

Case Study Of Geogrid Reinforcements In Maligcong Rice Terraces: A Proposed Restoration For A Cultural Heritage

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Abstract:

The Geogrid reinforcement case study on Maligcong Rice Terraces substantiates the feasibility of the proposed restoration. Soil exploration and slope stability analysis played pivotal roles in strengthening these justifications. The Swedish Weight Sounding Test identified loose and medium layers, albeit with constrained detailed information on loose layers. Penetration resistance trends indicated a direct proportionality to depth, reflecting prevalent sands. Subsurface layer examinations revealed uniform saturated soils with poorly graded sands and consistently inferior well-graded sands. Poorly-graded sands increased in medium layers, and rice paddy moisture content showed significant variability across surface layers. In slope stability analysis, Bishop's method supplemented Janbu's, yielding a conservative deterministic factor of safety. The bare slope appeared marginally stable deterministically but stable probabilistically. Introducing a water table shifted the scenario to instability, identified as the worst-case. Incorporating geogrid reinforcements under the worst-case scenario resulted in a marginally stable deterministic factor and a stable probabilistic factor. A 1-meter vertical spacing achieved stable factors in the worst-case, yet failed external stability requirements by the AASHTO-ASD method. AASHTO-ASD method-derived vertical spacing could be desirable probabilistically. Construction faced challenges, necessitating manual labor due to the infeasibility of machinery unfeasibility. Productivity rates remained practical, with divergence between traditional and proposed restoration in geogrid embedment length. Challenges included labor availability, upper paddy erosion, water-related issues, and achieving proper compaction, addressed by strategic methods. Cost-Benefit Analysis hinged on total cost and serviceability, with the proposed restoration surpassing the traditional method's Cost-Benefit Ratio, justifying its adoption.

Keywords: Slope stability analysis, Geogrid reinforcement, Rice terraces restoration

1. INTRODUCTION

Physical restoration of Rice Terraces has been a challenge in sustainable management of a Cultural heritage in Philippine Cordillera. Most studies revealed that gradual deterioration of rice terraces sites was attributed to intense rainfall associated with lack of attention due to urbanization and changing values of the community (Mori, Sasaki, & Tsujimoto, 2019) (Soriano & Herath, 2018). Increased vulnerability was greatly implied on abandoned rice terraces site in just a short period of time (Pepe, et al., 2019) Neglected sites were characterized by a deteriorated soil quality thus, increasing gully erosion (Tarolli & Brancucci, 2018)

Consequently, local government has taken action to alleviate the problem. One of the targets of the master plan for rice terraces, which runs from 2015 to 2024, is restoration of the rice terraces. But a lack of manpower is a common obstacle to the restoration of these landscapes (Mori, Sasaki, & Tsujimoto, 2019); (Soriano & Herath, 2018)). An ageing population and declining traditional practices call for the development of a workable restoration technique (Salazar, 2017). It takes a scientific foundation to create rice terraces in a way that is sustainable (Zoumides et al., 2021). In an effort to clarify the factors involved in rice terrace preservation, surveys should therefore continue to be conducted (Guimbat & Baguilat Jr, 2006). The consequences of climate change will not be immune to the rice terraces (Ducusin, Espaldon, Rebancos, & De Guzman, 2019). The relevance and efficacy of proposed scientific concepts developed on a terraced terrain must be continuously validated (Wakai, Sato, Tran, Karnjana, & Komori, 2021). In the world of civil engineering, the practice of bolstering embankments with geogrid reinforcement has become a well-established technique. Engineers and builders have embraced this method due to its remarkable efficiency and its track record of delivering impressive reinforcement outcomes. In fact, Xiaodong et al. (2010) noted that geogrids have proven to be highly suitable for a wide range of civil engineering projects.

Geogrids have the advantage of high tensile strength and low elongation rate and they are widely used in the highway embankments to improve the pavement performance and reduce the settlement. (Sha &

Xiaodong, (2013)). These reinforcing materials absorbs tensile forces on embankments. (Mincai, Wenkai, & Chao, 2021) Studied a 33-m-high single-tiered wrapped-facing geogrid reinforced soil embankment with the slope of 1 V:0.5H in China was monitored for 2 years during and after construction and found out that the results show that the geogrid tensile strains gradually increased during construction. Additionally, Geogrids exhibits longer serviceability. (Kiersnowska, Koda, Fabianowski, & Kawalec, 2016) Examined the durability of HDPE geogrids in a sanitary landfill and found that the material exhibited strong chemical resistance and maintained its mechanical properties after 20 years of service.

Geogrid reinforcement presents a promising solution for the restoration of failed rice terraces, leveraging the success observed in the application of Mechanically Stabilized Earth (MSE) walls in road embankments and retaining walls. The utilization of geogrids, which are high-strength polymeric materials, has demonstrated efficacy in stabilizing soil structures and preventing erosion. In the context of rice terraces, where traditional methods may fall short in addressing the challenges posed by steep slopes and soil instability, geogrids offer a versatile and resilient alternative. By incorporating geogrid reinforcement into the restoration process, the mechanical stability of the rice terrace structures can be significantly enhanced, reducing the risk of erosion, landslides, and overall structural failure. Drawing inspiration from the successful application of MSE walls in road engineering, the adaptation of geogrid technology for rice terrace rehabilitation holds great potential to mitigate environmental degradation and sustain the productivity of these vital agricultural landscapes. Further research and field trials are necessary to fully explore the feasibility and long-term effectiveness of geogrid reinforcement in the unique context of rice terrace restoration.

2. Objectives

The overarching aim of this study is to evaluate the technical and economic viability of using geogrid reinforcements for the restoration of collapsed rice terraces in Maligcong, Bontoc, Mountain Province. Specifically, the study seeks to:

1. Determine the subsurface soil profile and estimate the in-situ strength parameters of the rice terrace paddies adjacent to the failure site using the Swedish Weight Sounding Test (SWST).
2. Evaluate the slope stability of the terraces under various scenarios, including the worst-case condition of a saturated slope, using deterministic and probabilistic methods.
3. Analyze the effect of geogrid reinforcement design (spacing and embedment length) on the factor of safety.
4. Quantify the construction requirements, challenges, and costs associated with the geogrid-reinforced restoration method.
5. Compare the cost-benefit ratio of the proposed geogrid-reinforced method against traditional restoration techniques.

6. Scope and Limitation of the study

This study is focused on a specific failed rice terrace site located on the island of Luzon, Philippines, with GPS coordinates approximately at 17.1334°N, 120.9841°E. The collapse area encompasses approximately 2,169 m² at an elevation of 1,342.30 meters above sea level.

The methods employed to address the research objectives included geospatial surveying via drone, geotechnical investigation using the Swedish Weight Sounding Test (SWST) and laboratory classification, slope stability analysis using Limit Equilibrium Methods (Janbu and Bishop) with Slide 2 software, and a comparative cost-benefit analysis.

A primary limitation was the site's inaccessibility, which precluded the use of heavy machinery and limited soil investigation to the more portable SWST instead of Standard Penetration Test (SPT). Furthermore, the characterization of very loose surface layers was constrained by the SWST's resolution, limiting detailed probabilistic analysis for these strata. Future studies of a similar nature are recommended to involve collaboration with Local Government Units (LGUs) or State Colleges and Universities (SCUs) to mitigate logistical challenges and enhance resource availability.

8. LITERATURE REVIEW

9.1 Swedish Weight Sounding Test as an alternative in-situ test for Rice terraces

In this study, estimation of the strength parameters of Rice terraces using the traditional and widely used Standard Penetration Test (SPT) could be challenged by accessibility and practicality. The adoption of a portable, reliable and cost-effective means in soil investigation is ideal especially on remote sites such as in Rice terraces. This shall enable local communities to carry out subsurface investigations to mitigate geotechnical hazards at reasonable cost, at the same time avoiding invasive effects of the SPT.

The Swedish Weight Sounding Test as an alternative to the bulk and commonly used Standard Penetration Test have been extensively used in Japan and Sweden. There have been established correlations of the penetration resistance of SWST to that of the SPT-n. In 1914, the Geotechnical Commission of the Swedish State Railway established the standardization of SWS. As per JIS A 1221 specifications, Swedish Weight Sounding serves as a tool to measure the static penetration resistance of indigenous soils and evaluate soil hardness or subsoil composition. The Swedish Weight Sounding Test (SWST) gained popularity and is extensively utilized in Japan and several European nations. It serves as an in-situ static penetration test commonly employed in loose to medium dense sand, silt, clay, peat, and organic soils. The primary objective of the test is to acquire estimates for the shear strength of soil deposits based on SPT numbers (Tsukamoto, Ishihara, & Sawada, 2004). This straightforward method exhibits notable penetration capabilities and is employed in soil investigations reaching depths of up to 10 meters (Setiawan, et al., 2022).

Correlations suggested by Inada in Philippine setting validated by the study of Zarco et.al., in 2008. Results showed that P value signifies significant correlations between SPT-N and N_{sw} of the Highest, average and lowest values. Empirical equations proposed by Inada were proved to be suitable in the Philippine setting. Deviations on the results between the SPT data and that of SWST were also observed on the exposed layer of the soil. These deviations were attributed to the timing of the test in terms of weather condition and the surcharge of heavy construction equipment that have ran into the test points (Zarco, Peckley Jr., & Tan, 2008).

9.2 Potential of Geogrid in Rice Terraces

Geosynthetic-reinforced soil (GRS) embankments and retaining structures offer numerous advantages, including high construction efficiency, cost-effectiveness, reliable serviceability, and improved seismic performance, as emphasized by previous studies (Ferreira, Vieira, & Lopes, 2020) (Holtz, 2017) (Javankhoshdel & Bathurst, 2016) (Han, et al., 2019).

Geogrid reinforcement stands out as a widely adopted approach for enhancing soil strength in embankments as proven by numerous studies like (Prakash, Rathod, & Muthukkumaran, 2023) who provided an overview of geogrid's numerous applications, including pavements, airport runways, railroads, building foundations, MSE walls, bridge embankments, and landfills and found out that Geosynthetic reinforced mechanically stabilized earth walls improved the internal stability and shear strength of soil mass owing to geogrid's sufficient pull-out length and tensile strength. In a numerical simulation study, (Sha & Xiaodong, (2013)) also investigated geogrid-reinforced highway embankments and findings suggest that the geogrid can serve as a useful constraint on both vertical and horizontal deformations, particularly horizontal displacement.

As per (Ziegler, 2017) study, geogrid-reinforced constructions offer substantial advantages in terms of both economic and environmental aspects. In particular, when comparing the reinforced and unreinforced scenarios under the same load, a significant reduction in displacements and an enhancement in bearing capacity were observed. Thus, when applied to the stabilization of rice terraces, these innovative techniques not only fortify the structural integrity of these unique landscapes but also contribute to the preservation of the environment and the sustainability of rice cultivation. The dual benefits of economic efficiency and ecologic responsibility make geogrid reinforcement a pivotal solution for the enduring prosperity and resilience of rice terrace agriculture.

Additionally, a thorough analysis conducted by (Esmaeili, Naderi, Neyestanaki, & Khodaverdian, 2018) investigated how geogrids affected the high railway embankment's stability and settling. Using a thorough methodology that included finite element modeling and laboratory testing, the study produced

impressive findings. When compared to their unreinforced counterparts, embankments reinforced with a single geogrid layer shown an impressive 7.14% improvement in bearing capacity and an 11.24% decrease in settlement. These results demonstrated a noteworthy development in performance. These results highlight how adding geogrid reinforcement can improve the overall stability and settlement characteristics of high railway embankments, with real benefits. In 2023, (Ho, DeGeyter, & Zhang, 2023) conducted a comprehensive five-year performance evaluation of geogrid reinforcement in low-volume unpaved roads by comparing the results of the installation of geogrid from 2015 and 2020, their findings revealed that, despite the other parts of roadway having a lesser thickness of geogrid reinforced aggregate base (15 cm with one geogrid layer) compared to those (30 cm of ABC without geogrid), the geogrid's application effectively reinforced the surrounding aggregate. This reinforcement led to the formation of a more robust roadbed capable of supporting traffic loads and withstanding various weathering conditions over the past years.

In a direct comparison, the work of (Ramteke, Saxena, & Arora, 2014) delved into the performance of road pavement soil when stabilized with geogrids. Their findings revealed that geogrid-reinforced soil displayed greater strength and stiffness, outperforming the equivalent soil without geogrid reinforcement. Additionally, (Marto, Oghabi, & Eisazadeh, 2013) conducted an extensive review of prior research with a specific focus on soil reinforcement using synthetic materials, particularly geogrids under static loading conditions. Their findings suggest that geogrid reinforcement's shows potential for improving stability in rice terraces since the researchers observed a consistent and linear relationship between settlement and applied pressure in soils reinforced with geogrids. This suggests that as pressure increases, the settlement response follows a predictable and proportional pattern, showcasing the effectiveness of geogrids in stabilizing the soil.

1. *Design Of Geogrid MSE Walls for Rice Terraces*

Regarding design considerations, the majority of recommended design methodologies for GRS structures currently revolve around the principles of limit equilibrium Method (LEM), with a primary emphasis on slope stability, as indicated by FHWA (2008) and AASHTO (2020) guidelines. These methods heavily rely on the safety factor (FS) and empirically assumed failure geometry, resulting in conservative load estimates, as noted in studies by (Bathurst, et al., 2009), (Shukla, Das, & Sivajugan, 2011) (Song, Chen, Ma, & Zhao, 2018)

Design methodologies for Mechanically Stabilized Earth (MSE) walls incorporating geogrid reinforcement have been established. Notable methodologies in this regard include AASHTO, LRFD Bridge Design Specifications, and Publication No. FHWA-NHI-10-024, and FHWA GEC 011 - Volume I. Additional resources discussing ground improvement techniques are available in the FHWA Ground Improvement Manuals, specifically FHWA NHI-06-019 and FHWA NHI-06-020 (Elias et al., 2006). For further insights into earth retaining structures, one can refer to Earth Retaining Structures, FHWA-NHI-07-071 (Tanyu, Sabatini, & Berg, 2008) as well as AASHTO LRFD Bridge Construction Specifications, 2nd Edition, 2004, along with the 2006, 2007, 2008, and 2009 Interim Revisions.

2. *Existing studies on Rice Terraces*

Few studies on terraced topography were conducted by some neighboring countries of the Philippines encountering slope failures with matters of concern on restoring them. Mori et.al., in 2019 examined on what is the condition of the stable rice terraces versus that of the restored rice terraces. It was found that accumulation of carbon concentration was inherent to the abandoned rice terraces that have not been cultivated for years (Mori, Sasaki, & Tsujimoto, 2019).

Wakai et al. in 2021 conducted conventional slope stability analysis and found out that edge cliffs have extremely small Factor of safety and very large Factor of safety on the main rice terraces slope. In order to eliminate semi-infinite analysis theoretical concepts, their work opted to ignore these edge cliffs in their model. The application of specific length basing from the observed size of actual failure had yielded a more valid factor of safety. Thus, such application of specific length concept was recommended by the authors to be efficient and could be applicable on their rice terraces site. It was emphasized that the micro-topography of terraced terrains is irrelevant in slope stability analysis which integrates disasters (Wakai, Sato, Tran, Karnjana, & Komori, 2021).

Technical studies on the Philippine rice terraces were only focused on the history utilizing archaeological exploration i.e. radiocarbon dating and accelerator mass spectrometry (AMS) to elucidate the inception arguments of the rice terraces. Though those studies have tackled information that is more prominent on physical attributes of the site, some of the data could be useful in engineering studies.

In particular, Ifugao Rice terraces in Batad has been explored for the above-mentioned purpose by Acabado et al. in 2019. Accounts from the interviews described the sequence of constructing new agricultural terraces. The primary consideration in the construction process is the water source availability rather than the slope gradient of the area to be terraced. Workers can even create terraces on areas with more than 40 degrees gradient. In general, sequence of steps are excavation, levelling and wall construction. The first step of rice terraces construction is the digging of Irrigation channel followed by levelling of the surface area taking out the topsoil and lastly the construction of wall (Acabado, et al., 2019). Spatial information revealed a wall height range of 0.90m to 1.70m on lower levels, 1.30 to 11.30 m for mid-levels and 0.5 to 6m on higher levels.

Inherent to the cultivation of rice terraces for a higher yield crop production is obviously the utilization of Irrigation system. However, slope failure can be manifested as an integral hazard of the cropping process. The presence of water tends to induce high water content and thus, reducing the strength of the soils. The effect of infiltration on rice terraces were demonstrated on the study of Gerrard A.J. and Gardner R.A.M. in 2000. The study tackled several environmental issues driven by the pressure for an increased crop production in Irrigated terraces in Nepal. This included increased cultivated land and amplified water channels to cater double irrigation. Consequently, expansion of irrigation seemed to lead to major management problems (Gerrard & Gardner, 2000).

9. DEFINITION OF TERMS

Definition of Terms

AASHTO-ASD method - set of design guidelines published by American Association of State Highway and Transportation Officials on Mechanically Stabilized Earth walls which is based on Allowable Stress Design approach and Rankine active pressure concept.

Allowable Stress Design (ASD) An engineering design approach that emanates from the basic concept of ensuring that the stresses induced by the loads do not surpass the allowable stresses for the materials, thereby providing a safety margin.

Angle of Friction - is a key parameter in geotechnical engineering that characterizes the resistance of soil particles to sliding past each other. It is a measure of the frictional forces between soil particles and is especially relevant in granular soils such as sands and gravels.

Bishop's method - One of the Limit Equilibrium Method of slope stability analysis which consider vertical force equilibrium and over-all moment equilibrium in the slope inter-slices.

Cohesion - is a property of soil that describes the internal molecular attraction or bonding forces between soil particles. It represents the ability of soil particles to stick together and resist shear stresses.

Factor of Safety - is a measure used in geotechnical engineering to assess the stability of the slope under various conditions. It represents the ratio of the resisting forces to the driving forces acting on the slope, providing an indication of the margin of safety against slope failure.

Field Density Test - is a quality control test conducted on compacted soil in the field to assess is in-place density and determine the degree of compaction achieved during construction.

Global Factor of Safety - The factor of safety of the most critical slip surface based on slope stability analysis

Janbu's Method - One of the Limit Equilibrium Method of slope stability analysis which accounts the effects of water in soils. It obeys all moment equilibrium forces in the calculation of interslice forces.

Limit Equilibrium Method (LEM) - is a slope stability analysis technique used in geotechnical engineering to assess the stability of slopes or retaining structures. It involves evaluating the equilibrium conditions at potential failure surfaces to determine the factor of safety against sliding or collapse.

Moisture Content - is a measure of the amount of water present in a substance, expressed as the ratio of the mass of water to the mass of the dry solid. This parameter is commonly used in various fields,

including agriculture, construction, geotechnical engineering, and food science, where the amount of water in a material can significantly affect its properties and behavior.

MSE Walls - Mechanically Stabilized Earth (MSE) walls are a type of retaining wall constructed using soil reinforcements such as geogrids or geotextiles. These reinforcements provide additional tensile strength to the soil mass, enhancing stability and allowing for the construction of taller and more economical retaining structures.

Probability of Failure – is a measure used in geotechnical engineering to quantify the likelihood of a slope experiencing instability or failure. It's an essential aspect of slope stability analysis, where engineers assess the potential risks associated with different slope configurations and soil conditions.

Poorly Graded Sand – is a type of soil or aggregate that lacks a balanced distribution of particle sizes.

Rice Terraces - are agricultural landscapes created by terracing mountainsides or hillsides to create flat areas at different elevations.

Shear Strength – is a fundamental property that characterizes the soil's resistance to deformation or failure under applied forces that cause one layer of soil to slide or shift relative to another. It is a critical parameter in geotechnical engineering and is used in the analysis of soil stability, slope stability, and foundation design

Slope Stability Analysis – is an engineering process used to assess the potential for mass movement of soil and rock on slopes. The objective of slope stability analysis is to determine whether a slope is stable or prone to failure and, if failure is likely, to understand the mechanisms and factors contributing to that failure.

Soil Compaction – this refers to the process of increasing the density of soil by reducing the volume of air between soil particles. This is achieved by applying mechanical forces, such as rolling, tamping, or vibration, to the soil. The primary goal of soil compaction is to improve the engineering properties of the soil, including its strength, stability, and load-bearing capacity.

Swedish Weight Sounding Test (SWST) – is a field test used to measure the static penetration resistance for the purpose of judging the in-situ hardness/softness of compactness of the ground and the soil layer configuration.

Standard Penetration Test (SPT) – is a widely used in-situ geotechnical testing method to assess the properties of subsurface soils. A borehole is drilled into the ground using a hollow-stem auger or other drilling methods and a number of blows required to drive the split-spoon sampler a certain distance (usually the first 12 inches or 30 cm) is recorded. This is known as the Standard Penetration Resistance or "N-value."

Unit Weight – is a measure of the weight per unit volume of a substance. In the context of soil mechanics and geotechnical engineering, unit weight is often used to describe the weight of soil or other materials per unit volume.

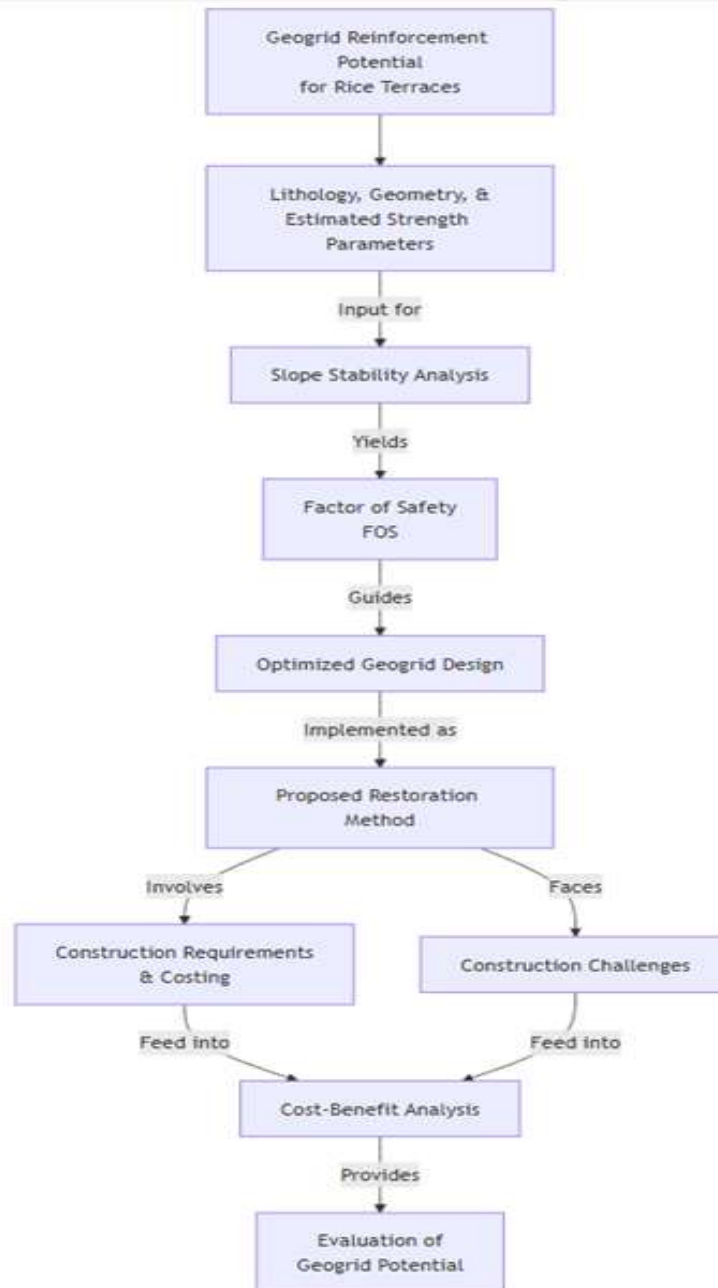
Unified Soil Classification System (USCS) – is a widely used system for classifying soils based on their engineering and physical properties.

Well Graded Sand – is a type of soil or aggregate that contains a broad range of particle sizes, contributing to a diverse and balanced distribution of particles.

10. THEORETICAL FRAMEWORK

The research framework guiding this study is presented in the figure below, illustrating the interconnected variables and processes that lead to evaluating the potential of geogrid reinforcement.

Figure 3: Theoretical Framework of the study



The research endeavors to showcase the transformative potential of Geogrid reinforcement in the restoration of rice terraces by exploring three critical variables: Cost-benefit analysis, encountered construction challenges, and the implications of Geogrid reinforcements on the stability of the rice terraces.

The stability implications of Geogrid reinforcements are encapsulated by the Factor of Safety, which not only serves as a critical metric but also forms the foundation for developing an optimized design for soil reinforcement. This optimized design was methodically implemented on the actual site under study, providing a real-world context for assessing its effectiveness. Throughout this process, construction challenges were documented, and construction requirements and costs were meticulously quantified.

The subsequent Analysis of Cost-benefit, incorporating the detailed construction parameters and costing, facilitated a comprehensive evaluation of the economic feasibility of the Geogrid reinforcement strategy. The profile and estimated strength parameters of the rice terraces played a pivotal role in slope stability analysis, contributing crucial inputs to assess the Factor of Safety.

Importantly, the Factor of Safety, serving as a common thread, guided not only the optimized design of soil reinforcement but also informed the development of an optimized design for Geogrid reinforcements specifically tailored for the rice terraces under investigation. This integrated approach ensures a thorough examination of Geogrid reinforcement's potential, aligning theoretical considerations with practical implementation for the holistic restoration of rice terraces.

11. METHODS

This study has considered quantitative-descriptive research method whereas the potential of geogrid reinforcement in the restoration of rice terraces had been presented according to the variables described in the theoretical framework of this study. Thus, the required variables have been supported by the following data gathering procedures:

11.1 Geospatial survey:

The use of drones for geospatial surveys has become increasingly common due to their ability to capture high-resolution photographs and geospatial data (Wood, Robinson, Costa, & Betran, 2021) These surveys have been used for a variety of purposes, including assessing building facilities (Jimoh & Sodiq, 2022), mapping marine habitats (Ventura, Bonifazi, Gravina, Belluscio, & Ardizzone, 2018), and monitoring the health of plantation-grown trees (Nazir, Terhem, Norhisman, Razali, & Meder, 2021) and conducting surveys of failed rice terraces (Park & Lee, 2022).

The data collected from drone surveys can be processed using specialized software such as Metashape Agisoft Software, which allows for the conversion of drone images to Comma Separated Values points (Park & Lee, 2022). Furthermore, the processed data can be imported into software like Autodesk Civil 3D for further analysis and processing, such as generating cross-sections adjacent to the failed rice terraces (Park & Lee, 2022). The reliability of the data delivered depends on different variables: the quality of the used imagery, image orientation, adopted scenario, GCP's availability and distribution (Jebur, Abed, & Mohamed, 2018)

11.2 Geotechnical Investigation:

The study have considered 36 soil specimens for 10 test points on the rice terraces adjacent to the failed rice terraces site (as shown in figure 2). These soil specimens were taken every one meter layer of the ground surface up to four meters on every test points. The samples taken through 6" diameter soil samplers were subjected to Soil Classification through Unified Soil Classification System (USCS) (ASTM D2487) and Unit weight determination adopting ASTM-D7263.

Such obtained parameters have facilitated estimation of the strength parameters through the in-situ test using the Swedish Weight Sounding Test with procedures referred to reference (Tsukamoto, Hyodo, & Hashimoto, 2016). The Nsw parameter from this test were converted into its equivalent SPT-n value using the equation by Inada 1960. From the SPT-n value, strength parameters cohesion and angle of friction were estimated using correlations by Karol (1960) and Peck et al. (1974) respectively.

11.3 Slope stability analysis

In the slope stability analysis of rice terraces, critical parameters such as cohesion, adhesion, unit weight, and terrace geometry were incorporated as crucial inputs. The analysis employed the Limit Equilibrium Method (LEM), prioritizing this method due to its focus on measuring stability, thus allowing for an exploration of the implications of geogrid reinforcement. Specifically, the Janbu method was chosen as the preferred LEM for its versatility, accommodating various slip surface shapes. This selection is especially relevant given the observed variability on-site, where slip surfaces ranged from slope failure to toe failure, encompassing both rotational and non-rotational scenarios. To account for the inherent variability in the data, a probabilistic approach was additionally adopted, recognizing and addressing the data's distributional characteristics. The analysis was aided by SLIDE 2 Rocscience software.

11.4 Site visits and Direct observation

Monitoring of Construction activities were inherent to pilot-testing of the optimized design of geogrid reinforcement on the rice terraces. This should include appropriate execution according to typical construction methods in the installation of geogrid reinforcements. However, challenges in the construction were anticipated because of the unique landscape of the rice terraces. In addition, the productivity rate based on estimation was yet to be validated. Hence, the study incorporated documentation and recording of what were observed on the site visits.

11.5 Quantity surveying analysis

Cost engineering was carried out using the measured scope of rice terraces restoration. This shall be in terms of the unit area which shall include manual hauling, excavation, dry riprap, filling and tamping and installation of geogrid reinforcement. The cost engineering had facilitated comparative cost of rice terraces restoration with geogrid reinforcement and that of without geogrid reinforcement.

11.6 Cost Benefit Analysis

Given the estimated engineering costs for both restoration with geogrid and that of with no geogrid reinforcement, the monetization of cost benefit could be measured through the serviceability of the restoration for both geogrid restoration and the traditional restoration of rice terraces. The study had adopted Cost-Benefit Ratio of the projected serviceability to the estimated cost per square meter of both restoration methods.

This study embarked on an in-depth investigation by employing a variety of soil testing methodologies to acquire critical soil parameters essential for the meticulous preparation of a comprehensive slope stability analysis. Soil testing is an indispensable component of geotechnical engineering, as it enables engineers and researchers to assess the physical and mechanical properties of soil, facilitating the evaluation of its stability under varying conditions. These tests encompass a wide range of techniques, including but not limited to standard penetration tests, triaxial tests, direct shear tests, and cone penetration tests. Each of these methods provides distinct insights into the soil's behavior, including factors such as cohesion, friction angle, moisture content, compaction characteristics, and permeability. The utilization of a diverse set of soil testing procedures ensures a holistic understanding of the soil's properties, thereby enhancing the accuracy and reliability of the subsequent slope stability analysis. Furthermore, such comprehensive data empowers engineers to make informed decisions when designing structures or implementing remedial measures to mitigate potential slope failures, which can have significant environmental, economic, and safety implications.

12. RESULTS AND DISCUSSION:

12.1 Test point locations

Figure 4 depicts the precise locations of the test points where the Swedish Weight Sounding Test (SWST) was conducted, resulting in a collection of 37 samples. Notably, the test points are strategically distributed across eight distinct elevations and are organized into groups based on these levels. Additionally, the figure highlights the collapsed area, estimated to cover 2619 square meters. This collapse has induced a noticeable alteration in the spillway, redirecting its course from the mid-level to the lower level due to the compromised section of the soil.

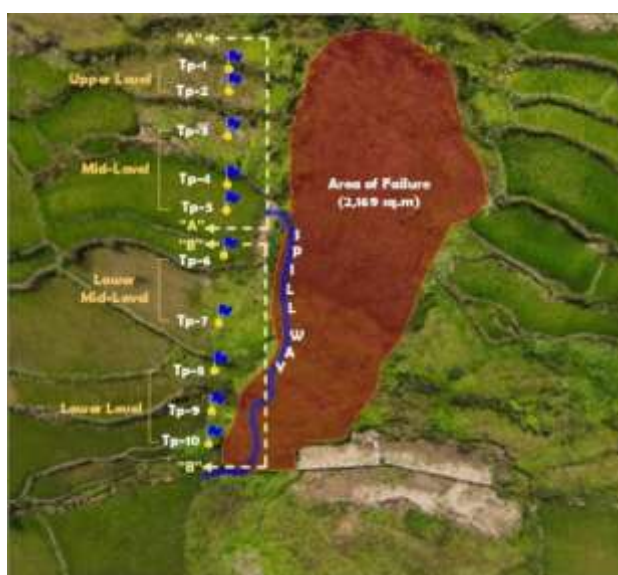


Figure 4: Location of test points adjacent to the failed zone of Rice terraces

12.2 Results of In-situ test using SWST

Upon conduct of SWST on Ten (10) test points, Penetration of the drill rod were evident while the load plates were being loaded in the equipment (figure 5). Hence, no recorded half-turns from the surface layer up to an average depth of 2.20 meters. This suggests loose soils were predominant on this layer. Beyond this layer were much stiffer soils on a depth range of 3 meters to 4 meters. It was noticed from test point 2 that the terminal depth of penetration coincides with the depth without rotation from the surface layer which implied hard material after a loose soil layer.

Testpoints	Depth without rotation from surface layer (m)	Terminal depth of penetration	
		Depth (m)	Average estimated SPT-n value
1	1.5	3.25	10
2	2	3	10
3	2	2	0
4	2	3.25	7
5	1.5	3.5	8
6	2.5	4	5
7	2.75	3	6
8	2.5	3.5	17
9	2.5	4	7
10	2.75	3.75	12
average	2.2	3.325	8.2

Table 1. Summary of SWST depth of penetration with its corresponding estimated SPT-n value

The outcomes of our study, focusing on sandy materials, diverge significantly from those reported by Armario et al. in 2023. In our investigation, the trend of penetration resistance consistently increases with depth within a uniform composition of sandy subsurface material. Conversely, Armario's study depicted an unstable trend, noting higher penetration resistance in the surface layer composed of fine-grained materials with relatively low plasticity. This observation reinforces the understanding that the application of the Inada formula tends to result in conservative values for Standard Penetration Test (SPT-n) in fine-grained materials (Armario, Follosco, Gargullo, Lu, & Luna, 2023).



Figure 5: Photo showing observed penetration where plates were not yet fully in place

12.3 Lithological characteristics, Soil classification and Strength parameters of Rice terraces site

Unit weight and Moisture Content of Rice terraces layers are summarized in table 2. The layers were subdivided into loose and medium layers. The loose layers was characterized by zero N_{sw} whereas penetration occurred without any recorded half-turns. Medium layers is described in this study as the layers with recorded half-turns.

Rice terraces paddies moisture content suggests saturated soils were predominant. Loose layers tend to have the average moisture content at 78.17% maximum value. This layer has also the greater variability compared to the medium layers. There was negligible difference on unit weight of both layers which have minimal variability. Though it can also be noticed from the results that lesser unit weight on the higher moisture content, Unit weight can still be dependent on the compaction of the sub-surface. Results can imply that deeper layer of the site is denser than that of the surface layer.

Table 2: Summary of Lithological Characteristics of Rice Terraces Soil Layers

Layer Type	Depth Range (m)	Moisture Content (%)				Unit Weight (kN/m^3)			
		Avg.	Std. Dev.	Max.	Min.	Avg.	Std. Dev.	Max.	Min.
Loose	0 - 2.75	54.63	11.09	78.17	39.90	16.78	1.13	18.84	14.09
Medium	3 - 4	51.19	7.66	72.16	39.01	17.10	1.22	18.77	14.88

Table 2. Summary of lithological characteristics of Rice terraces soil layers

Results from the Unified Soil Classification System (USCS), as presented in Table 3, indicate a prevalence of coarse-grained materials across all tested points. These materials exhibit low plasticity and show minimal changes in volume in response to variations in moisture content. This characteristic suggests a solid to semi-solid behavior, evidenced by the presence of cracks and fissures during the deformation process.

The majority of soil classifications point towards poorly graded sands with limited fines. Notably, well-graded soils are consistently less prevalent in both loose and medium layers. Additionally, there is an observable increase in the occurrence of poorly graded sands with depth among the test points, indicating a lack of particle size variety in the deeper layers.

Layers	Depth range (m)	Well graded sands (SW)	Poorly graded sands (SP)
Loose layers	0-2.75	7	11
Medium layers	3-4	5	14

Table 3. Results of Unified Soil Classification System

12.4 Estimated Strength Parameters

This study had utilized equation proposed by Inada (1960) to estimate the equivalent SPT-n values of the penetration parameter of the Swedish Weight Sounding Test:

$$N = 2 + 0.067 N_{sw} \quad \rightarrow \text{eq.1}$$

From the estimated values of SPT-n, the researchers came up with range of values of cohesion from the correlations proposed by Karol (1960) while the angle of friction were also estimated through the proposed correlation of Peck et al. (1974):

Soil Conditions	Dense	Medium	Loose
Cohesion (KPa)	48	5.48	5
SPT-n values	>30	10-30	<10

Consistency	SPT-n values	Angle of Friction for sands
Very loose	<4	25 to 30
Loose	4-10	27 to 32
Medium	10-30	35 to 65
Dense	30-50	65 to 85

Interpolating the range of values from the references, the strength parameters are shown in table 4. The loose layers have uniform value of zero N_{sw} meaning penetration of drill rods have occurred even there were no half-turns recorded. Consequently, cohesion and angle of friction have uniform range of values corresponding to a SPT-n value 2 when using equation 1. Cohesion of loose layers could range from 0 to 5 KPa while the angle of friction could range to 25 to 30 degrees.

Layers	Depth range	Cohesion (KPa)				Angle of Friction (degrees)			
		avg	Std dev	max	min	avg	Std dev	Max	Min
Loose layers	0-2.75 meters	-	-	-	-	-	-	-	-
Medium layers	3-4 meters	9.65	10.47	39.40	1.25	29.99	2.997	35.78	25.75

Table 4. Summary of strength parameters of based on N_{sw} to SPT-n parameter

The findings further indicate an augmented shear strength, notably within the deeper layers. The average cohesion in the medium layers aligns with the Medium soil consistency range, while the average angle of friction coincides with the upper limit of very loose consistency. Notably, the data sets for cohesion in

the medium layers exhibit substantial variability, while the sets for the angle of friction show comparatively less variability.

Field observations also point to the presence of cementation in samples extracted from the depth range of the medium layers as shown in figure 4. Despite this cementation, the primary material remains predominantly within the loose to medium sands consistency range. This suggests shear resistance that stabilizes at a consistent value after reaching the failure shear stress, indicative of a noteworthy degree of shear strength.



Figure 4: Photo showing more intact samples on the deeper layers

12.5 Geogrid Reinforced Soil Wall design for Rice terraces

The initial designs were formulated using the AASHTO-ASD method, with a primary focus on stability checks for overturning and sliding. The critical aspect of the design centered around determining the maximum height of the rice paddies. Geogrid E3030L, possessing an ultimate tensile strength of 30 kN/m, was selected as the key geogrid parameter.

In the design process, the calculated vertical reinforcement spacing for the geogrid material was determined to be approximately 0.35 meters, with an embedment length of 2.5 meters. These specifications were established for a structure with a height of approximately 3.2 meters, ensuring optimal stability and performance in accordance with the project requirements.

12.6 Slope stability analysis of Rice terraces

To assess the impact of geogrid reinforcement on rice terraces, a comprehensive slope stability analysis was conducted. Recognizing the inherent uncertainties associated with input parameters, especially those related to the medium layer, a probabilistic approach utilizing Latin Hypercube sampling was employed. This method was chosen for its ability to provide a more uniform coverage of the input space, addressing the need for thorough exploration while working within the constraints of limited computational resources.

The analysis employed the Limit Equilibrium method, utilizing both Janbu's and Bishop's methods. Janbu's method was selected due to its applicability in addressing observed failure slips, ensuring a more accurate representation of the field conditions. Concurrently, Bishop's method was utilized as a cross-verification tool, offering a supplementary check on the analysis results. This dual-method approach enhances the robustness and reliability of the slope stability assessment, contributing to a more comprehensive understanding of the geogrid reinforcement effects on the rice terraces.

The level of susceptibility in this study shall be described according to the range of values in reference (Peckley Jr., Bagtang, & Zarco, 2010):

<i>Factor of Safety</i>	<i>Level of susceptibility</i>
$F_s \geq 1.2$	Stable
$1.0 \leq F_s < 1.2$	Marginally stable
$0.7 \leq F_s < 1.0$:	Susceptible
$F_s < 0.7$	Highly susceptible

Table 5 provides an overview of the case scenarios and their respective results. The findings consistently show that Bishop's method is more conservative than Janbu's method across all scenarios. This is because Janbu's method accounts for pore water pressure. It's essential to highlight that Bishop's method only adheres to vertical and overall moment equilibrium, which sets it apart from Janbu's method, known for satisfying all equilibrium equations. The distinctive approach of Bishop's method has effectively cross-examined the outcomes of Janbu's method, underscoring Janbu's reputation as the most conservative method among similar approaches that fulfill all equilibrium equations (Duncan, 1996).

The examination of the bare slope in Case 1 shows a marginally stable factor of safety when employing a deterministic approach. However, under a probabilistic approach, the slope exhibits a stable factor of safety with an insignificant probability of failure.

In Case 2, the introduction of a water table at the surface renders the bare slope highly susceptible to failure, evidenced by a factor of safety less than 0.7. This configuration, with the water table at the surface, represents the most critical scenario in the analysis, resulting in a probability of failure as high as 89.516%.

Introducing geogrid material to the slope model with 1m vertical spacing and 2.5m embedment length in both Case 1 and Case 2 yields a marginally stable and stable condition, respectively, under a deterministic approach. In a probabilistic context, both cases demonstrate stability with a zero chance of failure, indicating that the specified 1-meter vertical spacing and 2.5m embedment length contribute to overall stability. However, this stability primarily addresses internal stability.

Contrastingly, design calculations utilizing the AASHTO-ASD method recommend a finer vertical spacing of 0.35m to specifically address external stability concerns such as overturning and sliding. Consequently, the researchers decided to test this derived design in Case 5. The analysis revealed a negligible decrease in the factor of safety, indicating that Case 4 and Case 5 exhibit almost identical results for addressing internal stability. This underscores the AASHTO-ASD method's effectiveness in stabilizing the rice terraces, proving its feasibility in addressing both internal and external stability aspects.

Case Scenarios	Brief Description	Global FOS Deterministic		Global FOS Probabilistic	Probability of Failure
		Janbu	Bishop's		
1	Bare slope	1.072	1.016	1.594	0.1%
2	Bare slope with water table on surface	0.433	0.30	0.572	89.516%
3	With geogrid reinforcement: 1m vertical spacing x 2.5m embedment length on case 1	1.733	1.662	2.675	0%
4	With geogrid reinforcement: 1m vertical spacing x 2.5m embedment length on case 2	1.113	1.129	1.68	0%
5	With geogrid reinforcement: 0.35m vertical spacing x 2.5m embedment length on case 2	1.007	1.018	1.579	0%

6	With geogrid reinforcement: 0.4m vertical spacing x 2.5m embedment length on case 2 on 3 rd rice paddy	1.109	1.073	1.899	0%
7	With geogrid reinforcement: 0.4m vertical spacing x 2.5m embedment length on case 2 on 7 th rice paddy	1.14	1.193	1.786	0%
8	With geogrid reinforcement: 0.4m vertical spacing x 3m embedment length on case 2	1.282	1.326	1.915	0%
9	With geogrid reinforcement: 0.4m vertical spacing x 4m embedment length on case 2	1.325	1.32	2.101	0%

Table 5 summary of slope stability analysis of various case scenarios

Recognizing that the global factor of safety remains marginally stable in Case 5, the researchers decided to refine the vertical spacing of reinforcement and simultaneously increase the embedment length, a modification applied to Cases 6, 7, 8, and 9. Notably, in Case 6 and 7, the critical slip failure transitioned from the lower tier paddy to the upper paddy (refer to figures 5 and 6). This observation suggests that reducing the vertical spacing of reinforcement on the critical slip surface may be favorable but could result in the emergence of another critical slip surface. Consequently, both cases failed to bring the factor of safety within the stable range.

However, increasing the embedment length proved effective, ultimately resulting in all global factors of safety exceeding 1.20, as evident in Cases 8 and 9. It is noteworthy that, in these instances, the factor of safety demonstrated a direct proportional relationship with the embedment length.

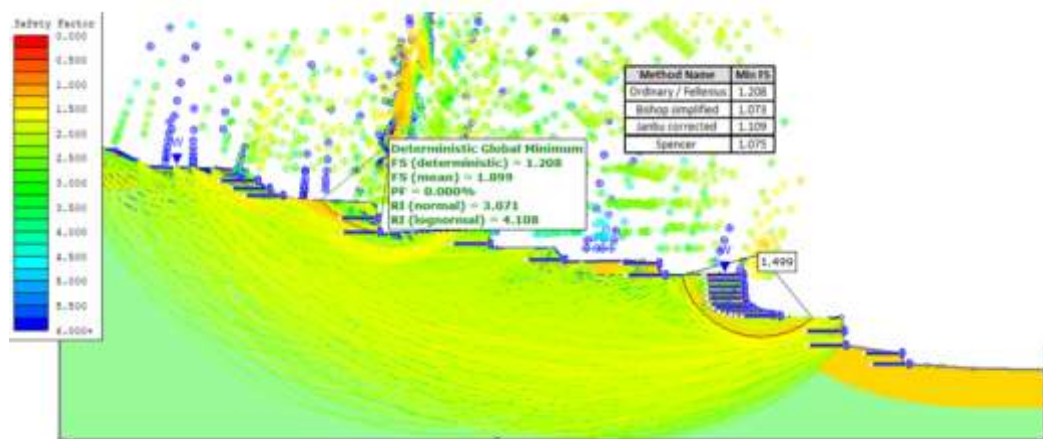


Figure 5. Case 6 shows a

decreased vertical spacing on the third-tier paddy inducing another critical slip surface.

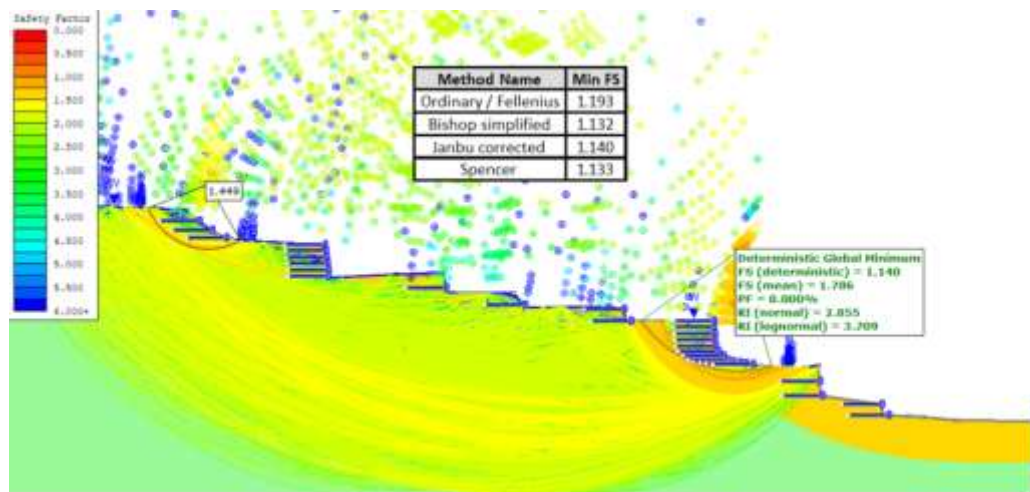


Figure 6. Case 7 shows that an increased vertical spacing on the seventh-tier paddy induced transferring back the critical slip surface on the third-tier paddy.

12.7 Comparative assessment of the Construction requirements in the proposed Rice terraces restoration
 With the above findings, the pilot-testing of the proposed restoration for rice terraces were carried out using design derived from AASHTO-ASD method. The construction coverage included 3 paddies of various heights and length. Table 6 summarizes the dimensional requirements of the proposed restoration for Rice terraces using geogrid E3030L.

Section ID	Height (m)	Width (m)	Length (m)	No. of layers
RT-1	1.9	2.5	20	6
RT-A	3.1	2.55	19.4	9
RT-B	2.80	2.5	6.8	8

Table 6. Dimensional requirements of the rice terraces to be restored

The RT-A section, located at the lowest level of paddies, stood as the tallest and assumed paramount importance due to its strategic position. It emerged as the most pressing area for restoration, as the failure in this section had severely disrupted the primary access routes for local communities. Adjacent to RT-A, the RT-1 and RT-B sections constituted the upper-level paddies. These sections played a critical role in impeding the further migration of landslide debris from the compromised upper portion of the rice terraces. To address these challenges comprehensively, the researchers determined that initiating the restoration process at the lowest point of the failed rice terraces, specifically in RT-A, would establish a foundational barrier, effectively safeguarding the upper levels.

Table 7 provides a concise overview of the construction requirements for each work item in the proposed restoration of rice terraces. These requirements encompass fundamental tools, manual materials, and portable equipment. Notably, the use of light to heavy equipment is not feasible at the rice terraces site due to accessibility constraints and the potential for detrimental effects on the landscape. As a result, the equipment requirements are minimal, with the plate compactor being the only applicable tool that can be easily transported to the site.

	Manpower requirement		Estimated duration
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Item of Works	Labor		Productivity per mandays (MD)	Materials, Tools and Equipment	With geogrid	Traditional
Manual Hauling	Laborers	6	Boulders - 0.5 m ³ Gravel - 0.3 m ³ Geogrid - 1 roll N. pegs - 30 pcs	Safety gloves Hard hats Safety shoes 4 gals pails	19 days	17 days
Excavation	Foreman Laborers	1 6	1 m ³	Shovel Wheel barrow 4 gals pails	42 days	22 days
Gravel Bedding	Foreman Laborers	1 4	1.2 m ³	Shovel Wheel barrow 4 gals pails	1 day	1 day
Backfilling & Compaction	Foreman Laborers	1 12	1.25 m ³	Plate compactor	15 days	5 days
Dry Riprap	Foreman Skilled labor Laborers	1 2 6	0.75 m ³	Boulders Minor tools	8 days	8 days
Geogrid	Foreman Skilled labor Laborers	1 2 5	50 m ²	EGrid3030L extruded Minor tools	2 days	-
TOTAL					87 days	53 days

Table 7. Summary of Construction requirements and estimated duration

In terms of the scope of work, a key distinction between the conventional restoration of rice terraces and the approach involving geogrid reinforcement lies in the inclusion of the geogrid installation item, a reduction in the quantity of excavation, and a decrease in the volume of backfilling and compaction. This deviation is primarily attributed to the additional requirement for embedding the geogrid material. The incorporation of geogrid into the restoration process extends the construction duration by approximately 164% compared to the duration of traditional restoration methods. Records indicate that, aligning with the adopted productivity rate in this study relative to the estimated duration, the project was completed as planned. It's noteworthy that the deficiency in manpower was particularly evident in the backfilling and compaction item.

Throughout the construction, a workforce of 6-8 personnel was allocated across all work items. This indicates that the productivity rate employed in the study remains feasible, with an acceptable margin for variance. The successful completion of the project underscores the adaptability of the chosen productivity rate, taking into account the specific challenges associated with manpower allocation in the backfilling and compaction tasks.

12.8 Construction challenges in the proposed Rice terraces restoration

The construction of the envisioned rice terraces was strategically planned to be carried out by leveraging the skills and experiences of local labor in the communities. The rationale behind this approach was the belief that the locals inherently possess the necessary expertise in restoring their rice paddies.

Simultaneously, the construction project was envisioned as an opportunity for them to assimilate geogrid reinforcements into their traditional methods of rice terrace restoration.

However, the engagement of local labor faced challenges, as only a limited number of workers could be invited to participate. The few available local laborers were already occupied with the restoration of their own paddies, rendering their involvement in the project difficult. Consequently, the construction had to proceed with laborers possessing similar experiences but hailing from a neighboring province adjacent to the study site. Despite the logistical adjustments, the project aimed to benefit from the collective knowledge and skills of these laborers, ensuring the successful integration of geogrid reinforcements into the restoration process.

The initial phase of staking and layout required meticulous attention, and this crucial step unfolded in the presence of the landowner at the study site. To ensure the precise demarcation of boundaries, benchmark boulders were strategically positioned along the edge-to-edge boundaries of the wall paddies. The involvement of the landowner contributed to the accuracy and alignment essential for subsequent construction stages.

An interesting observation emerged during the excavation phase, highlighting the impracticality of conducting excavation across the entire construction area in one continuous operation. This approach led to the unforeseen collapse of upper debris. In response, local insights prompted a strategic adjustment, suggesting that excavation be executed in smaller strips, typically ranging from 1.5 to 2 meters. This segmented approach minimizes the risk of collapse and enhances the overall stability of the construction process.

In addition to strip excavation, the construction team proactively considered the deployment of wooden logs as barriers. These logs had effectively functioned as a protective measure, retaining loose soils above the excavation site, as illustrated in figure 7.



Figure 7. Placement of wooden logs to avoid further erosion of the debris

A notable hurdle in the foundation preparation phase was the need for effective dewatering and removal of loose soils. The excavation activities unequivocally verified the existence of loose soils in the sub-surface. Compounding this challenge, the persistent downward flow of the spillway resulted in the accumulation of water in the lower paddies, as illustrated in Figure 8.

To counteract this issue, a strategic solution was implemented involving the piling of debris. This method served as a protective barrier, staunchly preventing any additional water intrusion into the excavation site. The deployment of debris as a barrier successfully addressed the challenge posed by water accumulation, ensuring a more controlled and conducive environment for subsequent stages of foundation preparation.



Figure 8. Excavation and dewatering process in the wall foundation preparation

The process of placing backfill involves working in layers, and each layer is carefully compacted to prevent any harm to the riprap wall (see figure 9). The compaction is done parallel to the facing panels of the wall. To assess the level of compaction achieved in the field, a Field Density Test (FDT) was conducted, as depicted in Figure 10. The aim is to ensure that the soil or backfill material is compacted sufficiently, providing stability and preventing settling over time. Typically, a common minimum compaction requirement is set around 95 for loose sands.

However, achieving proper compaction has been a challenge during construction. Table 1 illustrates that compaction on the geogrid layers reached only about 81%. It was also observed that the moisture content was within an acceptable range, indicating that loose soils had already been removed.



Figure 9. Geogrid placement in compacted layers



Figure 10. Conduct of FDT on the compacted layers of rice terraces

Section ID	Moisture Content	Relative Compaction
RT-1	31	76.15%
RT-A	25	81%
RT-B	25	80.27%

Table 8. FDT test result of the restored rice terraces at Maligcong.

13.8 Construction cost

The construction cost outlined in this study incorporates a 5% tax and a 20% mark-up. Prices for materials and labor rates were determined using local pricing standards and prevailing rates within the locality. Angular boulders were treated as a paid item on-site, while filling materials, which can be sourced on-site, were not accounted for as paid items.

Item of work	Percentage of expenses	
	With Geogrid	Traditional
Manual Hauling	12.18%	25.82%
Excavation	27.46%	18.81%
Gravel Bedding	0.59%	1.57%
Backfilling & Compaction	20.42%	13.83%
Dry Riprap	16.52%	39.96%
Geogrid	22.83%	-
Total	100%	100%

Table 9. Breakdown of percentage spent per item of work on geogrid reinforced restoration and that of the traditional.

As illustrated in Table 9, the predominant expenses in geogrid-reinforced restoration are primarily associated with excavation. The necessity for additional embedment length linked to the geogrid has led to prolonged excavation activities on-site. Furthermore, the presence of embedment length has elevated the Backfilling and Compaction item to the third position in terms of expenditure percentages. The second-highest expense is attributed to the Geogrid item, with costs dependent on the area coverage of the rice terraces slated for restoration.

Contrastingly, in the context of traditional rice terrace restoration, the top-ranking expense is allocated to the installation of dry riprap. In the absence of the geogrid component in traditional restoration, Dry riprap emerges as the costliest item. Following closely is the Manual hauling item, driven by a significant reduction in the quantities of Excavation as well as Backfilling and Compaction. Importantly, there is no longer a need for an extended area to accommodate embedment length of geogrid in this scenario. In order to address the price disparity between the proposed restoration of rice terraces using geogrid and the traditional restoration method, a cost comparison was conducted. To enable a straightforward comparison of both methods, the land area slated for restoration, measured in square meters, was adopted as a common denominator for calculating costs. Table 10 presents a price difference of php 474.21 per square meter between the proposed rice terraces restoration and the traditional one.

Rice terraces restoration method	Price per sq.m. in Philippine peso
With geogrid reinforcements(proposed)	893.46
Traditional	419.25

Table 10. Price per square meter of both Rice terraces restoration methods

12.9 Cost-Benefit Analysis (CBA)

In conducting a straightforward cost-benefit analysis, the researchers meticulously compared the costs and serviceability of both the traditional restoration method and the geogrid restoration method. The primary aim was to discern which approach strikes a more favorable balance between initial costs and the anticipated years of serviceability.

The assumed serviceability for geogrid mechanically stabilized earth walls is set at 35 years, as indicated in the study by Leshchinsky et al. (2020). This value served as a foundational parameter in the cost-benefit analysis conducted by the researchers.

In the absence of specific studies addressing the serviceability of traditional rice terraces, the researchers drew insights from the notion that the observed intensified damage to the rice terraces could be linked to shifts in local values, as suggested by (Guimbat & Baguilat Jr, 2006). This implies a historical pattern

of regular repairs to the rice terraces, a supposition reinforced by information gathered through random on-site interviews. Consequently, a conservative estimate of the serviceability of traditional restoration was assumed to be 10 years.

Using the formula of the Cost Benefit Ratio (CBR):

$$\text{CBR} = \text{Total benefits} / \text{Total cost}$$

Where:

$$\text{Total benefits} = \text{Serviceability in years}$$

$$\text{Total cost} = \text{Price per sq.m}$$

The parameters to come up with the monetization of Cost-Benefit was derived and presented in table 11. Comparing the Cost-Benefit Ratios, the geogrid restoration method has a higher ratio, indicating that it is more cost-effective compared to the traditional restoration method.

Rice terraces restoration method	Price per sq.m. in Philippine peso	Seviceability in years	CBR ratio
With geogrid reinforcements(proposed)	893.46	35	.039
Traditional	419.25	10	.024

Table 11. Calculated CBR ratio and CBR parameters of various restoration method

13. CONCLUSION:

The Geogrid reinforcement case study conducted on Maligcong Rice Terraces has provided compelling evidence affirming the feasibility of the proposed restoration approach for rice terraces. The utilization of soil exploration and slope stability analysis played a pivotal role in substantiating these justifications, bolstering the robustness of the findings.

The implementation of the Swedish Weight Sounding Test has proven valuable in identifying loose and medium layers within the sub-surface of the Rice Terraces paddies. However, it is essential to note that the detailed information pertaining to loose layers was constrained to a constant value, limiting the exploration of probabilistic parameters. Notably, given the prevalence of sands across all test points, the trend observed in penetration resistance indicates a direct proportionality to depth.

The examination of subsurface layers has unveiled a uniform presence of saturated soils across all strata. These consist of both Poorly graded sands and Well graded sands, with the latter consistently exhibiting inferior characteristics in all subsurface layers. Notably, the prevalence of poorly-graded sands escalates in the medium layers. Furthermore, the moisture content of rice paddies demonstrates significant variability across the surface layers.

Enhanced shear strength was particularly evident in the deeper layers, showcasing a noteworthy augmentation. The depth profile revealed a transition from loose to medium soil consistency in the loose layers, a transformation likely attributed to the observed soil cementation phenomenon in the field's deeper strata. In the medium layers, there was a discernible variability in Cohesion, while the Angle of Friction exhibited remarkable precision.

In the slope stability analysis, the integration of Bishop's method has proven to supplement Janbu's approach. Bishop's method yielded a more conservative value when assessing the deterministic global factor of safety. In the deterministic approach, the bare slope of the rice terraces appears marginally stable, while in the probabilistic approach, it exhibits stability. However, introducing a water table into the model shifts the scenario to instability, identified as the worst-case scenario.

Incorporating geogrid reinforcements under this worst-case scenario in the slope stability analysis results in a marginally stable factor of safety in the deterministic approach and a stable factor of safety in the probabilistic approach. Remarkably, a 1-meter reinforcement vertical spacing is adequate to achieve a stable factor of safety in the worst-case scenario under this study. Nonetheless, this spacing falls short of meeting the requirements for external stability when examined using the AASHTO-ASD method.

While finer vertical reinforcement spacing may lead to a reduction in factor of safety, an optimized spacing derived from the AASHTO-ASD method could maintain favorable factor of safety under the

probabilistic approach. Adjusting this derived spacing may introduce another critical surface, making it more appropriate to extend the embedment length if the goal is to increase the factor of safety.

In terms of construction requirements and costs, the utilization of light to heavy machinery to streamline construction proved unfeasible at the study site. This limitation necessitated a greater reliance on manual labor for the construction processes. The adopted productivity rates in this study, remained practical, with acceptable allowances evident in the implementation. The primary divergence between the traditional restoration and the proposed restoration, as outlined in this study, lies in the incorporation of the embedment length of the geogrid material. This difference resulted in increased excavation, backfilling, and compaction. Price per area metrics for both restoration methods were derived as part of the comprehensive study.

The construction of the proposed restoration method faced several challenges, notably the availability of local laborers, erosion of debris on the upper paddies, water-related challenges during foundation preparation, and the attainment of proper compaction. To address these challenges, segmental excavation works, the strategic placement of wooden barriers, and the creation of temporary earth barriers were implemented, effectively mitigating the impact of these hindrances.

Ultimately, the Cost-Benefit Analysis of the proposed restoration method hinged on the comprehensive evaluation of total cost and serviceability. The Cost-Benefit Ratio for the proposed restoration of rice terraces surpassed that of the traditional method, substantiating the justification for the adoption of the proposed restoration approach.

14. Recommendation:

Given that detailed information on loose layers was constrained to a constant value, future research should explore and incorporate probabilistic parameters for a more nuanced understanding. This can include conducting additional tests or utilizing other methods to capture the variability within loose layers.

The worst-case scenario in this study can be rationalized by conducting a comprehensive study on the dynamics of water tables in rice terrace environments. This shall enable comprehensive understanding on how seasonal variations, precipitation, and irrigation practices influence water table levels, and integrate this dynamic aspect into the slope stability analysis.

Given the difficulty in achieving higher compaction in saturated sands observed in this study, it is imperative to explore innovative methods that can enhance compaction levels for loose sands.

Furthermore, there is a need to initiate the monitoring of displacement and deformation in the proposed restoration. This exploration will provide valuable insights into the actual performance of the proposed restoration, serving as a foundation for continuous improvements in the design. Such monitoring mechanisms are essential for ensuring the effectiveness and long-term stability of the restoration efforts.

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