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Investigation of suitable methods to protect main Roads adjacent to Water bodies

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Abstract

Main roads near water bodies are prone to stability issues caused by erosion from rainfall, river flow, sudden water drawdowns, and human activities. This study examines four sites facing such challenges, identifying erosion causes and evaluating stabilization methods. Techniques such as gabion walls, bamboo crib walls, and vegetated soil bags were explored, balancing cost, constructability, and sustainability. Implemented solutions have shown promising performance, supporting eco-friendly infrastructure initiatives. The findings demonstrate the potential of combining conventional and bioengineering methods for effective slope stabilization. This research contributes to the advancement of sustainable practices for protecting road infrastructure, crucial for future applications in similar geotechnical conditions in Sri Lanka.

Keywords: Bamboo; Bio-slope engineering; Gabion wall; Slope stability; Stream bank erosion

1. Introduction

The stability of roads adjacent to water bodies has been a critical concern in many parts of the world. Roads located near rivers, lakes, and streams are prone to various forms of erosion, including hydraulic erosion caused by natural and human-induced activities. The stability of these road networks is often compromised due to fluctuating water levels, excessive rainfall, and changes in river catchments. Addressing these issues is crucial for ensuring the safety and resilience of the infrastructure, particularly in regions like Sri Lanka, where such roads are integral to transportation.

The problem of road embankment failures along riverbanks is especially prominent in Sri Lanka, where natural processes such as heavy rainfall, flooding, and water sudden drawdown, combined with human activities like sand mining, exacerbate erosion. In response, numerous stabilization techniques have been developed globally [1], [2], [3], [4], employing both rigid structures and bioengineering solutions. However, Sri Lanka lacks innovative, cost-effective, and environmentally sustainable approaches tailored to its unique geographical and hydrological conditions. This research paper seeks to bridge this gap by analyzing the root causes of instability and proposing suitable remedial strategies for problematic locations. This paper presents a comprehensive analysis of four unstable locations in Sri Lanka's Western Province: the left bank of the Kelani River along the low-level road (AB010) at the 26th-kilometer milestone (location 1), the right bank of the Halwathura Phalakotasa stream along the Ingiriya-Halwathura-Ekgaloya road (B068) at the 4th-kilometer milestone (location 2), the right bank of the Halkotiyawatta stream on Seelarathana Mawatha at the 1st-kilometer milestone (location 3), and the right bank of the Diyawanna Lake on Denzil Kobbekaduwa Mawatha at the 1st-kilometer milestone (location 4). Figure 1 depicts a map of the Western Province of Sri Lanka along with the identification of the locations.

Each site is characterized by distinct hydraulic conditions that contribute to road instability. Through detailed geotechnical investigations, the study identifies the causes of erosion at each site and evaluates appropriate stabilization methods, considering factors such as cost, constructability, and sustainability. This research contributes to developing more sustainable, long-term solutions for safeguarding Sri Lanka's road network managed by the Road Development Authority (RDA).

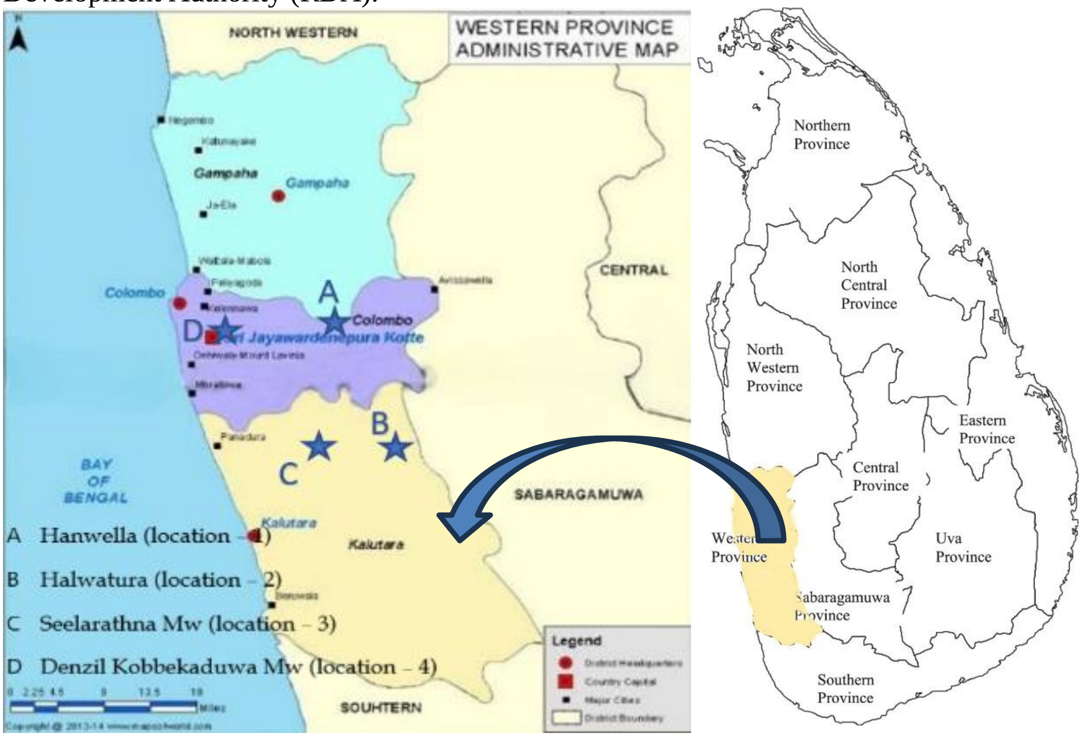

Figure 1 Map highlighting all identified problematic locations of the Western Province of Sri Lanka

2. Methodology

A comprehensive literature survey was conducted to explore various techniques employed in stabilizing roads adjacent to water bodies. Due to time constraints, four distinct problematic locations within the RDA road network, each exhibiting unique characteristics, were selected for the study. Sufficient geotechnical investigations were conducted to evaluate the subsoil conditions at these sites, taking into account the processes of degradation over time caused by both natural phenomena and human activities. The investigations also aimed to identify the root cause of the problem at each location.

Rectification processes were then formulated, and necessary designs were developed using the Limit Equilibrium Approach using the Morgenstern Price method implemented through SLOPE/W software (GeoStudio, 2018) to assess global stability. Additionally, the stability of the retaining structures used in rectification was assessed following BS8002 (1994) [5]. Special attention was given to the construction sequence to ensure the efficacy of the solutions.

Through the study of these four case histories, each characterized by different hydraulic flow conditions, guidelines will be established to inform similar projects in the future.

2.1 Establishment of subsoil condition

To determine the subsoil profile relevant to the retaining slope heights at four selected locations appropriate geotechnical investigations were conducted. This involved several methodologies including advancing boreholes with Standard Penetration Testing (SPT), Dynamic Cone Penetrometer (DCP) tests, Mackintosh Probe (MT) tests, laboratory sampling, and subsequent laboratory tests performed following BS 1377 Part 2 (1990). Additionally, hand augering methods were employed to identify subsurface layers. All problematic locations selected for investigation are presented in Figure 2.

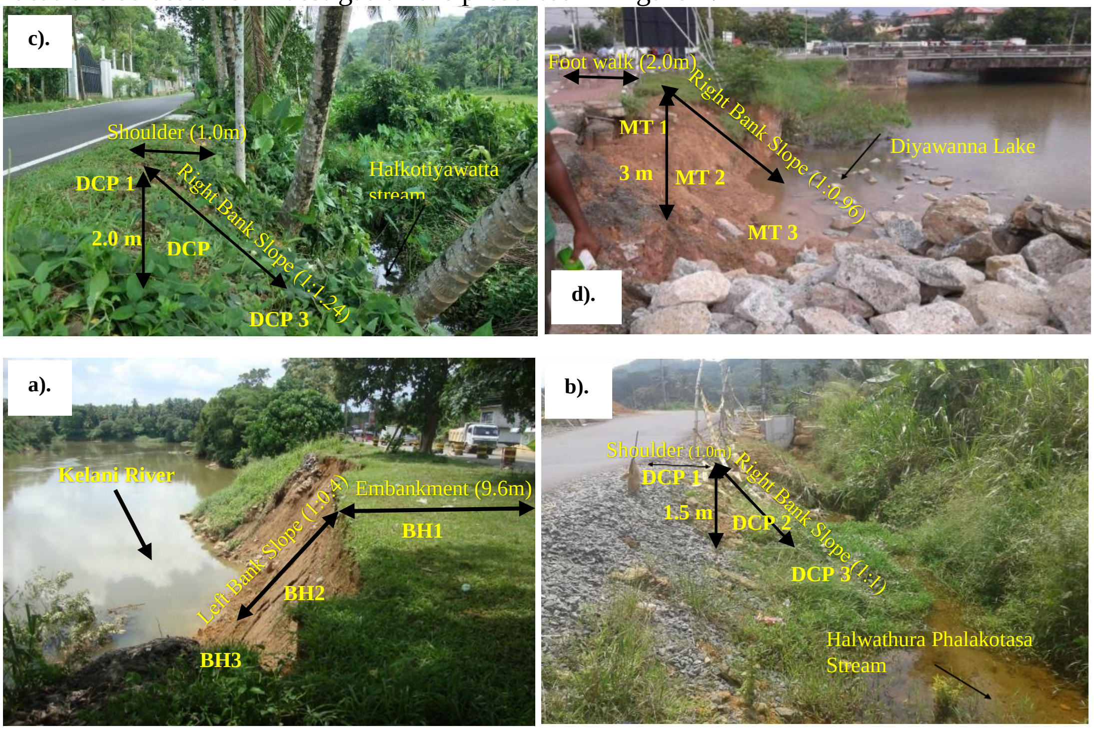

Figure 2 Photographs 'a,' 'b,' 'c,' and 'd' depict all selected problematic locations

Interpreting the geotechnical investigation, a geotechnical (ground) model was developed for stability analysis and design at the relevant problematic locations. Geotechnical design parameters were derived from the results of the geotechnical investigation, pertinent references, laboratory test results, and the author's previous experience with similar ground conditions. The geotechnical models used in the analysis, along with the geotechnical shear strength parameters, are illustrated in Figures 3 to 6.

2.2 Assessment of stability

The factor of safety (FoS) of the slope under varying water table conditions was evaluated through stability analysis using the Limit Equilibrium approach through SLOPE/W (2018) software at all identified problematic locations. Both circular and non-circular failure surfaces were considered, and stability analyses were conducted using the Morgenstern Price method.

The results of the analysis at location 1 (Table 1) indicate that the existing slope is marginally stable (FoS = 1.029) during low tide periods and stable during high flood levels. However, there is a risk of collapse (FoS = 0.59) due to the sudden drawdown of water level in the river within 6 hours after the flood recedes, owing to the rapid discharge of river water flow. Additionally, erosion resulting from floods, toe scour, and mass wasting of trees has been observed.

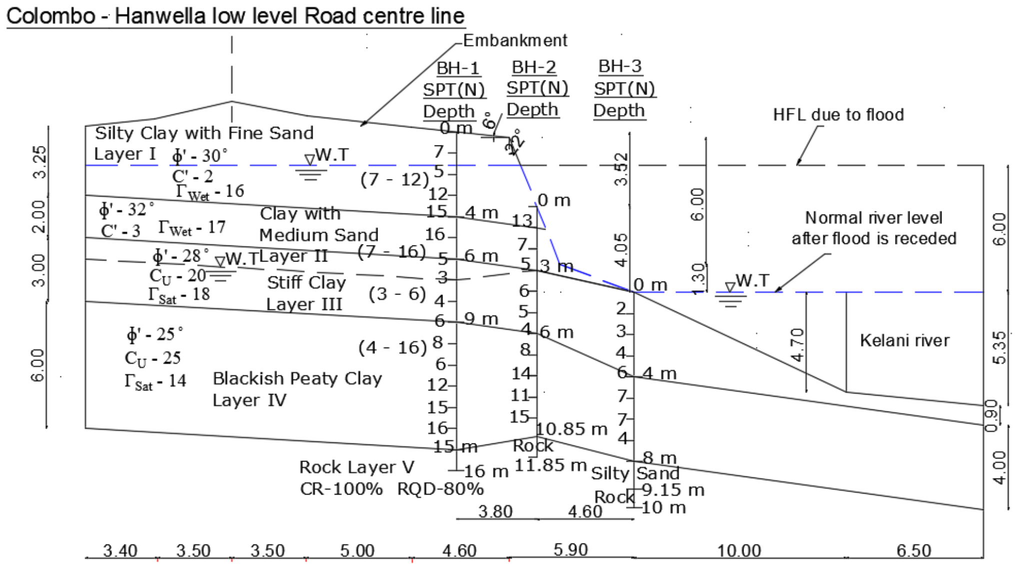

Figure 3 Subsoil profile with soil properties at location 1

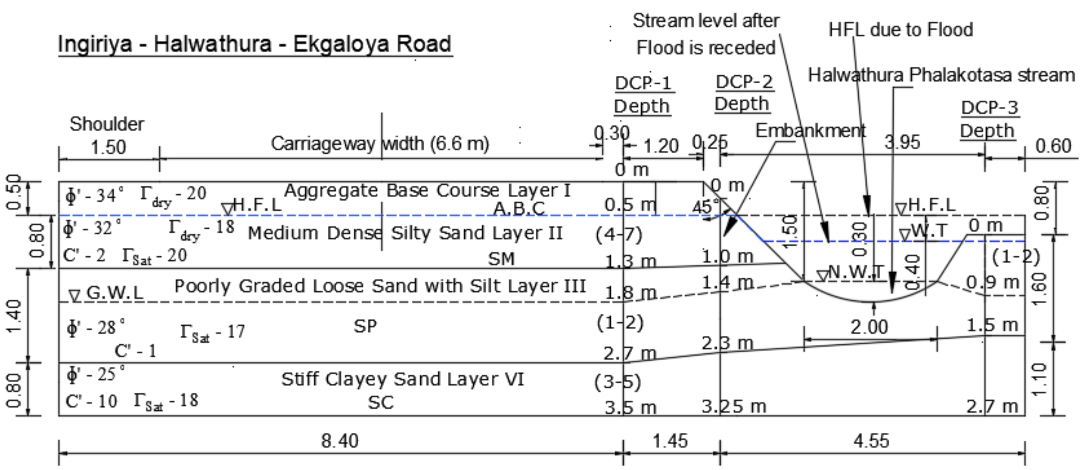

Figure 4 Subsoil profile with soil properties at location 2

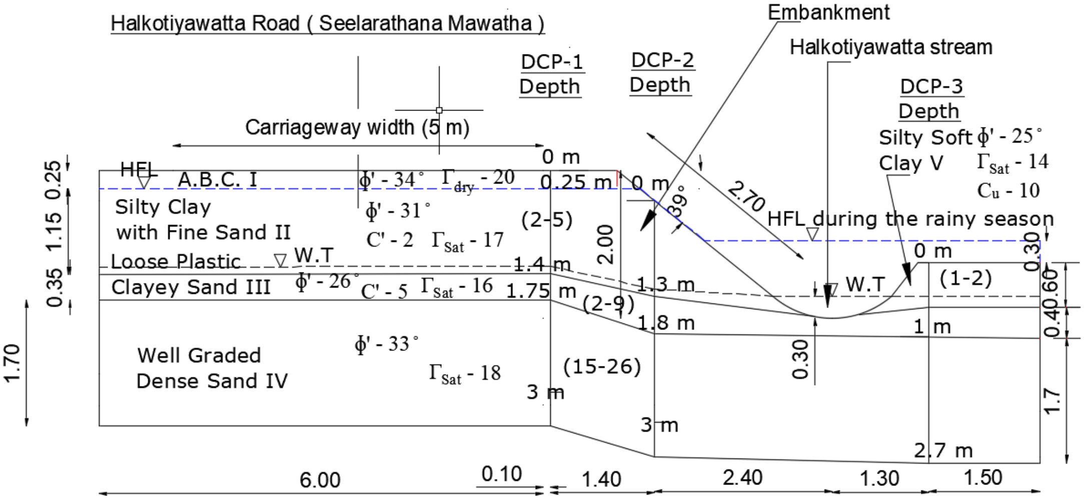

Figure 5 Subsoil profile with soil properties at location 3

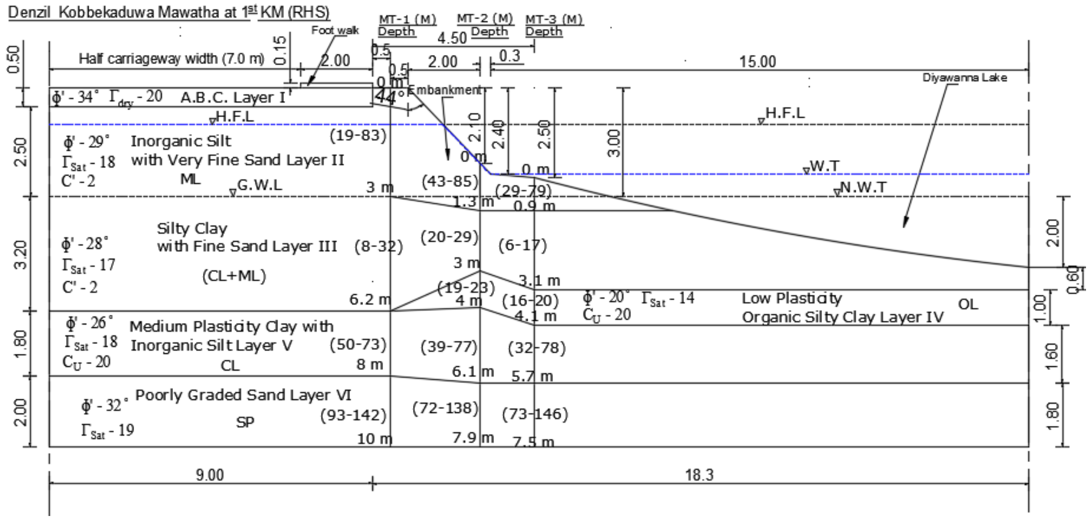

Figure 6 Subsoil profile with soil properties at location 4

Table 1 Summary of Global stability for deep-seated failure of existing slope at location 1

Methods	Types of failure	Minimum FoS		
		Normal G.W.T	High Flood level	Sudden drawdown
Grid and Radius	Circular	1.029	1.334	0.590

Based on the analysis results at location 2 (Table 2), it is evident that the current slope remains marginally stable (FoS = 1.257) during low tide and is secure during high flood levels. However, the slope is susceptible to collapse (FoS = 0.489) when there is a sudden drawdown of water levels in the stream within 2 hours after the flood recedes. This vulnerability is exacerbated during the heavily rainy season, as the groundwater level in the road section rises to the high flood level for a short period, with adjacent paddy fields on both sides of the road.

Table 2 Summary of Global stability for deep-seated failure of existing slope at location 2

Methods	Types of failure	Minimum FoS		
		Normal G.W.T	High Flood level	Sudden drawdown
Grid and Radius	Circular	1.257	1.358	0.489

Based on the analysis results at location 3 (Table 3), it is evident that the existing slope is stable during low tide periods (FoS = 1.455) but only marginally stable during high flood levels (FoS = 1.115). This instability is attributed to the closure and filling of the existing drain on the hillside with soil. During the rainy season, rainwater flows across the road to the other side, with the LHS having a higher elevation than the RHS, causing a rise in the groundwater table, which could potentially render the slope unstable.

Table 3 Summary of Global stability for deep-seated failure of existing slope at location 3

Methods	Types of failure	Minimum FoS	
		Normal G.W.T	High Flood level
Grid and Radius	Circular	1.455	1.115

Based on the analysis results at location 4 (Table 4), it is evident that the current slope remains marginally stable during both low tide (FoS = 1.114) and high flood levels (FoS = 1.133). However, the slope could experience a sudden collapse (FoS = 0.623) when there is a rapid drawdown of water levels in the lake within a day after the flood recedes. This vulnerability stems from the inadequate bridge opening for the lake flow's proximity to the embankment. Consequently, the channel experienced incision and widening due to hydrological alterations in the watershed at the same time, the erosion of the slope toe occurred due to the high velocity of discharge from Diyawanna Lake.

Table 4 Summary of Global stability for deep-seated failure of existing slope at location 4

Methods	**Types of failure**	**Minimum FoS**		
		Normal G.W.T	**High Flood level**	**Sudden drawdown**
Grid and Radius	Circular	1.114	1.133	0.623

2.3 Establishment of the most appropriate technique for stabilization and development of a design

2.3.1 Location 1

The study assessed the feasibility of two alternate rectification measures to retain the 6m height at location 1;

I. Gabion wall with Boulder packing
II. Anchored Sheet pile wall

A rubble pack was placed on the riverbed after excavation to the indicated profile to enhance the protection from erosion of the Peaty Clay layer. For the design, to be conservative the proposed gabion wall is assumed to have a vertical back and conform to the geometry outlined in Kerisel and Absi's (1990) charts in BS 8002:1994. The gabion basket is filled with rubble material assumed to have a friction angle of 45°, a rubble of specific gravity of 2.7 at a porosity of 0.4.

In external stability analysis, it is found that the resisting moment (M_r = 1,467 kNm/m) exceeds the overturning moment (M_o = 1,020 kNm/m) in the worse scenario according to the BS 8002 code. Additionally, it is confirmed that the resultant force falls within the middle third of the wall's base (e = 0.3 m < B/6 = 0.833 m) and the resistance to sliding (F = 262 kN/m) exceeds the disturbing force (P_{ha} = 205 kN/m) along the gabion base.

Figure 7 illustrates the stabilizing technique applied at location 1. Global stability was evaluated under various water table conditions using the Morgenstern Price Limit Equilibrium Approach through Slope/W software. A summary of the results is presented in Figure 8 and Table 5.

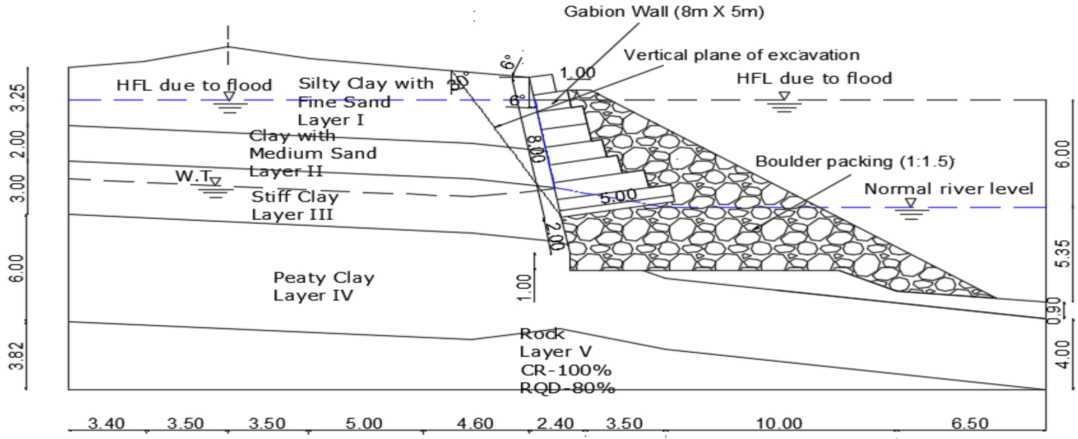

Figure 7 Proposed Gabion wall section (8 m X 5 m) at location 1

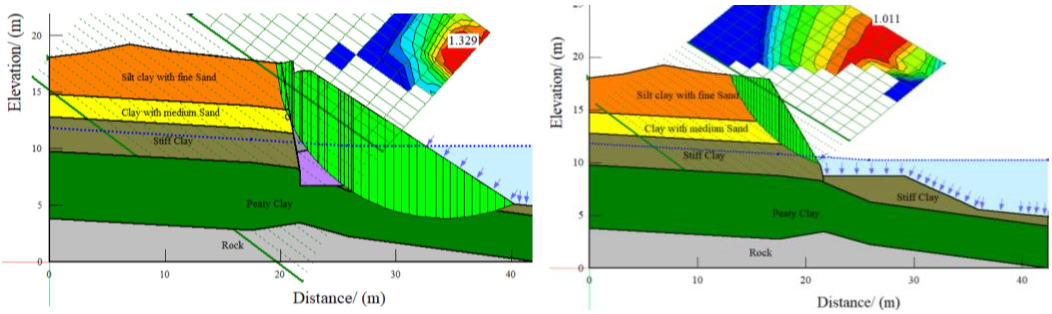

Figure 8 Assessment of stability at Location 1 with different water table conditions

Table 5 Summary of Analysis Results for Global Stability at Location 1

Type of rectification proposal	Water table condition	Minimum FoS Grid and Radius Effective stress analysis
Gabion wall (8 m X 5 m) Retaining structure with Boulder packing as proposal # I	After excavation for the construction (during the dry period)	1.011
	Normal River water level	1.329
	High Flood level (above 6m from RWL)	1.635
	Sudden drawdown after Flood has receded	1.286

The above results show that reasonable FoS values were achieved with the proposed rectification. The FoS when the slope is excavated for the construction of the gabion wall is low. Hence the excavation should be done in small segments during a period of dry weather.

The study also explored the utilization of steel sheet pile walls as another option under challenging soil conditions due to their versatility in cross-sectional variety, rapid construction, resistance to buckling during installation, reusability, high stiffness, relatively low weight, and capacity for length extension through welding or bolting.

In addressing the specific conditions at location 1, where weak subsoil and bedrock constraints limit embedment depth, sheet piles need to be anchored. With the limited embedment in a relatively weak Peaty Clay layer the sheetpiles need to be anchored to the bedrock.A Hot-rolled NS-SP-II U type sheet steel pile was chosen for the application. Tie rods utilizing Pre-stress bar anchors (ASTM A722) are applied at 8.0m intervals, corresponding to every twenty piles, as depicted in Figure9.

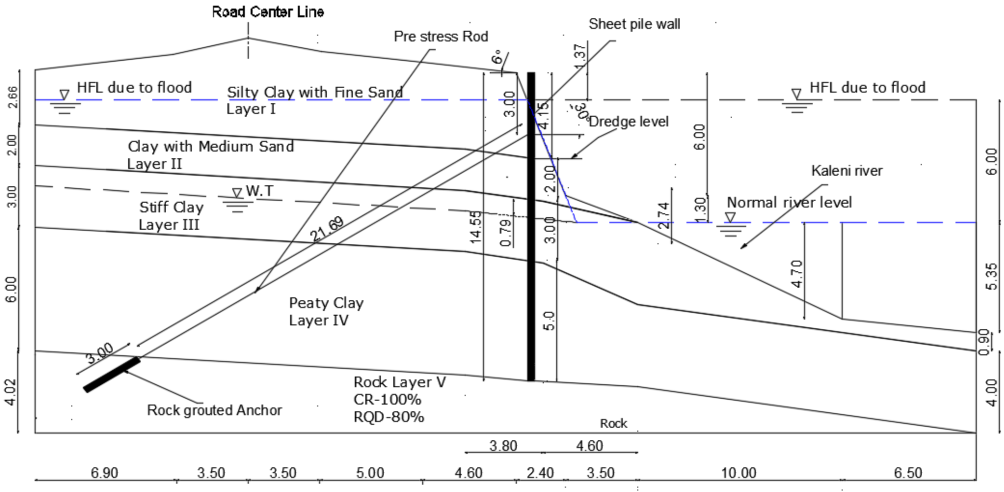

Figure 9 Proposed Anchored sheet pile wall

The global stability analysis was conducted under the worst-case scenario of sudden drawdown conditions, as depicted in Figure 10. Analysis results indicate that the sheet pile wall without lateral support will not withstand the conditions adequately (FoS = 0.867). With the provision of lateral support, the sheet pile wall was marginally stable (FoS = 1.005) in the worst-case scenario. Hence this solution was not implemented.

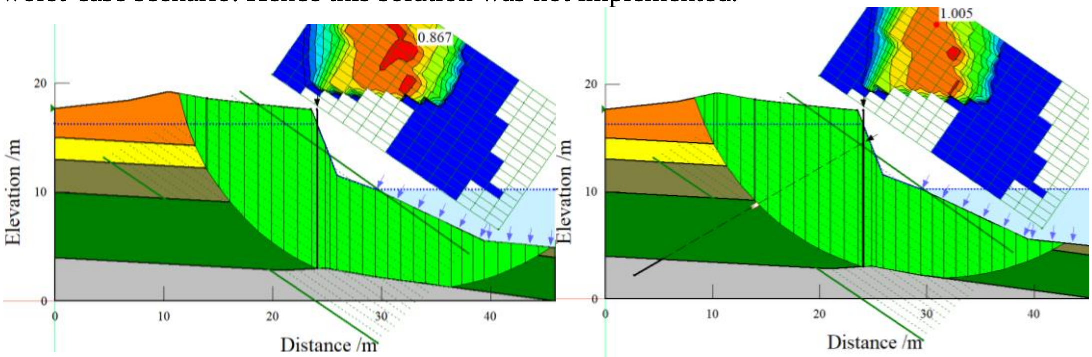

Figure 10 Assessment of Stability for sheet pile wall (without and without lateral support) with sudden drawdown after the flood has receded

2.3.2 Location 2

At the 2nd location, two alternate rectification measures were considered to protect the 1.5 m height. The alternative solutions are;

I. Vegetated live bamboo crib wall with Gabion at the toe (Bio-engineering wall)
II. Traditional Gabion wall

The Eco-engineering wall represented in Figure 11, comprises a Gabion wall at the base with a height of 1.5 m, followed by a Bamboo Crib Wall with a height of 0.7 m. The Bamboo Crib Wall incorporates horizontally placed live stakes spaced at 200 mm intervals (utilizing Erythrina subumbrans) and is filled with a combination of stone and excavated soil.

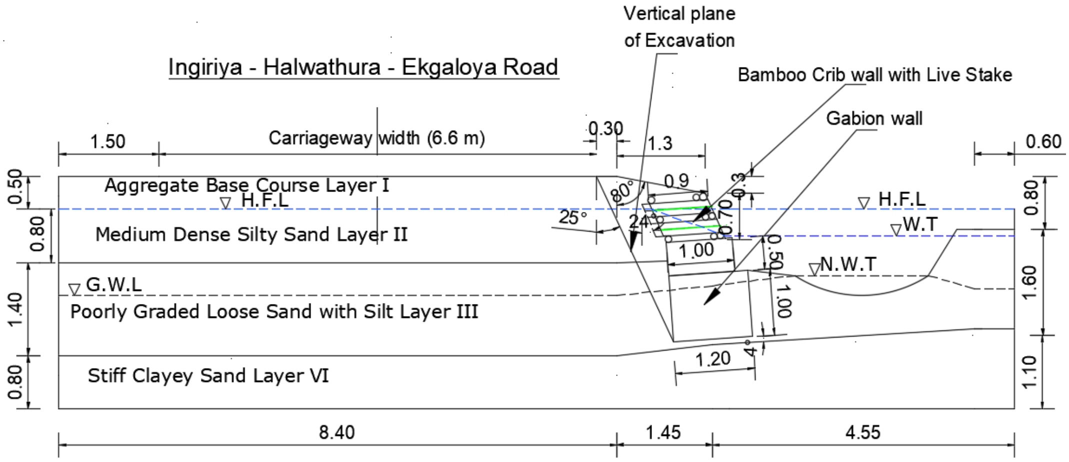

Figure 11 Proposed bioengineered retaining wall with Gabion at the toe

In the external stability analysis of the bamboo crib wall, it is determined that the resisting moment (Mr = 1.7 kNm/m) surpasses the overturning moment (Mo = 0.8 kNm/m) in the worse scenario following the BS 8002 code. Moreover, it is confirmed that the eccentricity falls within the inner half of the base (e = 0.065 m < B'/4 = 0.2 m), satisfying stability requirements.

Additionally, the bamboo crib wall demonstrates adequate resistance against sliding forces, with the applied force (F = 7.3 kN/m) exceeding the disturbing force (P_{ha} = 2 kN/m) along the base of the wall. To enhance stability, steel pegs with a diameter of 16 mm and lengths of 0.8 m are installed at 1.5 m intervals into the gabion wall to a depth of 0.6 m, securing the base layer of the crib against sliding.

The study also explored the application of the Gabion wall as an alternative solution at location 2. Global stability was evaluated for Both rectification measures under various water table conditions using the Equilibrium Approach through Slope/W software. The geotechnical model and a summary of the results corresponding to the two stabilization techniques are presented in Figure 12, Figure 13, and Table 6.

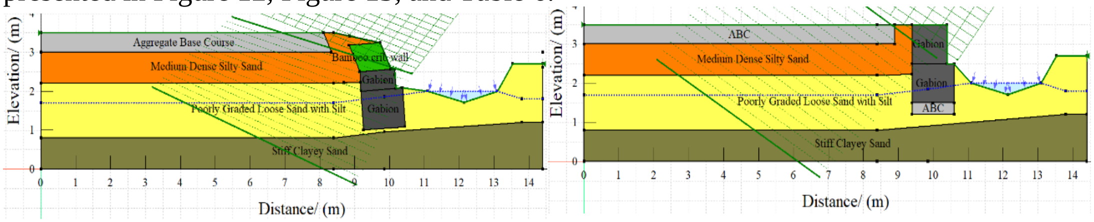

Figure 12 Models of Bioengineered retaining wall and Gabion wall

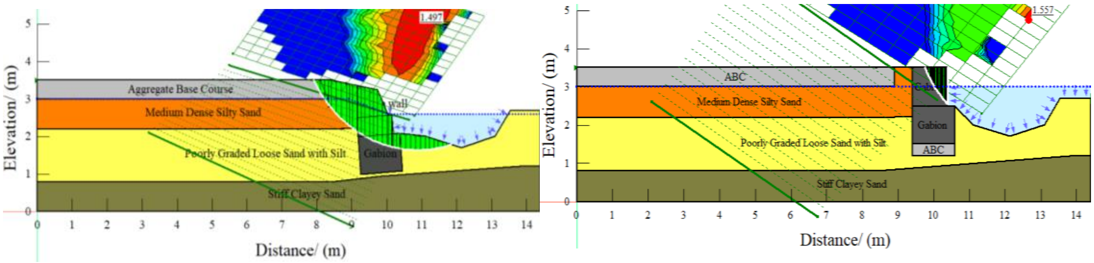

Figure 13 Assessment of Stability for Bamboo crib wall and Gabion wall

Table 6 Summary of analysis results for Global Stability at Location 2

Type of rectification proposal	**Water table condition**	**Minimum FoS (Grid and Radius)**
		Drained condition
Bioengineered retaining wall # I (Gabion wall at the base, overlain by Bamboo Crib Wall with horizontally placed live stakes)	After excavation for construction during the Dry period	1.049
	Normal stream water level	1.505
	High flood level (HFL)	1.616
	Sudden drawdown after Flood has receded	1.497
Traditional Gabion wall with compacted Aggregate Base Course layer underneath # II	After excavation for construction during the Dry period	1.007
	Normal stream water level	1.393
	High flood level (HFL)	1.537
	Sudden drawdown after Flood has receded	1.481

The above results show that the calculated Factor of Safety (FoS) satisfies the design criteria (i.e., FoS = 1.5). The photo of the Bioengineered wall the selected option, immediately after construction is shown in Figure 14.

Figure 14 Photographs taken at Location 2 on 21.03.2024 after the stabilization technique

2.3.3 Location 3

At the 3rd location, two alternate rectification measures were considered to protect the 2 m height. The alternative solutions are;

1. Vegetated flapped soil bag with a Gabion at the toe
2. Vegetated Gabion wall with Rubble packing at the toe

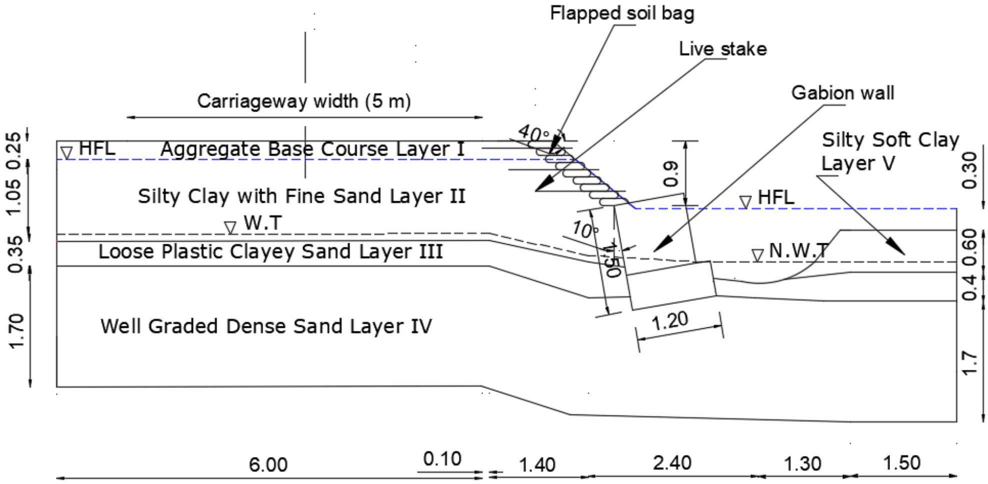

Figure 15. Proposed Gabion wall, overlain by flapped soil bags with nailed live stakes (1 m long and 20 cm in diameter) at a spacing of 0.5 m

Table 7 Summary of analysis results for Global Stability at Location 3

Type of rectification proposal	**Water table condition**	**Minimum FoS (Grid and Radius)**
		Drained condition
Bioengineered retaining wall structure # I	After excavation for construction during the Dry period	1.000
	Normal stream water level	2.386
	High flood level (HFL)	1.687
Vegetated Gabion wall structure # II	After excavation for construction during the Dry period	1.027
	Normal stream water level	1.596
	High flood level (HFL)	1.341

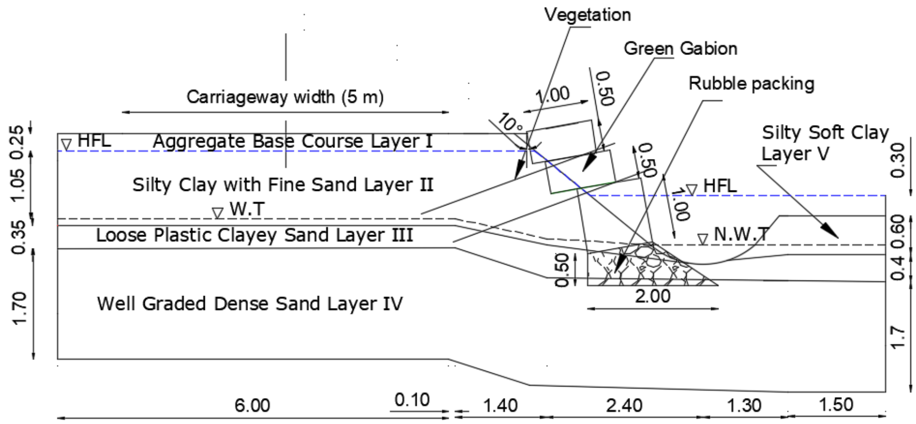

Figure 16. Proposed Vegetated Gabion wall (Gunny bags filled with pebble) with Rubble (Willow cuttings with a spacing of 0.3m & a length of 2m)

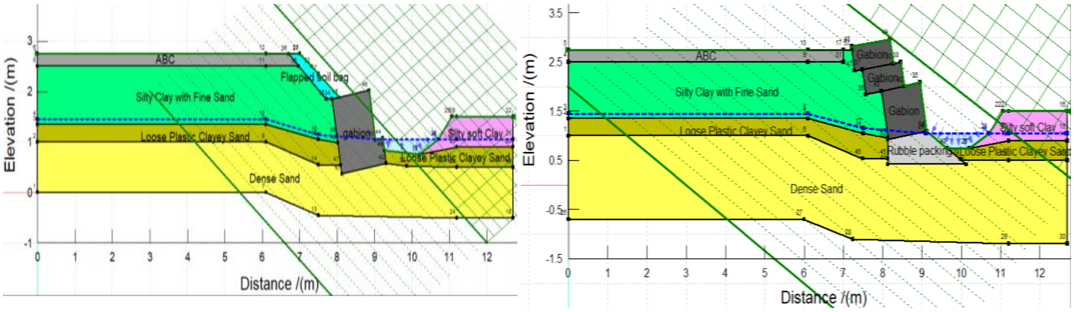

Figure 17. Models of Vegetated flapped soil-bag with Gabion and Vegetated Gabion wall

The two types of Eco-engineering walls proposed for the location are illustrated in Figure 15 and Figure 16. The geotechnical model and a summary of the results corresponding to the two stabilization techniques are presented in Figure 17, Figure 18, and Table 7.

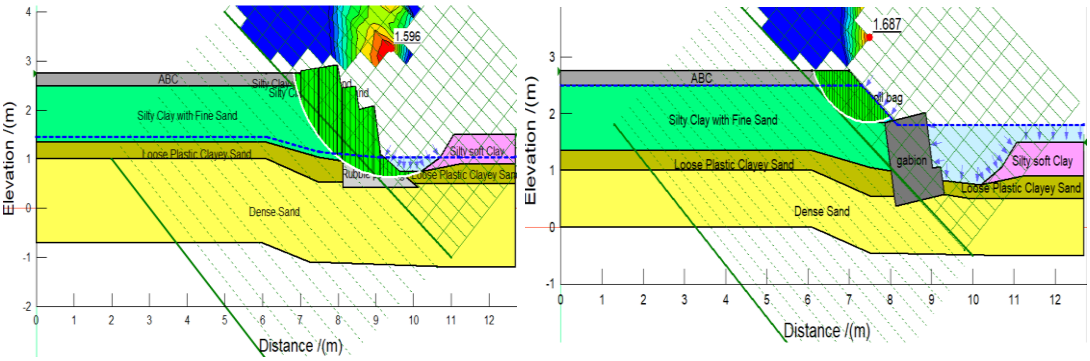

Figure 18. Assessment of Stability for bio engineered and vegetated Gabion walls

The above results show that the calculated Factor of Safety satisfies the design criteria. As the FoS after excavation for the construction is low it should be done in short segments during a period of dry weather.

2.3.4 Location 4

At the 4th location, two alternate rectification measures were considered to protect the 3 m height. The alternative solutions proposed are;

I. Gabion wall with Rubble packing at the toe
II. Gabion Wall with Vetiver Grass

The two alternates proposed, considering the water flow conditions are represented in Figure 19 and Figure 20. The results of the analyses are summarized in Figure 21 and Table 8.

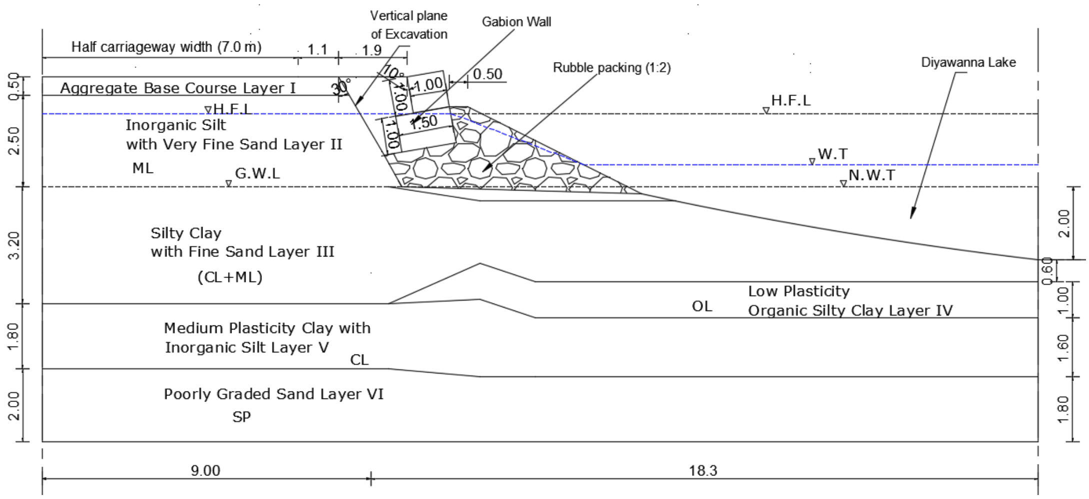

Figure. 19. Proposed Gabion Wall section with Rubble packing at the toe

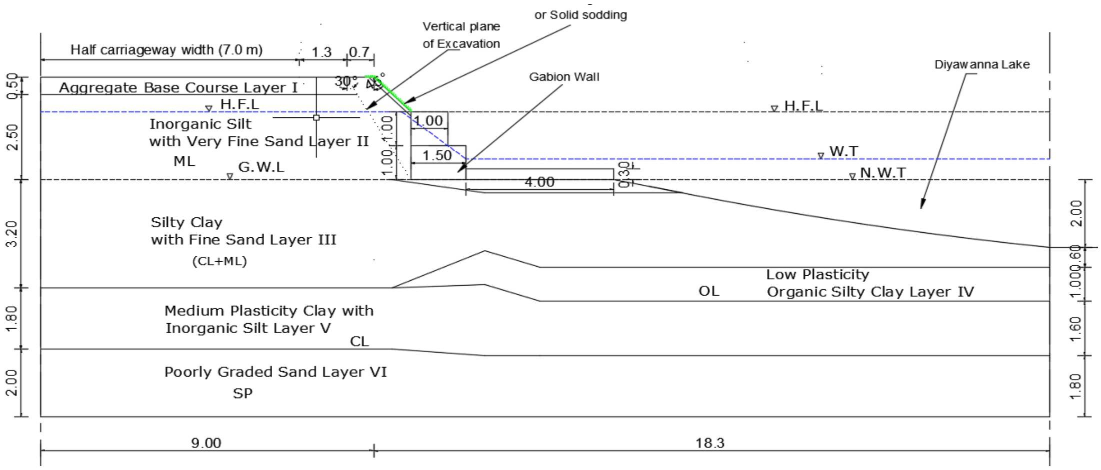

Figure 20. Proposed Gabion Wall at the toe, Reinforced with Solid Sodding

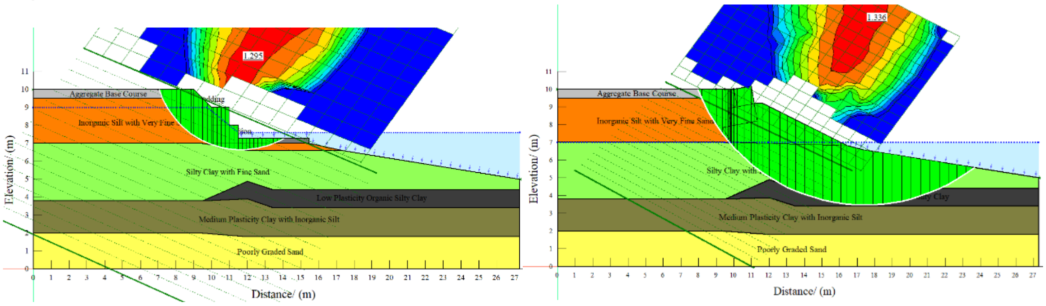

Figure 21. Assessment of Stability for proposal # I & II with various water table conditions

The Table 8 results show that the calculated FoS values are adequate with a value greater than 1.2 in the most critical sudden drawdown condition. As the FoS after excavation for the construction is low it should be done in short segments during a period of dry weather.

Table 8 Summary of analysis results for Global Stability at Location 4

Type of rectification proposal	Water table condition	Minimum FoS (Grid and radius) Drained condition
Gabion wall (2 m X 1.5 m) Retaining structure with Rubble packing as slope of 1:2 # I	After excavation for construction during the Dry period	1.057
	Normal Lake water level	1.336
	High flood level (HFL)	1.570
	Sudden drawdown after Flood has receded	1.242
Gabion Wall at toe, Reinforced with Vetiver Grass Overlay or Solid Sodding at a 45-degree angle # II	After excavation for construction during the Dry period	1.110
	Normal Lake water level	1.544
	High flood level (HFL)	1.660
	Sudden drawdown after Flood has receded	1.295

3. Summary of the Adopted Solutions and Performance

The adopted rectification measures classified according to the height of the slope in the summary presented in Table 9.

Table 9 Summary of adopted solutions based on height to be supported

Vertical height of slope protection / m	Type of waterbody	Appropriate stabilizing technique
0.5 to 1.5	Stream	Bio-engineering retaining wall (Vegetated live bamboo crib wall with Gabion at the toe)
1.5 to 2.5	Stream	Vegetated flapped soil bag with live stake retaining structure with Gabion at the toe
2.5 to 4.5	Lake	Gabion wall with Rubble packing at the toe
4.5 to 7.0	River	Gabion wall with Boulder packing

Acharya, 2020 and Acharya 2018 assessed the potential use of bamboo crib walls in Nepal, emphasizing their ability to support plant growth [1], [6]. Their findings, affirm the suitability of the Vegetated live bamboo crib wall approach for stabilizing road embankments near small streams, with a maximum height of 1.5 m presented in this study. This approach utilizes renewable, cost-effective materials and relies on labour-intensive techniques, enhancing its accessibility and affordability.

Live stakes, in conjunction with flapped soil bags, have been effectively utilized in Thailand to enhance soil retention, as studied by [4]. He reported satisfactory survival rates for live stakes when horizontally positioned between the soil bags, demonstrating the beneficial effects of this method over time. The results, outlined in Table 9 by the author, validate the efficacy of the Vegetated flapped soil-bag method for stabilizing road embankments adjacent to streams, with a maximum height of 2.5 m and 40°gradient.

The two eco-engineering approaches proposed in this study typically involve a combination of various vegetation covers, such as vetiver grass and live stakes, along with certain forms of gabion retaining structures. These combinations are aimed at enhancing soil stability and erosion control in stream bank restoration projects.

In developing nations like Sri Lanka, where sustainable infrastructure is vital for economic progress and poverty reduction, environmentally conscious construction practices play a crucial role in balancing development with environmental preservation. Given the growing emphasis on environmental sustainability and safety, there's increasing interest in eco-friendly construction methods, even if they incur additional costs.

Ensuring the durability and safety of vegetative crib walls and Vegetated flapped soil-bag with live stakes could lead to their widespread adoption, potentially replacing conventional civil engineering methods within their practical limitations.

The findings, as illustrated in Table 9 by the author, underscore the effectiveness of the Gabion wall with Boulder packing at toe approach in stabilizing road embankments near large rivers or lakes, particularly for structures with a maximum height of 8 meters and a boulder packing slope behind the gabion of 1:1.5. This approach offers several advantages, including ease of construction, environmental friendliness, permeability, sustainability, erosion protection, enhanced structural bearing capacity, and control over flow dynamics. By leveraging these attributes, this approach represents a dependable solution for mitigating erosion issues and ensuring the durability of riverbank infrastructure, thereby safeguarding the RDA road network.The implemented solutions have been performing very satisfactorily over the past 10 years. Figure 22 illustrates the post-construction performance of the adopted stabilization techniques at location 1 after 10 years of construction, at location 2 after 3 months of construction and at location 4 after 5 years of construction.

Figure 22. Photographs taken at Location 1, 2 and 4 showing the post-construction performance of the adopted stabilization techniques

4. Conclusion

The rectification solutions proven to be satisfactory for the selected four locations include both conventional hard engineering solutions and bio-engineering solutions coupled with hard engineering solutions. For each location, most appropriate option was selected after a rigorous assessment of the different design options. The conditions that lead to the failure were evaluated closely to ensure that those conditions are overcome by the selected rectification option. The proven success is an encouragement for future applications.

The satisfactory performance of vegetated bamboo crib walls highlights their potential as composite gravity walls, akin to concrete crib walls. Vegetative log crib walls typically feature inclinations of 20°–30° from vertical, facilitating plant growth, with the wall base inclined (5°–15°) to bolster sliding resistance. The success of these eco-engineering walls underscores their viability as a cost-effective slope management alternative, seamlessly integrating with other geotechnical measures even in large-scale slope failure scenarios. Soil bioengineering techniques, when conducive to plant growth, yield comparable or superior economic and environmental outcomes.

Incorporating plants into flapped soil bags prolongs their lifespan and enhances slope stability over time. However, blind replication without adherence to engineering principles is cautioned; thorough site investigation and assessment are paramount. Vegetative crib and vegetated flapped soil-bag techniques should be part of a comprehensive soil bioengineering system, emphasizing meticulous site assessment throughout.

In conclusion, the analysis suggests that for embankments higher than 4 meters with high water velocity, the Gabion wall with boulder packing is a viable stabilization technique. This method offers enduring environmental benefits and presents a sustainable solution to geotechnical challenges, ensuring effective slope management and protection against erosion while promoting environmental preservation. This integrated approach aligns with sustainable development goals, offering a reliable and eco-friendly alternative to traditional engineering methods.

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