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Impact of Dredging on Coastal Infrastructure: Case Studies from Okrika and Port Harcourt, Niger Delta

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Abstract

Sand excavations in river beds have compromised the safety of several bridges in recent years. Large scale sand mining from river beds is now common in the Niger Delta, due to the necessity of reclaiming land for development purposes and to meet construction needs in the region. There is currently no regulation as to where sand can be mined in river channels because of the lack of adequate understanding of the risks to coastal infrastructure involved with its abstraction. The phenomenon of bridge Abutment and bank failure induced by excessive dredging of sand river bed is considered. Two types of instability were distinguished, one relating to the equilibrium slope of the riverbed and the other riverbank instability. An empirical relationship in the form $X_s = 3H\tan(90 - \alpha)$ has been developed through analysis, supported by examples that a minimum distance of 94 m (for sand river beds) from a bridge should be observed for sand abstraction in order 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.

Keywords

Dredging, Impacts, Coastal Infrastructure, Niger Delta

1. Introduction

In recent years, the excavation of river sand has become increasingly widespread in the Niger Delta and has led to considerable changes in river beds. The practice which is mostly carried out illegally poses a huge threat to the safe operation of various river-crossing projects, particularly river-crossing bridges. The several potential adverse impacts of indiscriminate sand mining are well documented in literature (Bull & Scott, 1974; Collins & Dunne, 1990; Hackney et al., 2020; Haghnazar & Saneie, 2019; Koehnken & Rintoul, 2018; Lake & Hinch, 1999; Padmalal et al., 2008; Anooja et al., 2011; Ramli, 2016; Chen et al., 2021; Lekomo et al., 2021). As a summary, these includes: 1) bed degradation and consequent effects on channel and bank stability, 2) increased sediment loads, decreased water clarity and sedimentation; 3) changes in channel morphology and disturbance of ecologically important roughness elements in the river bed; 4) resuspension of contaminated sediment and release of contaminants with consequential ecological effects on bird nesting, fish migration, angling, etc. 5) modification of the riparian zone including bank erosion; 6) direct destruction from heavy equipment operation; 7) discharges from equipment and refueling; 8) Reduction in groundwater elevations; 9) impacts on structures and access; 10) biosecurity and pest risks; 11) impacts on coastal processes, 12) Nutrient Release and Eutrophication. 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 damage to the physical and biological environments of the river systems. Some also argue that it has become progressively recognized that some lateral dynamics associated with bank erosion have positive effects in terms of the promotion of riparian vegetation succession, the establishment and evolution of river and floodplain morphology, and the creation of dynamic habitats crucial for aquatic and riparian species.

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 & 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 extracted sand which serves mostly as construction material as well as fill for land reclamation projects, is persistent across the Niger Delta and also the predominant aquifer in the region. 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 & Gessler, 1999; Islam et al., 2018) and in the process threatening the safety and stability of major coastal infrastructures in the area.

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

$$\frac{\tau_c}{(\gamma_s - \gamma_w) D_s} = f\left(\frac{u_* D_s}{v}\right) \tag{1}$$

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;

u_* = shear velocity; and v = kinematic viscosity of fluid.

Its applicability is, of course, limited because the criterion was established for uniformly sized bed material. 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. According to Gessler (1970), better predictions of the ultimate bed slope are achieved using the criterion suggested by Gessler, which is based on the stochastic analysis of incipient motion in non-uniform bed material. In the case of a sediment mixture, Gessler (1967) observed that grains of the same size are partly in movement and partly at rest. Consequently, he treated the incipient motion of sediment mixtures as a probabilistic problem, hence he assumed that the fluctuations of the bed-shear stress are normally distributed.

According to Gessler (1967) and El-Gamal (1991), the following formula can be used to predict the critical shear stress of the sediment mixture and then the corresponding equilibrium bed slope:

$$\gamma_w h_f S_c = 0.045(\gamma_s - \gamma_w) D_{AVG} \tag{2}$$

where

D_{AVG} = average grain size of the armor coat corresponding to $\bar{q}$ = 0.5.

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 investigates the mechanisms of river bed and bank instability triggered by hydraulic sand mining within river channels and reviews case histories to illustrate the dangers posed to coastal infrastructures, especially jetty and bridge foundations and abutments, and to ensure that sand extraction is carried out in a sustainable way to maintain river equilibrium by determining the minimum safe distances from coastal infrastructure for sand extraction to be carried out safely.

2. 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 are frequently thick (greater than 10 m) and would inevitably impact on the road design. 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 construction and for reclamation.

3. 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.

Thirteen borings were made over water at three 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 0.75 m 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.

4. Results

The river system is subject to diurnal tidal inundation with Mean Tidal level averaging 1.52 m. Tidal velocities vary across the tidal cycle, with peak velocities up to 1.4 m/s occurring at mid ebb tide (**Figure 1**). Velocity data is important transport, dispersion and management of suspended particles dislodged during dredging operations.

The excavation of sand from the river bed created large borrows of 40 m diameter and 18 m in depth in scattered locations. These pits intercepted 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

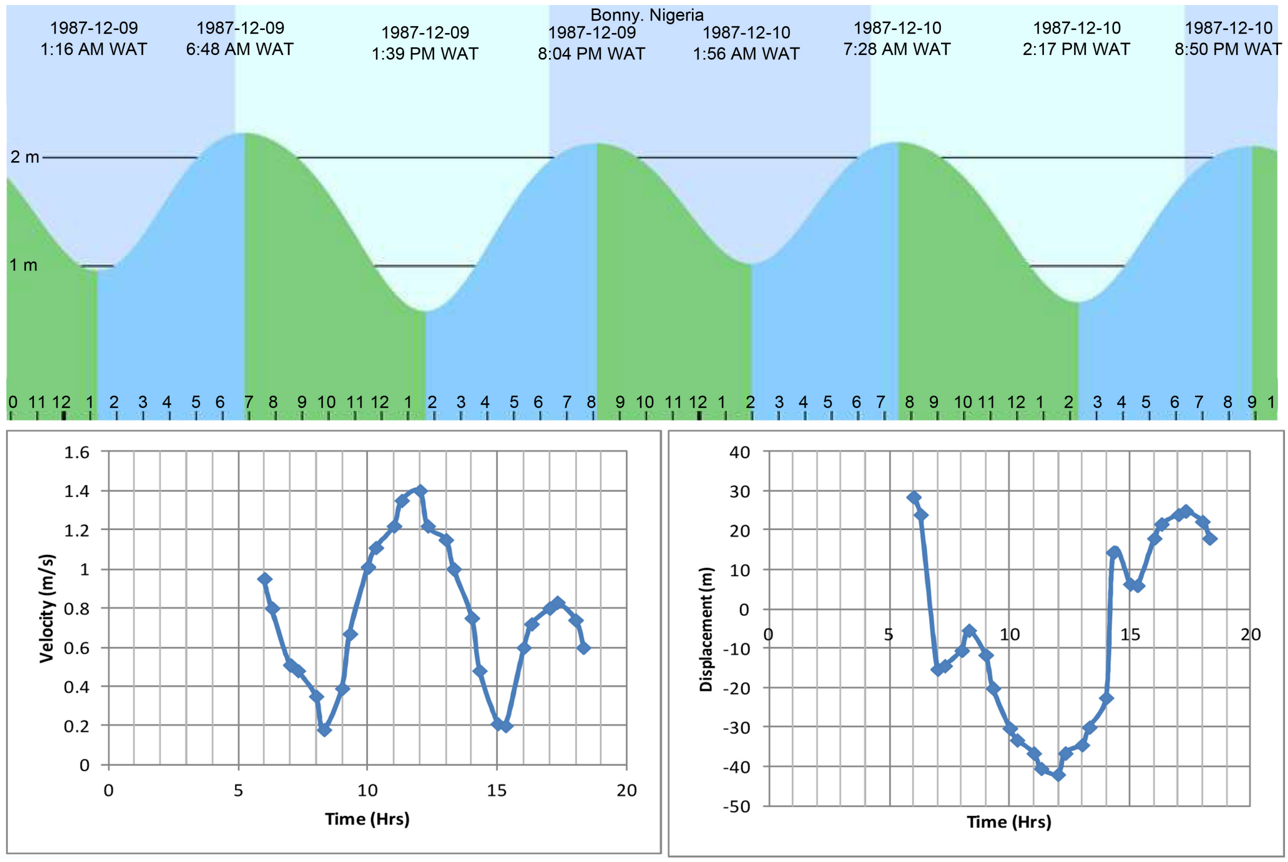

Figure 1. Tidal regime in study area.

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 to 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 can alter or redirect the direction of the main flow causing changes in the patterns of erosion and deposition.

4.1. Case Study 1

This case study is centered on the Amadi Creek, a tributary of Bonny River (Figure 2); where some 2 million·m^3 of sand was to be sourced for reclamation of swampland. The river width averages 200 m (but with only 100 m width at the narrowest point), while its length runs a course of over 3 km.

The composite stratigraphy beneath the river bed (Figure 3) which shows the

S/ No.	BH Ref	Northing	Easting	Design Depth (m)
1	BH1	0281233	0529074	15
2	BH2	0281135	0528595	15
3	BH3	0281282	0528347	15
4	BH4	0281334	0527836	15
5	BH5	0281915	0527430	15

Figure 2. Site drawing showing test points and coordinates.

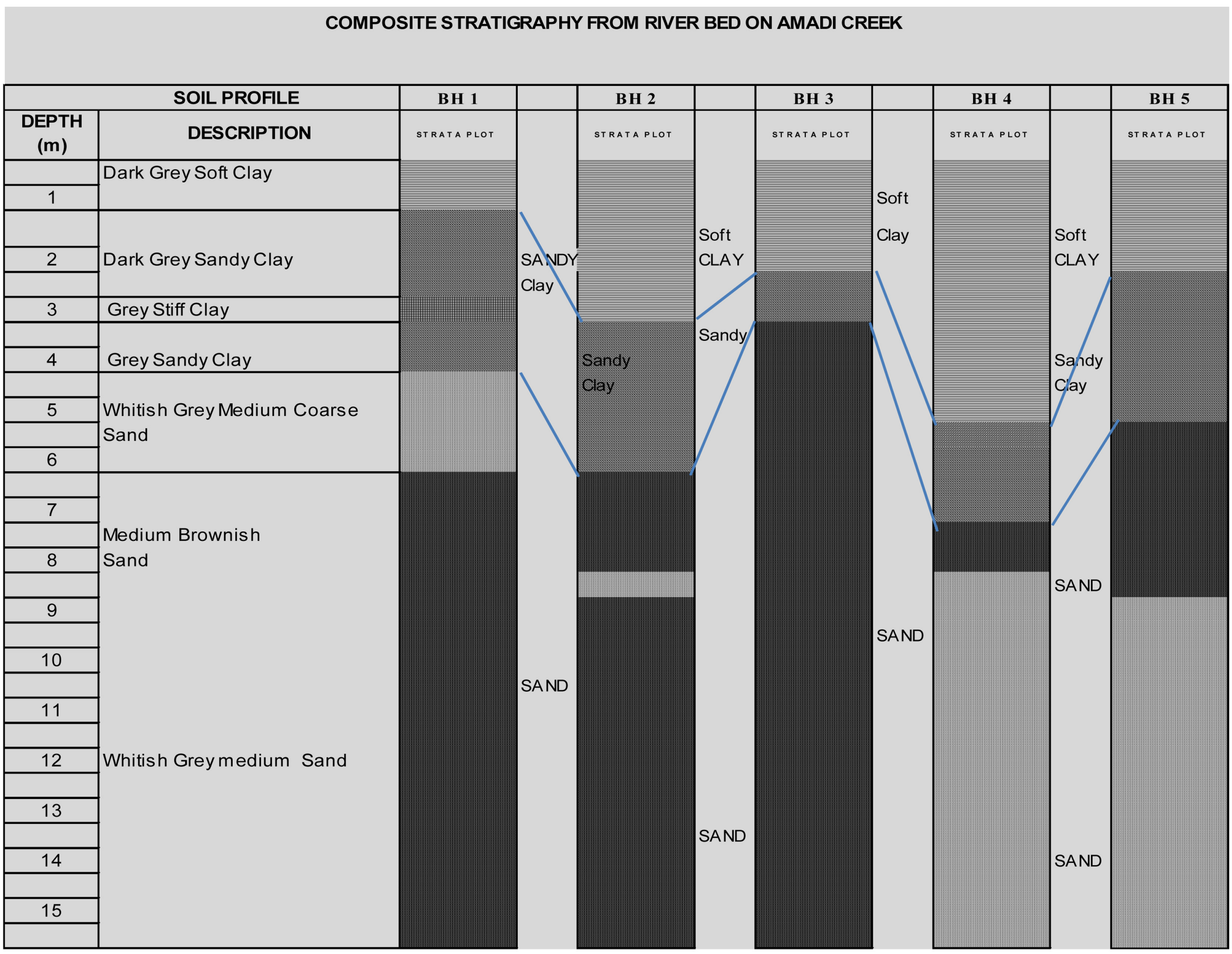

Figure 3. Lithostratigraphy of the River bed in study area.

vertical stratigraphic succession as well as lateral extent of each layer reveal a top silty clay (3.5 m to 6 m) thick overlying mostly medium sand that extend well beyond 15 m. This composite further indicates the available and dredgeable sand in the area and forms the basis of both bed and bank stability assessment.

It is observed that sand was encountered between 3.5 m to 6 m below river bed. It is also observed that the sand formation is persistent and laterally extend from BH1 to BH5 locations about a distance of more than 2 km. The potential performance of the sand for fill or as construction material or even as filter material can be assessed from its particle size distribution (**Table 1**). For example, the sand encountered here are mostly within the medium-coarse size fraction. The drainage properties were considered excellent with estimated average permeability of 0.007 m/sec. The angles of internal friction averages 32˚ while Bulk Unit weight averaged 18.8 kN/m^3.

Since the dredging was aligned principally along the central axis of the river, the distance to each river bank would be less than 50 m at the narrowest section. In this circumstance, the average slope from the base of the borrow pit to the base of the riverbank would be 41˚, which should present an unstable slope condition, if the bed materials comprised of sand. However, because the bed consists of at least 3.5 m thick clay (3.5 m to 6 m), bank instabilities were not observed, possibly because the dredging did not trigger them. This implies that the ability of sand borrowing in river channels to generate bank instability is dependent on the composition and stratigraphy beneath the river bed, which is much in line with (Abam, 2004; Okagbue & Abam, 1986).

Table 1. Particle size distribution statistics.

BH	Depth	D_{10}	D_{30}	D_{50}	D_{60}	$Cu = D_{60}/D_{10}$	$Cz = D_{30}^2 / (D_{10}*D_{60})$	$K = C*D_{10}^2$
NO.	(m)	(mm)	(mm)	(mm)	(mm)			(m/sec)
	7.5	0.24	0.38	0.53	0.63	2.63	0.96	0.006
1	10.5	0.34	0.47	0.7	1.2	3.53	0.54	0.012
	9	0.28	0.4	0.53	0.64	2.29	0.89	0.008
2	12	0.33	0.44	0.58	0.75	2.27	0.78	0.011
	15	0.23	0.37	0.49	0.56	2.43	1.06	0.005
3	9	0.27	0.37	0.47	0.54	2.00	0.94	0.007
	15	0.33	0.47	0.68	0.87	2.64	0.77	0.01089
4	10.5	0.17	0.34	0.46	0.54	3.18	1.26	0.003
	13.5	0.15	0.24	0.4	0.56	2.15	0.99	0.00169
5	9	0.23	0.39	0.56	0.76	1.69	0.93	0.00529
	12.5	0.23	0.37	0.52	0.65	2.83	0.92	0.005
	15	0.3	0.43	0.58	0.73	2.43	0.84	0.009

4.2. Case Study 2

Case history 2 is in the neighboring area of Okrika (Figure 4), where sand was abstracted randomly around 3 connecting bridges for reclamation in Abam-ama, Okrika, Kalio-ama and Oba-ama communities.

The erosion and lowering of the basal level around the abutment within the intertidal zone results in the detachment and suspension of the concrete protection to the abutment. This causes the sand backfill, hitherto confined by it to find an outlet as shown in Figure 5(a). The movement or flow of the sand, which is exacerbated by infiltration of rainwater into the abuttment results in the loss of support to the base course and collapse and failure of the asphaltic surface (Figure 5(b)).

4.3. Case Study 3

Only recently (2015), the Bridge at Nkpogu-NLNG, which is the upstream section of and feeds into Amadi Creek (case study 1 area) was threatened to the point of failure by accelerated erosion (Figure 6), variously ascribed to the an earlier dredging activity downstream of that location.

Unlike in case study 1, the river bed is underlain mostly by medium and coarse sand from top to 30 m (Figure 7). The angles of internal friction varied

Figure 4. Map showing dredging locations and threatened bridges.

Figure 5. Erosion of Abuttment base and failure of asphaltic surface.

Figure 6. Failures due to erosion of bridge abutment at Nkpogu.

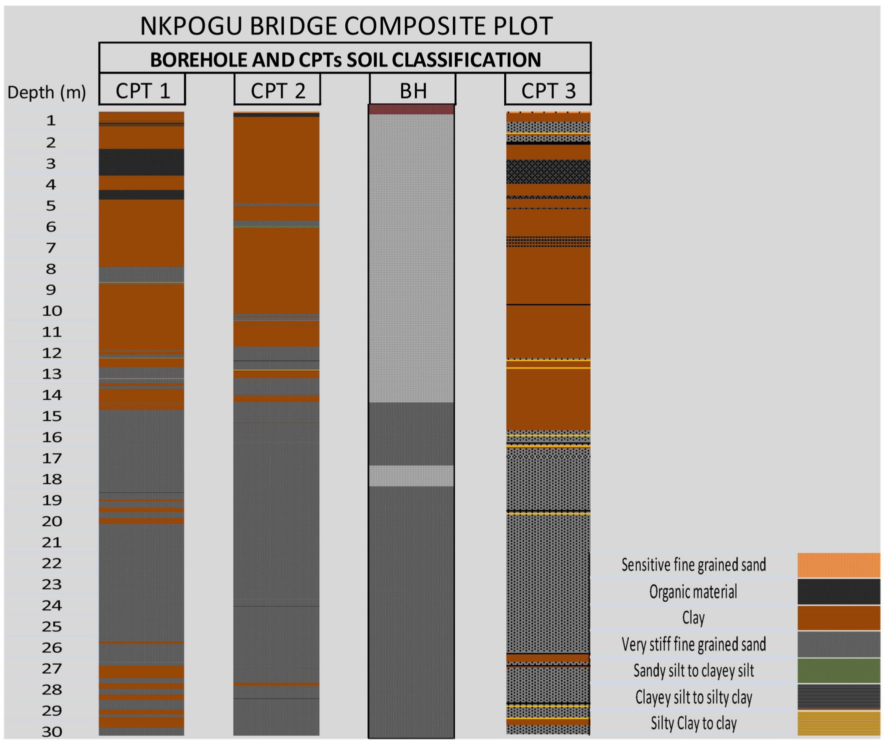

Figure 7. Lithostratigraphy composed of borehole log and CPT based SBT classification.

from 32˚ to 35˚ with effective particle size D_{10} averaging 0.15 mm and SPT N-values varying from 6 to 31.

In much the same fashion, the dredging lowered the basal level, increased ebb tide flow velocity which eroded the abutment and caused the bridge to fail.

5. Discussion

Assessment of Threat to Bridge and Other Coastal Structures

One major consequence of dredging the Amadi Creek 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 width of the channel at the narrowest cross-section was measured at 196 m. If sand excavation creates a 100 m wide and 18 m deep burrow at mid-stream as illustrated (Figure 8): The maximum angle of repose would be given by $\alpha = \tan^{-1}((18/48) = 41^{\circ}$.

Since the seabed is underlain by top clay, we expect some degree of vertical slope. A 3 m high slope has been assumed based on the properties of this material. This implies that a lower angle of repose should in reality be expected as:

$$\beta = \tan^{-1}(15/48) = 34^{\circ} \quad (3)$$

Work by Al-Hashemi and Al-Amoudi (2018) show that angle of repose of submerged sand can vary between 30 and 40 degrees depending on the size of the particles. With a D50 averaging 0.5 mm, an angle of repose of 36 degrees can be expected.

This computation shows that dredging a burrow that is 100 m wide and 18 m deep would create near unstable conditions. It is therefore recommended that on no account should the width of the burrow be larger than 100 m and deeper than 18 m. Where possible the width of the burrow should be reduced to between 60 m and 70 m to permit a lower angle of repose of between 25 and 29 degrees.

Figure 9 is a schematic to illustrate the spatial and angular relationship between the dredge point and typical coastal infrastructure at risk such as bridge pier and the river bank.

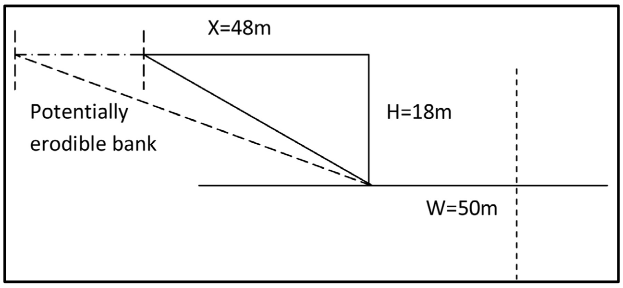

Figure 8. Dimensions of a section of the channel.

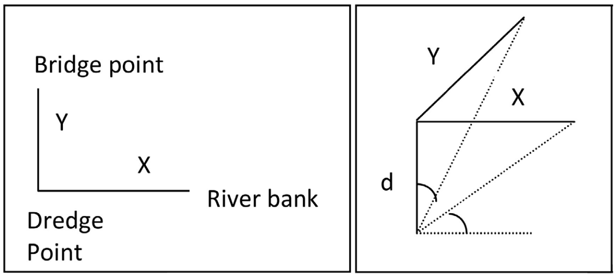

Figure 9. Schematics of dredged river channel showing angular relationships.

In respect of stability of river bank, the angle of declination (α) from river bank:

$$\alpha = \tan^{-1}(d/x); \quad X = d/\tan\alpha \tag{4}$$

By similar reasoning, the angle of declination from river bed at bridge point to dredge depth:

$$B = \tan^{-1}(d/y) \tag{5}$$

where d = dredge depth (m).

X = horizontal distance to river bank.

Y = horizontal distance to bridge footing.

Thus, the minimum safe distance from river bank to dredge point can be given as: X_{min} = d/tan(Angle of repose of dredged sand). In general, environmental safety of the river bank requires as a minimum horizontal distance, that, X is greater 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 94 m for a dredging operation requiring a dredging arm with a capacity of 18 m 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 Figure 10.

Assuming a circular borrow pit of depth Y and diameter D, a Longitudinal Area of Influence (LAI) (which is essentially the length across the channel of flow over which the pit can induce instability on the river bed) can be can be estimated by the equation:

$$\text{LAI} = D + 2Y/\tan\alpha \tag{6}$$

where α = angle of repose.

By the same token, the Area of Influence (AOI) on the river can be estimated by the expression:

$$\text{AOI} = (2Y/\tan\alpha + D)^2/4 \tag{7}$$

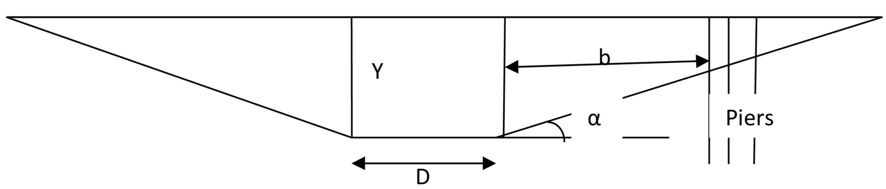

Figure 10. Schematics for assessing area of influence of sub-aqueous borrow pit. α = angle of repose. D = diameter of borrow pit.

The implication of this is that, if the measured width of a river channel is less than the predicted LAI (Equation (6)), 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 1.2 m/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, and then it is probable that additional scour arising from bed instability caused by the pit can be introduced. Such scour can be estimated by the expression:

$$S_i = Y - b\tan\alpha \tag{8}$$

where b is the distance from the borrow pit to the bridge pier.

For long-term conditions, α = 11˚.

For medium-term conditions, α = 18˚.

S_i is to be checked against the depth of pile embedment for assessment of continuing stability of the pile or pier as the case may be.

Based on the fore going, an empirical relationship $X_s = 3H\tan(90 - \alpha)$ is proposed for generic application to determine minimum safe distance for dredging in sand river beds.

6. Conclusion

Sand mining from river beds will continue for the foreseeable future. Bridge foundations as well as abutments can be vulnerable to scour and erosion, if the choice of dredging locations on river channels is not properly guided. There is need to develop regulation for sand mining activities in inland rivers, as has been done elsewhere (Meador & Layher, 1998). Based on this study it is shown that a minimum distance of 94 m (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. This work advocates and provides a basis for the development of river sand mining policies which should include ensuring the conservation of the river equilibrium and its natural environment, avoiding the aggradation at the downstream reach especially those with hydraulic structures such as bridges and jetties as well as ensuring that the rivers are protected from bank and bed erosion beyond its stable profile.

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 arise from river sand mining and this study is an effort in this direction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Abam, T. K. S., & Omuso, W. O. (2000). On River Cross-Sectional Changes in the Niger Delta. *Journal of Geomorphology, 34,* 111-126. https://doi.org/10.1016/S0169-555X(99)00129-4

Abam, T. K. S. (1993). Bank Erosion and Protection in the Niger Delta. *Hydrological Science Journal, 38,* 231-241. https://doi.org/10.1080/02626669309492665

Abam, T. K. S. (2004). Case Histories of Sand Search in the Niger Delta. *Environmental Geology, 46,* 165-172. https://doi.org/10.1007/s00254-004-1021-4

Al-Hashemi, H. M. B., & Al-Amoudi, O. S. B. (2018). A Review on the Angle of Repose of Granular Materials. *Powder Technology, 330,* 397-417. https://doi.org/10.1016/j.powtec.2018.02.003

Anooja, S., Baijulal, B., Maya, K., Sreebha, S., & Padmalal, D. (2011). Impact of Sand Mining on River Bed Changes and Bed Material Characteristics—A Case Analysis. In *National Seminar on Mining of River Sand and Its Impacts on the Environment* (pp. 173-181). CWRDM.

Bull, W. B., & Scott, K. M. (1974). Impact of Mining Gravel from Urban Stream Beds in the Southwestern United States. *Geology, 2,* 171-174. https://doi.org/10.1130/0091-7613(1974)2<171a:IOMGFU>2.0.CO;2

Chen, X., Wang, Y., Sun, T., Huang, Y., Chen, Y., Zhang, M., & Ye, C. (2021). Effects of Sediment Dredging on Nutrient Release and Eutrophication in the Gate-Controlled Estuary of Northern Taihu Lake. *Journal of Chemistry, 2021,* Article ID: 7451832. https://doi.org/10.1155/2021/7451832

Collins, B., & Dunne, T. (1990). *Fluvial Geomorphology and River-Gravel Mining: A Guide for Planners, Case Studies Included.* Special Publication 98. California Department of Conservation, Division of Mines and Geology.

El-Gamal, F. S. H. (1991). *Critical Shear Stress for Sediment Mixtures.* Ph.D. Thesis, Colorado State University.

Gessler, J. (1967). *The Beginning of Bed Load Movement of Mixtures Investigated as Natural Armoring in Channels* (Translated by E. A. Prych, Translation T-5, & W. M. Keck) (pp. 1-89). Laboratory of Hydraulics and Water Researches, California Institute of Technology.

Gessler, J. (1970). Self Stabilization Tendencies of Alluvial Channels. *Journal of the Waterways, Harbors and Coastal Engineering Division, 96,* 235-249. https://doi.org/10.1061/AWHCAR.0000016

Hackney, C. R., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., Aalto, R., Nicholas, A. P., & Houseago, R. C. (2020). River Bank Instability from Unsustainable Sand Mining in the Lower Mekong River. *Nature Sustainability, 3,* 217-225. https://doi.org/10.1038/s41893-019-0455-3

Haghnazar, H., & Saneie, M. (2019). Impacts of Pit Distance and Location on River Sand Mining Management. *Modeling Earth Systems and Environment, 5,* 1463-1472. https://doi.org/10.1007/s40808-019-00627-6

Islam, K., Al Kibriya, N., & Dustegir, M. (2018). Impact Analysis of Sand Dredging from

Alluvial Tidal River. *E3S Web of Conferences, 40,* Article No. 03036. https://doi.org/10.1051/e3sconf/20184003036

Koehnken, L., & Rintoul, M. (2018). *Impacts of Sand Mining on Ecosystem Structure, Process and Biodiversity in Rivers* (p. 159). WWF Review.

Lake, R. G., & Hinch, S. G. (1999). Acute Effects of Suspended Sediment Angularity on Juvenile Coho Salmon. *Canadian Journal of Fisheries and Aquatic Sciences, 56,* 862-867. https://doi.org/10.1139/f99-024

Lekomo, Y. K., Ekengoue, C. M., Douola, A., Lele, R. F., Suh, G. C., Obiri, S., & Dongmo, A. K. (2021). Assessing Impacts of Sand Mining on Water Quality in Toutsang Locality and Design of Waste Water Purification System. *Cleaner Engineering and Technology, 2,* Article ID: 100045. https://doi.org/10.1016/j.clet.2021.100045

Meador, M. R., & Layher, A. O. (1998). Instream Sand and Gravel Mining: Environmental Issues and Regulatory Process in the United States. *Fisheries, 23,* 6-13. https://doi.org/10.1577/1548-8446(1998)023<0006:ISAGM>2.0.CO;2

Okagbue, C. O., & Abam, T. K. S. (1986). An Analysis of Stratigraphic Control of River Bank Failure. *Engineering Geology, 22,* 231-246. https://doi.org/10.1016/0013-7952(86)90025-6

Padmalal, D., Maya, K., Sreebha, S., & Sreeja, R. (2008). Environmental Effects of River Sand Mining: A Case from the River Catchments of Vembanad Lake, Southwest Coast of India. *Environmental Geology, 54,* 879-889. https://doi.org/10.1007/s00254-007-0870-z

Peng, L.-S., & Pang, L.-X. (2014). Numerical Analysis of Adjacent Bridge Piles Influenced by Surcharge Loads on Soft Foundation. *Journal of Highway and Transportation Research and Development, 31,* 67-72. (In Chinese).

Porto, P., & Gessler, J. (1999). Ultimate Bed Slope in Calabrian Streams Upstream of Check Dams: Field Study. *Journal of Hydraulic Engineering, 125,* 1231-1242. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:12(1231)

Ramli, A. Y. (2016). *The Impact of Dredging on the Stability of Matakana Banks Ebb-Tidal Delta.* Ph.D. Thesis, University of Waikato. https://hdl.handle.net/10289/10648

Shields, A. (1936). *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung.* Ph.D. Thesis, Preussischen Versuchsanstalt für Wasserbau.

Thorne, C. R. (1982). Processes and Mechanics of Bank Erosion. In R. D. Hey, J. C. Bathurst, & C. R. Thorne (Eds.), *Gravel-Bed Rivers: Fluvial Processes, Engineering and Management.* John Wiley & Sons.