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Characterization and Classification of Soils in Landslide Residual Zones to Estimate the Presence of Shallow Slip Plane

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ABSTRACT

While landslide determination has traditionally relied on topography and geology, the connection between soil characteristics and landslide potential remains a relatively unexplored area. This study sets out to bridge this gap by investigating the relationship between soil properties and their classification and the likelihood of a shallow slip field triggering landslides. The research commenced with a survey of three landslide sites featuring diverse soil materials. Characterization and sampling were carried out on the residual zone left at the top of the landslide. The findings revealed that certain landslides could be identified as having potential slip planes only at a depth of 120 cm, while others could not. Two landslides in Magelang exhibited the presence of typical endopedon horizons, namely Bt (argillic). These argillic horizons serve as accumulation sites for fine and plastic clay materials. The low organic matter content also contributes to the instability and rapid dispersion of the structure. Meanwhile, the research also identified practical implications for landslide management. For instance, one of the landslides in Purworejo showed that the soil profile in the residual zone had low clay content and did not form a Bt horizon. However, the presence of shallow argillic with high clay content indicated a potential landslide risk. This finding suggests that landslides can be predicted based on soil characteristics, particularly the presence of argillic horizons. Moreover, the study identified specific soil types, such as Alfisols and Ultisols, as being prone to landslides. The Bt horizon, which can be protected by reducing erosion and runoff using silt pits, cover crops, and flow-breaking media, offers a practical solution for landslide prevention.

Keywords: Argillic, Landslide, Residual zone, Soil classification, Soil properties

INTRODUCTION

Landslides are generally caused by high rainfall, seismic activity, water level changes, and deep valley erosion that affect the shear strength of the materials that make up a slope. Marfai et al. (2008) explained that landslides are often found on mountainous and hilly slopes after heavy rainfall. Heavy rain conditions cause an increase in pore pressure in the unsaturated zone within the soil horizon, causing landslides (Yalcin, 2011). The nature and rate of geomorphological processes, including landslides, depend on the soil parent material and its weathering characteristics (Lee et al., 2001). Soil parent material significantly impacts landslide occurrence, as material variations often lead to different values of soil strength and permeability (Yalcin, 2007).

Landslides are always associated with the presence of a slide plane. Understanding slip planes describes the behavior of sensitive clays, soil shear strength, and landslide mechanisms (Zhang et al., 2018). Slip planes have been understood to be in deep soil layers (Luino et al., 2022). Slip planes are often associated with the boundary between soil material and host rock. Under certain conditions, rotational landslides allow soil material to act as a sliding plane (Yu et al., 2021). This slide plane is related to soil horizonization and its properties and can be found in shallow and deep horizons. Shallow horizons will trigger translational landslides, while deep horizons will trigger rotational landslides. A combination of both landslides is also possible, where the process begins with a translational landslide followed by a rotational landslide (Glenn et al., 2006; Xin et al., 2018).

Landslides influenced by soil properties refer to typical fine-textured soils or clays. Clays can create properties that are sensitive to the presence of water (Thakur et al., 2006). Landslides caused by sensitive clay layers can be divided into several mechanisms, including mudding, shrinking, sliding, and collapse (Noviyanto et al., 2020). The mechanism of silty clay is related to the level of sensitivity of the clay expressed by the ratio between the actual moisture content and the liquid limit (Liu et al., 2021). The expanding and contracting mechanism of clays is related to the shrinkage limit value of the soil. The sliding mechanism of clay is related to the water movement system in the soil. The collapsible clay mechanism is related to the soil shear strength and soil collapse potential.

Understanding the soil characteristics at the landslide crown is crucial for practical applications. As Cheng et al. (2016), landslide events leave the original soil profile at the landslide crown or residual zone. Changes in the morphology and physicochemical properties of soil in the landslide deposition zone are site-specific and depend on the

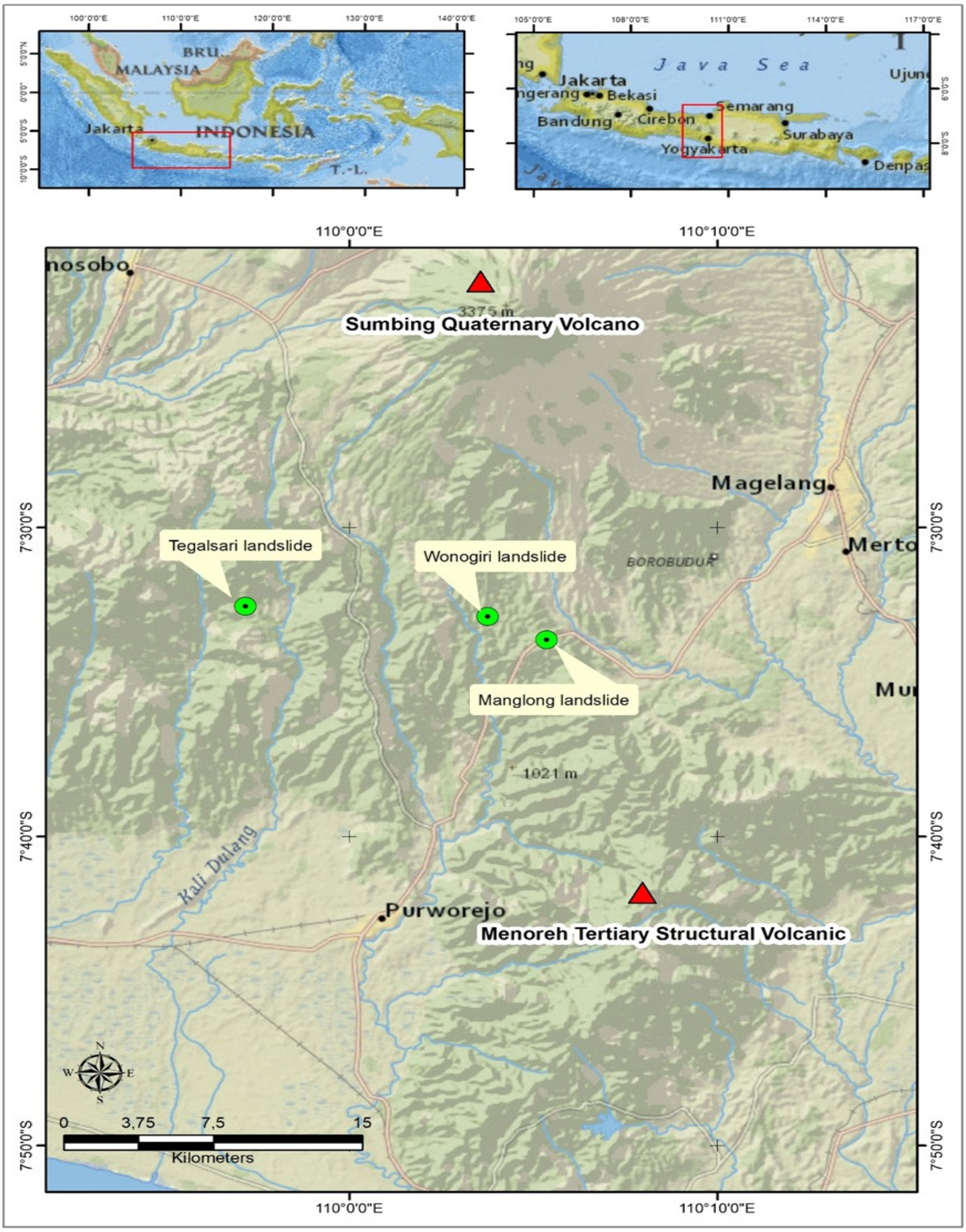

Figure 1. Study area.

type of landslide, its magnitude, and the type of soil parent material (Uyeturk et al., 2020). The research area, situated on the southern flank of Sumbing Volcano, falls within the volcanic transition area between Quarternary and Tertiary Volcanoes. The deposition of Sumbing Volcano ash during the Quarternary period produced thick surface soil and overlapped the thick weathered zone of Tertiary age rocks (Sartohadi et al., 2018). Previous studies have not delved into soil characteristics and classification, yet these data are crucial for resource management in landslide-prone areas.

MATERIALS AND METHODS

The research was conducted at three landslide sites with different constituent soil materials and similar volcanic transition zones. A soil sampling technique was employed at each horizon formation, which was identified based on soil color, beat, structure, texture, and other diagnostic properties. The observation of soil horizons followed the USDA manual. Sampling points were strategically located at the landslide crown, representing typically developed soil conditions not disturbed by the landslide. This forms the basis for identifying the presence of a landslide trigger horizon that acts as a sliding plane.

Observation of morphological characteristics includes soil thickness, soil horizon, horizon clarity, soil color, and characteristic properties. Soil characteristics were measured by several soil parameters such as soil pH with H_2O (Aquadest) and NaF (Sodium fluoride) solutions, organic matter content (Walkley and black method), bulk density (ring method), clay content (pipette method), amount of coarse fraction (pipette method), amount of Al-oxalate and ½ Fe-oxalate as a diagnostic of volcanic properties, base saturation (calculated as the proportion of the CEC occupied by base cations), and cation exchange capacity (1 N ammonium acetate extraction). The research location is presented in Figure 1.

The photograph of the landslide area was created using drones. The type of drone was a DJI Phantom 4 Pro, and the flight altitude was 80 meters. The drone was flown with a mission path set using Pix4D, a process of making a photo mosaic using Agisoft Metashape. The resulting orthophoto was then layered with ArcGIS and given the location point of the soil profile. A Ground Control Point was obtained using Geodetic GPS, and the resulting point was used to test the accuracy of the orthophoto results.

RESULTS AND DISCUSSION

Soil classification was observed at the crown of the landslide as it was considered unaffected by landslide movement and, therefore, still exhibited original soil characteristics. Soil classification is based on clearly defined and measurable soil characteristics, thus combining a morphological approach with strong genetic underpinnings (Urushadze et al., 2016). Several physical and chemical characteristics are used as soil-characterizing properties in the surface and sub-horizons. Soil characteristics are used to determine the diagnostic epipedon (surface horizon), diagnostic endopedon (sub horizon), and distinguishing components of the soil classification system. The soil characterization properties and soil classification are presented in Table 1.

The epipedon found in the crown of Tegalsari landslide is at a depth of 0 cm to 54 cm, and the endopedon is shown at 54 cm to 100 cm (Figure 2). The physical properties of the soil at epipedon and endopedon show loose, light, and porous properties. When wet, changes in color, soil texture, and soil consistency show that the endopedon can be categorized as a cambic endopedon. Cambic endopedon is a horizon resulting from physical changes, minimal chemical weathering, or displacement of soil particles (Gerasimova & Konyushkov, 2023). The cambic endopedon horizon has the characteristics of thickness $\geq$ 15 cm, very fine sand texture, and non-hard soil; it still contains some easily weathered minerals, genetic soil development without extreme clay accumulation, and no cutaneous clay is found. The epipedon horizon can be categorized as an umbra epipedon. Visually, in the field, the umbric epipedon is almost the same as the mollic epipedon, making it difficult to distinguish. Umbric and mollic epipedons show thick, dark-colored, organic matter-rich surface horizons. The difference between the umbric and molic epipedon is in the base saturation value using Ammonium acetate solvent, where the umbric epipedon shows a base saturation value $\leq$ 50%, while the molic epipedon shows a base saturation value $\geq$ 50%. The epipedon at the crown of the Tegalsari landslide shows a base saturation value of 18.52%, so it is categorized as a Cumbria epipedon.

Soil classification in landslide-prone areas helps the community recognize landslide vulnerability without having to analyze soil properties at a relatively expensive cost. The soil order of the landslide crown is classified as Inceptisols. The order Inceptisols are soils with cambic, sulfuric, calcic,

Table 1. Soil properties and soil classification.

Soil horizon	Solum (cm)	pH H_2O	pH NaF	OM (%)	BD ($g.cm^{-3}$)	Soil colour value	Soil colour chroma	Clay (%)	Coarse sand (%)	Al_o+ ½Fe_o (%)	BS (%)	CEC $cmol(+).kg^{-1}$
Tegalsari landslide area Epipedon = Umbric Endopedon = Cambic Soil classification = Humic Dystrudepts												
A	0 – 24	5.45	10.58	4.84	0.75	2.5	3	52.59	4.43	0.0020	18.52	22.89
A/Bw	24 – 54	5.63	10.66	2.56	0.74	3	3	48.93	5.96			
Bw	54 – 100	5.75	10.21	2.34	0.74	3	4	50.04	5.11	0.0022	19.13	21.53
Wonogiri landslide area Epipedon = Ochric Endopedon = Candic Soil classification = Typic Kandiudalfs												
A1	0 – 13	5.68	9.54	3.19	0.95	4	4	81.29	0.77	0.0015	34.73	16.76
A2	13 – 40	5.62	9.51	3.03	1.08	4	6	85.64	0.75			
A/Bt	40 – 69	5.48	9.44	1.88	0.89	4	6	83.32	0.69			
Bt	69 – 120	5.42	9.36	1.59	1.07	3	4	79.88	1.06	0.0012	38.31	12.61
Manglong landslide area Epipedon = Ochric Endopedon = Argilic Soil classification = Typic Plinthudults												
A1	0 – 22	5.52	9.61	2.84	0.95	3	4	68.33	1.63	0.0027	13.59	23.42
A2	22 – 40	5.57	9.54	1.65	0.84	2.5	2	73.69	0.75			
A/B	40 – 51	5.61	9.47	1.64	0.91	2.5	2	75.83	0.87			
B(PI)	51 – 65	5.72	9.52	1.09	0.91	3	3	73.26	1.28	0.0030	17.77	26.38
Bt1	65 – 135	5.66	9.59	1.09	0.91	3	2	67.21	1.55			
Bt2	135 – 160	5.81	9.64	1.25	0.98	2.5	3	60.90	1.34			

Remarks: OM = Organic Matter; BD = Bulk Density; BS = Base Saturation; CEC = Cation Exchange Capacity.

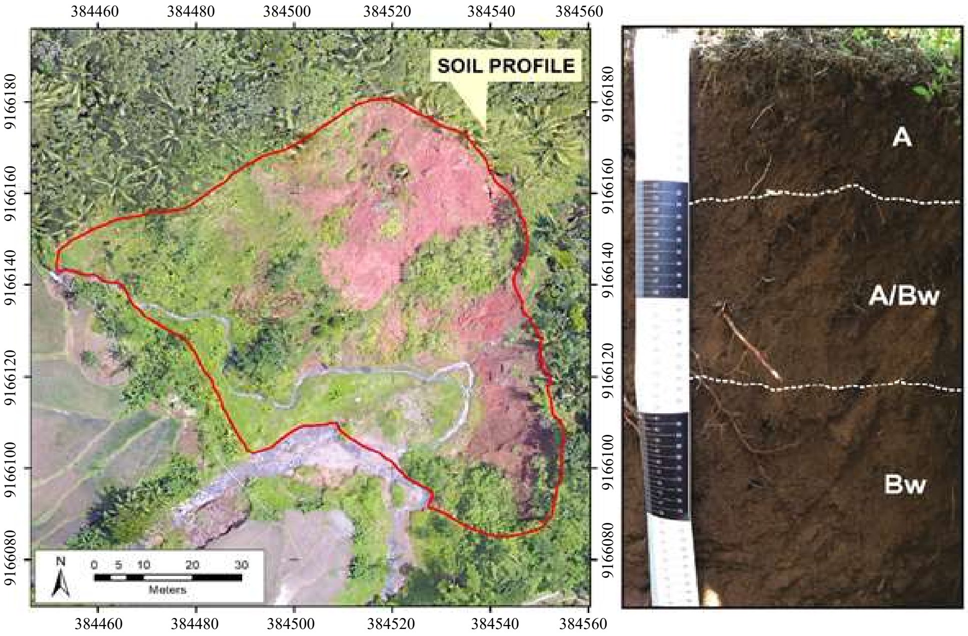

Figure 2. Soil profile in Tegalsari landslide area.

gypsic, petrocalcic, or petrogypsic endopedons to a depth of 100 cm and hystic, umbric, or plagen epipedons to a depth of 50 cm from the soil surface (Palmer, 2005). The order inceptisol will be written on the suffix of the name used, Ept. Inceptisol comes from the name inceptum, which means early soil that begins to develop. Inceptisols are relatively young soils and have a better soil profile development cthanEntisols. The inceptisols suborder is described by the udik (moist) moisture regime found in areas with even and sufficient rainfall throughout the year, thus naming the suborder Udepts. The key differentiator at the great group level is Dystr, which can be characterized by low base saturation values, while at the subgroup level is Humic, which is characterized by fine-grained humus content (Skorupa et al., 2017). The value of Alo + ½ Feo < 1 indicates that amorphous minerals are no longer influential, so the soil develops in the initial phase (Yanai et al., 2014). Soils with the Humic Dystrudepts subgroup are other Dystrudepts with a moist color value of 3 or less in the upper 18 cm thick mineral soil that have fine-grained humus content in the field and are characterized by moderate to high humus content. The characteristics of inceptisol soils do not make them prone to landslides. However, in the case of the Tegalsari landslide, the different layers of material underneath the inceptisols became the landslide slide plane. Thus, land management on inceptisol soils located on hills must also be done carefully to avoid triggering landslides.

The soil characteristics of the Wonogiri and Manglong landslide crown epipedons do not meet the criteria of other epipedon characteristics, therefore, they are classified as ochric epipedons. The Wonogiri landslide crown has epipedon horizon 0 cm to 69 cm, and the endo pedon at 69 cm to 120 cm (Figure 3). While, the Manglong landslide crown has epipedon horizon at 0 cm to 51 cm and the endo pedon at 51 cm to 160 cm (Figure 4). Bockheim and Gennadiyev (2000) explain that ochric epipedons fail to meet the requirements of other diagnostic epipedons because they are too thick, contain too little soil C-organics, or contain light soil color, and are usually found in alfisols, aridisols, entisols, inceptisols, oxisols, and ultisols. The genesis of ochric epipedons do not contribute to organically enriched soils. The ochre epipedon can be elevated above the argillic, candid, nitric, and spodic endo pedon horizons. Endopedon horizons enriched by clay content (Bt) are important for soil nutrient status, water retention, and geomorphic stability (Hopkins & Franzen, 2003).

Soils in humid areas cause some soil colloidal particles dispersed in rainwater, go through soil pores, and accumulate in the soil layer. Bockheim (2014) says that clay illuviation causes the subsurface soil layer more compact, heavier, and less permeable. Clay illuviation is found in the endo pedon horizon in Wonogiri and Manglong and is characterized by cutaneous clay and a high percentage of clay. Clay illuviation is also a criterion for characterizing the

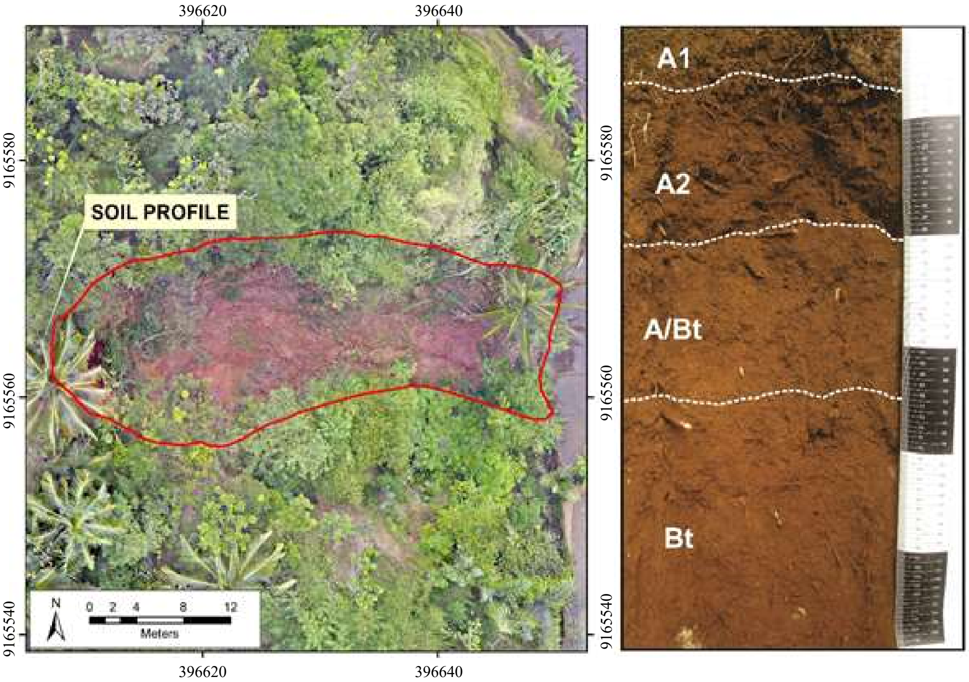

Figure 3. Soil profile in Wonogiri landslide area.

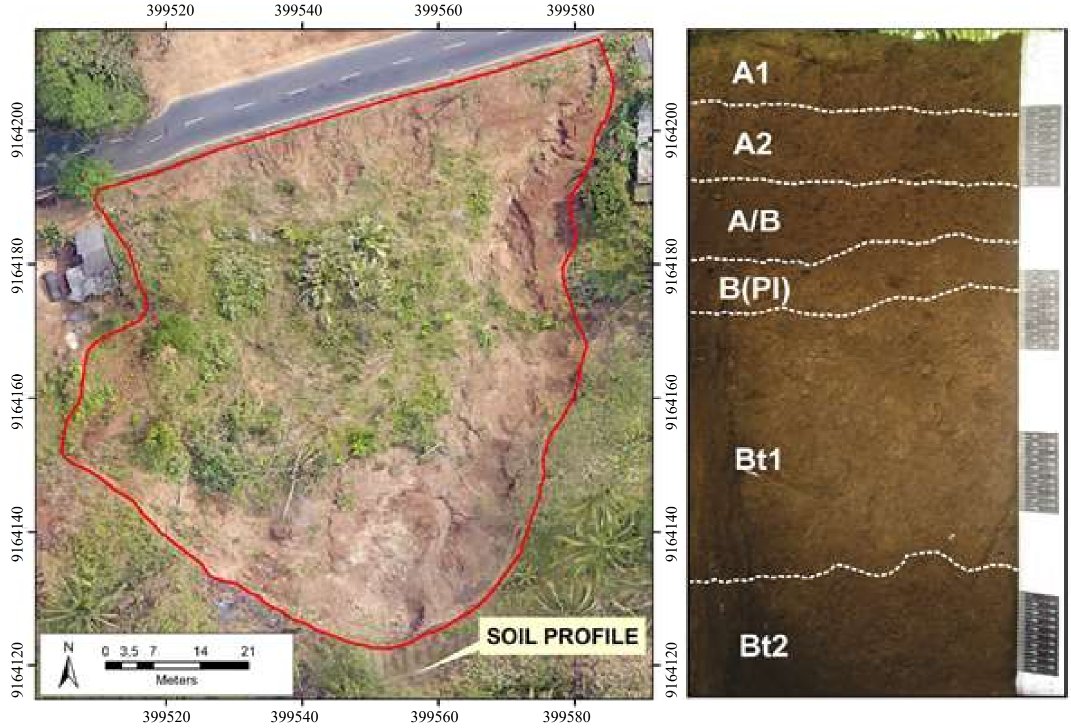

Figure 4 . Soil profile in Manglong landslide area.

subsurface horizons: argillic, natric, and candic. The endopedon horizon at the Wonogiri landslide crown is classified as a candlestick horizon, while the Manglong landslide crown is classified as an argillic horizon. Candic endopedon is a clay illuviation horizon with low clay activity, indicated by CEC value < 16 cmol(+).kg^{-1}. The argillic endopedon is a clay illuviation horizon with high clay activity criteria, indicated by a CEC value > 16 cmol(+).kg^{-1}. White (2003) explained that the argillic horizon is usually a subsurface horizon with a significantly higher percentage of phyllosilicate clay content than the horizon above.

The soil order at the crown of the Wonogiri landslide is alfisols, characterized by the presence of a candid horizon and base saturation > 35% (Bhattacharyya et al., 2015). Alfisols are soil types with high natural fertility, often found in humid or sub humid regions. The alfisols suborder is classified based on the soil moisture regime, namely udic, so it has a suborder name, Udalfs. The great group is indicated based on the difference in horizon sequence and another characteristic, where the great group naming on the Wonogiri landslide crown is Kand, so it is classified as Kandiudalf. The soil subgroup is typical because no other characteristic criteria can be classified, so the naming at the subgroup level is typical Kandiudalfs. A different order is found in the landslide crown of Manglong, which belongs to the ultisols order. The characteristics of ultisols are evidenced by a base saturation of < 35% (Purwanto et al., 2020). The suborder of ultisols is based on the udic moisture regime, hence the name Udults. Plintite was found at a depth of 51 cm to 65 cm. Plintit shows that the soil in Manglong is included in the criteria of old soil that has been weathered further. Plintite content is 6% in the B horizon. The presence of plintit makes a characteristic of the great group criteria so that it is classified as Plinthudults (Zhang et al., 2004). The Typic subgroup is used in Manglong ultisols soil because no other characteristics can be classified.

The argillic horizon with high (60 - 80%) clay content and candic horizon with very high (> 80%) clay content becomes a critical zone that has the potential to become a sliding plane. The high clay content of >60% results from highly weathered volcanic ash deposits (Pulungan & Sartohadi, 2017). The nature of clay, easily dispersed by water, will allow the soil structure to be loose (Wicki et al., 2020). Moreover, the high clay content in the Bt horizon is also higher in bulk density with low organic matter content. The Bt horizon's presence threatens the agricultural system practiced in landslide-prone areas (Wida et al., 2019). Instead of cultivating crops, the wrong technique will cause landslides. Therefore, it is necessary to conserve the Bt horizon from direct contact with the degree of water saturation (Lalitha et al., 2021). A doable and low-cost recommendation is to manage runoff and reduce erosion rates. Runoff management and reducing erosion rates can be done simultaneously, for example, by constructing silt pits, planting cover crops between production crops, and applying runoff-breaking media at gully erosion or concentration points of converging water flows. Thus, topsoil erosion will be reduced, and the water saturation level in the Bt horizon will be controlled.

CONCLUSIONS

The soil characteristics at the landslide crown as a residual zone are pristine and unaffected by the landslide event. An argillic or candid horizon is important and plays a role in triggering the landslide. The 80% clay content in the argillic horizon indicates that the potential landslide slide plane can be found in the shallow layer of less than 120 cm. These soils are distributed in the volcanic transition zone between the Quaternary and Tertiary volcanic systems. Finally, agricultural systems practiced in landslide-prone areas in the volcanic transition zone should pay attention to the argillic horizon hidden in the endopedon horizon.

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