

Evaluating Slope Instability in a Volcanic Caldera Environment Using GIS-Based 3D Analysis: Mt. Bawakaraeng, South Sulawesi

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ABSTRACT Landslides in volcanic terrains pose significant hazards to downstream communities, infrastructure, and watershed systems, particularly where steep slopes and complex geological conditions coexist. This study presents a GIS-based three-dimensional (3D) deterministic slope stability analysis to evaluate landslide susceptibility within the Mt. Bawakaraeng caldera, Sulawesi Island, Indonesia. The analysis integrates geotechnical, geological, hydrological, and topographic parameters obtained from field investigations, laboratory testing, remote sensing data, and a high-resolution 5-m Digital Elevation Model (DEM). Slope stability was evaluated using the factor of safety (FS), calculated through a Hovland-based 3D column method implemented within a GIS environment. Two critical collapse zones were identified and corresponded closely with documented historical landslide events. The calculated minimum FS values of 0.825 and 1.000 indicate unstable to marginally stable slope conditions, respectively. Numerical simulations indicate a progressive failure mechanism in which the collapse of a major slope unit can reduce the stability of adjacent slope units, potentially generating cascading landslide events. Monte Carlo simulations were additionally employed to identify critical slip surfaces and assess potential failure configurations. The simulated slip surfaces showed good agreement with observed landslide morphologies, supporting the reliability of the modeling approach. Potential failure volumes were also estimated to assess the downstream sediment hazard to the Jeneberang watershed. The results demonstrate that integrating GIS, high-resolution terrain data, and 3D deterministic modeling provides an effective framework for spatially explicit slope stability assessment in complex volcanic environments. The approach can support landslide hazard mitigation, watershed management, infrastructure planning, and sustainable development in mountainous regions prone to slope failure.

KEYWORDS Slope failure; landslide; stability factor; Mt. Bawakaraeng; GIS; 3D assessment model

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1 INTRODUCTION

1.1 Challenges posed by landslides in Indonesia

Indonesia is one of the country's most vulnerable to landslide hazards in the world due to its complex interaction of geological, climatic, and anthropogenic factors (Riyanti et al., 2017). The consequences of landslides in Indonesia are severe, including loss of life, damage to infrastructure, disruption of transportation networks, and long-term socio-economic impacts on affected communities. Rural and mountainous areas are particularly vulnerable due to limited access to early warning systems and disaster mitigation infrastructure (Rabby and Li, 2020). Landslides and debris flow in Indonesia are primarily triggered by intense and prolonged rainfall, which is common due to the country's tropical monsoon climate. The combination of high annual precipitation, steep topography, weathered volcanic soils, and deforestation significantly increases slope instability. According to data from Indonesia's National Disaster Management

Agency (BNPB, 2016), landslides are among the top three most deadly natural disasters in the country, with hundreds of fatalities and thousands of displaced persons annually.

Geologically, much of Indonesia is composed of young, unstable volcanic formations and tectonically active zones (Putriani et al., 2023). These conditions exacerbate the risk of slope failures, particularly in areas with inadequate land-use planning, unregulated hillside development, or agricultural practices that reduce slope stability (Kimura, 2024). In rural areas, deforestation for farming or plantation expansion is a major contributing factor, as it removes the root structures that help bind the soil, making slopes more vulnerable to collapse. In urban and peri-urban areas, rapid development often outpaces proper geotechnical assessments. Poor drainage systems, excavation without stabilization, and increased load from buildings on unstable slopes are common causes of anthropogenic slope failure (Hashimoto et al., 2020). Meanwhile, debris

flows, which are rapid movements of saturated soil and rock, often occur suddenly following heavy rains, posing a serious hazard due to their velocity and destructive power (Yanagawa et al., 2021). Climate change is also projected to intensify the problem. Increased variability in rainfall patterns, with more frequent and intense storms, may lead to higher incidences of rainfall-induced landslides and debris flows in the future (Jitousono et al., 2021). This highlights the urgent need for integrated risk assessment, early warning systems, and sustainable land management strategies (Sassa, 2016; Fathani et al., 2016). Despite numerous studies and monitoring programs, many areas in Indonesia remain under-assessed in terms of landslide susceptibility (Silalahi et al., 2019). A more comprehensive understanding of local geological conditions, hydrological triggers, and socio-economic vulnerabilities is essential to reducing disaster risk and enhancing community resilience (Shen et al., 2024).

1.2 Slope failure events at Mt. Bawakaraeng in South Sulawesi

Slope failure, including landslides and debris flows, is a significant natural hazard in many mountainous regions of South Sulawesi, often triggered by intense rainfall, steep terrain, geological instability, and human-induced land cover changes. One of the most notable and catastrophic examples in recent Indonesian history is the large-scale slope failure that occurred on Mt. Bawakaraeng in South Sulawesi in 2004, which has had lasting geomorphological, hydrological, and socio-economic impacts on the Jeneberang River watershed. Mt. Bawakaraeng is a dormant stratovolcano and the caldera geology is dominated by Quaternary volcanic products formed through multiple eruptive phases and collapse events. The main lithologies consist of andesitic-basaltic lava flows, pyroclastic deposits (tuffs, lapilli, and volcanic breccias), and reworked volcaniclastic materials. In many areas, weak pyroclastic layers overlie more competent lava flows, creating unfavorable shear-strength contrasts that promote slope instability. Geomorphologically, the caldera is characterized by steep, rugged terrain with slope angles commonly exceeding $30\text{--}40^\circ$. It forms a large volcanic collapse structure with deeply incised valleys and sharp ridgelines shaped by long-term erosion and repeated mass-wasting. As the headwaters of the Jeneberang River, the caldera experiences strong fluvial incision, with surface runoff concentrated along gullies that enhance slope undercutting and toe erosion, particularly during extreme rainfall events (Hasnawir, 2013). Prominent landslide scars, debris-flow channels, and accumulation zones indicate ongoing geomorphic adjustment. Thick unconsolidated volcanic deposits, combined with steep slopes and high rainfall, favor progressive and retrogressive slope failures involving large volumes of material. Vegetation

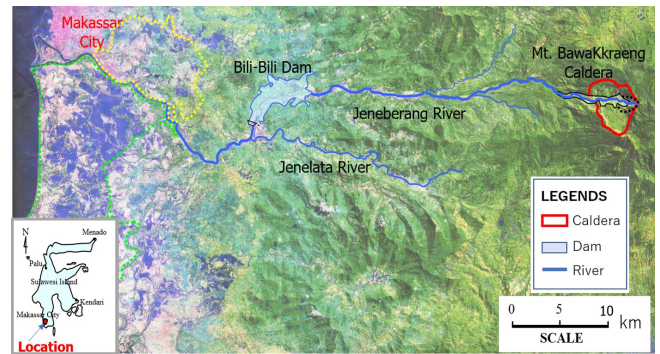


Figure 1. Remote sensing image showing the Jeneberang River watershed and the study area located at the Mt. Bawakaraeng caldera in the upper reaches.

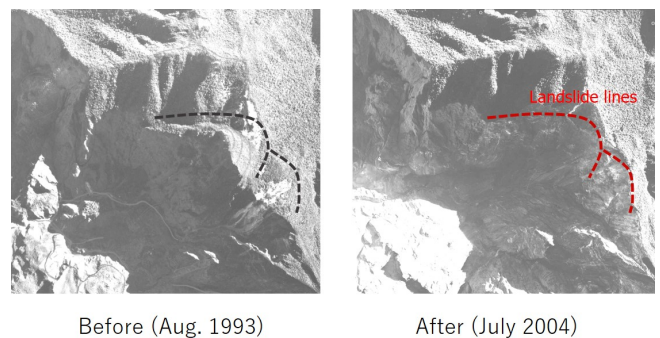


Figure 2. Comparison of slope conditions before (August 1993) and after (July 2004) the caldera landslide, highlighting the failure area (modified from JICA).

cover further influences slope stability, with densely vegetated areas providing greater resistance through root reinforcement, while deforested zones are more prone to erosion and shallow landslides. Based on Digital Elevation Model (DEM) data at a 1:25,000 scale, the Jeneberang River originates from the caldera of Mt. Bawakaraeng, a dormant volcano with an elevation of approximately 2,830 m. This watershed serves as a critical resource for downstream communities, supporting agriculture, domestic water supply, and hydropower generation through the Bili-Bili Dam, located about 35 kilometers downstream (Figure 1). On March 26, 2004, a massive landslide occurred on the northwest wall of the Bawakaraeng caldera, releasing an estimated 200 to 235 million m^3 of volcanic rock and debris. This event represents one of the largest documented slope failures in Indonesia and significantly altered the geomorphology of the upstream watershed (Satoshi et al., 2004).

Figure 2 shows the satellite image data taken on before and after landslide event. The collapse was characterized by high-relief slopes (700–800 meters), the presence of weak, weathered volcanic rock, and cumulative rainfall in the preceding weeks exceeding 700 mm (JICA, 2004). Although no singular trigger such as an earthquake was recorded, the landslide is believed to have been caused by a combination of long-term toe erosion by the Jeneberang River, hydrostatic

pressure from rainfall infiltration, and possible internal structural weaknesses within the caldera wall. The resulting debris avalanche traveled over 7 kilometers downstream, destroying vegetation, infrastructure, and farmland, and causing significant loss of life and property (Satoshi et al., 2009). The consequences of this slope failure extended far beyond the immediate area. Massive sediment loads have been continuously transported downstream into the Jeneberang River, leading to rapid siltation of the Bili-Bili Reservoir. This sedimentation has significantly reduced the dam's storage capacity and effectiveness for flood control, irrigation, and water supply. In addition, the morphology of the river channel has been altered, increasing the frequency and severity of debris flows during subsequent rainy seasons. Compounding these issues are ongoing land use changes in the watershed, particularly deforestation and the expansion of agriculture into steep, unstable areas. These activities further reduce slope stability and exacerbate sediment production, contributing to a cycle of degradation and hazard intensification. Given the scale and complexity of the 2004 landslide and its ongoing impacts, the Jeneberang watershed presents a critical case study for understanding the interactions between geological hazards, climate variability, land use dynamics, and disaster risk. This study aims to analyze 3D (three-dimensional) slope stability factors, evaluate sediment management strategies, contributing to improved hazard mitigation and watershed resilience in volcanic mountain environments.

2 METHODOLOGY

2.1 Integration of 3D Deterministic Models and GIS

Traditionally, deterministic approaches have been considered adequate for assessing both homogeneous and heterogeneous slopes. The stability index, commonly used as a safety factor, relies on geotechnical models and key physical and mechanical parameters (Leshchinsky and Huang, 1992). Calculating this safety factor requires geometric data, shear strength parameters, and pore water pressure information. While accurate data is important, the reliability of the deterministic model itself is critical for producing dependable results. Although natural slope failures are inherently 3D phenomena, 3D stability analyses are rarely performed (Lam and Fredland, 1993). This is largely due to the widespread availability of simpler two-dimensional (2D) software, which demands less data and is easier to use. Furthermore, there is no consensus on how to assign shear strength parameters (cohesion, c , and friction angle, ϕ) during analysis. Some studies ignore cohesion, while others estimate it based on average depth or interpolate shear envelope results (Hovland, 1977).

In deterministic distributed modeling, spatial varia-

tions in input parameters are assessed using aerial photos, satellite images, fieldwork, and laboratory analysis (Terlien et al., 1995). This data is then integrated into Geographic Information Systems (GIS), which provide powerful tools for processing and analyzing spatially distributed data (Dai and Lee, 2001; Tien and Wu, 2000). Slope failure hazard assessments require detailed information on fault locations, surface geology, terrain slope, groundwater, and historical landslide events. This data is often digitized and converted into raster format, which is preferred due to its simple structure and compatibility with remote sensing data. In raster GIS, the area is divided into cells or pixels, each representing homogeneous zones with assigned attribute values. Maps derived from these data provide essential parameters such as soil strength, density, depth, groundwater table, topography, and seismic acceleration for deterministic calculations (Van Westen, 1998). Recent GIS applications in slope stability mostly focus on statistical methods and artificial intelligence (AI) linking slope failure to influencing factors, with GIS mainly supporting data preparation and processing (Lee and Min, 2001; Ayalew and Yamagishi, 2005; Pradhan and Lee, 2010; Youssef et al., 2015; Mersha and Meten, 2020). Few studies have integrated GIS with deterministic slope stability models (Van Westen, 1993; Van Westen et al., 1997). Considering the complex 3D geometry of natural slope failures, applying a 3D model is a rational approach for assessing slope hazards at the caldera of Mt. Bawakaraeng, South Sulawesi, Indonesia.

2.2 3D Slope Stability Assessment Using Hovland's Model

Hovland (1977) appears to have been the first to analyze a 3D slope using the column method. His approach extends the assumptions of the two-dimensional ordinary method by considering all intercolumn forces at the base of each column as components of the column's weight. The results showed that the 3D analysis typically produces a factor of safety significantly higher than that obtained from two-dimensional analysis. All the methods discussed above rely on the column method, either neglecting intercolumn forces or making assumptions that have yet to be fully validated. These methods have primarily been justified based on experience with 2D analyses, and the accuracy of the 3D approaches has not been independently verified. While quantitative geotechnical analysis requires reliable material parameters, it is equally important assuming sufficient geotechnical data is available to identify appropriate failure mechanisms relevant to the study area and to select a geotechnical model that closely represents these mechanisms. Unfortunately, there has been a growing tendency to adopt the "infinite slope" model, a well-known one-dimensional approach representing potential failure along slip sur-

faces parallel to the ground surface. Although this model may be appropriate for shallow failures and some deep-seated failure areas, it often oversimplifies the complex realities of natural slopes. Landslides are closely linked to the geological and geomorphological characteristics of the study area.

Therefore, in this research, the slope unit serves as the fundamental object of study. A slope unit is defined as a portion of the land surface that contains a distinct set of ground conditions, differentiating it from adjacent units by explicit topographical features (such as break lines, streams, aspect, and slope) and geological form. Using GIS spatial analysis functions, the following parameters can be assigned to each pixel or polygon (into which the study area is divided): (a) topographical parameters (elevation, inclination, slope); (b) spatial distribution and size of landslides (including suspected critical slip surfaces and their boundaries); (c) mechanical properties for each pixel or polygon; and (d) groundwater conditions. By inputting these parameters into a deterministic slope stability model, safety factors or probabilities of failure can be calculated. Building on the model of Hovland (1977), a GIS grid-based 3D model is applied in this study for slope stability analysis.

All slope-related geological data can be illustrated as shown by the 3D view of the landslide body in Figure 4. Assuming that the vertical sides of each pixel column (see Figure 5) are frictionless (no side forces on the vertical sides of the pixel columns, or with their influence canceling out), the 3D safety factor can be expressed as Equation (1):

$$F_{3D} = \frac{\sum_J \sum_I (cA + W \cos \theta \tan \phi)}{\sum_J \sum_I W \sin \theta} \quad (1)$$

where,

F_{3D} = the 3D slope safety factor; W = the weight of one column; A = the area of the slip surface; c = the cohesion; ϕ = the friction angle; θ = the normal angle of slip surface; and J, I = the numbers of row and column of the pixel in the range of slope failure.

Without GIS, calculating the 3D safety factor using a column-based model would be a tedious and time-consuming task, especially when updating data or conducting multiple case studies. However, with the aid of GIS spatial analysis functions, slope stability data for the entire study area can be efficiently represented as vector layers (Figure 5). Each vector layer can then be converted into a grid-based layer using GIS tools, with the cell size adjustable to meet the required level of precision. The slope mass is thus evenly divided into columns corresponding to the grid cells. For each

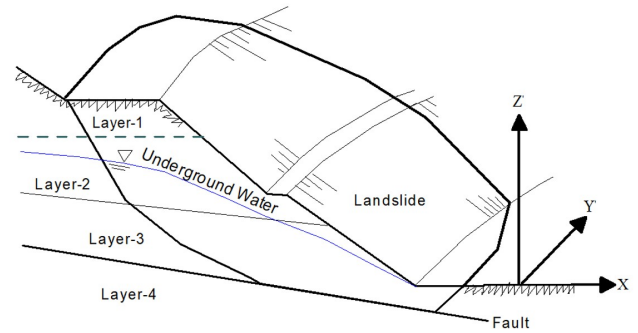


Figure 3. 3D representation of the landslide body.

column referencing the grid-based structure shown in Figure 5, spatial data such as surface topography, geological strata, groundwater, faults, and potential slip surfaces can be extracted from the corresponding grid-based layers. Using this grid-based spatial database, Equation (1) can be adapted into a GIS-compatible grid-based form. In this adapted model, all resisting and driving forces are calculated relative to the actual sliding direction, rather than the Y-axis direction used in the original Hovland model. This adjustment allows for a more realistic representation of slope stability conditions in three dimensions. With reference to Figure 4, the area of the slip surface for a single grid column is given by Equation (2).

$$A = \text{cellsize}^2 \left[\frac{\sqrt{(1 - \sin^2 \theta_{xz} \sin^2 \theta_{yz})}}{\cos \theta_{xz} \cos \theta_{yz}} \right] \quad (2)$$

The apparent dip in the principal direction of inclination of the landslide area can be calculated using the following equation:

$$\tan \theta_{Avr} = \tan \theta |\cos (Asp - Avr Asp)| \quad (3)$$

Therefore, the 3D slope factor of safety can be expressed based on equilibrium in the horizontal sliding direction as follows:

$$F_{3D} = \frac{\sum_J \sum_I (cA + [(Z_{ji} - z_{ji})\gamma' \cos \theta - u_{ij}] \tan(\phi)) \cos \theta_{Avr}}{\sum_J \sum_I (Z_{ji} - z_{ji})\gamma' \sin \theta_{Avr} \cos(\theta_{Avr})} \quad (4)$$

where,

for each grid, Z_{ij}, z_{ij} = the elevations of ground-surface and slip-surface; u_{ij} = the pore water pressure on the slip-surface; and γ = the unit weight.

The slip surface is determined through detailed geotechnical investigations; however, the exact geometry of the slip surface is often uncertain. Therefore, in slope stability analysis, it is crucial to identify the critical slip surface for accurate hazard evaluation. To

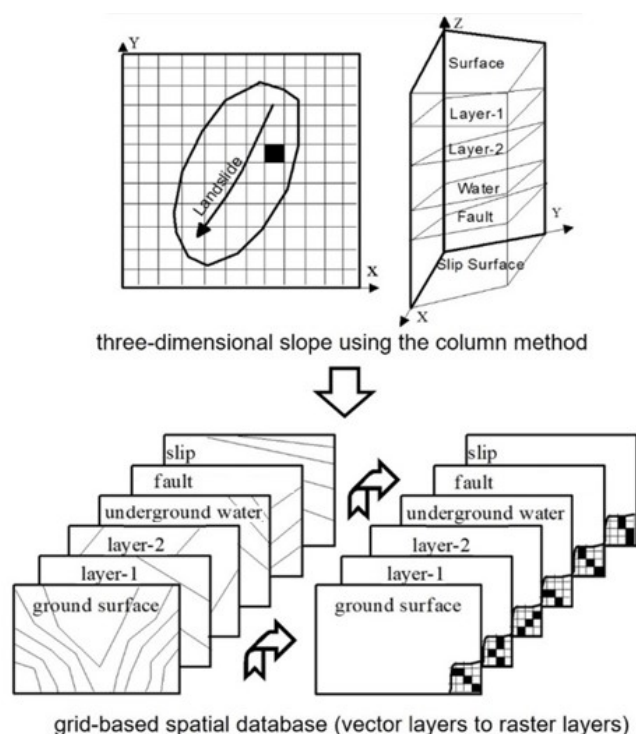


Figure 4. Grid-based spatial layers used to construct a three-dimensional slope stability model based on the column method.

detect this 3D critical slip surface, a search is conducted by minimizing the 3D safety factor calculated using Equation (4) through the Monte Carlo random simulation method. The initial slip surface is assumed to be the lower portion of an ellipsoid. This slip surface evolves based on variations in layer strengths and the conditions of discontinuous surfaces. Ultimately, the critical slip surface is identified by achieving a relative minimum in the 3D safety factor. The orientation of the ellipsoid's inclination is set to align with the main direction of inclination (dip) of the study area. The ellipsoid's inclination angle is generally assigned as the primary slope angle of the area, with allowances for certain fluctuations.

Figure 10 illustrates the flowchart of the GIS-based computational process used to obtain the minimum 3D factor of safety. The entire study area (or slope failure zone) is evenly divided into small rectangular meshes corresponding to the GIS grid-based pixels.

2.3 3D Slope Stability Assessment System

In this section, the complete computational process of the developed system is presented. For each computational step, the corresponding software interface, the implementation of key algorithms, and the associated data or results are described. The 3D slope stability assessment system consists of seven main menu categories, each offering specific functions. Figure 5

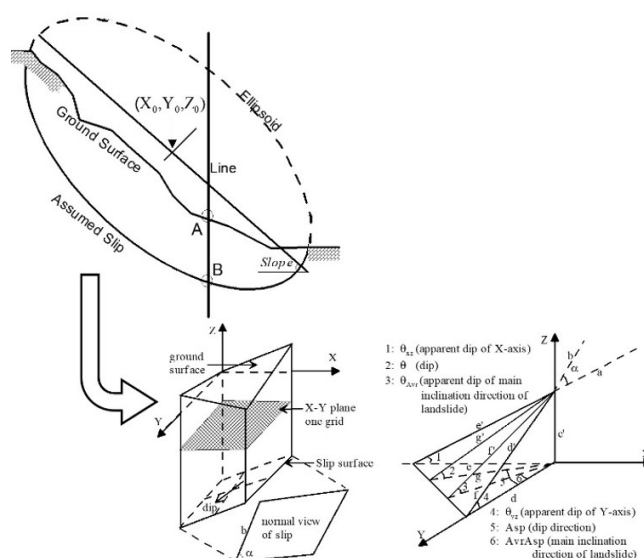


Figure 5. Slip surface geometry and three-dimensional view of a single grid column used to derive the three-dimensional factor of safety equation.

displays the user interface of the developed system, along with several submenu options. This analysis step involves the creation of a point dataset that consolidates all relevant geomorphological, geological, and hydraulic parameters. Figure 5 shows the interface used for generating this dataset. All input data are provided in ASCII file format, including: (i) surface elevation; (ii) surface aspect; (iii) surface slope angle; (iv) elevation of each stratum interface; (v) elevation of potential slip surfaces (discontinuities); and (vi) groundwater table elevation. Managing these spatial datasets in grid format is often inefficient. Therefore, a point dataset (in shapefile format) is created to store all relevant information. In this dataset, the shapefile is defined as the center point of each grid cell, and a feature table is used to link all geomorphological, geological, and hydraulic attributes. By utilizing GIS components from the MapObjects software, it is evident that shapefiles offer more efficient data management than grid-based datasets, particularly for tasks such as identification, and spatial analysis. The factors that will influence the safety factor of slope are the random variables that possess a certain random distribution, and then the safety factor is a random variable too and its probability distribution is determined by the distributions of parameters.

For the critical slip identification, a test for the suitable Monte Carlo random calculating time is performed in one case study; the trial calculating frequency is up to 1,000 times. The resulting minimum 3D safety factors of each trial calculation are illustrated in Figure 11. From this figure, it is clear that the minimum safety factor can be obtained after about 300 trial calculations. Based on the results of 300 trial calculations (see Figure 11), the difference among these values is

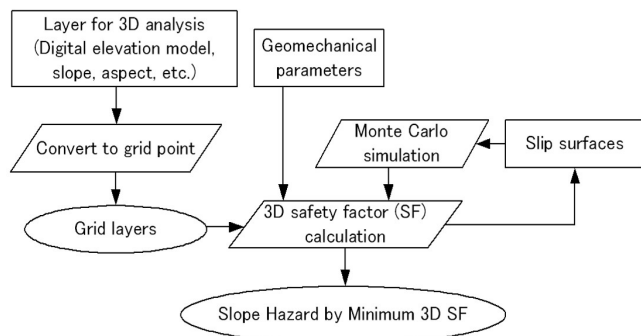


Figure 6. Flowchart of the computational process used to determine the minimum three-dimensional factor of safety.

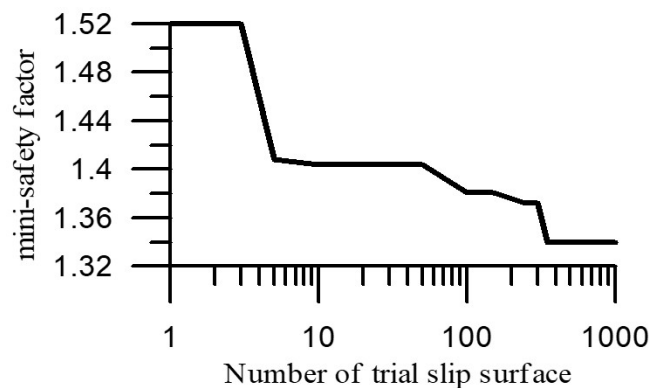


Figure 7. Trial calculations and the minimum three-dimensional factor of safety obtained from the Monte Carlo simulation.

not too large: the minimum value is 1.34 and its mode is 1.68. This critical slip search procedure is based on the minimum safety factor search that is calculated by the random selection of parameters. In slope stability analysis, the parameters c , ϕ , and γ are fundamental geotechnical strength parameters used to assess the potential for slope failure. Cohesion (c) represents the shear strength of soil or rock at zero normal stress. The friction angle (ϕ) reflects the resistance to sliding caused by inter-particle friction and interlocking. Unit weight (γ) is the weight of soil or rock per unit volume, including solids and pore water. By using the 3D assessment system, each slope unit polygon is defined by the geotechnical strength parameters as numerical data at attribute field (Figure 12). Figure 13 illustrates the algorithms of the developed system for calculating the 3D factor of safety. For each slope, the critical 3D safety factor is calculated by the Monte Carlo simulation, in the random simulation, the shape parameters of an ellipsoid are selected for the random variables; the slip surface is calculated by the coordinate conversion between the world and local coordinate system; the value of safety factor for each Monte Carlo selection is calculated by the total resistant and sliding forces which are summarized by the discrete columns of the landslide body.

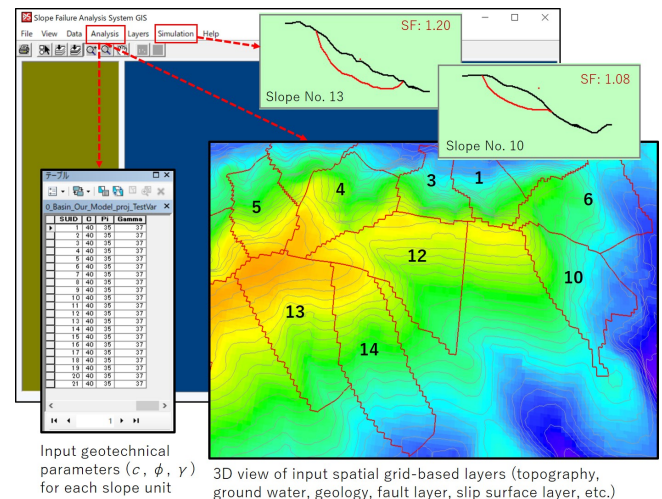


Figure 8. Development of the system-integrated spatial database for three-dimensional slope stability analysis and the corresponding simulation results.

3 ASSESSMENT OF SLOPE STABILITY: A CASE STUDY OF THE CALDERA OF MT. BAWAKARAENG

3.1 Construction of a Digital Elevation Model (DEM) at 1:25,000 Scale for deriving slope units

At an elevation of 2,830 meters, Mt. Bawakaraeng ranks as the third-highest peak on Sulawesi Island, Indonesia. Its proximity to Makassar City makes it one of the most popular hiking destinations in the region. However, on March 26, 2004, a large-scale collapse occurred on the inner side of the mountain's caldera wall. Figure 10 presents a 3D view of the constructed DEM of the caldera at a scale of 1:25,000, along with two historical collapse units identified through digitized lines derived from aerial photograph data. These two collapse areas are located in the source zone of the slope failures: (i) collapse Unit No. 1 spans a horizontal length of approximately 500 meters; and (ii) collapse Unit No. 2 is a significantly larger failure near the ridge, exhibiting a horseshoe-shaped collapse with a horizontal length of around 1,300 meters. The relative height of the failure slopes in both units is estimated at 700–800 meters. The failed bedrock in collapse unit No. 1 is believed to have had a thickness of approximately 150 meters, while in collapse unit No. 2, the bedrock thickness is estimated to have reached up to 400 meters. Based on spatial analysis, the estimated volume of collapsed material is approximately 53 million m^3 for collapse unit No. 1 and 182 million m^3 for collapse unit No. 2 resulting in a total volume of around 235 million m^3 .

The derivation of slope units for 3D slope stability analysis begins with the collection of essential spatial datasets, including a high-resolution DEM developed at a scale of 1:25,000, geological maps, geotechnical parameters, hydrological data, and land cover informa-

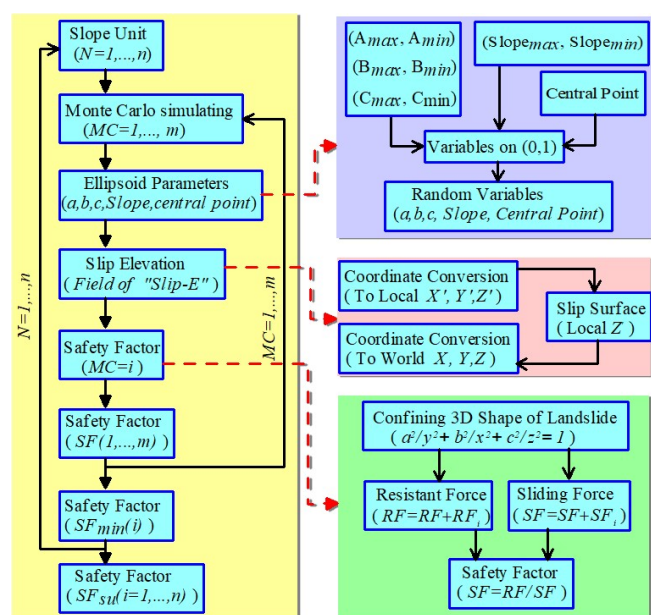


Figure 9. Algorithm of the developed system for calculating the three-dimensional factor of safety.

tion. The DEM undergoes preprocessing to correct errors, followed by the extraction of primary topographic attributes such as slope angle, aspect, curvature, and elevation gradients using GIS tools. Hydrological analysis is then conducted to identify drainage networks and ridgelines, which serve as natural boundaries for slope unit delineation. Based on these topographic and hydrological features, the terrain is segmented into discrete slope units each representing a geomorphologically homogeneous area characterized by similar slope stability conditions. Geological and geotechnical data are subsequently integrated into the slope units to incorporate critical parameters such as geotechnical data, discontinuities, and groundwater conditions. The resulting slope units are validated and refined through comparison with field observations, historical landslide inventories, and remote sensing data. Finally, the delineated slope units are formatted into GIS layers, enabling their use in deterministic slope stability models to evaluate safety factors, potential failure surfaces, and landslide susceptibility across the study area (see Figure 11).

3.2 Data inventory

A comprehensive data inventory was conducted to ensure accurate and reliable slope stability assessment. The primary categories of data include topographic, geological, geotechnical, hydrological, and land use information, all referenced at a scale of 1:25,000. High-resolution DEM with a 5-meter grid mesh were utilized to derive critical terrain attributes such as slope angle, aspect, curvature, and elevation. These parameters are essential for delineating slope units and iden-

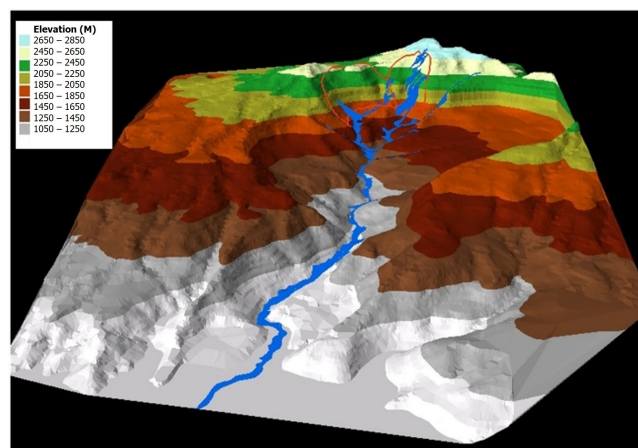


Figure 10. Three-dimensional view of the constructed Digital Elevation Model (DEM) of the caldera, with two historical landslide units highlighted by red solid lines.

tyfying potential failure zones. Geological data including lithology, structural features (e.g., faults, joints, and bedding planes), and stratigraphic boundaries were obtained from previous field observations and laboratory tests. The caldera area is dominated by volcanic soils and volcanic deposits (tuff, pyroclastic materials) with high porosity and variable weathering intensity. Geotechnical parameters such as soil cohesion (55 kN/m²), internal friction angle (30°), and unit weight (22 kN/m³) were analyzed based on observational data and used as general input for deterministic slope stability models. Hydrological data, including groundwater levels, surface drainage patterns, and infiltration characteristics, were also processed using GIS tools. Additionally, land use and vegetation cover data, typically derived from satellite imagery, were incorporated to assess surface conditions. Landslide inventory maps, based on historical records, field surveys, and remote sensing data, were used to validate model outputs and enhance hazard assessments. The integration of these diverse datasets within a GIS environment supports comprehensive spatial analysis, and facilitates data-driven decision-making in evaluation.

4 RESULTS AND DISCUSSION

Slope stability analysis was conducted using a GIS-based 3D deterministic model to assess potential failure zones within the Mt. Bawakaraeng caldera. The analysis employed geotechnical and topographic parameters derived from field surveys, laboratory tests, remote sensing data, and a high-resolution 5-meter DEM. The factor of safety (FS), which is the primary output of the model, serves as a quantitative indicator of slope stability. A safety factor below 1.0 indicates that the driving forces (e.g., gravity, water pressure) exceed the resisting forces (e.g., shear strength), implying imminent slope failure. Conversely, an FS greater than 1.0 implies stability under current conditions. Accord-

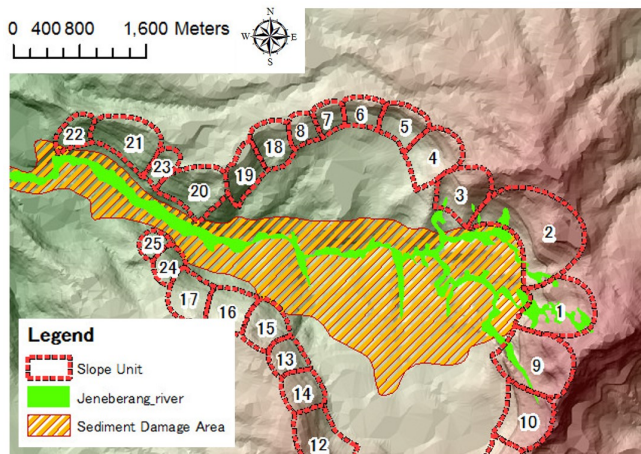


Figure 11. Slope units derived from the Digital Elevation Model (DEM), remote sensing data, and landslide inventory.

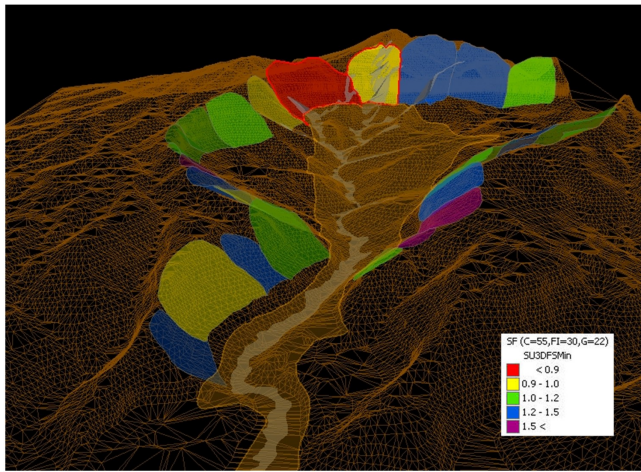


Figure 12. Three-dimensional view of the derived slope units within the Mt. Bawakaraeng caldera, showing the calculated minimum three-dimensional factor of safety for each unit.

ing to Janbu (1973) and Evert (2001), a minimum safety factor of 1.3 is generally recommended for temporary slopes with low-risk exposure, while a higher threshold of 1.5 is advised for permanent slopes where long-term stability and minimal risk are critical. Based on this classification, many slope units within the study area fall below these stability thresholds. Figure 12 displays the resulting 3D slope hazard map, highlighting spatial variations in safety factors across the caldera. The model enables spatially distributed hazard identification, providing valuable insight for both site-specific and regional slope risk assessments.

The simulation results reveal that slope unit no. 1, which corresponds to the smaller collapse area, has a minimum factor of safety (FS) of 1.000. In contrast, slope unit no. 2, which aligns with the larger historical collapse zone, has an FS of 0.825. Figure 13 illustrates the boundaries of the slope failures along with their principal sliding directions. According to this

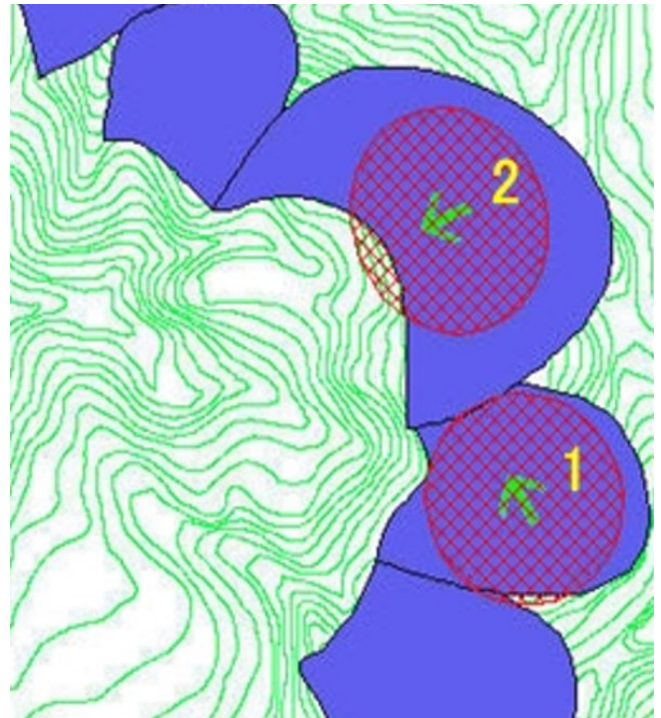


Figure 13. Simulation of slope failures (Nos. 1 and 2) together with their principal sliding directions.

3D slope failure simulation, the block of slope no. 2 fails first, followed by the failure of slope no. 1. This sequence occurs because the foot of slope no. 1 becomes unsupported due to the prior collapse of slope block no. 2, which had previously provided stability to slope block no. 1. These values are notably lower than those of adjacent slope units, many of which exceed the 1.3–1.5 safety threshold (Figure 14). The critical value of 0.825 strongly indicates an unstable condition, supporting the historical record of slope failure in this area. The second collapse unit, despite an FS of 1.000, lies on the threshold of failure and thus presents considerable hazard, particularly under conditions of elevated rainfall or seismic activity. These findings confirm the high susceptibility of these zones to future reactivation or progressive failure. Figure 15 illustrates several slope cross-sections, showing simulated critical slip surfaces generated by the Monte Carlo method that correspond closely to observed collapse morphologies. The spatial integration of input parameters, including lithological variations, groundwater conditions, and historical failure inventories, demonstrates the strength of GIS in managing and analyzing heterogeneous geospatial data. Moreover, the use of Monte Carlo simulation to identify critical slip surfaces adds an important probabilistic element to the deterministic model, enhancing its predictive capability. The role of groundwater and pore water pressure is particularly important in explaining these low safety factor values (Montgomery et al., 1997). As infiltration increases either due to heavy rainfall, poor drainage, or upslope water accumulation pore water pressure builds

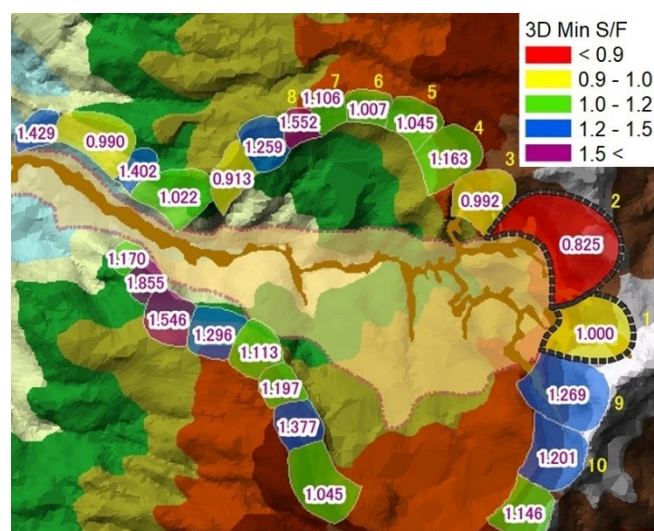


Figure 14. Distribution of the calculated minimum three-dimensional factor of safety for the defined slope units within the Mt. Bawakaraeng caldera.

within the soil and rock mass. This elevated fluid pressure reduces effective stress and, consequently, shear strength, which is a key resisting force in slope stability. In some cases, water pressure can become great enough to partially or fully support the overlying mass, effectively decoupling it from the base material (Beven and Kirkby, 1979). This condition significantly increases the likelihood of slope failure. Further compounding this risk is the behavior of unconsolidated material under varying moisture conditions. In dry states, materials generally exhibit a moderate to high angle of repose, ranging from 30° to 37° , depending on grain size and shape. Slightly moist conditions can temporarily increase slope stability due to surface tension between particles. However, once saturation is reached, this cohesion is lost, and the material begins to behave more fluidly, causing dramatic reductions in shear resistance (Ardizzone et al., 2024). Moreover, surface and subsurface drainage patterns play a critical role in regulating water flow and saturation levels within slope materials. The presence of natural drainage lines, if poorly developed or blocked by debris, can result in ponding or infiltration that significantly weakens slope integrity. In this study, while surface hydrology was modeled to some extent using DEM-derived flow algorithms, further detailed investigation is warranted. Future research should incorporate subsurface hydrological modeling and infiltration simulations to better quantify the hydrological contribution to slope instability. Additionally, land use and vegetation cover derived from satellite imagery provide important contextual information. Areas with dense vegetation typically exhibit higher slope resistance due to root reinforcement and better moisture regulation, while deforested or cultivated zones may be more prone to surface runoff, erosion, and shallow landslides (Iwahashi and Pike, 2007). Within the Mt. Bawakaraeng caldera,

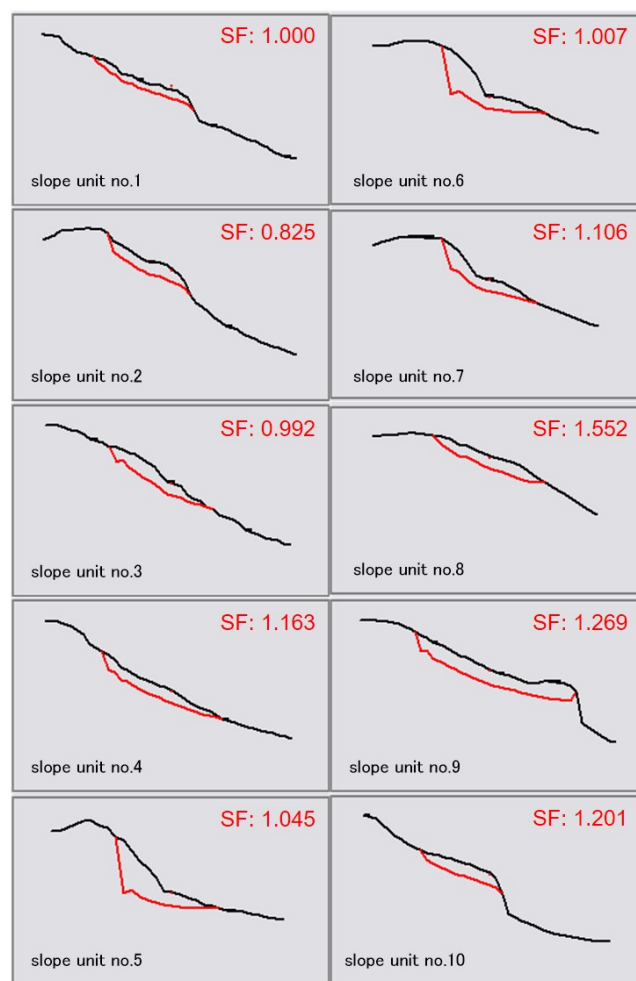


Figure 15. Slope cross-sections showing the ground surface and critical slip surfaces for each analyzed slope unit. Units 1 and 2 correspond to historical landslides within the Mt. Bawakaraeng caldera.

several unstable slope units coincide with areas of reduced vegetation, suggesting that land cover change may have contributed to instability. This highlights the need for integrated watershed management that includes reforestation and slope stabilization strategies. The integration of a landslide inventory compiled from historical records, aerial imagery, and field validation was essential in verifying the accuracy of the modeled safety factors. The spatial distribution of low-FS values aligns well with known landslide scars, thereby reinforcing the validity of the 3D slope stability model used in this study. Moreover, Table 1 presents an evaluation of the potential sediment volumes that may result from future slope failures within the Mt. Bawakaraeng caldera. These estimations provide essential input for assessing sediment hazards that could significantly impact the Jeneberang watershed. The findings contribute to enhancing hazard mitigation strategies and improving watershed resilience by quantifying the potential material available for downstream transport (Akbar et al., 2025). Furthermore, these comparisons serve as a benchmark for calibrating model

Table 1. Calculated minimum safety factors and estimated slope failure volumes for all slope units

Slope Unit No.	Slope Area (m ²)	Slope Thick (m)	Slope Volume (m ³)	Slope Degree (°)	Minimum Safety Factor
1	505,740.4	105	53,000,000	38.242	1.000
2	911,128.2	200	182,000,000	42.529	0.825
3	335,205.1	70	23,596,263	42.294	0.992
4	338,996.5	70	23,660,890	41.362	1.163
5	223,119.2	61	13,564,944	21.510	1.045
6	157,121.1	55	8,609,742	22.247	1.007
7	118,141.4	51	6,001,210	36.328	1.106
8	122,315.1	52	6,335,536	29.945	1.552
9	561,545.7	115	64,465,674	35.941	1.269
10	386,295.8	75	28,893,707	36.204	1.201
11	286,160.1	68	19,400,756	34.130	1.146
12	411,089.4	85	34,859,082	35.752	1.045
13	163,920.2	56	9,146,233	38.095	1.197
14	211,017.8	60	12,618,202	36.960	1.377
15	241,384.6	64	15,399,576	35.459	1.113
16	258,513.7	66	17,009,388	43.015	1.296
17	251,910.1	66	16,574,892	33.562	1.546
18	230,959.7	63	14,503,539	54.370	1.259
19	217,254.4	60	12,991,131	37.767	0.913
20	355,445.2	72	25,519,847	32.843	1.022
21	374,179.5	74	27,613,269	39.306	0.990
22	144,455.0	54	7,771,224	23.055	1.429
23	118,186.1	51	6,003,482	28.759	1.402
24	124,895.2	52	6,469,176	19.962	1.855
25	89,193.6	48	4,263,173	42.754	1.170

input parameters and refining the predictive capabilities of 3D slope stability assessments in similar volcanic mountainous environments.

The GIS-based developed system applied in this study enhances the deterministic 3D slope stability model by incorporating parameter variability and identifying critical slip surfaces. However, several limitations must be acknowledged. The reliability of Monte Carlo results is strongly dependent on the assumed probability distributions and ranges of input parameters. In many cases, these distributions are simplified due to limited site-specific data, which may not fully represent the true spatial and statistical variability of subsurface conditions. Assumptions related to slip-surface geometry, failure mechanisms, and material behavior remain deterministic and may oversimplify complex natural slope processes. The accuracy of 3D slope stability modeling is fundamentally constrained by the quality and completeness of the data inventory. Although this study integrates geotechnical, geological, topographic, hydrological, and remote sensing datasets within a GIS environment, several limitations remain. Geotechnical parameters are typically derived from limited field sampling and laboratory testing, which may not adequately represent the spatial heterogeneity of volcanic deposits, particularly in inaccessible or steep terrain.

Lithological boundaries and structural features are often generalized from surface observations and existing geological maps, introducing uncertainty in subsurface geometry. Topographic data, while derived from a high-resolution DEM, are subject to resolution and interpolation errors, especially in areas of dense vegetation, steep slopes, or shadowed terrain. These errors can influence slope unit delineation, slope angles, and volume estimations.

5 CONCLUSIONS

This study has investigated the slope failure phenomena at the caldera of Mt. Bawakaraeng, Sulawesi Island, Indonesia, focusing on the integration of GIS and a 3D deterministic slope stability model. The combination of geotechnical, geological, hydrological, and topographical datasets within a GIS environment enabled a comprehensive spatial analysis of slope stability conditions in this geologically complex area. The analysis began with the construction of a high-resolution DEM at a 1:25,000 scale, from which terrain attributes such as slope angle, aspect, and curvature were derived. These attributes were essential in delineating slope units, which served as the basis for subsequent hazard evaluation. Using the Hovland-based 3D column method, implemented within a GIS platform, the minimum safety factors of each slope unit were calculated. The results clearly identified two key collapse areas within the caldera, corresponding with historical landslide events, with safety factor values significantly lower than the surrounding terrain (0.825 and 1.000, respectively), indicating a high potential for instability.

In addition, the study demonstrates that slope failures in volcanic terrains are inherently 3D and complex in nature. Traditional two-dimensional models are often inadequate for capturing these complexities. By contrast, the use of a 3D GIS-based model provides a more realistic and spatially resolved picture of slope stability, which is especially important in mountainous and caldera environments like Mt. Bawakaraeng. Furthermore, the integration of GIS with geotechnical modeling opens up new opportunities for conducting scenario-based assessments. The approach offers a robust decision-support framework for geotechnical hazard assessment and future development planning in landslide-prone environments such as the Mt. Bawakaraeng caldera.

Future research should further enhance model precision by incorporating real-time hydrological monitoring, time-series satellite data, and the effects of seismic loading, enabling even more comprehensive and dynamic slope stability evaluations.

DISCLAIMER

The authors declare no conflict of interest.

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