Monitoring of riverbank stability and seepage undercutting mechanisms on the Iju (Atuwara) River, Southwest Nigeria

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Abstract. This paper presents the results of a monitoring programme designed to investigate the inherent factors contributing to channel instability and riverbank erosion on the Iju River, Southwest Nigeria. Detailed reconnaissance surveys and in situ measurements were used to determine the geomorphometric characteristics of the riverbanks at more than 15 locations along the river channel. Laboratory tests in combination with the Bank Stability and Toe Erosion Model (BSTEM) and Bank Erosion Hazard Index (BEHI) were conducted to determine the shear strength characteristics and erosion potential of the riverbanks. The BSTEM results indicate that the factor of safety (FS) decreased from the initial values of 2.64 and 4.42 to 1.09 and 0.51, respectively. Further correlation of FS with root depth and depth of tension crack showed that FS was positively correlated with root depth but decreased with an increase in the depth of tension crack. The high BEHI values of 26 and 32 gave credence to the assumptions regarding the high erosion potential of the Iju riverbanks. These research findings are essential for the development of a watershed-scale natural disaster mitigation plan for the Southwest region of Nigeria.

Keywords: Iju River, Stability analysis, Factor of safety, BSTEM, BEHI

1. Introduction
The instability of riverbanks is a common geomorphic feature in many riparian areas of Southwest Nigeria. An understanding of the key processes of riverbank retreat is essential for a detailed appraisal of the development of meandering channels and fluvial systems. The remarkably high rate of riverbank retreat currently occurring in many parts of Southern Nigeria has been attributed to natural and artificial events which produce flash floods that affect many low-lying watersheds and coastal regions. Consequently, stream/river impairments abound in these areas as a result of high volumes of watershed sediment yields that reduce the reservoir capacity, increase water quality problems and alter aquatic habitats [1,2]. The environmental challenges posed by these recurring natural phenomena are enormous and several millions of US dollars have been spent by the local, state and federal government agencies on gully erosion control and riverbank stabilization [3].

Riverbank retreat primarily occurs through the interconnected processes of fluvial erosion of cohesive bank sediments and mass failure of the bank under gravitational forces [4,5]. These processes have been found to occur through the combination of three dominant mechanisms: (i) seepage undercutting of the bank toe by exfiltration of groundwater from the bank; (ii) fluvial entrainment of soil particles from the riverbank by flowing water caused by hydraulic forces that remove the erodible bank materials; and (iii) gravity-driven bank failure or mass wasting of all or part of the riverbank due
to a decrease in shear strength of the bank materials [6-8]. Many documented cases of riverbank failures have reported an increase in the frequency of bank incisions and channel-width adjustments during the falling limb of river hydrographs. However, the significance of these processes in relation to riverbank instability and stream-channel adjustments within the watersheds of Southern Nigeria has not been fully understood.

There has been considerable debate on the reliability of results obtained from field (in situ) and laboratory (flume-scale) measurements of the hydraulic properties of riverbanks due to the challenges associated with: (1) accurate determination of seepage flow rates and sediment concentrations, (2) evaluation of seepage undercutting mechanisms and (3) some unavoidable scaling issues. Hence, many riverbank stability assessment tools have been developed for the reach-scale assessment of riverbank erosion potentials [4,8,9]. The Bank Stability and Toe Erosion Model (BSTEM) and the Bank Erosion Hazard Index (BEHI) have been widely used to evaluate the stability and erosion potential of riverbanks in many alluvial channels. For instance, Cancienne et al. [11] utilized the BSTEM model to investigate the stability of root-reinforced streambanks subjected to seepage undercutting. Their results suggest that the sensitivity of the BSTEM model to root cohesion was far lesser than that of water table elevation. Lindow et al. [12] combined lysimeter experiments and BSTEM modeling to investigate the stability of layered streambanks subjected to seepage erosion and bank undercutting. The authors stressed the inability of the BSTEM to predict seepage-induced failure of streambanks. However, they found that seepage gradient forces triggered pop-out failures and instability of the layered banks. Therefore, the primary aim of this research is to investigate the major factors contributing to the seepage-induced failure of riverbanks on the Iju River.

2. Materials and Methods

2.1. Study area

The Iju River (6°40'56"N, 3°8'46"E) is located in Ado-Odo/Ota Local Government Area of Ogun state in Southwest Nigeria (Figure 1). The river (also known as River Atuwara) and other adjoining streams make up small tributaries that feed into the 71.15 km-long Owo River, which flows southwest and empties into the Ologe Lagoon in Lagos state. The Iju River is an important component of the Owo River catchment. The entire catchment, which occupies a total area of about 1170.68 km² [13], falls within the humid tropical climate zone with a mean annual rainfall of about 1800 mm and a double rainfall maxima that are characterized by two high rainfall peaks. The study area, including the Owo River catchment, has a dense vegetation cover typical of savannah woodland with a dendritic drainage pattern that trends southward towards the South Atlantic Ocean.

Over the past three decades, many cases of human-induced modification of the natural hydrologic regimes of streams and rivers have been recorded in the Owo River catchment. The rapid increase in the population of Lagos and Ogun states of Southwest Nigeria has led to a series of alterations in the natural hydrologic disturbance regimes and sediment transport dynamics, thereby modifying the timing and sequence of sediment loading into the rivers, and thus causes a disruption of the entire fluvial system. These problems have been exacerbated by poor land-use practices, irrigation, overdrafting of groundwater, urbanization, and industrialization, especially in Agbara, Ota, Alimosho and other cities within the catchment area. Consequently, many cases of ecohydrological disasters are witnessed in these riparian areas due to overbank flood events that accentuate riverbank erosion and stream channel instabilities.

Geologically, the study area is entirely underlain by Oligocene to Recent coastal plain sands which are the youngest sedimentary unit in the stratigraphic sequence of the eastern Dahomey Basin. The fluvial system of the study area is characterized by wide undulating lowlands and stream channels which have stable and unstable bank heights that vary from 1.48 to 1.84 m. Along river courses, the sediments are predominated by coarse, poorly-sorted sands with clay lenses and occasional beds, while the coastal areas are primarily comprised of unconsolidated clayey sands. The Iju River displays low sinuosity index ($SI < 1.2$) with channel width that varies from 14 to 18 m. Bed sediments are predominantly composed of well-sorted medium-grained sand and gravel.
2.2. Geomorphometric characteristics of the riverbanks

Field reconnaissance surveys were conducted on the left and right banks of the river channel to investigate the inherent factors contributing to bank instabilities and channel width adjustments along the lower reaches of the river. Geomorphometric characteristics of the riverbanks such as bank face length, bank height, maximum bankfull depth, root depth, depth of tension crack, bank angle, and vegetation density were measured at twenty locations along the river reaches. Measurements across the river at different sites were used to draw cross profiles of the river channel and determine the morphology of the riverbed.

Generally, the banks of the Iju River can be divided into three main categories based on their stratigraphy and material composition, as follows (Figure 2): (1) Group 1 are composite banks comprised of sandy gravel at the base and an upper layer of silty clay; (2) Group 2 are homogeneous banks primarily made up of fine to medium-grained silty sand with occasional gravel and organic matter; and (3) Group 3 are layered banks which are characterized by upper alternating layers of silt and clay and a basal layer of imbricated coarse-grained sand with occasional gravel. Group 1 banks predominate the left side of the river channel and are sparsely observed on the right. This group is characterized by high values of bank height and bank angle with near-vertical bank faces that can be attributed to their relatively high shear strength values. Group 2 banks are limited to the fluvial plains on the right bank of the river, which present very low values of bank height and bank angle and owe their origin to many cycles of overbank flooding and sedimentation. Group 3 banks abound on both sides of the bank and are characteristically distinguished by the presence of many seepage erosion cavities, tension cracks and overhanging cliffs.
2.3. Geotechnical characteristics of the riverbanks

Undisturbed soil core samples were obtained from thirteen representative locations (six on the right bank and seven on the left bank) using standard U4 sampling tubes along with disturbed soil samples. The soil samples were subjected to a range of laboratory tests including particle size analysis, Atterberg limits, undrained triaxial tests, and phase relationship tests. A combination of sieve and hydrometer methods were used to determine the grain size distribution curves of the soil samples (Figure 3). Results of the tests show that the soils can be classified as inorganic clay, silty clay and silty sand following the Unified Soil Classification System (USCS). Majority of the soil samples ranging from IJ-2A to IJ-IC can be classified as inorganic clays of low to medium plasticity (ML) excluding IJ-1 which can be classified as inorganic clay of high plasticity (CH) and the IJA-2 series which are essentially non-plastic silty sand (SM).

2.4. Stability analysis of the riverbanks

The Bank Stability and Toe Erosion Model (BSTEM) was used to evaluate the stability of the riverbanks, and to determine the rate and amount of sediments eroded from the bank toe under differing geotechnical and hydrological conditions [5,14]. The BSTEM was developed by USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi, USA, as an effective mechanistic tool for evaluating riverbank erosion processes and channel width adjustments. The current version of the BSTEM model (version 5.4) is capable of evaluating both the geotechnical and hydraulic (fluvial) forces affecting riverbank stability by considering several factors including the river current dynamics, bank geometry, soil properties and groundwater conditions. Hence, the model is divided into two different submodels: a bank stability segment and a toe erosion segment [14]. The model calculates factor of safety (FS) as the ratio of the resisting force to the driving force by integrating three limit equilibrium-method models: horizontal layers, vertical slices, and cantilever failures. Following the shear stress equation proposed by Fredlund et al. [15] for the stability of soil slopes in unsaturated conditions, the BSTEM describes the shear stress for riverbanks as:

$$ S_r = c' + (\sigma_n - u_a) \tan \varphi' + (u_a - u_w) \tan \varphi^b $$

where $S_r$ = shear strength; $c'$ = effective cohesion (kPa); $(\sigma_n - u_a)$ = net normal stress on the failure plane at failure; $(u_a - u_w)$ = matric suction (kPa); $\varphi'$ = effective friction angle (°); and $\varphi^b$ = angle indicating increase in shear strength relative to matric suction. The stability of the riverbanks at different locations was analyzed using field measured geomorphometric characteristics of the banks and the geotechnical properties of the bank sediments which have been determined from laboratory tests.
2.5. Evaluation of erosion potential of the riverbanks

The erosion potential of the riverbanks was evaluated using the Bank Erosion Hazard Index (BEHI) which utilizes the geomorphometric characteristics of the banks and other key metrics to characterize the erosion potential of the riverbanks [16,17]. The BEHI is an alternative Rapid Geomorphic Assessment (RGA) method used for the assessment of riverbank hazard potential [18]. The BEHI integrates five riverbank key metrics which are based on the erodibility of the bank sediments (Table 1). The components of the riverbank metrics were obtained by direct measurement of bank height, bank angle, maximum bankfull depth and root depth, and visual estimation of vegetation density and surface protection. Based on Rosgen’s BEHI method [17], a BEHI value was determined using the measured riverbank variables at each of the bank sites. Subsequently, all the five bank metrics were given a risk rating of 1 (very low) to 10 (extreme).

Table 1. Scores of riverbank metrics used for the determination of BEHI [17]

| Category     | Bank Height Ratio (m/m) | Root Depth Ratio (%) | Root Density (%) | Bank Angle (°) | Surface Protection (%) | Total Index |
|--------------|-------------------------|----------------------|------------------|----------------|------------------------|-------------|
| Very Low     | Value                   | 1.0-1.1              | 1.0-0.9           | 100-80         | 0-20                   | 100-80      |
|              | Index                   | 1.0-1.9              | 1.0-1.9           | 1.0-1.9        | 1.0-1.9                | 1.0-1.9     |
| Low          | Value                   | 1.11-1.19            | 0.89-0.5          | 79-55          | 21-60                  | 79-55       |
|              | Index                   | 2.0-3.9              | 2.0-3.9           | 2.0-3.9        | 2.0-3.9                | 2.0-3.9     |
| Moderate     | Value                   | 1.2-1.5              | 0.49-0.3          | 54-30          | 61-80                  | 54-30       |
|              | Index                   | 4.0-5.9              | 4.0-5.9           | 4.0-5.9        | 4.0-5.9                | 4.0-5.9     |
| High         | Value                   | 1.6-2.0              | 0.29-0.15         | 29-15          | 81-90                  | 29-15       |
|              | Index                   | 6.0-7.9              | 6.0-7.9           | 6.0-7.9        | 6.0-7.9                | 6.0-7.9     |
| Very High    | Value                   | 2.1-2.8              | 0.14-0.05         | 14-50          | 91-119                 | 14-10       |
|              | Index                   | 8.0-9.0              | 8.0-9.0           | 8.0-9.0        | 8.0-9.0                | 8.0-9.0     |
| Extreme      | Value                   | >2.8                 | <0.05             | <5             | >119                   | <10         |
|              | Index                   | 10                   | 10                | 10             | 10                     | 10          |
3. Results and Discussion

3.1. Stability analysis

Stability analysis of the riverbanks was carried out on both sides of the river channel using the geotechnical and geomorphometric characteristics of the banks. The analysis was done by considering different depths to the water table, material properties of the banks, water surface elevation, depth of tension cracks, and effect of riparian vegetation (root cohesion). Stability analysis was conducted on the left side of the river channel over a 120-hr flow duration considering a 5-layer bank of maximum height and slope of 1.5 m and 81°, respectively. The result shows that the banks without tension cracks were mostly stable with factor of safety (FS) values that ranged from 1.85 to 2.64. However, a majority of the banks which have tension cracks were relatively stable and conditionally stable depending on the depth of the tension crack. Furthermore, two streamflow elevations of 0.55 and 1.2 m were simulated to account for seasonal variations in the river stage and its effects on bank stability. The result indicated an FS of 1.63 and 2.58 for streamflow elevations of 0.55 and 1.2 m, respectively.

To assess the role of tension cracks in the acceleration of the riverbank retreat, an analysis of the bank stability was carried out using three average values of tension crack depths: 0.2, 0.3, and 0.4 m. The result indicated FS values of 1.33, 1.22, and 1.09 for tension crack depth of 0.2, 0.3, and 0.4 m, respectively (Figure 4). In order to account for the effects of the riparian vegetation, a stability analysis was conducted by incorporating the root-reinforcement model (RRM) and using a root cohesion ($c_r$) of 0.9 kPa with an average root depth of 0.6 m. The result showed a 5.5% increase in FS from 1.63 to 1.72, indicating the significant effect of vegetation in increasing the stability of the bank.

The results obtained from the simulated bank with a minimum height of 0.95 m and bank angle of 77° showed that the bank was initially stable with FS of 4.42. The bank comprises an upper layer of partially consolidated silt (0.8 m) and an underlying 0.15 m-layer of moderately consolidated silt. However, FS gradually decreased from 4.42 to 0.51 (unstable) under a flow duration of 312 hrs. Similarly, a 6.1% increase in FS was obtained with a root cohesion of 0.9 kPa, for the simulation done by incorporating the effects of bank top vegetation (wet meadow grass with mean root depth of 0.6 m), indicating that FS increased from 4.42 to 4.69.

![Figure 4](image-url)

**Figure 4.** Geometry of the riverbank for a 120-hr flow duration showing: (a) FS for low river stage conditions, (b) FS with tension crack depth of 0.3 m, (c) FS with tension crack depth of 0.4 m and (d) FS for high river stage conditions.
Whilst stability analysis conducted with the BSTEM indicated that the riverbanks are marginally stable considering the shear strength properties of the bank materials. However, field observations showed sustained and gradual undercutting of the bank toe (left bank of the river channel) and subsequent failure that emanated from several tension cracks which commonly develop during low river stages (Figure 5). This failure mechanism can be summarized in two episodes: Episode I (rising limb of the river hydrograph) and Episode II (falling limb of the river hydrograph). In Episode I, the initial stability of the banks depends on matric suction because the majority of the banks are partially saturated as a result of the low water stage conditions [19]. However, under a steady rise in the river stage, water seeps into the banks causing the soil to attain partial or full saturated conditions which at the same time increase the $FS$ of the bank due to the hydrostatic pressure of the river on the bank. In Episode II, the falling limb of the river hydrograph induces seepage erosion processes that lead to the lowering of the water table which emerges from the bank face through many seepage erosion cavities (Figure 6). This exfiltration process triggers mass outwash of the fluidized bank sediments, which at the same time destabilizes the bank by reducing the shear strength of the soil, and thus, leads to the gradual retreat of the riverbank [20-22].

Figure 5. Typical failure mechanism of the riverbank (a) Top view of the bank showing tension cracks and overhanging cliffs (b) Horizontal extent of the tension cracks.

Figure 6. Mechanism of seepage undercutting of the riverbank. (a) Seepage erosion cavities on the bank face. (b) Seepage undercutting and tension crack-induced mass wasting.

3.2. Evaluation of erosion potential of the riverbanks
The results of the BEHI analysis indicate that virtually all the banks on the right side of the river channel had moderate BEHI values with an average total index of 26. In contrast, the banks on the left side of the river channel showed high erosion potential with an average (BEHI) value of 33 (Table 2). Analysis of the riverbanks with respect to BEHI revealed a negative relationship between the channel
width and the bank height. The result showed that BEHI and bank height decreased for every increase in channel width. Analysis of geomorphometric data collected from April 2017 to March 2019 indicated that the left side of the riverbank has an average bank erosion rate of 0.15 m/yr. Similarly, the relatively low root depth ratio displayed by the riparian slope, especially on the left side of the channel, demonstrates high susceptibility of the bank to erosion, given that majority of the banks has sparse vegetation cover with a maximum root depth of 0.15 m. The river channel had an average height of 1.47 m (left bank) and 0.93 m (right bank), while the mean bank angles were 85 and 71° for the left and right banks of the river channel, respectively. Overall, the absence of any form of surface protection coupled with active undercutting of the bank slope, and lack of secondary reinforcement in the form of vegetation (root cohesion) or riprap, all contributed to the high erosion potential of the riverbanks.

Table 2. Aggregate scores of riverbank metrics determined from the Iju River

| Bank Location | Bank Height Ratio (m/m) | Root Depth Ratio (%) | Root Density (%) | Bank Angle (°) | Surface Protection (%) | Total Index |
|---------------|-------------------------|----------------------|------------------|----------------|------------------------|-------------|
| Left          | 1                       | 8.5                  | 8                | 7              | 8.5                    | 33          |
| Right         | 1                       | 7.5                  | 4.5              | 5              | 8                      | 26          |

4. Conclusions
The lower reaches of the Iju River and other stream courses within the Owo River catchment have experienced many alterations in their natural hydrologic disturbance regimes and sediment transport dynamics brought about by artisanal sand mining and occasional dredging of the riverbeds. These effects have caused a disruption of the entire fluvial system, which have triggered many ecohydrological disasters and stream channel instabilities. This paper presents preliminary results of a proposed three-year monitoring programme initiated to evaluate the inherent factors contributing to channel instabilities on the river. Based on a series of field investigations, reconnaissance surveys, laboratory tests, and stability analysis, the following conclusions were drawn:

- The integration of BSTEM and BEHI methods showed that the banks of the Iju River are fairly stable and bank failures are seasonal as they mostly occur during the dry seasons (November to March), especially during the recession limb of the river hydrograph.
- A majority of the bank failures were triggered by seepage undercutting of the bank toe followed by geotechnical failures from pre-existing tension cracks. Consequently, bank retreat was higher in the banks comprised of different layers of sediments and much lower in banks dominated by overbank floodplain deposits.
- Planar (slab-type) and alcove-type failures constitute the dominant mechanisms of riverbank erosion on the Iju River and comprise more than 70% of all bank failures on the river channel. Pop-out failures dominate the composite and layered banks and typically occur during the recession limb of the river stage as water exfiltrates from the bank through the highly conductive layers. Cantilever failures were distinguished by the preponderance of many overhanging cliffs and tension cracks with depths ranging from 0.15 to 0.2 m.

Acknowledgements
The authors gratefully acknowledge the management of Covenant University for the conference support.

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