

LANDSLIDE HAZARD INVESTIGATION AND SLOPE STABILITY ASSESSMENT OF INDRAPURI HOUSING PEKANBARU, INDONESIA

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ABSTRACT: Housing development in Indrapuri, Pekanbaru, located in a hilly area with steep terrain, presents potential landslide hazards due to soil cutting and filling activities. This research is essential to determine whether the housing development at this location is stable from landslide hazards, necessitating a scientific slope stability analysis. The study aims to evaluate the safety factor of cut slopes, analyse landslide hazards based on soil characteristics, and assess the impact of slope height on landslide potential. The research methodology involves slope investigations, soil characteristic testing in field and laboratory settings, and slope stability evaluation using the Fellenius Method. Field investigation results indicate that slope heights vary from 2 m to 5 m, with a slope angle (α) of 68° . The soil shear strength parameter (ϕ) varies between 21.25° and 64.85° , while cohesion (c) ranges from 43.97 kN/m^2 to 84.56 kN/m^2 . These parameters can affect slope stability. At the Indrapuri site, variations in soil shear strength and cohesion are likely influenced by geological and environmental factors. Slope stability analysis reveals that the current slope conditions are stable from landslide hazards, with safety factor values ranging from 2.42 to 5.20. These values exceed the minimum threshold for slope stability ($SF \geq 1.25$), indicating stable conditions. However, under extreme rainfall conditions or additional loading, the safety factor may decrease significantly and approach the critical limit ($SF \leq 1.07$), potentially leading to slope failure.

Keywords: Slope stability, Landslide hazard, Slope angle, Soil characteristics, Safety factor

1. INTRODUCTION

In geotechnical engineering, slope stability is a key issue, especially for residential projects in hilly or rolling landscapes. In tropical regions like Indonesia, slope failures are frequently triggered by intense rainfall, complex soil behaviour, and unplanned land modifications. Many studies have emphasised that human activities like slope cutting and filling can disrupt the natural balance of slopes, increasing their vulnerability to landslides, particularly in the rainy season [1-3].

Despite increasing awareness, slope stability assessments in small-scale residential areas are often overlooked. Comprehensive investigations combining field observation, laboratory testing, and stability analysis are essential to ensure that development projects are stable and sustainable. Moreover, understanding the connection between slope geometry and soil properties such as shear strength and porosity is critical for forecasting landslide risks. Indrapuri Pekanbaru housing is built in a hilly area with varying heights. The hill is cut and spread onto the sloping land surface to produce flat land. Type 36 simple residential houses are constructed on flat land. Rainfall in this location is very high, with an annual average reaching 2500-3000 mm, especially during the rainy season from October to December. High rainfall intensity and

erratic rain cycles lead to increased water content in the soil, making the surface soil susceptible to erosion. This can trigger landslides, particularly on steep slopes [1].

The development of housing on this terrain may compromise slope stability. Slope stability in tropical climates, such as Indonesia, is prone to landslides, particularly in the rainy season, often accompanied by extreme rainfall [2]. Factors such as increased groundwater content and fine-grained soil characteristics in tropical areas can reduce slope stability. Slope stability problems arise when natural or engineered soil slopes lose their equilibrium. This process increases the likelihood of a landslide occurring [3]. On steep slopes, the process of cutting and filling the soil can disrupt the stability of the hill, especially when there are changes in seasons, such as heavy rain [4,5]. This process can cause the risk of landslides. Landslides are geological phenomena caused by various factors, including high rainfall, soil erosion, and decreased slope stability due to inadequate development [5].

In some cases, slope stability depends on how the slope angle interacts with soil characteristics. Soil characteristics include soil type, consistency, and shear strength [6]. Several studies have examined various aspects of slope failure. Slope failure is influenced by slope steepness [7,8]. Slopes can experience landslides with slope angles between 45°

and 55°, with an increased water content of 5% to 12% [7,9]. Various studies have demonstrated that the type of soil, its consistency, and the friction angle affect slope stability [10,11]. Saturated sandy clay soil has low soil strength, so that landslides can occur [12]. Increasing the water content until it reaches a saturated condition can remove cohesion from 30% to 45%, triggering slope failure [11]. Slope stability is also influenced by rainfall, shear strength, and soil grain size distribution [11,13-15]. Soil types with coarse grains are more vulnerable to landslides caused by rainwater infiltration [16,17]. Nevertheless, the probability of landslides increases on slopes with clay soil and an internal friction angle (ϕ) ranging from 11° to 15°. If the internal friction angle (ϕ) is higher than the slope angle (α), the slope is stable from landslides with $SF > 1.0$. Thus, slopes that do not meet this requirement become critical ($SF \leq 1$) and must be made stable by decreasing the motivating factor behind landslides. In addition to soil characteristics and slope angle factors, climate change that leads to greater extreme rainfall can heighten the risk of slope instability in tropical regions [4,17,18]. High rainfall intensity and unpredictable weather cycles will increase groundwater levels and the risk of landslides in areas with steep slopes, such as the research location.

Therefore, it is crucial to examine the relationship between soil properties and landslide occurrences on hill slopes, particularly in Indrapuri, due to implications for the safety and well-being of residents. While prior studies have often assumed homogeneous soil layers, this research distinguishes itself by considering the soil as stratified, featuring multiple distinct layers. Thus, this study aims to determine the safety factor of slopes subjected to cutting, considering the layered soil profile, and to analyse how variations in soil characteristics across these layers influence landslide hazards. Furthermore, the study explores the impact of slope height and angle on slope stability. The findings are expected to provide valuable guidance for homeowners and developers regarding the feasibility of housing development in Indrapuri, and if instability is detected, to recommend appropriate soil reinforcement or mitigation measures to enhance slope safety.

The next planned topic, the effect of varying slope angles on uniform and layered soils, will be validated by the finite element method or limit equilibrium analysis.

Several treatment methods, like the utilisation of retaining walls, soil nails, geosynthetics, and surface drainage systems, have been widely applied to enhance slope stability in steep terrains [19,20]. These methods can lower pore water pressure and raise soil shear strength, particularly under heavy rainfall conditions.

2. RESEARCH SIGNIFICANCE

This study provides original insights into slope stability in Indrapuri, Pekanbaru, where housing development occurs in hilly terrain highly susceptible to landslides. Unlike previous works on large-scale slope failures, this research examines small to medium cut slopes (2–5 m) within residential developments, offering novel perspectives on how soil heterogeneity and slope geometry influence stability. Integrating detailed field investigations, laboratory testing, and Fellenius Method analysis highlights the critical role of local soil properties and rainfall conditions in determining safety factors. The findings contribute new knowledge to sustainable housing planning in geologically sensitive regions.

3. RESEARCH METHODS

This study is being conducted at the same site as earlier studies [21], which is a 13,000 m² housing building site. This place may be found on Indrapuri Hangtuh Street in Pekanbaru, Indonesia, at 0° 31' 25.2" N, 101° 29' 42.1" E. A hill cut that creates the current slope is depicted in Fig. 1.



Fig. 1 Condition of the cut slope

This study utilised a combination of field investigations, laboratory analyses, and slope stability assessments to evaluate the soil conditions at the prospective construction site. Fieldwork comprised Cone Penetration Tests (CPT) or sondir conducted at two distinct locations, one at the slope crest and another near the base, and the collection of soil samples categorised as disturbed and undisturbed. Disturbed samples were obtained from depths ranging between 0.2 m and 1.6 m, whereas undisturbed samples were collected from 1.6 m to 2 m depth using a hand auger at three separate borehole sites.

Subsequent laboratory analyses were performed on these samples to characterise the soil properties pertinent to slope stability. The resulting laboratory data were incorporated into a stability model to

calculate the safety factor for the existing slope geometry, considering actual slope height and angle. To capture spatial variability in soil shear strength attributes, interpolation was performed using the measured data from the three boreholes and two CPT points. This approach enabled the development of representative soil profiles for slope stability evaluation.

3.1 Laboratory Soil Testing

Laboratory soil testing encompasses direct shear strength, liquid limit, plastic limit, and grain gradation assessments. Grain gradation testing aims to ascertain the distribution of soil grain size and type, using a sieve according to the ASTM C-136-06 method, based on values of the soil uniformity coefficient (C_u) and the grain gradation coefficient (C_c). Liquid limit testing uses the Casagrande tool, and plastic limit testing is performed by rolling the soil on a glass plate according to ASTM D4318 [24,25]. Direct shear strength testing provides horizontal and vertical stress to undisturbed soil to obtain the cohesion of the soil's shear strength value and friction angle.

3.2 Slope Stability

The Fellenius Method (1927) computes the Safety Factor for slope stability analysis. Due to its effectiveness in determining safety factors in difficult geotechnical circumstances, the Fellenius Method has been frequently used for slope stability investigations in tropical regions [2]. K. C. Onyelowe [19] resulted in an intelligent model to predict slope safety factors with measured geometry.

The forces acting on each slice's right and left sides produce zero results in the direction perpendicular to the landslide plane. Figure 2 displays a cross-section of the current slope following the survey and measurement. The general equation of the Fellenius method is as follows:

$$SF = \frac{\text{Sum of moments of shear resistance along the landslide plane}}{\text{Sum of moments of the weight of the landslide mass}} \quad (1)$$

$$SF = \frac{\sum M_r}{\sum M_d} = \frac{\sum_{i=1}^n ca_i + (W_i \cos \alpha_i - u_i a_i) \tan \phi}{\sum_{i=1}^n W_i \sin \alpha_i} \quad (2)$$

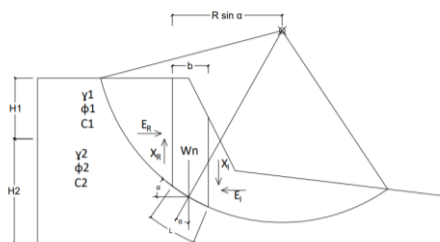


Fig. 2 Geometry of existing slope

In this equation, SF represents the safety factor, ϕ denotes the soil's friction angle (degrees), c indicates the soil cohesion measured in kN/m^2 , a refers to the length of the circular slip surface segment at the i^{th} slice (meters), W_i is the weight of the i^{th} soil slice in kN , u_i corresponds to the pore water pressure at the i^{th} slice (kN/m^2), and α_i is the angle illustrated in Fig. 2. The threshold values for the slope's safety factor are summarized in Table 1.

Table 1. Classification of Slope Stability

Safety Factor	Slope Condition
$SF \leq 1.07$	Unstable
$1.07 < SF < 1.25$	Critical
$SF \geq 1.25$	Stable

Source: Bowles, 1991

4. RESULTS AND DISCUSSION

4.1 Slope Geometry from Field Investigation

The geometry of the existing slope, comprising its height, angle, and cross-sectional profile, was determined from the findings of the field investigation. Figure 2 shows the geometry of the current slope based on field data. According to the findings of the geometry measurements, the housing slope height ranges from 2 to 5 meters, and the slope angle is $\alpha = 68^\circ$. Figure 2 depicts a stratified soil layer from the ground surface to a depth of 5 meters.

4.2 Landslide Hazard Study Results on Soil Characteristics

4.2.1 Results of Field Geotechnical Investigations

The sondir test results indicate that the hard soil layer is located at a depth of 15.4 meters at the slope crest and a depth of 9.6 meters near the base. Three test spots were used for the bored test and hand bore. Disturbed and undisturbed soil samples were gathered at every site, ranging from 1.6 to 2.0 meters below the ground surface. The sand at the three test locations varies in colour from yellowish-brown to blackish-brown, according to the visual evaluation of the hand boring test.

4.2.2 Results of Laboratory Soil Testing

The grain gradation test results determine the soil grain size distribution from the grain gradation coefficient (C_c) value and the uniformity coefficient (C_u). The uniformity coefficient (C_u) and grain gradation coefficient (C_c) values are 2.33 and 1.112, respectively. Based on the C_c and C_u values, the soil type in this research location is well-graded sand. High C_u and moderate C_c values indicate well-graded soil; however, under intense rainfall, the fine fraction may still be mobilised, potentially initiating

surface erosion, especially on steep slopes with poor vegetation cover [11].

Table 2. USCS Classification System

Group symbol criteria		Symbol group
Coarse-grained soil	Sand containing 50% or more retained on the No. 200 sieve	SC
	Gravel contains many refined grains. PI > 7	
	Sand containing more than 50% of coarse fraction passing sieve No. 4	

Based on Table 2, the type of soil at this research location is SC, namely, well-graded clay sand. Due to its ability to bear heavy weights, well-graded sand is frequently employed in construction [13]. Other soil parameters based on laboratory test results can be seen in Table 3.

Table 3. Slope Soil Geotechnical Parameters

Parameters	Symbol	Range	Average
Water content (%)	ω	13.83 - 21.15	17.49
Wet unit weight (kN/m ³)	γ_b	20.9 - 22.2	21.6
Dry unit weight (kN/m ³)	γ_{dry}	17.7 - 19.3	18.5
Friction angle (°)	ϕ	21.25°-64.85°	43.05
Cohesion (kN/m ²)	c	43.97 - 84.56	64.26
Liquid Limit (%)	LL	21.41- 33.72	27.56
Plasticity Index (%)	IP	4.81 - 11.48	8.15
Specific gravity	G _s	2.5 - 2.57	2.53

Based on Table 3, the soil water content of the study location is included in the low water content category at an average of 17.49%. Sandy soil tends to have a lower water content value than clay soil. The average wet soil density is 2.16 tons/m³, and the average dry soil density is 1.85 tons/m³.

The value of the soil plasticity index (PI) indicates the plasticity characteristics of the soil. The liquid limit (LL) and plastic limit (PL) values, which characterise the soil's plasticity characteristics as the water content varies, are used to calculate the soil plasticity index. The soil's liquid limit value at this study site ranges from 21.41 to 33.72%, with an average of 27.56%, while the Plasticity Index (PI) for the soil at the study site is 4.81 - 11.48% and an average of 8.15%.

The soil type in the Low Plasticity category can be obtained from the IP value, so the soil type at the research location is sand. The internal friction angle (ϕ) is an angle that reflects the ability of soil grains to interlock and withstand shear forces before experiencing deformation or shear. Laboratory results indicate that the internal friction angle ranges from 21.25° to 64.85°. Substrates with small internal friction angles are especially susceptible to collapse and landslides in moist conditions, as their

shear strength diminishes. As the internal friction angle rises, so does the shear strength of the soil [27,28]. Therefore, when examining slope stability, it is crucial to establish the soil's internal friction angle. Due to their reduced internal friction angle, fine-grained soils are more susceptible to landslides [26].

The soil cohesion value (c) from the laboratory tests at this research location ranges from 43.97 kN/m² to 84.56 kN/m². Due to the lack of cohesiveness in non-cohesive soils such as sand and gravel, the shear strength of these materials is greatly influenced by the friction between their particles [24-26]. This soil can only achieve cohesion through negative water pressure or clay.

The soil's porosity at this site varies between 28% and 34%. Low porosity indicates that the pore space in the soil is smaller or less. Soils with low porosity tend to be denser and slower to absorb water. As a result, the soil finds it harder to absorb and retain water, which can reduce the likelihood of water saturation during heavy rainfall. Low porosity increases stability, reflected in a more significant safety factor, even under rainfall or surface runoff conditions. Low porosity (28–34%) limits water infiltration, reducing the likelihood of pore pressure buildup during heavy rainfall events, thus maintaining higher shear strength and increasing SF even under saturated conditions [27]. Water saturation decreases the shear strength of soils and increases pore pressure, which often contributes to landslide occurrences. Landslide events not only change the soil structure but also change the particle size in the soil [14].

Specific gravity (G_s) values of 2.50–2.57 indicate that the slope soils consist mainly of mineral materials such as sandy loam or low-plasticity clay, with minor organic or lightweight minerals like kaolinite, resulting in slightly lower bulk density than pure mineral soils. Direct shear tests show varying cohesion and internal friction angles across layers, influenced by particle density [28,29]. While lower G_s generally reduces friction angle, the combination of high cohesion in the upper layer and high friction angles in the lower layer ensures overall slope stability even at steep slope angles [30].

4.2.3 Analysis of Slope Stability

The results of the slope stability analysis according to the Fellenius method are applied to ascertain the safety factor value for a slope composed of layered soil. The first layer is 2 m deep, and the second layer is more than 2 m deep. Table 4 shows the parameters of soil shear strength of each layer with a slope height of 2-5 m. Table 4 shows the slope safety factor values for 2m, 3m, 4m, and 5m heights with a 68° slope.

Table 4. Slope Safety Factors Based on Soil Layer Properties at Various Locations

Loc.	H	Soil Layer	c (kN/m ²)	ϕ (°)	γ (kN/m ³)	α (°)	SF
1	2	1	84.56	21.25	17.9	68°	5.20
		2	65.43	64.85	17.4		
2	3	1	84.56	21.25	17.9	68°	3.11
		2	65.43	64.85	17.4		
3	4	1	84.56	21.25	17.9	68°	2.52
		2	65.43	64.85	17.4		
4	5	1	84.56	21.25	17.9	68°	2.24
		2	65.43	64.85	17.4		

The findings of the slope stability analysis are shown in Table 4, which includes information from four slope locations along with their safety factor (SF). Each site is assumed to have a uniform slope ($\alpha = 68^\circ$), with the soil layer characteristics demonstrating the cohesion (c) and angle of internal friction (ϕ) for the two layers presented in Table 4.

The identification of the hill and the stability analysis of the slope after cutting and filling operations to a low location indicate that the safety factor of the current slope ranges from 2.24 to 5.20. This value indicates that the slope is stable because $SF > 1.25$. This occurs because the cohesion of the first and second soil layers is relatively high, where the soil with high cohesion can provide additional retaining force, so that the slope can still be stable even though the hill is steep [6,30,31]. The high cohesion of the upper layer and strong frictional resistance of the lower layer act together to create a resisting force exceeding the driving force, despite the steep slope angle [3,32]. The interaction between these layers forms a composite resistance mechanism that contributes significantly to overall slope stability.

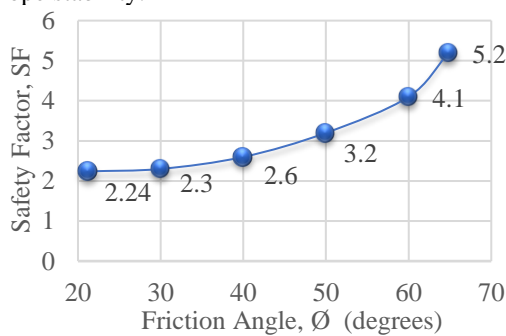


Fig. 3 Relationship between Friction Angle (ϕ) and Safety Factor (SF)

Figure 3 depicts the connection between the resulting safety factor (SF) and the soil's internal friction angle (ϕ). The data show a consistent increase in SF with higher ϕ values, indicating that soil layers with greater shear resistance contribute significantly to slope stability. This relationship supports the observed high SF values despite steep

slope angles due to the high friction angle exhibited by the lower layers of soil [5]. Because the second dirt layer has a larger friction angle than the first, it can withstand the first layer's friction angle and act as a stable foundation for the weaker first layer.

Although the existing slope condition is considered stable, the current slope angle (α) of 68° should be noted as being significantly greater than the soil's internal friction angle (ϕ), which is between 21.25° and 64.85° . According to previous studies [13,33,34] When the slope angle (α) is higher than the soil's internal friction (ϕ), there is a high probability of significant slope instability, leading to an increased risk of landslides, especially when the moisture content or additional load increases on the slope.

Therefore, further research must explore more effective mitigation methods in anticipating future landslide hazards. Preventive measures, such as slope reinforcement using retaining walls and drainage to control excessive soil moisture due to heavy rainfall, must be considered [35]. Future work will include validation using finite element methods (e.g., Plaxis 2D) or LEM-based software (e.g., Geoslope) to contrast the safety factors acquired through the Fellenius method, thereby ensuring the robustness of the slope stability predictions.

4.2.4 Slope Height's Impact on Landslides

Figure 4 illustrates the connection between slope height and slope safety factor. Figure 4 illustrates the connection between slope height and safety factors. The slope height ranges from 2 to 5 meters. According to Fig. 4, if the slope height increases, the slope safety factor decreases. The reduction in SF is more pronounced for slopes higher than five meters. The slope's height rises in proportion to its increasing angle. The slope's angle increases with slope height [5,36].

At a slope angle greater than 68° , the SF value can be close to or even lower than 1.0, indicating a high risk of landslides, especially if the soil is saturated [18,37]. The soil can become saturated due to high rainfall, impacting slope stability [27]. Steep slopes with high water content are very susceptible to landslides [18,38].

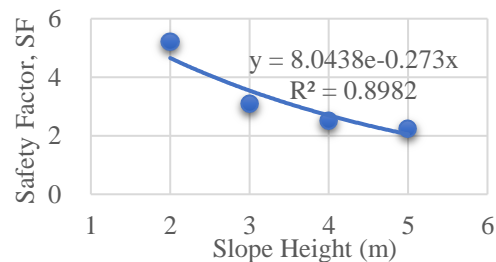


Fig. 4 Relationship between slope height and safety factor

The finding that steeper slopes increase landslide risk is consistent with previous studies in tropical regions, showing that landslide risk increases with increasing water content due to high rainfall [2]. Because slope angle influences how gravity works on the soil mass, it is essential for slope stability. With elevation increases of greater magnitude, the soil mass becomes heavier and the pore water pressure at the slope's base intensifies, leading to a greater driving force and reduced stability of the hill [38]. Furthermore, steeper slopes increase the likelihood of landslides because of increased gravitational forces and decreased retention forces from soil friction and cohesiveness [5,6].

In addition to internal factors such as slope angle and soil characteristics, human activities around the study area can also disrupt slope stability. Infrastructure development without proper preparation and landslide risk management measures, especially during high rainfall, will disrupt slope stability. Therefore, the impact of human activities on the environment should be included in future studies to support effective risk management. In slope stability and geotechnical engineering, this includes assessing how infrastructure development, deforestation, and land-use changes affect soil strength, landslide potential, and surrounding ecosystems. For example, the construction of roads and housing on sloping land will cause changes in drainage patterns and reduce the soil-bearing capacity. At the same time, tree felling removes the vegetative cover that holds the soil in place, making the slope vulnerable to erosion and landslides.

5. CONCLUSION

This study assessed the slope stability of a residential area in Indrapuri, Pekanbaru, using field investigations, laboratory tests, and slope stability analysis based on the Fellenius method. The results indicate that the current slope conditions, with heights ranging from 2 to 5 meters and a slope angle of 68°, are considered stable, as reflected by SF values ranging from 2.24 to 5.20.

The stability is influenced by the high cohesion in the upper soil layer (43.97–84.56 kN/m²) and the high friction angle in the lower layer (up to 64.85°), providing a composite resisting force that counteracts potential sliding. Furthermore, the low soil porosity (28%–34%) contributes to reduced water infiltration and lower pore pressure during heavy rainfall, helping to maintain shear strength even under saturated conditions.

However, the slope angle exceeding the internal friction angle in some layers presents a latent risk, especially under increased moisture content or loading. Although the current SF values are well

above the critical threshold ($SF \leq 1.07$), slope failure may still occur under extreme conditions.

Therefore, preventive actions like surface drainage and mechanical reinforcement (e.g., retaining walls) should be implemented to mitigate potential landslide hazards further. Future research will include validation using finite element (e.g., Plaxis 2D) and limit equilibrium methods (e.g., Geoslope) to enhance the reliability of the stability analysis and evaluate different slope reinforcement scenarios under various rainfall intensities.

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