COMPREHENSIVE GEOTECHNICAL ANALYSIS OF LANDSLIDE RISK FACTORS: INSIGHTS FROM KARO REGENCY, NORTH SUMATERA, INDONESIA

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Abstract
This study explores geological and geotechnical factors impacting landslide risk in Karo Regency, Sumatera Utara, Indonesia, a region inherently susceptible to landslides due to its volcanic terrain. Analyzing seven landslide sites, the research combines field slope geometry measurements and soil bulk density tests with detailed laboratory investigations, including Triaxial Unconsolidated Undrained (Triaxial UU) testing. Findings reveal critical insights into soil behavior, stability, and variations in shear strength parameters. The Unified Soil Classification System (USCS) identifies prevalent soil types, dominated by poorly graded sands and gravelly sands. Triaxial UU testing exposes significant variations in shear strength parameters, highlighting soil heterogeneity. This comprehensive study contributes to geotechnical engineering, emphasizing the need for tailored mitigation strategies and multidisciplinary approaches in effective landslide risk management in Karo Regency.

Keywords: *disaster, geological vulnerability, slope*

INTRODUCTION

Indonesia, characterized by its diverse topography, is prone to geological hazards, with landslides being a significant concern due to their devastating impact on both human settlements and the natural environment. The archipelagic nature of Indonesia, comprising numerous islands with varying geological compositions, elevations, and climates, contributes to the complex dynamics of landslide occurrences across the country. The susceptibility to landslides in Indonesia is exacerbated by factors such as heavy rainfall, seismic activities, volcanic eruptions, and human interventions like deforestation and improper land use (Chikalamo et al., 2020; Faris & Fawu, 2014; Heidarzadeh et al., 2020). The densely populated nature of certain regions intensifies the potential consequences of landslides, posing threats to lives, infrastructure, and ecosystems.

Over the years, researchers and authorities in Indonesia have recognized the urgency of understanding and mitigating landslide risks. Various studies, like those focusing on regions such as Karo Regency, have investigated geological conditions, soil engineering properties, and contributing factors to better comprehend the triggers and mechanisms of landslides. These endeavors aim not only to enhance the scientific understanding of landslide susceptibility in the Indonesian context but also to inform practical measures for disaster risk reduction, land use planning, and infrastructure development. The unique geological challenges posed by Indonesia make it a compelling case study for landslide research, providing insights that are not only applicable locally but also contributing to the global understanding of landslide dynamics in regions with similar characteristics. As Indonesia continues to grapple with the multifaceted nature of landslide risks, ongoing research endeavors play a crucial role in developing strategies to safeguard communities and promote sustainable development in landslide-prone areas.

The field of landslide studies has evolved significantly, propelled by a growing awareness of the profound impacts of landslides on communities and landscapes. Current research in landslide susceptibility extends beyond mere identification and assessment, incorporating a multidisciplinary approach that considers geological, geomorphological, and environmental factors. Notable studies by Reichenbach et al. (2018), Ozturk et al. (2021), and Pacheco Quevedo et al. (2023) underscore the importance of this holistic perspective, providing a foundation for understanding the intricate interplay of elements contributing to landslide occurrences. Soil engineering properties, a critical facet of landslide vulnerability, have garnered increased attention in recent studies. The works of McKenna et al. (2012), Sigdel and Adhikari (2020), Kamal et al. (2022), and Olabode et al. (2022) have advanced our comprehension of the mechanical behavior of soils, offering insights into how soil characteristics influence landslide initiation and propagation. Particularly, McKenna et al. (2012) pioneering research on shallow landslides, utilizing indices based on soil density and particulate content, has set a precedent for predictive modeling with a commendable 79% accuracy.

Geographical variations in landslide susceptibility, as evidenced by studies in diverse regions like Cox's Bazar, Bangladesh, and central-western Nepal, highlight the need for site-specific analyses. The comprehensive investigation by Kamal et al. (2022) into the Kutupalong Rohingya camp emphasizes the importance of understanding localized geological conditions, engineering features, and human interventions contributing to landslide risk. Advancements in technology, such as electrical resistivity tomography (ERT) employed by Olabode et al. (2022), showcase the integration of innovative tools in landslide research. This not only aids in subsurface geological exploration but also complements traditional geotechnical tests, providing a more comprehensive understanding of soil properties and landslide potential.

Despite the advancements in landslide research, a critical examination reveals discernible gaps in our understanding, particularly in the context of Karo Regency, Indonesia (Qarinur et al., 2024). This study aims to bridge these gaps and contribute meaningfully to the existing body of knowledge. The dearth of comprehensive investigations into the soil properties influencing landslide susceptibility in this specific region necessitates a focused exploration. Previous studies, while valuable, often lack specificity to local conditions, limiting their applicability in diverse geographical contexts.

The primary aim of this research is to conduct a meticulous analysis of soil engineering properties in Karo Regency, offering a nuanced understanding of the factors contributing to landslide vulnerability. By leveraging robust methodologies, including Triaxial Unconsolidated Undrained (Triaxial UU) testing and the Unified Soil Classification System (USCS), the study endeavors to provide a detailed insight into the mechanical behavior, shear strength, and classification of soils in the region. This targeted approach is crucial in unraveling the intricate relationships between geological, environmental, and human-induced factors that amplify landslide risks.

METHODS

Study Area

Karo Regency, located in the northern part of Sumatra, Indonesia, encompasses a diverse and unique geographic and geological landscape. The area is characterized by its volcanic terrain, marked by the presence of numerous volcanoes and steep slopes. This geographic setting, while contributing to the region's fertility, also exposes it to various geological hazards, making it essential to understand the inherent risks associated with the local environment. The regency area covers a significant portion of land, featuring a mix of flat plains and undulating hills, with volcanic mountains serving as prominent geographical landmarks. These volcanic formations contribute to the region's fertile soil, supporting rich agricultural activities.

Geologically, Karo Regency is prone to hazards such as landslides due to the combination of volcanic soil composition and steep slopes. The porous nature of volcanic soil makes it susceptible to erosion, especially during periods of heavy rainfall. This vulnerability underscores the importance of recognizing and addressing geological risks to enhance the resilience of the local population and infrastructure. Karo Regency's geographic and geological characteristics define its identity, presenting a balance between the benefits of fertile volcanic soil and the inherent risks associated with potential hazards like landslides. Understanding this interplay is crucial for implementing effective measures to mitigate the impact of geological events and ensure the sustainable development of the region.

According to Figure 1, the study undertakes a meticulous exploration of geological data derived from soil investigations conducted at seven distinct landslide locations, unraveling the intricate geological narratives shaping these terrains. The focus areas such as Kutabuluh, Sarinembah, Kutambelin, Jl. Trans Liang Melas Datas (location 1 and 2), Jl. Lintas Berastagi-Lau Kawar, and Kutambaru present unique compositions, unveiling a wealth of information critical for understanding the geological dynamics predisposing these regions to landslides. Table 1 displays the coordinates of the soil investigation sites, providing essential spatial information for the study.

In Kutabuluh, the geological data points to Ppal - Limestone Members, characterized by oolitic or recrystallized limestones. This suggests a geological history rich in carbonate deposition, potentially influencing the stability of the area and its susceptibility to landslides. Sarinembah reveals Tlbu - Butar Formation, marked by interbedded shales and sandstones, oil shales, and mudstones. The intricate layering of sedimentary formations speaks to a complex geological setting, emphasizing the role of sediment dynamics in shaping the vulnerability of the region to landslides. The geological profile of Kutambelin features Qvt - Toba Tuffs, comprising rhyodacitic tuffs welded in part. The presence of volcanic tuffs underscores a history of explosive volcanic activity, contributing to the geological conditions that may influence landslide occurrences. Both locations along Jl. Trans Liang Melas Datas exhibit a consistent geological composition characterized by Tlbu - Butar Formation.

This includes interbedded shales and sandstones, oil shales, and mudstones, highlighting the persistent role of sedimentary formations in shaping the terrain's susceptibility to landslides. The geological data from Jl. Lintas Berastagi-Lau Kawar introduces Qvbs - Singkut Unit, featuring andesites, dacites, microdiorites, and tuffs. The prevalence of volcanic and intrusive formations speaks to a diverse geological history, shedding light on potential triggers for landslides in this specific location. Lastly, Kutambaru shares similarities with Kutambelin, featuring Qvt - Toba Tuffs, with rhyodacitic tuffs welded in part. The recurrence of volcanic formations suggests a shared geological history, emphasizing the importance of volcanic activities in shaping the landscape's susceptibility to landslides.

The presence of faults in several locations, such as Kutambelin, Jl. Trans Liang Melas Datas (locations 1 and 2), and Jl. Lintas Berastagi-Lau Kawar, does not show a significant primary influence on landslide occurrences in Karo Regency. This is evident as other landslide events are not situated near areas adjacent to faults. In essence, this study seeks to decipher the geological nuances present at each of these landslide locations, providing a comprehensive understanding of the specific soil compositions and formations that contribute to the risk of mass movements. By unraveling these geological narratives, the research aims to contribute valuable insights to the broader field of landslide risk assessment and mitigation strategies, fostering a more resilient approach to managing geological hazards in diverse and dynamic terrains.

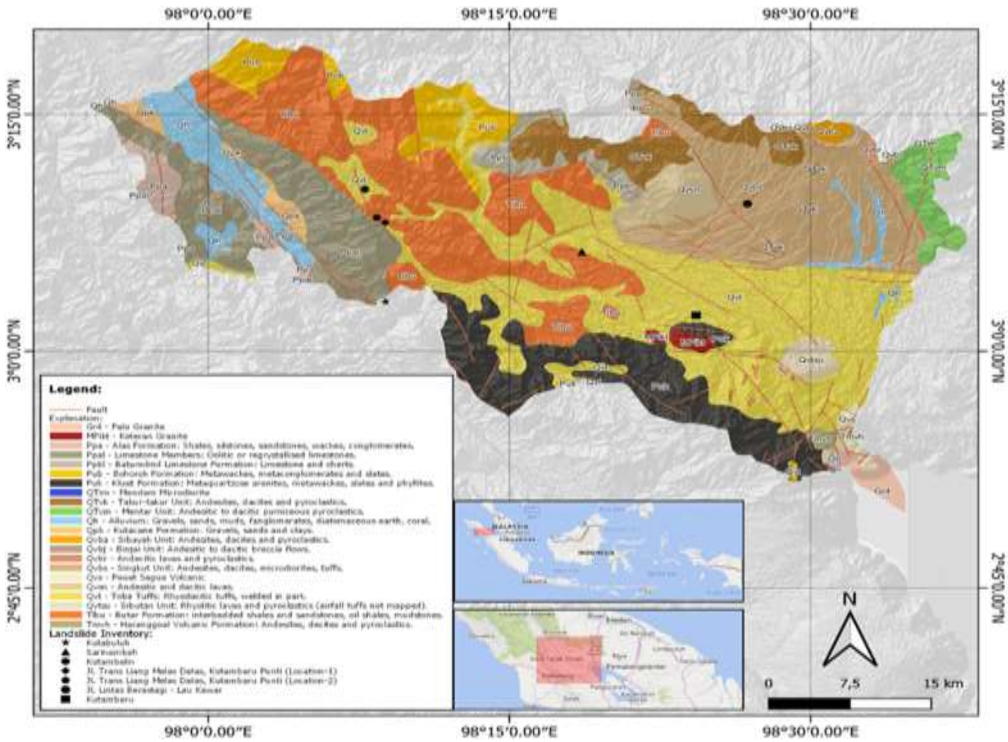

Figure 1. Geological map of the Karo Regency, Indonesia

Table 1. Soil investigation coordinate.

No.	Location	Coordinate	
		Latitude	Longitude
1	Kutambaru	3.038028	98.405306
2	Jl. Lintas Berastagi-Lau Kawar	3.155472	98.447694
3	Sarinembah	3.104831	98.310258
4	Kutabuluh	3.052152	98.147402
5	Jl. Trans Liang Melas Datas (location 1)	3.141114	98.140148
6	Jl. Trans Liang Melas Datas (location 2)	3.135760	98.147099
7	Kutambelin	3.170918	98.130179

Site Investigation

Site investigation is a crucial facet of understanding the geological and geotechnical aspects of a given area, providing essential insights for various applications, including infrastructure development and landslide risk assessment. This comprehensive study centers on site investigation methodologies, specifically emphasizing two key types of tests: measuring slope geometry and conducting soil bulk density tests. One of the fundamental aspects of this study involves the meticulous measurement of slope geometry at landslide sites. Qarinur's methodology, as outlined in 2015, utilizes a distance-measuring tool known as a hypsometer or range finder (Qarinur, 2015).

This innovative tool proves instrumental in accurately measuring both horizontal distances and the height from the user's eye to the target object. The hypsometer offers a precise means of capturing slope dimensions, contributing valuable data for the characterization of terrain features and the identification of potential landslide-prone areas. In conjunction with slope measurement, this study incorporates soil bulk density tests to delve into the subsurface characteristics of the investigated sites. Bulk density, a key indicator of soil compaction, is assessed according to the specifications laid out in SNI 03-3637-1994 (Badan Standardisasi Nasional, 1994). This test aids in evaluating the mass of soil per unit volume, contributing crucial information for engineering applications. Soil bulk density serves as a critical parameter in assessing the compactness of soil, offering insights into its porosity and overall stability.

The sampling methodology employed in this study encompasses two primary types: disturbed and undisturbed samples. Disturbed samples, obtained through conventional means, allow for the examination of index properties such as moisture content, particle size distribution, and consistency limits. Undisturbed samples, on the other hand, offer a pristine representation of the soil's mechanical properties, enabling a detailed analysis of its shear strength, compressibility, and other key characteristics. This dual-sample approach ensures a comprehensive understanding of both the immediate surface properties and the deeper mechanical behavior of the soil.

Laboratory Testing

This comprehensive study revolves around the meticulous laboratory testing procedures employed for a thorough analysis of soil properties. The research encompasses an array of essential tests, each aligned with specific standards to ensure precision and consistency in the obtained results. Table 2 is a detailed exploration of the laboratory tests conducted, along with their corresponding standards. The determination of water content, a fundamental parameter in soil analysis, follows the standards outlined in SNI 1965:2008.

This test provides insights into the moisture content of the soil, which is vital for understanding its engineering and environmental characteristics. The specific gravity of soil, a measure of its density relative to the density of water, is determined in accordance with the guidelines set by SNI 1964:2008. This parameter is significant in assessing soil composition and porosity. Sieve analysis, conducted in accordance with SNI 3423:2008, is a pivotal test for determining the particle size distribution of soil. This information is crucial in classifying soil types and assessing their suitability for various applications.

Hydrometer analysis, also following the standards of SNI 3423:2008, complements sieve analysis by providing additional insights into the finer fractions of soil particles. This test aids in refining the understanding of soil composition. Liquid limit testing, adhering to the standards of SNI 1967:2008, is essential for characterizing the consistency and behavior of fine-grained soils. This information is valuable in geotechnical and construction-related analyses.

The plastic limit of soil, a critical parameter influencing its plasticity and deformation characteristics, is determined using the standards established in SNI 1966:2008. This test aids in understanding the soil's structural behavior. Triaxial unconsolidated-undrained testing, conforming to the specifications outlined in SNI 4813:2015, is a sophisticated test used to analyze the shear strength and stress-strain characteristics of soil under specific conditions. This test provides valuable data for geotechnical engineering applications.

Table 2. Laboratory experiments standard.

No.	Test	Standard
1	Water Content	SNI 1965:2008 (Badan Standardisasi Nasional, 2008e)
2	Specific Gravity	SNI 1964:2008 (Badan Standardisasi Nasional, 2008b)
3	Sieve Analysis	SNI 3423:2008 (Badan Standardisasi Nasional, 2008a)
4	Hydrometer Analysis	SNI 3423:2008 (Badan Standardisasi Nasional, 2008a)
5	Liquid Limit	SNI 1967:2008 (Badan Standardisasi Nasional, 2008c)
6	Plastic Limit	SNI 1966:2008 (Badan Standardisasi Nasional, 2008d)
7	Triaxial Unconsolidated-Undrained	SNI 4813:2015 (Badan Standardisasi Nasional, 2015)

RESULTS AND DISCUSSION

Slope Geometry

This study focuses on the in-depth analysis of slope geometry and the subsequent classification of mass movements based on meticulous measurements. The data collected from various locations provides valuable insights into the nature of slope instability and the predominant materials involved. Figure 2 and Table 3 elucidates the findings from the slope geometry measurements and the corresponding mass movement classifications.

The slope geometry analysis at Kutambaru reveals a rotational movement characterized by the predominant presence of fine materials, with a slope angle of 61°. This classification suggests a rotational sliding pattern, emphasizing the role of finer particles in the mass movement dynamics. In the case of Jl. Lintas

Berastagi-Lau Kawar, with a slope angle of 45°, the geometry measurements indicate a translational movement predominantly involving coarse materials. This classification points to a horizontal sliding or shearing of larger particles, shaping the nature of mass movement in this location. Sarinembah, with a slope angle of 20°, exhibits a lateral spread movement, with the predominant presence of fine materials.

This classification suggests a lateral expansion of soil, indicating a distinctive type of mass movement influenced by the characteristics of finer particles. Similar to Jl. Lintas Berastagi-Lau Kawar, Kutabuluh, with a slope angle of 63°, showcases a translational movement, with the mass movement predominantly involving coarse materials. This consistency in classification implies similarities in the nature of sliding or shearing processes, likely influenced by the coarser composition of materials.

The slope geometry measurements at Jl. Trans Liang Melas Datas (location 1), with a slope angle of 41°, reveal a translational movement primarily characterized by coarse materials. This consistency in movement classification across different locations underscores the significance of coarse materials in shaping mass movement dynamics. Similar to location 1, Jl. Trans Liang Melas Datas (location 2), with a slope angle of 30°, exhibits a translational movement predominantly involving coarse materials.

This parallel classification suggests commonalities in the underlying geological and geotechnical factors influencing mass movement in these locations. Kutambelin, with a slope angle of 30°, concludes the study with a translational movement classification predominantly involving coarse materials. This translational pattern, coupled with the prevalence of coarse materials, distinguishes the mass movement characteristics in this location.

The analysis of slope geometry and mass movement classifications provides valuable insights into the dynamics of slope instability in different locations. The consistency in movement classifications across various sites underscores the role of material composition in influencing mass movement behavior. These findings contribute significantly to the understanding of landslide risk and lay the foundation for targeted mitigation strategies in areas prone to specific types of mass movements.

Soil Bulk Density Tests

The study initiates with the essential task of determining soil bulk density in the field, a key parameter for comprehending the mass and density of natural soil. The tool employed for this purpose is a steel core barrel with internal dimensions measuring 36 mm in diameter and 72 mm in height (Figure 3a). Sampling takes place both on the surface of the natural soil surrounding the landslide and on the landslide slip surface (Figure 3b). This dual sampling strategy ensures a holistic understanding of the soil density variations across different terrain conditions.

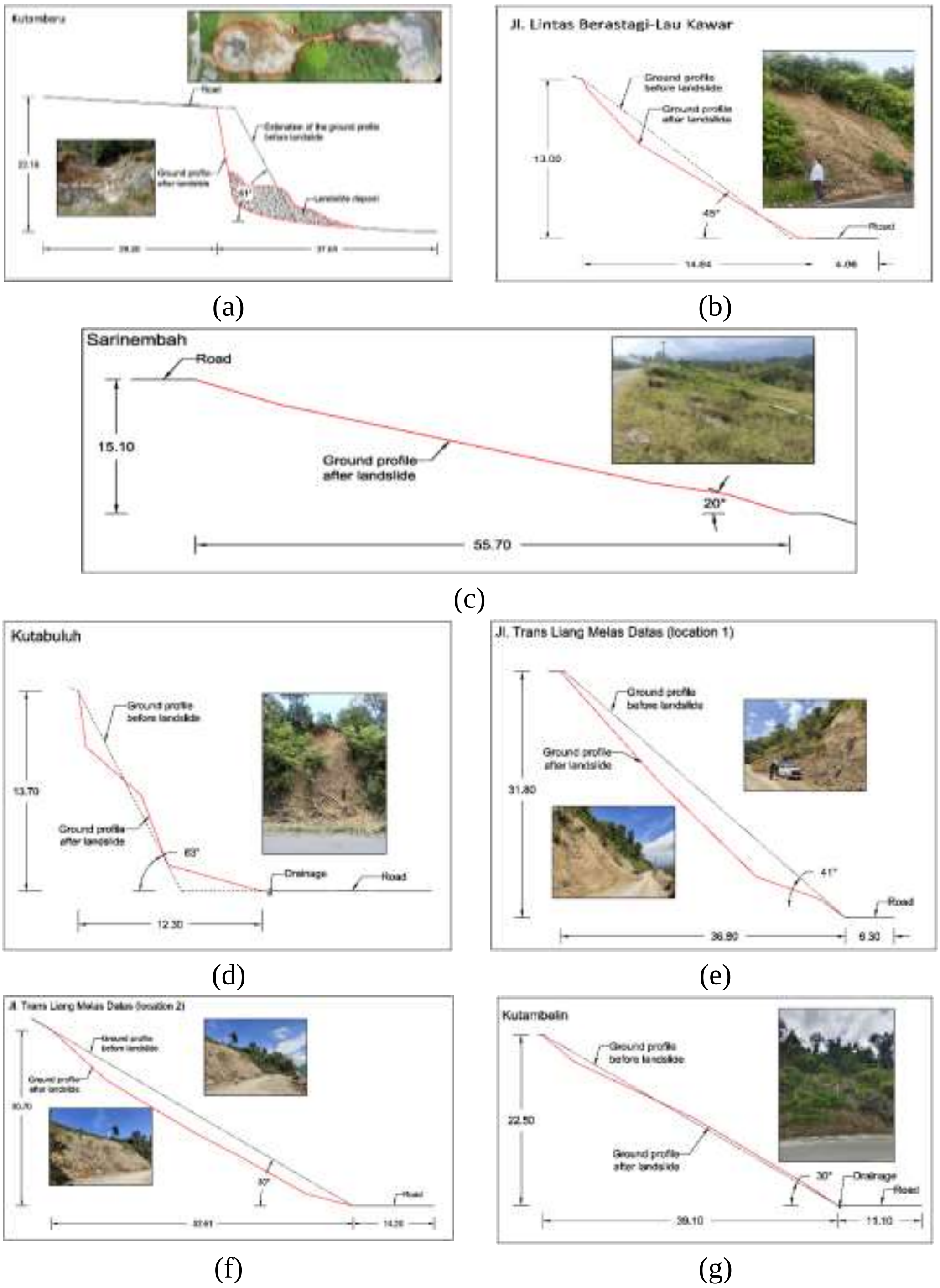

Figure 2. Condition of soil testing points in the field: (a) Kutambaru; (b) Jl. Lintas Berastagi-Lau Kawar; (c) Sarinembah; (d) Kutabuluh; (e) Jl. Trans Liang Melas Datas (location 1); (f) Jl. Trans Liang Melas Datas (location 2); (g) Kutambelin.

Table 3. The results of the classification of soil/rock mass movements.

No.	Location	Movement	Material
1	Kutambaru	Rotational	Predominantly fine
2	Jl. Lintas Berastagi-Lau Kawar	Translational	Predominantly coarse
3	Sarinembah	Lateral Spread	Predominantly fine
4	Kutabuluh	Translational	Predominantly coarse
5	Jl. Trans Liang Melas Datas (location 1)	Translational	Predominantly coarse
6	Jl. Trans Liang Melas Datas (location 2)	Translational	Predominantly coarse
7	Kutambelin	Translational	Predominantly coarse

The values obtained from soil bulk density testing in the field hold significant relevance in subsequent laboratory analyses, particularly in the creation of soil mechanical testing samples for triaxial tests. Triaxial testing is a sophisticated laboratory procedure used to assess the mechanical properties of soil, providing crucial insights into its shear strength, consolidation characteristics, and stress-strain behavior. The correlation between field bulk density values and laboratory testing underscores the importance of accurate field measurements in informing laboratory investigations.

The study encapsulates a comprehensive summary of soil bulk density test results, presented in Table 4. This table provides a detailed overview of bulk density (γ_b) and dry density (γ_b) values for various locations, both on the natural soil surface and the corresponding landslide slip surfaces. Notable observations from the results include variations in density values between different locations and distinctions between natural soil and slip surface conditions.

These results provide a nuanced understanding of the soil densities across different locations and conditions, crucial for assessing the stability and susceptibility of these areas to landslides. The variations observed in bulk and dry densities emphasize the heterogeneity of soil conditions and the importance of considering both natural and slip surface characteristics in landslide risk assessments. The integration of field and laboratory data in this study contributes valuable insights to the broader field of geotechnical engineering and landslide mitigation strategies.

Soil properties

This comprehensive study focuses on soil index properties testing, a vital component of geotechnical investigations, with a specific emphasis on moisture content, Atterberg limits, specific gravity, and grain size analysis. The results obtained from these tests offer valuable insights into the engineering and geological characteristics of soil in different locations, aiding in the assessment of landslide risk.


(a)


(b)

Figure 3. Soil bulk density tests: (a) steel core barrel; (b) sampling process.

The detailed procedures and summarized test results are outlined below. The summary of Table 4 which presents the results of soil index properties testing across multiple landslide-prone locations, reveals diverse soil characteristics. In Kutambaru, both on the natural surface and slip surface, high water content is noted, while Jl. Lintas Berastagi-Lau Kawar displays relatively lower water content. Sarinembah stands out with significant Atterberg limits, indicating substantial plasticity, and Kutabuluh exhibits a balanced composition of moisture and plasticity.

Variations in grain size composition are evident, with Kutambaru and Kutambelin showcasing predominantly sandy soils, while Sarinembah has a notable presence of silt/clay. These nuanced findings provide a comprehensive understanding of the distinct soil properties at each location, essential for evaluating landslide susceptibility and guiding geotechnical decisions and risk mitigation strategies.

The plasticity index values indicate that the soil plasticity primarily influences the type of landslide movement. For instance, the highest plasticity index value, recorded at Sarinembah (26.8%), is associated with lateral spread movements, characterized by relatively slow but continuous displacement. In contrast, locations with plasticity index values below 8% or classified as non-plastic tend to experience translational and rotational landslides, which occur more abruptly.

Soil classification

This study focuses on the classification of soil in landslide-prone areas, specifically in Karo Regency, utilizing the Unified Soil Classification System (USCS). The classification of soil is a crucial aspect in understanding its behavior and, in the context of this study, its role in landslide occurrences. The results, summarized in Table 5 provide valuable insights into the prevalent soil types in various locations. The USCS is a widely used system for soil classification, categorizing soils based on their physical and mechanical properties. In the context of landslide risk assessment, the USCS helps identify the soil types that may contribute to slope instability.

Table 4. Summary of soil index properties.

No	Location	Bulk density (γ_b, gr/cm^3)	Dry density (γ_d, gr/cm^3)	Water Content (%)	Specific Gravity (-)	Atterberg Limits Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI) (%)	Grain Size Gravel (%)	Sand (%)	Silt/ Clay (%)
1	Kutambaru	1.13	0.75	51.30	2,47	0.00	0.00	NP	0.00	95.48	4.52
2	Kutambaru (slip surface)	1.21	0.80	51.55	2.37	0.00	0.00	NP	0.51	95.35	4.14
3	Jl. Lintas Berastagi-Lau Kawar	1.84	1.46	26.28	2.60	0.00	0.00	NP	0.23	96.69	3.08
4	Sarinembah	1.72	1.29	37.49	2.60	57.61	30.81	26.80	0.00	95.99	4.01
5	Kutabuluh	1.87	1.45	21.23	2.61	32.55	25.13	7.41	16.02	82.29	1.69
6	Kutabuluh (slip surface)	1.83	1.35	29.58	2.61	0.00	0.00	NP	4.99	94.59	0.41
7	Jl. Trans Liang Melas Datas (location 1)	2.00	1.65	18.19	2.62	0.00	0.00	NP	17.50	78.63	3.87
8	Jl. Trans Liang Melas Datas (location 2)	1.91	1. 61	19.27	2.68	25.45	18.42	7.03	4.92	89.04	6.04
9	Jl. Trans Liang Melas Datas (location 2) (slip surface)	1.99	1.72	15.15	2.64	22.47	16.81	5.66	9.27	84.04	6.70
10	Kutambelin	1.70	1.34	21.88	2.48	0.00	0.00	NP	19.49	76.14	4.37
11	Kutambelin (slip surface)	1.95	1.69	16.32	2.65	0.00	0.00	NP	5.22	91.31	3.47

These classifications consistently point to the prevalence of poorly graded sands and gravelly sands with minimal fines in the analyzed locations, as denoted by the SP group symbols. However, exceptions include Sarinembah and Kutabuluh, where well-graded sands and gravelly sands are identified (SW group symbol), and Kutabuluh, where silty sands are also present (SW-SM group symbol). The uniformity in soil classification across various locations suggests a commonality in soil types associated with landslide occurrences in Karo Regency.

The dominance of poorly graded sands and gravelly sands underscores their potential role in slope instability. However, the presence of well-graded sands and silty sands in certain locations adds nuance to the understanding of soil behavior. This study's findings contribute valuable information for landslide risk assessment and can guide mitigation strategies tailored to the specific soil types identified in Karo Regency.

Table 5. Summary of soil classification USCS system.

No	Location	Group Symbols	Typical Names
1	Kutambaru	SP	Poorly graded sands and gravelly sands, little fines.
2	Kutambaru (slip surface)	SP	Poorly graded sands and gravelly sands, little fines.
3	Jl. Lintas Berastagi-Lau Kawar	SP	Poorly graded sands and gravelly sands, little fines.
4	Sarinembah	SW	Well-graded sands and gravelly sands, little fines.
5	Kutabuluh	SW-SM	Well-graded sands, gravelly sands, and silty sands.
6	Kutabuluh (slip surface)	SP	Poorly graded sands and gravelly sands, little fines.
7	Jl. Trans Liang Melas Datas (location 1)	SP	Poorly graded sands and gravelly sands, little fines.
8	Jl. Trans Liang Melas Datas (location 2)	SP	Poorly graded sands and gravelly sands, little fines.
9	Jl. Trans Liang Melas Datas (location 2) (slip surface)	SP	Poorly graded sands and gravelly sands, little fines.
10	Kutambelin	SP	Poorly graded sands and gravelly sands, little fines.
11	Kutambelin (slip surface)	SP	Poorly graded sands and gravelly sands, little fines.

Triaxial

This study employed Triaxial Unconsolidated Undrained (Triaxial UU) testing to determine soil shear strength values in various locations prone to landslides. The primary objective was to assess the angle of internal friction (φ) and cohesion (c) using the triaxial UU testing method. The results, outlined in Table 6 offer crucial insights into the mechanical behavior of soil in different locations. The triaxial UU test results reveal significant variations in soil shear strength among the studied locations.

Notably, Kutabuluh displays a high angle of internal friction (φ) at 40.00°, indicating good resistance to shear forces. On the contrary, Sarinembah exhibits an angle of 0.00°, suggesting minimal resistance to shear. Jl. Lintas Berastagi-Lau Kawar displays substantial cohesion (c) at 90.00 kN/m², indicating the soil's ability to withstand shear stresses even in the absence of significant internal friction. These findings are crucial for understanding the soil's stability in response to external forces, providing valuable data for landslide risk assessments.

The variations in shear strength parameters underscore the heterogeneity of soil conditions in different locations, emphasizing the need for tailored geotechnical solutions and mitigation strategies in landslide-prone areas. A material with low cohesion or internal friction is more prone to failure under shear stress, indicating higher landslide susceptibility. In addition, triaxial data can be utilized in limit equilibrium or finite element analyses to predict failure zones.

Table 6. Summary of triaxial UU test results.

No	Location	Angle of internal friction (φ) °	Cohesion (c) kN/m^2
1	Kutambaru	11.00	36.00
2	Kutambaru (slip surface)	28.00	25.00
3	Jl. Lintas Berastagi-Lau Kawar	25.00	90.00
4	Sarinembah	0,00	84,00
5	Kutabuluh	40.00	10.00
6	Kutabuluh (slip surface)	18.00	32.00
7	Jl. Trans Liang Melas Datas (location 1)	28.00	60.00
8	Jl. Trans Liang Melas Datas (location 2)	9.00	92.00
9	Jl. Trans Liang Melas Datas (location 2) (slip surface)	25.00	40.00
10	Kutambelin	19.00	15.00
11	Kutambelin (slip surface)	8.00	5.00

CONCLUSION

In conclusion, this comprehensive study delving into the intricate dynamics of landslide risk factors in various locations within Karo Regency yields profound insights. The meticulous analysis of slope geometry, soil bulk density, index properties, soil classification, and Triaxial Unconsolidated Undrained (Triaxial UU) test results collectively provides a nuanced understanding of the complex interplay of geological, geotechnical, and environmental factors influencing slope stability.

The consistent movement classifications across different locations underscore the pivotal role of material composition, with findings indicating rotational, translational, and lateral spread movements predominantly involving fine or coarse materials. Soil bulk density tests, conducted with a steel core barrel, reveal variations in natural soil density, serving as a crucial foundation for subsequent laboratory investigations, particularly triaxial tests. The integration of field and laboratory data enhances comprehension of soil stability and susceptibility to landslides.

Index properties testing, including analyses of moisture content, Atterberg limits, specific gravity, and grain size, provides detailed insights into soil characteristics, contributing to a comprehensive understanding of distinct soil properties crucial for landslide risk assessment. The Unified Soil Classification System (USCS) aids in identifying prevalent soil types, with poorly graded sands and gravelly sands dominating, emphasizing their potential role in slope instability.

Triaxial UU testing unveils significant variations in soil shear strength parameters, emphasizing soil heterogeneity and the need for tailored geotechnical solutions in landslide-prone areas. Geologically, landslide occurrences are predominantly situated within the Butar Formation (Tlbu), composed of sandstones, and the Toba Tuffs (Qvt), consisting of rhyodacitic tuffs. Additionally, not all landslide sites are located near fault zones. Instead, they are more influenced by road construction activities that involve cutting slopes without adequate reinforcement.

Therefore, further research is necessary to identify other contributing factors, such as earthquakes and rainfall, to obtain more comprehensive and reliable results. Overall, these findings contribute substantially to the broader field of geotechnical engineering, providing a foundation for targeted mitigation strategies and emphasizing the importance of multidisciplinary approaches in managing landslide risks across diverse terrains in Karo Regency.

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