PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.8866

eISSN 2348-1900

RESEARCH ARTICLE

Stability assessment of Maligcong rice terraces: Linking soil properties and geometry to factor of safety

Rhonjhon R Garming

College of Engineering and Information Technology, Kalinga State University, Bulanao, Tabuk City 3800, Philippines

*Correspondence email - grhonjhon@gmail.com

Received: 14 April 2025; Accepted: 15 May 2025; Available online: Version 1.0: 01 July 2025

Cite this article: Rhonjhon RG. Stability assessment of Maligcong rice terraces: Linking soil properties and geometry to factor of safety . Plant Science Today (Early Access). https:/doi.org/10.14719/pst.8866

Abstract

Rice terraces, renowned for their agricultural and cultural significance, are found across Southeast Asia, South America and Africa. Despite their resilience, these landscapes face threats from climate change, land-use changes and declining traditional knowledge. In the Philippines, the Cordillera rice terraces, a United Nations Educational, Scientific and Cultural Organization (UNESCO) world heritage site, suffer from land abandonment, pest infestations and insufficient government support yet technical stability assessments remain limited. The Maligcong rice terraces, like many traditional systems, experience instability, but comprehensive studies on their structural integrity are scarce. This study investigates the stability of these terraces by linking soil properties, terrace geometry and the factor of safety (FoS). Soil characterization revealed predominantly sandy compositions with varying moisture content and hydraulic conductivity across layers. Non-invasive techniques, including portable *in-situ* soil testing and geophysical methods (geo resistivity), effectively captured soil properties. Drone surveys integrated with Agisoft Metashape and Civil 3D provided accurate geometric modeling. While geometric parameters such as height and width influence terrace design, statistical analysis showed they had minimal impact on FoS. Instead, groundwater fluctuations, particularly water table rise during rainfall, significantly affected stability by increasing pore water pressure and reducing effective stress. Sensitivity analysis confirmed that the most critical stability parameters-cohesion, friction angle and unit weight are concentrated in the surface layer. This study highlights the vulnerability of rice terraces due to soil strength limitations and hydrogeological factors. The findings emphasize the necessity of integrating soil and water assessments into conservation strategies to ensure the long-term sustainability of these culturally and agriculturally valuable landscapes.

Keywords: angle of friction; factor of safety; multiple linear regression; rice; Swedish weight sounding test; terraces

Introduction

Rice terraces, seen across regions like Southeast Asia (China, Indonesia and Philippines), South America (Peru) and Africa (Ethiopia), are not only vital for agriculture but also hold immense cultural significance (1-4). This includes UNESCO world heritage sites such as the Jatiluwih rice terraces in Bali, the Honghe Hani rice terraces in China and rice terraces of the Philippine Cordillera. However, many of these landscapes, particularly those in Cordillera region, face serious threats due to climate change, urbanization and the loss of traditional knowledge (5-9). In particular, the Maligcong rice terraces struggle with challenges such as land abandonment, limited government support and pest infestations (10). Despite their historical importance, a comprehensive understanding of what threatens their stability is still missing. This study aims to fill these gaps by quantitatively examining soil properties, water table conditions and terrace geometry. By doing so, this research provides insights to support effective conservation strategies that can preserve these UNESCO-recognized cultural landscapes for the future.

Existing literature reveals significant gaps in detailed stability analyses of rice terraces in the Philippines, particularly in identifying crucial parameters for stabilization. For instance, some studies emphasize that the effective angle of friction plays a more critical role than slope angle in preventing landslides, while others examine the impact of landslides and soil conditions on terrace stability (11-13). Moreover, the study explored slope stability in Vietnam, suggesting improved methods for accurate safety assessments (14).

Additionally, current studies on Philippine rice terraces have primarily focused on the causes of degradation and the challenges of restoration, but these findings can be expanded into detailed engineering assessments. One study emphasized the significance of water sources over slope gradients in the construction of the Ifugao rice terraces, a UNESCO world heritage site (15). Research also demonstrate that seepage risks and intense rainfall contribute to landslides and sediment buildup, posing serious threats to terrace stability (16, 17). Abandoned terraces accumulate higher carbon concentrations, complicating restoration efforts (18). Hard pans essential for stability, are much deeper on these abandoned areas. The importance of monitoring water table fluctuations has been highlighted in several studies (19, 20). Despite these valuable findings, a deeper and more localized analysis is urgently needed to address these diverse threats effectively (21).

To address these gaps, this study adopts a probabilistic slope stability analysis within the input-process-output (IPO) framework. The probabilistic approach is employed due to its superiority over the deterministic method in accounting for inherent uncertainties and variabilities in soil properties and external conditions that influence slope stability (22). This approach allows for a more nuanced understanding of how different factors such as soil characteristics, water table fluctuations and terrace geometry interact influencing stability (23). The Spencer method, combined with sensitivity analysis and Latin-hypercube sampling (LHS), helps assess how variations in soil and water table conditions impact stability (24, 25). The analysis uses LHS to explore a wide range of possible scenarios and employs limit equilibrium methods (LEM), including Bishop's and Janbu methods, to calculate the FoS (25). To better understand how water infiltration impacts stability, the study applies the Green-Ampt model and its adaptations for stratified soils. Additional insights into how rainfall and surface runoff affect slope stability are provided by related studies (26, 27). By integrating these methods, the study not only identifies key threats but also proposes targeted strategies to mitigate them. Additionally, linear regression techniques effectively predict the FoS using soil and geometric properties (28, 29), supporting timely conservation actions to prevent slope failures (30).

Proposed theoretical framework of the study

The theoretical framework proposed illustrated in Fig. 1. This aims to bridge the gap between scientific analysis and practical conservation strategies for the Maligcong rice terraces. By combining probabilistic analyses with non-destructive testing methods and predictive modeling, this research seeks to deliver a clearer and more detailed understanding of the factors influencing terrace stability (i.e., layered strength parameters and geometry) Furthermore, non-destructive geophysical methods, such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES), have proven useful in assessing subsurface conditions without causing further damage to these fragile landscapes (31-34). The integration of advanced 3D modeling tools like Agisoft Metashape and Autodesk Civil 3D, offers new opportunities for accurately visualizing and monitoring these landscapes (35-37). Such tools can help capture the complex interactions between soil properties, water dynamics and terrace geometry, making stability assessments more reliable. Aligning with UNESCO's goals of preserving cultural landscapes, the findings of this study are expected to provide a strong scientific foundation for sustainable restoration practices. By enhancing our understanding of these ancient agricultural systems, this research is expected to contribute significantly to their resilience and sustainability for generations to come.

Materials and Methods

Geo-spatial survey for determination of slope geometry

This data gathering procedure utilized a combination of total station surveying, drone photogrammetry, Agisoft Metashape and Autodesk Civil 3D to establish an accurate geometrical model of the rice terraces in Maligcong.

First, ground control points (GCPs) were established throughout the study area using a total station (TS). These provided accurate reference coordinates that improved the georeferencing and spatial accuracy of the resulting maps and models. The GCPs were strategically placed at key locations in stable and unstable areas, including near the collapsed section. The TS measurements provided precise coordinates, following the universal transverse mercator (UTM) coordinate system, which were essential for georeferencing the aerial images captured by the drones. These GCPs were crucial for ensuring the accuracy of the subsequent 3D model generated in Agisoft Metashape.

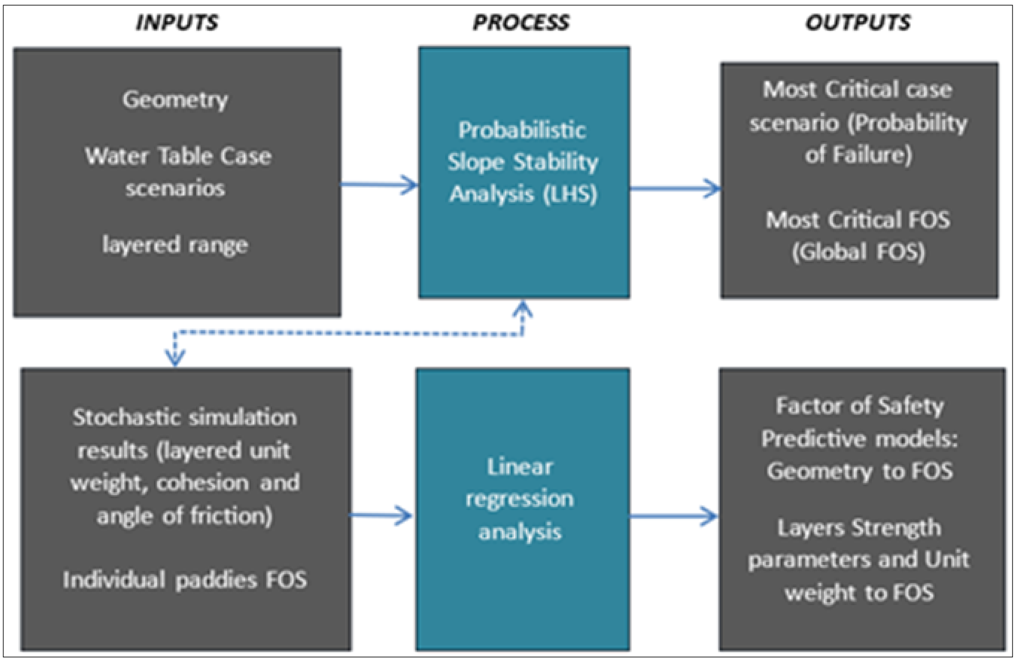

Fig. 1. Theoretical framework of the study.

Following the establishment of the GCPs, a drone survey was conducted over the Maligcong rice terraces. Several closely overlapping drone shots were captured to ensure adequate image overlap. The drone images were taken from various angles to ensure comprehensive coverage of the terraces, especially around the collapsed site. These images were then imported into Agisoft Metashape, where they were processed using structure-from-motion (SfM) and multi-view stereo (MVS) algorithms. The result was a dense point cloud that formed the basis for the 3D model of the terrain.

Once the 3D model was generated, it was aligned with the GCPs to ensure proper georeferencing. The model was then exported from Agisoft Metashape and converted into a Civil 3D-compatible CSV file. This conversion enabled the model to be processed further within Autodesk Civil 3D, allowing for the extraction of a section of the rice terraces adjacent to the collapsed area. The terrain features and cross-sectional profiles of the extracted section were then created, providing a detailed representation of the topography. This section was exported as an AutoCAD DWG file for slope modelling. The DWG file was subsequently imported into Rocscience SLIDE 2.0 software for slope stability analysis.

Combined *in-situ* and laboratory testing approach for strength parameters, physical properties and characterization

The study employed a combination of laboratory and *in-situ* tests to obtain the geotechnical parameters necessary for slope stability analysis, particularly in the area adjacent to the collapsed section of rice terraces.

In-situ tests involved soil specimen extraction and penetration resistance measurements to estimate the strength parameters required for the analysis. Sieve analysis focused on soil classification, unified soil classification system (USCS), which provided essential information for applying various correlations, including those between the NSW parameter and SPT-N values, as well as between SPT-N values and strength parameters. Additionally, laboratory tests included measurements of unit weight, which were also crucial for the analysis.

A total of 36 soil specimens were collected from 10 test points located on the rice terraces adjacent to the failed section (Fig. 2). Samples were taken at 1 m intervals from the ground surface to a depth of 4 m at each test point. Soil samples were extracted using a 6-inch diameter soil sampler and were subsequently subjected to soil classification USCS, according to ASTM D2487. Unit weight determination was conducted under moist conditions following ASTM D2487 guidelines.

The data obtained from these tests enabled the estimation of strength parameters through additional *in-situ* testing using the Swedish weight sounding test (NSW), following the procedure outlined previously (38). The NSW values from this test were converted into equivalent SPT-N values using Inada equation (39). From the SPT-N values, the strength parameters, cohesion and angle of friction, were estimated using the correlations established (40, 41).

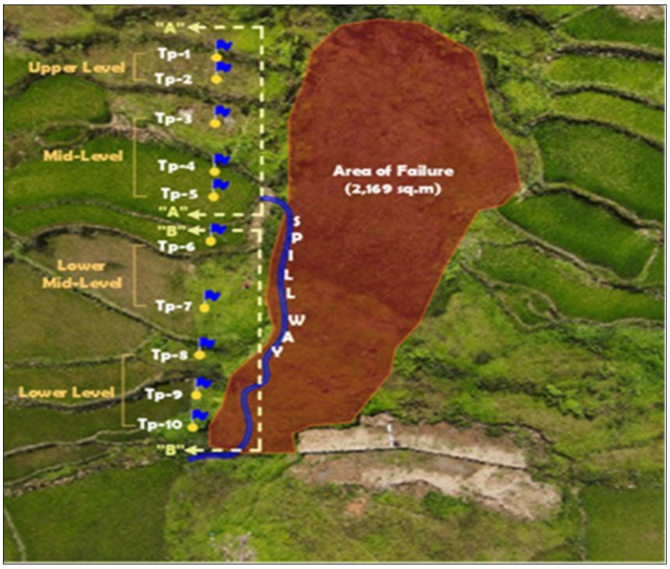

Fig. 2. Specific location of test points.

Geo resistivity method for inferred geologic layer and potential water table location

To augment the depth limitation of the *in-situ* test, the study adapted a geophysical method (geo resistivity), which had provided an inferred geologic profile and potential water table depth.

A one-dimensional geo resistivity survey utilizing the Schlumberger array was conducted at the site to examine subsurface properties. The purpose of the survey was to identify the water table, deduce the composition of the various geological layers and calculate their resistivity values.

Ideally, the survey should be carried out on wide, level to undulating terrain, with the opposing electrodes positioned equally and in a straight-line alignment. However, due to the site's topography, one electrode was placed toward the South-Southwest (SSW) and the other toward the North-Northeast (NNE). Additionally, there was an elevation rise between the first and last electrodes.

The inferred geological layers were established through interpretation of geo resistivity values recorded from the survey. These values were plotted and processed using W-Geosoft WinSev 4. The work of on resistivity values of important rock groups provided preliminary basis for interpreting the results (42).

Potential case scenarios in the analysis

The study provided valuable insights into potential scenarios that may affect slope stability, drawing on three key sources of information. First, hydraulic conductivity estimates were derived through Hazen's correlations. Second, hydromet data from the disaster risk reduction management information system (DRRMIS) of the Department of Science and Technology were recorded. Third, the potential water table levels were deduced from Geo resistivity results indicating inferred geologic layers.

The study examined different scenarios involving fluctuating water tables and ponding, with assumptions based on practical conditions, utilizing the Green-Ampt infiltration model. The equation provided was specifically used to compute both the infiltration rate and the total volume of infiltration (43, 44).

$$F(t)=Ks\cdot t+\Psi f\cdot\Delta\theta\cdot\ln\left(\frac{F(t)}{\Psi f\cdot\Delta\theta}\right) \quad \text{(Eqn. 1)}$$

where: F(t) = cumulative infiltration (m or cm); Ks = saturated hydraulic conductivity (m/s or cm/h); Ψf = wetting front capillary suction head (m or cm); Δθ = change in volumetric water content = θs–θi; θs = saturated water content; θi = initial water content; t = time (s or hr)

The analysis also incorporated the estimated hydraulic conductivity, which was determined using the D10 parameter through Hazen's formula. In addition, Green-Ampt parameters for different soil texture classes were applied (43, 44). These included values for the wetting front suction head and effective porosity.

Slope stability analysis

The collected data was analyzed using two approaches: a deterministic method, which utilized a single mean value and a probabilistic method, which treated the data as random variables. This allowed for a comparison of both approaches in simulating the observed failure slip on-site. For the probabilistic analysis, the slope stability evaluation was framed as an overall slope analysis to capture potential slip surfaces. To account for data variability, the LHS method was applied, generating 100 simulation samples. Material properties were assigned a normal distribution based on the results from the Swedish weight sounding test (SWST) penetration resistance, measured at 1 m intervals down to a depth of 4 m.

Given that the cohesion parameter had a single value of zero, it was assigned a small range between 0 and 0.20 kPa to enable the use of the probabilistic approach. For layers with no penetration resistance data, the minimum range of values was derived from the correlation proposed earlier (41).

The analysis was confined to processing the input parameters required for slope stability evaluation. The study employed SLIDE2 Rocscience software, which uses the Mohr-Coulomb shear strength model suitable for soils, to calculate the FoS and probability of failure (PoF). The PoF was determined using the following equation:

PoF = (Number of simulations with FS < 1) / (Total number of simulations) (Eqn. 2)

To ensure accuracy, Janbu's simplified method was utilized, as it is applicable to various slip surface shapes and is known for achieving reliable numerical convergence. This method considers the varying heights of side forces above the base of the slice (45). Additionally, the ordinary method of slices, including Fellenius' and Bishop's methods, was applied as a quality check for the FoS.

The study also incorporated scenarios with fluctuating water tables and ponding, based on realistic assumptions. The Green-Ampt infiltration method was used to model infiltration and was applied to calculate both the infiltration rate and total infiltration (43).

Multiple linear regression and sensitivity analysis

To identify and analyze the key parameters influencing the stability of the Maligcong rice terraces and their impact on the FoS, the results of a stochastic simulation from the probabilistic analysis were subjected to multiple linear regression (MLR). Unit weight, cohesion and angle of friction for each soil layer served as predictor variables for the FoS. Sensitivity analysis was also conducted to determine the most critical layer parameters, complementing the insights gained from the correlation relationships identified through MLR.

To evaluate the correlation between geometry and the FoS, boundary limits of the overall slope model were adjusted to enable a detailed stability analysis for individual paddies. The overall slope geometry comprised eight paddies with varying heights and widths. These dimensions were analyzed using frequency distribution and subsequently regressed as predictor variables for the FoS of individual paddies.

Results and Discussion

Soil classification, moisture content and estimated hydraulic conductivity of the Maligcong rice terraces

The study of the Maligcong rice terraces identified the soil at the site as predominantly sandy. Based on the USCS, these sandy materials, with minimal fines, were classified into well-graded sands (SW) and poorly graded sands (SP). Their distribution across all layers exhibited an irregular pattern, as depicted in Fig. 3. A decreasing trend in SW was observed with increasing depth, indicating a distinct reduction pattern across the soil layers (Table 1).

In terms of moisture content, partially saturated soils were predominant throughout all layers. The surface layer (layer 1) and the deepest layer (layer 4) showed more consistent moisture content values. However, these layers were less saturated compared to the mid-layers (layer 2 and layer 3).

The estimated hydraulic conductivity values aligned with those typically expected for similar soil types. Notably, the results revealed an increasing trend in hydraulic conductivity with depth.

The soil classification, critical for determining strength parameters, identified the material as predominantly sands with minimal fines across all depth layers. This aligns with the previous study that observed sandy soil types in the surface layers of rice terraces (18). However, other studies reported organic-rich sediments in surface layers of other rice terraces, indicating variations in soil composition across different sites (15, 46).

The gradation analysis categorized the soil into SW and SP. These two types were uniformly distributed within the uppermost layer (up to 1 m), but deeper layers showed a noticeable decline in well-graded sands. This trend could reflect historical sedimentation or erosion processes, similar to that fine particles like clay are often displaced under waterlogged conditions, leading to reduced fines at deeper levels (47).

Moisture content analysis revealed that mid-layers exhibited the highest saturation levels, consistent with the highly permeable nature of sandy soils. Saturation levels in the slope material suggest significant subsurface water accumulation which linked subsurface water pressure to slope instability and collapses in terraced landscapes (48).

Table 1. Maligcong soil properties per layers

Soil depth from surface in meters		Moisture content	Soil classification	Estimated hydraulic conductivity (mm/hr)
0-1 (layer 1)				
	Mean	48.02		
	Std. deviation	7.42	SW or SP	336.33
	Maximum	64.57		
1-2 (layer 2)				
	Mean	60.43		
	Std. deviation	9.77	SW or SP	388.30
	Maximum	78.17		
2-3 (layer 3)				
	Mean	50.04		
	Std. deviation	9.63	SW or SP	409.97
	Maximum	72.16		
3-4 (layer 4)				
	Mean	52.64		
	Std. deviation	6.39	SW or SP	461.42
	Maximum	65.53		

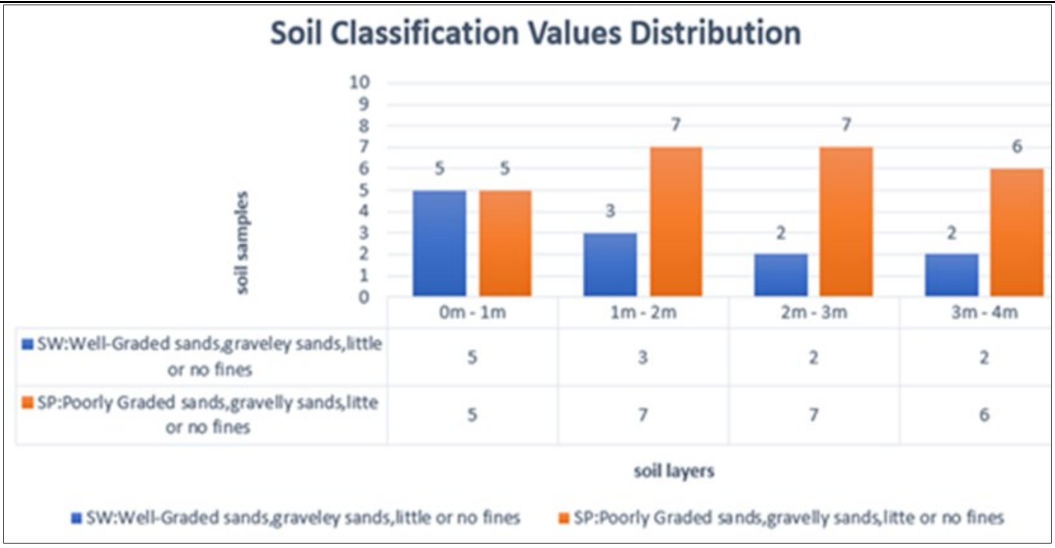

Fig. 3. Soil layers distribution of the soil classification.

These findings underscore the critical role of high-water saturation in destabilizing slopes.

The Maligcong rice terraces, characterized by loose, saturated sands, are notably susceptible to liquefaction during earthquakes and heavy rainfall. Liquefaction is a well-documented phenomenon in loose, saturated sands, which lose shear strength and behave like a fluid under seismic or hydrodynamic loading (49). Particle size distribution analysis confirmed the presence of clean sands (SP or SW), with less than 5 % fines, a condition that further heightens liquefaction susceptibility. Research highlights that even small additions of fines around 10–30 % silt content can significantly increase the potential for liquefaction (50, 51).

One of the primary motivations for this study is the large-scale collapse observed at the research site. Evidence of deep-seated landslides, including the failure of approximately 8 to 10 rice paddies, pointed to the possibility that liquefaction may have played a significant role in triggering the collapse. Liquefied layers, particularly at substantial depths, can undermine the stability of overlying soils, leading to extensive slope movements. Conducting a comprehensive liquefaction potential assessment of the Maligcong soils is crucial to understanding their contribution to the observed landslide and evaluating the terraces' vulnerability to future seismic and hydrological events.

Maligcong rice terraces inferred geological layers

The inferred geological layers of the study site included topsoil that emanated from a sandstone parent material. Resistivity values, depth thickness and specific layers are summarized in Table 2.

The study took into account several key site observations, including: (a) the area is underlain by volcaniclastics from the Malitep formation, which includes lower volcanic flows, breccia and tuff, as well as upper volcanic conglomerate, sandstone and tuff; (b) pebbly sandstone was noted in the surrounding area during field investigations and (c) the site is located on the southeastern slope of a hill with moderate terrain, identified as an old landslide deposit characterized by a concave topography, scattered spherical boulders and a slope gradient that differs from the surrounding areas.

The geo resistivity analysis indicates that the topsoil layer exhibits elevated resistivity values, likely due to its unconsolidated nature and the presence of unsaturated pore spaces. Beneath this, a fine sandstone layer demonstrates a noticeable decrease in resistivity, suggesting higher moisture content and increased conductivity. This reduction in resistivity is likely influenced by recent rainfall and irrigation activities, which have saturated the pore spaces within this layer. The sudden drop in resistivity values corresponds to the increase in moisture content observed, reinforcing the impact of water infiltration (Table 1).

Table 2. Inferred geologic layers of Maligcong rice terraces

Resistivity (ohm.m)	Thickness (m)	Depth (m)	Inferred geologic layers
24	1.4		Topsoil
13	2.8	1.4	Fine sandstone
27	47	4.2	Tuffaceous sandstone
17		51	Pebbly tuffaceous sandstone

However, the geo resistivity-based depth estimates appear to be overestimated compared to SWST results. At most test locations, the penetration limit is reached at 3–4 m, contradicting the geo resistivity findings that suggest deeper layer. This discrepancy can be attributed to the electrode layout on undulating terrain, which may have distorted resistivity measurements and led to inaccuracies (52, 53). To resolve this inconsistency, actual specimen extraction was conducted, ensuring a more precise assessment of the subsurface conditions. Thus, confirming the presence of weathered sandstone on 3-4 m depth, as shown in Fig. 4.

Considering the resistivity data and the distinct characteristics of each layer, the water table is inferred to lie at the boundary between the fine sandstone layer (approximately 13 ohm.m) and the tuffaceous sandstone layer (approximately 27 ohm.m). This transition occurs at depths ranging from about 1.4 to 4.2 m, where the fine sandstone gives way to the more compacted tuffaceous sandstone.

Height and width range of the rice terraces paddies adjacent to the failed site in the Maligcong rice terraces

The Maligcong rice terraces exhibit horizontal lengths ranging from 3.7 to 8.7 m and heights varying between 0.80 and 2.60 m. These dimensions correspond to approximate slope angles ranging from 6 to 24 degrees (Fig. 5, 6).

The width of the rice paddies predominantly ranges from 6 to 7 m, with paddies exceeding 8 m being relatively uncommon (Fig. 7). In general, the paddy walls are not particularly tall, with the majority having heights of less than 2 m. However, the maximum recorded height reaches up to 2.60 m (Table 3). Notably, there is greater variability in the widths of the rice terraces compared to their heights

Fig. 4. Weathered sandstone encountered at deeper layers.

The geometric measurements of the Maligcong rice terraces reveal a height range shorter than those reported for the Banaue rice terraces (15). This difference implies that the Maligcong rice terraces were likely constructed on a mountain with a gentler slope compared to the steeper terrain of the Banaue rice terraces. The irregular and organic patterns observed in the height and width of the terraces align with previous study, which suggest that the design of rice terraces is often influenced by the availability of water sources rather than strict adherence to topographic constraints (15). These observations also highlighted ancient design challenges in terraced landscapes (48).

Potential water table case scenarios of Maligcong rice terraces

Water table case scenarios can be assumed to include water level rise up to the surface and potential for ponding. This is based on rainfall data, assumptions in geo resistivity and estimated hydraulic conductivity.

The Green-Ampt infiltration analysis was used to quantify infiltration rates over time. Ponding was assumed to occur within an hr when rainfall intensity exceeded approximately 50 cm/hr (Table 4). The infiltration estimates in the table further suggest that 11 hr of intense rainfall could raise the water table to the surface, assuming an initial depth of 4.20 m.

These data offer useful insights for potential scenarios, particularly the plausible rise in the water table. A conservative worst-case scenario for overtopping was estimated at a water level of approximately 0.30 m. This estimate is based on the measured elevation difference between the paddy pathways, which function as water barriers and the surface soil of the rice paddies.

The results from the water table case scenarios suggest that water table rise and ponding can occur even in soils with a high infiltration rate. This indicates that, in some cases, rainfall intensity may play a more significant role than the infiltration rate in controlling water table fluctuations. This finding contrasts with where, water table fluctuations and ponding to low infiltration rates caused by organic matter clogging (12). Therefore, it is evident that water table rise and ponding are not solely dependent on low infiltration rates; even soils with high infiltration can experience such phenomena under certain conditions.

Table 3. Descriptive statistics of the geometric parameters

Descriptive	Height (m)	Width (m)
Mean	1.55	5.94
Standard deviation	0.678	1.67
Maximum	2.60	3.70
Minimum	0.80	8.70

Table 4. Hourly values of calculated infiltration amount and infiltration rate

Time (hr)	Infiltration amount (F) (cm)	Infiltration rate (f) (cm/hr)
1	58.65	49.97
2	107.57	48.23
3	155.44	47.59
4	202.84	47.25
5	249.98	47.04
6	296.95	46.90
7	343.79	46.80
8	390.55	46.72
9	437.23	46.66
10	483.86	46.61
11	530.45	46.57
12	576.99	46.53

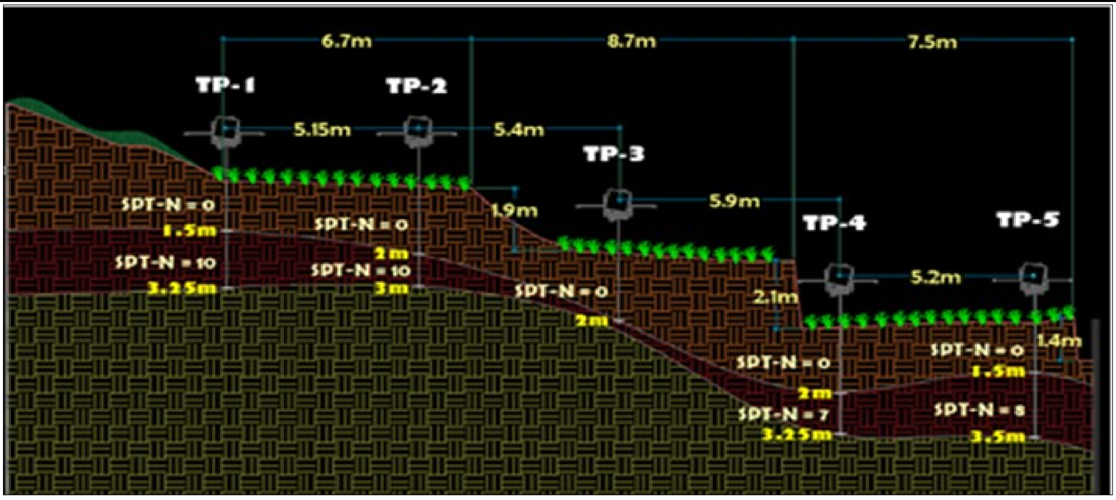

Fig. 5. Cross-sectional area of the upper to mid paddies.

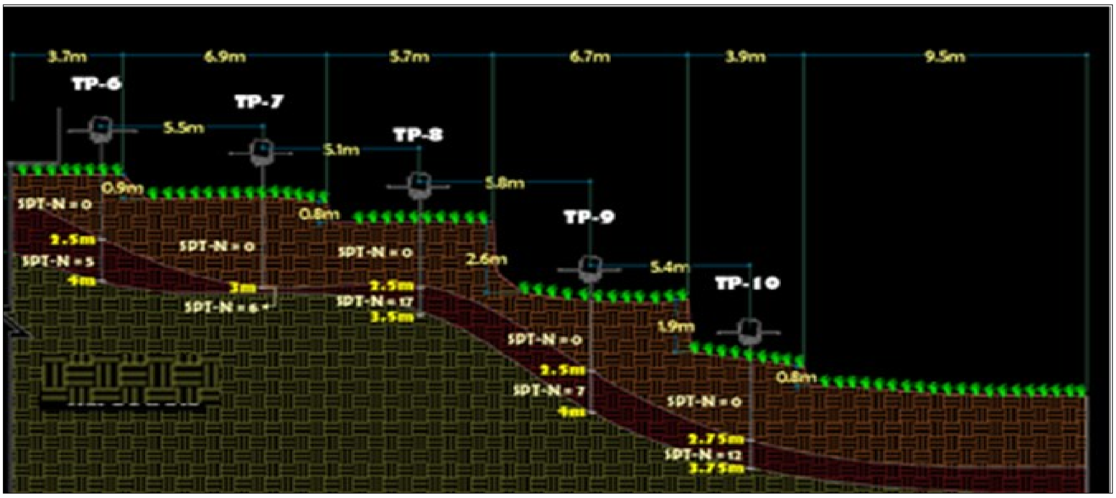

Fig. 6. Cross-sectional area of the mid to lower paddies.

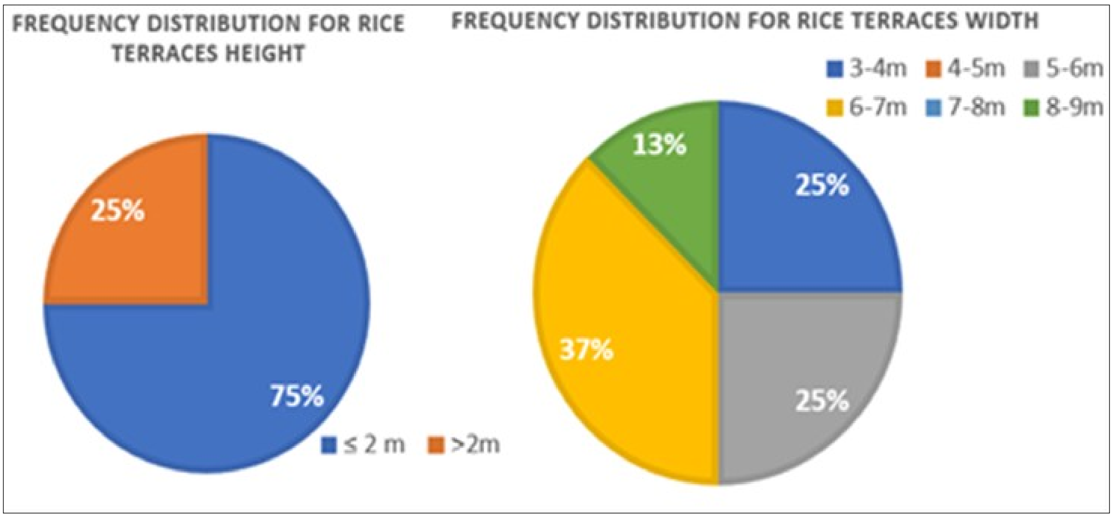

Fig. 7. Frequency distribution of height and width measurements of the study site.

Several studies have shown that the rise in groundwater table due to rainfall infiltration can significantly impact the stability of slopes, even in sandy soils known for their high permeability (8, 13, 48, 49, 52). The rapid rise of the groundwater table during rainfall events can lead to an increase in pore water pressure, reduced soil suction and decreases effective stress and shear strength of the soil (26, 45, 54).

Given the case scenarios analyzed, it is plausible that water table rise could lead to instability in the rice terraces, particularly in the dry-stone walls. Altered soil permeability and water infiltration could result in structural collapse due to water saturation (48). Additionally, the slope instability becomes more pronounced when the water table reaches 25 % of the slope height, with the FoS decreasing significantly (19). Similarly, a critical water level of around 70 % of the embankment height, beyond which failure becomes more likely (16). These findings underscore the importance of carefully managing water table fluctuations to maintain the stability of terraced landscapes.

Critical water table case scenario and associated factor of safety (FoS)

The most critical water table case scenario for the Maligcong rice terraces is case 7, where the water table is at the surface with a 0.3 m ponding load. This scenario exhibited the lowest FoS values, with Janbu's method indicating a FoS of 0.079 and Bishop's method, FoS of 0.186.

Across all the evaluated scenarios (cases 1 to 8), the FoS consistently indicated instability, with values less than 1.0 (Table 5). This was further supported by a 100 % PoF in all scenarios, regardless of the analysis method used (Janbu or Bishop).

The results showed that water table fluctuations only become critical in affecting the Fos once the water table is within 1 m of the rice paddies' surface. The scenarios with the water table deeper than 1 m (cases 1 to 4) exhibited the same FoS values, indicating that the deeper water table had no significant impact on slope stability.

The most critical water table case scenario was identified as case 7, where the water table is at the surface with a 0.3 m ponding load. This scenario resulted in the lowest FoS values (0.079) with Janbu's method and 01.186 with Bishop's method. The results further showed that water table fluctuations only affect the FoS once the water table is within 1 m of the rice paddies' surface, highlighting the sensitivity of the system to changes in groundwater conditions.

The Maligcong rice terraces are prone to slope instability due to the high permeability of sandy soils, which allows rapid groundwater rise during rainfall (54, 55). This increases pore water pressure, reduces soil suction and effective stress and weakens shear strength, compromising slope stability (56).

Comparing the two analysis methods, Janbu's method consistently produced more conservative results, with lower FoS values compared to Bishop's method, both in the deterministic and probabilistic approaches (57).

The results of the slope stability analysis for the Maligcong rice terraces indicate a critical vulnerability to slope instability, with all the evaluated scenarios exhibiting a FoS consistently below 1.0, suggesting a high PoF. This is a concerning finding, as the rice terraces are an important agricultural landscape that provides various ecosystem services and cultural values (58, 59). This can increase pore water pressure, reduce soil suction and effective stress and weaken shear strength, compromising slope stability (60).

The presence of soil pipes and preferential flow paths in the rice terraces can also influence the relationship between groundwater conditions and slope stability (61). While soil pipes can enhance drainage during rainfall events and help maintain slope stability, clogging of these pipes can lead to a rise in the water table and a reduction in stability.

Research should explore potential mitigation strategies to enhance slope stability under critical water table scenarios. This could include the implementation of drainage systems, such as horizontal drains or subsurface drainage galleries, to effectively lower the groundwater table and dissipate pore water pressure (62, 63).

Additionally, the integration of soil improvement techniques, such as soil compaction or the use of stabilizing additives, could help increase the shear strength and overall stability of the slopes (62). The installation of retaining structures, such as concrete walls or sheet piles, could also be considered to provide additional support and prevent slope failures (64).

Furthermore, the use of geogrid reinforcements could be a valuable addition to the mitigation strategies. Geogrids are synthetic materials that can be used to reinforce soil and improve the stability of slopes (57, 65-67). By incorporating geogrid reinforcements, the tensile strength and overall stability of the rice terraces can be enhanced, helping to counteract the destabilizing effects of the critical water table scenarios.

Table 5. FoS and PoF of the probabilistic slope stability analysis

Case	Brief description	Global FoS probabilistic		Probability of failure (PoF)	
		Janbu	Bishop's	Janbu	Bishop's
1	Bare slope without WT	0.749	0.797	100 %	100 %
2	WT 4 m below the surface	0.749	0.797	100 %	100 %
3	WT 3 m below the surface	0.749	0.797	100 %	100 %
4	WT 2 m below the surface	0.749	0.797	100 %	100 %
5	WT 1 m below the surface	0.696	0.771	100 %	100 %
6	Water table at the surface	0.092	0.205	100 %	100 %
7	Water table at the surface plus ponding load 0.3 m	0.079	0.186	100 %	100 %
8	Ponding load 0.3 m	0.696	0.771	100 %	100 %

Factor of safety and layered cohesion, angle of friction and unit weight

The results of the regression analysis indicate a notable correlation between the soil properties of the Maligcong rice terraces and their slope stability characteristics. Specifically, the soil properties of layer 1, including cohesion, angle of friction and unit weight, are statistically significant predictors of the FoS for the slopes (Table 6).

Among these predictors, the unit weight of layer 1 stands out with the strongest correlation, explaining 73.5 % of the variability in the FoS. In comparison, cohesion and angle of friction of layer 1 have similar coefficients of determination, explaining 16.4 % and 15.7 % of the variability, respectively.

The regression model further reveals that the cohesion of layer 1 has the most significant effect per unit on slope stability, as indicated by the highest regression coefficient. Increases in the angle of friction and unit weight of layer 1 result in only slight increases in the FoS.

The sensitivity analysis, corroborates these findings, showing that changes in the layer 1 parameters such as cohesion, angle of friction and unit weight values would significantly impact the calculated FoS (Fig. 8).

Based on the provided regression model and results, the soil parameters in the surface layer (layer 1) can be used to directly predict the FoS for the Maligcong rice terraces slopes. The predictive equation is as follows:

FoS = 0.008 + 0.043 * (layer 1 cohesion) + 0.001 * (layer 1 angle of friction) + 0.002 * (layer 1 unit weight)

This equation shows that among the three critical parameters, the cohesion of layer 1 has the most significant effect on slope stability, as indicated by the highest regression coefficient of 0.043. In contrast, increases in the angle of friction and unit weight of layer 1 result in only slight increases in the FoS, with regression coefficients of 0.001 and 0.002, respectively.

The regression analysis has highlighted the crucial role of the soil properties in the surface layer (layer 1) of the Maligcong rice terraces in determining the slope stability characteristics. Among the identified critical parameters, the unit weight of layer 1 stands out as the most influential factor, explaining 73.5 % of the variability in the FoS.

This finding is consistent with previous studies that have emphasized the importance of soil density and compaction in slope stability (68). Soil properties, particularly the unit weight, are crucial in recognizing potentially unstable slopes and optimizing the design of slope stabilization structures (69).

Table 6. MLR results on predictor variables per soil layer to FoS

Predictors	*p*-value	r squared
Layer 1: Cohesion (kN/m^2)	0.000	0.164
Layer 1: Angle of friction (deg)	0.000	0.157
Layer 1: Unit weight (kN/m^3)	0.000	0.735
Layer 2: Cohesion (kN/m^2)	0.579	0.002
Layer 2: Angle of friction (deg)	0.513	0.007
Layer 2: Unit weight (kN/m^3)	0.924	0.004
Layer 3: Cohesion (kN/m^2)	0.424	0.005
Layer 3: Angle of friction (deg)	0.540	0.003
Layer 3: Unit weight (kN/m^3)	0.790	0.003
Layer 4: Cohesion (kN/m^2)	0.381	0.001
Layer 4: Angle of friction (deg)	0.621	0.008
Layer 4: Unit weight (kN/m^3)	0.829	0.001

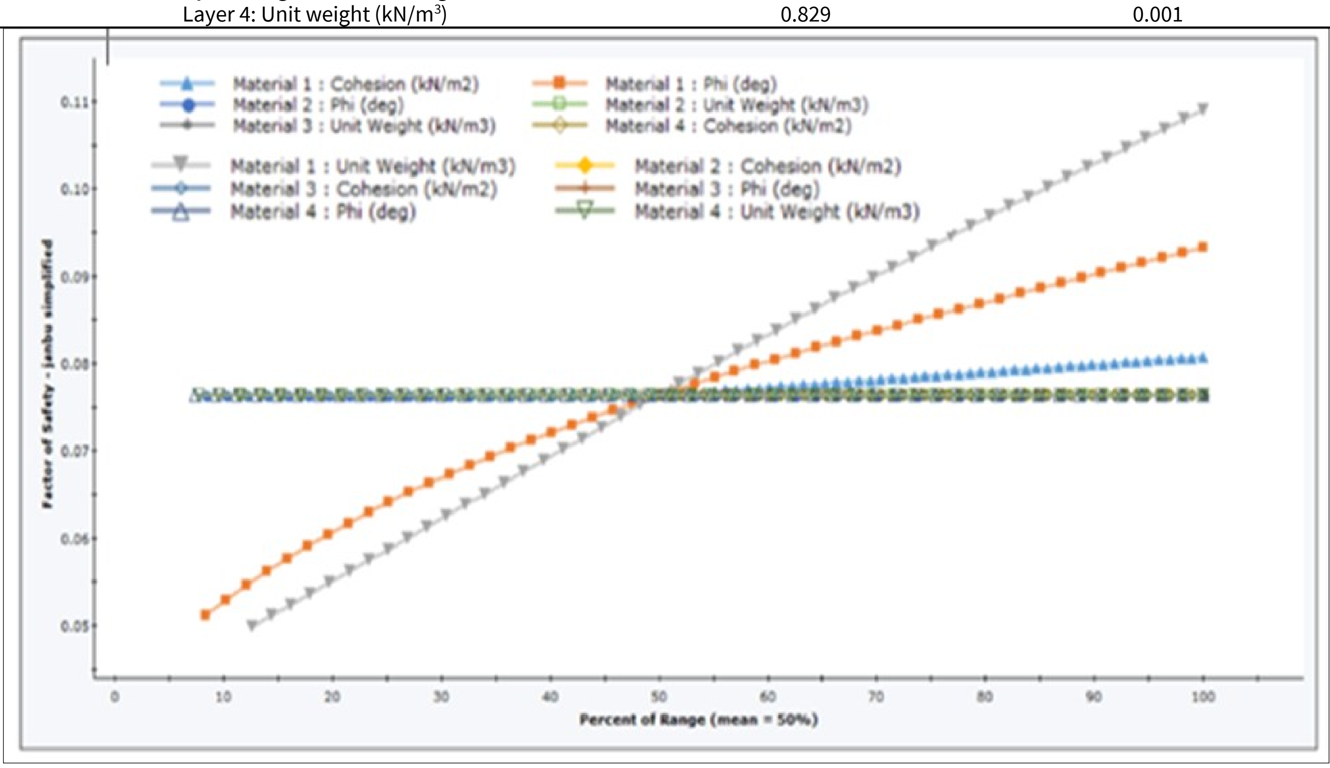

Fig. 8. Sensitivity analysis of the probabilistic analysis.

In addition to the unit weight, the cohesion and angle of friction of layer 1 have also been identified as critical parameters. The regression model revealed that the cohesion of layer 1 has the most significant effect on slope stability, while the sensitivity analysis showed that changes in the angle of friction would significantly impact the calculated FoS.

These findings align with the previous study, demonstrating the ability to effectively predict the strength properties of soils, including cohesion and angle of friction, using simple soil parameters such as moisture content and particle size distribution (70). The importance of accurately modeling these critical soil properties has also been highlighted on the use of MLR analysis for predicting soil shear strength (71).

The focus on the surface layer (layer 1) soil properties is further supported by the literature, which emphasizes the need for careful consideration of the upper soil layers in understanding the complex interactions within agricultural landscapes. Applying high-resolution digital elevation models (DEMs) for digital soil mapping requires thoughtful consideration of spatially coupled soil processes and properties, particularly in the surface layers (72).

Additionally, the work of previous researchers has demonstrated the importance of understanding the correlations and spatial variability of soil properties in predicting slope stability and other soil-related phenomena (73). These findings underscore the need for a comprehensive approach that considers the complex interactions between the critical soil parameters and the overall stability of the Maligcong rice terraces (74).

Given the importance of soil properties, particularly the unit weight and cohesion of the surface layer (layer 1), implementing soil improvement techniques could be a valuable strategy. This could include soil compaction, the addition of stabilizing additives or the use of geosynthetic reinforcements to increase the shear strength and overall stability of the slopes. To address the rice terraces' vulnerabilities, geogrid reinforcements offer a valuable solution, enhancing slope stability without altering the landscape's authentic appearance (75, 76).

The use of geogrids has been extensively studied in the context of slope stabilization, exploring their application in enhancing the stability of river levees (77). The ability of geogrids to improve the tensile strength, soil-geogrid interaction and overall stability of slopes makes them a promising solution for addressing the vulnerabilities of the Maligcong rice terraces.

Influence of geometric parameters on FoS

Based on the provided results, the geometric parameters of the Maligcong rice paddies, specifically the height and width, play a significant role in determining the slope stability and FoS.

Regarding the width of the paddies, the results indicate that those with wider widths and taller heights generally exhibited an unstable safety factor, except for the topmost paddy, which has a gentle slope face.

However, the statistical analysis showed that the *p*-values for both height and width as predictors of the FoS are not statistically significant (*p*-value for height = 0.052 and width = 0.425). Consequently, the coefficients of determination (r-squared) for these geometric parameters were found to be negligible, suggesting that they do not have a strong direct correlation with the FoS.

This finding suggests that while the height and width of the rice paddies play a role in their slope stability, there are likely other factors, such as the soil properties and groundwater conditions, that have a more significant influence on the overall FoS (78). The results highlight the need for a comprehensive approach that considers both the geometric and geotechnical parameters when assessing the stability of the Maligcong rice terraces.

To further understand the role of geometric parameters in slope stability, additional research could explore the interactions between the height and width of the paddies, as well as their relationship with other factors, such as slope angle and curvature (79). This could provide a more nuanced understanding of how the physical characteristics of the rice terraces contribute to their overall stability and resilience.

Additionally, the integration of advanced techniques, such as machine learning algorithms and geospatial analysis, could be valuable in predicting and mapping the slope stability of the Maligcong rice terraces (80-82). These approaches can help identify the critical geometric and geotechnical parameters that influence the stability of the rice terraces, ultimately informing the development of targeted mitigation strategies.

The individual slope stability analysis of the eight rice paddies, showing that taller paddies with heights ranging from 1.4 to 2.6 m consistently exhibited instability (FoS<1) based on the Janbu method of global FoS calculation (Table 7). When analyzed using the Bishop's method, instability was observed in paddies with heights between 1.9 and 2.6 m. This suggests that the height of the rice paddies is a critical factor in determining their slope stability (Fig. 9). Taller paddies are more prone to instability and a lower FoS, as the increased height can lead to higher shear stresses and a greater potential for slope failure (83, 84).

Conclusion

This study aimed to assess the stability of the Maligcong rice terraces by examining soil properties, geometric characteristics and groundwater conditions. The findings confirm the predominantly sandy nature of the soil, a layered subsurface structure and the influence of water table fluctuations on slope stability. The study highlights the vulnerability of the terraces to instability due to factors like water table rise and the predominance of loose sands prone to liquefaction. Unlike previous studies that may have focused on geometric factors, this research demonstrates the significant impact of soil properties, particularly the cohesion, angle of friction and unit weight of the surface layer, on the FoS. The identification of liquefaction potential and its role in

Table 7. Results of slope stability analysis of individual paddies

Paddies	Height (m)	Width (m)	Global FoS probabilistic		Probability of failure (PoF)	
			Janbu	Bishop's	Janbu	Bishop's
1	1.9	6.7	1.34	1.538	0 %	0 %
2	2.1	8.7	0.702	0.767	100 %	100 %
3	1.4	5.2	0.949	1.018	100 %	13 %
4	0.9	3.7	1.635	1.968	0 %	0 %
5	0.8	6.9	1.472	1.633	0 %	0 %
6	2.60	5.7	0.769	0.847	100 %	100 %
7	1.90	6.7	0.692	0.755	100 %	100 %
8	0.80	3.9	1.618	1.793	0 %	0 %

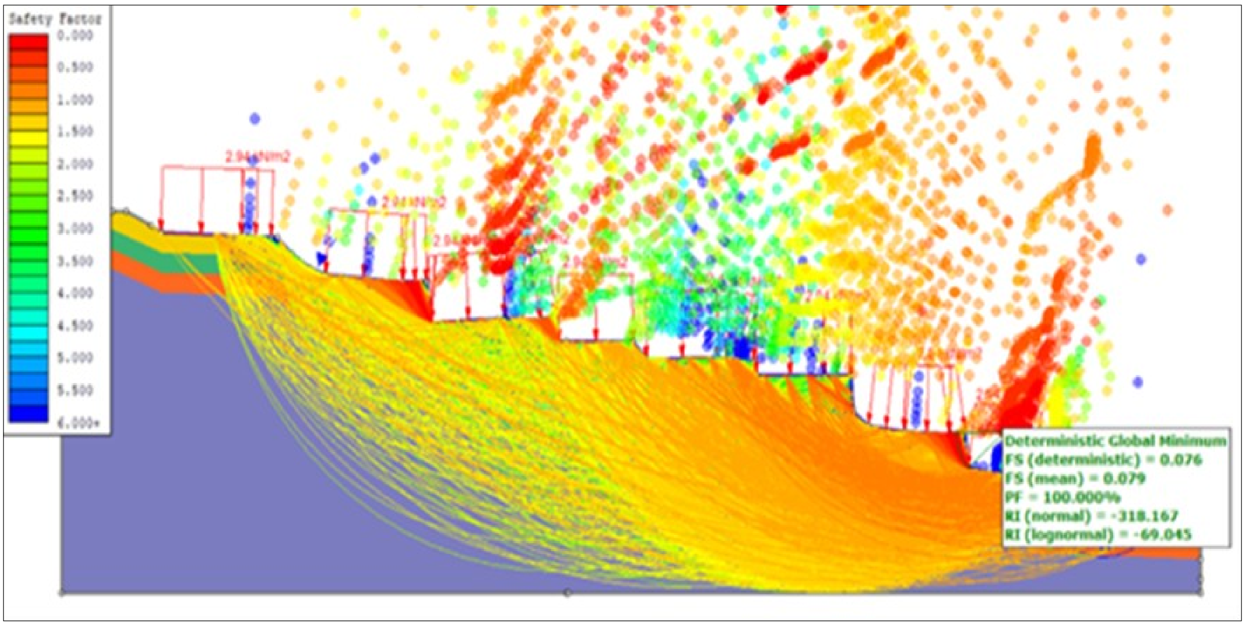

Fig. 9. Critical failure slips implied on taller paddies.

triggering deep-seated landslides adds a valuable dimension to understanding the overall risk of these terraces. Concrete recommendations include implementing soil improvement techniques such as soil compaction, stabilizing additives or geosynthetic reinforcements and integrating geogrid reinforcements to enhance slope stability while preserving the terraces' authentic appearance. A limitation of this study is the lack of direct validation of the inferred subsurface structure and water table position through soil specimen extraction and long-term groundwater monitoring. Future studies should focus on conducting comprehensive liquefaction potential assessments, long-term monitoring of groundwater levels and pore water pressure and implementing and evaluating the effectiveness of the recommended soil improvement techniques. Additionally, assessing the impact of seismic activity on the liquefaction and slope failure will be critical for designing effective disaster risk reduction strategies. These future research directions will contribute to a more comprehensive understanding of the factors influencing the stability of the Maligcong rice terraces and similar terraced landscapes, thereby informing more effective conservation strategies.

Acknowledgements

The author sincerely expresses profound gratitude to the Department of Science and Technology (DOST) for its invaluable financial support, which made this research possible. The funding provided has been instrumental in facilitating the necessary resources and enabling the successful completion of this study. Special appreciation is also extended to the Mines and Geosciences Bureau (MGB) for their generous resource assistance, particularly in providing access to Geo resistivity equipment. Their support has significantly contributed to the data acquisition and analysis, strengthening the technical foundation of this research.

Compliance with ethical standards

Conflict of interest: Author does not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work the author used ChatGPT in order to improve language and readability. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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