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RESEARCH ARTICLE

Slope Stability Analysis Using the FEM Method and Landslide Vulnerability Zoning Using the GIS Kriging Method as the Basis for Structural-Non-Structural Mitigation Formulation Against Landslide Disasters in Sumberarum Village, Songgon District, Banyuwangi Regency, Indonesia

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Abstract

Songgon District is one of the areas in Banyuwangi Regency that has a high vulnerability to landslides due to steep slope topography, high rainfall, and tectonic and volcanic activity from Mount Raung. This study aims to analyze slope stability, identify landslide-prone zones, and develop an appropriate disaster mitigation strategy matrix in the area. The research method used is an integrative approach that combines numerical modeling based on the 3D Finite Element Method, and Geographic Information System (GIS)-based spatial mapping with Kriging interpolation techniques. Slope stability analysis was conducted at 15 critical review points spread across the Songgon area. The modeling results show significant variations in slope stability levels, where several critical points show safety factors below the safety limit FK < 1.25. Based on the spatial zoning generated through GIS Kriging, the study area is mapped into three vulnerability zones: low, medium, and high vulnerability zones. As an output of the mapping and analysis of geotechnical parameters, a comprehensive disaster mitigation matrix was prepared, including structural recommendations (such as slope reinforcement and drainage improvements) and non-structural recommendations (such as community-based early warning systems and evacuation route mapping) to minimize the risk of future disaster impacts.

Keywords: Mitigation, Landslide, Slope Stability, GIS

1. Introduction

Songgon District is located at the foot of Mount Raung (Efendi et al., 2024). Several large rivers flow through the sub-district, making Songgon prone to landslides, flooding, and volcanic eruptions. According to the Regional Disaster Management Agency (BPBD), flooding occurred in Songgon District on May 11, 2023, triggered by heavy rainfall. Furthermore, on June 22, 2018, a landslide occurred on the slopes of Mount Raung due to heavy rain, resulting in flash floods and damaging 328 houses.

Extreme weather, such as heavy rain, is one of the triggers for landslides. Therefore, it is important to conduct research at the foot of Mount Raung to identify areas with high landslide potential and develop a matrix of landslide mitigation measures. Previous research on floods and landslides in the Raung Mountains, impacting the upstream and downstream rivers, includes (Hidayat and Sukimin, 2024) and (Efendi et al., 2024). These include landslide potential analysis (Sandi et al., 2011) and disaster mitigation measures (Pratikno et al., 2021), (Widayanti et al., 2021), (Fariza and Handayani, 2022), (Erwanto et al., 2023) and (Santoso et al., 2025).

Research by (Ebrahim et al., 2024), (Karimov et al., 2025), (Hilman et al., 2026) (Saepuloh and others, 2025) and (Laksita et al., 2024) focuses on a pure soil mechanics approach using FEM and LEM. This approach is highly accurate, but is localized to a single slope point. On the other hand, GIS-based regional mapping often ignores real-world geotechnical parameters. Research such as that conducted by Hong-in et al., 2024, is confined to the laboratory scale, testing a single slope stabilization method. These laboratory-scale models cannot address the heterogeneity of natural soil masses, boundary conditions, and complex slope geometries in the field. Literature outputs (Umar and Lin, 2024; Zhu et al., 2022) stop at academic documents, providing Factor of Safety (FK) values or deformation contour maps without follow-up. Consequently, there is no conceptual bridge that transforms these geotechnical figures into practical mitigation policy formulations that can be implemented by stakeholders or local communities.

Based on this methodological gap, the authors integrated the FEM method, which applies micro-scale analysis, with the GIS kriging method, which applies macro-scale zoning (Cordoba et al., 2019; Kundu et al., 2026; Nath et al., 2021), as a basis for formulating landslide mitigation measures in the Sumberarum Village area. Although FEM and GIS have been widely used separately in landslide studies, this study offers a novelty by integrating the Kriging method for accurate spatial zoning, validated with FEM numerical simulations, to produce a comprehensive mitigation blueprint for an area with specific volcanic geological characteristics in Sumberarum Village, Banyuwangi (Assyidiqi et al., 2026)(Munirwan and others, 2025).

The problem-solving approach involves analyzing slope stability at the foot of Mount Raung using the FEM method and mapping landslide-prone zones using the GIS Kriging method as the basis for formulating structural and non-structural mitigation matrices. The study location is Sumberarum Village, Songgon District, Banyuwangi Regency, a village largely located at the foot of Mount Raung (Pratama and Misbahudin, 2026).

2. Method

2.1 Survey and Sampling of Disturbed Soil

Including SNI 8460-2017 Geotechnical planning, survey data and soil sampling should include ground surface elevations and slopes, water levels, layer interface elevations, excavation heights and dimensions of geotechnical structures should be treated as geometric data. Soil investigations should provide a description of the ground conditions relevant to the work to be carried out and establish a basis for the assessment of relevant geotechnical parameters for all stages of construction.

Where the coordinate location of each point is presented in table 1 below.

Table 1. Coordinate Points of Sampling Locations and Landslide Analysis Locations

Point Location	X	Y
1	-8.180297°	114.143073°
2	-8.184783°	114.151223°
3	-8.196441°	114.150601°
4	-8.197694°	114.158540°
5	-8.206373°	114.168261°
6	-8.214196°	114.155026°
7	-8.216804°	114.166477°
8	-8.222756°	114.159274°
9	-8.217800°	114.151074°
10	-8.224827°	114.140967°
11	-8.210350°	114.143243°
12	-8.228190°	114.135701°
13	-8.218303°	114.144668°
14	-8.212191°	114.134752°
15	-8.198392°	114.141063°

A survey was conducted at the sampling locations to record the coordinates, distances, and elevations from the sampling points to the north, south, west, and east.

Soil sampling was conducted at the coordinates specified in Table 1. The soil samples taken were disturbed, or soil samples taken without preserving their original condition. The soil sampling method used was the test pit method, which adheres to SNI 8460:2017. The test pit method involves testing the condition of the subsurface soil layer by digging an open hole to visually inspect the soil structure and directly sample the soil. This method can be performed manually using a digger or with heavy equipment and is used to investigate shallow soil and rock. The general procedure is as follows:

-Site Determination: Determine the location of the test pit excavation that will provide representative data on the conditions of the observation area.

-Manual/Mechanical Excavation: Excavate the hole manually or using heavy equipment, depending on the required depth.

-Visual Documentation: Record descriptions of rock/soil types, strata, and horizon geometry within the test pit.

-Sampling: Collect soil samples from the desired layers for further analysis in the laboratory.

-Re-evaluation: After excavation, an evaluation is carried out of the material bearing capacity conditions and the relationship of the excavation location to the surrounding land forms

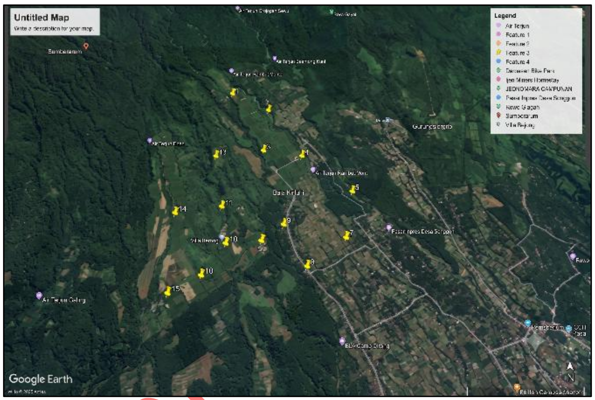

Fig. 1. Sampling Point Location

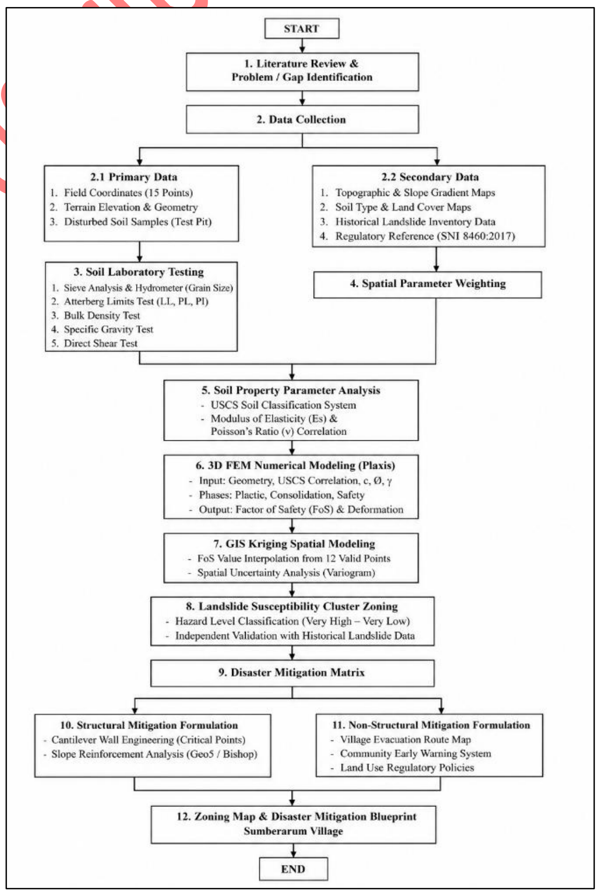

Fig 2. The research flow diagram

Spatial analysis methods like Kriging require a sufficient sample size. Fifteen points is an ideal threshold for a village-scale area to produce a stable interpolation model without incurring cost overruns and excessive laboratory testing time. Sample points were placed along the transition zone from the plains (settlements/low vegetation) to higher elevations on the left side of the map (the foothills of Mount Raung). Several point clusters (such as points 10, 13, 14, and 15) were placed very close to valley incisions or watercourses. Zones near streams or waterfalls have very high soil saturation levels. Constant water infiltration drastically reduces the effective stress of the soil. Sampling in these areas is crucial for modeling the critical conditions of slopes facing maximum pore water pressure in FEM simulations. Points such as points 4, 5, 7, 8, and 9 were placed close to the boundaries of residential areas or roads. In line with the research's ultimate goal of formulating structural and non-structural mitigation, sampling near residential infrastructure is crucial. The Safety Factor (FK) values generated from the FEM at these points will directly determine whether the residential area requires a retaining wall or simply non-structural zoning (evacuation routes). The research flow diagram is as follows.

2.2 Soil Testing

Soil sample testing was conducted in the Civil Engineering Department's soil testing laboratory, Banyuwangi State Polytechnic. The purpose of the soil sample testing was to obtain soil classification and parameters, which would later be used in disaster mitigation structure planning. The soil sample testing consisted of:

- Sieve Analysis Test (SNI 1975:2012)
  Sieve analysis is performed by vibrating a soil sample through a set of sieves, each with a successive and progressively smaller aperture or diameter. This sieve analysis is performed on soil retained on the No. 200 sieve.
- Hidrometer (SNI 03-3423-1994)
  Hydrometer analysis is one method for determining the size distribution of soil particles, for particles smaller than 0.075 mm in diameter. Sieve analysis, on the other hand, is used to determine the size distribution of soil particles larger than 0.075 mm in diameter.
  Hydrometer analysis is based on the principle of sedimentation (sedimentation) of soil particles in water. When a sample is dissolved in water, the soil particles will settle at varying rates depending on the shape, size, and weight of the soil.
- Atterberg Limit Test (SNI 1967:2008)
- Atterberg Limit testing involves determining the Liquid Limit, Plastic Limit, and Plasticity Index. The purpose of this testing is to describe the soil's sensitivity to water addition, as an indicator of the soil's compressibility, and as a basis for soil classification using the USCS and AASHTO methods.
- Bulk Density Test (SNI 03-3637-1994)
- Soil bulk density is the ratio of the weight of the Soil to its volume in its natural state in the field. It can be used to determine the dry bulk density in soil compaction experiments. The greater the dry bulk density, the higher the density. Bulk density can also determine other soil parameters.
- Spesific Gravity Test (SNI 1964 : 2008)
  Soil specific gravity is the ratio between the weight of soil grains and the weight of distilled water with the same content at a certain temperature.
- Consolidated Direct Shear (SNI 1964 : 2008)
  Soil shear strength is the soil's internal resistance per unit area to failure or displacement along a shear plane in question.
  The direct shear test is a simple and direct test. It is performed by placing a soil sample in a shear box. The box is split, with the bottom half being fixed and the top half translatable. Boxes are available in several sizes, but typically have a diameter of 6.4 cm or a square of 5.0 x 5.0 cm. The soil sample is carefully placed inside the box, and a loading block, including porous stones with teeth for rapid drainage, is placed on top of the soil sample. A normal load Pv is then applied. The two halves of the box are slightly separated, and the loading block and the top half of the box are joined together.

2.3 Soil Parameter Analysis

Analysis of laboratory test results to process data obtained from the test results. The results of the sieve and hydrometer tests are analyzed to obtain the cumulative percentage value that passes the sieve and the hydrometer results are calculated for the percentage of clay and silt categories in equation 1 and grain diameter in equation 2 to be classified.

$$N = \frac{a.R_{CP}}{Ws} x100\% \quad (1)$$

$$D = A\sqrt{\frac{L}{t}} \quad (2)$$

The results of the Atterberg limit test were analyzed to obtain the liquid limit, plastic limit, and plasticity index values. The liquid limit test data were analyzed using equation 3 to obtain the liquid limit (LL) parameter.

$$LL = Wn\left(\frac{N}{25}\right)^{0,121} \quad (3)$$

N = the number of blows that causes the groove to close at a certain water content;
LL = liquid limit corrected for groove closure at 25 (%);
Wn =Water content (%

To obtain the water content value from the test, a calculation is carried out using equation 4.

$$Wn = \frac{Water\ Weight}{Dry\ Soil\ Weight} \times 100\ \% \quad (4)$$

Plasticity Index (PI) = Liquid Limit (LL) – Plastic Limit (PL) .... (5)

The results of the bulk density test are analyzed to obtain the dry and wet soil bulk density values. Analysis of the soil bulk density values from the test data is based on equation 6.

$$\gamma = \frac{W}{V} = \frac{W_2 - W_1}{\frac{1}{4}\pi d^2 t} \quad (6)$$

Where: W1 – W2 = Weight of wet soil (gr)
W1 = Weight of soil in the ring and ring weight (gr)
W2 = ring weight (gr)
d = Inner diameter of the ring (cm)
t = Ring height (cm)
V = Volume of soil (cm³)

The results of the specific gravity test are analyzed to obtain the specific gravity value of the soil using equation 7.

$$Gs = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} \times k \quad (7)$$

Where :
W1 = Weight of empty pycnometer (gr)

W2 = Pycnometer Weight + dry soil sample (gr)
W3 = Weight of pycnometer + soil sample + distilled Water (gr)
W4 = Weight of pycnometer + distilled water (gr)
K = Correction Factor for temperature

The results of the direct shear test were analyzed to obtain the cohesion value, soil friction angle, and maximum shear stress value. The shear stress equation is

$$\tau = c + \sigma_n \cdot \tan\varphi \quad (8)$$

Laboratory testing was only carried out at locations 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 13, because locations 14 and 15 are located on very steep slopes, so the soil sampling team could not reach these locations. The results of soil parameter testing at locations 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 13 were analyzed to obtain soil classification and property values. The soil classification method used was the USCS (Unified Soil Classification System). Then, the soil classification data was used for data correlation based on (Umum, 2005) in predicting the value of the soil Elastic Modulus and Poisson's number.

2.4 Slope Stability Analysis Using FEM Method

Landslide potential analysis was conducted by modeling the slope in Plaxis V20 3D. Where the results of the survey coordinates of the sampling location, elevation above sea level and soil data from the results of soil testing were used as input. Soil data was modeled with the Mohr Coloumb type. Soil parameter data that needed to be input were the value of the soil bulk density (γsaturated and γunsaturated), the cohesion value and the angle of internal friction from the direct shear test, the soil dilatation value, the soil modulus of elasticity and the Poisson number obtained from the correlation of soil data, and the soil permeability value. Then the calculation process was carried out by modeling in the plastic, consolidation and safety phases. Plaxis modeling was carried out in 12 models, namely modeling for points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 13. At locations 14 and 15, modelling could not be carried out because soil testing was not carried out in the laboratory, so the soil property data was incomplete. Soil data obtained from laboratory testing and interpolation results were used as input parameters in the Plaxis analysis. The sieve analysis data were grouped into soil types using the USCS. From the known soil types, correlations were performed according to Bowless (1997) to obtain Young's modulus and Poisson's ratio. The soil parameter data are shown in the following table 4.

2.5 Landslide Disaster Zoning Using GIS Kriging Method.

The results of the Plaxis modeling in the form of deformation analysis data against plastic calculations, deformation analysis data against consolidation calculations and safety factor values against potential landslides, were plotted using the GIS Kriging method.. (Nur et al., 2024)(Algoritma et al., 2022)(Darwis et al., 2021) (Mira et al., 2021) Kriging is a geostatistical interpolation method based on spatial autocorrelation (dependence between spatial data). This method produces the most accurate predictions because it considers the distance between points, the direction and distribution pattern (anisotropy).

2.6 Structural Mitigation with Cantilever Wall Planning

Structural mitigation measures against landslide hazards are physical or engineering efforts undertaken to reduce the potential for landslides or minimize their impact on the environment and communities. Structural land design utilizes cantilever walls. The advantages of retaining walls are:

- Retaining soil mass movement, primarily to prevent soil movement or landslides on steep slopes, suitable for areas with high landslide potential, such as roadside cliffs and hills.
- Stabilizing slopes and surrounding structures
- Can function as permanent structures
- Improving land utilization

The minimum and maximum dimensions for retaining wall design are based on SNI 8460:2017 Geotechnical Design Requirements. A slope stability analysis is then performed using the retaining wall. The slope stability analysis is based on the safety factor, sliding moment, and resisting moment. The slope stability analysis uses the Simplified Bishop Method. This slope stability analysis method is used to calculate the safety factor (FK) for landslides in the form of a circular slip surface. Slope stability analysis using Geo 5.

3. Result

3.1 Soil Parameter Analysis Results

The results of soil sample tests at locations 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 13 which have been carried out in the soil testing laboratory of the Civil Engineering Department, Banyuwangi State Polytechnic, next is soil data analysis to obtain physical and mechanical parameters of the soil. After obtaining the physical parameters, the soil is then classified using the USCS (Unified Soil Classification System) method and continued to predict the value of the modulus of elasticity and the value of the Poisson number by conducting a correlation based on the correlation table. Table 2 shows the results of soil classification using the USCS method.

Table 2. Soil Classification using the USCS method

No.	Location	Soil Clasification
1	Point 1	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
2	Point 2	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
3	Point 3	SW-SP, CL (Fine Grain Sand, Low Plasticity Inorganic Clay)
4	Point 4	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
5	Point 5	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
6	Point 6	SW-SP, CH (Fine Grain Sand, Fine Grain in the form of high plasticity inorganic clay)
7	Point 7	SW-SP, CL (Fine Grain Sand, Low Plasticity Inorganic Clay)
8	Point 8	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
9	Point 9	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
10	Point 10	SW-SP, CL (Fine Grain Sand, Low Plasticity Inorganic Clay
11	Point 12	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)
12	Point 13	SW-SP, MH&OH (Fine Grain Sand, Fine Grain in the form of Inorganic Silt & Organic Clay Medium Plasticity)

The results of the unit weight, specific gravity and Direct Shear tests were analyzed using equations (6), (7), and (8). To obtain the cohesion parameters and internal shear angle from the direct shear test, an approach was made using a linear equation by making a relationship between the maximum shear stress value at each additional load and normal stress.

Table 3. Results of Soil Data Analysis

No	Location	cohesi c (kN/m2)	Ø	Saturated Bulk Density γ (kN/m3)	Unsaturated Bulk Density γ (kN/m3)
1	Point 1	1,693	19,8	15,2	10,52
2	Point 2	3,31	20,4	16,8	11,65
3	Point 3	1,3166	28,7	15,6	9,871
4	Point 4	3,5033	25,2	15,6	10,34
5	Point 5	4,622	22,8	19,1	14,8
6	Point 6	1,6786	10,1	16,7	11,59
7	Point 7	4,5309	17,1	16,7	9,39
8	Point 8	2,9491	34,3	16,5	11,12
9	Point 9	3,3967	34,3	17,4	11,65
10	Point 10	1,614	17,2	17,1	11,59
11	Point 12	2,6686	14,3	16	10,94
12	Point 13	1,1868	16,2	16,7	9,57

3.2 Slope Stability Analysis Results

Landslide potential analysis was conducted by modeling the slope in Plaxis V20 3D. Where the results of the survey coordinates of the sampling location, elevation above sea level and soil data from the results of soil testing were used as input. Soil data obtained from laboratory testing and interpolation results were used as input parameters in the Plaxis analysis. The soil parameter data are shown in the following table 4.

Table 4. Parameter input on Plaxis

No	Location	Soil Type	**Cohesi c (kN/m²)**	**Ø**	Saturated Bulk Density **γ (kN/m³)**	Unsaturated Bulk Density **γ (kN/m³)**	**Modulus Young E (kN/m²)**	Poisson Ratio **V**	**Atterberg Limit LL**	**PL**	**PI**
1	Point 1	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	1,693	19,8	15,2	10,52	10000	0,3	42,46	38,10	4,37
2	Point 2	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	3,31	20,4	16,8	11,65	10000	0,3	45,23	41,67	3,56
3	Point 3	SW-SP, CL (Slightly Fine Grained Sand, Low Plasticity Inorganic Clay)	1,3166	28,7	15,6	9,871	15000	0,3	45,52	32,46	13,07
4	Point 4	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	3,5033	25,2	15,6	10,34	10000	0,3	48,84	45,00	3,84
5	Point 5	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	4,622	22,8	19,1	14,8	10000	0,3	39,27	37,57	1,70
6	Point 6	SW-SP, CH (Fine Grain Sand, Fine Grain in the form of high plasticity inorganic clay)	1,6786	10,1	16,7	11,59	8000	0,3	42,29	22,50	19,79
7	Point 7	SW-SP, CL (Slightly Fine Grained Sand, Low Plasticity Inorganic Clay)	4,5309	17,1	16,7	9,39	15000	0,3	67,53	38,10	29,43
8	Point 8	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	2,9491	34,3	16,5	11,12	10000	0,3	48,97	40,00	8,97
9	Point 9	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	3,3967	34,3	17,4	11,65	10000	0,3	46,84	38,10	5,17
10	Point 10	SW-SP, CL (Slightly Fine Grained Sand, Low Plasticity Inorganic Clay)	1,614	17,2	17,1	11,59	15000	0,3	49,10	41,67	16,60
11	Point 12	SW-SP, ML&OL (Fine Grain Sand, Fine Grain in the form of Silt & Organic Clay)	2,6686	14,3	16	10,94	10000	0,3	45,64	32,50	5,46
12	Point 13	SW-SP, MH & Oh (Fine Grain Sand, Fine Grain in the form of Inorganic Silt & Organic Clay Medium Plasticity)	1,1868	16,2	16,7	9,57	5000	0,3	55,72	40,18	15,72

The soil data was modeled with the Mohr-Coulomb type. Then the calculation process was carried out by modeling in the plastic, consolidation and safety phases. Plaxis modeling was carried out in 12 models, namely modeling for points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 13. The output of the modeling was the deformation of the soil after being treated with consolidation loads and the safety factor against landslides.

According to Bowless (1989), if the safety factor value is >1.25, it is declared safe. The results of slope stability modeling, at locations 4 and 5, failed running due to soil body calllapse in the plastic deformation analysis phase. The deformation results in the plastic deformation calculation phase at location 4 were 22.24 m and at location 5 were 4.963 m. The high deformation resulted in the program being stopped and unable to run in the next phase, namely the consolidation and safety deformation calculation phase. Therefore, at locations 4 and 5, slope reinforcement is necessary to anticipate landslides. Figure 2 and Figure 3 are the deformation results of slope stability calculations at points 4 and 5 in plastic conditions, and failure occurred in consolidated conditions. The planned slope reinforcement is a retaining wall with a cantilever wall model.

Table 5 Slope Stability Modeling Results

No.	Location	Total Deformation Due To Plastic Calculation (M)	Total Deformation Due To Consolidation Calculation (M)	Safety	Description
1	Point 1	2,222 x 10-3	2,233 x 10-3	1,148	Safe
2	Point 2	0,6711 x 10-3	0,6712 x 10-3	8,438	Safe
3	Point 3	2,768 x 10-3	2,769 x 10-3	4,299	Safe
4	Point 4	22,24 (Collapse)	Failed to Calculation	Failed to Calculation	Not Safe
5	Point 5	4,963 (Collapse)	Failed to Calculation	Failed to Calculation	Not Safe
6	Point 6	0,02092	0,02096	1,729	Safe
7	Point 7	5,567 x 10-3	5,565 x 10-3	3,047	Safe
8	Point 8	9,880 x 10-3	9,882 x 10-3	4,852	Safe
9	Point 9	4,882 x 10-3	4,884 x 10-3	6,59	Safe
10	Point 10	4,788 x 10-3	4,791 x 10-3	2,516	Safe
11	Point I 12	0,07216	0,07243	1,438	Safe
12	Point 13	0,1085	0,1088	2,617	Safe

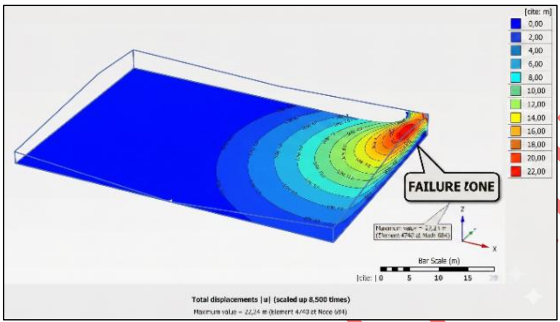

Fig. 3 Deformation at location 4

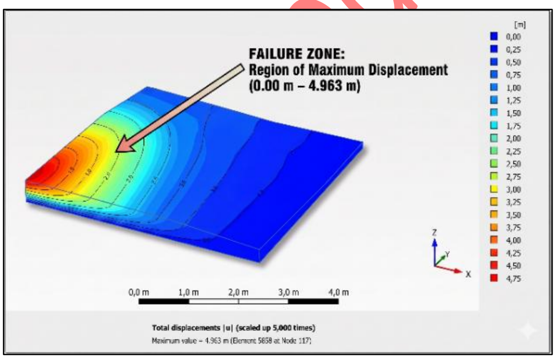

Fig. 4 Deformation at location 5

Figures 3 and 4 show that this failure is highly localized, concentrated entirely at the corner. Considering that the analysis used the Consolidation option, this surge in excess pore water pressure drastically reduces the effective soil stress in the corner area, causing the soil to undergo local plastic shear failure before water dissipation.

3.3 Landslide Disaster Zoning Results Using the GIS Kriging Method

The results of the Plaxis modeling in the form of deformation analysis data against plastic calculations, deformation analysis data against consolidation calculations and safety factor values against landslide potential, were plotted using the GIS kriging method. The following image is the result of the landslide-prone zoning plot.

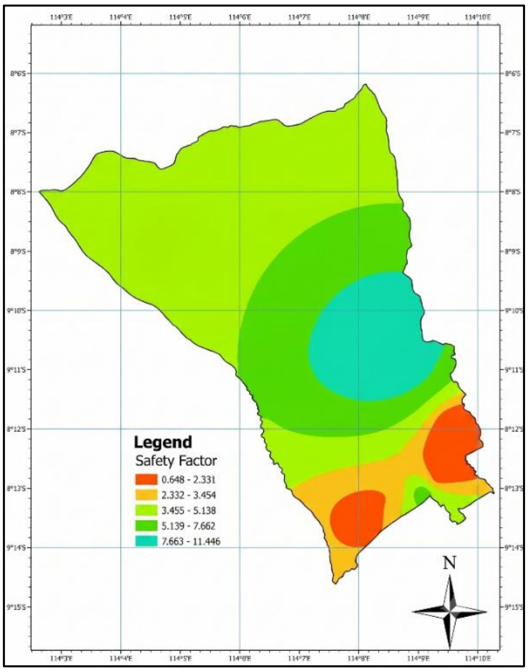

Fig. 5 Landslide Vulnerability Zoning with Safety Score Indicators in Sumberarum Village, Songgon

Figure 5 shows the landslide vulnerability zoning, with the parameter indicator of the Plaxis modeling results for the landslide safety factor. Where the zoning is divided into 5 clusters. Red represents a very high landslide safety factor, yellow represents a high landslide risk, light green represents a moderate landslide risk, dark green represents a low landslide risk, and light blue represents a very low landslide risk.

3.4 Structural Mitigation

(Kamal et al., 2023) (Lutfi et al., 2023) (Priyono et al., 2023) Structural mitigation measures against landslide hazards are physical or engineering efforts undertaken to reduce the potential for landslides or minimize their impact on the environment and society. Planning for structural mitigation measures in Sumberarum Village, Songgon, is focused on locations at points 4 and 5. Due to the results of modeling and analysis using Plaxis, there was very high collapse and deformation, so it is necessary to plan structural reinforcement of the soil. Structural planning of the soil uses a retaining wall with the Cantilever Wall type.

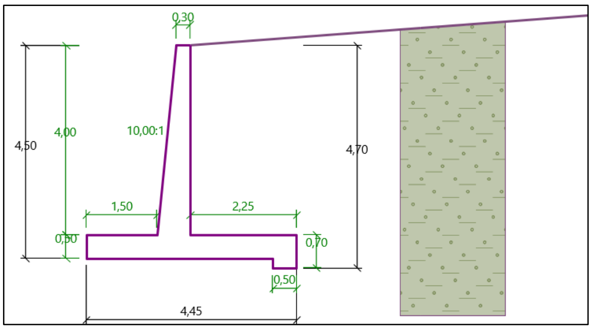

Fig 6. Planning of a retaining wall with a cantilever wall type at location point 4

Figure 6 shows the design of the retaining wall at Location 4. The minimum and maximum dimensions for the retaining wall are based on SNI 8460:2017 Geotechnical Design Requirements. A slope stability analysis was then conducted with the retaining wall in place. The analysis was based on the safety factor, sliding moment, and resisting moment. The slope stability analysis used the Simplified Bishop Method. This slope stability analysis method is used to calculate the safety factor (FK) for landslides in the form of a circular slip surface. The slope stability analysis was performed using Geo 5. A summary of the output of the slope stability analysis using the Bishop method is as follows.

Table 6. Output of Geo Slope Stability Analysis 5 Point 4

No.	Parameter	Value	
1.	Sum of active forces (Fa)	157,36 kN/m	
2.	Sum of passive forces (Fp)	251,76 kN/m	
3.	Sliding moment (Ma)	1310,85 kNm	Acceptable
4.	Resisting moment (Mp)	2097,13 kNm	
5.	Factor of Safety	1,6	

Figure 7 is the planning of the retaining wall at location 5. The minimum and maximum dimensions for the planning of the retaining wall are based on the reference SNI8460:2017 Geotechnical Design Requirements.

Slope stability analysis using Geo 5. Recapitulation of slope stability analysis output using the Bishop method as follows.

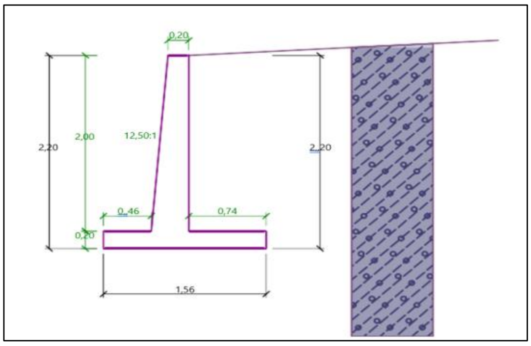

Fig 7. Planning of a retaining wall with a cantilever wall type at location point 5

Table 7 Output of Geo Slope Stability Analysis Point 5

No.	Parameter	Value	
1.	Sum of active forces (Fa)	36,77 kN/m	
2.	Sum of passive forces (Fp)	64,78 kN/m	
3.	Sliding moment (Ma)	115,09 kNm	Acceptable
4.	Resisting moment (Mp)	202,78 kNm	
5.	Factor of Safety	1,76	

4. Discussion

Laboratory test results show that the soil at the research location is dominated by a mixture of sand and clay. It is predicted to be volcanic residue soil because it has a low cohesion value (c), around 1.18 to 4.62 kN/m. In particular, sample location point 6 has the lowest internal friction angle value with a value of 10.10, this indicates that location point 6 has a higher clay and silt content compared to other sampling locations.

The results of 3D finite element modeling (3D FEM) on the slopes of Sumberarum Village show fluctuations in Safety Factor values that are very sensitive to variations in geometry and local hydrological conditions, where several critical points recorded FK values < 1.25 at locations 4 and 5. When compared with previous FEM-based landslide studies, these findings strengthen the mechanistic patterns that often occur in volcanic residual soils. For example, (Kundu and others, 2026) in their analysis of the Shirur landslide confirmed that FEM modeling was able to capture the initiation of early phase cracks (progressive failure) due to the loss of slope toe resistance before macro failure occurred. Similarly, the deformation pattern at the critical point of the Sumberarum slope shows the accumulation of maximum shear strain which is concentrated in the slope toe area due to a combination of natural slope cutting for vegetation/access and water infiltration.

The slope failure characteristics in this region show mechanistic similarities to the studies of (Karimov and others, 2025) on the Pekmez landslide and (Nath and others, 2021) in the Darjeeling-Sikkim Himalayas. When the slope reaches a critical state, FEM visualizes the dynamic transition of the slip plane, influenced not only by static loading but also by the development of a bottom-up plastic zone (bottom-up progressive failure). A thorough interpretation of this phenomenon indicates that the residual volcanic soil at the foot of Mount Raung has high intrinsic vulnerability; post-peak shear strength degradation occurs once the critical strain zone is exceeded, triggering massive rotational-translational slip failures, as identified in the vulnerability cluster mapping.

FEM modeling results at locations 4 and 5 indicated failure. Meanwhile, modeling results using the Janbu method at location 4 yielded a safety factor of 0.92 and the Bishop method a safety factor of 0.93, both of which were deemed unacceptable. Modeling using the Janbu method at location 5 yielded a safety factor of 2.58 and the Bishop method yielded a safety factor of 2.59, both of which were deemed acceptable. There are differences in the analysis results using the FEM compared to the Janbu and Bishop methods at location 5. Failure in the FEM modeling results at location 5 occurred during the consolidation analysis condition, where excess pore pressure was still very high and had not had time to dissipate, resulting in a decrease in the soil shear strength and causing failure. Meanwhile, LEM can calculate it by assuming stable long-term drainage conditions (Saim and Kasa, 2023) (Bagaskoro et al., 2024; Begum and Rao, 2025; Melentijevic et al., 2025). In LEM analysis such as the Bishop and Janbu methods, pore water pressure is generally modeled statically through the water pressure coefficient or the assumption of a uniform groundwater table. In contrast, FEM modeling (Plaxis) is able to accommodate dynamic consolidation phase analysis, where the dissipation or accumulation of pore water pressure is calculated gradually at each node of the triangular element. During rainfall periods, the slow dissipation of fine-grained soil layers (CH/CL classification based on the USCS) triggers an increase in excess pore water pressure. This decreases the effective stress ($\boldsymbol{\sigma}'$) of the soil locally, a softening phenomenon that cannot be detected by the rigid slip plane assumption in the LEM. The LEM method ignores the stress-strain relationship of the material and treats the soil mass as a rigid block that fails simultaneously along a unilaterally determined failure plane. On the other hand, the FEM uses a perfectly elastic-plastic Mohr-Coulomb constitutive model (or Hardening Soil). This model considers the soil stiffness (Es) and Poisson's ratio (V) derived from the USCS empirical correlation (Bowles, 1996). Thus, the FEM is able to simulate stress redistribution within the slope body when a small area of the element begins to yield.

The results are specific and detailed to the cross-section of the area being studied. Therefore, the landslide mechanism analysis is presented at a micro-scale. This limits the data required to create a landslide zoning map using the Kriging GIS method. Therefore, the more soil data and stability analysis points collected, the more detailed the zoning grouping results will be. The use of Ordinary Kriging spatial interpolation techniques to compile a regional landslide susceptibility map in Sumberarum Village requires critical evaluation, given the limited input data, which relies on only 12 valid FEM analysis points due to terrain accessibility constraints (points 11, 14, and 15 could not be surveyed). This limited data quantity (small sample size constraint) has mathematical implications for the stability of the experimental semi-variogram model.

From a spatial statistical perspective, the limited number of control points can increase the Nugget Effect, reflecting high micro-scale random variability or undetectable laboratory measurement errors within the inter-sample range. The implication for zoning maps is the risk of generalization bias, where the delineation boundaries between vulnerability clusters (Very High to Very Low) experience an excessive smoothing effect. Areas far from the 12 main monitoring points potentially harbor high uncertainty in the estimated FK values. To mitigate this uncertainty and ensure the accuracy of the zoning remains reliable for public policy, this study implemented a validation step. The interpolated spatial vulnerability map was independently cross-validated using local historical landslide inventory data in Songgon District. The overlap results demonstrated that the majority of past landslide traces fell within the radius of the "High" to "Very High" clusters delineated by Kriging. This confirms that, despite the limited sample size, the purposive geotechnical sampling method, which locks in critical areas (waterfall paths and residential slopes), maintains the reliability of the spatial mapping results. The slope stability analysis results at points 4 and 5 failed due to soil collapse during the plastic deformation analysis phase. Therefore, structural mitigation using cantilever walls is recommended, as outlined in the design plan in Figures 5 and 6. The determination of the cantilever retaining wall structure as the preferred structural mitigation measure at the critical point of the Sumberarum slope is based on careful geotechnical, topographic, and construction feasibility considerations. The reinforced concrete cantilever retaining wall was chosen because it works by utilizing the self-weight of the soil above the heel slab to resist overturning moments and lateral sliding forces of the active soil mass. This structure does not require a large back space like geogrids, does not rely on soil pullout forces like soil nailing, and is able to provide rigid structural retaining forces instantly. The engineering combination proposed in this study—integrating cantilever wall construction at the foot of critical slopes equipped with weep holes for internal drainage—is the most optimal and safe solution, according to SNI 8460:2017 standards, to protect the residential areas of Sumberarum Village from the threat of landslides.

In addition to structural mitigation, non-structural mitigation is also needed to minimize the causes of landslides. Non-structural landslide mitigation measures are non-physical or non-engineering measures aimed at reducing the risk and impact of landslides through education, planning, policies, and early warning systems (Ridha et al., 2024)

Table 8. Non-Structural Mitigation

No	Activity	Action	Purpose	Executor
1.	Safe Spatial Planning	- Regulate land use according to landslide vulnerability. - Prohibit or restrict development in high-landslide-prone areas. - Establish protected areas, forests, and water catchment areas.	Reducing risk exposure	local government, PUPR

2	Community Education and Counseling	- Educate the community about the early signs of landslides and evacuation methods. - Disaster response training in schools, villages, and agencies. - Encourage the community not to cut down trees on steep slopes or dig indiscriminately.	Increasing community awareness and preparedness	BPBD, schools, village government
3	Early Warning System	- - Installation of ground movement, rainfall, and soil moisture detectors. - -Warning announcements via sirens, community radio, or text messages. - Increasing community preparedness for extreme rainfall.	Allow time for evacuation	PVMBG, BMKG, BPBD
4	Regulation and Law Enforcement	- Establishment of regional regulations regarding development in disaster-prone areas. - Supervision of building permits on steep slopes. - Sanctions for those who damage slope-retaining vegetation (illegal logging).	Imposing sanctions for obeying the rules	Law Enforcement Officers, Village Officials
5	Community Empowerment and Participation	- Involve the community in monitoring slope conditions around their homes. - Form disaster preparedness groups (KSB) at the village/sub-district level. -Conduct community service to clean water channels and repair drainage.	Increasing public awareness of the dangers of landslides	Volunteers, KSB, alert village
6	Monitoring and Mapping of Vulnerable Areas	- Conduct geological surveys and mapping, rainfall, and land use. - Create landslide vulnerability zoning maps as a reference for regional planning. - Routine monitoring by technical agencies	Menentukan prioritas mitigasi	BNPB, PVMBG
7	Preparedness and Emergency Response Plan	- Develop a contingency plan in case of a landslide (evacuation routes, assembly points, logistics) - Conduct regular evacuation simulations in schools and residential areas. - Provide evacuation signs and disaster risk maps..	Improve rapid response	Volunteers, KSB, alert village
8	Land Rehabilitation and Conservation	- Reforestation in landslide-prone areas with strong, deep-rooted plants. - Maintaining forest vegetation cover to prevent loss. - Soil and water conservation (terracing, planting vetiver grass, etc.).	Resist erosion and rainwater	Environmental services, community

5. Conclusion

The integration of the 3D Finite Element Method (3D FEM) and GIS-Kriging spatial interpolation in this study provides a significant scientific novelty in bridging micro-scale geotechnical analysis of a single slope with regional macro-scale risk mapping. This hybrid approach successfully overcomes the limitations of conventional limit equilibrium (LEM) methods by providing a dynamic simulation of the stress-strain redistribution of volcanic residual soil, while mitigating spatial transmission through probability-based variogram modeling in areas with limited spatial access points.

The case study in Sumberarum Village, Songgon District, yielded the following key quantitative findings:

1. Identification of Critical Points: Of the 12 physical-mechanical observation points analyzed for validity through 3D FEM numerical reconstruction, three slopes were identified as unstable and critical (Factor of Safety below the safety threshold).
2. Safety Factor (FK) Range: Simulation results show a highly contrasting FK value variation, ranging from the most critical value of 0.648 to 2.331 in the zone of maximum shear strain accumulation at the toe of the residential slope, to a range of 7.663 to 11.446 in the stable terrain zone.

3. Effectiveness of Mitigation Measures: The structural mitigation engineering formulation, which included a 4-meter-high cantilever retaining wall integrated with a subsurface drainage system (weep hole), proved effective in immediately increasing slope stability. Based on the reinforcement analysis, this structural mitigation measure significantly increased the critical slope's Safety Factor to a value of FK > 1.50, which meets the long-term safety criteria according to the national standard SNI 8460:2017.

The practical implications of these findings are crucial for local landslide risk management. The resulting Kriging-based vulnerability cluster map serves not only as a visual representation but also as an operational blueprint for local governments in prioritizing slope restriction development in high-hazard zones. Furthermore, the integration of non-structural mitigation matrices—such as elevation-based relief route delineation and a community early warning system—provides adaptive, layered protection to minimize the risk of material losses and loss of life in residential areas on the slopes of Mount Raung.

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