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Impact of Dredging the Okpoka River on Coastal Infrastructure: A Case Study of the Akpajo Bridge

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Abstract:
The Akpajo Bridge is deteriorating by the day and steadily awaiting eventual collapse due to extensive sand excavations in river beds proximal to the bridge. Sand mining has deepened the river channel, altered the hydrodynamics of the channel flow, increased river discharge beneath the bridge, accelerated shoreline erosion, scoured the piers thereby reducing the axial pile capacities supporting the bridge and ultimately compromising the safety of the bridge. Large scale sand mining from river beds is continuing on a scale never seen before in the Niger delta, due to the necessity of reclaiming land for development purposes and to meet construction needs in the region. Regulations are weak, monitoring of sand mining is non-existent. There is also a general lack of understanding of the risks to coastal infrastructure involved with sand mining in river beds. This paper investigates the threat to the stability and safety of the Akpajo bridge caused by the extensive mining of sand in the area. It establishes through computational analysis that a minimum distance of 94m (for sand river beds) from a bridge should be observed to guaranty the safety of bridge foundation. For clay riverbeds, slightly shorter minimum distances can be considered safe. The study further shows that the capacity of sand borrowing in river channels to generate bank instability is dependent on the composition and stratigraphy beneath the river bed.

INTRODUCTION

The excavation of sand from riverbeds is an age long practice in the Niger delta. It was initially considered sustainable when only artisanal miners were involved. The 1980s witnessed the involvement of large-scale operators who usually deploy a range of dredgers. The several potential adverse impacts of indiscriminate sand mining are well documented in literature (Bull and Scott, 1974; Collins et al.; 1990, Lake and Hinch, 1999; Padmalal et al 2008; Anooja et al 2011;). The most significant of these being: (a) bed degradation and consequent effects on channel and bank stability, (b) increased sediment loads, decreased water clarity and sedimentation; (c) changes in channel morphology and disturbance of ecologically important roughness elements in the river bed; (d) resuspension of contaminated sediment and release of contaminants with consequential ecological effects on bird nesting, fish migration, angling, etc. e) modification of the riparian zone including bank erosion; (f) direct destruction from heavy equipment operation; g) discharges from equipment and refueling; (h) Reduction in groundwater elevations; i) impacts on structures and access; (j) biosecurity and pest risks; (k) impacts on coastal processes. On the lowering of the base level of the river, Padmalal et al (2008) reported a case study in which riverbed in the storage zone was lowered at a rate of 7–15 cm y^{-1} over the past two decades. The lowering of base level, in turn, causes accelerated river bank erosion which imposes severe damages to the physical and biological environments of the river systems.

A majority of bridge damage accidents are caused by the unreasonable excavation of river sand by altering the hydrodynamics around bridge piers which in combination with reduced axial pile frictional capacity and exposes bridge foundations. Consequently, foundations are scoured, which reduces bearing capacity. The Chinese Code for Design of Bridges Foundation (Peng and Pang 2014) stipulates that the loads on top of friction piles should be mainly borne by pile side resistance. The dredging around bridge foundations loosens the soil, reducing the frictional resistance of the piles, leading to reduced bearing capacity of the pile foundation, thereby threatening the safety of structures and even leading to bridge collapse.

The dredged sand is used mostly for construction and as fill for land reclamation projects. Reclamation has remained a veritable source of creating new land for development in the region, where usable land is a premium. This is due to a combination of factors including: relatively low elevation of the region with respect to surface water level and widespread occurrence of compressible sediments. Extensive areas of swamp land are therefore periodically reclaimed by Hydraulic sand-fill, dredged from surrounding rivers and creeks.

Due to lack of understanding of the ground response to the excavation and removal of surrounding sand materials, such river bed and neighboring river banks progress into degradation, beginning with insipient motions of grains (Porto and Gessler, 1999) and in the process threatening the safety and stability of major coastal infrastructures in the area.

The process of incipient motion and suspension in natural rivers is closely related to the problem of critical shear stress of sediment mixtures Shields (1936), van Rijn (2022). Shields (1936) proposed his widely accepted criterion for incipient motion of uniformly sized bed material:

$$\frac{\tau_c}{(\gamma_s - \gamma_w)D_s} = f\left(\frac{u_* D_s}{\nu}\right) \qquad \text{...1}$$

Where τ_c = critical shear stress;
G_s = specific weight of sediment;
G_w = specific weight of the fluid;
D_s = diameter of the grains;
υ*= shear velocity; and υ = kinematic viscosity of fluid.

The critical depth-averaged velocities at initiation of motion and suspension for sediment with d50 between 0.1 and 2 mm was proposed by L.C. van Rijn (2022) and presented graphically in Fig. 1.

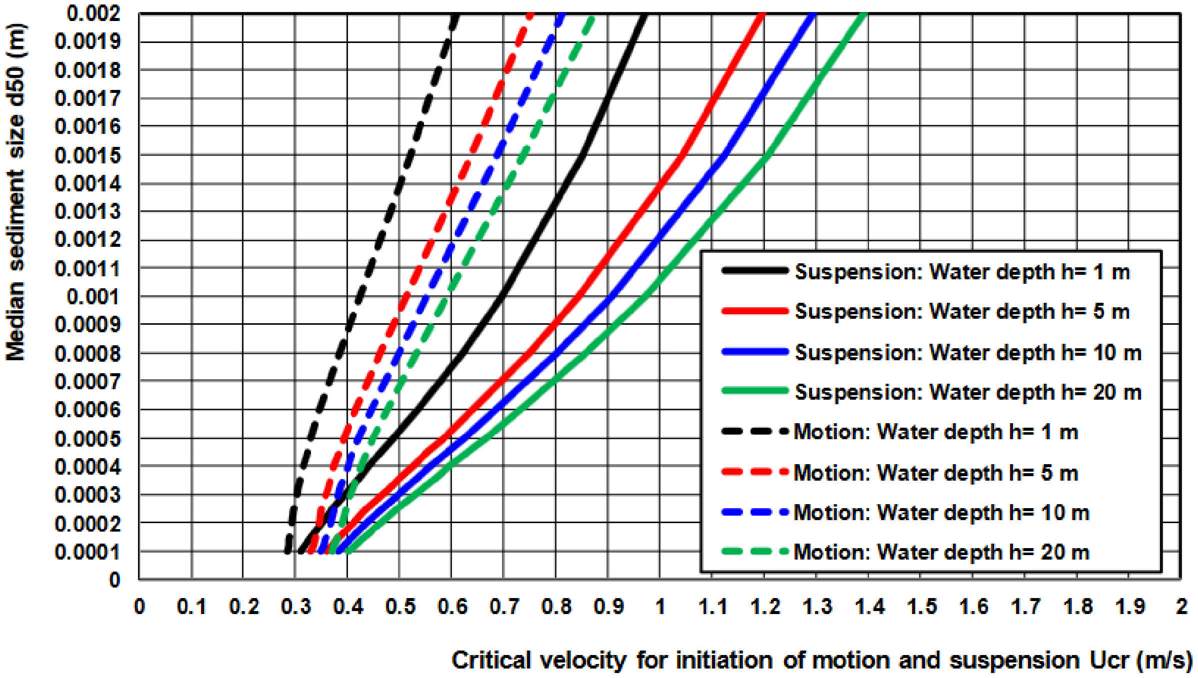


Figure 1: Depth-averaged velocity at initiation of motion and suspension (after van Rijn, 2022)

The applicability of the equations by Shields (1936) and van Rijn (2022) are limited because the criterion was established for uniformly sized bed material, a condition hardly met by all riverbeds in an attempt to generalize the criterion for sediment mixtures a number of authors have suggested the use of a single "representative" diameter for the mixture.

This equilibrium slope of river beds differs from the stable slope of river banks which have been elaborately discussed by several researchers, including, Thorne (1982), Abam (1993), Abam and Omuso (2000). Consequently, two types of equilibrium slopes are implicated by sand borrow in river channels. This paper explores the mechanisms of river bed and bank instability triggered by hydraulic sand mining within river channels and focuses on the Akpajo bridge foundations and abutments to illustrate the dangers posed to its stability and safety, and to ensure that sand extraction is carried out in a sustainable way to maintain river equilibrium by determining minimum safe distances for dredging purposes.

REGIONAL GEOLOGY AND SITE DESCRIPTION

The geological formations in the area consist of the Quaternary sedimentary deposits, and the Tertiary Coastal Plain Sands, generally referred to as Benin Formation. The Quaternary sediments give rise to alluvial plains. The alluvial plains include the estuarine sediments, which are under the influence of tidal brackish waters along the coast and in the estuaries of rivers and creeks.

The general geology of the area therefore reflects the influence of movements of rivers, in the Niger delta and their search for lines of flow to the sea with consequent deposition of transported sediments. The surface deposits in this area comprises silty and sandy-clays. These surface layers vary in thickness from 4m to about 9m and very rarely 12m before transiting to sandy formation. The sandy layers underlying the silty-sandy clay are predominantly medium to coarse in grain sizes and found to exist in mostly medium state of compaction. It is this sand that is widely extracted through dredging for construction and reclamation.

METHOD OF INVESTIGATION

Tidal data was obtained from records of ADCP measurement in nearby creeks. Information on tidal velocity is important not only for predicting the initiation of particle entrainment, but also for the management of transported/buoyant pollutants, which in this case would largely be silt dislodged by the dredging process. Tidal velocities determine the extent of transport of silt particles re-suspended by a dredging operation and assist in the choice of optimum locations for silt curtains to prevent wide spread silt contamination.

Four borings were made in study sites using a workshop fabricated light shell and auger percussion rig mounted on a portable barge. During the boring operations, disturbed samples were regularly collected at depths of 0.75m intervals and also when change of soil type is noticed. All samples recovered from the boreholes were examined, identified and roughly classified in the field and used in the production of lithostratigraphy of sediments beneath the seabed. Particle size distribution analysis was carried out in accordance with the British standards (BS 1377 of 1990) in order to classify the sandy units.

RESULTS

The river system is subject to diurnal tidal inundation with Mean Tidal level averaging 1.52m. Tidal velocities vary across the tidal cycle, with peak velocities up to 1.4m/s occurring at mid ebb tide (Fig.2), with depth averaged velocities that are able to entrain and transport sediments generated as a result of dredging within the river system.

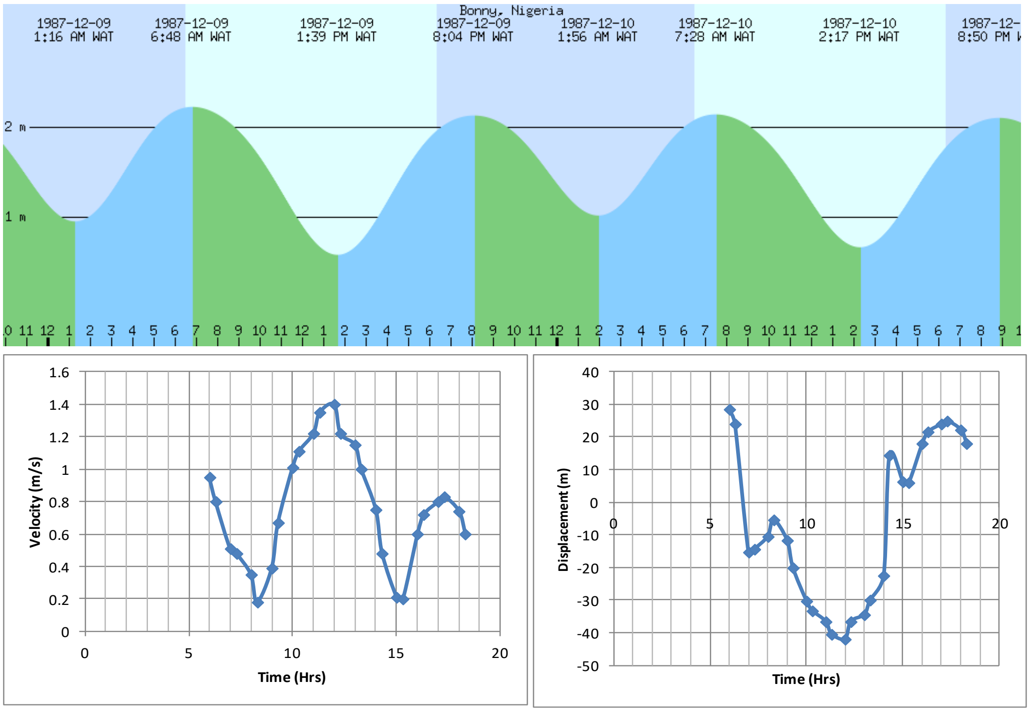


Fig. (2): Tidal regime in study area

The excavation of sand from the river bed created large borrows of 40m diameter and 18m in depth in scattered locations. These pits intercept and trapped bed load, creating a deficit in the transported sediment and disrupting the sediment transport equilibrium of the river/creek. In a bid to re-establish this equilibrium, the river increases its appetite for erosion, beginning from the most vulnerable areas. Firstly, sub-aqueous slope failures will occur in the near vertical slopes of the pits, altering the bathymetry and creating a steeper basal configuration with comparatively faster flow velocities, with correspondingly higher erosive power and increased capacity for transportation of entrained sediments.

The identification and prediction of the spatial distribution of bank processes, the tendency for lateral channel mobility, and its controlling factors collectively form an important issue. As a first approximation, the lateral mobility distribution at a river network scale can be related to interaction between Stream Energy and boundary resistance. It is also well recognized that bank retreat is the integrated product of three interacting groups of processes (subaerial processes, erosion processes, and mass wasting).

Extraction of aggregates alters the channel geometry and flow pattern, thereby redirecting the main flow trajectory, causing changes in the patterns of erosion and deposition.

CASE STUDIES

An estimated 1.5x10^6 m^3 of sand has been extracted for various construction activities through dredging of the riverbed between 1980 and 2022. In order to fully appreciate the dredging impact on this river, three case studies on the same river at different reaches as shown in Fig (3) are presented.

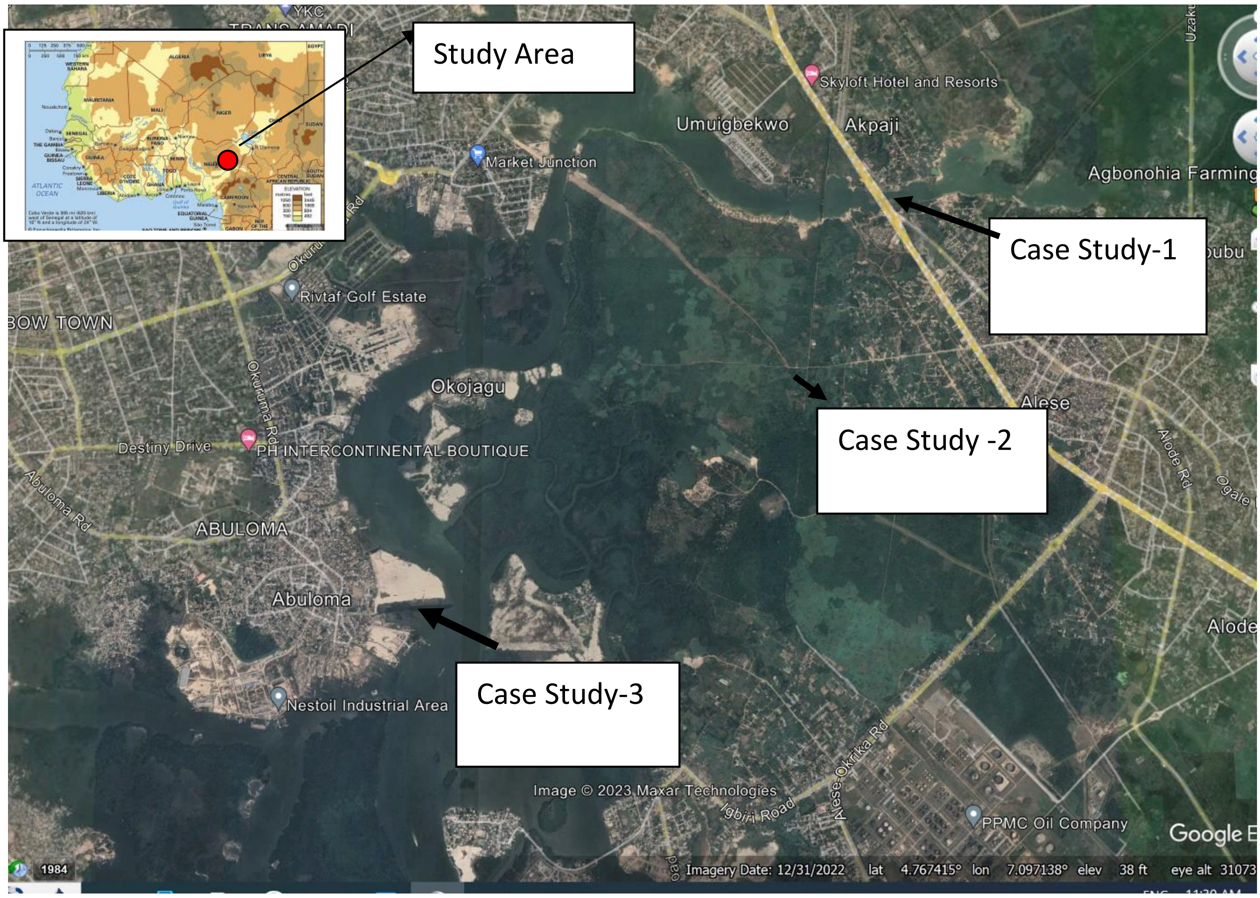


Fig. (4): Relative locations of Case Studies

Case Study 1

Comparative satellite imageries of the Akpojo bridge area in 1985 and 2022 (Fig.4) reveals significant changes in landuse triggered by sand dredging within the creek channel. As a result, sections of the creek show shorelines that have shifted, resulting in the widening as well as deepening of channel cross-section.

1985 2022

Fig. (4): Comparative Satellite images of the Upstream Okpoka Creek at Akpajo Bridge

In much the same fashion, the dredging lowered the basal level, triggering sub-aqueous slope and riverbank instabilities. The evacuation of the additional volume of water in the excavated space within the diurnal tidal cycle implies that flow velocities and by extension the discharge would be increased. Measured tidal velocity based on timing of floats indicated an increase of 37% in the peak ebb tide flow velocity. The combined effect of slope instability caused by basal lowering of the riverbed and the increased tidal discharge through the bridged channel section eroded the abutment and is currently threatening the stability of the bridge itself. Fig. (5) shows the current state of the bridge abutment, with eroded banks and scoured piles which effectively reduces pile capacity.

Fig. (5): Akpajo Bridge abutment deterioration Upstream Reach Okpoka River

Repeated attempts to protect the bridge with crushed stones gabion construction have failed, because the protective structure could not withstand the turbulence associated with the increased flow.

Case Study 2

This case study explores the on-going Worji-Alode Bridge Crossing, some 1km downstream of the Akpajo bridge. This section has steeper and actively eroding banks (Fig.6) as well as deeper basal levels occasioned by dredging of sand in the river channel. Although the soil is generally firm to stiff, they lose strength rapidly when in contact with water.

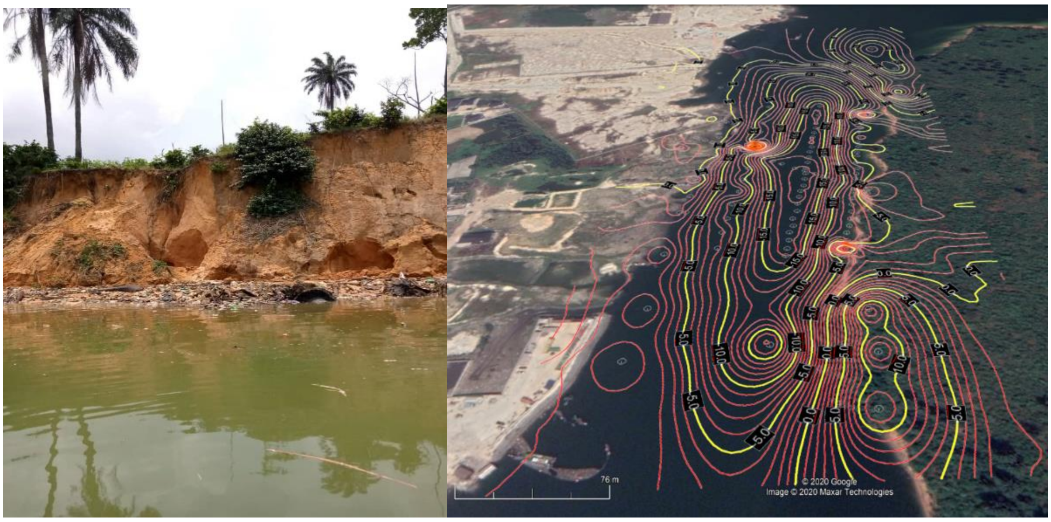


Fig. (6): Riverbank conditions and Bathymetry at midstream Okpoka River at Alode-Worji crossing

The geologic cross-section (Fig.7) shows the preponderance of sand at shallow depths overlain by a firm to stiff sandy clay top soil varying in thickness from 3m to 9m on the Alode end and mostly soft organic clay with thicknesses between 4 to 6m at the Worji end (Table 1). The top of the sand layer coincides with the low-tide level. Fluvial erosion of the top section of the sandy layer results in steepening the riverbank and increasing its vulnerability to failure. Slope stability analysis of the riverbanks indicate factors of safety between 1.1 and 1.3. This state of marginal stability suggests that the emergence of any additional causative factor is likely to cause bank failures. This further implies that additional bank stabilization measures are necessary to protect the abutments as well as coastal infrastructure in the area.

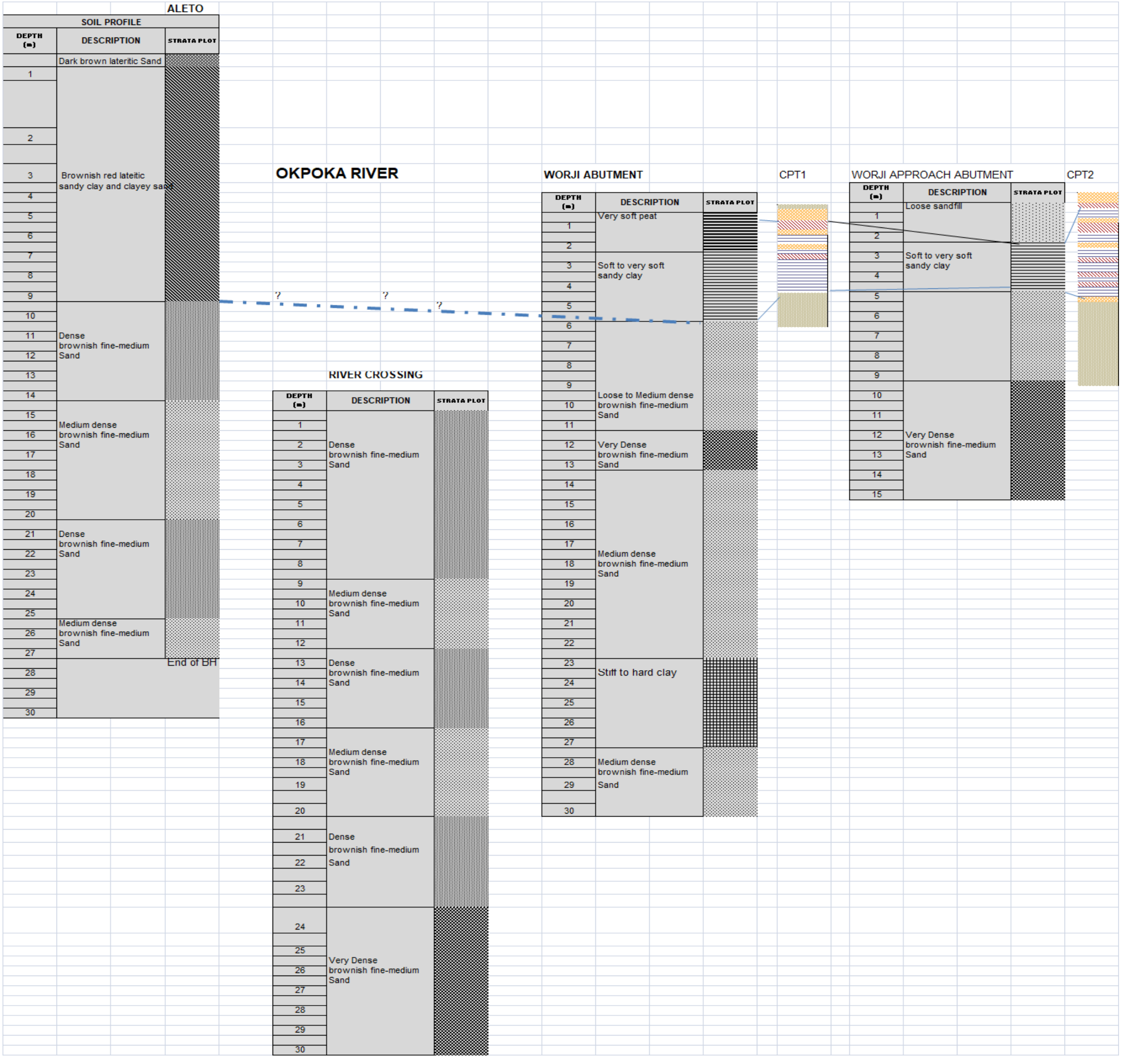


Fig. (7): Geologic cross-section of the midstream Okpoka River

Table (1): Geotechnical properties of the riverbank soils

BH No.	Depth (m)	Natural Moisture Content (%)	Bulk Unit Weight γ (kN/m³)	Undrained Cohesion Cu (kN/m²)	Friction Angle φ (Deg.)	LL	PL	PI	Description of Sample
1 (Alode end)	1.5	13.5	20.7	75	11	30.2	9.2	21	Stiff dark brown sandy clay
	3	12.7	20.3	98	13	27	8.9	18.1	Stiff reddish dark brown silty clay
	6	14.8	20.4	90	16				Stiff reddish brown sandy clay
3 (Worji End)	3	26	16.2	16	2	22.7	15.7	7	Very soft to soft dark grey silty clay
4 (Worji End)	3	49	15.3	25	2	23.3	16.8	6.5	Soft to soft dark grey silty clay

Case Study 3

This case study explores the incidence of accelerated erosion triggered by dredging neighbouring sections and deepening of river channel up to 14m (Fig.8). This activity compromised the functioning of a drainage channel, resulting in discharge redistribution and consequently accelerated erosion (Fig.9). By measuring channel dimensions and flow velocity, discharges from the interconnected drainage channels were computed and compared to values prior to dredging. The results indicated 30% increase in discharge through the tertiary channel, suggestive of lateral channel expansion, which is equated to accelerated bank erosion, of approximately 3m.

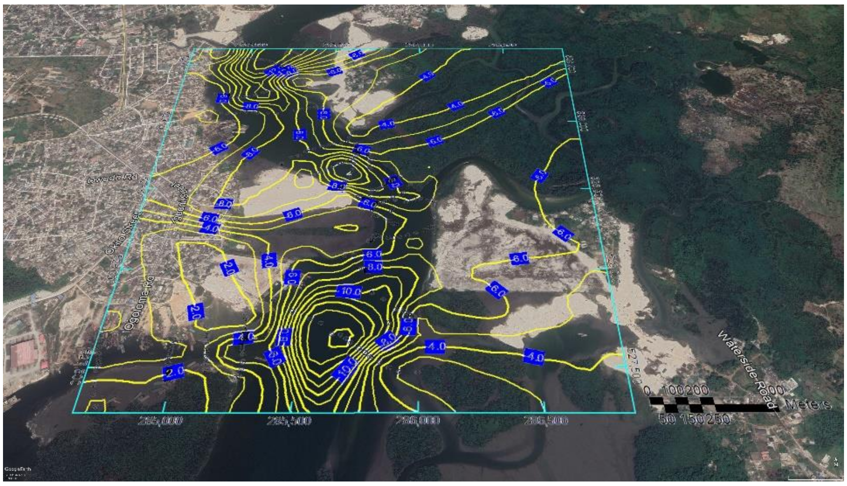


Fig. 8: Bathymetric contours superimposed over Satellite imagery of section of study area

Fig. (9): Failed sections of River Bank due to accelerated erosion

DISCUSSION

Assessment of Threat to Bridge and Other Coastal Structures

One major consequence of dredging the Okpoka River is the deepening of the water channel which has implications on the stability of coastal infrastructure and river banks, besides the dislodgement of aquatic ecosystem and effects on the physical hydrology. In some cases, these potential effects are evaluated during Environmental Impact Assessment.

To further illustrate the effect of channel deepening on bank stability, the channel cross-section at the narrowest reach was 50m wide and 3m deep in 1980. By 2022, this section has widened to 95m and 8m deep. This translates to a discharge of $2.43 \times 10^5 m^3/hr$ in a tidal cycle in 1980 against $3.28 \times 10^6 m^3/hr$ in a tidal cycle in 2022. The discharge of such large volumes beyond the design discharge is bound to scour the bridge piers and erode the abutments, the evidence of which is already manifested in Fig. (5). Furthermore, dredging of the riverbeds deepens the basal level of the riverbanks, making them less stable and more erodible. Due to the narrow width of the channel close to the bride, the effect of lowering the basal level on bank stability is felt much faster. The deeper the sand Burroughs, the wider their potential lateral impact on the channels.

The minimum safe distance from river bank or bridge structure to dredge point has already been determined by Abam *et al;* (2023) considering angle of repose of dredged sand materials in the area. In general, environmental safety of the river bank requires that as a minimum horizontal distance, X is greater than d/Tan (Angle of repose); i.e, the ratio (d/X) should always be less than 0.32 and must not exceed 0.40.

The angle of internal friction in shear test, which approximate the angles of repose, ranged from 26° to 32°. Under submerged conditions, these angles would range from 28° to 33°. Applying a factor of safety FS = 1.5; these angles of repose would then range from 18° to 22°. At FS = 2.5 which takes account of the sensitivity of the coastal infrastructure, the corresponding angles of repose would be 11° to 13°, which would translate to a minimum safe distance of 94m for a dredging operation requiring a dredging arm with a capacity of 18m of dredged depth.

The instability created by the presence of a sub-aqueous borrow pit would extend over an area, the longitudinal extent of which can be estimated by considering the schematics in Fig. (10).

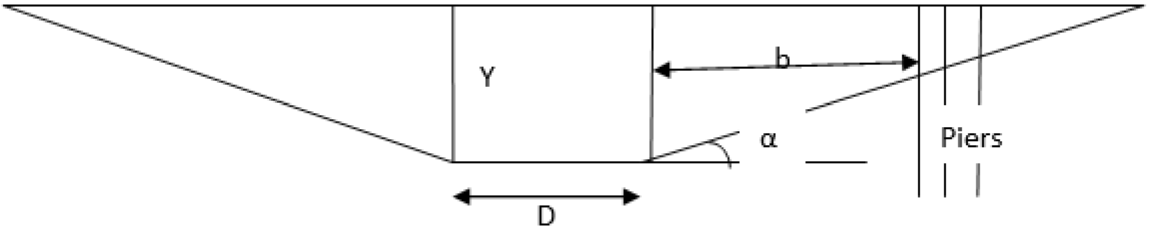
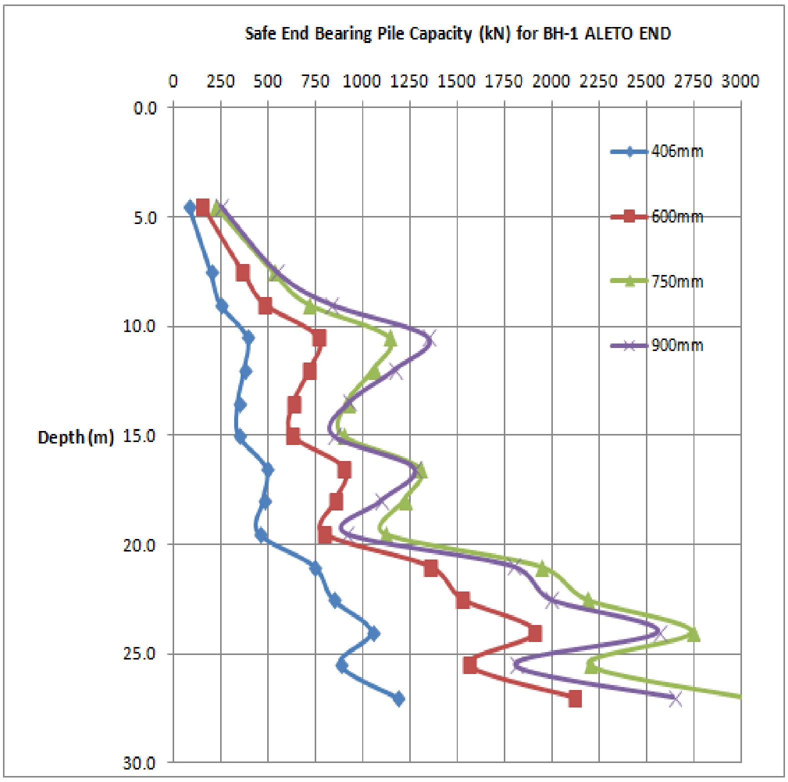


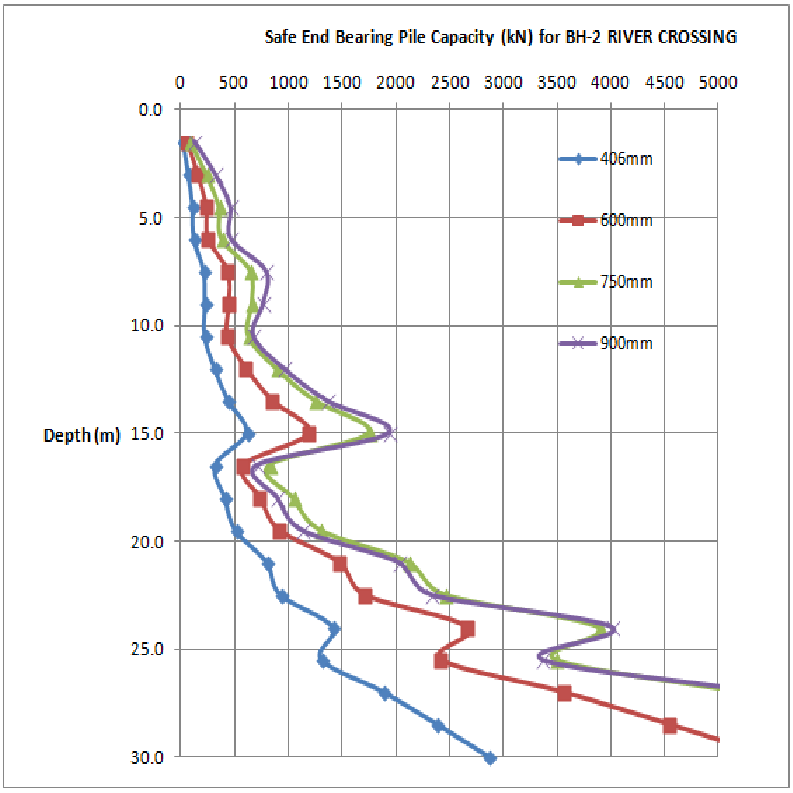
Fig. (10): Schematics for assessing area of influence of sub-aqueous borrow pit

α = angle of repose
D = diameter of borrow pit

The implication of this is that, if the measured width of a river channel is less than the predicted safe distance, then river bank instability induced by dredging is imminent.

The potential for scour for the bridge foundation and abutment was also assessed based on the hydrology of the study area, with tidal velocities peaking at 1.2m/s. The turbidity of the water indicated the movement of substantial suspended load in the flow. Since there is reasonable narrowing of the flow area at bridge crossing location, the river flow velocities are expected to increase significantly. Under these flow conditions, it is highly probable for the development of scour around the bridge piers and abutments. Furthermore, if a bridge pier is within the area of influence of a borrow pit, then it is probable that additional scour arising from bed instability caused by the pit can be introduced. Such scour is to be checked against the depth of pile embedment in order to assess its significance with respect to the continuing stability of the pile or pier as the case may be. Fig. (11) presents the axial pile capacities for various pile diameter on the proposed Worji-Alode crossing. Scour resulting in the removal of 8m of bed material is expected to reduce axial pile capacity by 34% or more.





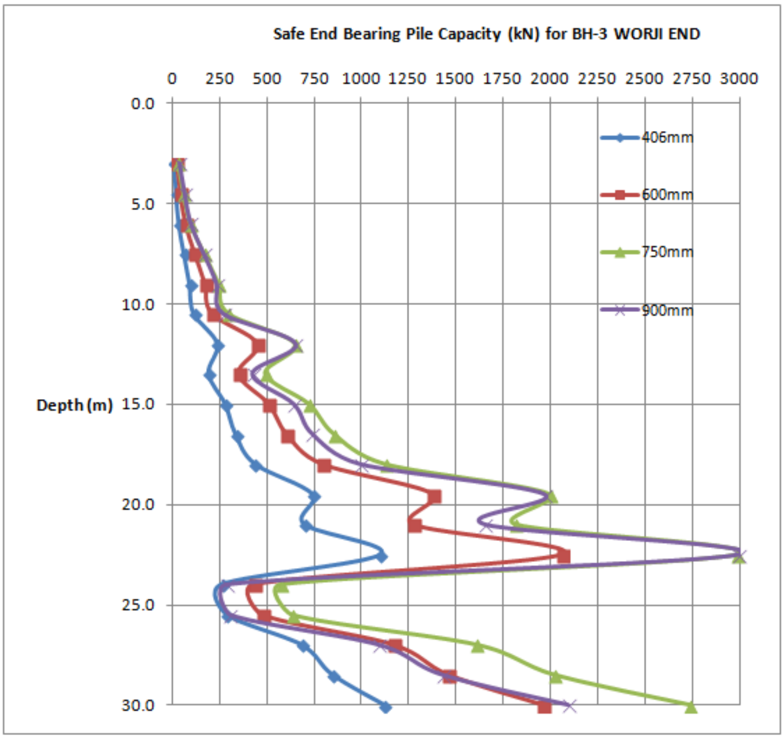


Fig. (11): Axial pile capacity of driven piles across the Okpoka River.

CONCLUSION

Sand mining from river beds has considerably altered the river form and is threatening the stability of coastal infrastructure. Bridge foundations as well as abutments can be vulnerable to scour and erosion, if the choice of dredging locations on river channels are not properly guided. There is need to develop regulation for sand mining activities in inland rivers. Based on this study it is shown that a minimum distance of 94m (for sand river beds) from a bridge should be observed to guaranty the safety of bridge foundation. Furthermore, it is concluded that the ability of sand borrowing in river channels to generate bank instability is dependent on the composition and stratigraphy beneath the river bed.

RECOMMENDATION

There is a need for the Ministries of Environment to be equipped with the necessary planning and management tools to deal with the problems that arises from river sand mining and this study is an effort in this direction.

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