Buletin Profesi Insinyur 8(2) (2025) 050–055
http://dx.doi.org/10.20527/bpi.v8i2.294
ISSN 2654-5926

Analytical and Numerical Analysis of Retaining Wall Stability in Soft Soil: A Case Study of the Sakan–Mendawai Drainage Project in Palangka Raya

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This study aims to analyze the stability of a counterfort retaining wall constructed on soft cohesive soil at the Sakan–Mendawai drainage project in Palangka Raya. Analytical methods based on Rankine's earth pressure theory were used to calculate safety factors against overturning, sliding, and bearing failure, resulting in values of 5.644, 4.513, and 10.741, respectively. To complement the analysis, numerical modelling using PLAXIS was applied specifically to estimate the overall stability of the wall–soil system, yielding a safety factor of 1.503. The results confirm that the design meets standard safety criteria under static loading conditions. While the numerical model was limited to overall safety assessment, the combination of analytical and numerical approaches offers a clear and practical evaluation of retaining wall performance in soft soil contexts.

Keywords: Retaining wall, soft soil, stability analysis, Rankine theory

Submitted: 6 July 2025
Revised: 18 July 2025
Accepted: 20 July 2025
Published: 24 July 2025

Introduction

Urban drainage infrastructure presents unique geotechnical challenges, particularly in areas dominated by soft cohesive soils. These soils, characterized by high moisture content, low shear strength, and high compressibility, significantly complicate the design and performance of retaining wall systems. The behavior of soft soils under varying loads often results in excessive settlement, pore water pressure buildup, and long-term deformation (Rosli et al., 2020; Yuan et al., 2023). Such instability has been linked to insufficient drainage, material inadequacy, and suboptimal design strategies (Alimohammadi & Memon, 2023; Chen et al., 2022).

Recent studies emphasize the importance of integrating effective drainage mechanisms and structural reinforcements to enhance consolidation and minimize lateral soil pressures (Yao et al., 2024). Advanced solutions such as drainage piles, lightweight fills, and fiber-reinforced soils have shown promise in improving both the strength and durability of retaining structures in soft subgrade environments (Monkul & Özhan, 2021; Sajjad et al., 2022). Similarly, appropriate material selection, such as biopolymers, geotextiles, or nano-stabilizers, has been shown to influence both the flexural performance and long-term resilience of these systems (Akerele & Aduwenye, 2023; Majeed et al., 2024).

In soft soils where excavation exceeds critical depths, conventional methods using cemented retaining walls often encounter challenges such as crack propagation and brittle failure under stress (Liang et al., 2022). Thus, a growing body of research recommends the integration of flexible retaining systems, like sheet-pile walls or diaphragm walls, along with drainage and soil improvement techniques (Thendar et al., 2023; Lin et al., 2023). However, the success of such strategies depends on a site-specific understanding of soil properties, loading conditions, and wall-soil interaction.

Despite the wealth of literature addressing individual components of retaining wall performance, there remains a need for integrated methodologies that combine analytical and numerical perspectives. While analytical methods such as Rankine's theory provide fundamental insight into lateral pressure distribution and wall stability, numerical simulations offer a more detailed understanding of stress paths, deformation patterns, and global safety factors under varying conditions (Jiang et al., 2021; Mashayekhi & Khanmohammadi, 2024).

This study proposes a comprehensive design optimization approach for counterfort retaining walls constructed in soft soil environments. Taking the urban drainage project in Sakan–Mendawai, Central Kalimantan, Indonesia as a case study, the research integrates analytical methods with numerical modelling to evaluate stability against sliding, overturning, and bearing failure. The novelty of this work lies in the systematic coupling of traditional geotechnical design principles with advanced modelling strategies for infrastructure built on challenging subgrade conditions. The findings contribute meaningfully to the evolving discourse on sustainable geotechnical design by highlighting the critical role of hydrological dynamics in slope stability analysis. Moreover, the results offer practical and evidence-based insights for urban infrastructure planning and risk mitigation in soft soil regions, where environmental sensitivity and construction challenges often intersect.

How to cite this article:
Faradila, A., Saputra, N.A., Ansyari, R.M., Alfaridzi, R. (2025) Analytical and Numerical Analysis of Retaining Wall Stability in Soft Soil: A Case Study of the Sakan–Mendawai Drainage Project in Palangka Raya. *Buletin Profesi Insinyur* 8(2) 050-057

 ISSN 2654-5926

Materials and Methods

Study Location

This research was conducted at the site of the Sakan–Mendawai Main Drainage Project, located along Jalan Sakan–Mendawai, Tjilik Riwut Km 1, in Palangka Raya, Central Kalimantan, Indonesia (Figure 1). The study area was chosen due to its challenging subgrade conditions, which consist of soft cohesive soils commonly encountered in low-lying urban regions. These soils pose risks for structural stability, particularly in the construction of retaining walls for drainage infrastructure. The retaining structure under study supports the drainage channel, and its performance is heavily influenced by the characteristics of the surrounding subsoil.

Figure 1 Study Location: Sakan–Mendawai Drainage Corridor in Palangka Raya, Central Kalimantan

Soil Investigation and Laboratory Testing

Field investigations were followed by laboratory testing to characterize the soil's geotechnical behavior. The collected soil samples were tested to determine moisture content, specific gravity, unit weight, and consistency limits. Laboratory analysis yielded a moisture content of 29.85%, indicating a high-water retention characteristic typical of soft clays. The specific gravity was measured at 2.58, and the bulk density of the soil was found to be 1.85 grams per cubic centimeter. The Atterberg limits testing revealed a plastic limit (PL) of 42.60%, a liquid limit (LL) of 25.00%, and a plasticity index (PI) of 17.60. These values confirm that the soil has a relatively high plasticity and is susceptible to volumetric changes under variations in moisture content. The results are consistent with previous classifications of fine-grained, compressible soil with low shear strength, which justifies the need for a reinforced retaining system.

Subsurface Profiling and Soil Classification

Subsurface soil conditions were further explored using Cone Penetration Testing (CPT). The CPT provided continuous profiles of cone resistance (q_c), which were used to identify and categorize the types of soil layers along depth. These values formed the basis for defining stratigraphic zones and supported the analytical and numerical modelling processes. The classification also allowed differentiation between relatively stiffer and weaker layers, which is critical in determining the wall's base level and predicting potential failure surfaces.

Based on the Cone Penetration Test (CPT) data, the subsoil conditions at the project site consist of stratified layers with varying cone resistance values (qc), indicating differences in soil strength and composition. The topmost layer, extending from the ground surface to a depth of 4.8 meters, is composed of organic clay with a qc value of 0 kg/cm³, reflecting extremely soft and highly compressible material with minimal bearing capacity. This is followed by a layer of stiff clay between elevations –4.8 m to –5.4 m, showing a modest qc of 10 kg/cm³. Below this, from –5.4 m to –7.0 m, the soil transitions into silty sand to sandy silt with a significantly higher qc of 82.5 kg/cm³, indicating improved strength and stiffness. The next layer, extending to –7.6 m, consists of sandy silt to clayey silt with a qc of 63.33 kg/cm³. The deepest layer encountered, from –7.6 m to –9.4 m, comprises clayey silt to silty clay, exhibiting the highest qc of 108.89 kg/cm³. This stratigraphy highlights a gradual increase in cone resistance with depth, which is crucial for evaluating bearing capacity and stability in retaining wall design over soft soil formations.

Analytical Design and Stability Evaluation

The design of the retaining wall followed conventional geotechnical analysis principles, with emphasis on stability against overturning, sliding, and bearing failure. Rankine's earth pressure theory was employed to calculate the lateral loads acting on the wall. Stability against overturning was assessed by calculating the ratio of resisting moment to the overturning moment. For soft cohesive soils, a minimum safety factor of 2.0 was adopted. The sliding resistance was calculated by comparing the passive and frictional forces resisting movement to the active horizontal forces, again requiring a safety factor of no less than 2.0. For the bearing capacity check, classic bearing capacity theory was applied, incorporating parameters such as soil cohesion, effective footing width, soil unit weight, and bearing capacity factors. The ultimate bearing capacity was computed and compared to the applied structural pressure, and the resulting safety factor was required to exceed 3.0 to ensure long-term serviceability under anticipated loading.

Numerical Modelling Framework

In addition to the analytical evaluation, a numerical modelling approach was employed to simulate the soil–structure interaction and to verify the results under realistic field conditions. A finite element model was developed to represent the geometry of the retaining wall and the adjacent soil strata in a two-dimensional plane strain condition. Material parameters obtained from laboratory tests and CPT results were assigned to the respective soil layers. The construction process was simulated in stages to account for incremental loading and wall backfilling, which enabled the observation of stress redistribution and displacement behavior at each phase of construction.

The numerical analysis incorporated appropriate boundary conditions, mesh refinement strategies, and convergence criteria to ensure that the simulation accurately reflected expected field performance. Outputs such as displacement vectors, stress concentration zones, and global stability indicators were generated for qualitative

 ISSN 2654-5926

assessment. The modelling process was intended to serve as a complement to the analytical calculations, providing a more nuanced understanding of potential failure mechanisms and identifying zones of critical deformation.

Specifically, vertical fixity was applied to the model base to simulate firm foundation support, while the lateral boundaries were assigned roller conditions to allow vertical movement but restrict horizontal displacement. This boundary setup reflects realistic constraints on the soil mass surrounding the wall. Mesh refinement was applied adaptively, with denser meshing concentrated near the wall–soil interface and along anticipated failure surfaces, where stress and deformation gradients are expected to be higher. This approach enhances numerical accuracy and ensures that critical behavior zones are adequately captured in the simulation.

Results and Discussion

Structural Configuration and Geometric Characteristics of the Retaining Wall

The counterfort retaining wall analyzed in this study was designed to support drainage infrastructure built on soft subsoil in Palangka Raya. As shown in Figure 2, the wall has a total height of 4.8 meters and a base width of 5 meters, with segmented components including a 2-meter toe, 1-meter heel, and 1-meter rear extension. The vertical segment includes a 0.4-meter-thick base slab and a 2.2-meter retained height. This configuration aims to improve resistance against sliding, overturning, and bearing capacity failure.

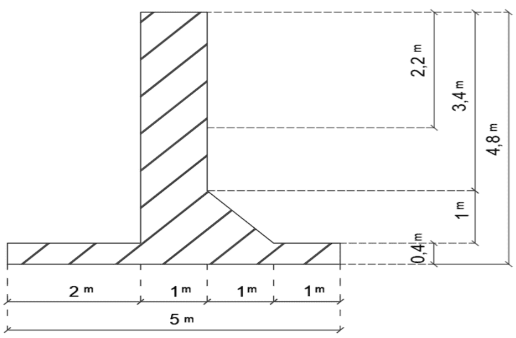

Figure 2 Cross-Sectional Dimensions of Counterfort Retaining Wall Design

Stability analysis employed Rankine's earth pressure theory, a classical framework used to estimate lateral earth pressures under simplified assumptions of cohesionless soil and wall-soil interaction. While idealized, Rankine's model remains widely applied and has been extended in recent research to account for inclined backfills, wall rotation, and stress arching effects (Luo et al., 2021; Wang et al., 2022). In this study, it provided a basis for calculating active pressures and resulting structural demands.

Recent developments combine Rankine theory with computational modelling for enhanced accuracy (Topalska & Mihova, 2024). Furthermore, understanding shear interaction at the wall-soil interface is essential for predicting sliding behavior, and can be informed by laboratory shear tests and micro-mechanical modelling (Guo et al., 2020; Wang et al., 2021). Materials such as geofoam are also increasingly used to reduce lateral loads in soft soil environments (Gunawan, 2022, 2024).

Analytical Evaluation of Stability

Analytical evaluation of the counterfort retaining wall was performed to verify its stability under static loading conditions. The assessment addressed three primary failure modes (i.e., overturning, sliding, and bearing capacity) using both manual calculations based on Rankine's earth pressure theory and simulation validation through Plaxis. The resulting safety factors were compared with the minimum requirements specified in SNI 8460:2017.

For overturning stability, the calculated factor of safety was 5.64, significantly exceeding the minimum requirement of 2.0 for cohesive subsoils. This indicates a strong resistance against rotational failure due to lateral earth pressures. Similarly, the sliding stability factor was determined to be 4.51, also well above the minimum standard of 1.5, confirming that the wall has sufficient horizontal resistance provided by base friction and passive resistance at the toe. The bearing capacity evaluation yielded a safety factor of 10.74, indicating that the vertical stress transmitted to the subgrade is far below the ultimate bearing capacity of the foundation soil. This high value suggests conservative design with respect to vertical loading.

Figure 3 presents a finite element model of a counterfort retaining wall constructed using PLAXIS in a two-dimensional plane strain condition. The model includes multiple soil layers with different material properties, representing stratified subsoil conditions. The retaining wall structure is defined using plate elements, with interface elements along the wall-soil contact to capture shear interaction accurately.

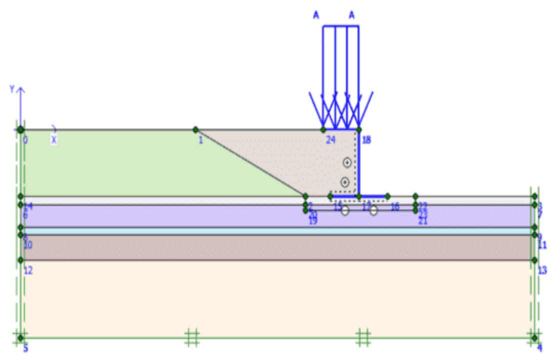

Figure 3 Finite Element Model of Retaining Wall Using PLAXIS

A vertical distributed load is applied to the backfill surface to simulate surcharge or operational loading. Boundary conditions are defined by fixing the base vertically and restraining the lateral movement of the model sides. The green markers indicate initial stress conditions and mesh boundaries. This setup allows for detailed analysis of lateral displacement, stress distribution, and global stability performance of the wall under static conditions.

In addition to these individual checks, the overall global stability of the wall–soil system was analyzed using finite element simulation via Plaxis. The resulting factor of safety was 1.503, marginally above the minimum requirement of 1.5. Despite its proximity to the threshold, the structure is still considered safe, though further attention to construction quality and material variability in the field is recommended to ensure performance reliability.

Figure 4 shows the material database interface in PLAXIS where various soil layers and interfaces are defined for the numerical model. The project includes seven distinct soil types: Organic Clay, Clay, Silty SAND to sandy SILT, Sandy SILT to clayey SILT, Clayey SILT to silty CLAY, Bedrock, and a Fill layer ("Timbunan"). These classifications reflect the stratified subsurface conditions identified from CPT data and field observations. While detailed numerical values of parameters such as stiffness modulus, cohesion, or friction angle are not displayed in this interface, each material entry is conceptually assigned representative geotechnical characteristics that allow the model to simulate realistic soil behavior and interaction with the retaining wall system under static loading conditions.

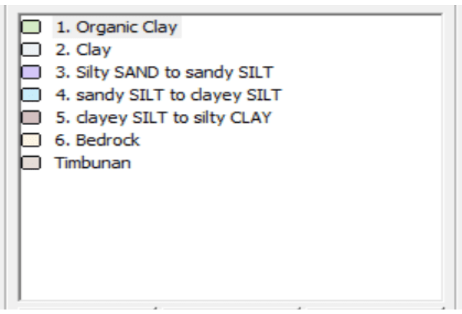

Figure 4 Soil and Interface Material Types Defined in PLAXIS

A summary of the analytical evaluation is presented in Table 1. Based on both manual and numerical assessments, all evaluated stability criteria meet or exceed the relevant design standards, and the structure is therefore classified as stable.

Table 1. Summary of Stability Evaluation Results

Description	Manual Calculation and Plaxis	Safety Standard (SNI 8460:2017)	Conclusion
Stability Against Overturning	5.644	2	SAFE
Stability Against Sliding	4.513	1.5	SAFE
Bearing Capacity Stability	10.741	3	SAFE
Overall Stability (Plaxis Software)	1.503	1.5	SAFE

Discussion of Stability Evaluation

The analytical and numerical evaluation of the counterfort retaining wall's stability demonstrates a satisfactory performance under static loading conditions. Using Rankine's earth pressure theory as the basis for lateral load estimation, the design adheres to classical geotechnical principles where active earth pressure is assumed to act as a function of wall height and soil friction angle (Liu et al., 2022; Zhang et al., 2023). Despite its simplifying assumptions, Rankine's model remains widely used due to its straightforward application and compatibility with limit equilibrium methods (Arama et al., 2021).

Nonetheless, Rankine's approach has limitations, particularly in soft cohesive soils where wall rotation and complex stress states may not be adequately captured (Lu et al., 2023; Zhou et al., 2023). Studies suggest that analytical safety factors can be conservative and must be calibrated with site-specific conditions and validated using numerical methods (Luo et al., 2021; Liang & Chen, 2023). In this research, the calculated safety factors for overturning (5.64), sliding (4.51), and bearing capacity (10.74) all exceed national safety standards (SNI 8460:2017), confirming the structural reliability under conventional loads.

Numerical modelling using PLAXIS further validated these results, producing an overall factor of safety of 1.50, marginally above the 1.5 threshold. This aligns with findings from recent literature that emphasize PLAXIS's capability in capturing soil–structure interaction with greater fidelity, especially in complex configurations or under dynamic influences (Feligha et al., 2023; Bekkar et al., 2024).

In addition, the global safety factor obtained from the PLAXIS simulation (1.503) lies very close to the minimum required value of 1.5. While technically acceptable, such a narrow margin demands special attention in practice. Construction tolerances, material variability, and unforeseen external loads may compromise performance if not properly managed. Therefore, it is advisable to apply stringent quality control measures during construction and consider more conservative assumptions in future designs to ensure adequate long-term safety.

Furthermore, simulations that consider material properties, water content, and reinforcement strategies have shown strong agreement with field observations, underlining the value of integrating empirical data and advanced modelling (Hassan & Zakraia, 2024; Zhao et al., 2022; Hasan et al., 2024). While both analytical and numerical methods yielded safety factors that satisfy the required thresholds, a noticeable gap exists between their results. This discrepancy arises primarily from the differences in their underlying assumptions. Analytical approaches, such as Rankine's theory, rely on simplified models that assume uniform soil properties and idealized failure surfaces. In contrast, numerical modelling with PLAXIS incorporates more realistic features, including soil–structure interaction, stress redistribution, and non-linear deformation behavior. Recognizing this contrast is essential for engineers to make informed decisions when selecting design methodologies, especially in projects involving complex subsurface conditions.

Conclusion

This study conducted an integrated analytical and numerical analysis of a counterfort retaining wall constructed on soft soil at the Sakan–Mendawai drainage project in Palangka Raya. Analytical results using Rankine's earth pressure theory showed safety factors of 5.644 for overturning, 4.513 for sliding, and 10.741 for bearing capacity—all exceeding the minimum thresholds. A complementary finite element simulation using PLAXIS produced an overall stability factor of 1.503, indicating that the structure meets safety requirements under static loading.

The findings demonstrate that the combination of classical limit equilibrium analysis and targeted numerical modelling offers a robust and efficient methodology for assessing the stability of retaining walls in cohesive subgrade conditions. While the numerical analysis in this case was not employed for design optimization, its application in evaluating overall safety reinforces the analytical outcomes and captures complex soil–structure interactions. This approach provides a practical framework for future studies addressing retaining wall performance in geotechnically challenging environments, especially where full-scale field testing is limited.

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