Slope Stability Analysis Against Landslides Using the Bishop Method (Case Study: Katapop II, Salawati District, Sorong Regency)

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Sorong Regency has hilly and mountainous topography, making it prone to landslides, especially on steep slopes during periods of high rainfall. Landslides in this area can damage infrastructure and threaten human safety. These conditions highlight the importance of slope stability analysis to identify potential landslides and mitigation efforts to minimize disaster impacts. This study aims to analyze slope stability under saturated and unsaturated conditions and to determine the soil characteristics in Katapop II, Sorong Regency. The method used was the Bishop method utilizing GeoStudio software and manual calculations to validate the Safety Factor (SF) values. Based on the calculation results, the slopes in Katapop II were categorized as unstable under saturated conditions, with safety factors (SF) of 0.798 from the software analysis and 0.53 from manual calculations. Under unsaturated conditions, the safety factors (SF) were 2.69 from the software analysis and 2.70 from manual calculations, indicating stable conditions. The soil characteristics were identified as clay according to the AASHTO classification system, inorganic clay according to the USCS classification system, and silt loam according to the USDA classification system.
Keywords: Slope Stability, Bishop Method, Safety Factor (SF), Soil Characteristics.

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1. Introduction

Sorong Regency is a region topographically dominated by hills and mountainous areas, making it highly vulnerable to landslides, particularly during periods of intense rainfall [1] [2] [3]. Landslides are among the most destructive geological hazards because they can damage infrastructure, disrupt transportation networks, and threaten human safety [4]. The steep slopes distributed throughout this region are the main factor increasing the potential for landslides, especially during periods of high rainfall intensity. Landslides are among the most common natural disasters occurring in areas with certain slope gradients and can cause significant damage to infrastructure such as roads, bridges, and buildings, while also posing threats to human safety.

Landslides are natural disasters that frequently occur and result in major damage. Slope stability is controlled by several factors, including slope geometry, soil properties, groundwater conditions, rainfall infiltration, and external loading [5] [6] [7] [8]. Among these factors, rainfall-induced pore water pressure is considered one of the primary causes of slope failure in tropical regions [3] [9]. Who explained that landslides generally occur on steep topography with slope angles ranging from 15° to 45°, particularly during heavy rainfall.

One of the areas in Sorong Regency with a high potential for landslides is Katapop II, located in Majener Village, Salawati District. If a landslide occurs in this area, the impacts would not only be limited to physical

damage but could also disrupt the social and economic conditions of the local community. The potential for significant material losses and risks to human safety highlights the need for an in-depth technical study related to slope stability analysis in the area. However, only limited studies have compared manual Bishop calculations with GeoStudio analyses for tropical clay slopes in eastern Indonesia. Therefore, this study evaluates slope stability under saturated and unsaturated conditions and compares the results obtained from both approaches [10] [11].

2. Literature Review and Problem Statement

Slope

A slope is a surface of soil or rock that is inclined relative to a horizontal plane. Slopes can be formed naturally through geological processes such as erosion, tectonic movement, and weathering, resulting in landforms such as hills, mountains, and valleys. In addition, slopes may also be formed due to human activities, such as road construction, mining excavations, or earth. Based on the constituent materials, slopes can be classified into soil slopes and rock slopes. Several factors influence slope stability, including slope geometry, material properties, groundwater conditions, geological conditions, external factors, and landslide mechanisms. According to Varnes [12], landslides can be classified into rotational slides, translational slides, debris flows, rock falls, and soil creep. The types of landslide mechanisms include:

1. Translational Slide
2. Rotational Slide
3. Debris Flow
4. Soil Creep
5. Block Movement
6. Rock Fall

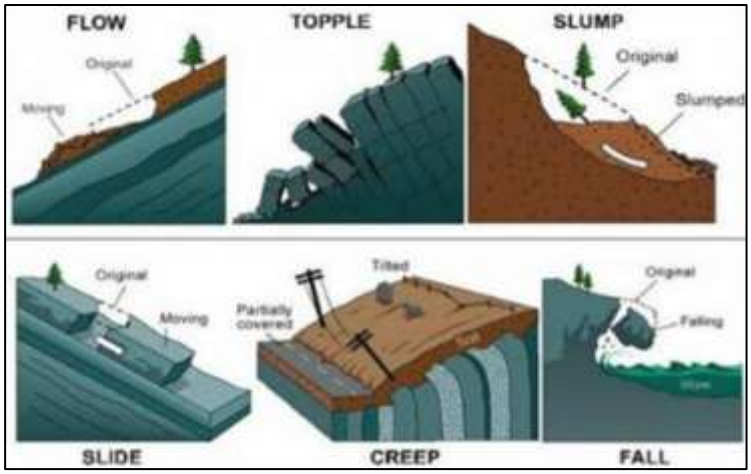

Figure 1. Landslide Patterns
Source : Varnes, 1978

Soil Classification

A soil classification system is a method used to group various types of soils with similar properties into specific categories to facilitate their utilization. Soil classification is essential for predicting engineering behavior, including compressibility, permeability, and shear strength. This system aims to identify the main characteristics of soil using simple index test results. The obtained data then serve as the basis for determining soil classification. The following are three methods of soil classification:

AASHTO

The AASHTO (American Association of State Highway and Transportation Officials) soil classification system was first developed in 1929 and underwent several revisions until 1945. This system was designed by the Committee on Classification of Materials for Subgrade and Granular Type Roads of the Highway Research Board and was codified in ASTM D-3282 and AASHTO M 145. Initially, soils were classified into eight main groups, namely A-1 through A-8. The 1945 revision retained these eight groups but added several subgroups: two in A-1, four in A-2, and two in A-7. Group A-8 refers to peat or swamp soils, which are classified visually and are not included in the technical tables. Each group is evaluated using the Group Index, which is obtained through an empirical formula :

USCS

The USCS (Unified Soil Classification System) was first developed by Arthur Casagrande and later refined by technical institutions such as the United States Bureau of Reclamation (USBR) and the United States Army Corps of Engineers (USACE). Currently, this system has been adopted as a standard by the ASTM International through ASTM D2487. The USCS classifies soils into two main categories:

a. Coarse-grained soils, These consist of gravel and sand, which are soils with less than 50% by weight passing through the No. 200 sieve.
b. Fine-grained soils, These are soils with more than 50% by weight passing through the No. 200 sieve.

The soil classification systems commonly used include those developed by the United States Department of Agriculture and the United States Public Roads Administration. Due to differences in particle size limits among these systems, it is important to specify the classification system used when reporting analysis results. In Indonesia, particularly at the Soil Research Institute (LPT, 1979), the classification system commonly used is the USDA system. In this system, soils are categorized into various textural classes based on the proportions of sand, silt, and clay fractions, which are determined using the soil texture triangle diagram. The use of the soil texture triangle involves determining the percentages of the three main fractions (sand, silt, and clay), and then plotting these values on the diagram to accurately identify the soil textural class.

Bishop Method

Bishop developed one of the most widely used limit equilibrium methods for circular slip surface analysis [12]. The Bishop Simplified Method generally provides safety factors that are very close to rigorous limit equilibrium solutions while requiring relatively simple calculations[13] [14]. In this method, the slip surface is assumed to be circular and divided into several vertical slices. Each slice is analyzed based on the equilibrium of vertical forces and moments, with the assumption that the resultant horizontal and vertical forces acting on the sides of each slice are equal to zero. The Bishop simplified method assumes a circular slip surface and satisfies moment equilibrium while neglecting interslice shear forces, producing accurate factors of safety for most practical slope problems.

Alan W. Bishop refined this method through the slice approach, in which vertical forces are considered without generating significant uplift pressure [. The complete equation for the Bishop Method is derived from the equilibrium of moments and forces acting on each slope slice.

Bishop Method Equation

$$F = \frac{\sum_{i=1}^{i=n}[c'bi+(wi-ui.bi)tg\ \varphi r]\frac{1}{\cos\theta i((1+tg.\theta i.\varphi')/F}}{\sum_{i=1}^{i=n} wi.Sin.\theta i} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Description:

F = Safety Factor

C = Effective soil cohesion (kN/m²)
φ = Internal friction angle (°)
bi = Width of the i-th slice (m)
Wi = Weight of the i-th soil slice (kN)
ui = Pore water pressure of the i-th slice (kN/m²)
θi = Slice angle (°)

Slice Weight Equation (Wi)

$$Wi = \gamma . Ai \quad \text{.....(2)}$$

Description:
Wi = Weight of the i-th soil slice (kN)
γ = Unit weight of soil (kN/m³)
Ai = Cross-sectional area of the i-th slice (m²)

Slice Angle Equation (θi)

$$\theta i = \text{Sin}\left(\frac{xi}{R}\right) \quad \text{.....(3)}$$

Description:
θi = Angle of the i-th slice (°)
xi = Distance from the center point of the slice to the center of rotation (m)
R = Radius of the slip circle (m)

Driving Force Equation (T)

$$T = Wi.\text{Sin}(\theta i) \quad \text{.....(4)}$$

Description:
T = Driving force (kN)
Wi = Weight of the i-th soil slice (kN)
θi = Angle of the i-th slice (°)

Pore Water Pressure Equation (u)

$$u = \gamma w.9\, hi \quad \text{.....(5)}$$

Description:
u = Pore water pressure (kN/m²)
γw = Unit weight of water (9.81 kN/m³)
hi = Depth below the groundwater table (m)

Pore Water Pressure Force Equation (bu)

$$bu = bi.u \quad \text{.....(6)}$$

Description:
bu = Pore water pressure force (kN)
bi = Width of the i-th slice (m)
u = Pore water pressure of the i-th slice (kN/m²)

Mi(θ) Equation

$$Mi(\theta)Cos\theta i((1tg\ \theta i\ tg\ \varphi')F \quad \text{.....(7)}$$

Description:
θi = Angle of the i-th slice (°)
φ' = Internal friction angle (°)
F = Assumed safety factor

Resisting Shear Force Equation

$$(c.bi+(Wnbu*Tan\varphi)*1/m(\theta).....(8)$$

Description:

c = Soil cohesion (kN/m²)
bi = Width of the i-th slice (m)
Wi = Weight of the i-th soil slice (kN)
u = Pore water pressure of the i-th slice (kN/m²)

GeoStudio Software

GeoStudio is a geotechnical software package used to analyze various problems in geotechnical engineering, such as slope stability, groundwater flow, pore water pressure, and soil deformation. GeoStudio is capable of analyzing landslides through the SLOPE/W module, which is specifically designed for slope stability analysis. GeoStudio SLOPE/W has become one of the most widely used software packages for slope stability analysis because it supports several limit equilibrium methods and groundwater conditions [15].

This software supports various analytical methods, including the Bishop, Janbu, Spencer, and other Limit Equilibrium methods. In this study, slope stability analysis was carried out using GeoStudio with the Bishop Method to calculate the Factor of Safety (FS) under saturated and unsaturated soil conditions. The parameters considered in the analysis include pore water pressure (u), cohesion (c), and the internal friction angle (φ).

3. Method

This study began with field data collection through hand-boring tests at three locations (the top, middle, and toe of the slope) to a depth of 2 meters, as well as a topographic survey to obtain contour and slope geometry data. Soil samples obtained from the hand-boring tests were examined in the laboratory to determine the physical and mechanical properties of the soil, including water content, unit weight, specific gravity, grain size analysis, and direct shear strength. These data were used as input parameters for slope modeling using GeoStudio (SLOPE/W) and manual calculations using the Bishop Method. The analysis was conducted under two conditions: saturated soil conditions (worst-case condition) and unsaturated soil conditions (existing condition). The results obtained from GeoStudio provided the Safety Factor (SF) values and the location of the critical slip surface, which were then validated through manual calculations using Microsoft Excel. The approach used in this study was an analytical method involving AutoCAD for slope geometry planning. The activities were carried out directly in the field and through literature studies to obtain information regarding slope stability and landslide potential. The methodology adopted in this study is consistent with previous slope stability investigations reported in the literature [7] [14].

Data Collection

Primary data were collected directly from the research site, including:

1. Direct slope measurements in the field, to obtain slope height, slope angle, and slope cross-sections. These data were acquired from mapping surveys using a Theodolite.
2. Soil sampling in the field, for laboratory testing at the Universitas Muhammadiyah Sorong Civil Engineering Laboratory. The tests conducted included water content, unit weight, specific gravity, grain size analysis, Atterberg limits, and direct shear strength tests.

Data Analysis

1. Analysis using GeoStudio with the Bishop Method under saturated and unsaturated conditions.

2. Manual analysis using the Bishop Method to validate the results obtained from the software analysis.

4. Results and Discussion

Geometry Analysis

The results of slope measurements using a Theodolite provided field data that were subsequently processed using Autodesk Civil 3D to obtain the slope contours. Based on these contours, the slope geometry shown in Figure 2 was obtained, as presented below:

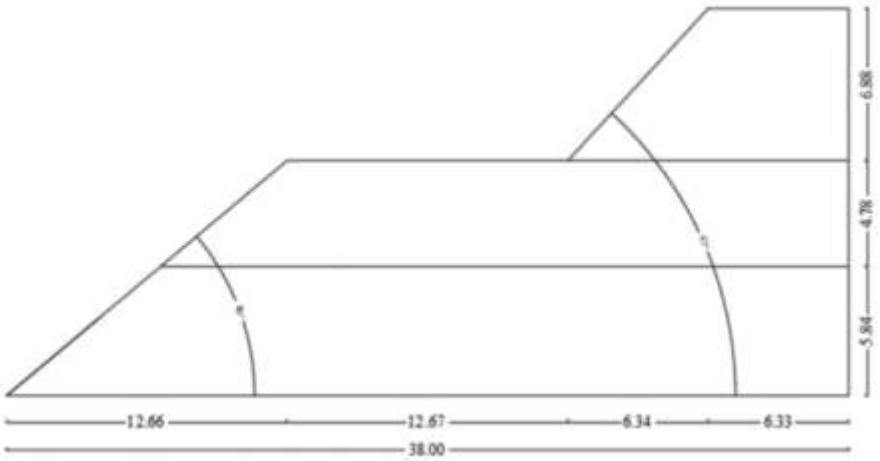

Figure 2. Slope Geometry
Source : Personal Documentation

Test Results

The following are the summarized results of the water content, unit weight, specific gravity, grain size analysis, Atterberg limits, and direct shear strength tests under saturated and unsaturated conditions, as shown in Table 1.

Table 1. Summary of Test Results

Testing	Sample			
	Top	Middle	Toe	Unit
a. Saturated Water Content	30.38	33.81	35.29	%
b. Unsaturated Water Content	26.03	36.08	25.39	%
c. Saturated Unit Weight				
d. Unsaturated Unit Weight	12.94	12.74	12.74	kN/m^3
e. Specific Gravity	12.65	12.30	12.56	kN/m^3
f. Grain Size Analysis	2.60	2.59	2.58	gr/m^3
	Sand 23.50 %	Sand 36.50 %	Sand 23 %	%
	Silt 61.50 %	Silt 52 %	Silt 64.50 %	%
a. Liquid Limit (LL)	Clay 15 %	Clay 64.50 %	Clay 12.50 %	%
b. Plasticity Index (PI)	58.65	57.35	58.36	%
c. Saturated Cohesion	33.21	31.56	32.86	%
d. Unsaturated Cohesion	15.70	14.17	13.73	kN/m^2
e. Saturated Internal Friction Angle	18.60	16.66	17.64	kN/m^2
f. Unsaturated Internal Friction Angle	15.56	18.54	24.49	(°)
	25.39	27.14	30.20	(°)

Source : Soil Mechanics Laboratory Test Results

Soil Classification

Soil classification can be conducted systematically based on laboratory test results or through visual identification. Both approaches follow the same principles and will produce similar descriptions or classifications. Based on the laboratory test data, the soil properties from the slope can be classified as follows:

a. USCS Classification System
   Based on the analysis of the three soil samples (top, middle, and bottom), all samples show a percentage passing the No. 200 sieve greater than 50%. The plasticity characteristics indicate a liquid limit (LL) above 50% and a plasticity index (PI) above 11.
   From the Atterberg limits results, the plasticity index plotted against the liquid limit falls above the A-line and to the right of LL = 50%, indicating high plasticity clay. Based on the Unified Soil Classification System, all samples are classified as CH, which represents inorganic clay with high plasticity. This type of soil generally has expansive characteristics and low engineering stability.
b. USDA Classification System
   Based on grain size analysis of the top, middle, and bottom soil samples, the proportions of sand, silt, and clay were analyzed using the soil texture triangle of the United States Department of Agriculture. The results show that all samples are classified as Silt Loam, meaning the soil is dominated by silt particles with moderate amounts of clay and sand.
c. AASHTO Classification System
   Based on laboratory analysis of the three soil samples (Top, Middle, and Toe), all samples show a percentage passing the No. 200 sieve greater than 35%, with liquid limit (LL) greater than 40% and plasticity index (PI) greater than 11. According to the American Association of State Highway and Transportation Officials, all samples are classified as A-7-6, which represents high-plasticity clay soil. This soil type generally has poor engineering properties for road construction due to low bearing capacity, high compressibility, and significant volume change with moisture variation.

Slope Stability Analysis (Saturated Condition)

The following are the results of software and manual calculations under unsaturated conditions, as shown in Figure 3 and Table 2.

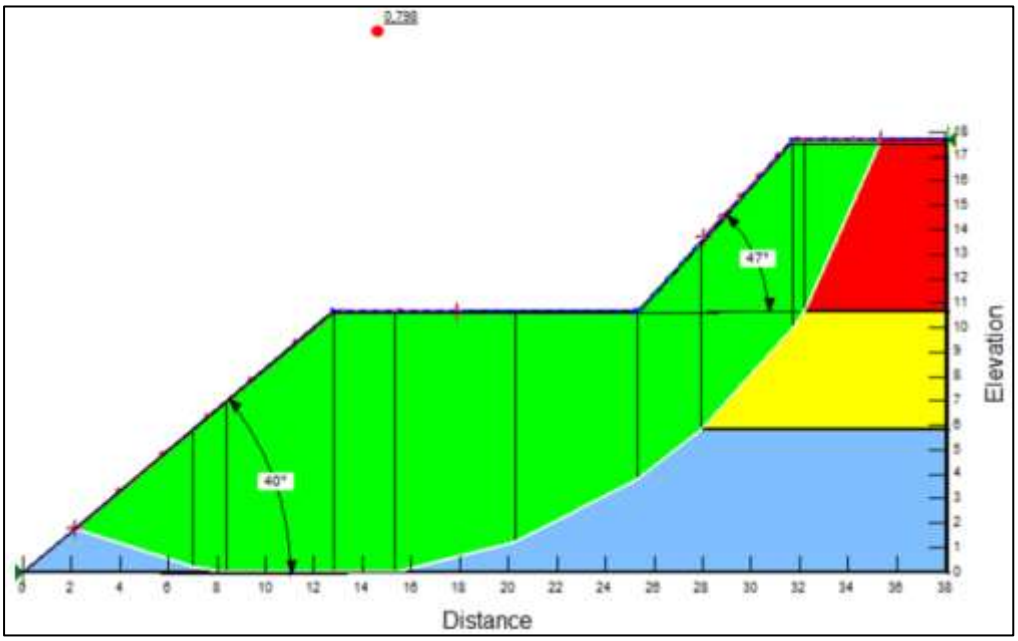

Figure 3. Software Analysis Results (Saturated Condition)
Source : Personal Documentation

Table 2. Summary of Manual Calculation Results (Saturated Condition)

No Slice	*bi (m)*	*h (m)*	*θ i (°)*	*Wi (kN)*	*Wi*Sin (θ i)*	*hi (m)*	*u = hi*yw (kN/m²)*	*bu (kN)*	*Mi*	*(c.bn + (Wn – bu)*Tan φ)*1/mi*	*SF*
1	3.09	4.13	64.94	137.50	124.56	4.13	40.52	125.19	0.928	49.374	
2	0.49	7.25	55.19	45.96	37.73	7.25	71.12	34.85	1.028	9.547	
3	3.17	7.89	47.34	384.88	283.04	7.89	77.40	245.36	1.171	73.391	
4	3.17	7.45	35.85	302.35	177.08	7.45	73.08	231.68	1.203	52.222	
5	4.78	8.28	23.50	498.75	198.89	8.28	81.23	388.26	1.185	78.737	
6	4.79	10.12	9.98	616.96	106.89	10.12	99.28	475.54	1.101	94.233	0.50
7	3.10	10.62	0.70	188.78	2.31	10.62	104.18	322.96	1.008	-8.476	
8	4.49	8.74	10.99	662.18	126.26	8.74	85.74	384.97	1.155	154.994	
9	1.40	6.15	19.24	109.69	36.15	6.15	60.33	84.46	1.244	22.465	
10	4.64	2.95	27.84	160.20	74.82	2.95	28.94	134.28	1.310	50.677	
(∑)					1167.74					577.164	

Source : Manual Calculation Results

The slope stability analysis in Katapop II indicates that the slope, consisting of silty clay soil with characteristics of being easily saturated and having low shear strength, has a potential for rotational failure due to a safety factor value of less than 1 (SF = 0.798 from software analysis and 0.50 from manual calculations), especially under fully saturated conditions. Therefore, slope reinforcement measures are required even though no landslide has yet occurred in the field.

Slope Stability Analysis (Unsaturated Condition)

The following are the results of software and manual calculations under unsaturated conditions, as shown in Figure 4 and Table 3.

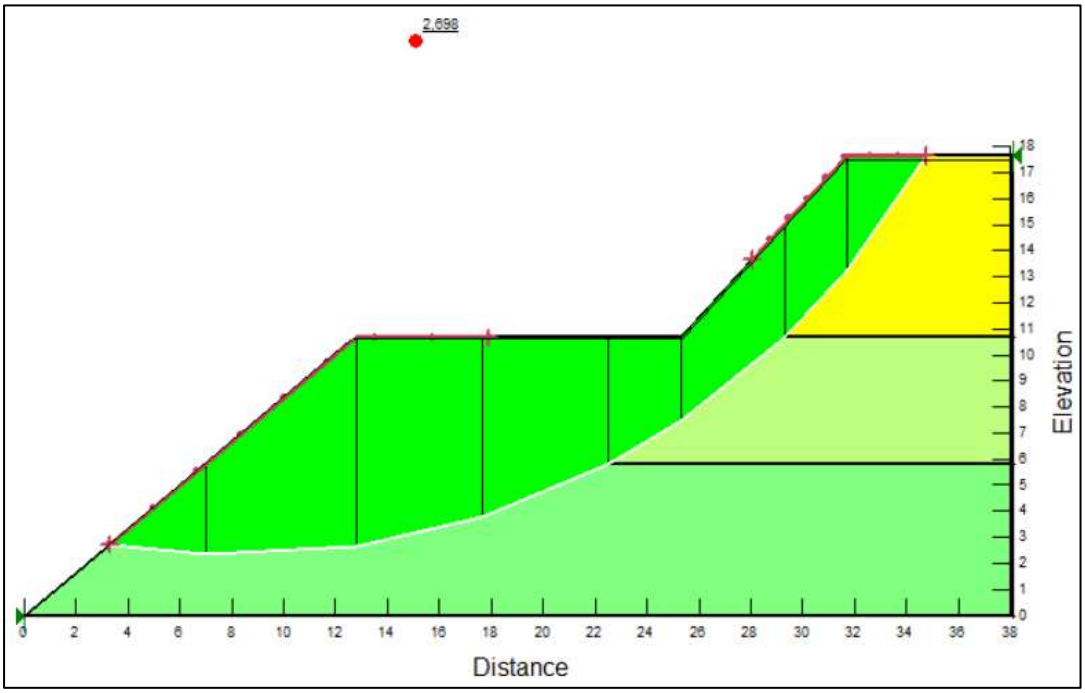

Figure 4. Software Analysis Results (Unsaturated Condition)
Source : Personal Documentation

Table 3. Summary of Manual Calculation Results (Saturated Condition)

No Slice	*b (m)*	*h (m)*	*θi (°)*	*Wi (kN)*	*Wi.Sin (θi) (kN)*	*Mi*	*(c.bi + Wi*Tan φ)*1/ma*	*SF*
1	3.72	2.73	62.06	116.39	102.83	0.624	187.839	
2	1.93	4.91	48.03	119.80	89.08	0.800	111.330	
3	4.41	4.23	35.86	225.27	131.97	0.922	204.977	
4	2.45	4.12	24.56	124.64	51.81 84.10	0.989	105.924	
5	5.11	5.96	13.19	368.59	11.31 92.56	1.023	297.857	2.70
6	5.11	7.55	1.45	447.12	64.11	1.005	348.577	
7	4.69	6.32	15.57	344.91	627.76	1.021	277.578	
8	4.69	2.26	30.07	127.96		0.974	159.226	
(∑)							1696.31	

Source : Manual Calculation Results

Based on the slope stability analysis using the Bishop Method, the safety factor (SF) obtained is 2.698 from the software analysis and 2.70 from manual calculations. This indicates that the slope, consisting of three soil layers with specific mechanical characteristics, is in a stable and safe condition against failure, as the SF value is well above the minimum requirement (SF ≥ 1.5). Therefore, no additional reinforcement is required as long as there are no extreme changes in field conditions.

Comparison of Manual Method and GeoStudio Software Results

The following is a comparison between manual calculations and GeoStudio results using the Bishop Method, as shown in Table 4.

Table 4. Summary of Safety Factor (SF) Values

	Calculation Method		
Condition	Software Geostudio	Manual Method	Description
Saturated	0.72	0.50	Stable < 1
Unsaturated	2.69	2.70	Unstable > 1,5

Source : Comparison Analysis Results of Software and Manual Calculations

The results demonstrate that groundwater conditions significantly influence slope stability. Under saturated conditions, the safety factor decreased below unity, indicating an unstable slope. This phenomenon occurs because increasing pore water pressure reduces effective stress and consequently decreases soil shear strength [3] [6] [16].

Conversely, under unsaturated conditions, the safety factor increased to approximately 2.70, indicating stable conditions. Similar observations have been reported in previous studies on tropical clay slopes, where suction contributes to increasing apparent cohesion and improving slope stability [4] [9] [17].

The comparison between manual calculations and GeoStudio shows only minor differences. These discrepancies are mainly associated with the numerical iteration process and slice discretization implemented in GeoStudio, whereas manual calculations involve several simplifying assumptions [2] [14] [18].

Overall, the findings confirm that the soil at Katapop II is highly sensitive to groundwater fluctuations because it is dominated by high-plasticity clay. Therefore, adequate drainage systems and groundwater control should be considered to improve long-term slope stability [5] [7] [19].

5. Conclusion

This study concludes that, based on soil classification using the American Association of State Highway and Transportation Officials, Unified Soil Classification System, and United States Department of Agriculture, the soil at the research location is classified as A-7 (clay), CH (inorganic clay), and silt loam. The observed landslide is categorized as a rotational failure with a curved slip surface, influenced by variations in shear strength parameters between soil layers, where cohesion and internal friction angle decrease from the top layer to the bottom layer. Based on slope stability analysis using GeoStudio (Slope/W) and the manual Bishop Method, it was found that under unsaturated conditions, the safety factor (SF) values are 2.69 and 2.70 (stable). However, under saturated conditions, the SF values significantly decrease to 0.79 and 0.50 (unstable), due to increased pore water pressure that reduces the soil shear strength. The results obtained in this study are consistent with previous investigations on clay slope stability using the Bishop Method and demonstrate the importance of considering groundwater conditions in slope design [1] [7] [20].

6. Refereces

[1] Bishop, A. W. (1955). The use of the slip circle in the stability analysis of slopes. *Geotechnique*, *5*(1), 7–17. doi: 10.1680/geot.1955.5.1.7.
[2] Morgenstern, N. R., & Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Geotechnique*, *15*(1), 79–93. doi: 10.1680/geot.1965.15.1.79.
[3] Fredlund, D. G., & Rahardjo, H. (1993). *Soil mechanics for unsaturated soils*. John Wiley & Sons.
[4] Fredlund, D. G. (2006). Unsaturated soil mechanics in engineering practice. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(3), 286–321.
[5] H. C. Hardiyatmo. (2018). *Mekanika Tanah II* (8th ed.).
[6] B. M. Das and K. Sobhan. (2018). *Principles of Geotechnical Engineering* (9th ed.).
[7] Duncan, J. M., Wright, S. G., & Brandon, T. L. (2014). *Soil strength and slope stability*. John Wiley & Sons.
[8] H. B. Seed and R. V. Whitman. (1970). *Fundamentals of Soil Mechanics*.
[9] D. M. Cruden and D. J. Varnes. (1996). *Landslide Types and Processes," in Landslides: Investigation and Mitigation, Transportation Research Board Special Report 247*.
[10] Clague, J. J., & Stead, D. (2012). *Landslides: types, mechanisms and modeling*. Cambridge University Press.
[11] Wright, S. G., & Duncan, J. M. (1991). Limit equilibrium stability analyses for reinforced slopes. *Transportation Research Record*, (1330). doi: 10.1061/(ASCE)0733-
[12] Michalowski, R. L. (2002). Stability charts for uniform slopes. *Journal of Geotechnical and Geoenvironmental Engineering*, *128*(4), 351–355. doi: 10.1061/(ASCE)1090-0241(2002)128:4(351).
[13] Griffiths, D. V, & Lane, P. A. (1999). Slope stability analysis by finite elements. *Geotechnique*, *49*(3), 387–403. doi: 10.1680/geot.1999.49.3.387.
[14] Griffiths, D. V, & Fenton, G. A. (2004). Probabilistic slope stability analysis by finite elements. *Journal of Geotechnical and Geoenvironmental Engineering*, *130*(5), 507–518. doi: 10.1061/(ASCE)1090-0241(2004)130:5(507).
[15] Bowles, J. E., & Guo, Y. (1996). *Foundation analysis and design* (Vol. 5). McGraw-hill New York.
[16] J. A. Knappett and R. F. Craig. (2019). *Craig's Soil Mechanics* (9th ed).
[17] Fredlund, D. G., & Krahn, J. (1977). Comparison of slope stability methods of analysis. *Canadian Geotechnical Journal*, *14*(3), 429–439. doi: 10.1139/t77-045.
[18] Highland, L. M., & Bobrowsky, P. (2008). *The landslide handbook-A guide to understanding landslides* (Number 1325). US Geological Survey.

[19] Rock, A. C. D.-18 on S. and. (2017). *Standard practice for classification of soils for engineering purposes (unified soil classification system) 1*. ASTM international.

[20] *AASHTO, Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (M145)*. (2020).