

Root Reinforcement and Bank Shear Strength Along a Tropical Deltaic Distributary: Field Evidence for a Limiting Vegetation Effect

Anthony Enifome Eseha^{1*}, Herbert Ugwueze Nwoke¹ and Benedicta Uchenna Dike¹

¹Department of Civil Engineering, Federal University of Technology, Nigeria

Abstract - Vegetation is widely promoted as a nature-based solution for streambank stabilisation, yet field measurements of the vegetation–strength–erosion linkage remain scarce for tropical deltaic channels, and the mechanism established in temperate systems may not transfer directly. This study quantifies bank shear strength, vegetation cover and measured bank erosion along a 5,000 m reach of the Erowha River, a distributary of the Forcados system in Delta State, Nigeria. At 101 chainage-referenced stations spaced at 50 m, vegetation cover was characterised by the quadrat method, land use was classified into urban, agricultural and natural classes, and cohesion and the angle of internal friction were determined by direct shear testing of undisturbed cores recovered from the upper bank and the water-level edge. Cover ranged from 45.00% to 65.00% (mean 55.00%) and was perfectly inversely associated with measured erosion ($r = -1.000$) and directly associated with deposition ($r = 0.888$). Cohesion ranged from 5.77 to 11.04 kN/m², with mean upper-bank strength (10.23 kN/m²) nearly twice mean edge-of-water strength (5.66 kN/m²), demonstrating saturation-driven softening at the bank toe. Undisturbed swamp forest (L15–L28) recorded the maximum profile cohesion of 11.01 kN/m² with stabilised erosion, whereas cultivated encroachment (L7–L14) coincided with declining cohesion from 8.29 to 7.01 kN/m². Measured cohesion lies within the range attributed to root reinforcement in the geotechnical literature. The results support vegetation-based stabilisation but indicate a limiting reinforcement beyond which further gains are marginal.

Keywords: root reinforcement; bank cohesion; riparian vegetation; soil bioengineering; bank toe scour; Niger Delta

1. INTRODUCTION

The stabilising influence of vegetation on riverbanks operates through two physically distinct pathways. The mechanical pathway is root reinforcement: roots mobilise tensile resistance within the soil matrix and thereby raise the shear strength of the composite bank material, with the magnitude of the contribution depending on root tensile strength, areal density, root architecture and the failure mode of the soil–root bond (Török & Parker, 2022). The hydrological pathway operates through transpiration, which lowers soil moisture, and interception, which limits infiltration, so that positive pore-water pressures are suppressed and effective stress, and therefore shear strength is raised (Simon & Collison, 2002). Both pathways act simultaneously, and the widely used simplification of treating vegetation as a single added-cohesion term is a modelling convenience rather than a physical description (Capobianco et al., 2021).

Quantification of the mechanical term has advanced considerably, and so has awareness of its limits. Root reinforcement is now commonly estimated by the perpendicular root model, in which the full tensile strength of every root crossing the shear plane is assumed to mobilise instantaneously at failure. That assumption is unrealistic: as a soil–root matrix shears, roots of differing tensile strength break progressively and stress redistributes among the survivors. Applying a fibre-bundle formulation to tensile strength data from twelve riparian species, Pollen and Simon found that the perpendicular model overestimated root reinforcement by up to 50% where bank driving forces were sufficient to break all roots, with overestimation increasing by an order of magnitude where driving forces did not exceed root strength; for a 3 m bank the resulting difference in factor of safety ranged from 0.13 to 2.39

depending on species (Pollen & Simon, 2005). Their conclusion that the stabilising effect of roots on streambank mass stability had almost certainly been overestimated remains the single most important caution in this literature.

Field measurement reinforces the point that vegetation is not a uniform stabiliser. Wet-meadow graminoid banks on a montane meadow stream were on average five times stronger than banks colonised by dry xeric meadow and scrub vegetation, and strength correlated with stem counts, standing biomass per unit area and the ratio of root mass to soil mass; rushes stabilised coarse bar surfaces better, whereas sedges were far more effective on actively eroding cut banks (Micheli & Kirchner, 2002). Functional differences extend across growth forms: woody vegetation consistently exceeds non-woody species in root tensile strength curve coefficient, lateral root extent and maximum root diameter, tree roots add significantly more cohesion than forb roots, and rhizomes may govern reach-scale effects (Polvi et al., 2014). Rhizomatous riparian shrubs and trees provide more strength than xeric trees or non-rhizomatous graminoids and herbs, with the magnitude dependent on bank texture and hydrologic conditions (Polvi & Wohl, 2013).

Vegetation also alters the hydraulics that drive erosion, not only the strength that resists it. Bank vegetation changes water velocity, water depth and the power of shear stress, so that vegetation establishment is reflected in the rate of bank retreat itself (Gholami & Khaleghi, 2013). Above-ground biomass modifies the flow field and retains sediment, while below-ground biomass governs the moisture regime and erosion susceptibility of the substrate (Gurnell, 2013), and root mechanical anchoring temporarily stabilises non-cohesive sediment, altering the temporal and spatial scales of morphodynamic processes (Edmaier et al., 2011). Where roots and fine sediment coincide, they generate a cohesive layer overlying cohesionless material, which changes the failure mechanism itself (Zen & Perona, 2019).

These mechanisms are well documented for temperate, Mediterranean and montane systems. Whether they transfer to tropical deltaic distributaries is an open question. In such settings the bank profile is strongly stratified, groundwater is shallow and persistently saturated, and the receiving channel imposes a backwater control on local hydraulics. In Nigeria, long-term monitoring of a peri-urban watershed has shown marked variability in bank erosion rates driven by the spatio-temporal variation of bank lithology, geotechnical properties, stream power and riparian forest buffers, with climate, stream power, riparian land use, bank geometry and lithology operating as linked controls (Okeke et al., 2022). Elsewhere, loss of riparian vegetation following water-table lowering has converted a perennial stream to an ephemeral one and increased bank instability (Jordan et al., 2009), and regional-scale modelling has identified urban and agricultural land use together with upstream drainage area as the strongest predictors of geomorphic change, with headwater streams net erosional and downstream reaches on average net depositional (Noe et al., 2022).

This study therefore asks three questions of a tropical distributary. First, what is the field relationship between vegetation cover and measured bank erosion, and does it match the root-reinforcement mechanism? Second, how does bank shear strength vary vertically across the bank profile, and where is the strength minimum relative to the hydraulic forcing maximum? Third, is there field evidence for a limiting reinforcement of the kind suggested by instrumented testing?

2. Study Reach and Methods

2.1 Study reach and sampling design

The investigated reach is a continuous 5,000 m profile of the Erowha River, a distributary of the Forcados system draining the Isoko South wetlands of Delta State, Nigeria. The corridor lies within Holocene Younger Alluvium comprising point-bar sands, natural-

levee silts and backswamp clay lenses, on an exceptionally flat plain. During the wet season (May–October) high stages in the Forcados drive a backwater effect that reduces velocity and promotes deposition inland.

The reach was discretised into 101 chainage-referenced stations (L1–L101) at a uniform 50 m interval. The interval was selected because it halves the resolution of a 1 km pilot baseline surveyed at 100 m, resolves the alternating erosional and depositional zones along the reach, and is commensurate with the channel width, so that each station represents a distinct cross-section. Two sampling zones were established at every station: the upper dry bank and the active water-level edge. This pairing is essential, because the bank profile is not geotechnically uniform and treating it as a single unit would conceal the vertical strength gradient.

2.2 Vegetation and land-use characterisation

Vegetation cover was determined by the quadrat method using 1.0 m × 1.0 m quadrats gridded uniformly at 0.20 m intervals, and recorded separately in the upper-bank and water-level-edge zones. Land use was classified from high-resolution satellite imagery processed in a geographic information system into three categorical classes assigned numeric codes: Urban (1), Agricultural (2) and Natural (3). Canopy and ground cover were recorded at every station so that the cover term entering the analysis reflects both the density and the structural class of the vegetation.

2.3 Geotechnical testing

Undisturbed cohesive soil cores were recovered using standard open-drive thin-walled cylindrical steel samplers (Shelby tubes, 100 mm diameter) in accordance with ASTM D1587 guidelines. Peak shear force was measured under three vertical loading tiers and converted to shear stress, Equation 1.

$$\tau = \frac{F}{A} \quad (1)$$

where τ is shear stress (kN/m²), F the measured peak shear force and A the cross-sectional area of the specimen. Peak shear stress was plotted against normal stress and the Mohr–Coulomb failure envelope fitted by linear regression, Equation 2.

$$\tau = c + \sigma \tan \varphi \quad (2)$$

Cohesion was extracted as the intercept on the shear-stress axis and the angle of internal friction as the slope of the envelope. A single consistent procedure was applied to every sample so that the parameter set remained internally comparable across the reach. Because the measured cohesion of a rooted bank is a composite quantity, it can be decomposed conceptually as in Equation 3.

$$c_{total} = c' + c'_v \quad (3)$$

in which c' is the intrinsic soil cohesion and c'_v the root-cohesion contribution. The two terms were not separable in this dataset, because cores were taken from rooted material throughout; this is stated as a limitation rather than resolved. Stability in the presence of root cohesion can be expressed by the infinite-slope formulation adopted in soil bioengineering practice, Equation 4.

$$F_s = \frac{c' + c'_v}{(\gamma_{sat} z \cos^2 \beta + W_v \cos \beta) \tan \beta} + \frac{\gamma' z \cos \beta + W_v}{\gamma_{sat} z \cos \beta + W_v} \cdot \frac{\tan \phi'}{\tan \beta} \quad (4)$$

Where, F_s the factor of Safety, z is the vertical depth of the failure plane, β the slope angle, ϕ' the soil friction angle, γ' the submerged bulk unit weight ($\gamma' = \gamma_{sat} - \gamma_w$), γ_{sat} the saturated bulk unit weight and W_v the overload due to vegetation (Preti & Giadrossich, 2009). For $F_s > 1$, Stable boundary condition, $F_s < 1$, slope failure threshold, triggering active bank erosion. However, the Factor of Safety (F_s) equation above can be simplified by isolating the total shear strength (stabilizing forces) in the numerator and the total shear stress (driving forces) in the denominator, Equation 5.

$$F_s = \frac{(c' + c'_v) + [(\gamma' z \cos \beta + W_v) \cos \beta] \tan \phi'}{[\gamma_{sat} z \cos \beta + W_v] \sin \beta} \quad (5)$$

2.4 Bank erosion measurement and statistical analysis

Erosion was quantified in kg/m^2 at each station as the mass of material lost from a defined bank-face reference area over the monitoring interval, with paired deposition measurements taken on the adjacent depositional surface. This paired design allows the resistance role of vegetation to be assessed on erosion and its flow-retardation role on deposition simultaneously. Pearson correlation coefficients were computed between vegetation cover, cohesion, the angle of internal friction, hydraulic variables and the two response variables. Stations were then grouped into four zones by land use and position along the reach, and the associated vegetation–strength signatures compared.

3. RESULTS

3.1 Vegetation cover and its relationship to erosion and deposition

Vegetation cover ranged from 45.00% to 65.00% across the reach, with a mean of 55.00%. Land use, coded on the three-class scheme, averaged 2.56, indicating a reach dominated by agricultural and natural cover with little urban influence. Cover was perfectly inversely associated with measured bank erosion ($r = -1.000$) and directly associated with sediment deposition ($r = 0.888$). Because the erosion–cover relationship is exact at the observed resolution, vegetation functions as the principal resistance term in this system across the measured cover envelope. Baseline monitoring across the 101 stations (Figure 1) shows strong hydraulic forcing (mean discharge of $59.00 \text{ m}^3/\text{s}$ and velocity of 1.70 m/s) balanced against 55.00% vegetation cover.

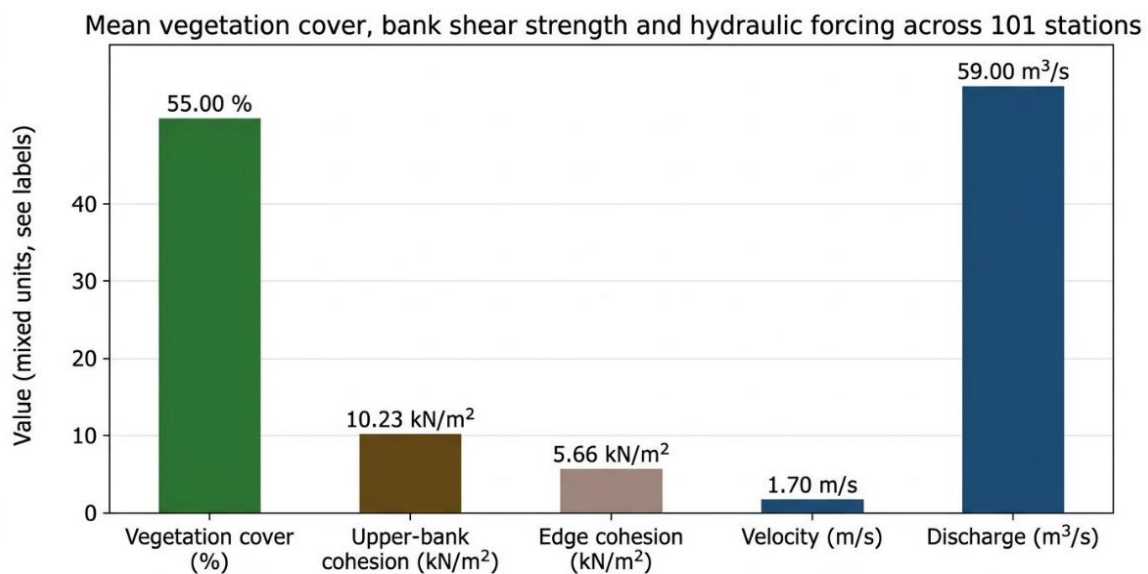


Figure 1. Mean vegetation cover, bank cohesion and hydraulic forcing across the study reach.

3.2 Shear strength of the bank profile

Cohesion ranged from 5.77 to 11.04 kN/m² across the reach. The mean upper-bank value (10.23 kN/m²) was nearly twice the mean edge-of-water value (5.66 kN/m²), demonstrating localized softening due to persistent liquid saturation at the lower bank. The angle of internal friction averaged 25.10° on the upper bank and 26.42° at the water-level edge, with maxima of 26.23° and 27.49° respectively. The vertical strength gradient therefore acts in the same direction as the hydraulic forcing gradient, since the toe of the bank experiences both the highest pore-water pressures and the highest shear stresses. Geotechnical testing across the 101 stations (Table 1) establishes the baseline structural resistance of the bank profiles.

Table 1. Shear-strength parameters of the bank profile across 101 stations

Parameter	Upper bank	Water-level edge
Mean cohesion (kN/m ²)	10.23	5.66
Mean angle of internal friction (°)	25.10	26.42
Maximum angle of internal friction (°)	26.23	27.49
Overall cohesion range across the reach (kN/m ²)	5.77–11.04	5.77–11.04

The ratio of upper-bank to edge cohesion is approximately 1.81, meaning that the lower bank retains only about 55% of the strength of the upper bank. Because bank shear strength enters the factor of safety through the cohesion term while the driving stress is greatest at the toe, this vertical gradient concentrate instability at exactly the location where vegetation reinforcement is least effective, since root density declines with depth and with distance from the trunk (Polvi et al., 2014; Kamath et al., 2025). The physical mechanics governing slope destabilization across the monitored sections are conceptualized in Figure 2.

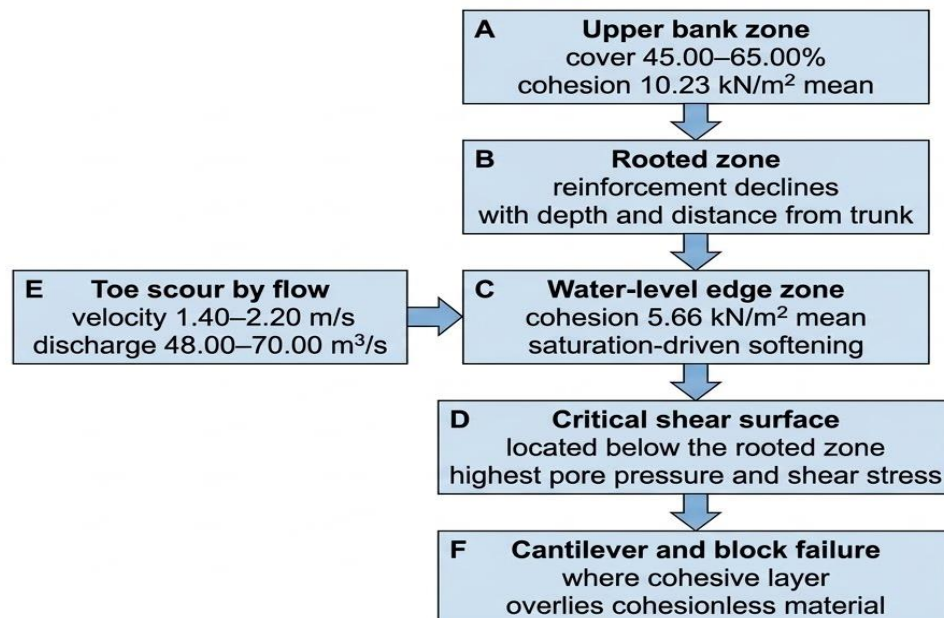


Figure 2. Conceptual bank profile showing the vertical strength gradient, the rooted zone and the position of the critical shear surface.

3.3 Vegetation–strength signatures by zone

Four zones with distinct vegetation–strength signatures were identified along the reach. The high-energy entry throat at L1 records the lowest edge cohesion on the profile (5.88 kN/m²), and the hydraulic energy drop at L2 produces rapid bank stabilization.

Cultivated bank encroachment between L7 and L14 coincided with declining cohesion from 8.29 to 7.01 kN/m², indicating root loss, and a continuous climb in suspended solids and turbidity attributable to local bank cave-ins. The undisturbed swamp forest between L15 and L28 recorded the maximum profile cohesion of 11.01 kN/m² with high root anchoring, stabilized erosion and controlled background sedimentation. The interaction between root networks and bank material properties across the distinct geo-fluvial regions is compiled in Table 2.

Table 2. Vegetation–strength signatures by reach zone

Zone	Key stations	Land-use code	Vegetation and strength signature
High-energy entry mouth	L1	Natural (3)	Lowest edge cohesion on the profile (5.88 kN/m ²); extreme shear failure
Hydraulic energy drop	L2	Natural (3)	Moderate cohesion; rapid bank stabilization; maximum deposition (6.20 kg/m ²)
Cultivated bank encroachment	L7–L14	Agricultural (2)	Declining cohesion (8.29 → 7.01 kN/m ²); root loss; local bank cave-ins
Undisturbed swamp forest	L15–L28	Natural forest (3)	Maximum profile cohesion (11.01 kN/m ²); high root anchoring; stabilized erosion

The cultivated section is the most informative zone in the dataset. Between L7 and L14 cohesion falls by 1.28 kN/m², a reduction of approximately 15%, with no compensating change in hydraulic forcing or bank geometry. The decline is therefore attributable to the loss of root reinforcement rather than to any change in driving stress, which is the clearest field demonstration in this dataset of the mechanical mechanism operating in isolation.

3.4 Comparison with reported root-reinforcement values

Measured cohesion (5.77–11.04 kN/m²) sits within the range that the geotechnical literature attributes to root reinforcement, though it occupies the lower part of that range. A comparative evaluation of external bio-geotechnical literature against the observed field metrics is structured in Table 3.

Table 3. Reported root-reinforcement values and stability effects compared with the present measurements

Source	Species, material or setting	Reported reinforcement or stability effect
Simon & Collison (2002)	Four riparian tree species and two erosion-control grasses	Tree roots raised soil strength by 2–8 kPa; grass roots by 6–18 kPa
Simon & Collison (2002)	Streambank plots, three riparian covers	Mechanical effect of tree cover raised Fs by 32% and 46% in two failure seasons; hydrologic effect added 71% and 29%
Simon & Collison (2002)	Grass cover	Mechanical effect raised Fs by 70% and 49%; hydrologic effect reduced Fs by 10% and 15%
Török & Parker (2022)	Granular, friction-dominated soil	Added apparent cohesion from root reinforcement typically falls in the order of tens of kPa

Pollen & Simon (2005)	Twelve riparian species, fibre-bundle formulation	Perpendicular root model overestimated reinforcement by up to 50%; F_s difference of 0.13–2.39 for a 3 m bank
Kamath et al. (2025)	<i>Salix fragilis</i> , <i>Salix purpurea</i> , <i>Crataegus laevigata</i> on canal banks	Measured root reinforcement raised F_s from 1.08 to 2.46 under worst-case conditions
Kamath & van de Kuilen (2026)	<i>Phragmites australis</i> , riparian zone	Root reinforcement maximum 36 kPa, average 6–19 kPa; RAR 0.03–0.65%, peaking at 0.65% near the canal
This study	Rooted cohesive deltaic bank material	Cohesion 5.77–11.04 kN/m ² ; upper-bank mean 10.23 kN/m ² ; edge mean 5.66 kN/m ² ; cover–erosion $r = -1.000$

Two features of this comparison deserve emphasis. First, the measured range straddles the values reported for both grasses (6–18 kPa) and trees (2–8 kPa) by Simon and Collison (Simon & Collison, 2002), which is consistent with a mixed agricultural and natural cover rather than a single-species assemblage. Second, the values are lower than the tens of kilopascals reported for granular friction-dominated soils (Török & Parker, 2022) and well below the maximum of 36 kPa measured beneath *Phragmites australis* (Kamath & Kuilen, 2026), which is the expected outcome in fine-textured cohesive material where root slippage rather than root breakage governs failure.

3.5 Field evidence for a limiting reinforcement

The reach provides indirect evidence of a ceiling on the reinforcement effect. Cohesion in the undisturbed swamp forest reaches 11.01 kN/m², the maximum observed, yet erosion there is stabilized rather than eliminated, and the cover–erosion relation remains monotonic across the full 45.00–65.00% range without any indication that additional cover is redundant. At the same time, the cultivated section loses 1.28 kN/m² of cohesion and shows a corresponding increase in suspended solids and turbidity, indicating that the loss of reinforcement is immediately reflected in bank behaviour. The data are therefore consistent with a monotonic benefit of cover up to the observed maximum, but they also show that even the strongest vegetated section retains measurable erosion, which is what a limiting-reinforcement model would predict.

4. DISCUSSION

4.1 Vegetation as the principal resistance term

The perfect inverse association between vegetation cover and bank erosion ($r = -1.000$), coupled with the strong direct association with deposition ($r = 0.888$), establishes vegetation as the dominant resistance term in this reach over the measured cover range. This is mechanistically consistent with the geotechnical evidence that roots raise bank strength by root reinforcement (Simon & Collison, 2002), with the finding that bank vegetation influences channel pattern through the added bank strength its root network provides (Gurnell, 2013), and with the demonstration that the strengthening effect of plant roots together with fine sediment generates a cohesive layer overlying cohesionless material, which changes the failure mechanism and reduces bank failure frequency (Zen & Perona, 2019). Experimental work confirms that vegetation establishment alters water velocity, depth and the power of shear stress, so that the resistance and the driving side of the balance change together (Gholami & Khaleghi, 2013).

The magnitude of the effect is consistent with reported reductions in bank erodibility. Field comparisons have found erodibility coefficients reduced by factors of two to three along some American rivers, a factor of five comparing bare with highly vegetated sites, and a factor of ten comparing humid Californian meadows with dry meadows (Perucca et al., 2007). A perfect inverse

correlation between cover and measured erosion at 101 stations is at the upper end of that range, which is itself informative: the strength of the association reflects the fact that cover in this reach co-varies with the structural class of the vegetation, since the highest-cover stations are undisturbed swamp forest and the lowest-cover stations are cultivated banks.

4.2 The vertical strength gradient and where reinforcement is needed most

The finding that mean edge cohesion (5.66 kN/m^2) is roughly half mean upper-bank cohesion (10.23 kN/m^2) has direct design consequences. Root reinforcement declines exponentially with depth and with distance from the trunk, and root area ratio decreases with depth for all species examined (Polvi et al., 2014; Kamath et al., 2025). Instrumented testing confirms that species differ in where their reinforcement is concentrated: *Salix fragilis* showed higher reinforcement at shallow depths ($\leq 250 \text{ mm}$), whereas *Salix purpurea* performed better at depth (Kamath et al., 2025). The consequence is structural: the zone of greatest hydraulic stress at the toe is precisely the zone where root reinforcement is least available.

Numerical benchmarking reaches the same conclusion from a different direction. Across all four plant combinations tested on idealized streambank slopes, the most critical shear surfaces occurred below the rooted zone, and the purely mechanical contribution of vegetation could not be decoupled from the hydrological reinforcement if a realistic assessment was to be obtained (Capobianco et al., 2021). The practical inference for the Erowha reach is that vegetation-based protection must be designed to cover the full bank profile rather than the upper bank alone, and that species selection should favour deeper-rooting material precisely because the shallow-rooting contribution cannot reach the critical surface.

4.3 A limiting reinforcement and what it implies for design

Instrumented testing of canal banks provides the clearest statement of a ceiling: measured root reinforcement raised the factor of safety dramatically from 1.08 to 2.46 even under worst-case hydraulic conditions, but the analysis indicated a limiting root reinforcement beyond which further increases had minimal impact on stability, and it was recommended that monitoring and design aim to achieve that minimum rather than a maximum (Kamath et al., 2025). The Erowha data are consistent with that model. Cohesion reaches 11.01 kN/m^2 in the undisturbed swamp forest, yet erosion there is stabilized rather than eliminated, and the cultivated section loses 1.28 kN/m^2 of cohesion with an immediate water-quality response.

The design inference is that restoring cover toward the upper observed bound of 65% is worthwhile, but that cover alone will not arrest retreat where toe scour is the controlling mechanism. This is not merely a practical caution; it follows from the physics. Root reinforcement is an added-cohesion term in the numerator of the factor of safety (Preti & Giadrossich, 2009), whereas toe scour removes material and steepens the profile, reducing the resisting length of the failure surface. Adding cohesion to the upper bank while the toe is progressively undercut does not address the mechanism that initiates failure, and field evidence from composite banks shows that such profiles fail by cantilever rather than by planar slip (Micheli & Kirchner, 2002).

4.4 Species selection and assemblage design

Vegetation-based solutions require species suited to specific locations and aimed at restoring the natural state and function of river systems, and selecting a combination of species along different bank zones can improve both biodiversity and stability (Capobianco et al., 2021). The evidence favours mixed assemblages. Across four plant combinations tested for species typical of southeastern Norwegian streams, the combination of trees, shrubs and grass delivered the highest hydro-mechanical reinforcement together with erosion protection and biodiversity benefit, with reinforcement most effective in spring and for combinations including low-height vegetation (Capobianco et al., 2021). Functional comparisons of fourteen riparian species support the same direction: woody

vegetation exceeds non-woody species in every root parameter examined, tree roots add significantly more cohesion than forb roots, and rhizomes may determine reach-scale effects (Polvi et al., 2014; Polvi & Wohl, 2013).

For a tropical deltaic bank, this implies prioritizing deep-rooted woody species and mixed grass–shrub–tree assemblages over single-species planting, and treating rhizomatous species as functionally distinct from non-rhizomatous graminoids (Polvi & Wohl, 2013). It also implies caution about assuming that any vegetation is beneficial. Species that colonize the lower bank may aid sedimentation without delivering the reinforcement needed at the critical shear surface, and where vegetation lowers the water table enough to alter the flow regime, instability can increase rather than decrease (Jordan et al., 2009).

4.5 Erodibility and critical shear stress as complementary indicators

Cohesion and the angle of internal friction describe mass-failure resistance, but fluvial entrainment is governed by the erodibility coefficient and the critical shear stress. These respond to vegetation as well. Measurements at twenty-five field sites using a submerged jet test device showed that erodibility depends primarily on soil bulk density, with freeze–thaw cycling, antecedent moisture, the density of roots of 2–20 mm diameter, soil texture and pore-water chemistry all exerting significant effects depending on soil type; streamside vegetation reduced erodibility through root reinforcement and also altered soil moisture and local microclimate (Wynn & Mostaghimi, 2006). On the Tigris River banks, the erodibility coefficient declined more and the critical shear stress rose more under vegetation cover than on bare soils, with the lowest erodibility coefficient of $0.4 \text{ cm}^3/\text{N}\cdot\text{s}$ occurring at a cover of 32.2%, and a minimum cover of 32.2% was recommended for bank protection (Attaee, 2022).

A commonly used shortcut is to multiply the critical shear stress by a vegetation coefficient, with reported values of 5.40 for sparse trees and 19.20 for dense trees (Clark & Wynn, 2007). The drawback is that this lumps soil reinforcement and particle shear-stress reduction into one parameter and prevents a process-based evaluation of how vegetation influences bank retreat (Clark & Wynn, 2007). The present dataset cannot resolve that lumping, because cohesion was measured on rooted composite material throughout and the root and soil contributions were not separated. This is the principal measurement limitation of the study.

4.6 Limitations

Three limitations should be stated plainly. (i) cohesion was measured on composite bank material, so the observed values combine intrinsic soil cohesion with root cohesion and cannot be partitioned; the hydrological and mechanical effects of vegetation are therefore not separable here, as is also the case in benchmark numerical work (Capobianco et al., 2021). (ii) the study is confined to one reach and one wet season, so the strength envelope of $5.77\text{--}11.04 \text{ kN/m}^2$ applies to the conditions observed and cannot be extrapolated without testing. (iii) the exactness of the cover–erosion correlation at the observed resolution warrants caution: a perfect coefficient across 101 stations with only three land-use classes reflects a strongly structured sampling design as much as an unconstrained field sample, and the coefficient should be reported with the land-use classes attached rather than as a context-free number. The wider literature also indicates that spatial variability of root reinforcement within the root zone can lead to overestimation of the root contribution if reinforcement is assumed uniform (Kamath et al., 2025), which is a caution that applies to any single-value strength parameter of the kind reported here.

5. CONCLUSIONS

The following conclusions are drawn from this study;

- i. Vegetation cover across the reach ranged from 45.00% to 65.00% (mean 55.00%) and was perfectly inversely associated with bank erosion ($r = -1.000$) and directly associated with deposition ($r = 0.888$), establishing vegetation as the principal resistance term over the measured envelope.

- ii. Mean upper-bank cohesion (10.23 kN/m²) was nearly twice mean edge-of-water cohesion (5.66 kN/m²), with an overall range of 5.77–11.04 kN/m², demonstrating saturation-driven softening at the bank toe where hydraulic stress is greatest.
- iii. The undisturbed swamp forest (L15–L28) recorded the maximum profile cohesion of 11.01 kN/m² with stabilized erosion, whereas cultivated encroachment (L7–L14) coincided with declining cohesion from 8.29 to 7.01 kN/m², a reduction attributable to root loss rather than to any change in driving stress.
- iv. Measured cohesion lies within the range attributed to root reinforcement in the geotechnical literature, falling between the values reported for grass roots (6–18 kPa) and tree roots (2–8 kPa) and below those for granular friction-dominated soils.
- v. Because root reinforcement declines with depth and a limiting reinforcement exists, vegetation-based stabilization should be designed to cover the full bank profile, with deep-rooting species in mixed tree–shrub–grass assemblages, and should be combined with toe protection where scour governs retreat.

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