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Comparative Analysis of Analytical and Numerical Methods on the Safety Factor of Retaining Walls

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A B S T R A C T

The stability of retaining walls is a major concern in geotechnical design, especially in landslide-prone areas such as Indonesia. A comprehensive analysis requires an in-depth understanding of the failure mechanism and the factors that influence its stability. Therefore, a comparison of various analytical and numerical methods in the stability of retaining walls is an important step to determine the most effective approach. The data were collected through laboratory tests and field investigations of soil properties. The retaining wall design was modeled using Plaxis and Midas software. The analysis focused on comparing the safety factor values obtained from the Rankine method with those derived from Plaxis and Midas simulations. The results show that Rankine provides a high safety factor, namely 2.54 for rotation and 2.447 for shear. Rankine, although simple, remains relevant for uniform soil conditions. Plaxis can provide more detailed deformation and pressure distribution predictions with a safety factor reaching 2.95 in the third excavation stage. Meanwhile, Midas provides a comprehensive analysis of axial force and bending moment with a safety factor value that tends to be smaller. This study provides new insights into how each method can be used effectively for different technical conditions, and provides practical guidelines for geotechnical planners in choosing the appropriate analysis method to improve the efficiency and safety of retaining wall design.

1. Introduction

Indonesia is one of the countries that is prone to natural disasters, including landslides. The landslide that occurred caused great losses, both in terms of material and casualties. A technical solution that can sustain the construction load effectively is required to address the landslide. Building retaining walls is a frequently used technique [1]–[4]. A retaining wall is a

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construction meant to support the ground behind it. The purpose of retaining walls is to support the weight of sloped soil and buildings, earthquake loads, machine loads that produce vibrations, and others [5]. It prevents sliding down and rupturing slope-faced slopes in cuts and fills by maintaining the earth mass's steep-faced slope. The backfill or retained material pushes the structure, which tends to slide or topple it, or both [6], [7].

Retaining walls must be designed appropriately to ensure their effectiveness, especially in the face of dynamic loads and varying soil conditions [8], [9]. Retaining walls must be designed taking into account various factors, including soil characteristics, external loads, and environmental conditions [10], [11], [12]. Inappropriate design can cause structural failure, which is economically detrimental and endangers human safety. In the design process, a retaining wall's stability is evaluated using the safety factor parameter, which measures the ratio between the retaining force and the driving force [13]. The safety factor is the main indicator to ensure the structure can withstand external loads without failing.

Various methods can be used to evaluate safety factors, ranging from the simple Rankine method to finite element-based analysis using software such as Plaxis and Midas [14]–[16]. The Rankine method provides a fast analytical approach and is suitable for simple soil conditions [10], while Plaxis and Midas allow more detailed analysis, including deformation and soil pressure distribution [17], [18]. Research on the stability of retaining walls has been carried out using various analytical and numerical methods. Studies using the Rankine analytical method have been widely used because of their simplicity and ability to provide initial estimates of active and passive earth pressure. However, the Rankine approach tends to be less accurate in dealing with heterogeneous or complex soil conditions [19], [20].

Additionally, numerical studies such as with Plaxis 2D and 3D show better capabilities in predicting soil lateral deformation and stress [21]. Plaxis 3D is considered more accurate than Plaxis 2D [22]. Other research using Plaxis on soldier piles found that stability was greatly influenced by the depth of embedment and characteristics of supporting elements, such as the use of horizontal lagging [23], [24]. On the other hand, Midas is also a tool that can carry out numerical analysis of retaining wall evaluation. This software can also provide predictions of safety factor values for retaining walls [25]. The results of this software are considered capable of evaluating the planned retaining wall design by outputting various parameters [26]. Previous research has shown that analytical and numerical methods have been used to analyze the stability of retaining walls. However, much research has not been comparing analytical methods and numerical analysis for the design of spun pile-based retaining walls.

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This research aims to compare analytical and numerical methods in analyzing the stability of spun pile-based retaining walls. By comparing the Rankine, Plaxis, and Midas methods, this research aims to identify critical parameters that influence the performance of spun piles in various technical conditions such as safety factors. This research is expected to provide a more comprehensive insight into the behavior of spun pile-based retaining walls. It is also hoped that the findings of this research can become a practical reference for geotechnical planners in choosing appropriate analysis and design methods, thereby increasing the efficiency and safety of retaining walls.

2. Research Method

This research employs a comparative analysis method to evaluate the stability of retaining walls using three approaches: Rankine, Plaxis, and Midas. This method was chosen to compare the accuracy of calculating safety factors, deformations, and internal force distribution under various excavation conditions [5], [27], [28]. The case study was conducted on a basement retaining wall at Regina Maris Hospital, Medan. The research began with collecting technical data related to soil and retaining walls through field cone penetration tests (CPT) and laboratory tests. Soil data obtained includes physical and mechanical properties. Data processing was done by comparing the results of the three methods, namely Rankine, Plaxis, and Midas, to evaluate safety factors.

2.1 Data Collected

The data collection including soil characteristics, retaining wall parameters, and environmental conditions surrounding the site were undertaken in this study. Data is acquired through field investigations, laboratory tests, and comprehensive literature reviews to ensure accuracy and relevance. The soil properties data obtained are presented in **Table 1**. The spun pile data is described in **Table 2**.

Table 1. Soil Characteristic Data

Parameters	Unit	Gravelly Coarse Sand Some Silt	Gravelly Coarse Sand Some Silt	Silty Fine Sand Some Clay	Silty Fine Sand Some Clay	Silty Fine Sand
Model Material	-	Soft Soil Model	Soft Soil Model	Soft Soil Model	Soft Soil Model	Soft Soil Model
Depth	m	3.50-4.50	7.50-8.00	13.5-14.00	27.50-28.00	33.50-34.00
Drainage type	-	Drained	Drained	Drained	Drained	Drained
γ - Unsat	kN/m^3	15.886	16.896	11.944	18.34	13.003
γ - sat	kN/m^3	18.054	18.416	17.043	20.809	17.642
E	kN/m^3	8000	8000	5000	5000	6000
v (Nu)	-	0.35	0.35	0.25	0.25	0.25
C_ref	kN/m^3	4.22 x10^{-4}	4.51×10^{-4}	9,61×10^{-4}	4,81×10^{-4}	8,14×10^{-4}
Ø	-	37°	39°	26°	42°	33°
Ψ (Psi)	-	0	0	0	0	0
λ (Lambda)	-	0.0029	0.020	0.025	2.0	2.0
κ (Kappa)	-	0.0012	0.00249	0.0025	0.002	0.002

Source: Data Analysis (2024).

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Table 2. Spun Pile Parameters

Parameters	Symbol	Value	Unit
Wide	L	0.8	m
Spunpile Length	B	14	m
Depth	-	14	m
Concrete Quality	F'c	35	MPa
EConcrete	-	$4700\sqrt{F'c}$	MPa
Modulus of Elasticity	E	27805.574	KN/m^2
Inertia	I	0.020	m^4
Cross-sectional area	A	2564	cm^2
Normal Stiffness	EA	71.293.491	kN/m
Flexural Stiffness	EI	556.111.48	kN/m

Source: Data Analysis (2024).

2.2 Data Analysis

The analysis begins with the Rankine approach to calculate active and passive soil pressure based on soil physical parameters, such as cohesion, internal friction angle, and unit weight [20], [29]. The results of this calculation are used to determine the shear force and rotation moment and evaluate the safety factor. Further simulations were carried out using Plaxis with a finite element approach [30]. A three-stage excavation model was created to predict soil deformation, pressure distribution, and retaining wall response to active and passive loads. Deformation analysis and safety factors at each stage are used to identify potential instability and load redistribution patterns during excavation. The Midas method is used to complete the analysis by reviewing the parameters of axial force, bending moment and maximum shear force on the retaining wall [20]. These data provide a detailed picture of the structural behavior of retaining walls under varying loads. A comparison of the results of the three methods is carried out to evaluate the advantages of each, compare the safety factor values, and identify the most suitable method for the technical conditions and design needs.

3. Results and Discussions

3.1 Rankine

The analysis of retaining wall stability relies heavily on accurate calculations of active and passive earth pressures, which are essential for assessing the forces exerted on the structure. The results of these calculations are summarized in **Table 3.**

Table 3. Effective Soil Pressure

Depth (m)	Ka	Ko	Kp	σ_v' (kN/m)	σ_h' (kN/m)	σ'_a (kN/m)	σ'_p (kN/m)	u (kN/m)
9.00	0.89	0.37	0.97	201.480	27.650	66.42	58.92	49.05
15.00	1.11	0.56	0,39	292.520	41.848	82.743	203.54	107,91
21.00	0.83	0.33	0,20	722.200	24.660	61.936	366.03	166,77

Source: Data Analysis (2024).

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Table 3 shows that at a depth of 9 m, the effective vertical pressure reaches 201.48 kN/m, with an active earth pressure of 66.42 kN/m and a pore pressure of 49.05 kN/m. At a depth of 15 m, the vertical pressure increases to 292.52 kN/m, while the active earth pressure and pore pressure increase to 82.74 kN/m and 107.91 kN/m. At a depth of 21 m, the effective vertical pressure jumps to 722.2 kN/m, while the active earth pressure decreases slightly to 61.94 kN/m, with a pore pressure reaching 166.77 kN/m. Overall, the vertical and pore pressure show an increasing trend with increasing depth, although the active earth pressure varies due to changes in soil parameters at each depth.

The total force resulting from passive earth pressure is calculated to be 73.741 kN/m and passive earth pressure force is 628.496 kN/m, representing the total passive force acting on the retaining wall. This result highlights the significant contribution of both active and passive earth pressures to the stability analysis, which will be used to determine moments, shear forces, and safety factors. Based on the results of the retaining wall stability analysis, the total force due to active earth pressure (Pa) is calculated as 386.0394 kN/m, with the centroid located at Z' = 4.19 m. The rotational moment caused by active earth pressure (Ma) is recorded at 1100.00 kN/m³, while the total moment (Mb), which combines the moments from both active and passive pressures, reaches 2794.554 kN/m³.

Stability analysis against rotational moments indicates a safety factor (Fgl) of 2.54, exceeding the minimum threshold of 1.5, confirming the wall's stability against overturning. Furthermore, the shear force analysis yields a total horizontal force ($\sum Rh$) of 642.363 kN/m. Considering the contribution of passive earth pressure, the safety factor against sliding (Fgs) is calculated at 2.447, which is greater than the minimum required value of 2.0. These results demonstrate that the retaining wall has good stability against both sliding and overturning, ensuring the structural safety during its operational life.

3.2 Plaxis

The deformation and stability of various important components were evaluated using the Finite Element Method in a recent structural analysis of a building site. Critical metrics like shear force, bending moments, and safety factors were meticulously computed, emphasizing the deformation of spun pile walls and different excavations. The following horizontal and vertical deformations were determined by the spun pile deformation study conducted during excavation phases I, II, and III.

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Table 4. Deformation and Displacement

Item	Horizontal Displacement		Vertical Displacement		Deformation	
	m	mm	m	mm	m	mm
Spun Pile Walls	-	-	-	-	$19.80*10^{-3}$	19.80
First Excavation	557.25×10^{-6}	0.55725	-3×10^{-3}	-0.003	$19.83*10^{-3}$	19.83
Second Excavation	580.08×10^{-6}	0.58008	-3.19×10^{-3}	-0.00319	$137.90*10^{-3}$	137.9
Third Excavation	597.02×10^{-6}	0.59702	-3.57×10^{-3}	-0.00357	$19.88*10^{-3}$	19.88

Source: Data Analysis (2024).

Table 4 shows the total deformation as well as horizontal and vertical displacements observed in the spun pile wall and during each excavation stage. For the spun pile wall, only the total deformation was measured, amounting to 19.80 mm. During the first excavation stage, horizontal displacement reached 0.55725 mm, vertical displacement was -0.003 mm, and total deformation w as 19.83 mm. A significant increase was observed in the second stage, where horizontal displacement reached 0.58008 mm, vertical displacement was -0.00319 mm, and total deformation surged to 137.9 mm, marking the highest stress experienced by the structure. In the third stage, horizontal displacement increased to 0.59702 mm, vertical displacement reached -0.00357 mm, and total deformation to 19.88 mm. This data highlights the second stage as the critical phase, though the overall deformation remained within acceptable limits to maintain structural stability.

Table 5. Maximum Shear Force and Bending Moment

Excavation Stage	Shear Forces	Bending Moment
	kN/m	kNm/m
First Excavation	0.73434	3.49
Second Excavation	0.602.11	2.92
Third Excavation	1.36	6.21

Source: Data Analysis (2024).

The analysis of maximum shear forces and bending moments during the excavation process reveals variations in values across each excavation stage (**Table 5**). In the first excavation stage, the maximum shear force was recorded at 0.73434 kN/m, with a maximum bending moment of 3.49 kNm/m. During the second stage, the maximum shear force decreased to 0.60211 kN/m, while the maximum bending moment dropped to 2.92 kN/m. Conversely, in the third excavation stage, the maximum shear force increased significantly to 1.36 kN/m, with a rise in the maximum bending moment to 6.21 kNm/m. These results indicate that soil

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conditions and load distribution influence variations in shear forces and bending moments throughout the excavation process.

Table 6. Safety Factor

Item	Safety Factor
First Excavation	1.81
Second Excavation	1.82
Third Excavation	2.95

Source: Data Analysis (2024).

Table 6 presents the safety factor values across different excavation stages. During the first stage, a safety factor of 1.81 was recorded, indicating that the structure was stable and secure. In the second stage, the safety factor slightly increased to 1.82, remaining well above the commonly accepted critical threshold of 1.5 for stability assessment. By the third stage, the safety factor rose significantly to 2.95, demonstrating a notable improvement in structural stability. These findings confirm that the retaining wall consistently maintained a safe and stable condition despite changes in loading and soil conditions throughout the excavation process.

3.3 Midas

Table 7 presents the results of calculating the main technical parameters obtained from the analysis using Midas.

Table 7. Main Technical Parameters from Midas SoilWork Analysis

Item	Maximum Moment ton-m	Horizontal Deflection cm	Maximum Shear Force ton	Axial Force ton
First Excavation	2.447	0.7	1.16	-
Second Excavation	4.1	1.12	1.56	-
Third Excavation	4.5	1.17	2.93	12.88
Basement Wall	24	2.42	15,64	68,72

Source: Data Analysis (2024).

In the structural stability analysis at various excavation stages and the condition of the basement wall, significant changes in maximum moment, horizontal deflection, maximum shear force, and axial force were observed. At the First Excavation Stage, the maximum moment was recorded at 2.447 ton-m with a horizontal deflection of 0.7 cm and a maximum shear force of 1.16 tons. Axial force was not recorded at this stage, but the shear force remained within safe limits. At the Second Excavation Stage, the maximum moment increased to 4.1 ton-m, with a horizontal deflection of 1.12 cm and a maximum shear force of 1.56 tons. Although there was an increase in shear force, these values remained within safe limits. At the Third Excavation Stage, the maximum moment was recorded at 4.5 ton-m with a horizontal deflection of 1.17 cm, while the shear force significantly increased to 2.93 tons. At this stage, the axial force was recorded at 12.88 tons. Despite the increase in shear force, the high axial

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force still remains within safe limits when considering the strength of the materials used. At the Basement Wall condition, the maximum moment was recorded at 24 ton-m with a horizontal deflection of 2.42 cm and a maximum shear force of 15.64 tons. The axial force was recorded at 68.72 tons. Overall, despite the increase in shear force and moment at each stage of excavation, the safety factor value was 1.64. This value indicates that the structure is in a safe condition because it is more than 1.5.

3.4 Safety Factor

Safety factor analysis plays an important role in evaluating the stability of retaining walls during various stages of excavation. Based on the Rankine method, the value of the safety factor against rotation reaches 2.54, and against shear is 2.447, both exceeding the required minimum stability threshold, namely 1.5 for rotation and 2.0 for shear. These results show that the Rankine method provides a simple but quite effective theoretical approach to analyze the initial stability of structures. Meanwhile, analysis using PLAXIS produced a safety factor of 1.81 in the first excavation stage, increased to 1.82 in the second stage, and reached 2.95 in the third stage. This value indicates the accuracy of the finite element method in modeling actual deformation and soil-structure interaction. In the Midas method, the minimum safety factor was recorded as 1.64 in basement wall conditions, which although lower, is still within safe limits (>1.5), especially for practical applications involving significant axial forces.

Each method has unique advantages and disadvantages. The Rankine method excels in its simplicity and is suitable for initial design, but is less capable of modeling complex soil conditions or dynamic loads [29]. PLAXIS offers more detailed and realistic results thanks to its finite element approach, especially in the analysis of deformation and soil pressure [16]. However, this analysis requires longer computing time and complete soil parameter data. Midas, on the other hand, provides additional information such as axial forces and bending moments, making it a very useful tool for advanced studies, although safety factor values tend to be conservative [18].

This study's results align with previous research that also compared various analysis methods. Babaei Abbas found that finite element methods, provide more accurate results in predicting soil deformation and stress than conventional methods, although they require more computational time [31]. Research by Hu Weidong concluded that passive earth pressure contributes significantly to increasing stability, especially in walls exposed to large lateral loads [32]. This finding is consistent with the results of this study, where the Rankine method provides a higher safety factor but lacks detail in modeling the actual deformation.

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In addition, a study by Murat Hamderi shows that Midas is superior in providing more comprehensive axial force and bending moment analysis, but its safety factor results tend to be more conservative [33]. The results of this study support these findings, where Midas provides a lower safety factor value than PLAXIS, but remains within safe limits. The similarity of these findings shows that previous research and this research both emphasize the importance of choosing an analysis method that suits technical needs and soil conditions. Overall, this research strengthens previous results that combining traditional and modern methods can provide more comprehensive and reliable analysis results.

Theoretically, this research contributes to further understanding of the relationship between deformation, earth pressure redistribution, and safety factors. These results can be used as a guide to determine the analysis method that best suits the project needs. The Rankine method can be a fast and efficient solution in simple soil conditions. However, for projects with complex soil conditions or requiring high accuracy, PLAXIS or Midas can provide more detailed and relevant results for safe construction design and execution.

4. Conclusion

This study shows that the Rankine, Plaxis, and Midas methods have their respective advantages in the stability analysis of retaining walls. The Rankine method produces high safety factors, namely 2.54 for rotation and 2.447 for shear. Plaxis, with a finite element approach, is able to model deformation and earth pressure distribution more realistically, with a safety factor reaching 2.95 in the third excavation stage. Midas provides detailed analysis of axial force, bending moment, and shear force, although its safety factor tends to be smaller. These results contribute to a deeper theoretical understanding of the relationship between deformation, safety factors, and redistributions of earth pressure in retaining wall stability. These findings emphasize the importance of selecting appropriate analysis methods based on soil conditions and design requirements. This study serves as a guide for improving the accuracy and efficiency of retaining wall designs, ensuring structural stability and cost-effectiveness in geotechnical applications.

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