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Case Study Method: Relationship between Fully Softened and Residual Shear Angle and Liquid Limit in Problematic Clay Soil

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ABSTRACT

Problem clay soils often experience a significant decrease in shear strength from peak strength to residual strength, which greatly affects slope stability and geotechnical structures. This study examines the empirical relationship between the angle of repose in fully softened and residual conditions and the liquid limit in various types of problem clay soils through a methodological case study approach. This research method is based on the need to comprehend how to operate clay soils under critical conditions, especially on slopes that have experienced movement or are in a remolded condition. The fully softened condition represents the strength of soil that has been loaded to a considerable displacement but has not yet reached the residual condition, while the residual condition represents the minimum strength that can be achieved after a very large displacement. This case study method aims to identify and analyse the mathematical correlation between shear strength parameters (fully softened and residual angles of repose) and the liquid limit as an index of plasticity that can be easily determined in the laboratory. This case study method aims to identify and analyse the mathematical correlation between shear strength parameters (fully softened and residual shear angles) and the liquid limit as an index of plasticity that can be easily determined in the laboratory. The methods used include a comprehensive literature review of previous research, secondary data collection from various geotechnical projects, and statistical analysis to determine trends in the relationship between these parameters. A case study approach was used to validate the empirical correlations found in the literature with local soil conditions. Linear and nonlinear regression analyses were applied to develop prediction equations that can be used in geotechnical engineering practice.

Keywords: clay soil, fully softened shear strength, residual shear strength, liquid limit, landslide

INTRODUCTION

Problematic clay soil is one of the greatest challenges in modern geotechnical engineering, especially in areas with geological formations dominated by fine sediments. In Indonesia, problematic clay soil is widespread in various regions, from low-lying coastal areas to volcanic slopes that have undergone intensive weathering processes (Sadono et al., 2017). The characteristics of clay soil, which are highly sensitive to changes in water content, have a high potential for swelling and shrinkage, and experience a significant decrease in shear strength after undergoing remolding or displacement, mean that this material requires special attention in the planning and design of geotechnical structures (Sari et al., 2017).

The phenomenon of shear strength reduction from peak to residual conditions in clay soils has been the focus of intensive research since the mid-20th century. Peak strength represents the maximum strength that can be mobilized by the soil at relatively small displacements, while residual strength is achieved after the soil has undergone enormous displacements and the soil particle structure has been completely oriented parallel to the shear plane (Raj Bhat, 2022). Between these two extreme conditions, there is a fully softened condition, which represents a state in which the soil has lost most of its structural strength but has not yet reached the perfect particle orientation seen in the residual condition. Understanding these three strength conditions is very important in slope stability analysis, especially for slopes that have previously experienced movement or are in conditions that allow for large displacement (Erlangga et al., 2024).

Laboratory tests, such as direct shear tests or ring shear tests, require time, money, and expertise to directly determine the shear strength parameters of clay soil, which are not always available in every project (Das, 2019). Therefore, the development of empirical correlations between shear strength parameters and more easily determined property indices, such as the liquid limit, is invaluable in geotechnical engineering practice. The liquid limit, which is the boundary between the plastic and liquid states of cohesive soil, can be determined quickly and easily using standard equipment available in almost all geotechnical laboratories. More importantly, the liquid limit has a fundamental relationship with the mineralogical composition and surface characteristics of clay particles, which in turn influence the shear behaviour of the soil (Kırım & Cebeci, 2020).

Research on the relationship between fully softened and residual shear angles and liquid limit has very broad practical implications in various aspects of geotechnical engineering. In long-term slope stability analysis, the use of appropriate strength parameters is crucial to the safety and economy of the design. The use of peak strength for slopes that are prone to large displacement will result in an unconservative and potentially failed design, while the use of residual strength for all conditions will result in an overly conservative and uneconomical design (Nugroho et al., 2024).

The fully softened condition is particularly relevant for the analysis of slopes that have experienced past movement but are currently stable, or for slopes that are predicted to experience significant displacement but not reach the residual condition. A thorough understanding of when to use fully softened strength versus residual strength requires consideration of the loading history, drainage conditions, and potential displacement that may occur during the design life of the structure (Xu et al., 2018).

Although numerous studies have been conducted to develop correlations between shear strength parameters and liquid limits, most of these were conducted on clay soils from Europe, North America, and several other Asian countries. The correlations developed from these soil databases may not be fully applicable to Indonesian clay soils, which have different mineralogical characteristics and geological histories. Volcanic clay soils, which are commonly found in Indonesia, for example, have unique characteristics compared to sedimentary clay soils, which form the basis of most previous studies (Powrie, 2018).

In addition, the high variability in the mineralogical composition of clay soils, ranging from highly active montmorillonite to relatively inert kaolinite, results in a very wide range of liquid limits and may require different correlation approaches for each mineralogical group. This study seeks to identify these gaps and contribute to a deeper understanding of the behaviour of Indonesian clay soils in the context of the relationship between shear strength and plasticity index. A methodological case study approach was chosen to enable in-depth analysis of the available data and critical evaluation of the empirical correlations found in the literature (Einav, 2007).

LITERATURE REVIEW

Basic Concepts of Clay Soil Shear Strength

The concept of shear strength in clay soil has undergone significant evolution since Coulomb first formulated shear failure criteria in the 18th century. Terzaghi and Casagrande in the early 20th century developed an understanding of the role of pore water pressure in soil shear strength, which later led to the concept of effective stress introduced by Terzaghi (Terzaghi et al., 1996). Fundamental contributions to understanding the differences between peak, fully softened, and residual strength through a series of comprehensive studies on various types of clay soils (Einav, 2007).

The concept of fully softened strength was first introduced by Skempton and Hutchinson (1969) in the context of first-time slide analysis. They defined fully softened strength as the strength of soil that has been remoulded and reconsolidated at the same stress as field stress, but has not yet undergone sufficient displacement to reach residual conditions. In a fully softened state, the original soil structure has been destroyed, but the clay particles have not yet been perfectly oriented parallel to the slip plane. The fully softened angle of repose (φ'fs) is generally 2-5° smaller than φ'peak for normally consolidated soils, but this difference can be greater in overconsolidated soils with strong structures (Powrie, 2018).

Residual strength represents the minimum strength that clay soil can achieve after undergoing a very large displacement, usually in the order of tens to hundreds of millimetres. Under these conditions, the clay particles have become fully oriented parallel to the shear plane, creating a very slippery surface with a minimum coefficient of friction. The residual friction angle (φ'r) can be much smaller than φ'peak or φ'fs, especially in clay soils with high clay mineral content and high plasticity. Research by Bishop et al. (1971) shows that φ'r can reach values as low as 8-12° in clay soils with very high liquid limits, compared to φ'peak which may reach 25-30° in the same soil (Bardanis, 2024).

Liquid Limit and Plasticity Characteristics

The liquid limit (LL), first introduced by Atterberg in the early 20th century and later standardised by Casagrande in 1932, is one of the most fundamental property indices in the characterisation of cohesive soils. The liquid limit is defined as the moisture content at which soil transitions from a plastic state to a liquid state, or more specifically, the moisture content at which soil has an undrained shear strength of approximately 2 kPa. Determination of the liquid limit using the Casagrande cup or fall cone test has become a standard procedure in almost all international geotechnical testing standards (Sudrajat, Nuraini, et al., 2023).

The liquid limit value of clay soil is greatly influenced by its mineralogical composition, particularly the type and amount of clay minerals it contains. Clay minerals such as montmorillonite, which have a crystalline structure with expandable interlayer spacing, produce a very high liquid limit (reaching 400-800% in some cases), while kaolinite, which has a non-expanding crystalline structure, produces a relatively low liquid limit (usually 40-60%). Illite and other mixed clay minerals have liquid limits between these two extremes (Sudrajat, Isradi, et al., 2023).

The relationship between liquid limit and other geotechnical characteristics has been the subject of extensive research since the mid-20th century. Casagrande (1948) created a plasticity chart that sorts cohesive soils by their liquid limit and plasticity index. This chart is still used today as the main way to sort soils in the Unified Soil Classification System (USCS). Skempton (1953) introduced the concept of activity, defined as the ratio between the plasticity index and the percentage of clay fraction (particles < 2 μm), as an indicator of the mineralogical activity of clay soils. High activity (> 1.25) indicates the presence of active clay minerals such as montmorillonite, while low activity (< 0.75) indicates inert clay minerals such as kaolinite (Lian et al., 2020).

The liquid limit is essentially a function of the specific surface area of clay particles and the characteristics of the forces between them. Clay minerals with large specific surface areas, such as montmorillonite (which can reach 800 m^2/g), require more water to lubricate the particle surface and reach the liquid limit condition compared to clay minerals with small specific surface areas such as kaolinite (10-20 m^2/g). This phenomenon also explains why soils with high liquid limits tend to have low residual friction angles, as the thicker layer of water between clay particles reduces direct contact between particles and lowers the coefficient of friction between particles (Wang et al., 2020).

A comprehensive study of more than 300 clay soil samples from various locations around the world found a strong correlation between the liquid limit and the residual angle of repose. They developed the empirical equation $\varphi'r = 29° - 0.12LL$ for soils with a liquid limit between 50% and 500%, which shows a linear decrease in the residual angle of repose with an increase in the liquid limit. This correlation has been validated by many other researchers and has become one of the most widely used empirical relationships in geotechnical engineering practice for the initial estimation of residual friction angle.

Empirical Correlation and Research

The development of empirical correlations between shear strength parameters and the liquid limit has been a focus of research since Skempton (1964) first identified that the residual angle of repose has a negative correlation with the liquid limit. Skempton's seminal research was based on back-analysis of various landslides that occurred in the United Kingdom, where he found that the angle of repose on pre-existing shear surfaces was consistently lower than the peak angle of repose measured on intact samples.

Data from various locations in North America and confirmed the downward trend of φ'r with increasing liquid limit. He also observed that the dispersion of data was quite significant, especially in the high liquid limit range, indicating that factors other than liquid limit also influence the residual angle of repose. These factors include specific mineralogical composition, non-clay fraction content, and pore water chemical characteristics.

The shear mechanism under residual conditions is highly dependent on the mineralogical composition of the soil. They categorise residual shear behaviour into three main types: sliding mode (for soils with high content of platy minerals such as montmorillonite and illite), turbulent mode (for soils with a dominant content of non-platy minerals), and transitional mode (for soils with a mixed composition). In sliding mode, clay particles are perfectly oriented parallel to the shear plane and produce a very low φ'r, while in turbulent mode, particles undergo rolling and tumbling, producing a relatively higher φ'r.

Stark and Eid (1994) conducted a comprehensive study collecting data from 358 ring shear tests on various types of clay soil. They developed a database that included information on the liquid limit, plasticity index, clay fraction, and residual shear angle for each sample. Statistical analysis of this database yielded several important correlations: (1) $\varphi'r = 29° - 0.12LL$ for all data, (2) $\varphi'r = 30° - 0.14LL$ for soils with $CF < 50\%$, and (3) $\varphi'r = 28° - 0.11LL$ for soils with $CF > 50\%$, where CF is the clay fraction. These correlations show fairly high correlation coefficients (R^2), ranging from 0.75 to 0.85, indicating that the liquid limit is indeed a good predictor of the residual angle of repose.

For the fully softened angle of repose, in various normally consolidated clay soils, it has been shown that φ'fs can be estimated using the correlation $\varphi'fs = 30.4° - 4.2 \log(PI)$, where PI is the plasticity index. Since the plasticity index has a strong correlation with the liquid limit (especially for soils with consistent mineralogy), this correlation can be converted into liquid limit form. Wesley (2003) analysed data from tropical residual clay soils and found that φ'fs generally ranges from $\varphi'r + 2°$ to $\varphi'r + 5°$, depending on the degree of overconsolidation and the stress history of the soil.

The Context of Indonesia and Tropical Clay Soil

Clay soils in Indonesia have unique characteristics compared to sedimentary clay soils, which are the focus of most international research. Most clay soils in Indonesia are residual soils resulting from the intensive weathering of volcanic rocks or folded sediments, with a mineralogy dominated by secondary clay minerals resulting from the weathering of feldspar, mica, and other primary minerals. The tropical climate with high rainfall and constant temperatures produces deep weathering profiles with geotechnical characteristics that differ from those of clay soils in temperate climates (Miao & Wang, 2022).

Extensive studies on residual clay soils in Indonesia and other Southeast Asian countries have found that these soils generally have a relatively low to moderate liquid limit (30–80%) despite their high clay fraction content. This indicates that the mineralogy is dominated by low to moderate activity clay minerals, such as kaolinite and halloysite, which are common weathering products in humid tropical conditions. The residual angle of repose of these soils is generally in the range of 13-18°, which is higher than predicted correlation developed for sedimentary soils (Ohayon & Pinkert, 2021).

Volcanic clay soils commonly found in Java, Sumatra, and other volcanic islands have specific characteristics that need to be considered. These soils often contain amorphous minerals such as allophane and imogolite in the early stages of weathering, which can produce an unusually high liquid limit relative to the actual clay content. In the later stages of weathering, these amorphous minerals transform into halloysite and then metahalloysite or kaolinite, resulting in changes in plasticity and shear strength over geological time (Sadono et al., 2017).

Indonesia's complex geological context, with its wide variation in parent rock, microclimate conditions and tectonic history, results in enormous diversity in the characteristics of clay soils. Clay soils derived from limestone weathering will have very different characteristics from clay soils derived from andesite or basalt weathering. Similarly, marine clay soils in coastal areas will differ from lacustrine or fluvial clay soils. Therefore, developing empirical correlations that can be applied generally throughout Indonesia is a challenge that requires a very large and representative database of various geological conditions.

METHODOLOGY

This study uses a methodological case study approach to analyse the relationship between the fully softened and residual angles of repose and the liquid limit in problematic clay soils. The case study approach was chosen because it allows for in-depth analysis of the available data and critical evaluation of the application of empirical correlations from the literature in the context of Indonesian clay soils. The case study method also provides flexibility to integrate various types of data and information from different sources, including laboratory data, back analysis results from landslide cases, and regional geological information (Wu et al., 2021).

Problematic clay soils are commonly found in many areas of Java Island. The distribution of problematic clay soils across Java Island led the author to take research samples in the Special Region of Yogyakarta, Banten Province, West Java Province, Central Java Province, and East Java Province. The Ministry of Energy and Mineral Resources of the Republic of Indonesia has actually mapped problematic clay soils, but according to the author, there are still many details regarding the characteristics and mechanical properties of the distribution of problematic soils and the characteristics of these soils. The unique characteristics of problematic clay soils can cause potential damage or disasters, so the author feels that further study of this type of soil is important (Duong & Suzuki, 2022).

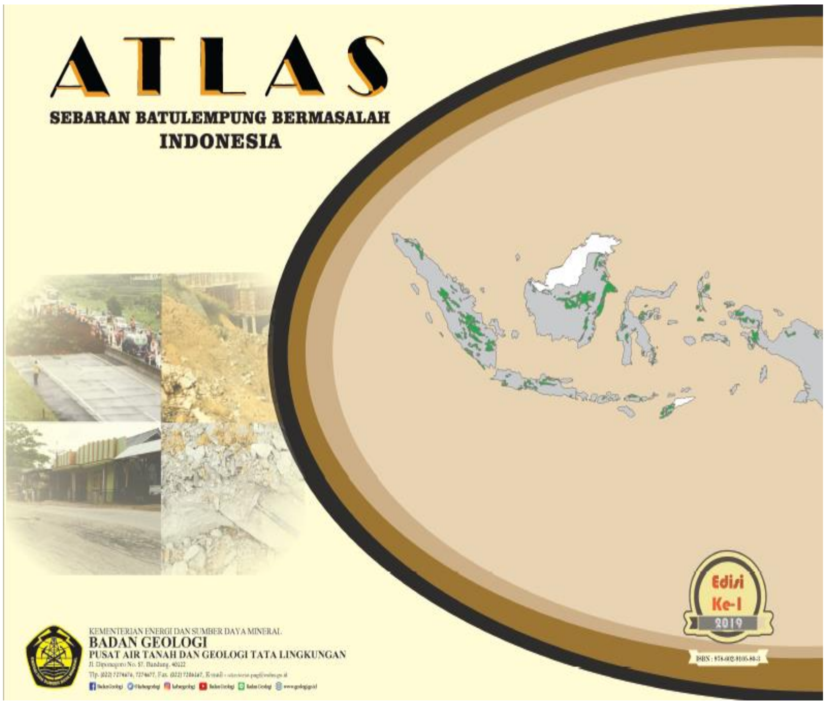

Figure 1. ATLAS, Distribution of problematic clay rocks in Indonesia, Ministry of Energy and Mineral Resources, Geological Agency, Groundwater and Spatial Geology Agency of the Republic of Indonesia

Case Study Approach

A methodological case study approach to analyse the relationship between fully softened and residual angle of repose and liquid limit in problematic clay soils. The case study approach was chosen because it allows for in-depth analysis of available data and critical evaluation of the application of empirical correlations from the literature in the context of Indonesian clay soils. The case study method also provides flexibility to integrate various types of data and information from different sources, including laboratory data, back analysis results from landslide cases, and regional geological information (Habibbeygi & Nikraz, 2018).

The research focuses exclusively on problematic clay soils, characterized by a plasticity index exceeding 15% and the capacity to undergo a substantial reduction in strength from peak to residual states. The geographical focus is on Indonesia, but comparative data from other Southeast Asian countries with similar geological conditions will also be considered. This research does not include new laboratory testing but relies entirely on secondary data available from literature, project reports, and previous research databases.

Comprehensive Literature Study

A comprehensive literature review was conducted to establish a theoretical foundation and identify empirical correlations developed by previous researchers. The literature reviewed included international journal publications, conference proceedings, standard geotechnical textbooks, and research reports from various institutions. Scientific databases such as Google Scholar, ScienceDirect, ASCE Library, and Scopus were used for systematic literature searches using relevant keywords.

Literature selection criteria include relevance to the research topic, quality of research methodology, sample size and data representativeness, as well as the reputation of the publication and researchers. Priority is given to studies that provide raw data or detailed information about land properties, testing conditions, and analytical methodologies, thereby enabling re-analysis or independent validation. Literature that only provides final correlations without supporting data is still reviewed for context and comparison but is given less weight in the analysis (Habibbeygi & Nikraz, 2018).

From the literature review, various empirical correlations between φ'r or φ'fs and the liquid limit were identified and documented, including mathematical equations, applicability ranges, and coefficients of determination (R^2). These correlations were then categorised based on soil type (sedimentary vs residual, marine vs non-marine), dominant mineralogy, and geographical region. A critical analysis was conducted for each correlation, evaluating the strengths and limitations of the methodology used, as well as its relevance to the Indonesian context (Das, 2019).

Specific Case Analysis

As an integral part of the case study methodology, several landslide cases or specific geotechnical problems were analysed in depth to provide practical context and validation for the correlations developed. Case selection is based on the following criteria: adequate documentation of soil properties and strength parameters, availability of comprehensive laboratory investigation results including residual or fully softened strength testing, back analysis performed using solid methodology, and representativeness of problematic clay soil conditions commonly found in Indonesia.

The results of the analysis of these specific cases offer informative perspectives on the practical application of empirical correlations and help to identify conditions where extra caution or additional investigation is required. Systematic differences between back-calculated parameters and correlation predictions were analysed to identify the need for modifications or correction factors for Indonesian soil conditions. Complete documentation of each case was compiled as part of the research results, providing a valuable reference for geotechnical practitioners when dealing with similar problems in the future (Wu et al., 2021).

FINDINGS AND DISCUSSION

Weak Soil Foundation Unable to Resist Soil Movement

The incidents in Brebes, Banjarnegara, Hambalang, and the landslide at KM 72 of the Cipularang Toll Road in Figure 1 occurred in 2024. Several media outlets covered these incidents, which went viral in Central Java. They occurred during heavy rain when the soil foundation was unable to withstand the movement of the earth, causing damage to the buildings above. The author wishes to study these events in more detail and hopes to obtain information and solutions regarding them. Based on the distribution map of problematic clay soil, the location is included in the problematic clay soil map of Central Java Province. The Indonesian geological map includes the area in the problematic clay soil distribution. The location is part of the Halang Formation (Tmph), which consists of andesite sandstone, tuff conglomerate, and napal, interbedded with sandstone. Above the sandstone layer, there are traces of worms. Small foraminifera indicate a late Miocene age and thickness approximately 800 m.

Figure 2. Damaged Houses in Winduaji Village, Paguyangan District, Brebes Regency, Central Java

The landslide disaster killed more than 100 people. The landslide material almost buried an entire hamlet in Banjarnegara. The location of the landslide in Jemblung Hamlet is now prohibited from being used as a residential area and, according to reports, is now only planted with trees. Residents relocated their houses near the site to Bandingan Village, Karangkobar Subdistrict, a short distance from the incident site. Looking at the Indonesian geological map, the area is part of the Ligung (QTIc) formation, which consists of tuffaceous claystone, cross-bedded tuffaceous sandstone, and conglomerate, with localized plant remains and young coal, indicating that this member was deposited in a non-marine environment. It was previously referred to as the lower member of the Ligung Formation (van Bemmelen, 1937).

Figure 3. Jemblung Hamlet in Banjarnegara Nearly Disappeared, Swallowed by a Landslide

The road was split by the river flow, even though the concrete road was the main road for residents' activities. The incident occurred during heavy rain, causing the Bobojong River to overflow and resulting in the collapse of the bridge connecting the villages. The information obtained was that the retaining wall of the bridge had collapsed, causing the incident. The author wishes to study this incident in more detail and hopes to obtain information and solutions. Based on the distribution map of problematic clay, the location is included in the map of problematic clay in West Java Province. Looking at the Indonesian geological map, the area is included in the Kencana and Limo mountain breccia and lava formations, which are andesite and breccia blocks with numerous pyroxene phenocrysts and basalt lava.

Figure 4. Route divided by river flow

A landslide affected the Cipularang Toll Road at KM 72, causing the shoulder of the toll road to collapse. The incident was investigated in detail, and it is hoped that information and solutions will be found. Based on the distribution map of problematic clay rocks, the location is included in the map of problematic clay rocks in West Java Province. Based on the Indonesian geological map, the location is included in the tuff sandstone and conglomerate unit, namely tuff sandstone, conglomerate, tuff, and breccia.

Figure 5. Repairs at KM 72 of the Cipularang Toll Road affected by a landslide

The Failure of Strong Soil Shear

Most slope failures occur on soils with high plasticity indices. Clay soils with high plasticity are classified as CH according to the Unified Soil Classification System and have a liquid limit of more than 50. Soils containing montmorillonite and marine shales from the Tertiary, Cretaceous, and Permian periods contain montmorillonite. Marine shales are the most problematic shales from an engineering perspective because, when excavated, they tend to form unstable slopes. Clay soils with high plasticity, rigidity, and overconsolidation are highly susceptible to changes in climate and weather, as such conditions can result in soil weathering in areas directly exposed to water and air. This automatically results in a decrease in soil shear strength.

Table 1. Estimated Shear Strength Failure

Soil Type	Typical ranges of strain at failure Ɛ*f* %	
	CU test	CD test
Undisturbed clay:		
Normally consolidated	15-20	15-20
Overconsolidated	20+	4-15
Remoulded clay	20-30	20-25
Brittle soils	1-5	1-5
Compacted boulder clay:		
Dry of o.m.c	3-10	4-6
Wet of o.m.c	15-20	6-10
Compacted sandy silt	8-15	10-15
Saturated sand:		
Dense	25+	5-7
Loose	12-18	15-20

The shear strength of soil is its ability to resist loads or forces that can cause landslides, collapses, sliding, or shifting. Two components that make up the shear strength of soil are the angle of repose (φ) and soil cohesion (c). The values of these two parameters can be determined by direct shear tests, direct shear tests, and other tests. In the case of landslides involving high plasticity stiff overconsolidated clay, the use of cohesion (c) and angle of friction (φ) in peak strength is considered overly optimistic. Soil investigations of this type of soil, either by sounding or standard penetration test (SPT), produce high safety figures because it is classified as hard or stiff clay if QC and NSPT are correlated with undrained strength for slope stability calculations. In reality, this type of soil is often found in landslide cases. One approach to dealing with landslides in problematic clay soils is to identify the fully softened shear strength or residual shear strength.

Practical Applications in Geotechnical Design

The application of the correlation between the angle of repose and the liquid limit in geotechnical engineering practice requires a thorough understanding of the conditions under which the fully softened versus residual strength parameters should be used. The selection of the appropriate parameter depends heavily on the type of geotechnical problem, the loading history, and the potential displacement that may occur during the design life of the structure. The following is a general guide for parameter selection in various design situations:

1. Stability of Natural Slopes or New Excavations
   Peak strength is generally appropriate for short-term stability analysis of natural slopes that have never experienced movement or of newly excavated slopes on undisturbed soil. For long-term stability, fully softened strength may be more appropriate, especially if the slope experiences gradual deterioration due to weathering or creep. Residual strength only needs to be considered for ultimate limit state analysis or if there are indications that the slope has experienced movement in the geological period.
2. Reactivation of Previous Landslides
   For slopes with a history of movement or landslides, especially if there are indications of pre-existing slip surfaces (slickensided surfaces, old scarps), residual strength should be used for zones along old slip surfaces. Soil outside the slip zone may still have peak or fully softened strength. Mixed-mode analysis using different parameters for different zones may be necessary to reflect realistic conditions.

3. Embankments on Soft Ground
   For the analysis of embankment stability on soft clay soil, the fully softened strength of the foundation soil is generally appropriate for long-term stability. This is because the soil will undergo significant remoulding due to construction and consolidation, but the displacement may not be large enough to reach the residual condition. Peak strength can be used for short-term (end of construction) stability if the rate of loading is fast enough that the undrained condition dominates.
4. Permanent Retaining Structures
   For the design of retaining walls or permanent slope support structures, the selection of parameters depends on the potential for movement. If the structure is designed to prevent movement entirely (displacement < a few centimetres), peak or fully softened strength is appropriate. If the structure is designed with a greater tolerance for movement or if there is a risk of progressive failure, residual strength must be considered, especially for back-of-wall soil that may experience significant shearing.

CONCLUSION

The residual angle of repose shows a strong and consistent negative correlation with the liquid limit ($r = -0.82$, $p < 0.001$), confirming the findings of previous international studies. The liquid limit has been proven to be a reliable indicator for initial estimation of the angle of repose, especially for clay soils with relatively consistent mineralogy and composition.

Required Modifications for the Indonesian Context Indonesian residual clay soils, which are generally dominated by kaolinite and halloysite resulting from volcanic weathering, exhibit residual angles of repose that are consistently 2-3° higher than predictions using standard international correlations.

An understanding of the factors that influence the relationship between the angle of repose and the liquid limit helps engineers interpret test results and make more informed design decisions. Validation through back analysis of local cases provides confidence in the application of correlations to Indonesian conditions.

REFERENCES

Bardanis, M. (2024). Direct Shear Testing of Various Hard Soils and Weak Rocks from Greece. *Geotechnical and Geological Engineering*, *42*(5), 3231–3250.

Das, B. M. (2019). *Advanced Soil Mechanics*. CRC press.

Duong, N. T., & Suzuki, M. (2022). Rate Effects on Peak and Residual Strengths of Overconsolidated Clay in Ring Shear Tests. *Periodica Polytechnica Civil Engineering*, *66*(1), 298–309.

Einav, I. (2007). Soil Mechanics: Breaking Ground. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1861), 2985–3002.

Erlangga, E., Sadono, K. W., & Putranto, T. T. (2024). Analisa Perbandingan Penurunan Awal Bendungan Tipe Material Timbunan Urugan Batu dan Urugan Tanah (Studi Kasus Bendungan Digoel-Papua): Comparative Analysis of the Initial Decline of Dam Material Type of Stone Urugan Embankment and Soil Urugan (Digoel Dam. *Bentang: Jurnal Teoritis Dan Terapan Bidang Rekayasa Sipil*, *12*(1), 83–96.

Habibbeygi, F., & Nikraz, H. (2018). Effect of Shear Rate on the Residual Shear Strength of Pre-Sheared Clays. *Cogent Geoscience*, *4*(1), 1453989.

Kırım, G., & Cebeci, A. (2020). Investigation of Shear Strength of Prefailed Overconsolidated Clayey Slopes by Fast Shearing. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *24*(2), 340–361.

Lian, B., Wang, X., Peng, J., & Huang, Q. (2020). Shear Rate Effect on the Residual Strength Characteristics of Saturated Loess in Naturally Drained Ring Shear Tests. *Natural Hazards and Earth System Sciences*, *20*(10), 2843–2856.

Miao, H., & Wang, G. (2022). Shear Rate Effect on the Residual Strength of Saturated Clayey and Granular Soils under Low-to High-Rate Continuous Shearing. *Engineering Geology*, *308*, 106821.

Nugroho, U., Wardani, S. P. R., & Setiadji, B. H. (2024). Rigid Pavement Acceleration-Velocity Dynamic Behavior Induced by Traffic Load. *Civil Engineering and Architecture*, *12*(3), 1386–1394.

Ohayon, Y. H., & Pinkert, S. (2021). Experimental Evaluation of the Reference, Shear-Rate Independent, Undrained Shear Strength of Soft Clays. *International Journal of Geomechanics*, *21*(11), 6021031.

Powrie, W. (2018). *Soil Mechanics: Concepts and Applications*. CRC Press.

Raj Bhat, D. (2022). Shear Rate Effect on Residual Strength of Typical Clay Soils. *Innovative Infrastructure Solutions*, *7*(1), 36.

Sadono, K. W., Pamungkas, G., Eko Suprapto, R., & Supratama, T. (2017). Analisis Geologi Teknik Pada Kegagalan Bendung Cipamingkis, Bogor, Provinsi Jawa Barat. *Proceeding Seminar Nasional Kebumian Ke*, *10*.

Sari, U. C., Wardani, S. P. R., & Partono, W. (2017). Influence of Pore Water Pressure to Seepage and Stability of Embankment Dam (Case Study of Sermo Dam Yogyakarta, Indonesia). *MATEC Web of Conferences*, *101*, 5007.

Sudrajat, K. M., Isradi, M., Prasetijo, J., Aden, T. S., & Rifai, A. I. (2023). Stabilization of Expansive Clay with Sand on CBR Value. *European Journal of Science, Innovation and Technology*, *3*(5), 1–8.

Sudrajat, K. M., Nuraini, A., Isradi, M., Prasetijo, J., & Hamid, A. (2023). *Effect of Fly Ash Addition in West Jakarta Cengkareng Area Soil on CBR Value*, *08*(09), 2795–2800. https://doi.org/10.47191/etj/v8i9.11

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil Mechanics in Engineering Practice*. John Wiley & Sons.

Wang, L., Han, J., Liu, S., & Yin, X. (2020). Variation in Shearing Rate Effect on Residual Strength of Slip Zone Soils Due to Test Conditions. *Geotechnical and Geological Engineering*, *38*(3), 2773–2785.

Wu, S., Lok, T., Xu, Y., Wang, W., & Wu, B. (2021). Rate-Dependent Behavior of a Saturated Reconstituted Clay under Different Over-Consolidation Ratios and Sample Variance. *Acta Geotechnica*, *16*(11), 3425–3438.

Xu, C., Wang, X., Lu, X., Dai, F., & Jiao, S. (2018). Experimental Study of Residual Strength and the Index of Shear Strength Characteristics of Clay Soil. *Engineering Geology*, *233*, 183–190.