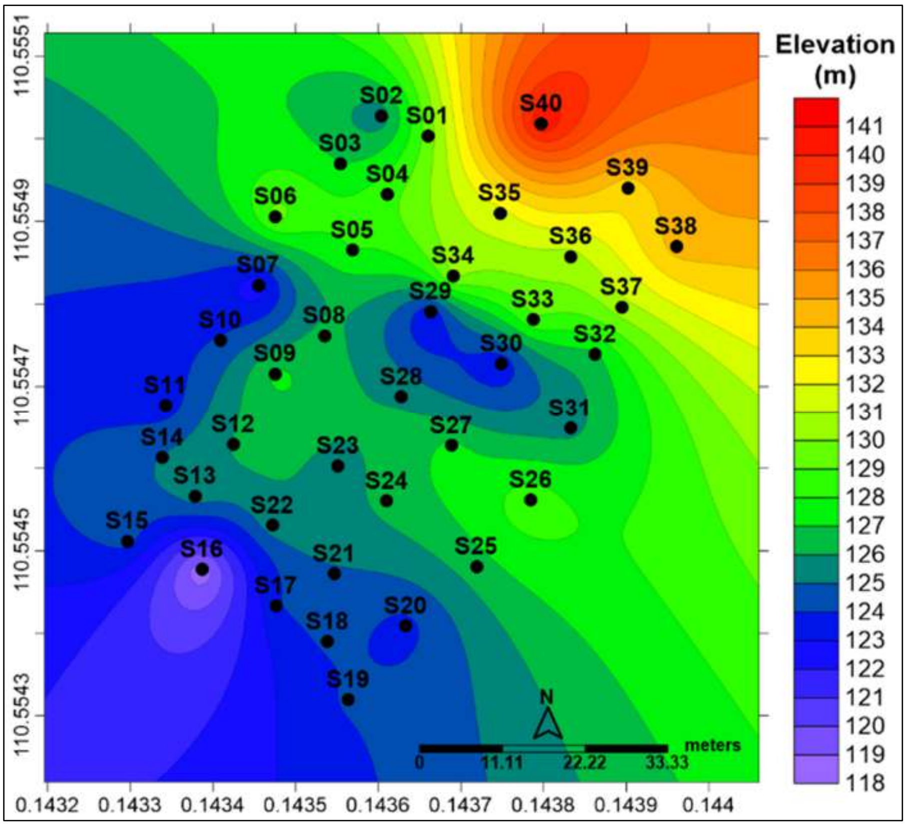
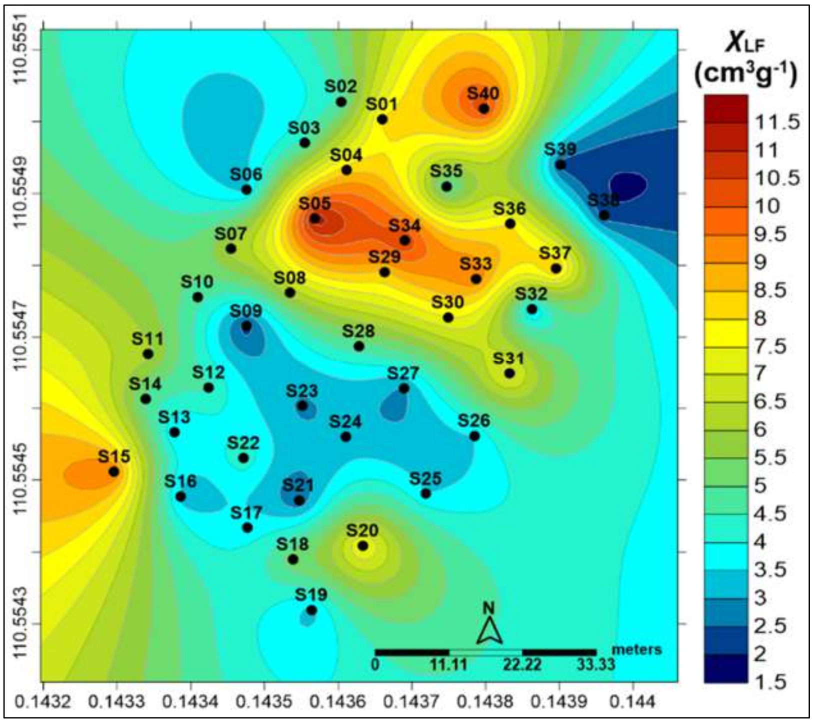


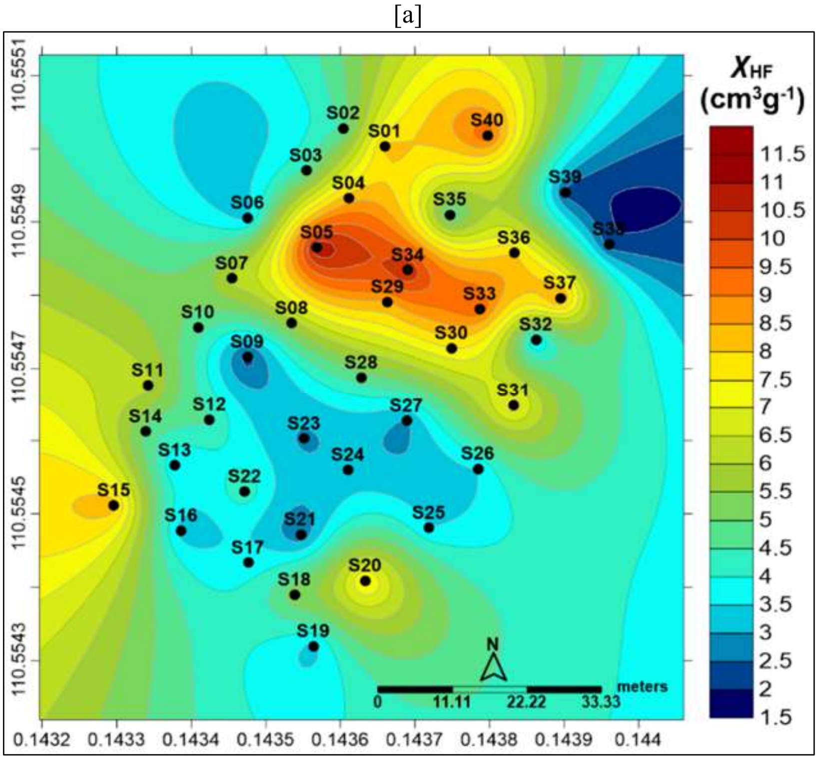
Figure 2. Topographic contour map and sampling points.

Magnetic susceptibility measurements were conducted in two frequencies to obtain frequency-dependent susceptibility percentage χ_{FD} and identify landslide-prone areas. The percentage χ_{FD} is the result of subtraction between low-frequency susceptibility χ_{LF} and high-frequency susceptibility χ_{HF}. The measurement results show that the average values of low-frequency χ_{LF} and high-frequency χ_{HF} are 5.555 cm^3/g and 5.478 cm^3/g, respectively. The low-frequency χ_{LF} and high-frequency χ_{HF} of 36 out of 40 samples have the same values.

Soils containing superparamagnetic grains are used as indicators to identify landslide-prone areas. The magnetic susceptibility measurement results of low-frequency χ_{LF} and high-frequency χ_{HF} are shown in Figure 3.



[a]



[b]

Figure 3. Magnetic susceptibility measurement results; [a] by low frequency χ_{LF} and [b] by high frequency χ_{HF}.

The measurement results of the frequency-dependent susceptibility percentage χ_{FD} were plotted at the research location based on the coordinates of 40 samples so that the distribution of susceptibility values from the lowest to the highest was obtained. Magnetic susceptibility values were measured in two frequencies to get the percentage of frequency-dependent susceptibility χ_{FD}.

A total of 36 points from 40 measurement points have zero percent. The contour map of the distribution of soil frequency-dependent susceptibility values is shown in Figure 4.

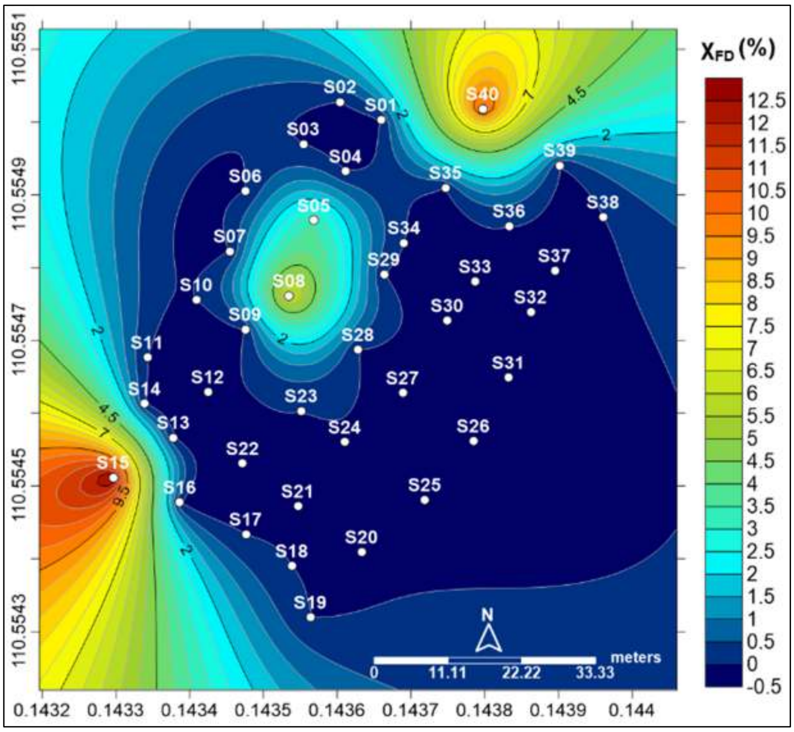


Figure 4. Contour map of frequency-dependent susceptibility percentage χ_{FD} distribution.

Discussion

Research on the characteristics of soil samples in various locations enables more appropriate land management and mitigation measures to be formulated, especially in landslide-prone areas. The soil samples in this study are distributed at different elevations and slopes. This indicates a variation in the distribution of landslide potential at the study site, as it has distinct characteristics. Soil magnetic susceptibility analysis is conducted by identifying the content of superparamagnetic grains in soil samples (Menshov et al., 2020). The presence of these grains can be known through the frequency-dependent susceptibility value χ_{FD}. Soils containing superparamagnetic grains have a fine texture and readily absorb water (Dhani et al., 2021). An excellent ability to absorb water will cause the water content in the soil to increase so that the soil experiences an increase in load or mass, and the bond between soil grains will weaken (Ramdhani et al., 2016). This condition will make the slope unstable, making the soil more prone to landslides (Susilo et al., 2022).

Most of the areas in the study site have a zero percentage of χ_{FD}. This indicates that there is no change in the magnetic susceptibility of the soil samples when the frequency of the applied magnetic field is varied (Dearing, 1999). These surface soil samples do not contain sufficient amounts of magnetic minerals, so they cannot affect the magnetic response to frequency variations. The 40 surface soil samples at a depth of 20-30 cm showed that 36 samples contained less than 10% superparamagnetic grains, two other samples contained superparamagnetic grains between 10% and 75%, and the last two samples contained more than 75% superparamagnetic grains. These results indicate that the surface soil at the study site is generally dominated by soils containing less than 10% superparamagnetic grains. The content of superparamagnetic grains can usually describe the size of surface soil grains that affect the ability of soil to absorb water (Budiman et al., 2018). A total of 36 samples containing less than 10% superparamagnetic grains are soils with coarse grains, two other samples containing between 10% and 75% superparamagnetic grains are soils with fine to coarse grains, and the last two samples containing more than 75% superparamagnetic grains are soils with finer grains (Dearing, 1999).

Soil samples containing more than 75% superparamagnetic grains are fine-grained soils found northeast and southwest of the study site. This area is suspected to have a high level of landslide vulnerability, as shown in Figure 5. Surface soils containing superparamagnetic grains have distinctive physical properties, namely a fine texture and the ability to absorb water (Budiman et al., 2018). Soils containing fine-textured superparamagnetic grains have a high ability to absorb water, thus causing an increase in soil mass (Muhardi and Wahyudi, 2020). The increase in soil mass is due to the accumulation of water contained by the soil. In addition, the presence of water in the soil also causes the binding force between soil grains to decrease. The water absorption by soil containing superparamagnetic grains creates a water-saturated condition so that the soil pores will be filled with water.

If significant mass gain occurs, especially on steep-to-steep slopes, the increased water pressure can reduce the overall strength of the soil. This can increase landslide potential as the soil material loses bearing capacity due to increased water pressure overloading the soil particles (Watakabe and Matsushi, 2019). Both soil samples are also located on topography with steep slopes (Subarkah et al., 2024). Slope can trigger landslides because it has a sliding plane that can encourage the movement of landslide mass (Perdhana et al., 2023). This condition makes the soil more unstable and more prone to landslides (Szuszkiewicz et al., 2021).

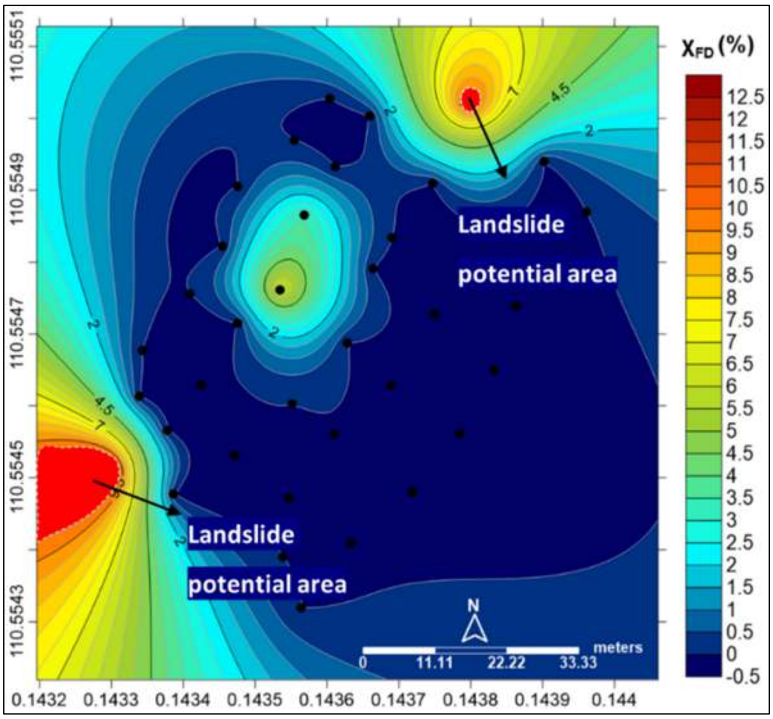


Figure 5. Potential landslide area at the study site (red area).

Superparamagnetic grains in surface soils can quickly absorb and store water in large quantities (Budiman et al., 2018). Excessive water accumulation in soil can increase soil mass and reduce friction between soil particles, making it easier to shift. As a result, water-saturated soils tend to become more unstable, increasing the risk of landslides. The superparamagnetic characteristics of the grains can cause a solid reaction to external magnetic fields. Fine-sized superparamagnetic grains can exert mechanical effects on the surrounding soil. Under certain conditions, the attractive force between superparamagnetic grains can cause the cohesion between soil particles to be lowered. This can reduce the internal strength of the soil, making it more susceptible to environmental changes or external pressures that can trigger landslides (Dhani et al., 2021). These landslide triggers can include heavy rainfall and vibrations caused by earthquakes and human activities.

The variation in superparamagnetic grain content represents the difference in the level of vulnerability at each point of the study site, which is thought to be influenced by several factors, namely geological conditions, mineral composition, and slope. In general, the geological conditions at the study sites play a role in the formation of slide planes in landslide-prone areas (Perdhana et al., 2023). The existence of slide planes and hilly topography significantly affects the stability of slopes and triggers the movement of soil masses (Fan et al., 2023). Each observation point is also likely to have a similar mineral composition but with different percentages, thus affecting the stability and physical characteristics of the soil in the area (Wu et al., 2021). This is evidenced by the difference in color and structure of soil samples at each point. The mineral composition of the soil samples representing the non-landslide-prone areas is generally dominated by clay minerals, as found in sample 38, sample 5, and sample 8, shown in Figures 6[a], 6[b], and 6[c]

(Budianta et al., 2022). These clay particles are cohesive and can bind water, making them relatively more stable than sandy and gravelly soils (Kang et al., 2022). The mineral composition of soil samples representing landslide-prone areas is generally dominated by sandy and gravelly soils, such as in sample 40 and sample 15, shown in Figures 6[d] and 6[e], respectively. These soils are more easily dislodged and eroded than clay soils, thus reducing slope stability (Flumignan et al., 2023).

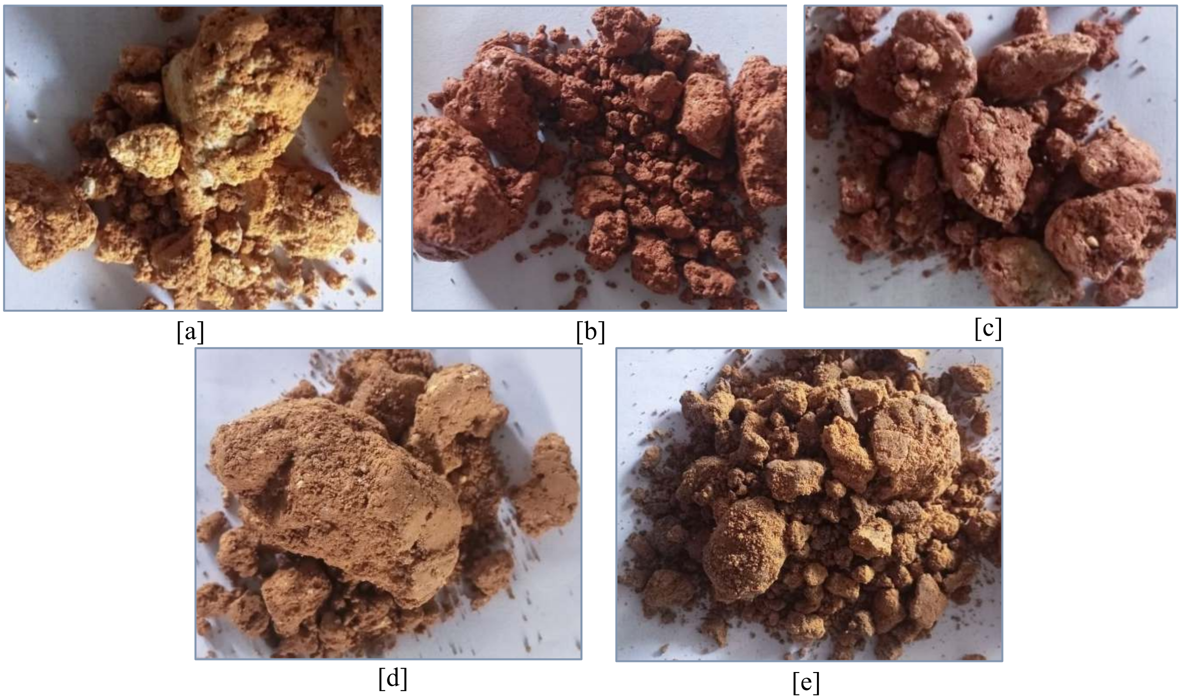


Figure 6. Soil samples in non landslide-prone areas;; [a] Sample 38 ($\chi_{FD} = 0\%$), [b] Sample 5 ($\chi_{FD} = 3{,}51\%$), dan [c] Sample 8 ($\chi_{FD} = 6{,}45\%$), and soil samples in landslide-prone areas; [d] Sample 40 ($\chi_{FD} = 10{,}48\%$), and [e] Sample 15 ($\chi_{FD} = 12{,}63\%$).

Soil sample 38 in Figure 6[a], with a light brown soil color, indicates the presence of sufficient and stable levels of iron oxide, which has generally undergone further weathering and thus has good stability. It also shows the possibility of clay content contributing to cohesion between grains, strengthening the overall soil structure.

Soil samples 5 and 8 in Figures 6[b] and 6[c] have a color that tends to be darker red and homogeneous. The red color usually indicates the presence of stabilized iron oxides, such as hematite, which suggests this soil has undergone a more advanced weathering process and is relatively more stable. These soils are usually denser and have strong grain bonds, making them more resistant to erosion and movement. On the other hand, soil samples 15 and 40 in Figures 6[d] and 6[e] have a slightly lighter and uneven color. The light brown or yellowish color seen in these samples is generally associated with minerals that are younger or still in the process of weathering, such as clays or iron oxides that are not yet fully stabilized (goethite). This lighter, inconsistent color may indicate the presence of easily decomposed and less stable minerals, increasing the risk of landslides when the soil is water-saturated or disturbed by external activity. The slope also significantly influences the landslide potential at the study site. A steeper slope means a higher risk of landslides (Harjadi et al., 2022). This is due to the stability of the hill; when the slope is steeper, there is increased pressure on it, leading to instability in the soil's ability to bear the load due to the rise in the Earth's gravitational force (Agung et al., 2023). The probability of landslides in mountainous regions with steep slopes is more significant compared to flat or gently sloping areas (Muhardi and Wahyudi, 2019). The slicing connects two points where soil samples contain more than 75% superparamagnetic grains. The profile shows that areas with steeper slopes (at location S40) are more prone to landslides than more gentle areas (at location S15), as shown in Figure 7.

The management of landslide-prone areas, especially at the study site, should be done through a comprehensive approach that considers the topographic condition and the level of vulnerability by the results of landslide mapping based on magmatic susceptibility. Land use that will be utilized for residential areas should consider slope stability, especially in the northeast and southwest of the study site. This management can be initiated by implementing mitigation measures, namely stabilizing the slopes through geotechnical engineering techniques by installing retaining walls around the potentially landslide-prone slopes in the northeast and southwest of the study site (Liu et al., 2022). Second, an adequate drainage system should be implemented to drain surface water from accumulating in certain areas (Syazwan et al., 2021). This is because increased water content in the soil can reduce soil cohesiveness, triggering soil movement. Third, revegetate landslide-prone areas to improve slope stability (Li et al., 2021; Restele et al., 2023). This is because plant roots strengthen the soil structure and reduce erosion risk.

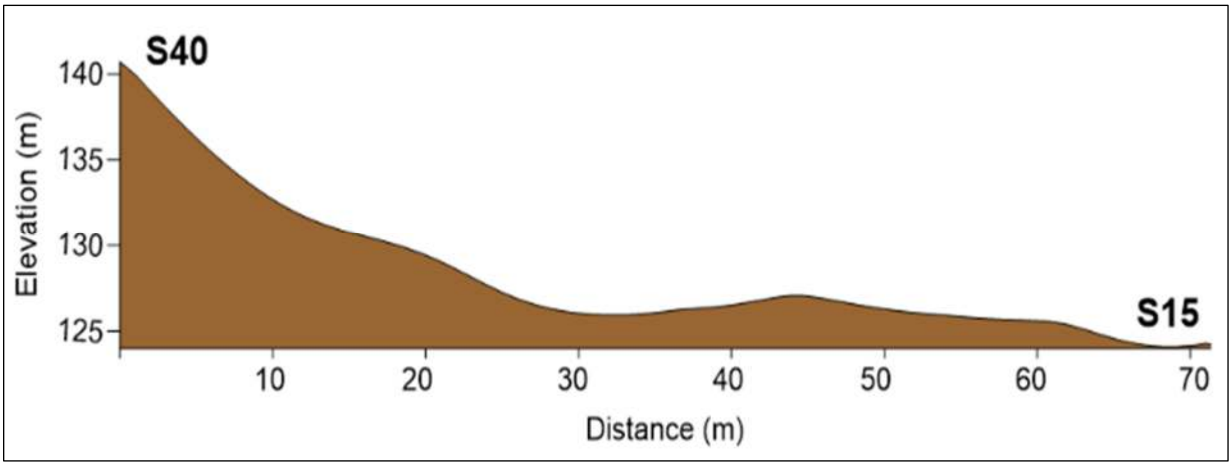


Figure 7. Slope profile connecting two points of landslide-prone area (from S40 to S15).

Conclusion

Landslide-prone areas in Sabang Merah, Sanggau Regency, planned for residential development, were mapped by identifying landslide indicators based on their magnetic properties. Landslide potential was identified through superparamagnetic grains in 40 soil samples spread across the study site. The results showed that 36 soil samples contained less than 10% superparamagnetic grains, two contained 10%-75% superparamagnetic grains, and two contained more than 75% superparamagnetic grains. The interpretation results show that soil samples with more than 75% superparamagnetic grains indicate landslide-prone areas at the study site, located in the study site's northeast and southwest parts.

Management of landslide-prone areas, especially at the study site, should be carried out at the two locations identified as landslide-prone areas by the results of the mapping of the landslide-prone regions based on magnetic susceptibility, namely in the northeast and southwest. This management can be initiated by conducting mitigation measures to improve slope stability, i.e., installing retaining walls, implementing drainage systems, and revegetating in the northeast and southwest parts of the study site.

Further research is needed to identify the mineral content directly impacting slope stability. Soil mineral content affects soil cohesiveness, which controls the binding force of soil particles. In addition, hydrological studies are also needed to observe subsurface water flow so that soil movement patterns influenced by such flow can be better understood. Additional research in the surrounding area is also essential so that the analysis results can reflect conditions in a larger area.

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