Role of SWCC in Seasonal Stability of Expansive Residual Soil Slopes: Numerical Modelling and Empirical Assessment

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ABSTRACT

Indonesia experiences not only extreme fluctuation in temperature and rainfall intensity, like in Langsa District, Indonesia, but also temperature and rainfall changes due to climate change, which can be a trigger for slope stability. Infiltration of water during the precipitation process on unsaturated expansive residual soil types can create a significantly unstable situation in the slope zone, caused by an increase in pore water pressure in the short term. The study aims to determine the magnitude of deformation and the safety factor (SF) using the Bishop and Morgenstern methods for slope stability conditions. The analysis considered pore water pressure (PWP) at the soil water characteristic curve (SWCC) during dry and rainy seasons. One of the important things to evaluate slope stability and/or all deformations is the laboratory grain-size distribution of the existing soil mass. Climate variations may cause significant swelling and shrinkage due to changes in water content and grain size, which can trigger initial movements at the toe of the slope. A susceptible soil layer was identified between depths of 0.0 and 6.0 m. The critical SF during wetting, representing rainfall infiltration, was found to be SF = 1.543, whereas during drying or evaporation in the dry season, it increased slightly to SF = 1.566. It was discovered that the SWCC shape changed significantly at fine-grain content above ± 20–30%, characterized by an increase in AEV and residual water content, leading to a nonlinear decrease in unsaturated permeability. Different SWCCs across layers are caused by variations in particle size with depth.

1. INTRODUCTION

Unsaturated soil is a type of soil where the pores contain air, thus its pressure is influenced by two key factors: suction (matrix suction) and saturation level (S_r). The quantity of air within the pores notably influences the hydraulic and mechanical characteristics. Consequently, the effective stress state in unsaturated soils is influenced not only by the net stress ($\sigma - u_v$), but also by factors such as suction and degree of saturation, which are closely associated with the soil water characteristic curve (SWCC) hysteresis. Rainwater infiltration primarily causes residual soil slope instability by reducing strength due to suction loss. Residual soil contains macropores that facilitate quick infiltration, whereas micropores retain significant suction in dry conditions. Residual soils frequently exhibit sensitivity to extended periods of rainfall, leading to significant alterations in shear strength. Particle size influences pore size [1, 2], thereby impacting the correlation between suction and water content. SWCC shows a rapid decline in the small suction range (< 10 kPa) within coarse-grain layers, whereas fine-grain layers can retain more water before reaching saturation [3]. Consequently, particle size influences not just pore size distribution but also hydraulic conductivity (k). Generally, particle size influences SWCC and permeability, which subsequently dictate the mechanical behavior of unsaturated soils during rainfall infiltration, particularly in highly sensitive residual soils, notably at the slope of a site comprised of a mixture of clay, sand, and rock materials [3].

Most of the Langsa District area is dominated by monsoonal rainfall patterns. This rainfall pattern has a unimodal monthly rainfall distribution with one peak rainy season in October - March and a dry season in April – September. Geotechnically, in the Langsa area, the weathering of tuffaceous rocks and breccia produces residual soil types, including silty clay, clayey silt, sandy silt, and silty sand. In tropical regions, residual soil types are generally found in unsaturated conditions with relatively low groundwater levels [4]. In Indonesia, slope failures dominated by residual soil types typically occur during the rainy season due to increased pore water pressure. The total potential landslide hazard area in Langsa City is 1,994.68 hectares, and the potential multi-

hazard area reaches 22,423.50 hectares, classified as low hazard. Langsa Baro Sub-district has the highest landslide hazard area, at 1,800.65 hectares. Meanwhile, Langsa Sub-district is prone to landslides, with a potential affected area of 194.03 hectares. A multi-hazard susceptibility assessment was conducted to determine the potential exposure of the population and the potential losses in the Langsa area. The assessment was categorized by exposure and loss classes, as well as environmental damage classes. However, although these areas are categorized as a low-hazard classification, Langsa City can be classified as a high-hazard class. Langsa Baro, East Langsa, and West Langsa can be classified as a moderate-hazard class for multi-hazards, so that the slope sliding area needs to be investigated and avoided for the safety purposes of the Langsa Depo Development project area.

The Langsa area has a high potential for multi-hazard incidents, including landslides and flooding, particularly in unsaturated residual soil layers. This makes it susceptible to slope sliding and other related issues (flood). Soil hydraulic properties are used as a reference point for comprehending the behavior of underground water flow in unsaturated conditions within the field of geotechnical engineering practice. Generally, soil hydraulic properties are highly dependent on the soil permeability function and the SWCC. The soil permeability function reflects the grain size distribution (GSD) characteristics of the soil, whereas the SWCC illustrates the relationship between water content and soil suction [5].

Unstable slopes have the potential to trigger landslides, leading to loss of life as well as damage to critical infrastructure, including buildings, roads, bridges, irrigation networks, and other essential facilities [6]. Landslide analyses indicate that the overtopping process can be categorized into three stages, such as surface erosion, backward erosion, and water–material rebalancing based on the evolution of the longitudinal section [7]. The slope tends to be gentler when the material contains a low proportion of fine particles. As the median grain size increases, collapse progression accelerates; however, the presence of coarse particles within the slope material can inhibit the rate of damage development [8]. The collapse width expands as debris from the breach sides accumulates at the toe of the slope channel. Consequently, the slope morphology evolves in response to variations in the erosion rate [9]. The erosion rate exhibits a more rapid increase in the vertical direction than in the lateral direction as the fine particle content rises. This research builds on prior qualitative and quantitative studies that identified limitations in understanding the correlation between landslide behavior and grain size composition [10].

The parameters commonly investigated in landslide studies include slope gradient, residual slope height, and related geomorphological factors. Several researchers have suggested that the slope gradient tends to increase with a decrease in median grain diameter and an increase in fine particle content, whereas the duration of the landslide extends with a larger median diameter and a lower proportion of fines [11]. However, a residual slope height is typically observed in landslides containing large boulders or unjointed rock masses near the base. By connecting the quantity of deformation and the factor of safety (SF) to soil mechanics parameters influenced by particle size, the impact of particle size can be quantified. These metrics are cohesion (c), weight volume (γ_{unsat}, γ_{sat}), elasticity modulus (E), and internal friction angle (ϕ). To quantify the impact of particle size on soil mechanics parameters during simulations, these parameters are incorporated into the deformation and safety factor (SF) calculation formula.

Tropical waters play a crucial role in maintaining temperature stability in the Indonesian Archipelago, with an average temperature of approximately 28°C for coastal areas, 26°C for lowland areas, and 23°C for highland areas. Indirectly, soil suction plays a significant role in reducing excess pore water pressure in the unsaturated zone (vadose zone). Caused by effects of soil suction and evaporation, the zone maintains a stable water content, resulting in a negative pore water pressure distribution curve [12]. During the rainy season, water infiltration occurs in the unsaturated zone, resulting in the formation of a perched water table within the impermeable soil layer. This can cause changes in the behavior of underground water flow over time, resulting in a positive increase in excess pore water pressure [13]. Suppose the effective soil stress decreases significantly and the pore water pressure increases beyond the total stress in the soil. In that case, soil particles will be carried away by the underground water flow, which can result in slope failure [14]. External conditions, such as climate change and land use, as well as problems with urban drainage systems, are contributing factors to changes in the behavior of underground water flow. In tropical areas, residual soil types are often found in unsaturated conditions with relatively low groundwater levels [15]. One of the primary characteristics of residual soil types is their heterogeneity, characterized by relatively diverse and variable grain-size distributions [16].

The phenomenon of slope failure dominated by residual soil types occurs in the rainy season due to the influence of increased pore water pressure [17]. In geotechnical terms, the principles and theories of unsaturated soil mechanics are essential for accurately describing the engineering behavior of soil in the field, which is primarily influenced by soil suction and the water-soil characteristic curve [18]. This study aims to determine the magnitude of deformation and the SF using the Bishop and Morgenstern methods for slope stability conditions. If the characteristics of residual soil and unsaturated conditions, particularly suction and air sensitivity, are well understood, the drainage system is carefully considered, and the foundation and slope design complies with unsaturated soil geotechnical principles. Supervision guarantees that the soil structure is not harmed during field construction, and some significant aspects of residual soil and unsaturated conditions can be used as land infrastructure. These procedures can turn leftover dirt into a sturdy, secure infrastructure location. Specifically, the aim of this study is to quantify the effect of particle size distribution on the residual soil SWCC and permeability function through laboratory characterization and numerical simulation. It also seeks to clarify how differences in hydraulic properties govern slope deformation mechanisms and SF changes during rainfall infiltration.

2. MATERIALS AND METHODS

The quantitative macro laboratory test data are expressed as a measure of the landslide vulnerability level, allowing for the calculation of the SF value. In this study, field samples were collected, specifically from disturbed soil. Generally, various activities were conducted in the laboratory to measure matrix suction. Data collection was conducted in a laboratory in accordance with ASTM and SNI standards related to

expansive clay soil [19]. The collected data comprised both primary and secondary sources. The following factors were considered in data collection: data type, location of data acquisition, and the amount of data required, among others [20].

Related to the case study of landslides in the East Aceh region, based on the selected location coordinates, primary data is required. The objective of collecting adequate primary data is to evaluate the methods needed to address the landslides. Primary data is used to obtain the physical and mechanical properties of the soil, including matric suction. Soil data required for landslide analysis include macro-level tests, such as: bulk density (γ), soil moisture content (w); void ratio (e); porosity (n); grain density (G_s); unconfined compressive strength (q_u); triaxial parameters ($c; \phi$); matric suction (s), osmotic suction (π), and total suction (ψ) using the filter paper method. Moisture equilibrium can be measured using the filter paper method within the range of 10 to 10^6 kPa.

The calibration connecting the suction and filter paper water content affects the matric suctions (u_a-u_w) and total suction (matric plus osmotic suctions) derived from filter paper measurements. Since the soil sample is considered to be salt-free, the total suction is considered to be close to the matric suction. As a result, three calibration curves are suggested in the literature and ASTM D 5298. The time it takes for the filter paper and soil to reach a moisture balance, ensuring the accuracy of the calculated suction value, is known as equilibration time. The duration for measuring soil suction using the Whatman No. 42 filter paper method is approximately ± 7 days (about 168 hours). During this period, equilibrium is attained through water vapor at the site of matric suction measurement, where the filter paper comes into direct contact with the soil; it is achieved through water contact. The equilibrium time is influenced by factors such as the type of soil (ranging from silty clay to clay), its weight-volume density (between 14.4 and 16.0 kN/m³), initial water content (between 54.2 to 117.4%), the use of an airtight container, and placement in a laboratory with a constant temperature (approximately 20–25°C).

The adjustment model for the SWCC functions on the same principle as Van Genuchten, Brooks–Corey, and/or Fredlund–Xing. To obtain model parameters, the measurement data for content and suction are subjected to an equation-fitting process. The fitting process begins by selecting the appropriate SWCC approach model according to the soil type: van Genuchten (1980) is suitable for granular to medium clay soils, while the simpler Brooks–Corey (1964) model is suited for sand and silt. Fredlund–Xing (1994) model provides the highest degree of flexibility and is suitable for a wide range of suctions. The approach is based on two models: van Genuchten and Fredlund–Xing. They each have distinct suction ranges: the van Genuchten model is appropriate for suctions below < 1500 kPa, whereas the Fredlund–Xing range extends to 10^6 kPa. It should be noted here that the wider the suction range, the more stable the parameters obtained.

The fitting procedure employs the GeoStudio (SEEP/W) software. To summarize, the function of the x-axis is to act as a suction log for charting the outcomes of the saturated zone, air entry value (AEV), and residual zone. Next, the process advances with a nonlinear regression (least squares) approach for initial parameter estimation to numerically determine the parameters saturated water content (θ_s) obtained by porosity data, boundary water (θ_r) determined by high suction data, AEV is the first slope change, and initial value of shape parameter from van Genuchten in determining slope SWCC at transitition zone (n). For clay soil, the n value should be small, and its pore distribution should be wide and non-uniform. The next step is to evaluate the fit's quality by looking at the statistical parameter, including the coefficient of determination (R^2), root mean square error (RMSE), and whether the parameters are physically consistent. This approach is flexible and low-cost, but it needs a calibration curve for the finite element method (Seep/W) during the fitting process. To verify the mathematical method, suction range testing was conducted between 100 and 1500 kPa. Since variations in suction have the biggest impact on shear strength for unsaturated soil zones in this range, slope stability studies often concentrate on 0–300 kPa at the existing study area.
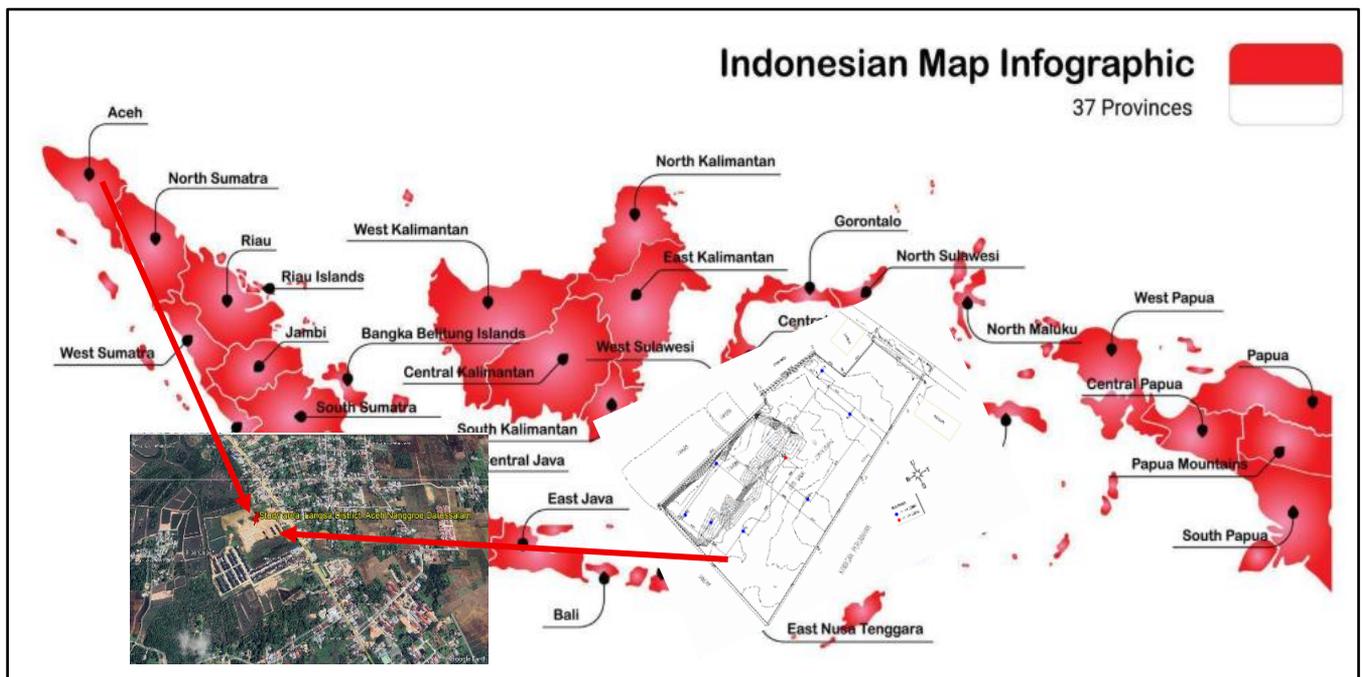

Figure 1. Study area: Langsa District

2.1 Site characteristics

The study area reviewed in this research is located in Langsa District, Aceh Nanggroe Darussalam Province, Indonesia, with coordinates of 4°31'40.67" N and 97°54'27.92" E, as shown in Figure 1. Soft unsaturated soil layer in Langsa has low landslide potential under dry conditions, but it can increase significantly when saturated with water. The primary triggering factors are rising groundwater levels, inadequate drainage, and increased loads on the soft soil [21, 22].

2.2 Laboratory sample collection

Table 1. Influence the grain size distribution (GSD) on landslide potential

Grain Size	Unsaturated Suction	Sensitive to Water	Landslide Potential
Coarse grain	low	low	Medium or high, depending on the drainage system
Fine grain	High	High	Low in drying condition, high saturated

Fieldwork was intended to obtain data on subsurface soil types, technical properties, and bearing capacity directly in the field. This fieldwork consisted of 1 (one) deep boring point with a depth of 50.50 m and 7 (seven) sounding points with a capacity of 2.50 tons. This work also included a sampling test and the collection of undisturbed and disturbed samples. Because it affects factors including permeability (k), density (γ), pore structure, cohesion (c), internal friction angle (ϕ), erosion potential, and unsaturation features (suction), GSD is essential in landslide potential analysis. The GSD influences on landslide potential are displayed in Table 1 and Figure 2.

If the stability of unsaturated conditions is managed, it is not hazardous. Changes in water content are crucial. Suction diminishes, and shear strength might drop by 30 to 70% during the rainy season. There is a greater chance of landslides or deformation. Unsaturated soil engineering technique is therefore essential for design. SWCC and permeability tests can both be conducted using a single sample hole. Samples from the same depth can be used for both. However, the uniformity of the soil on the slope determines the validity of the results. A combination of geological characterisation, multi-depth sampling, GSD uniformity, index attributes, field observations, and correlation between points and depths is used to verify sample representativeness. One sample is appropriate and supported by science if the slope is shown to be homogeneous. Several samples are needed if they are heterogeneous [23, 24].
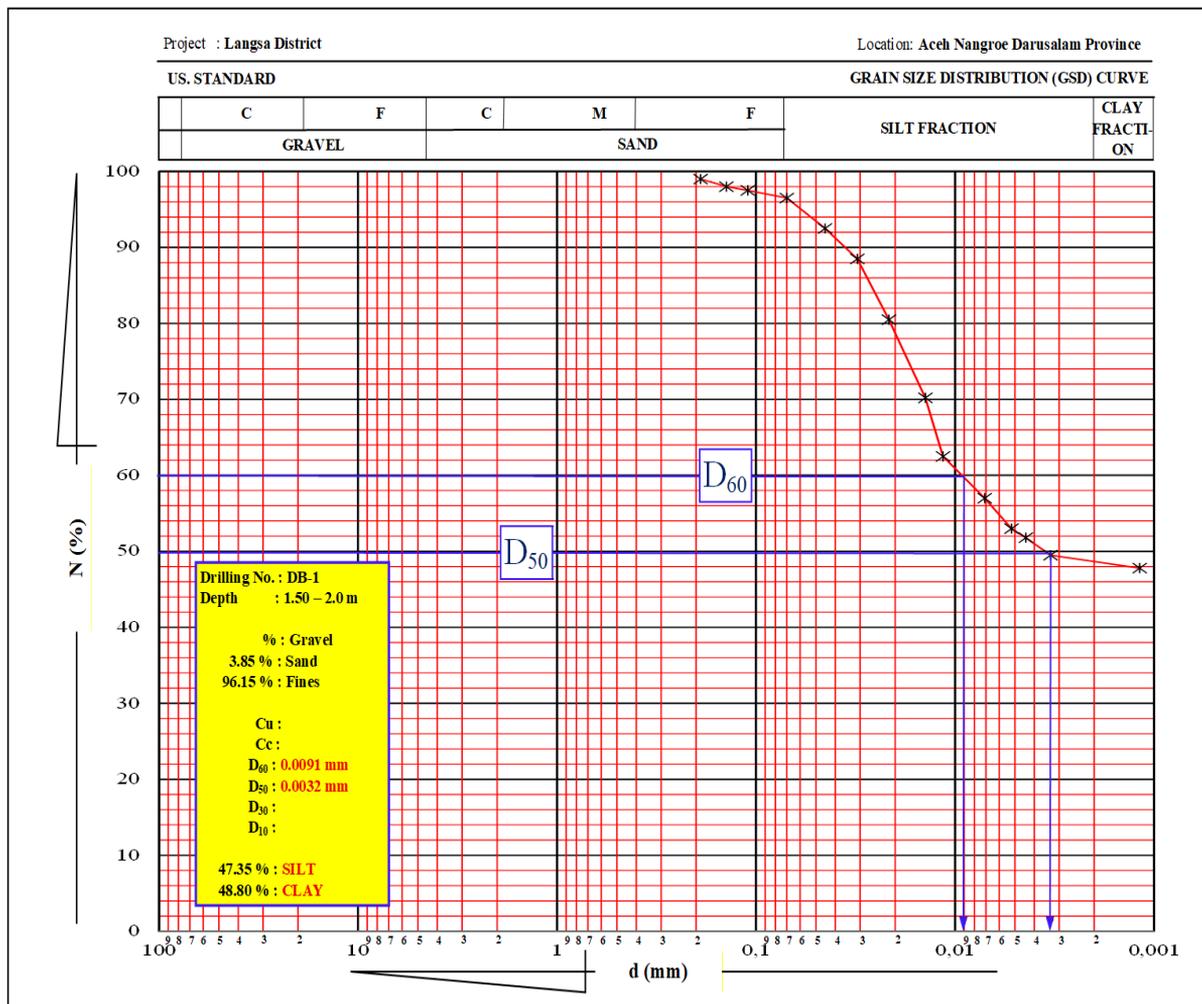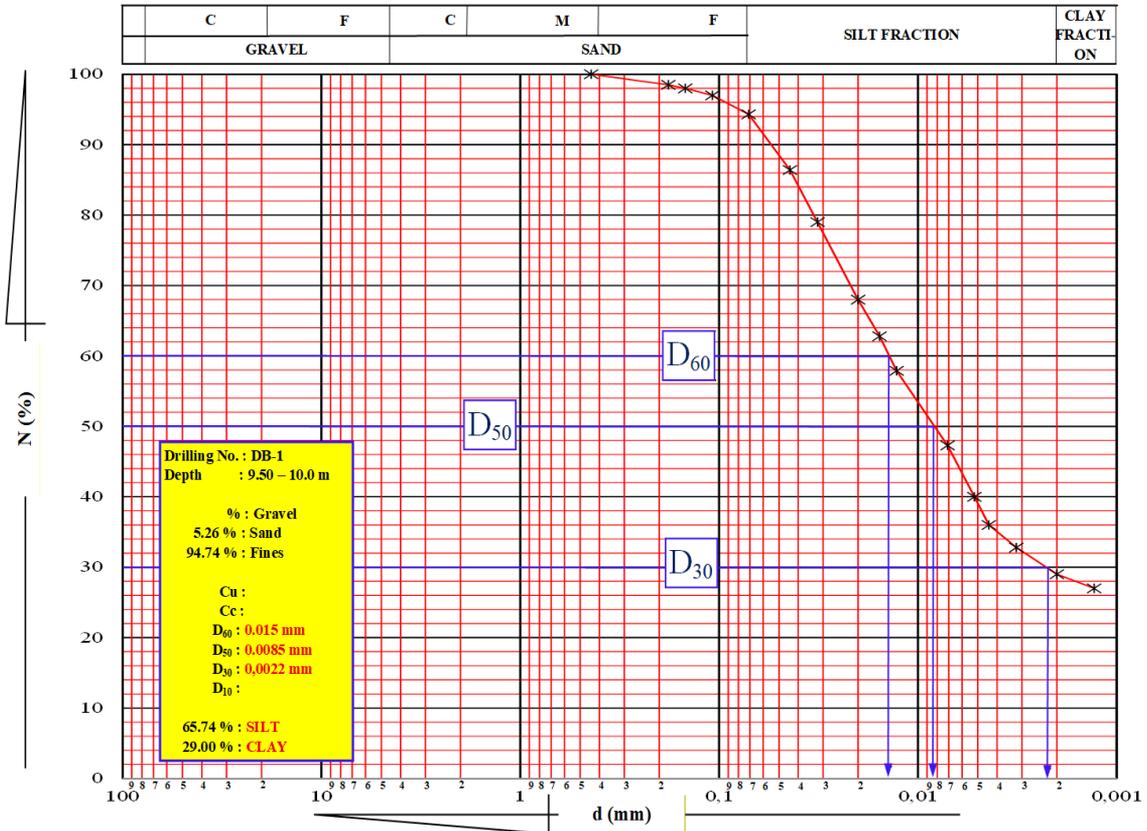
Project : Langsa District
Location: Aceh Nangroe Darusalam Province
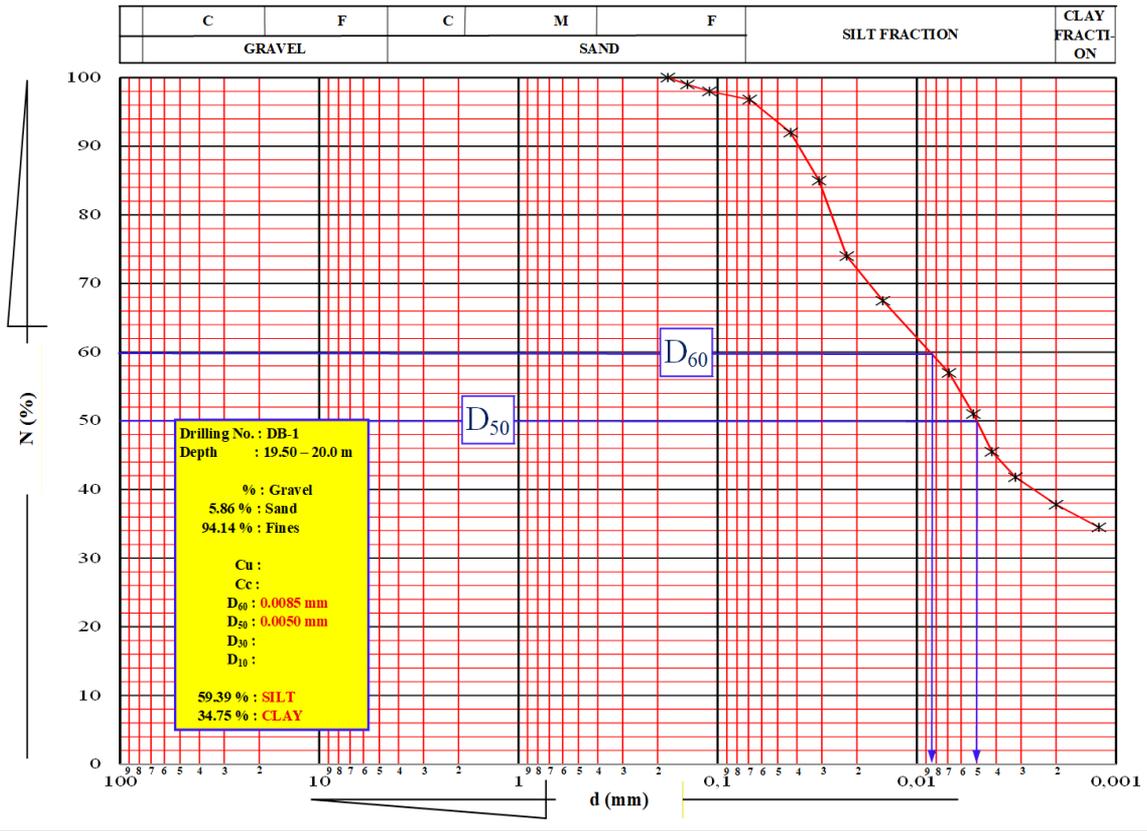
US. STANDARD
GRAIN SIZE DISTRIBUTION (GSD) CURVE

C	F	C	M	F	SILT FRACTION	CLAY FRACTI-ON
GRAVEL			SAND			

Drilling No. : DB-1
Depth   : 9.50 – 10.0 m

    % : Gravel
5.26 % : Sand
94.74 % : Fines

Cu :
Cc :
D_{60} : 0.015 mm
D_{50} : 0.0085 mm
D_{30} : 0,0022 mm
D_{10} :

65.74 % : SILT
29.00 % : CLAY

Project : Langsa District
Location: Aceh Nangroe Darusalam Province

US. STANDARD
GRAIN SIZE DISTRIBUTION (GSD) CURVE

C	F	C	M	F	SILT FRACTION	CLAY FRACTI-ON
GRAVEL			SAND			

Drilling No. : DB-1
Depth   : 19.50 – 20.0 m

    % : Gravel
5.86 % : Sand
94.14 % : Fines

Cu :
Cc :
D_{60} : 0.0085 mm
D_{50} : 0.0050 mm
D_{30} :
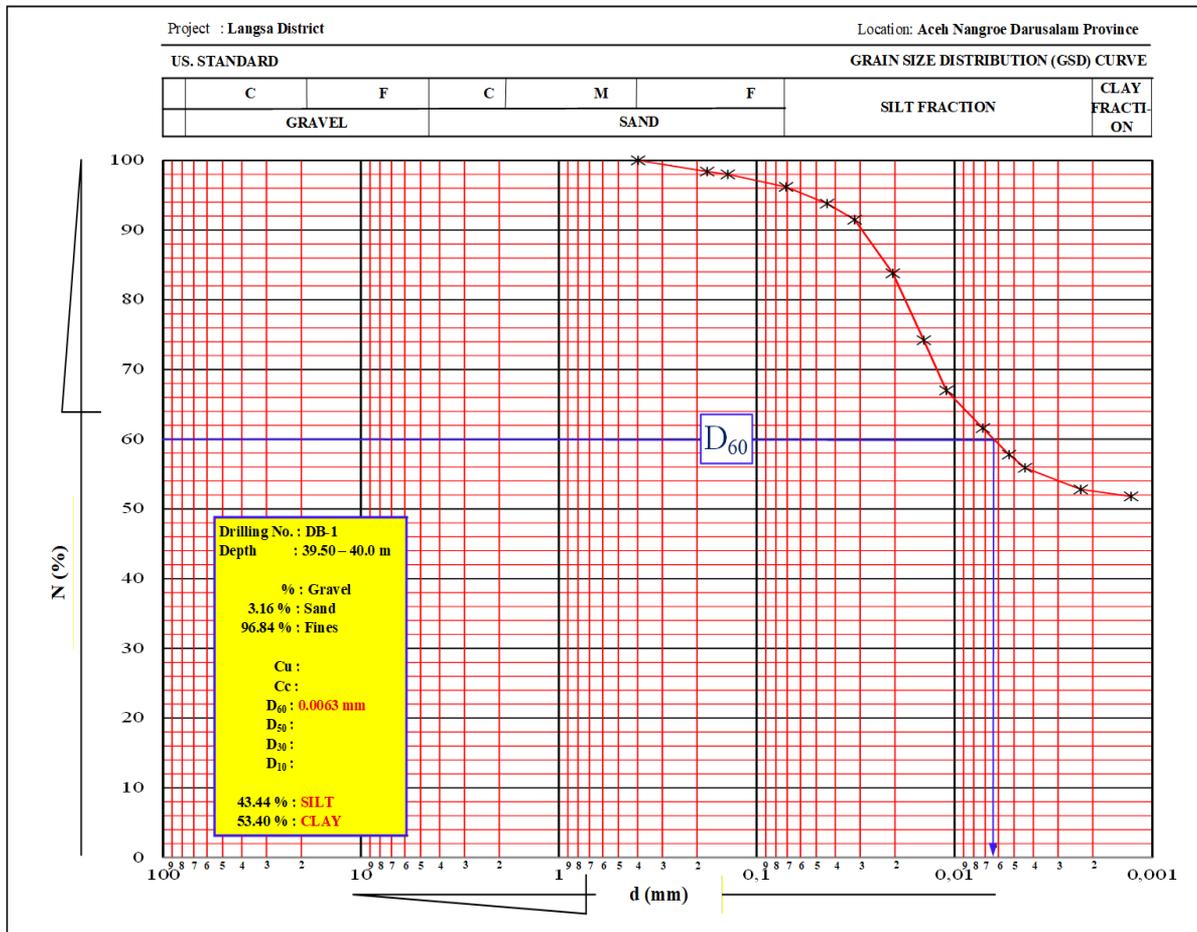D_{10} :

59.39 % : SILT
34.75 % : CLAY

Figure 2. Typical of laboratory GSD

2.3 The effect of grain size distribution on water content (*w*) and soil water characteristic curve

The effect of GSD on water content and soil suction (SWCC) on residual soil types, reviewed based on laboratory test data (physical and mechanical properties), as well as soil suction (filter paper method) from the measurement location, can be used to analyse the slope stability [25]. The size of soil particles affects the potential for landslides in unsaturated soil layers, as shown in Table 1. The finer the soil grain size, the greater the potential for increase due to suction, but the more sensitive it is to saturation. Figure 2 shows the grain size from the existing study area. Because these strata contain an unsaturated soil zone, SWCC modeling used the depth from BH-01, which is close to the ground surface (up to -5.00 m). The permeability function and SWCC were predicted using these samples. Saturated soil samples have been representative. The slope following certain field observations, such as the slope zone, landslide mechanism, hydrological fluctuations, and the depth of the slip plane at the slope's crest, toe, and body, makes saturated soil sampling representative.

Figure 2 illustrates that the statistical parameters of GSD play a key role in characterising the influence of depositional processes within the Langsa study area. Generally, standard deviation and skewness are regarded as environmentally sensitive indicators, whereas the mean value represents the transport competence of the dynamic system associated with the Krueng River.

3. RESULTS AND DISCUSSION

3.1 Grain size analysis to soil water characteristic curve prediction

The results of the granulometric analysis of the study area samples are presented in Table 2. In the study area, the most prominent layer consists of a clay and silt layer. Clay with grain size (< 0.002 mm) has fine pores, a large surface area, and can hold water and has high matric suction, so that it is more stable under unsaturated conditions, but can soften drastically when fully saturated [26]. In other parts, silt has a medium grain size, ranging from 0.002 to 0.06 mm, medium porosity, and medium stability; it is moderately susceptible to changes in water content. However, both of these soil layers are required for evaluation.

Predicting SWCC graphically at coarse-grained soil (sand) will result in big pores and easy water escape, leading to a steep SWCC. On the other hand, small pores and strongly trapped air are produced by fine-grained soil (clay), which results in the mild SWCC. The finer the grain size, the higher the AEV, because greater suction is required to expel air from small pores. It may be inferred that the SWCC exhibits a longer desaturation range, that the transitions are gradual rather than abrupt, and that the AEV point is difficult to clearly identify only from Figure 2 and Table 2. These observations suggest that the current soil sample tends toward well-graded conditions.

Table 2. Summary of soil characteristics at the prediction of vadose zone (-6.0 m depth from ground surface)

Physical Properties	Value Range
Liquid limit % (LL)	13.50 – 62.5
Plastic limit % (PL)	32.40 – 50.95
Plasticity index % (PI)	29.80 – 87.55
Water content (w_c)	54.19 – 117.40
Soil classification (USCS & AASHTO)	CH – MH
Specific gravity (G_s)	2.386 – 2.601
Wet unit weight (t/m^3)	1.440 – 1.601
Dry unit weight (t/m^3)	0.662 – 1.038
Mechanical Properties	**Value Range**
Unconfined cohesion (c) (kg/cm^2)	0.140
UU Triaxial cohesion (c) (kg/cm^2)	0.24
Internal shear angle ($^\circ$)	3.5
Consolidation test	
Coefficient of consolidation (C_v) (cm^2/sec)	2.45×10^{-4} – 4.462×10^{-4}
Compression index (Cc)	0.55 – 1.97

AEV, SWCC, and water retention capacity will all be higher at shallow depths. AEV will be lower, and water will drain more quickly at the deep SWCC than it will at the shallow depth. AEV and boundary water (θ_r) will increase with increasing clay concentration, and the SWCC curve will eventually slow down. Strong water adsorption and a high specific surface area are linked to an increasing clay concentration. Unsaturated permeability can be obtained directly from SWCC; in coarse-grained soils, permeability rapidly declines following AEV, whereas in fine-grained soils, the decline is more gradual. Each layer's groundwater flow is influenced by GSD; in the sand layer, flow is fast when saturated but nearly stops when unsaturated. Even with high suction, the flow in the clay layer will be sluggish but still significant. Matrix suction plays an important role in unsaturated soils, where suction provides apparent cohesion, and shear strength increases when the soil is relatively dry.

Grain size and gradation have a considerable effect on fine-grained soils when dry, and they drastically lose strength when saturated (during the rainy season). Coarse-grained soils react to rain more quickly, and stability is more dependent on the drainage system.

3.2 Geological conditions of the unsaturated soil problem

Because much of the soil consists of young alluvium (river and estuary sediments), grain size tends to vary considerably; it can consist of clay and silt [27]. Due to the prevalence of clastic and alluvial sediments, the soil structure tends to be relatively young in age, with high porosity depending on the texture. Groundwater and drainage conditions in coastal or estuarine areas will influence groundwater saturation levels. Due to the dominance of alluvial deposits in the lowlands, the soil layer is relatively young and has not been significantly consolidated. This can affect soil strength, permeability, and the potential for subsidence and landslides.

The problem of unsaturated soil must be considered as well in evaluating slope stability. The shape of the SWCC is determined by the pore distribution, which is controlled by grain size and gradation. AEV and water retention are directly correlated with clay concentration. Different SWCCs are produced by depth variations, which also impact slope stability and water flow. Therefore, rather than assuming a homogeneous soil, current slope stability assessments should account for layer-specific SWCCs.

3.3 Physical and mechanical properties data

Based on Figure 3, small grain size or fine-grain soil has a high suction, where q_c tends to be high in the unsaturated layer, so that the soil appears strong, but is sensitive to saturation. Finally, landslides can occur quickly after rainfall. Cone Penetration Test (CPT) data (q_c, f_s, F_R) can be used to map weak zones that are prone to landslides, especially when integrated with water content and SWCC data.
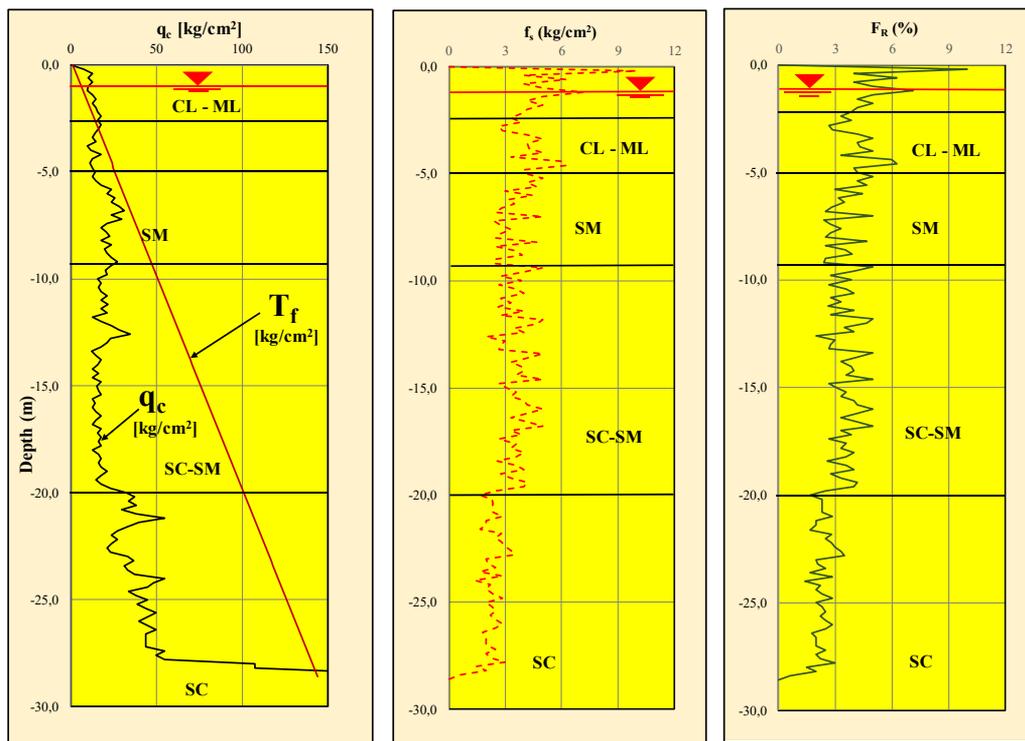

Figure 3. Typical of a Cone Penetration Test (CPT) test result

Figure 4 presents the results of field investigations conducted at the study site, including Standard Penetration Test (SPT), boreholes (BH), and boring logs used for sampling. These tests were performed to establish correlations between SPT data and the bulk density of various soil layer types. SPT is essential for empirical validation and classification. Good numerical calibration should maintain consistency across both field data sets, not just the agreement of the numerical results.

Depth	Soil type	$\overline{N}$	N'	γ_m (t/m³)	γ_{sat} (t/m³)	γ_{sat} (kN/m³)
0 / 1				0,66		6,62
2 / 2,8	Organic Silty Clay	3,40	1,28		1,440	14,40
3 / 4 / 5	Silty Clay (SC)	6,27	2,66		1,554	15,54
6 / 7 / 8 / 8,9	Silty Sand (SM)	9,18	4,36		1,69	16,93
9 / 10 / 11 / 12 / 13 / 14 / 15 / 16 / 17 / 18	Sandy Clayey Silt	6,44	3,22		1,600	16,00
19 / 20					1,598	15,980
21 / 22 / 23 / 24 / 25 / 26 / 27	Silty Clay (SC)	17,13	8,56		2,04	20,41
28 / 29 / 30 / 31 / 32 / 33 / 34 / 34,7	Silty Sand (SM)	42,55	21,28		3,08	30,84
35 / 36 / 37 / 38 / 39 / 40 / 41 / 42 / 43 / 44 / 45 / 46 / 47	Silty Clay (SC)	20,48	10,24		2,176	21,763
48 / 48,5	Silty Sand (SM)	32,08	16,04		2,65	26,53
49 / 50 / 50,5	Silty Clay (SC)	31,25	15,63		2,62	26,19

Figure 4. N-SPT and weight volume (correlation)

Additionally, the mechanical and physical characteristics are displayed in Table 2. It is clear from Table 2 that physical characteristics (porosity, permeability, water content, unit weight) are determined by grain size. Physical characteristics influence mechanical attributes (cohesion, friction angle, suction). The possibility of landslides in unsaturated soil will be greatly influenced by the mix of the two. Due to their high suction, fine soils (clay and silt) typically appear sturdy when dry, but as they become saturated, they become extremely vulnerable to landslides. Sharp suction gradients, air buildup at layer boundaries (perched water), and possible slide surfaces in the transition zone are all brought on by variations in SWCC between layers. SPT and CPT are complementary rather than mutually exclusive. Zoning and model parameters are areas where CPT shines.

3.4 Estimation of soil water characteristic curve

Technically, seepage modelling was performed based on data processing on water content (w_c) and soil permeability function (k_w) using finite element analysis from Geostudio geotechnical software. The purpose of this modelling was to understand the phenomenon of pore water pressure distribution over time, specifically at each depth, especially at the top of the slope, caused by rainwater infiltration. The processed data on water content (w_c) and soil suction (ψ_s) were used to input parameters for seepage analysis, such as saturated water content (θ_s), and to plot the best-fit results in the SWCC curve modelling, particularly for residual soil samples, as shown in Figure 5.

Generally, the results of processing the soil permeability (k_w) and soil suction (ψ_s) function data are used in inputting parameters for seepage analysis, such as the saturated soil permeability coefficient (k_{sat}), as well as the estimation results for the soil permeability function, especially for residual soil samples, as shown in Figure 6 [28].

Generally, Figures 5 and 6 illustrate that the surface soil layer transitions from fine-grained to coarse-grained. This indicates that the extent of matric suction is affected by both the shape and dimensions of soil pores and the chemical composition of the air, given that the soil layer is presumed to be free of salt. Interestingly, the highest water flow occurs at a depth of 39.50 to 40.00 m, although the conductivity value is less than the conductivity at the surface because of the dominance of the coarse-grained layer.

Seepage analysis was conducted in two conditions, including equilibrium conditions (steady-state) with a normal groundwater table depth of -1.00 m for the embankment stabilization area of the Langsa Warehouse Development Project, based on SPT data. Regarding the changing conditions (transient), the analysis was conducted by incorporating the distribution of maximum daily rainfall intensity for the Langsa City area, Aceh Province, Indonesia, which was 106,150 mm/day, or approximately 1.229×10^{-6} m/s. During wetting conditions, seepage analysis was reviewed during the first 2 days, and for drying conditions, it was reviewed again within the next 3 days, as shown in Figure 7. Seepage potential significantly influences landslide potential because it increases pore water pressure (u), which reduces the effective soil stress; it also reduces suction in unsaturated soil, thereby reducing apparent strength, and can cause uplift and internal erosion. The direction of seepage flow determines whether a slope becomes stable [29].

Based on the geotechnical perspective, beyond the findings of previous studies, the application of fundamental principles and specialised techniques, such as advanced apparatus and laboratory testing using unsaturated soil mechanics devices, is essential to accurately determine the best-fit SWCC and to define the corresponding permeability function [30]. In unsaturated soil analysis, the SWCC defines the relationship between water content and matric suction. The SWCC

represents the soil's behavior and its capacity to facilitate infiltration and groundwater storage processes, which are influenced by the GSD characteristics of the soil type. The SWCC model typically comprises three distinct zones that describe the desaturation process in soils: the boundary, transition, and residual conditions [31]. Although few publications explicitly measure parameters, such as the matric suction, water retention, etc.

Several simulations in Figure 8 have been performed during days of heavy rain, during which water seeps into the slope, reducing suction and increasing pore water pressure. During the slope becomes saturated and collapses, where leaking water/irrigation channels occur on the slope. When lateral seepage occurs into the weak zone, local landslides can occur following downward seepage, and water drains out quickly.

The higher the pore water pressure (or lower the suction) in unsaturated soil, the greater the potential for landslides. Prolonged rainfall, seepage, or poor drainage can increase pore water pressure, making it the primary trigger for landslides. Table 3 and Figure 9 indicate that rainfall induced a desaturation process within the unsaturated soil layer over a period of 0 to 5 days, taking place via the interconnecting pores and gaps.
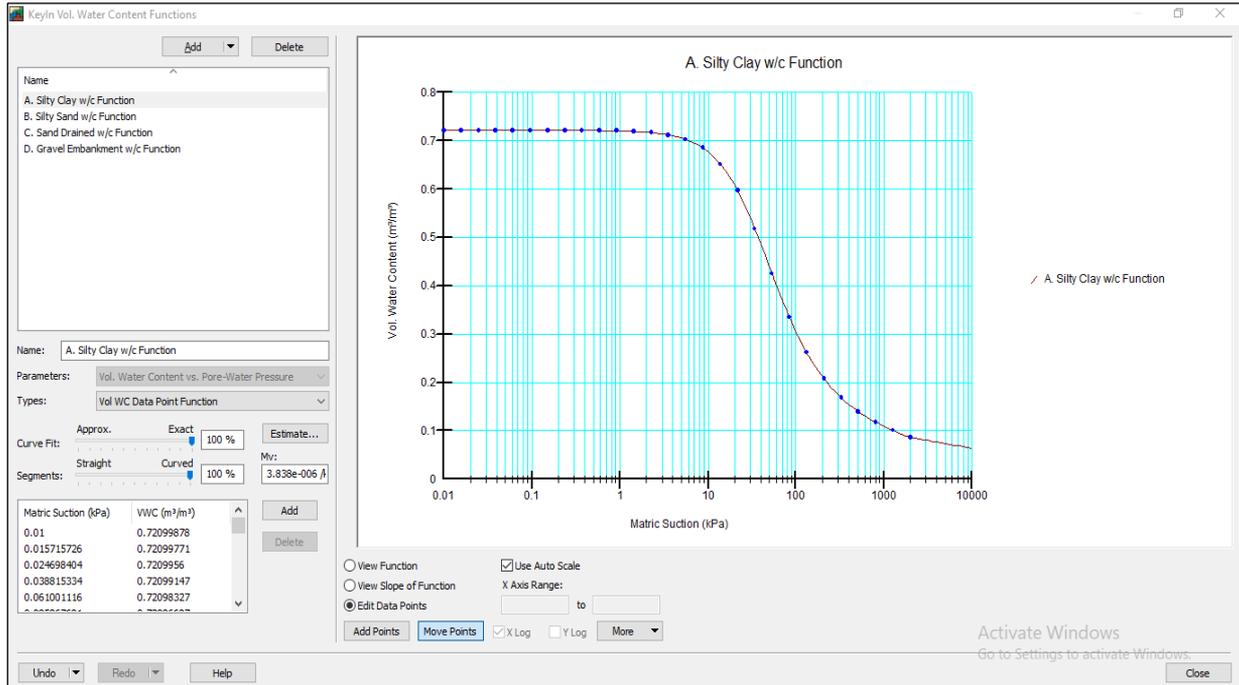
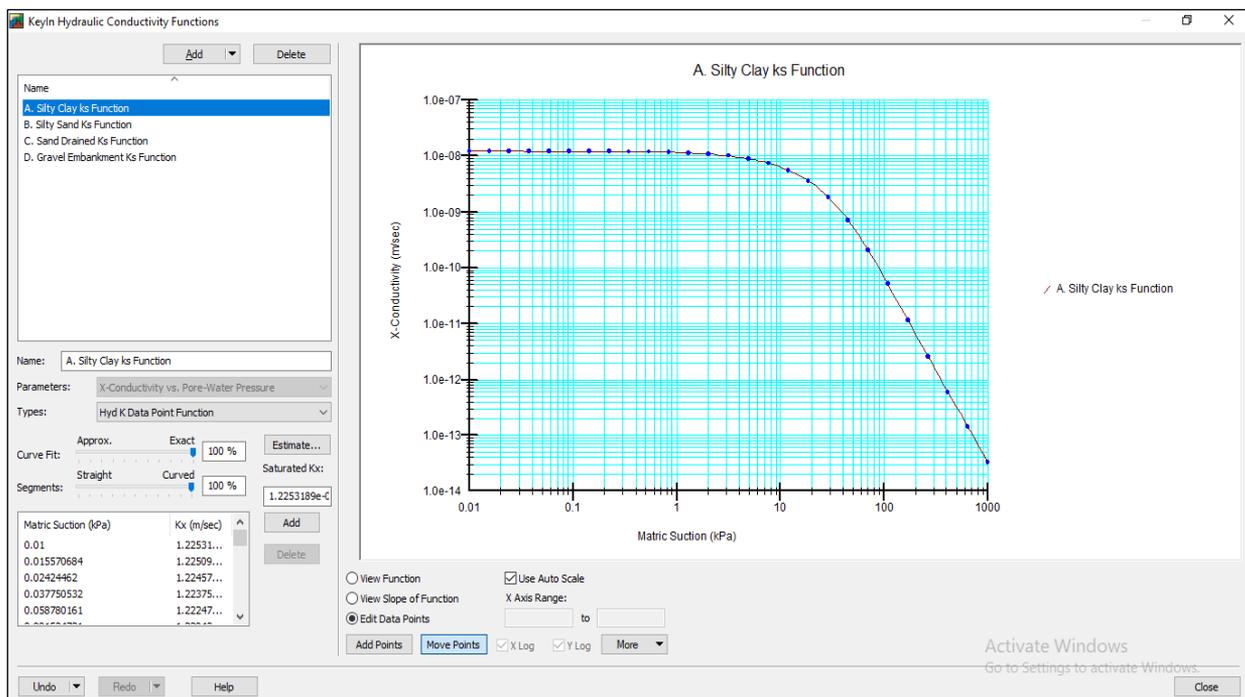**Figure 5.** Seepage analysis based on water content (w_c)

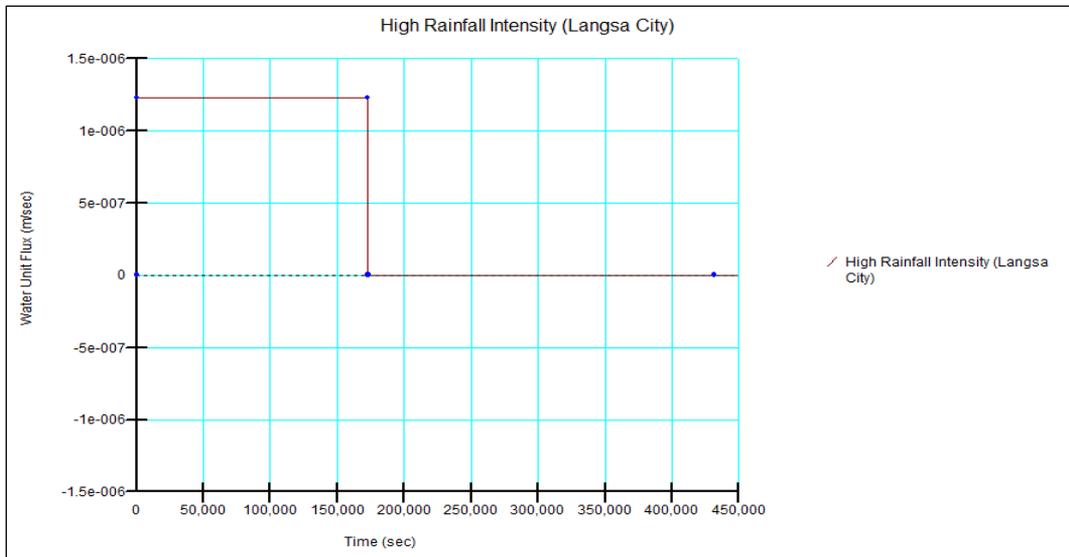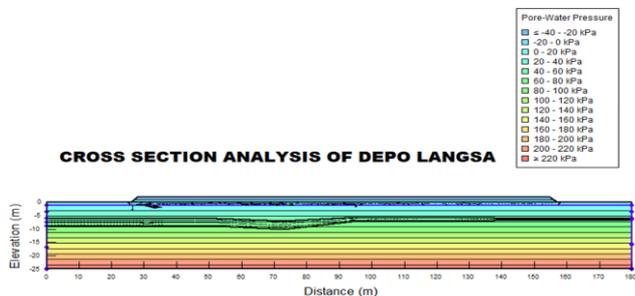**Figure 6.** Seepage analysis parameters using the soil permeability function (k_w)
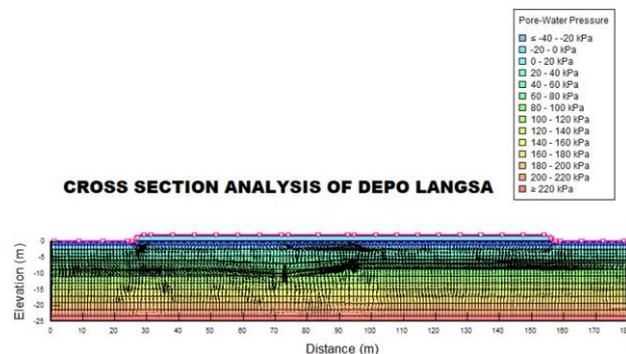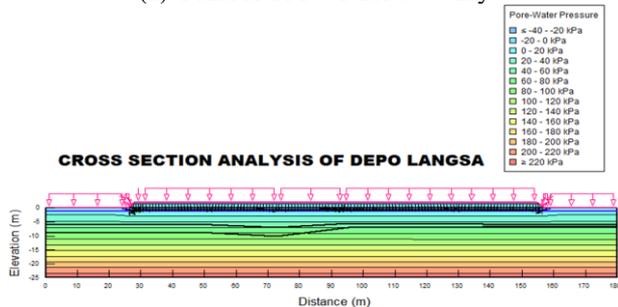
41

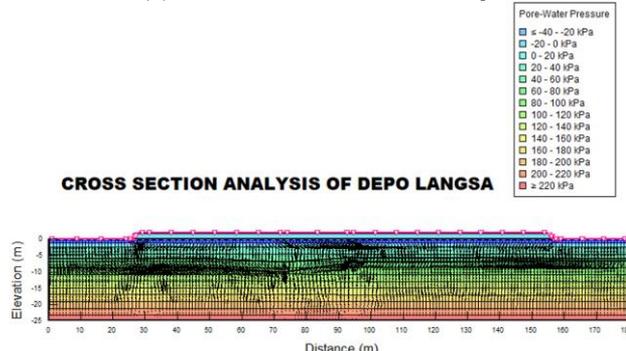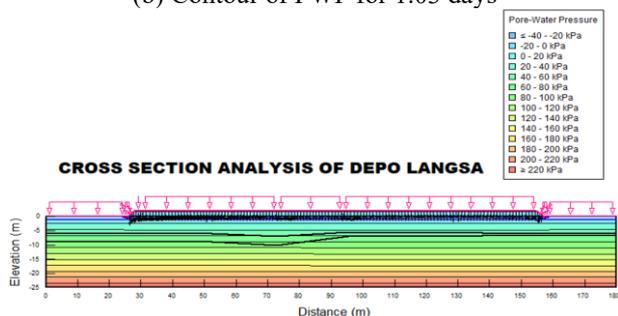**Figure 7.** Data input of the intensity of maximum rainfall

(a) Contour of PWP for 0.00 day

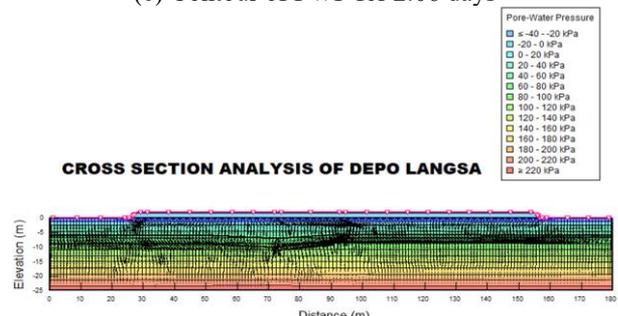(b) Contour of PWP for 1.03 days

(c) Contour of PWP for 2.06 days

(d) Contour of PWP for 3.00 days

(e) Contour of PWP for 4.04 days

(f) Contour of PWP for 5.00 days

Figure 8. Pore water pressure (PWP) contours for t = 0.00 to 5.00 days

Table 3. Magnitude of distribution of pore water pressure (PWP)/day at the depth of soil layer from ± 0.00 m to –6.00 m

Value of PWP	0 Days	1 Days	2 Days	3 Days	4 Days	5 Days
Max. PWP (kPa)	49.040	50.634	52.745	53.502	53.918	54.187
Avg. PWP (kPa)	16.554	19.312	22.068	22.402	22.563	22.665

Notes: The PWP distribution review was conducted for residual soil samples (silty clay) at depths ranging from ± 0.00 m to –6.00 m, with the groundwater table at –1.00 m.

3.5 Slope stability and deformation analysis

Technically, slope stability and deformation modelling

were performed based on SPT test data using Geostudio geotechnical software. The purpose of this modelling was to determine the magnitude of stability and deformation on residual soil slopes due to rainfall infiltration (during rainy seasons) and evaporation (during dry seasons). Based on the modelling results in the slope stability analysis using geotechnical software (Figure 10), it can be seen that the critical SF achieved during rainy conditions was 1.543. During evaporation conditions, the critical SF was 1.566.
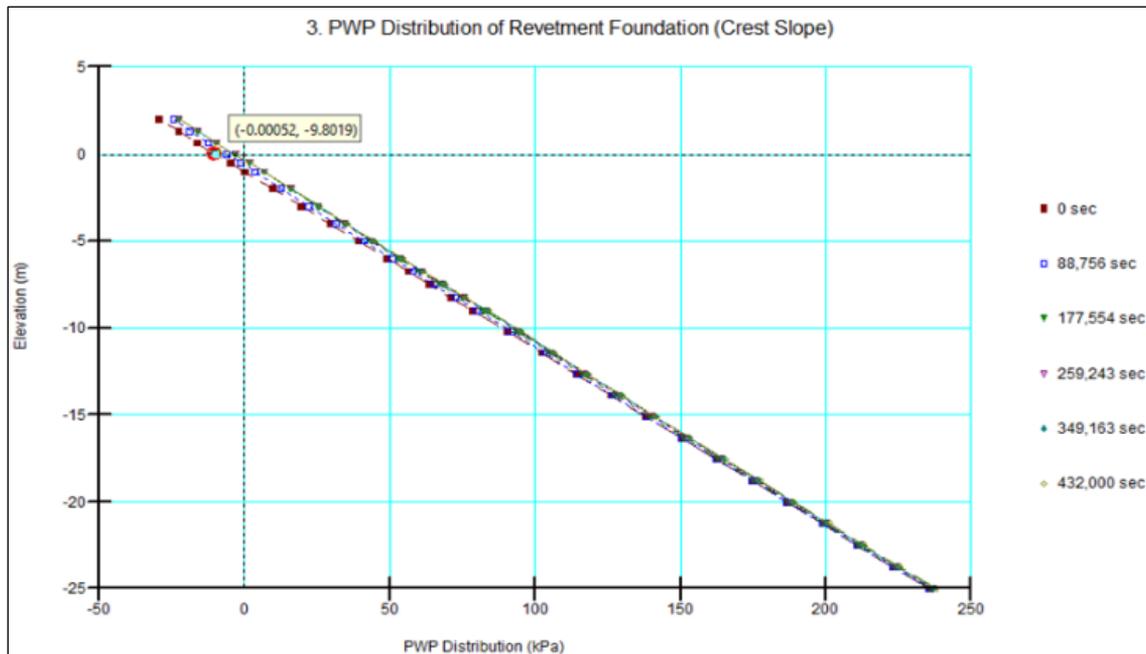

Figure 9. Modelling of pore water pressure distribution (PWP) for t = 0.00 to 5.00 days

(a) Slope stability during the rainy season

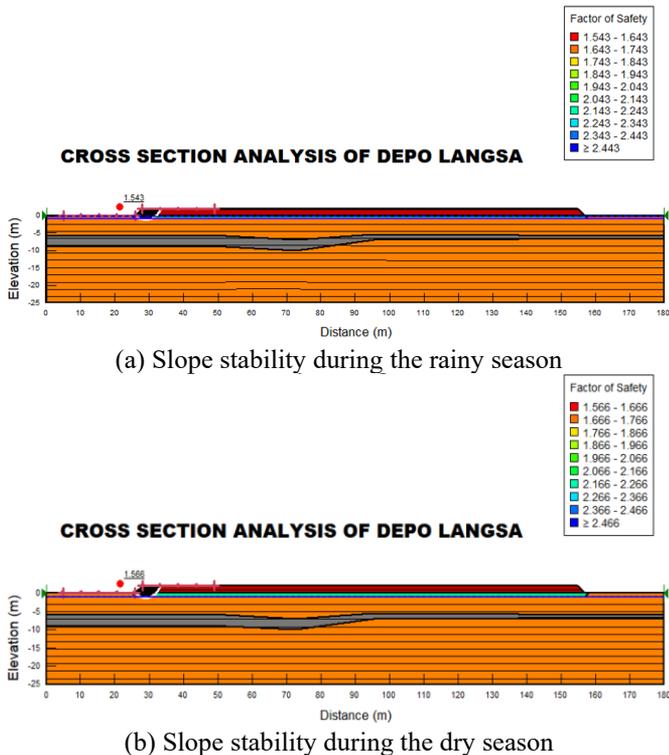(b) Slope stability during the dry season

Figure 10. Slope stability results at rainy & dry seasons

The characteristics of extensive remaining soil were replicated throughout the wet and dry periods through estimated measurement of the SWCC curve and permeability function conducted in the laboratory. Examining seepage in unstable conditions (the process of infiltration) and in steady conditions (the process of evaporation) relies heavily on laboratory analysis. The susceptible soil layer was present from a depth of 0.0 to 6.0 m. The vital SF during the process of wetting, where infiltration occurred during the rainy season, was determined to be SF = 1.543. Furthermore, during the processes of drying or evaporation in the dry season, the calculation resulted in SF = 1.566. According to unsaturated soil mechanics theory, suction increases the shear strength; when it rains, suction diminishes, and the SF sharply declines.

The simulation model utilised in the regional study of deformation and slope stability analysis took into account factors such as rainfall impact, pre-existing environmental states, and physical and/or mechanical attributes. A refined SWCC model, along with the permeability function, was established by examining infiltration analysis grounded in the precipitation potential model derived from the specific area under investigation [32]. By assessing the impact of matric suction down to a depth of -6.00 m, the zone of slope failure attributed to ground effects was assessed [33]. The key takeaway from this research is that rainfall infiltration, driven by the rainfall potential model for rainfall event simulation, was the primary factor initiating the detected landslide event [34].

According to the findings of this research, the cyclic swelling phenomenon resulting from alternating wet and dry conditions causes a slow breakdown of the bonds within the unsaturated expansive soil composition [35]. Simultaneously, the restructuring and realignment of the particles will induce modifications in the shear strength properties (c; ϕ). When the slope area is not treated with any enhancements, the rising number of swelling-shrinkage repetitions and the degradation process will also persist [36].

Typically, the simulation outcomes are in close agreement with the findings from the current site assessment. The chosen investigative approach is suitable for replicating the likelihood

of landslides in partially saturated, weathered soils [37]. This approach made it clear that its application in assessing deformation and slope stability aligns with pinpointing crucial slip surfaces that correlate to the lowest SF, and it's a sensible match with observational studies [38].

Although there may not seem to be much of a difference between the SF of 1.543 and 1.566, these figures clearly have technical relevance in geotechnical engineering. These explanations are both practical and conceptual. According to the physical interpretation, SF = 1.566 means the resisting force is 1.566 times the driving force, or 56.6% higher than the threshold of instability (SF = 1.0). While SF = 1.543 indicates that the retaining capacity is approximately 54.3% greater than the driving force. Groundwater conditions are extremely dynamic in the setting of geotechnical uncertainty, where soil parameters have significant uncertainties, such as c' can fluctuate by ± 20–30 % and ϕ' can vary by ± 2 to 3°. The SF difference of 0.023 is quite modest in relation to these uncertainties.

In the rainy season, the SF is only slightly diminished because the soil stays unsaturated and matric suction has not fully released, thereby continuing to contribute to the shear strength of the soil. Only the shallow layers of unsaturated soil are affected by rainfall of high intensity but short duration, which means that the decrease in matric suction is limited and does not result in a reduction of shear strength on the slip plane. As a result, the SF only changes slightly. Because of the soil's capacity for air retention, the decrease in suction power during the rainy season is significantly reduced. This phenomenon helps maintain the matric suction's contribution to shear strength and keeps the disparity in SFs between dry and rainy seasons relatively small. The shear plane, located at a depth of 0–6 m within the unsaturated soil zone characterized by fine particles with high air retention capacity, does not intersect the interface between saturated and unsaturated zones. Consequently, changes in matric suction during the rainy season are limited and do not lead to significant variations in the SF. The seasonal variation in SF is negligible, as rainwater does not penetrate to the shear plane in the unsaturated zone, where water retention is high. Consequently, the matric suction and shear strength of the soil remain fairly consistent throughout the seasons.

It does not suggest that the various analysis techniques, mesh discretization, parameter rounding, and numerical approaches could have significantly altered the stability requirements. To better understand landslide dynamics in unsaturated soils, further research must adopt a multidisciplinary, field-data-driven approach that integrates experiments, numerical modelling, and long-term monitoring. For example, soil suction (matric suction) can be measured more accurately and continuously using a high-pressure tensiometer or a TDR/FD-based moisture sensor; more common laboratory experiments on unsaturated soils, such as triaxial test without saturation, SWCC during various wet-dry cycles; and investigation of how repeated rain-dry cycles affect the deterioration of shear strength during climate changes. Suction measurements and modeling in unsaturated soils are usually performed by using the framework of unsaturated soil mechanics, with a focus on the relationship between suction and water content or suction and degree of saturation (SWCC).

Other suggestions would be related to validation and field scale, such as: extending the study to the natural slope scale (field scale) from the laboratory scale; utilizing real landslide data to validate the model and analytical findings; setting up long-term slope monitoring devices, like: piezometers, inclinometers, and sensors for soil moisture and rainfall. A more thorough hydro-mechanical coupled model (water flow–soil deformation) that incorporates changes in soil properties over time, such as porosity changes, softening from infiltration, and calibration of numerical models using long-term field data, would require numerical analysis.

4. CONCLUSION

This study successfully determined the magnitude of deformation and the SF of slope stability at Langsa District, Indonesia, by applying the best-fit SWCC and the permeability function obtained from laboratory testing. The results revealed that the vulnerable soil layer extends from the surface to a depth of 6.0 m, with SF values of 1.543 during wetting (rainy season) and 1.566 during drying (dry season). These findings indicate that rainfall infiltration, driven by climatic variability, is the dominant factor influencing slope deformation and triggering instability. The cyclic swelling and shrinkage of unsaturated expansive soils further contribute to the gradual degradation of shear strength parameters (c; ϕ) over time. Overall, the simulation model demonstrated good agreement with field observations, validating that the applied approach effectively evaluates deformation behavior and stability conditions in partially saturated, weathered soils, while accurately identifying the critical slip surfaces associated with the lowest safety factor.

This study shows that particle size is the main controlling factor linking soil microstructural properties to the hydraulic and mechanical responses of slopes. Soils with finer particle sizes have higher air entrainment and water retention values, which cause suction release to occur more slowly but significantly impact the reduction in shear strength during rainfall infiltration. In contrast, coarser-grained soils exhibit a rapid hydraulic response but with relatively limited strength loss. These findings indicate that particle-size-based soil classification should be explicitly considered in slope stability analyses of unsaturated soils, especially for predicting failure time and mechanisms. The research study demonstrated that increasing the fine fraction not only increases the AEV value but also shifts the mechanism of slope strength loss from rapid drainage in coarse-grained soils to gradual suction loss in fine-grained soils due to high water retention. Different SWCCs across layers are caused by variations in particle size with depth, which in turn produce suction gradients and water buildup in the transition zone. Slope stability is more affected by this condition than by variations in the internal friction angle alone.

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