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Swelling potential of volcanic residual soils in Sumatra (Indonesia) in relation to environmental issues

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ABSTRACT

Swelling potential characterization of clay-silt soil is an essential issue in stabilization, settlement, consolidation, and land suitability studies. This article attempts to explain the swelling characteristics of soils around the area of West Lampung, Lampung Province, Sumatra, Indonesia, in relation to environmental issues. An investigation in relation to the soil swelling potential was carried out using 15 disturbed soil samples collected in the study area. The methods used were analyses of clay mineral geochemistry, physical characteristics, and the free swell ratio. These results showed that the soil in the study area was Quaternary tropical volcanic residual soil. These soils were formed in a proximal volcanic hydrothermal alteration environment. The soils of the study area have characteristics of high plasticity, a reddish-brown colour, and are clayey silt grained (MH) (USCS). The soils had loose physical characteristics in dry conditions; however, these soils tend to be plastic and sticky in wet conditions. Evidence of groove erosion was found at the soil surface. Based on XRD analysis, kaolinite, halloysite, and montmorillonite were types of clay minerals found in the soil. The soil had a clay content of 11.05–78.9%, a liquid limit value > 50%, a plasticity index value of 16.7–36.9%, a shrinkage value of 14.24–36.89%, a soil activity of 0.38–2.47, and an FSR value of 0.69–0.95. These characteristics have implications for swelling soil potential. The results showed that the soils in the study area had medium to very high swelling potential. These results suggest a risk of erosion in the area, which could cause soil degradation and a change in water quality. These soils are likely to affect land productivity and aquifer replenishment and will cause negative environmental and economic impacts. Thus, soil improvement techniques are needed. It is important to maintaining vegetative cover these soils and revegetation may be required.

KEY WORDS: volcanic, residual soil, swelling potential, environmental issues, West Lampung, Sumatra

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1. Introduction

Characterization of soil swelling potential plays a crucial role in geology, geotechnics, and environmental sciences. Swelling potential characterization of clay-silt soil is an essential issue in stabilization, settlement, consolidation, and land suitability studies (ÇİMEN ET AL., 2012; ESTABRAGH ET AL., 2013; SOLTANI ET AL., 2017). Soil is a part of

the earth's crust composed of minerals and organic matter. Minerals come from rock and physical weathering and have clay to boulder particle sizes. Organic matter comes from the remains of plants, animals, and humans either that have been, or are undergoing, decomposition (MANI BHARATHI ET AL., 2019; STETSYUK & VESELOVA, 2017; TAQI ET AL., 2016). Based on the parent material, soil is divided into two types, namely: residual soil and sedimentary

soil (BRADY & WEIL, 2004; WEIL & BRADY, 2016). Residual soil is formed directly from source rock due to rock weathering, which is dominated by the hydrolysis process (LATIFI ET AL., 2017; LATTIMORE & GLINOW, 2010; WESLEY L., 2009; WESLEY L.D., 2013). In Indonesia, residual soils occupy 53% of the land area. Based on geological age, the residual soil is from the Quaternary period. ADITIAN ET AL., (2018) stated that the soil is the foundation on which the infrastructure stands.

Soil generally consists of various types of grains, soil with a silt-clay grain size is often found in locations with soil engineering problems, such as the potential for swelling. It is commonly stated that in swelling soil the soil changes its physical volume due to its water content (MOHAMMED & ABED, 2020; XU ET AL., 2014). The volume changes because the soil contains phyllosilicate clay minerals (2:1 structure), such as those of the smectite clay mineral group. The swelling and shrinking of the soil's volume occur when it is in wet and dry conditions. In wet conditions, the soil volume will increase and vice versa, when dry the soil volume will decrease. This condition occurs because the clay minerals in the soil have the property of being able to absorb and remove water. When in wet conditions, clay minerals will absorb water, so an increase in the volume of the soil occurs. Inversely proportional when it is in dry conditions, clay minerals will release water so that the soil volume reduction process will occur (CHURCHMAN & LOWE, 2012; STELL ET AL., 2019; WILSON S.G. ET AL., 2017).

The nature of the swelling-shrinking characteristics that belong to this type of soil results in cracking and happens during the dry season. Cracks that arise will affect the surrounding hydrological conditions. These conditions will affect slope stability, agricultural productivity, and plantations (JIANG ET AL., 2013; KIRBY ET AL., 2003; QI & VANAPALLI, 2016; STEWART ET AL., 2016; YOO ET AL., 2006). On the other hand, the process of swelling and shrinking of the soil will cause the walls of the building to be severely damaged (AL-YAQOUB ET AL., 2017; PUSCH & YONG, 2006; STELL ET AL., 2019).

In Indonesia, these swelling soils can be found in various regions. On the island of Java, they can be found around the North Coast (Semarang and Purwokerto), Central and South regions (Boyolali, Ngawi, and Yogyakarta), Western regions (Majalengka, Purwakarta, Bogor, and Bandung). On the island of Sumatra, soils with swelling

potential can be found in Padang. This article attempts to explain the swelling characteristics of soil around the western part of the Island of Sumatra, particularly in the area of West Lampung, Lampung Province, Indonesia, related to an environmental issues. The information generated can be used by various parties to assess the likely land use, land degradation, soil fertility, and soil quality (STELL ET AL., 2019).

2. Geological setting of West Lampung

West Lampung and its surroundings have a hilly and mountainous topography. This area is at an altitude of 850 to 1180 m a.s.l. with the lowest point being in the Liwa City area, and the highest point in the Sekincau region, West Lampung. The study area is in the Western Transect Road (JALINBAR) Liwa-Sumberjaya (Fig. 1). The West Lampung area and its surroundings are composed of Tertiary-Quaternary volcanic rocks deposited on land. The southern part of the West Lampung area is dominated by volcanic rock of sandy tuff and crystal glass tuff, which has loose physical characteristics. In contrast, in the north, west, and east, it is dominated by the residual soil formed due to volcanic material weathering (IQBAL ET AL., 2020). Based on the classification of volcanic facies (BOGIE, 1998), the study area is in the proximal facies (RAJABI ET AL., 2012; SELLES ET AL., 2015), while based on INDARTO ET AL. (2007), the study area is located in a propylitic-argillic hydrothermal alteration environment.

Based on parent rock petrographic analysis, the West Lampung area is composed of volcanic rock: sandy tuff, crystal glass tuff, and volcanic breccias that have a mineral composition consisting of volcanic glass, alkaline feldspar, quartz, plagioclase, muscovite, pyroxene, sericite, opaque mineral, clay minerals, and iron oxide. Based on the Igneous Rocks Classification of VERMA & RIVERA-GÓMEZ (2013), these rocks are medium volcanic rocks. Volcanic glass are transformed into clay minerals and iron oxide.

Sandy tuff and crystal glass tuff is commonly called the Ranau Tuff. These deposits are a pyroclastic flow type deposited on the land. Based on the Tuff Classification, these deposits belong to lithic and crystal tuff types. These tuff types are mostly volcanic glass and feldspar, while volcanic breccias have gravel tuff components and a sand to clay matrix.

Fig. 1. Research area, sampling location, and simplified regional geological map (modified from www.big.go.id)

3. Materials and methods

The characteristics of swelling soil generally can be measured in the laboratory (direct method) and from empirical correlations (indirect method). [AL-RAWAS & GOOSEN \(2006\)](#) and [KAYABALI & DEMIR \(2011\)](#) stated that the direct method is not suitable for the rapid identification of swelling soil. Direct methods usually use sophisticated tools. This type of analysis implies a high degree of complexity and takes a long time to obtain the results. An example of the direct method is the Free Swell Ratio (FSR) method ([PRAKASH & SRIDHARAN, 2004](#)).

In contrast, the indirect method is carried out based on experience. This method results in quick and reliable identification of swelling soil. Examples of indirect methods that have been widely used until now are plotting data on soil physical properties (grain size and Atterberg limit) into a soil swelling potential diagram ([MUTLUTÜRK & BALCIOĞLU, 2015](#)). This study uses both direct and indirect methods.

Volcanic residual soil samples were taken from Liwa-Sumberjaya West Transect Road spread over

15 locations (see Fig. 1). The samples were taken from a 50 cm depth from the slope surface using 1 kg plastic bags (disturbed sample). The soil was then tested at the Geological Engineering laboratory, Faculty of Geological Engineering, Padjadjaran University, Indonesia, to determine its physical properties such as grain size (ASTM D422-63) ([ASTM, 2007](#)), Atterberg limit (ASTM D4318 - 17e1) ([ASTM, 2017](#)), soil type based on ASTM and USCS standards (ASTM D2487-17) ([ASTM, 2017](#)), and soil activity ([SKEMPTON, 1953](#)). The obtained soil physical properties were plotted into a soil swelling potential diagram, which has been used by previous researchers ([MUTLUTÜRK & BALCIOĞLU, 2015](#)).

Another method used is the Free Swell Ratio (FSR) analysis introduced by [PRAKASH & SRIDHARAN \(2004\)](#). This method uses 50g of soil (clay size) sample immersed in two test tubes filled with water and kerosene, which is then allowed to stand for 24 hours to assess the volume change. This parameter was then recorded, compared, and then matched into a soil classification based on the Free Swell Ratio table (Table 1).

Table 1. Free Swell Ratio (FSR) table (the grey shading is the FSR value in all soil sample)

Free Swell Ratio	Soil expansivity	Clay type	Dominant clay mineral type
< 1	Negligible	Non swelling	Kaolinitic
1.0 - 1.5	Low	Mixture	Kaolinitic and montmorillonite
1.5 - 2.0	Moderate	Swelling	Montmorillonite
2.0 - 4.0	High	Swelling	Montmorillonite
>4	Very high	Swelling	Montmorillonite

The qualitative and semi-quantitative XRD analysis was conducted using spectrometre of xray diffractor (Shimadzu 7000 tool), SIROQUANT database software (ANONYMOUS, 2020), and ICDD PDF-4 Minerals 2018 RDB in the Mineral Chemistry Laboratory, at the Research Center for Geotechnology, LIPI, Bandung, Indonesia. The analysis was conducted to determine the clay mineral types and their abundances. The sample used to determine the type of clay mineral in the soil was soil with a clay grain size (passes

through sieve No. 200). Samples were analyzed with diffraction angles (2 Theta) between 10 and 40 (degrees) and without treatment.

4. Results

From direct observation, the study soil had a reddish-brown color (Fig. 2A) and loose physical characteristics; however, this soil tends to be plastic and sticky in wet conditions. On the soil surface, it can be observed in groove erosion (see Fig. 2B).

A

B

Fig. 2. The soil of the study area (A) and groove erosion (B)

4.1. Clay mineral geochemistry characteristics

Based on XRD analysis (Fig. 3 and Fig. 4), the clay minerals present were kaolinite, halloysite, and montmorillonite. Halloysite was the most prominent mineral present in the soil sample at 35.1–76%, followed by montmorillonite with 10.1–23.7%, and

also kaolinite with 6.1–12.7%. The XRD analysis also found quartz. This mineral is not a clay mineral. This mineral is the most abundant mineral found on the earth's surface and it is resistant to mechanical and chemical weathering. Quartz was present in the soil samples at a percentage of between 1.2–35.1% (see Fig. 3 and Fig. 4).

Fig. 3. Percentage of clay mineral

Fig. 4. Typical of XRD diffractogram on A. S3; B. S7; and C. S9

4.2. Soil engineering characterization

Based on the geotechnical laboratory analysis (Table 2), the soil samples had a gravel grain of between 0–3.18%, sand grain of 3.1–48.63%, silt grain of 7.87–77.63%, clay grain of 11.05–78.9%, a liquid limit of 52.54–121.17%, plasticity index

value of 17.82–36.9%, and a shrinkage limit value of between 14.24–36.89%. According to the Unified Soil Classification System/USCS, all samples were a high plasticity clayey silt (MH). The soil samples had a soil activity of 0.38–2.47 and Free Swell Ratio (FSR) value of 0.69 to 0.95.

Table 2. Physical properties of the soil samples in this study

Sample code	Gravel content (%)	Sand content (%)	Silt content (%)	Clay content (%)	Liquid limit (%)	Plasticity index (%)	Shrinkage limit (%)	Activity	Free Swell Ratio (FSR)	USCS
S01	1.30	40.50	47.15	11.05	70.37	34.40	20.62	0.38	0.80	MH
S05	0.59	10.43	63.46	25.52	53.35	23.30	14.24	1.39	0.95	MH
S07	0.00	5.79	70.53	23.68	52.73	21.20	15.70	1.46	0.70	MH
DS11	0.48	12.69	53.52	33.31	71.50	30.75	22.33	1.29	0.91	MH
X24	0.00	6.12	58.76	35.12	94.51	28.85	25.09	1.47	0.78	MH
X33	0.17	3.10	77.63	19.10	81.30	27.36	23.11	0.85	0.91	MH
X19	0.05	9.37	69.47	21.11	96.56	31.11	33.28	0.81	0.92	MH
X20	0.00	32.07	47.78	20.15	64.80	17.82	28.55	1.57	0.69	MH
DS14	0.10	5.46	64.58	29.86	121.17	35.17	26.89	0.99	0.86	MH
S02	0.02	8.10	55.07	36.81	67.65	36.60	16.79	1.16	0.79	MH
S03	0.06	34.40	50.87	14.67	56.70	22.16	18.75	0.85	0.84	MH
S04	3.18	48.63	32.65	15.54	54.75	16.70	22.05	1.33	0.94	MH
S09	0.32	43.74	35.34	20.60	52.54	23.64	19.88	1.11	0.90	MH
S10	0.13	21.17	50.97	27.73	61.00	28.65	22.33	1.17	0.90	MH
Y01	0.01	13.22	7.87	78.90	71.00	36.90	36.89	2.47	0.70	MH

4.3. Swelling potential characteristics

The physical properties (Table 2) used for plotting data are: clay content, sum of silt and clay content, plasticity index, shrinkage limit, liquid limit, and activity of soil. Based on the swelling diagram created by [WOODWARD & LUNDGREN \(1962\)](#) (Fig. 5), the soil samples were between 1.5% swelling potential curve to 25% swelling potential (low to high swelling potential), with some samples below the 1.5% curve and some samples above the 25% curve. The samples which were below the 1.5% swelling curve were from locations S1, S3, and X33. The samples which were on the 1.5% swelling potential curve were from location X19 and S4. The location S9 was on a 5.0% swelling potential curve. Locations X20, DS14, S10, S5, and S7 were above 5.0% swelling potential curve. On the other hand, location DS11, S2, X24, and Y01 were above the 25% swelling potential curve.

Based on the [VAN DER MERWE \(1964\)](#) swelling potential diagram (Fig. 6), the soil samples had a medium to very high swelling potential. In line with the diagram (Fig. 7), of [PINCUS ET AL. \(1993\)](#), the soil samples had a medium to very high swelling potential. Some samples such as locations X20, S4, S7, S5, S9, and S3 had a medium to high swelling potential. Other samples had a high to very high swelling potential, as shown by the samples from locations S10, S2, Y01, S1, DS11, X33, X24, X19, and DS14.

From the [HOLTZ & GIBBS \(1956\)](#) degree of expansion/swelling potential (Table 3), the soil samples from the study area were between medium to very high swelling potential. Also, on the [CHEN \(1988\)](#) degree of expansion (see Table 3), all soil samples were between a medium to very high swelling potential. Samples from location X20 and S04 had a medium swelling potential. In contrast, other samples from locations S5, S7, DS11, X24, X33, X19, S3, S9, and S10 had a high swelling potential. The rest of the samples from locations S1, DS14, and Y01, had a very high swelling potential.

In terms of soil activity ([SKEMPTON, 1953](#)), it was determined that only samples from location S1 showed an inactive soil (<0.75). Soil samples from locations S10, S9, S3, S2, DS14, X19, and X33 had soils with normal activity (0.75–1.25). The other soil samples, namely S5, S7, DS11, X24, X20, S4, and Y01, had soils with an active condition (>1.25) (see Table 2).

Fig. 5. Soil swelling potential on [39] diagram

Fig. 6. Soil swelling potential on [40] diagram

Fig. 7. Soil swelling potential on [41] diagram

Table 3. Chen (1988) and Holtz & Gibbs (1956) degree of an expansion/swelling table (the grey shading is the physical characteristics value in all soil sample)

	Holtz & Gibbs (1956)		Chen (1988)		
Degree of expansion	Colloid content (%, -1 [^])	Plasticity index (%)	Shrinkage limit (%)	Liquid limit (%)	Plasticity index (%)
Low	<15	<18	>15	<30	0 - 15
Medium	13 - 23	15 - 28	10 - 16	30 - 40	10 - 35
High	20 - 31	25 - 41	7 - 12	40 - 60	20 - 55
Very high	>28	>35	<11	>60	>35

5. Discussion

The study area was located in a propylitic-argillic hydrothermal alteration environment composed of Tertiary-Quaternary volcanic rocks and their weathering soil (volcanic residual soil). The volcanic rocks in the study area were medium volcanic rocks, sandy tuff, crystal glass tuff, and volcanic breccia type. The tuff was lithic and crystal tuff, which is from pyroclastic flow (IQBAL et al., 2020).

According to direct observations in the field and geotechnical laboratory analysis, the soils of the study area had characteristics of high plasticity, reddish-brown colour, and were clayey silt grained (MH) (USCS). The soil had loose physical characteristics; however, this soil tends to be plastic and sticky in wet conditions. Evidence of groove erosion was found at the soil surface. The FSR value indicated that the soils of the study area were kaolinitic (see Table 1 and Table 2). There were variations in the values of soil activity (see Table 1). According to SKEMPTON (1953), soils with an activity value of <0.75 and with an activity value between 0.75–1.25 consists predominantly of kaolinite. Also, soil with an activity value > 1.25 consists predominantly of montmorillonite.

To strengthen the results from the geotechnical laboratory, XRD analysis was carried out to

determine the types of clay minerals and their abundance. Based on XRD analysis, all soil samples contained kaolinite, halloysite, and montmorillonite clay minerals. These types of clay minerals can be explained as follows: kaolinite and halloysite are secondary minerals commonly found in Andisols and are produced from the weathering of volcanic material in the tropics (JOUSSEIN ET AL., 2005; WILSON ET AL., 2017). Halloysite is a clay mineral in the kaolinite group (JOUSSEIN ET AL., 2005). Halloysite and kaolinite originate from the weathering of feldspars (WILSON, 2006). Montmorillonite is a subclass mineral in the smectite group, produced from the weathering of mica, and can be formed in tropical climates (BUOL ET AL., 2011; VELDE & BARRÉ, 2009; WILSON, 2006). This mineral is formed in conditions of poor drainage (CHURCHMAN & LOWE, 2012; UDDIN, 2018). Montmorillonite in volcanic soils usually forms from the weathering of volcanic ash and volcanic glasses, most often in the presence of water (VELDE & BARRÉ, 2009, ARANCIBIA-MIRANDA ET AL., 2016). Some researchers have stated that the presence of kaolinite, halloysite, and montmorillonite simultaneously indicates that the area is in a hydrothermal alteration environment (VELDE & BARRÉ, 2009, WYERING ET AL., 2014).

The swelling potential was determined by the physical properties plotted on a potential swelling diagram. The clay content and activity of soil were used by [WOODWARD & LUNDGREN \(1962\)](#) to identify the swelling potential. [VAN DER MERWE \(1964\)](#) used the index of plasticity and the clay content for his diagram. In addition, [PINCUS ET AL. \(1993\)](#) used the liquid limit and index of plasticity for their swelling diagram. On the other hand, [CHEN \(1975\)](#) and [HOLTZ & GIBBS \(1956\)](#) used the liquid limit, shrinkage limit, index of plasticity, and fines content (silt and clay) to determine the swelling characteristics. Based on the above results, the soil samples from locations X20, S4, S7, S5, S9, S2, and S3 had a medium swelling potential. The soil samples from locations Ds11, X24, X33, X19, S10, S1, Ds14, and Y01 had a high to very high swelling potential.

The results obtained in this study illustrate that volcanic residual soils in the tropics have a swelling potential, even though [FAEZEHOSSADAT & JEFF \(2016\)](#) stated that soils with a high swelling potential are most probable in arid/semi-arid regions, and less likely in the tropics. Hence the potential for swelling in tropical volcanic residual soils should be cause for concern.

The variety of values of engineering characteristic possessed by the soils in the study area indicate natural heterogeneity. Geological processes of soil formation play an important role in heterogeneity, such as hydrothermal alteration and weathering processes. The hydrothermal alteration process will change the characteristics of surrounding rocks and then soil ([MAEDA ET AL., 2012](#); [WILSON, 2004](#)). A volcanic hydrothermal system forms during the process. The process of changing physical and mechanical conditions of surrounding rocks occurs when the hydrothermal fluid that passes through the host rock changes its composition by adding, removing, or redistributing the host rock components at certain temperatures, pressures, and chemical conditions ([WIJAYA ET AL., 2017](#)). This process is known as direct crystallization from solution ([CHESWORTH, 2008](#)) and generally, this process will produce montmorillonite and kaolinite. [PUTRA ET AL., \(2019\)](#) and [ZHANG ET AL. \(2018\)](#) stated that close to the alteration environment, the physical and mechanical conditions of the surrounding rock/soil would change and have a high potential to swell.

In connection with weathering, this can be explained as follows. A rock with a certain composition will produce a residual soil that has a specific clay mineral composition. The same thing was expressed by [DURN \(2003\)](#) and [WILSON \(2006\)](#). As it is known from [CHESWORTH \(2008\)](#),

that the source rock of the study area consists of volcanic glass and iron oxide, these materials will turn into halloysite and montmorillonite through the replacement process (a process in weathering).

Related to the environmental issue, especially soil degradation. The soils of the study area are similar to the cambisol, andosol, and oxisol soil types. These soil types have an acid pH, low to middle cation exchange, middle to very low base saturation, moderate to well-drained conditions, rapid infiltration due to the presence of large cracks, have a dispersive property, and high salt levels. These characteristics imply that these soils from the study area have a high risk of erosion, and so they could cause soil degradation and change the water quality ([ISSAKA & ASHRAF, 2017](#); [PHUONG ET AL., 2017](#)).

According to [STELL ET AL. \(2019\)](#), soils with a swelling potential such as those soils in the study area, will have important environmental implications. These soils will have direct implications for the hydrological conditions and the ability of plants to grow. They will affect land productivity and aquifer replenishment. On the other hand, these soils will cause negative environmental and economic impacts, such as landslides, trees to tilt, cracks and damage to highway surfaces, infrastructure, and pavements ([ADEM & VANAPALLI, 2014](#); [FAUZI ET AL., 2017](#); [EMARAH & SELEEM, 2018](#); [SHE ET AL., 2019](#); [YANG ET AL., 2019](#)). Because of these reasons, soil improvement techniques are needed in the study area so that negative environmental impacts do not occur. Maintaining vegetative cover and revegetating bare areas in this kind of soil may be required.

6. Conclusions

1. The soils of the study area are Quaternary tropical volcanic residual soils formed in a proximal volcanic propylitic-argillic hydrothermal alteration environment.

2. These soils are formed from weathered sandy tuff, crystal glass tuff, and volcanic breccias.

3. The soils of the study area have characteristics of high plasticity, a reddish-brown color, and are clayey silt grained (MH) (USCS). These soils have loose physical characteristics; however, they will tend to be plastic and sticky in wet conditions. At the surface of the soil can be found evidence of groove erosion.

4. These soils have medium to very high swelling potential because of their clay mineralogy (kaolinite, halloysite, and montmorillonite).

5. These soils can cause negative environmental and economic impacts, so it is necessary to maintain vegetative cover and to revegetate bare areas.

Suggestions for further study

Other approaches/methods are needed to uncover the heterogeneity of Quaternary tropical volcanic residual soils, so that their character and behavior can be better understood in cases concerning land use and regional development.

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