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RESEARCH ARTICLE

Slope Stability Analysis Through the Application of Digital Imagery and Field Validation Using SMR and Q-Slope Methods: A Case Study of Bandar Lampung City, Indonesia

Zaki Hilman [1,*], Edo Kharisma Army [2], Rezki Naufan Hendrawan [1], Ryan Ensya Aria Dzikri [1], Rifqy Iqbal Fachri [1], Gibrani Salomo Pardede [1], Hanif Miftah Sani [1], Zakaria Situmeang [1]

[1] *Sumatera Institute of Technology, Geology Department, Faculty of Technology and Industry, South Lampung, Lampung, Indonesia*
[2] *Sumatera Institute of Technology, Mining Department, Faculty of Technology and Industry, South Lampung, Lampung, Indonesia*

* Corresponding author : zaki.hilman@gl.itera.ac.id
Tel.:+62-82127996059
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Abstract

The investigation is on slope stability in cities such as Bandar Lampung by combining digital imagery from Geographic Information Systems (GIS) and field validation using Slope Mass Rating (SMR) and Q-Slope methods. The research study emphasizes the area of study, which is the city of Bandar Lampung, as the topography is highly diverse and the incidence of landslides is high. The Analytical Hierarchy Process (AHP) employed slope stability assessment by indicating vital parameters such as slope gradient, Normalized Difference Vegetation Index (NDVI), rock type and rainfall, and used AHP to produce a detailed slope stability map, classifying the areas surveyed into three degrees of hazards: low, medium and high.

Of these results, low hazard areas occupy an area of 101.56 km^2, medium hazard areas area covers 52.79 km^2, and high hazard areas occupy an area of 25.47 km^2. Field validation using SMR and Q-slope methods at vital sites revealed that most slopes fall into classes of stability, poor to very poor. The dominant types of landslides identified are planar and wedge failures. Based upon the Q-Slope Stability Chart recommended stable slope angles from a range of 42° to 61° were established for different sites.

This study shows that these areas are characterized by medium to high hazards, offering steep slopes that have little or almost no vegetational cover, thus greatly enhancing the possibilities of landslides taking place. A Well established correlation between GIS-based mapping and field observation proves how accurate the results would be in the integration of SMR and Q-Slope approaches that would give even better recommendations for slope stabilization measures or landslide mitigations. Findings of the research provide significant information for the matters of urban spatial planning and pro-active disaster risk management in landslide-prone regions of Bandar Lampung.

Keywords: Slope Stability, Geographic Information Systems, Slope Mass Rating, Q-Slope, Bandar Lampung City

1. Introduction

Landslides or slope instability occur when the applied stress exceeds the shear strength of the slope material. This imbalance can be intensified by factors such as increased pore water pressure or excessive overburden from external loads. In addition, weak soil properties, unfavorable slope geometry, stratified soil layers, and discontinuities within the rock mass further reduce slope stability. These causes can be broadly categorized into internal and external factors. Internal factors originate within the slope itself, primarily due to water infiltration and its effect on material strength. External factors include climatic and weather influences, processes like weathering and erosion, ground subsidence, seismic activity, and human interventions such as uncontrolled extraction of soil, sand, or rock, which disrupt the equilibrium between the load at the slope's crest and its base. (Damares et al., 2024; Farazi et al., 2018). Bandar Lampung City has a medium risk for landslides (BNPB, 2024). Based on the regional geology, Bandar Lampung's lithology ranges from volcanic, sedimentary, to metamorphic rock. It is also affected by the Great Sumatran Fault. These geological variations, combined with differences in rock resistance, significantly influence slope stability and susceptibility to landslides (Kurniawan, 2019; Mangga et al., 1993).

Slope stability analysis is a geotechniquely oriented study identifying potential landslide sites, their causes, and effective prevention measures. The critical parameters that provide the basis of the study include slope geometry, the orientation of the rock discontinuity planes, lithological characteristics, and the degree of pore water saturation. Pyroclastics in the Bandar Lampung region demonstrate wide variability in that they can be easily weathered, which can be further hastened by in situ deterioration due to very high rain intensity, sometimes extending over periods of weeks (Agustina et al., 2020; Fareka et al., 2020; Pradhan et al., 2023).

This research implements Geographic Information System (GIS) to create the landslide susceptibility maps and validate it via field method using Slope Mass Rating (SMR) and Q-Slope. GIS provides spatial determination through several parameters, such as slope gradients, land use through vegetation cover index, lithology, and rainfall intensity. SMR is based on the analysis of rock discontinuity and slope orientation to evaluate the stability of slopes, while the application of Q-Slope can be applied for modeling safe slope design. Combination of these methods aims to provide a comprehensive analysis of slope stability, especially in areas with complex geological and topographical characteristics like Bandar Lampung (Bar and Barton, 2017; Idris et al., 2024; Romana et al., 2015; Wibowo et al., 2022; Xu et al., 2023).

In addition, this study applies the Analytic Hierarchy Process (AHP) as a multi-criteria decision-making tool to improve the accuracy of slope stability mapping. AHP integrates geotechnical and spatial data by prioritizing critical parameters and assigning weights based on their relative importance, resulting in robust susceptibility maps. Validation will be carried out at selected research sites using SMR and Q-Slope to assess the influence of rock structure orientation and slope geometry. This integrated approach not only enhances the reliability of slope stability assessments but also provides actionable insights for landslide risk mitigation in Bandar Lampung (Aminudin et al., 2023; Machay et al., 2023; Patil and Panhalkar, 2023).

Therefore, expectations are that this research's findings will significantly contribute to local authorities' efforts in formulating landslide disaster mitigation attempts. Further, such research results will offer technical recommendations for safe slope design and improving disaster preparedness levels in the Bandar Lampung region.

2. Materials and Methodology

The study focuses on slope stability analysis in Bandar Lampung. These regions exhibit high variability in geological formations, slope angles, land use, and rainfall intensity, making it ideal for slope stability studies. GIS data that are being used in this research are topographic data to generate Digital Elevation Models (DEM); geological information through Tanjungkarang Regional Geological Map; land use data, obtained using the Normalized Difference Vegetation Index (NDVI); and rainfall data, to assess its impact on slope stability (Hardianto et al., 2020; Reichenbach et al., 2018).

The Analytical Hierarchy Process (AHP) method was employed for creating a slope stability hazard map to assign weights to the following parameters: slope gradient, NDVI, rock type, and rainfall. The hazard map is classified into zones, namely low, medium, and high susceptibility to landslides. Utilizing GIS based approaches is an efficient technique in managing and analyzing large datasets, which are to be adopted for identifying the critical zones needing extensive field validation (Ahmad et al., 2023; Dhungana et al., 2023).

Field validation is essential to confirm the accuracy of GIS-based analysis outputs. In this study, the Slope Mass Rating (SMR) method is applied to evaluate rock slope stability by incorporating geological and geometric factors. SMR provides a qualitative classification system that categorizes slopes as stable, partially stable, or unstable. This approach assigns numerical ratings based on key parameters such as rock mass quality, discontinuity orientation, slope geometry, weathering, groundwater conditions, and rock type and structure, offering a comprehensive assessment of slope stability (Kinde et al., 2024; Radityo et al., 2024; Romana et al., 2015).

This study analyzes rock mass kinematics on joints and potential rock mass slope failure mechanisms considering slope angles and structural discontinuities such as joints and lineaments. Using a joint analyses stereographic projection, kinematics assess possible patterns of deformation and slope failures such as planar, wedge, and toppling failures. Planar failure occurs when a sliding plane is present and its dip is equal to or less than the friction angle, and is approximately parallel to the slope face. Wedge failure occurs when discontinuities intersect and a slope parallel block form line of intersection that is steeper than the slope face and toward the dip. Toppling failures are rock block or columns that rotate forward and can occur as block topple which bottom elements are already detached. Systematic joint control of rock mass and slope geometry are the primary factors of structural slope kinematic analysis. (Bera and Saha, 2024; Hoek and Bray, 1981; Putra and Choanji, 2016).

The Q-Slope method was used to estimate the maximum allowable slope angle without reinforcement by integrating various parameters such as rock quality, joint number, joint roughness, joint alteration, orientation factor, environmental and geological condition, and strength reduction factor. It provides recommendation for safe slope angle and determine the critical angle at which slope remain stable without any additional structural support (Bar and Barton, 2017; Kouhdaragh et al., 2022).

Both SMR and Q-Slope methods have been considered flexible empirical methods that can achieve relevant results in rock slope stability analysis, which can investigate the stability status and provide appropriate support systems for discontinuous rock slopes. Although these two systems have apparent benefits, they still lack something if done separately. Therefore, using both methods can provide more complete analysis (Table 1) (Azarafza et al., 2022, 2020; Jorda-Bordehore et al., 2018).

Table 1. Advantages of SMR and Q-Slope in rock slope quantification (Azarafza et al., 2022).

Factors	SMR	Q-Slope	SMR & Q-Slope
Stability conditions	*	*	*
Failure mechanisms	*	-	*
Recommendation of Support system	*	-	*
Rock mass parameters	-	*	*
Discontinuity network	-	*	*
Quick analysis	-	*	*
Stress dimension	-	*	*

Once the hazard map is generated and field validation is conducted, the results from SMR and Q-Slope analyses were correlated with the GIS based slope stability map. The correlation helps to verify the accuracy of the GIS model and provides insights into any discrepancies between predicted and observed stability conditions. The field data was collected from specific locations identified as potential landslide prone areas in the GIS analysis. This comparative approach ensures that the theoretical model aligns with real-world observations.

3. Results and Discussion

The slope stability or landslide susceptibility map was produced prior to the field activities using the Analytical Hierarchy Process (AHP) approach. This method applies weighting to each parameter used in slope stability analysis. These parameters include slope gradient (Fig 1), NDVI to assess land use (Fig 2), lithology from the regional geological map (Fig 3), and the rainfall map (Fig 4). The weighting process for landslide-prone zones is a modification of the method developed by Hardianto in his previous research (Hardianto et al., 2020; Januar et al., 2016) (Table 2).

Table 2. Landslide susceptibility weight (modified after (Hardianto et al., 2020).

Parameters	Classification	Class	Score	Weight
Slope gradient	<8%	Very Low	1	57%
	8-15%	Low	2	
	15-30%	Medium	3	
	30-45%	High	4	
	>45%	Very High	5	
NDVI	-0,103 - 0,569	Water	7	24%
	-0,028 - 0,425	Industrial	6	
	-0,073 - 0,532	Settlement	5	
	-0,105 - 0,538	Ricefield	4	
	0,020 - 0,487	Open field	3	
	0,222 - 0,505	Moor	2	
	0,320 - 0,736	Plantation	1	
Lithology	Igneous and metamorphic rocks	Low	1	12%
	Sedimentary and pyroclastic rock	Medium	2	
	Alluvial	High	3	
Rainfall intensity	Very Dry (<1500 mm/year)	Very Low	1	7%
	Dry (1501 - 2000 mm/year)	Low	2	
	Moderate (2001 - 2500 mm/year)	Medium	3	
	Wet (2501 - 3000 mm/year)	High	4	
	Very wet (>3000 mm/year)	Very High	5	

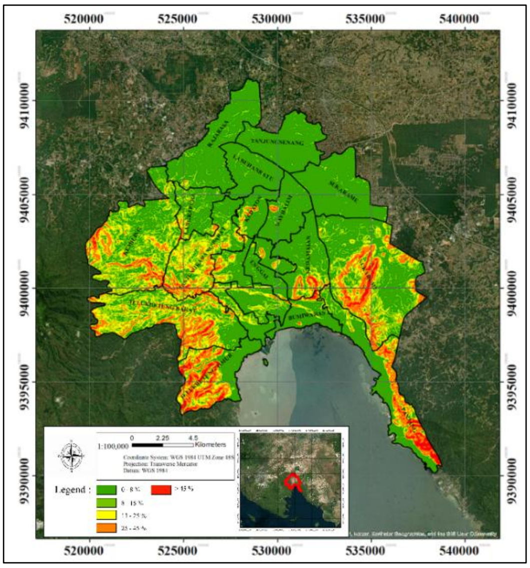

Fig 1. Slope Gradient Map of Bandar Lampung City.

Slope condition in Bandar Lampung varies due to various topographies from hill, lowland, and valley. Generally, this steep-to-very-steep hilly area in Bandar Lampung has slopes of more than 25°. These slopes are usually found in areas with volcanic rock such as Lampung Formation (Qtl) and Quaternary volcanic rocks (Qhv), as these are susceptible to landslides, especially in sparsely vegetated or human disturbed areas.

On the other hand, in lowlands and valleys, generally, the slopes are gentle to moderate, ranging from 0° to a maximum of 15°. Much of this area consists of alluvial deposits (Qa), which are weakly bound soils subject to less stability when loaded under excess water, especially with rainfall.

NDVI data shows that areas with low vegetation cover (urban and industrial areas), tend to have a higher landslide risk. While the areas with denser vegetation cover (forest and plantation), tend to be more stable. Vegetation acts as natural stabilizer by reinforcing the soil and reducing the surface runoff during rainfall.

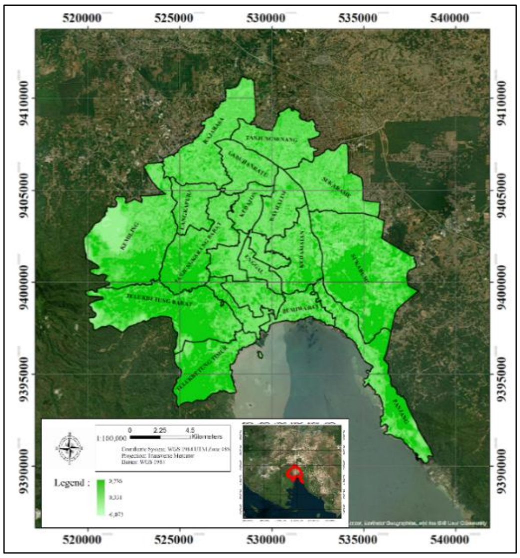

Fig 2. NDVI Map of Bandar Lampung.

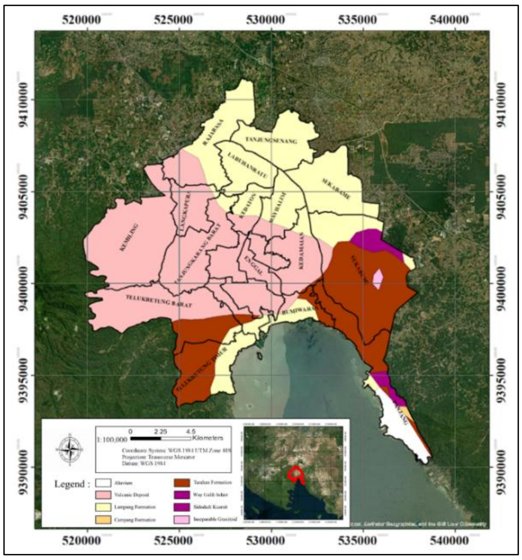

Fig 3. Lithology Map of Bandar Lampung.

Based on the geological data, Bandar Lampung City has a complex and diverse landscape due to the influence of Indo-Australian Plate and Eurasian Plate activity. This tectonic setting has brought variations in landscape, ranging from hills to lowlands. All of these formed through continued volcanic activity, tectonic deformation, and sedimentation processes over multiple geological periods.

Within Bandar Lampung, the geological framework presents different characteristics of stability, based on the types of underlying rocks. Regional geological maps show that areas predominantly hosted by resistant rock forms, such as igneous and metamorphic rocks, present low susceptibility to instability. On the contrary, sedimentary and alluvial deposits have more erosive and weathering actions that contribute significantly to slope failure hazards.

Bandar Lampung's rainfall intensity for 2023 period is around 2.001-2.500 mm/year, which falls under moderate class. The total number of rainy days is around 76 to 166 days per year. Rainfall intensity information can be useful not only for landslides but also for flood mitigation.

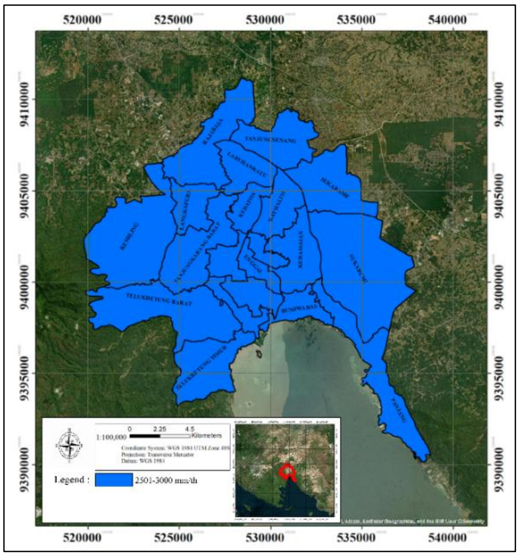

Fig 4. Rainfall Intensity Map of Bandar Lampung.

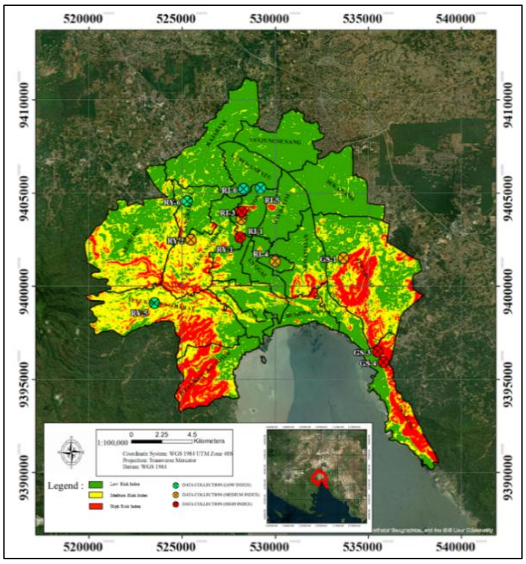

Fig 5. Landlslide Susceptibility Map of Bandar Lampung and Field Validation Location.

Each parameter was then weighted to create the Landslide Susceptibility Map of Bandar Lampung. Resulting in 3 classes of susceptibility: low risk symbolized by the green color covers around 101,56 km^2; medium risk, symbolized by yellow color covers 52,79 km^2; and high risk symbolized by red color covers 25,47 km^2 (Fig 5). Field validation was conducted using stratified random sampling method in each class with 4 locations per class. In some locations, the slope orientation varies, so the measurement is executed more than once. Field validation was only done on rock slopes, while for the slopes comprising of soil, the measurement was not done. Sample was also taken from the location to be tested in the lab for Unconfined Compression Test (UCS). This test can show a rock's strength, along with the relationship between stress and strain.

It was confirmed that for the low risk area (green) exhibited an absence of slopes, which serve as the primary parameter in the analysis. Given this condition, slope measurements were deemed unnecessary for these areas. Field observations in the low risk area were represented by observation codes RI-5, RI-6, RY-5, and RY-6 (Fig 6).

Fig 6. Field validation in low risk class.

The medium risk area (yellow) shows the existance of slopes that can be measured and validated using SMR and Q-Slope methods. These slopes were represented with codes GS-1 and GS-2 (1 location), RI-1 and RI-2 (1 location), RI-4, and RY-2. These 4 locations are composed of tuff with variation of the size (tuff ash and tuff lapilli) (Fig 7).

Fig 7. Field validation in medium risk class.

Lastly, the high risk area (red) also shows the existance of slopes that can be measured using SMR and Q-Slope. These slopes are represented by GS-3, GS-4, RY-1.1 and RY-1.2 (1 location), and RI-3. These 4 locations are composed of andesite, schist, and tuff ash lithology (Fig 8).

Fig 8. Field validation in high risk class.

Both medium and high risk class was observed using scanline method and weighted to get the Rock Mass Rating (RMR) (Bieniawski, 1989). Weight of each RMR parameter is summarized in Table 3. It shows that all slopes are classified under fair to good rock. The lowest rating at 50,4 can be found in the medium risk, while the highest rating at 67,3 can be found in the high risk class.

After obtaining the RMR values, the data processing can be continued to the next stage, which involves kinematic analysis to identify the types of slope failures in the research area (Hoek and Bray, 1981). This analysis was conducted using strike and dip direction data of both the slope and discontinuities. Identifying types of slope failures is critical for determining appropriate weightings in the SMR method. Based on the analysis, there are only two possible slope failures; planar and wedge failures (Fig 9).

The SMR weighting was carried out through field observations of the slope and the discontinuity geometry, and along with RMR. All those observations then weighted according to the parameters developed by Romana in 1985 (Romana et al., 2015). Table 4 summarized all of the research area SMR values, ranging from lowest at 5.4 (very bad) in medium risk index to highest value with 47.3 (normal) in the high risk index. Recommendations on slope stabilization as per Romana (1985) are re-excavation for very bad class, slope correction for bad class, and systematic reinforcement for the normal class.

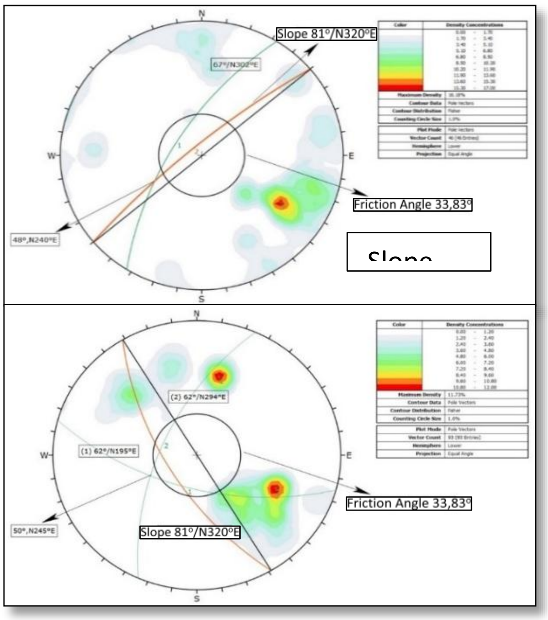

Fig 9. Kinematic Analysis of the Research Area.

Table 3. Rock Mass Rating of the Research Area.

Sample Code	Rock Strength	RQD	Spacing of Discontinuities	Condition of Discontinuities	Ground Water Condition	RMR	Description	Risk Index
GS-1	4	20	8	13,6	4,8	50,4	Fair Rock	Medium
GS-2	4	17	8	14	8,3	51,3	Fair Rock	Medium
GS-3	2	20	8,7	17,89	10	58,59	Fair Rock	High
GS-4	2	20	8,2	20,78	15	65,98	Good Rock	High
RI-1	4	20	11	18	15	68	Good Rock	Medium
RI-2	4	20	10	18,2	15	67,2	Good Rock	Medium
RI-3	4	20	10	18,3	15	67,3	Good Rock	High
RI-4	2	20	10	18,9	15	65,9	Good Rock	Medium
RY-1.1	4	20	9,98	14,79	15	63,77	Good Rock	High
RY-1.2	4	20	8,66	15,36	13,49	61,51	Good Rock	High
RY-2	4	17	8,73	15,01	14,82	59,56	Fair Rock	Medium

Table 4. Slope Mass Rating of the Research Area.

Sample Code	F1	F2	F3	F4	RMR	SMR	Description	Risk Index
GS-1	1	1	-60	15	50,4	5,4	Very Bad	Medium
GS-2	1	1	-60	15	51,3	6,3	Very Bad	Medium
GS-3	1	1	-60	15	58,59	13,59	Very Bad	High
GS-4	1	1	-60	15	65,98	20,9	Bad	High
RI-1	1	1	-50	0	68	18	Very Bad	Medium
RI-2	1	1	-50	0	67,2	17,2	Very Bad	Medium
RI-3	0,7	1	-50	15	67,3	47,3	Normal	High
RI-4	1	1	-50	0	65,9	15,9	Very Bad	Medium
RY-1.1	0,7	1	-60	0	63,77	21,77	Bad	High
RY-1.2	0,85	1	-60	0	61,51	10,51	Very Bad	High
RY-2	0,85	1	-60	0	59,56	8,56	Very Bad	Medium

Table 5. Q-Slope of the Research Area

Sample Code	RQD	Jn	Jr	Ja	O-Factor	Jwice	Srf	Q-Slope	Risk Index
GS-1	92,16	3	1,5	1	0,5	0,3	20	0,35	Medium
GS-2	88,3	2	1,5	2	0,5	0,5	20	0,41	Medium
GS-3	93,13	4	3	3	0,5	0,3	20	0,17	High
GS-4	90,6	6	1,5	6	0,5	0,8	20	0,08	High
RI-1	98,06	2	1,5	6	0,5	0,5	20	0,15	Medium
RI-2	97,8	9	1,5	6	0.5 and 0.8	0,5	20	0,01	Medium
RI-3	97,9	2	1,5	6	0,75	0,5	20	0,23	High
RI-4	98,1	2	1,5	6	0,5	0,5	20	0,15	Medium
RY-1.1	96,25	3	1,5	2	0,75	0,7	20	0,63	High
RY-1.2	91,98	6	1,5	2	0,5	0,5	20	0,14	High
RY-2	88,92	6	1,5	4	0,5	0,5	20	0,07	Medium

Table 6. Slope Angle Recommendation of the Research Area

Sample Code	Q-Slope	Actual Slope (Degree)	Slope Recommendation (Degree)	Risk Index
GS-1	0,35	76	55	Medium
GS-2	0,41	82	57	Medium
GS-3	0,17	80	49	High
GS-4	0,08	65	42	High
RI-1	0,15	83	49	Medium
RI-2	0,01	80	22	Medium
RI-3	0,23	81	52	High
RI-4	0,15	79	49	Medium
RY-1.1	0,63	81	61	High
RY-1.2	0,14	66	48	High
RY-2	0,07	82	42	Medium

The results of Q-Slope weighting are provided in summary (Table 5), with the lowest weighted value of 0.01 (the medium risk index) and the highest of 0.63 (the high risk index). The Q-Slope values of each slope were then plotted on the Q-Slope Stability Chart to find out if all or some of the slopes in the study area were stable and if needed also to find how much adjustment should be carried to make them stable. The study area Q-Slope Stability Chart is presented in Fig 10. These results mean that all slopes within the study area are unstable and need adjustments in slope angle. Table 6 includes recommendations of the difference between the actual and suggested totals based on the Q-Slope Stability Chart.

Following the SMR and Q-Slope analyses, results indicate that weighting and slope stability maps have been developed on the bases of four parameters for quite valid results. This is well proven from the fact that unstable slopes were identified within the medium and highrisk classes while none fell under the low-risk (green) class. While there was no direct correlation between hazard index classes and SMR classes, both types of classification consistently signified unstable conditions through Q-Slope analysis. The reason for the variance is that some parameters in the field validation methodologies, like Q-Slope, cannot be attained from remote sensing data alone and should have direct observation and measurement in the field.

The integrated strategy emphasizes the need of using both laboratory and field observations for accurate assessment of slope stability, which in turn increases the reliability of landslide hazard mapping.

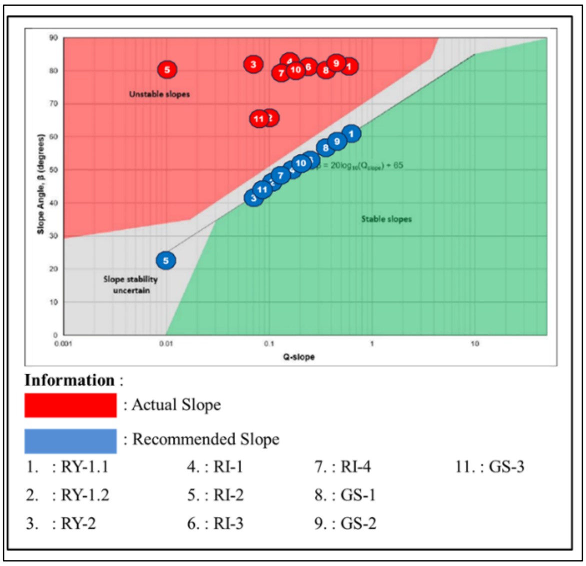

Fig 10. Q-Slope Stability Chart of the Research Area

4. Conclusions

This research successfully demonstrated GIS analysis in combination with field validation using Slope Mass Rating (SMR) and Q-Slope approaches for assessing slope stability in a landslide-prone region. GIS efficiently mapped landslide susceptibility using slope gradient, NDVI, geology, and rainfall data to produce a hazard map, while field observations was done for validation. SMR and Q-Slope confirmed this correlation between GIS model and field data to prove the reliability of unstable slopes analysis.

Quite notably, high-risk areas could be interventioned estimated at slope re-excavation or reinforcement while medium-risk areas were associated with improvement in stabilization, for example through rock bolts or retaining walls. Vegetation management was identified as one of the important factors that could reduce susceptibility to landslides. The findings are fundamental in giving guidance to the local authorities in reducing landslide risk, enhancing preparedness, and monitoring priorities in slopes.

Limitations of the study in spatial resolution and field data collection exist even in the efficiency shown. Future research direction is towards incorporating advanced technologies like radar for precise assessments and near-real-time monitoring. This research also provides a powerful, generic, and replicable framework on slope stability assessment that could be extended for use in other similar regions across the world towards improved disaster management risk and early warning systems.

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