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Sustainable Riverbank Protection: Utilization of Coconut Coir And Vetiver Grass For Riverbank Stability With Prediction Using BSTEM

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Abstract: Riverbank erosion is a natural process that can be accelerated by human activities. It can cause abruption to riverbank stability which will lead to several problems, including flooding, sediment pollution, and habitat loss. There are several ways to improve riverbank stability, including using non-structural protection methods such as the utilization of coconut coir mats and vetiver grass. In this study, one of the objectives is to identify the most suitable fibre and vegetation to be used to construct sustainable riverbank protection measures. Through the reviews of past research, the most feasible geotextile for enhancing the stability of the riverbank is the coir fibre. Coconut coir mats are made from the fibres of coconut husks. They are biodegradable and environmentally friendly. They work by providing a physical barrier that protects the soil from erosion by wind and water. They also help to improve the water retention capacity of the soil. Vetiver grass is a deep-rooted grass that is very drought tolerant. It can grow in a variety of soil conditions and is very effective at stabilizing slopes. It also helps to improve the water quality of streams and rivers. A study had been conducted to the evaluation of the performance of using Vetiver grass and coconut coir to improve riverbank stability in a selected location of Sungai Pusu that crossed within IIUM Gombak. Preliminary fieldwork was carried out to install coir mats and Vetiver grass on the selected site. This study also aims to assess riverbank stability using soil testing, riverbank profiling method, and BSTEM simulation. From the data that were collected, the riverbank profiles from all conditions were plotted from the software and generated factor of safety (Fs) values. To evaluate the accuracy, importance, and relevance of the findings, the obtained results from fieldwork set were contrasted and analysed with results from simulation set.

Keywords: Riverbank stability, coconut coir, Vetiver grass, BSTEM, Sungai Pusu

1. Introduction

In the last decades, several approaches to riverbank stabilization structures have been developed to assist in protecting riverbanks and avert the river's lateral migration. These structures help in improving the riverbank's strength and diminish the hydrodynamic forces acting on it. However, the structures of riverbank stabilization available such as riprap, revetments, and retaining walls are hard approaches that were proven to be requiring high costs and have negative environmental impacts [1]. Therefore, immediate actions need to be taken to minimize the rate of riverbank erosion that abrupt riverbank stability through soft approaches by using

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bioengineering methods [2]. The said bioengineering methods that will be given the focus area by using coconut coir and Vetiver grass for bank stabilization. Various types of geotextiles fiber and vegetation were extensively researched, and the results found that coir fiber and Vetiver grass are the most sustainable as riverbank protection in terms of optimizing riverbank stability.

Coconut coir and Vetiver grass have been widely used as non-structural riverbank protection approaches, thanks for their less cost in terms of material (able to be sourced from locals), labor (hand-labor), and once it is put in place, they are able to self-maintain and re-generate once established although it requires several seasons to be developed [3]. In the recent past, both coconut coir and Vetiver grass have been researched to encourage sustainable riverbank protection. Because of their economic values, self-regulating and low labor characteristics, both coconut coir and Vetiver grass have drawn significant research focus for diversity in the application of protecting riverbanks from erosion. For that reason, fieldwork data collection of the riverbank alongside soil testing and the Bank Stability and Toe Erosion Model (BSTEM) simulation had been conducted to investigate the riverbank stability by incorporating the application of coconut coir and Vetiver grass on the riverbanks. The flowchart of this study was shown in Fig. 1 below.

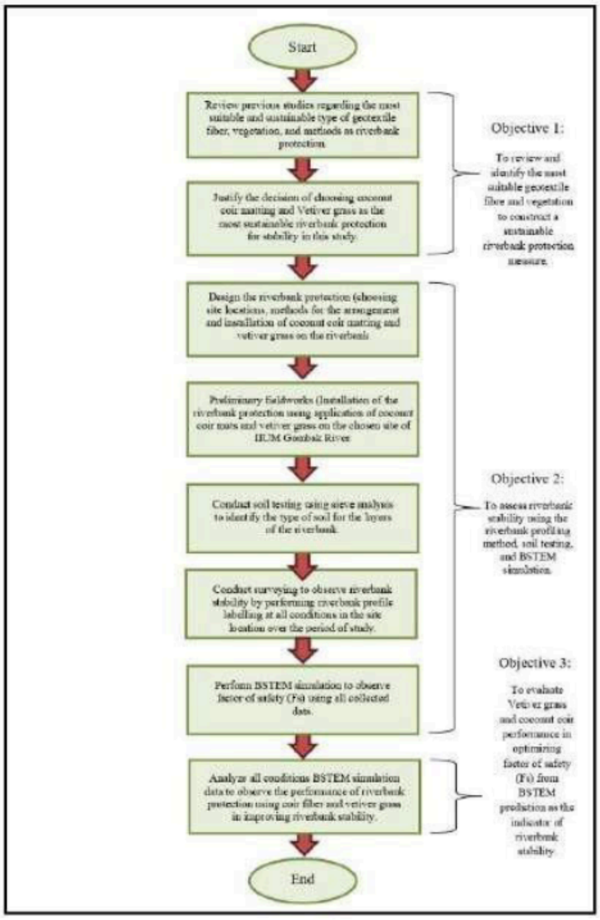


Fig. 1 – Flow chart of the methodology for this study

2. Riverbank Stability

Riverbank instability is the cause of riverbank failure, which a study of riverbank stability with the right parameters able to help to understand better the failure pattern based on the resultant factor of safety (FOS) [4]. The stability of riverbanks is significantly influenced by geometry, soil characteristics including cohesion, angle of friction, and coefficient of permeability. By calculating the factor of safety (FS), which is represented by Eq. 1 below:

$$FS = \frac{c'L + S \tan \text{ø}b[W \cos ß + P \cos(\alpha - ß) - U] \tan \text{ø}'}{W \sin B - P \sin(\alpha - B)}, ß = \frac{1\,(\alpha + \text{ø}')}{2} \quad (1)$$

where c' is effective cohesion, L is length of the failure plane, $ø_b$ is the angle used to determine the rate of increase in shear strength due to increasing matric suction, β is the failure plane angle, α is the angle of riverbank, and ø' is the effective friction angle of the soil.

Table 1 below provides a classification system for assessing the stability of a riverbank based on the Factor of Safety (Fs). The Factor of Safety (Fs) is a numerical value used to evaluate stability of a slope. If Fs value is greater than 1.0, the riverbank is considered stable. If the Fs value is equal to 1.0, the riverbank is in critical state, indicating that it is on the verge of instability and requires immediate attention. If Fs value is less than 1.0, the riverbank is deemed unstable, signifying a high risk of erosion or failure. This classification helps in determining the necessary measures to be taken to protect and stabilize the riverbank.

Table 1 – Determination of riverbank stability [5]

Factor of Safety (Fs)	Condition
> 1.0	Stable
= 1.0	Critical
< 1.0	Unstable

3. Site Investigation

The initial phase of this study area's location and gathering relevant data essential for the research. The study area is situated at IIUM Gombak, and the river in focus is a downstream section of the Sungai Pusu. It is worth noting that Sungai Pusu serves as a significant source of Gombak River, which happens to be the largest watercourse in the Gombak District.

However, upstream of Sungai Pusu as shown in Fig. 2, various detrimental activities such as illegal construction, illegal logging, and illegal farming have been taking place. These activities have had a negative impact on the ecosystem of Sungai Pusu. Furthermore, during the site visits, a thorough assessment of the geomorphological condition of the riverbank was conducted, revealing notable observations of erosion along the riverbank. In Fig. 3, One site location had been observed which are the riverbank in front of the IIUM Cultural Centre (ICC).

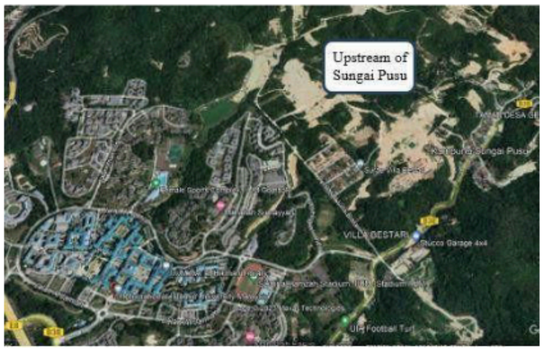


Fig. 2 – The situation of Sungai Pusu's upstream

Fig. 3 – Site location of riverbank in front of ICC IIUM

4. Desk Study

The initial step involves conducting a desk study in Table 2 to enhance comprehension regarding the utilization of sustainable materials for protecting riverbanks against erosion. It entails examining and analyzing research papers, case studies, textbooks, and government guidelines related to riverbank erosion, as well as exploring potential solution approaches. It is essential to identify a specific approach for creating sustainable protection measures for riverbanks during this stage, as it serves as a prerequisite for progressing to the subsequent stage.

Table 2 - Summary of application of coconut coir, Vetiver grass and applications of both geotextile and vegetation by past researchers.

Experimental Setup	Authors	Country	Methods	Results
Application of Coconut Coir	Balan et. al. (2015)	Kerala, India	Focus on land slopes and choose certain plots (fieldwork). Use coir geotextile mesh. The plots were divided into control plot (CP), coir geotextile alone (CG), and coir geotextile planted with pineapple crop (CGC).	The moisture content of CGC was shown to be about double that of CP.
	Basu et al. (2019)	Kolkata, India	Observe slope of the embankment where it is installed with a coconut fibre-based geotextile net.	The usage of geotextile net significantly lessens the erosion rate impact and decreases indentation depth from 9.0 to 5.1 cm. Knotted geotextile net was more efficient than woven one.
Application of Vetiver Grass	Aziz and Islam (2023)	Dhaka, Bangladesh	Develop several models to simulate hilly terrain and conduct experiments to evaluate the effectiveness of vetiver plants in preventing soil erosion. Among the models, four had vetiver plants, while the remaining model served as a control with no vegetation. One model has both jute geotextiles.	When compared to bare soil, vetiver was able to lower the burden of erosion by almost 94%–97% for sandy silt. The solution that included vetiver grass and jute geotextile was the most successful at minimising erosion. Compared to bare soil, vegetation decreased cumulative runoff by 21% and improved infiltration by 19% for sandy silt.
	Badhon et. al (2021)	India	Study the influence of vetiver grass roots on shear strength of soil-roots matrix. The study used four different soil types (Pubail clay, Dredged sand, Buriganga clay and Sylhet sand). The soil samples are tested for its composition (grain size distribution, specific gravity, moisture content and Atterberg limits)	It was found that shear strength has increased by up to 50%. Increase in safety analysis factor of up to 20.6%.
Application of Both Geotextile and Vegetation	Gaviola et al. (2020)	Philippines	Investigated using a factorial experimental design in a Completely Randomized Design (CRD) to study the effects of coconut fibre geotextiles and grass cover on soil surface and vegetation. The experiment involved three levels of treatment for the geotextiles and two levels of treatment for grass cover, resulting in six combinations plus a control setup with no geotextile or grass cover.	Between planted and unplanted plots, there is a noticeable variation in the rate of soil erosion. Vetiver grass may prevent up to 56% of all soil erosion by effectively strengthening the soil to reduce erosion. 0.5x0.5inch eye-opening geotextiles may prevent up to 65% of soil erosion, 1.0x1.0inch eye-opening geotextiles can prevent up to 49% of soil erosion, and 1.5x1.5inch eye-opening geotextiles can prevent up to 40% of soil erosion.
	Cereno et al. (2009)	Philippines	Investigated the effectiveness of using a combination of hydroseeding and coco-nets in slope protection. The study involved constructing test boxes with a 65-degree slope and a surface area of 106 cm by 63 cm.	The combined use of hydroseeding and coconuts prevented erosion problems in the test specimens.

5. Decision-Making In Selecting Riverbank Protection Measure

This study specifically focuses on the non-structural approach, which incorporates sustainable features and emphasizes minimal alteration to the natural riverbank structure, while considering environmental factors and utilizing organic materials. Among the available options, several techniques have been identified as potential sustainable protection measures: the variation of cellulose fiber for soil erosion mitigation and the utilization of Vetiver grass.

Based on the findings, it can be concluded that the application of coconut coir is a more viable choice compared to jute, kenaf, oil palm empty fruit bunch (OPEFB), sisal, hemp, bagasse, wood, and straw fibres. Coir fibre shows outstanding advantages with none to fewer detriments for soil erosion management compared with other types of fibres. The durability, inherent strength, porosity, hygroscopicity, and biodegradability of coconut fibre make it a popular choice [6].

The selection of Vetiver grass with coconut coir matting is influenced by various factors, including its deep and dense root, climate adaptability, and material cost [7]. Vetiver grass is commercially used in various industries in Malaysia and is relatively affordable. Additionally, both materials require minimal maintenance as they are known for their strength and ability to withstand extreme conditions such as drought and flood.

6. Preliminary Fieldworks

6.1 Installation of Coir Mat and Vetiver Grass on Riverbank

Fig. 4 – Step by step of the installation of sustainable riverbank protection

Fig. 4 illustrated a series of steps to install the coir mat and Vetiver grass on riverbank as protection. Initially, the state of the riverbank failure is assessed to understand the extent and severity of the erosion. This evaluation is critical for planning the subsequent interventions effectively. Following the assessment, the identified area of the affected riverbank is cleared of vegetation and debris to prepare its surface for the installation. This step ensures a stable base for the following measures and eliminate obstacles that could hinder stabilization efforts.

The next stage involves cutting coir mat to the desired dimensions. Once prepared, the coir mat is carefully laid on the exposed riverbank. This layer acts as a protective barrier, preventing soil displacement while facilitating the establishment of Vetiver grass. The subsequent step involves planting Vetiver grass through the coir mat. The grass is planted in a systemic manner to ensure uniform coverage and maximize its soil-stabilizing potential. Finally, the planted Vetiver grass is watered to encourage root development and growth. This process demonstrates an integrated approach towards riverbank stabilization, combining reinforcements through coir mats with ecological benefits of Vetiver grass.

7. Testing

7.1 Sieve Analysis Test

For this study, the test was conducted according to the British Standard 410 (BS410). To ensure the soil is in a dry state, the soil samples underwent a drying process using a dry oven. This was necessary because the soil samples were collected from an area near a river, where the soil was saturated. The BS410 standard requires sieves ranging from No. 4 to No. 200, as well as a mechanical sieve shaker. Lastly, the amount of soil retained in each sieve was weighed to an accuracy of 0.1% of its total mass.

7.2 Surveying for Riverbank Profiling

Manual surveying was done by using steel levelling staff and measuring tape, accompanied with riverbank profile labelling to observe its stations and elevations clearly. Using the equipment and method mentioned just now, the cross-section profile of the riverbank to observe the net change of the width and depth of the riverbank and provide insight into the process of erosion and stability of the riverbank happening on the section chosen. The data obtained from the fieldwork will be presented in the form of graphs to exhibit the stability of the riverbank against time for all conditions. For the flow parameters, it was measured using a flow meter device.

7.3 BSTEM Simulation for Riverbank Stability Analysis

BSTEM (Bank Stability and Toe Erosion Model), which was developed by the National Sediment Laboratory of the United States [8]. The primary objective of BSTEM is to evaluate the impact of hydraulic erosion on the existing bank profile, particularly at the bank toe. By employing the derived profile, the model assesses the stability of the eroding bank through simulations. It considers various factors such as water-table elevation, stage tension fractures, vegetation, and toe protection. Two models, namely the bank stability model and the bank toe erosion model, are available for analysis.

If the factor of safety (Fs) exceeds 1.3, the bank is considered stable, as it provides a safety margin for uncertain or changing data. Banks with Fs values between 1.0 and 1.3 are deemed "hypothetically stable" but with limited room for error. Slopes with Fs values below 1.0 are classified as unstable.

8. Result and Discussion

8.1 Visual Inspection Analysis

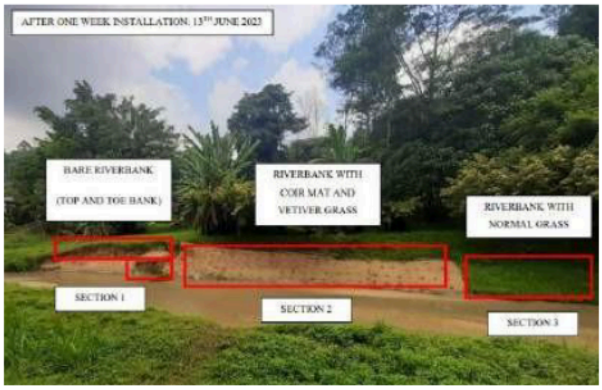


Fig. 5 – Variations in section conditions

The visual inspection evaluation from Fig. 5 reveals that section of riverbank incorporating Vetiver grass with coir mat yield superior outcomes compared to other conditions. In these instances, Vetiver grass itself provides robust support to the riverbank, while coconut coir supplies essential nutrients effectively. The assessment demonstrates that despite some vegetation being washed away by the river flow, coconut coir aids in the growth of Vetiver grass. Additionally, the use of coconut coir has been proven to promote the root development of Vetiver grass, as evident as in the observation on the vegetation roots on all conditions below [9].

Eq. (2) below calculates the cohesion due to roots (Cr) in the soil:

$$Cr = \frac{1}{A}\sum_{n=1}^{n-N}(A_r T_r)_n[\sin(90-\xi) + \cos(90-\xi)\tan\phi'],$$
$$\text{where } \xi = \tan^{-1}\left(\frac{1}{\tan\theta + \cot x}\right) \quad (2)$$

Cr represents the additional strength provided by the roots in the soil, measured in kPa. Tr is the tensile strength of roots (kPa), indicating their strength in tension. Ar is the area of roots in the plane of the shear surface, representing the cross-sectional area of roots intersecting the shear plane. Ø' is the friction angle of soil (degrees), showing the internal friction and resistance to shear stress. N is the total number of roots crossing the shear plane, and n refers to each individual root in the summation. A is the area of the shear plane over which shear stress acts. The equation also includes a derived angle ξ where Θ is the angle of shear distortion (degrees), describing soil deformation, and X is the initial orientation angle of fibre relative to the failure plane (degrees), describing root orientation relative to the failure plane.

Table 3 - The measurement of vegetation roots length and cohesion due to roots, Cr values for all condition during the period of the study

Conditions	Data results taken	Measurement of vegetation roots (cm)	Cohesion due to roots (kPa)
Bare riverbank	13/6/2023	0.0	0.0
	27/10/2023	0.0	0.0
	13/11/2023	0.0	0.0

Riverbank with normal grass	13/6/2023	4.0	1.4
	27/10/2023	4.0	1.4
	13/11/2023	4.0	1.5
Riverbank with coir mat and Vetiver grass	13/6/2023	5.0	0.5
	27/10/2023	8.0	1.5
	13/11/2023	10.0	3.0

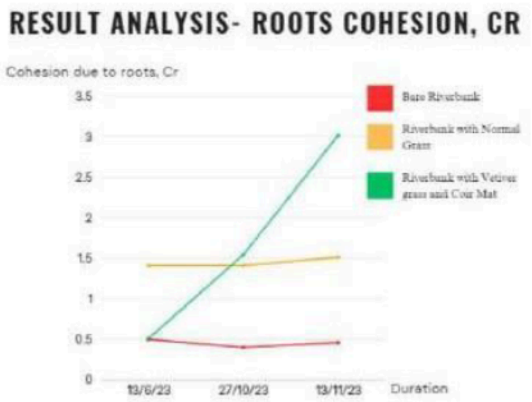


Fig. 6 - Line graph depicting the trend of cohesion due to roots, Cr against duration for all conditions

After the calculation of Cr for all conditions in Table 3, graph in Fig. 6 shows vegetation plays a crucial role in riverbank stability. Roots act as anchors, bind soil particles, and filter water, protecting against erosion. Lack of vegetation weakens banks and leads to collapse. Normal grass, though less effective than specialized plants, still contributes significantly. Its roots stabilize soil and absorb rainwater. Conserving existing grass is important. Vetiver grass, when its rapid growth and deep roots, is a powerful weapon against erosion. Biodegradable coir mats can initially support Vetiver's establishment by minimizing erosion and providing a moist environment. Nature-based solution, combining native vegetation and biodegradable materials, offer a sustainable and effective way to protect riverbanks [10].

8.2 Bank Stability and Erosion Model (BSTEM) Simulation

As been observed during the fieldwork monitoring, all conditions undergo different rate of erosion as represented in the BSTEM model and produced a predicted result of Factor of Safety (Fs) values. Additionally, in BSTEM calculations, the riverbank is considered unstable when Fs value is less than 1.0, conditionally stable when Fs value is between 1.0 and 1.3 and is considered stable when Fs is more than 1.3. Figure below shows the comparison of results for all conditions throughout the period of study. Meanwhile, table below shows the Bank Stability Model and Toe Erosion Model's summary output with Fs values for all the riverbank condition tested. Utilizing the limit equilibrium method, the BSTEM model calculates the safety factor (Fs) for bank stability through several approaches including the horizontal layer method, the vertical slice method, and the cantilever shear collapse method [11]. The primary formula for computing the safety factor is as in Eq. 3:

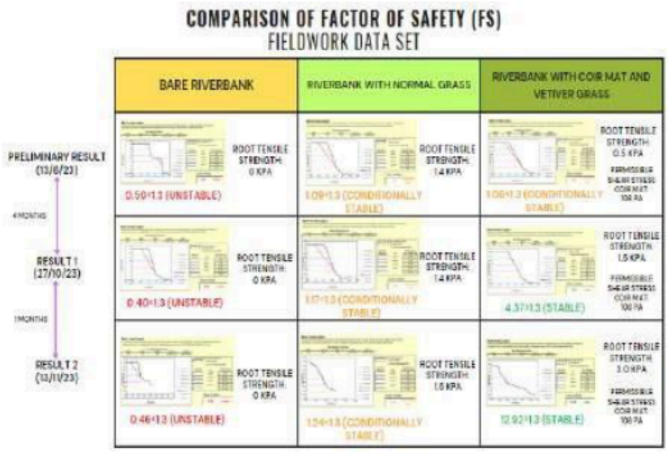
$$F_s = \sum_{i=1}^{I} \left(c_i' L_i + (\mu_a - \mu_w)_i L_i \tan\varphi_i^b + [W_i \cos\beta - \mu_{ai} L_i + P_i \cos(\alpha - \beta)] \tan\varphi_i'\right) / \sum_{i=1}^{I} \left(W_i \sin\beta - P_i \sin[\alpha - \beta]\right) \quad (3)$$

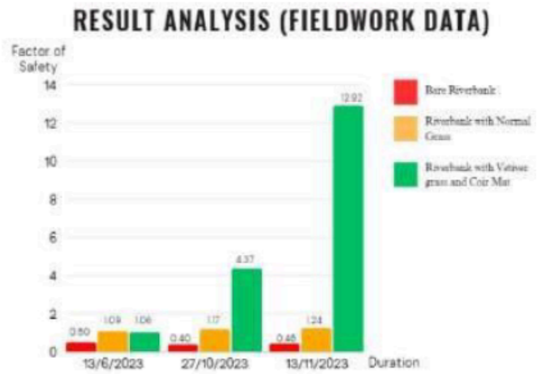
where Li is the length of the failure plane integrated into the i-th layer (m), Wi is the weight of the ith layer (kN), and ci′ is the effective cohesion of the ith layer (kPa); b = failure-plane angle (degrees from horizontal); a = local bank angle (degrees from horizontal); I = number of layers; and Pi = hydro-static-confining force owing to external water level (kN/m) operating on the i-th layer.

The value of Factor of Safety (Fs) demonstrated the stability level of each section of riverbank, also indicating the efficiency of the chosen approach of the application of Vetiver grass and coconut coir as sustainable riverbank protection. Their effectiveness is illustrated through the percentage difference of initial and final Fs values. In this scenario, evaluating the efficiency of different conditions involves comparing the percentage difference between Fs values of bare riverbank, riverbank with normal grass and riverbank with Vetiver grass for fieldwork data and other conditions for simulation data. The higher the percentage difference, the higher the Fs values thus stability of the riverbank will increase and vice versa.

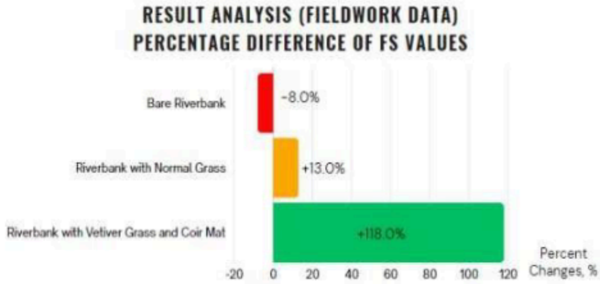
8.2.1 BSTEM Output for Fieldwork Results

Table 4 - Comparison of Factor of Safety (Fs) for fieldwork data set.





(a)



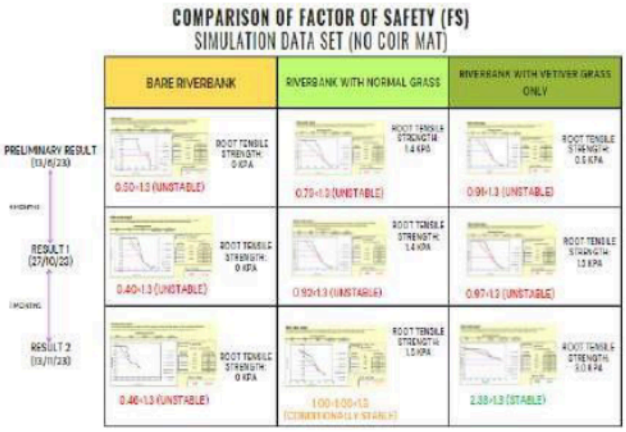
(b)

Fig. 7 – (a) Factor of Safety (Fs) for all conditions of fieldwork (b) Percentage differences of Fs values for fieldwork data.

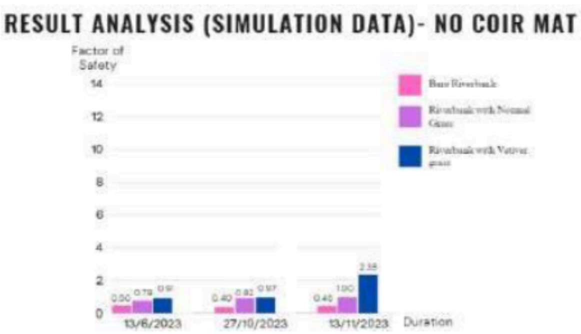
Table 4 summarizes the results of Factor of Safety values for all conditions throughout the observed period for fieldwork data. Fig. 7(a) and Fig. 7(b) analysed the effectiveness of different treatments against riverbank erosion. While all banks experienced declining stability over time, the bare bank (-8.0%) and normal grass riverbank (+13.0%) showed gradual to moderate decreases. The clear winner was the riverbank reinforced with Vetiver grass and coir mat (+118.0%), which despite starting with the lowest stability, rapidly improved, showcasing superior long-term erosion resistance. This combination is the most effective mitigation measure based on its remarkable ability to quickly increase bank stability against erosion.

8.2.2 **BSTEM Output for Simulation Results**

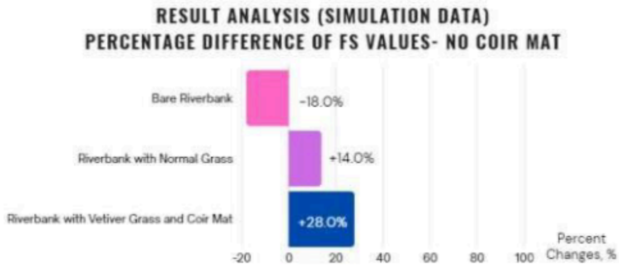
Table 5 - Comparison of Factor of Safety (Fs) for simulation data set- no coir mat.


COMPARISON OF FACTOR OF SAFETY (FS)
SIMULATION DATA SET (NO COIR MAT)

	BARE RIVERBANK	RIVERBANK WITH NORMAL GRASS	RIVERBANK WITH VETIVER GRASS ONLY
PRELIMINARY RESULT (13/6/23)	ROOT TENSILE STRENGTH: 0 KPA 0.50<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.4 KPA 0.70<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 0.5 KPA 0.91<1.3 (UNSTABLE)
RESULT 1 (27/10/23)	ROOT TENSILE STRENGTH: 0 KPA 0.40<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.4 KPA 0.92<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.5 KPA 0.97<1.3 (UNSTABLE)
RESULT 2 (13/11/23)	ROOT TENSILE STRENGTH: 0 KPA 0.46<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.5 KPA 1.00<1.00<1.3 (CONDITIONALLY STABLE)	ROOT TENSILE STRENGTH: 3.0 KPA 2.38>1.3 (STABLE)



(a)

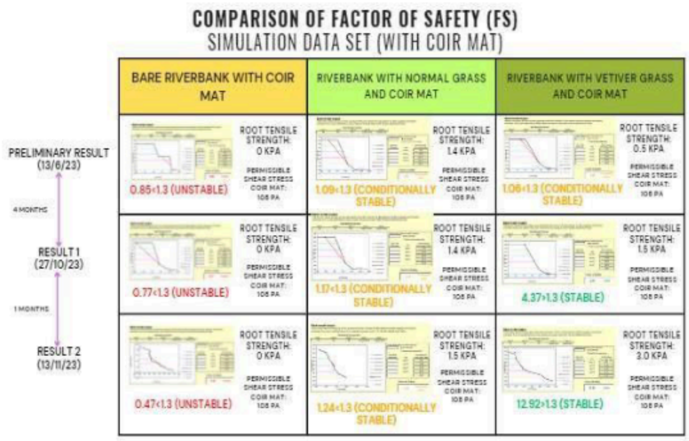


(b)

Fig. 8 - (a) Factor of Safety (Fs) for all conditions of simulations with no coir mat (b) Percentage differences of Fs values for simulations data with no coir mat.

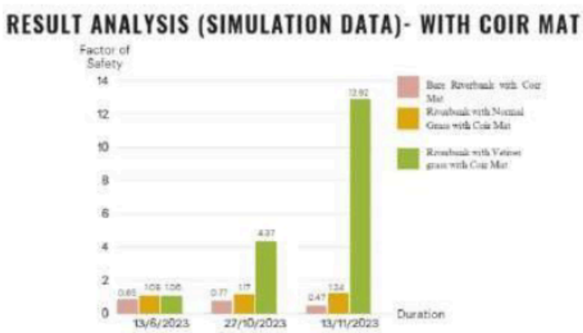
Without coir mat, the simulations from Table 5 exposed the true effectiveness of vegetation in riverbank stabilization. Fig. 8(a) and Fig. 8(b) shows that while bare soil predictably eroded (-18% Fs), normal grass offered minimal improvement (+14% Fs). However, Vetiver grass alone could reach a higher effectiveness than other conditions. Despite a low initial factor of safety, it achieved a phenomenal +28% increase, proving its superiority in erosion resistance, even without coir mat reinforcement. But its effectiveness is relatively low due to the absence of supporting role of coconut coir Thus, Vetiver grass emerges as the champion, conquering its starting disadvantage without coir mat to achieve outstanding long-term stability against water pressure.

Table 6 - Comparison of Factor of Safety (Fs) for simulation data set- with coir mat.

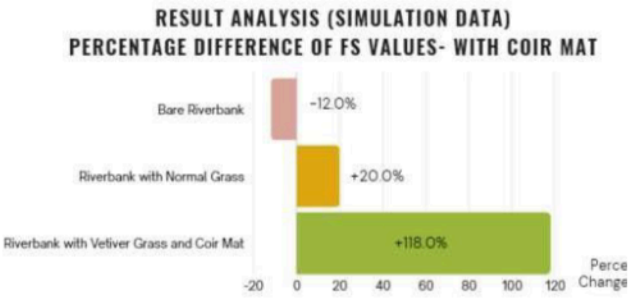

COMPARISON OF FACTOR OF SAFETY (FS)
SIMULATION DATA SET (WITH COIR MAT)

	BARE RIVERBANK WITH COIR MAT	RIVERBANK WITH NORMAL GRASS AND COIR MAT	RIVERBANK WITH VETIVER GRASS AND COIR MAT
PRELIMINARY RESULT (13/6/23)	ROOT TENSILE STRENGTH: 0 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 0.85<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.4 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 1.09<1.3 (CONDITIONALLY STABLE)	ROOT TENSILE STRENGTH: 0.5 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 1.06<1.3 (CONDITIONALLY STABLE)
RESULT 1 (27/10/23)	ROOT TENSILE STRENGTH: 0 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 0.77<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.4 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 1.17<1.3 (CONDITIONALLY STABLE)	ROOT TENSILE STRENGTH: 1.5 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 4.37>1.3 (STABLE)
RESULT 2 (13/11/23)	ROOT TENSILE STRENGTH: 0 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 0.47<1.3 (UNSTABLE)	ROOT TENSILE STRENGTH: 1.5 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 1.24<1.3 (CONDITIONALLY STABLE)	ROOT TENSILE STRENGTH: 3.0 KPA PERMISSIBLE SHEAR STRESS COIR MAT: 108 PA 12.92>1.3 (STABLE)

4 MONTHS
1 MONTHS



(a)



(b)

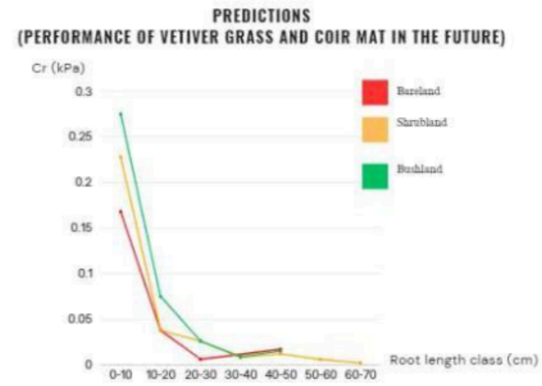
Fig. 9 - (a) Factor of Safety (Fs) for all conditions of simulations with no coir mat (b) Percentage differences of Fs values for simulations data with no coir mat.

Different scenarios were shown in Table 6 against riverbank erosion, highlighting the combined power of Vetiver grass and coir mat. Fig. 9(a) and Fig. 9(b) demonstrates that while bare soil under coir mat still suffers (-12% Fs), a worrying sign, normal grass and coir mat show limited improvement (+20% Fs). The real winner, however, is Vetiver grass and coir mat. Despite starting with a low Fs, this combo delivers a staggering +118% increase, showcasing unmatched stability and erosion resistance. This combination emerges as the champion, overcoming its initial disadvantage to provide superior long-term protection against water pressure. It is not only effective but also a sustainable and potentially cost-effective solution for erosion mitigation.

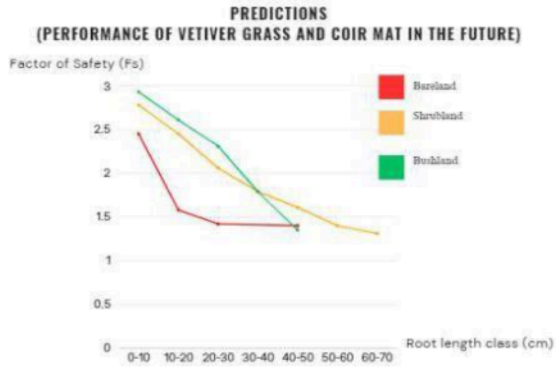
8.3 Bank Prediction on the Performance of Riverbank Protected with Vetiver Grass and Coir Mat in the Future

Table 7 - BSTEM simulations results of Fs values from past study data on Cr values of each Vetiver grass root length class.

Location	Root Length Class (cm)	Cr (kPa)	Fs
	0 to 10	0.168	2.45
	10 to 20	0.038	1.58
Bareland	20 to 30	0.006	1.42
	30 to 40	-	-
	40 to 50	0.017	1.40
	0 to 10	0.228	2.78
	10 to 20	0.038	2.45
	20 to 30	0.026	2.06
Shrubland	30 to 40	0.008	1.79
	40 to 50	0.012	1.61
	50 to 60	0.006	1.40
	60 to 70	0.002	1.31
	0 to 10	0.275	2.93
	10 to 20	0.075	2.61
Bushland	20 to 30	0.026	2.31
	30 to 40	0.009	1.79
	40 to 50	0.015	1.35



(a)



(b)

Fig. 10 – (a) Predictions for cohesion due to roots (Cr) values against root length class (cm). (b) Predictions for Factor of Safety (Fs) against root length class (cm).

From Table 7, the trend summarizes in both Fig. 10(a) and Fig. 10(b) reveals an intriguing relationship between root length class and cohesion due to roots parameters. Cohesive resistance (Cr) tends to decrease with increasing root length. This is because the longer the roots, while penetrating deeper, are less abundant in deeper soil layers, which leads to lower root area ratio. Bushland boasts the highest root area (0.108%), nearly double that of shrubland and 5 times that of bare land. Conversely, the highest tensile resistance is observed in bare land (48.3 MPa), more twice that of bushland and shrubland. Notably, root area ratio contributes significantly more to cohesion resistance that tensile resistance across all land types. For effective soil reinforcement, promoting Vetiver grass's denser root networks in shallower soil layers must be on top priority [12].

9. Conclusion

To be concluded, visual inspection and data analysis reveals the section of riverbank employing Vetiver grass and coir mat outperforms both bare riverbank and riverbank with normal grass. From visual examination, riverbank section with Vetiver grass and coir mat exhibit robust visual evidence of soil stability. Vetiver grass provides primary structural support while coir mat offers additional reinforcement. Analysis of soil composition of the riverbank confirms its suitability for supporting growth and effectiveness of Vetiver grass with coir mat and as input data for BSTEM simulation. The analysis of

BSTEM highlights the combination of Vetiver grass and coir mat as a prominent stabilizing agent through its highest value of Factor of Safety compares with bare riverbank and riverbank with normal grass.

The application of coir mat shows its improvement on all conditions compares to without coir mat, further confirming its supportive role as the best geotextile alongside with vegetation such as Vetiver grass. The prediction using BSTEM simulation shows declining Factor of Safety values as the cohesion resistance by longer class of root length of Vetiver grass supported with coir mat due to its reducing ratio area root. To raise Fs values and preserve the stability of the riverbank, plants such as Vetiver grass with thick and shallow root systems coupled with coir mat as supplementary measures should be promoted to establish a firm foundation for soil in top levels.

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