

Developments in river bank protection schemes in the lower Niger delta basin

Abstract

This paper evaluates the performances of four revetment schemes at Sagbama, Otuokpoti, Sagbagraia and Opokuma/Opokuma in the lower Niger River Basin. The evaluation criteria are; reconnaissance survey, physical examination of revetment components, review of design calculations, and action photographs of defective components. The Sagbama and Otuokpoti schemes were designed for 2% annual exceedance probability (AEP) using Pilarczyk 1990 equations and constructed in Profix mattress revetment. Edge failure occurred at Sagbama due to deflected river flow caused by an upstream depositional bar. The Sagbagraia scheme was constructed of rock – filled gabion mattress, in PVC coated twisted wire mesh. The entire revetment system was constructed inside the potential failure surface. Due to combined effects of reduced effective stresses, high pore pressure and poor drainage bank triggered deep – rotational failure 5years after construction. The Kolokuma/Opokuma revetment was constructed in anchored steel – sheet pile. The choice of anchored steel – sheet pile is incompatible with shore bathymetry resulting to insufficient embedment depth and eventual collapse. Only Sagbama and Otuokpoti schemes performed adequately for 30 and 25years respectively, thus attesting the suitability of Pilarczyk equation for revetment design. The assessment on impact of design on successful project implementation revealed that the non-engagement of design consultants with core competence in hydraulic/river engineering underpins the prevalence of faulty designs and widespread revetment failures being experienced in the region. Finally, this study recommends the need for river training and the establishment of hydro meteorological stations to forestall the dearth of data currently undermining river basin development initiatives.

Keywords: revetment, sinuosity, stability criterion, gabion, slope stability, Niger delta

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Introduction

In the Niger Delta, floodplains and maritime shore are used for human settlement and for economic development. These ecosystems are home to over 70 percent of the population, oil and gas installations but at the same time threatened by natural hazards of flooding and erosion. The scourge of flooding and erosion problems are exacerbated due to human settlements situated at the concave banks which are also the active zones of erosion processes. Concerns over the adverse impacts of river bank erosion on the socio economic development of the region has dominated political discourse for decades. Government commitment to flood and control in the Niger Delta dates back 1954 to 1961, when the Federal Government of Nigeria commissioned the NEDECO¹ studies. These studies provided a concise description of the Niger Delta, river systems, guided in the selection of different flood and erosion protection options and navigation. Furthermore, the creation of the Niger Delta Development Board (NDDDB) in 1966 demarcated Niger Delta as “Special Area” which deserves special consideration. Its major terms of reference were to submit schemes designed to promote the physical development of the Niger Delta together with cost estimates for implementation of such schemes. The NDDDB was primarily an investigational body without executive powers to implement the designed schemes. In 1981, the Federal Government of Nigeria, through Niger Delta Basin Development Authority commissioned further studies of the Niger Delta with special emphasis on Flood and erosion Control and Improvement of

Inland Waterways.¹ This report provided detailed bathymetric and hydrographic data of the Nun and Forcados river system, sediment transport in rivers and long shore transport along the coast. The report presented plausible options to address the flood and erosion problems, and earmarked several prototype schemes for erosion and flood control, land reclamation and waterways improvement. Further the Federal Government of the Nigeria, through the Niger Delta Basin Development Authority also commissioned the Democratic People’s Republic (DPR) of Korea to investigate possible flood protection measures in the Nun and Forcados River Area.² The Report focused on provision of hydro metrological data for the designs of flood controls schemes, economic development of the Basin and general improvement in the living standard of the people. The DPR Report¹ recommendations for physical data acquisition towards development of a master plan. In 1981, the Rivers State Government commissioned Zinkcon International B.V. (Dutch) Company to undertake the design and construction of Flooding and Erosion Protection works for 16 towns and villages. The contract engagement commenced with the construction of two flooding and erosion prototype schemes at Otuokpoti and Sagbama towns. Sagbama town is situated on the left bank of Forcados River, while Otuokpoti is situated also on the left bank of Ekole creek, a distributary of Nun River. The prototype schemes were the construction of composite revetment (profix materials system which offered combined advantages of reduced hydraulic loading and green solution for river bank protection. The remaining fourteen

schemes were abandoned due to change of government and lack of political will to continue with the implementation. The development of flood and erosion problems in the Niger Delta gained impetus with the creation of Niger Delta Development Commission. So far, no fewer than 100 shore protection schemes had been sanctioned with No Single Success. It is against the backdrop of these failures that, this study is undertaken with the following objectives:

1. To review the performances of the prototype shore protection works in the Lower Niger River Basin, particularly the Nun and Forcados rivers system.
2. The causative factors responsible for failure of revetment structure and the deficiencies in each scheme.
3. Recommendation of appropriate revetment type based on the performance of the successful schemes.
4. Identify research gaps and data acquisition programme to improve overall standard design procedures and estimation of design parameters.
5. Finally, to increase knowledge base required in drawing up design brief that would enhance communication between the client, consultants and the contractors shall be achieved.

This paper is organized in the following sequence. The introductory section provides a review commissioned studies in chorological

order. Section 2 begins with assessment of channel plan forms using channel sinuosity (S) and stability criterion (S_{cr}) at critical erosion and flooding locations. Section 2 also provides the Description of the study area and hydrologic characteristics. Section 3 presents review of existing shore protection works in the Nun and Forcados river systems with assessment of their performances. Section 4, and then elaborate the design of revetment mattress option based on its successful performances in the Lower Niger River Basin over other options. Section 5, ends with conclusions and recommendations towards establishment of hydro meteorological stations, as solution to the dearth of stream flow data and to identify research gaps that would improve the planning and management of water resources in the basin.

Description of study area and hydrologic characteristics

The Niger River and Benue River forms a confluence at Lokoja and then flows Southwards into the vast Niger Delta covering approximately 30,000Km². The River Niger bifurcates at Asamabiri into River Nun and River Forcados, which progressively spilt into several distributaries with no fewer than 30 outlets including estuaries into the Nigeria gulf of Guinee. A total of 250 Km³/yr of water discharges into the gulf of Guinea. Rainfall in the Niger Delta is typically 2700mm – 3000mm/year, while actual evaporation is about 1000mm/year.³ Table 1 shows the cross-sectional details of the rivers at the study stations while Figure 1 shows the study map.

Table 1 Cross-sectional detailed at study stations

S/N (1)	Stations (2)	River (3)	Dry Season water Surface Width (m) (4)	Bank full Width(m) (5)	Maxi Depth Dry season m (6)	Depth flood season (m) (7)	Mean Flow Velocity m/s (8)	Bank Gradient (Degree) (9)	Inflection radius (km) (10)	Inflection Length (km) (11)
1	Aboh	Niger	1110	3100	8.8	14.5	1.40	35°2'	3.45	12
2	Asambiri	Niger	1110	1600	8.10	13.8	1.36	50°11'	3.00	15
3	Kaiama	Nun	350	680	7.40	13.5	1.30	34°2'	3.00	11
4	Kolokuma/Opokuma	Nun	355	650	6.5	11.00	1.35	32°15'	7.5	8
5	Sagbagreia	Nun	355	660	6.3	10.9	1.30	33°20'	1.50	7
6	Sagbama	Forcados	500	700	4.0	11.30	1.45	29°53'	1.60	5.0
7	Otuokpoti	Ekole Crk	250	300	5.20	11.10	1.30	28°4'	1.75	8.0
8	Patani	Forcados	510	550	8.50	26.5	1.50	43°2'	2.0	10

Source: DPRK (1980, Nedeco – Haskoning (1980), NDES(2013).see locations (column 2) in Figure 1.

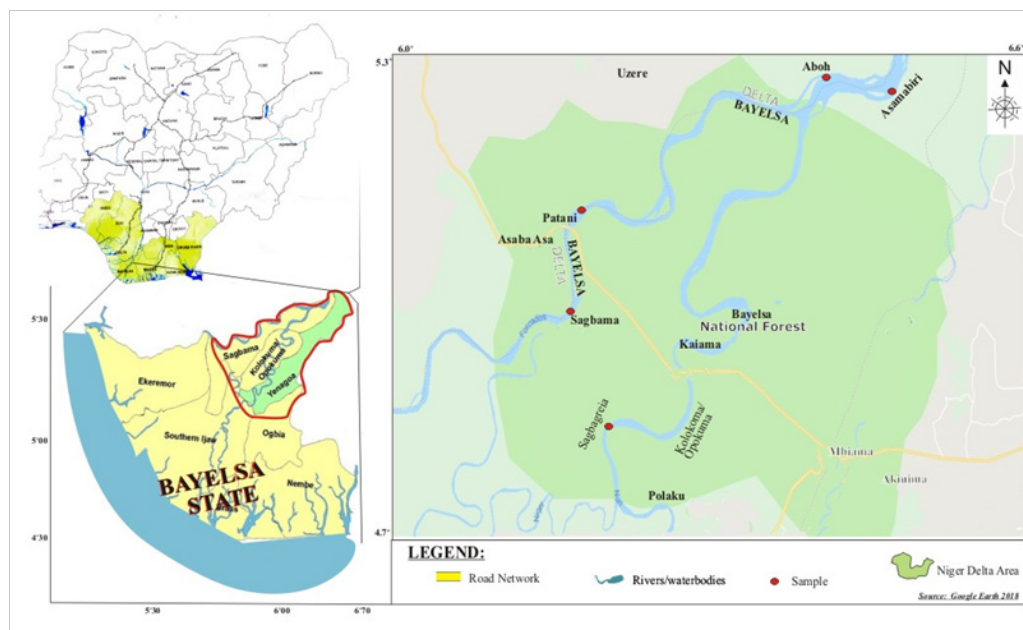


Figure 1 Map of the study area.

Survey of alluvial channel pattern in lower Niger River basin

Chang,⁴ and Deng & Singh⁵ investigated the mechanism and conditions for change in channel pattern, using theory and field data from 70 alluvial rivers having different chemical patterns. They recommended that river management and training works should help rivers achieve and maintain a sinuosity (s) close to 1.57 and a stability criteria $S_{cr} > 0.2$. Accordingly, the sinuosity and stability criterion parameters comprehensively reflects the stability of an alluvial river, thus Equations 1-3, defining S and S_{cr} were applied to evaluate the channel pattern changes caused by changes in flow conditions at inflexion points where shore protection works are situated in the Lower Niger River Basin. Table 2 shows the computations of sinuosity and stability criteria at erosion locations.

$$S = L_s/L_m = 2\pi R/12B \dots \dots \dots (1)$$

$$\xi_0 = \xi_0 = \frac{B^{9/13}}{H} \dots \dots \dots (2)$$

Where ξ_0 = morphologic coefficient, S_{cr} = stability criterion, S = channel sinuosity, J = Channel slope; H is water depth and R = radius in any position of the thalweg.

The sinuosity was calculated as the ratio of the curvilinear length (along the curve) to distance (straight line) between the inflexion points.

$$S_{cr} = \frac{0.319n^{11/13}}{J^{11/56} \sqrt{\xi_0}} \dots \dots \dots (3)$$

Consequently, Equation 1, 2 and 3 defining the Sinuosity (S) and Stability criterion (S_{cr}) have been used to assess the channel pattern and conditions of morphological changes at the concave banks and the results are shown in Table 2.

The towns and villages in the lower Niger River Basin are clustered around the concave banks of the Nun and Forcados river systems. The concave banks have physiographic advantage that they are at higher elevation than the back swamps, thus less prone to flooding, but at the

same time, they are zones of severe bank erosion. It is therefore, of a great importance to scientifically characterize the inflection points in terms of their stability criterion and sinuosity.

The channel sinuosity (S) varies between 0.1047 and 0.491 while the stability criterion (S_{cr}) was generally less than 0.1 except at Patani station. Deng & Singh,⁵ reported that the closer the channel sinuosity of an alluvial river is to 1.57 and stability criteria greater than 0.20. The failure of the concave banks to meet the stability criteria is indicative of channel instability, erosion and channel migration and in general morphological problems at those locations.

Review of existing shore protection works

A revetment is a slope engineered shore protection structure designed to protect and stabilize an eroding shoreline against erosion by currents and wave actions. The types of revetment commonly used for river bank and shore protection and stabilization may be found in standard tests.⁶⁻⁸ In order to evaluate the performance of the existing shore protection schemes, a reconnaissance survey, and physical examination of the components of each revetment scheme and action photographs were taken. Structural failure of the revetment may be attributed to any of the three fundamental mechanisms or induced by any combination of the following;

1. Erosion of the armour layer when the surface is notable to withstand the forces applied by waves and currents.
2. Undermining when the waves or current action causes scouring of erodible material at the toe of the armoured slope, causing it to be undermined and then collapse.
3. Overlapping problems do not arise because the shore protection works are situated on the concave banks, which are higher and not easily flooded.
4. Revetment failure occurs most frequently due to failure of the under layer when the cumulative action of hydraulic forces (drainage) were not accommodated in the designs.

The various components elements of the revetment structure are listed in Table 2 to enable a component by component evaluation performance evaluation of each scheme (Table 3).

Table 2 Channel pattern changes evaluated with sinuosity and stability criteria.

S/N	R reach	River	n	B	ϵ_o	S_{cr}	S	Depth	J	$\sqrt{\epsilon_o}$
1	Aboh	Niger	0.041	1135	8.967866	0.066011	0.1506	14.5	0.000077	2.91506
2	Asamabiri	Niger	0.035	1300	11.51933	0.050869	0.1047	12.4	0.000069	3.394013
3	Kiama	Nun	0.03	425	5.030068	0.066903	0.1428	13.1	0.000072	2.242781
4	KOI/Opok	Nun	0.036	550	6.909174	0.066607	0.4909	11.4	0.000072	2.628531
5	Sagbagrea	Nun	0.029	556	7.085553	0.055506	0.1122	11.2	0.000068	2.66187
6	Sagbama	Forcados	0.028	520	6.704955	0.055391	0.1676	11.3	0.000068	2.589393
7	Otuokpoti	E. Creek	0.31	300	5.508585	0.066805	0.1146	9.4	0.000062	2.347037
8	Patani	Forcados	0.026	510	2.820932	0.461555	0.1047	26.5	0.000068	1.679563

Where S: Channel Sinuosity; S_{cr} : Stability criterion; B: Bankfull channel width; Average flow depth: roughness coefficient

Table 3 Evaluation of existing shore protection works

Revetment Components											
S/N	Location	River	Revetment	Armour Layer	Filter Layer	Subsoil Condition	Crest	Toe	Edge Detail	Year	Remarks
2	Otuokpoti	Ekole Creek	Proefix Mattress	As a Sagbama	Ditto	Ditto	Ditto	Ditto	Ditto	1982	Profix mattress performed adequately for about 25 years and failed due to inadequate edge protection
3	Sagbagreia	Nun	Gabion mattress constructed of gabion mattress, rock-filled in PVC coated wire mesh with stone sizes; 200–250mm	High pour water pressure with high hydrostatic pressure gradient during flood recession. Reduce effective stresses in the bank trigger deep-seated rotational failure (plates 1 and 2). Also increased unit weight caused by infiltrating water into the banks	Description of Filter Integrity and failure	Poor compaction of slope before laying gabion mattress.	Surface drainage infiltrating into the bank through cracks caused by increase water weight of the bank material and poor pressure built-up trigger crest failure.	Poor anchorage and failure	Inadequate edge protection and failure	2005	Failure caused by underground water drainage infiltration into cracks and high pore pressured gradients during flood recession. Gabbon mattress failed 5 years after construction

Table Continued

Revetment Components										
S/N	Location	River	Revetment	Armour Layer	Filter Layer	Subsoil Condition	Crest	Toe	Edge Detail	Year
4	Okokuma Kolokuma	Nun	Anchored steel-sheet piles	Wrong choice of revetment, steel-sheet pile option not compatible with site bathymetry, caused restricted access to the river and berthing of canoes.						Insufficient embedmen depth and collapse during flood conditions.

Armour layer: outer layer of a revetment; Gabion: rectangular or tubular basket made from steel; Geotextile: permeable synthetic fabric; Revetment: a bank protection system with no slope retention capability; Scour: local removal of soil particle by hydraulic forces.

Abbreviation/Notation

ASCE, America Society of Civil Engineers; ICE, Institution of Civil Engineers, London; Eol, Expression of Interest; S_{cr} , Stability criterion; S, Channel sinuosity; NDES, Niger Delta Environmental Survey; J, Channel slope; ξ_o , Morphologic coefficient.

Performance evaluation of the four schemes

The main factors controlling dictate the choice of revetment may be classified under:

1. Hydraulic loading.
2. Bank slopes.
3. Level of turbulence.

Other factors such as flexibility and permeability are related to the ability of the revetment structure to transfer pressure forces to and fro the river bank. Considering columns 8 and 10 in Table 1), that the banks are very steep and slopes greater than 34o degrees with moderate to very heavy hydraulic loading and low permeabilities. Consequently, the sheet-pile revetment option adopted for Opokuma/ Kolokuma shore protection is in-appropriate. Sheet-piles are available in standard length of 39ft ($\approx 13\text{m}$), given the existing bank heights, they were not driven to the required embedment depth. The result was failure and collapse under flood conditions (Plate 1–3). Furthermore, sheet-piles offer restricted access to the foreshore and have adverse effect on the community lifestyle.

The Sagbagreia scheme was constructed of box gabions (Maccaferri Gabions). The gabion protection was laid on non-woven geotextile filter fabrics. The main problems with this scheme are:

1. The whole protection system, including geotextile was constructed inside the potential failure surface.
2. Existence of high hydraulic gradient and seepage flow with low hydraulic pressure during flood recession.
3. Insufficient to anchorage to counter balance hydraulic forces and scour erosion during flood. The high pour water pressure in the bank material during flood recession (rapid lowering of the water level in the river) reduces effective stresses in the bank material causing desiccation and deep-seated rotational failure (Plates 4–6).



Plate 1 Collapsed sheet pile wall at Opokuma/Kolokuma.



Plate 2 Typical view of concave bank of Nun River.



Plate 3 Composite bank failure at Sagbagreia.



Plate 4 View of tension crack Sagbagreia.



Plate 5 Deep-rotational failure at Sagbagreia.



Plate 6 Southwards migration of R. Nun at Opokuma/Kolokuma.

The Otuokpoti and Sagbama flood and erosion protection works were constructed of profix mattress, the armour layer, granular and geotextile filter comprised the profix mattress system. The profix mattress system failed due to instability of the subsoil which generated localized slip failure around the middle portion of the armour layers while the toe and crest components of the revetment system are in-tack and performing adequately. In summary, combining the lessons from the performance of the above schemes with physical understanding of the problem; a gabion mattress or cable block revetment be an excellent choice for the lower Niger River Basin and particularly the Niger Delta with regard to the very heavy hydraulic loading, bank slopes, flexibility and accessibility to the foreshore.

Discussion and development of appropriate shore protection scheme

The better performing schemes of Otuokpoti and Sagbama were designed using the Pilarczyk's equation⁹ which failed 30 years after completion and also survived the 2012 centenary flood with a discharge of about 30,000m³/sec. Pilarczyk's equation have been recommended for design of riprap, cabled concrete block, box gabions and asphalt mattresses while Hemphill & Bramley,¹⁰ is recommended for riprap, loose or interlocking concrete blocks and gabion mattresses.⁸ In view of the poor designs, failed installations with concomitant financial wastage characterizing the development of the shore protection works in the Lower Niger River Basin. The flowcharts for both preliminary and detailed design respectively adopted from Escaramaia⁸ are presented to guide prospective designers. Figures 2 & 3 shows typical flowchart for preliminary and final design stages respectively.

The causes of failure of the investigated schemes call for special attention in some critical aspects of the design process namely:

1. Flood frequency Analysis.
2. Slope stability analyses.
3. Design of filters.
- a. Designers should pay attention to screening and evaluation of

- flood series for non-stationary. The non-stationary in the flood series may be investigated by examining the dependence structure of the flood series using standard statistical test such as Mann-Kendal test for trend; Spearman's Rank Correlation Coefficient test for randomness, Mann-Whitney etc.
- Selection of appropriate probability distribution model to characterize the flood series. A number of models are used in fitting annual maximum series; LP3, EV1, Log-normal, GEV etc. and the model(s) that fit best a given location is selected for estimation the flood quantiles.
 - Once a suitable model has been selected, the parameters that fit the model need to be identified. The methods of parameter estimation are;
 - Method of moments.
 - Methods of maximum likelihood
 - Probability weight moment's method.
 - Goodness of fit test/plotting analysis: the suitability of a distribution is investigated by the goodness of fit tests such as L-moment Ratio diagrams, Anderson-Darling (AD), the Kolmogorov-Smirnov (KS), Probability Plot Correlation Coefficient (PPCC) test, chi-squared tests, etc.
 - Selection of appropriate distribution and quantile estimation. Flood defenses are designed for a particular annual exceedance probability and associated risks.

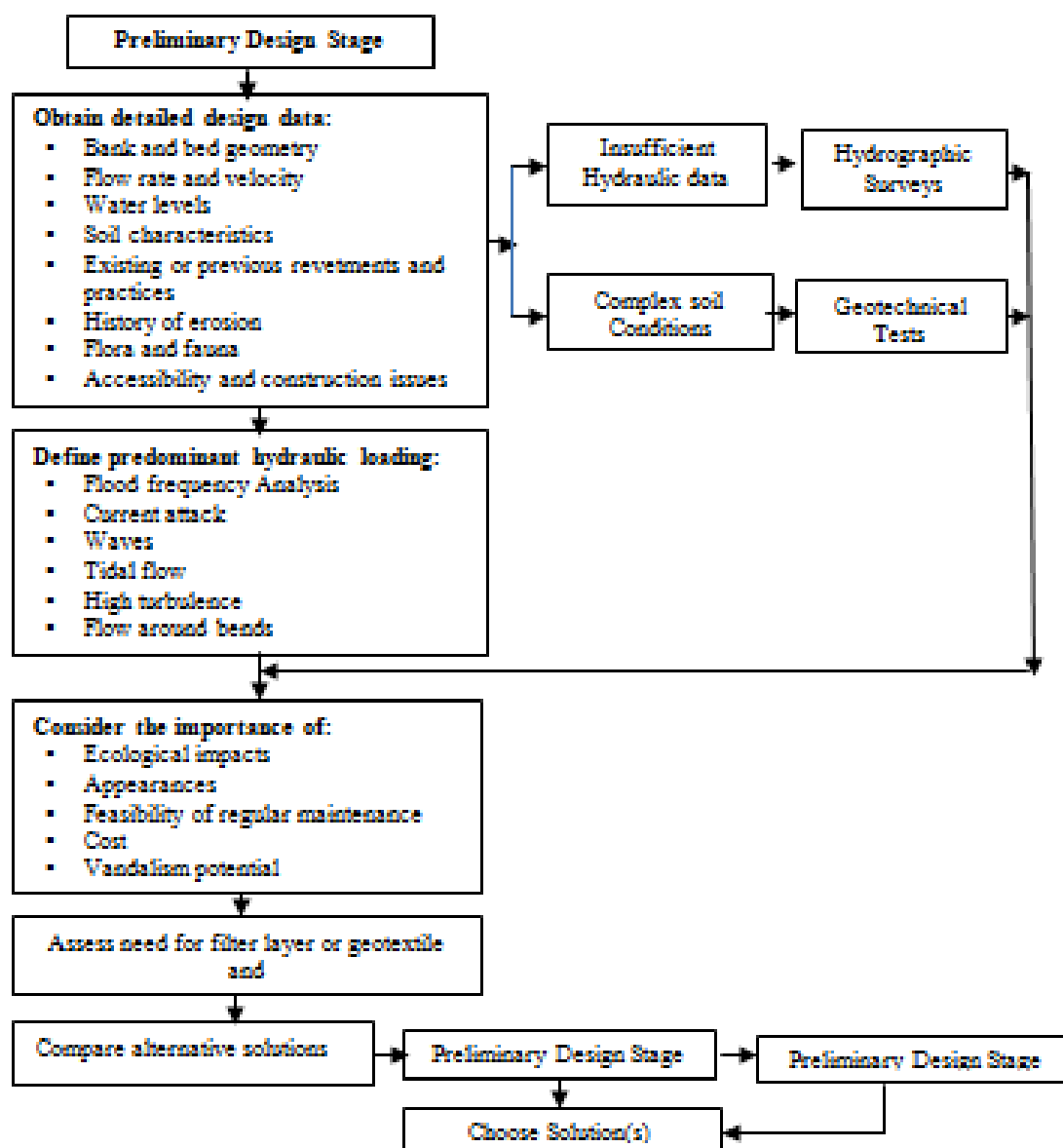


Figure 2 Flowchart for preliminary/conceptual design.

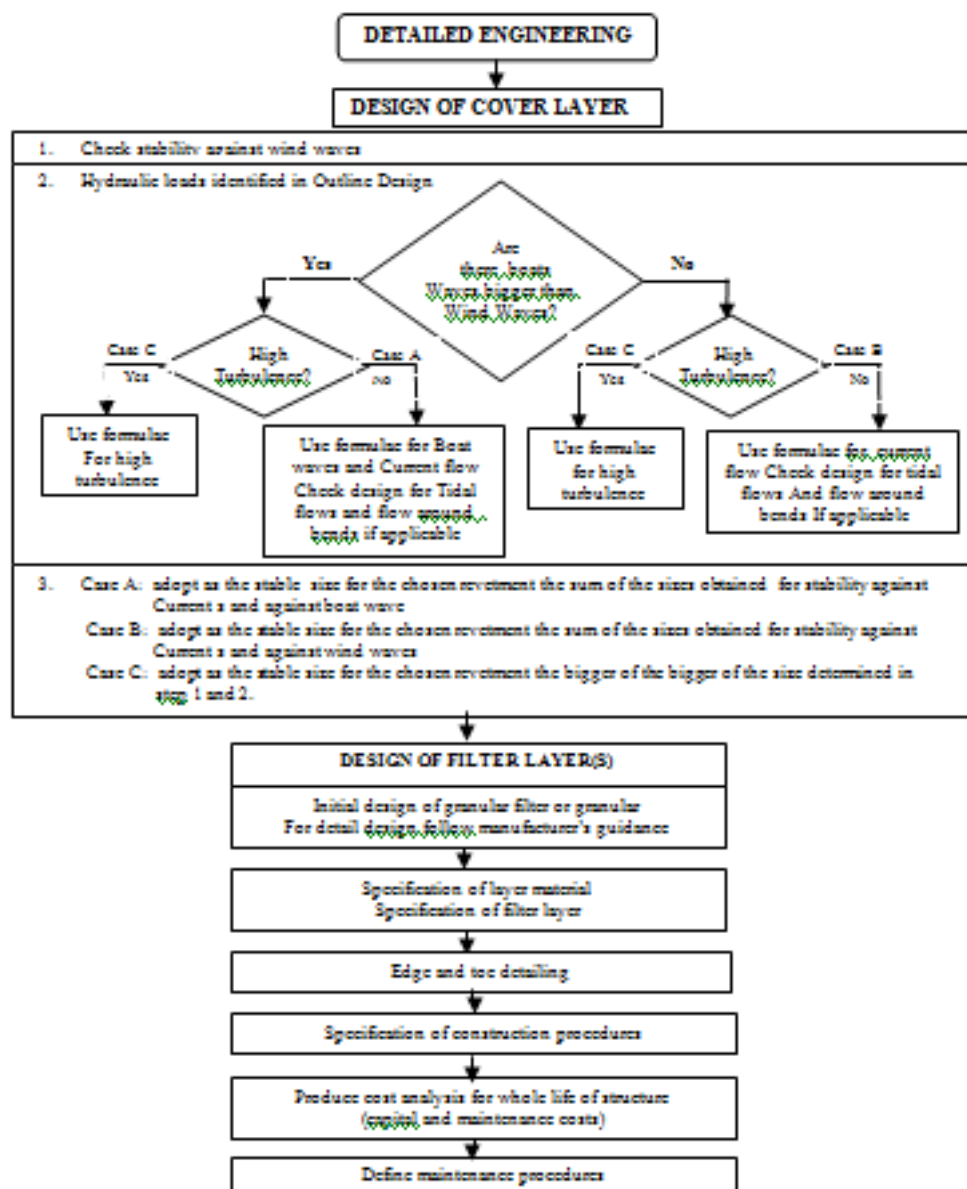


Figure 3 Flowchart for detailed design.

1. Slope Stability Analysis is a critical component of revetment integrity and should be designed for the most critical conditions. Critical condition occurs during flood recession, when the water level drops rapidly and the embankment is saturated with water, increasing the load while the water pressures decreases the shear strength. Slope instability occurs when the sliding forces in a slope exceed the frictional forces, determined by soil properties, such as cohesion, C , and angle of repose, ϕ . The standard methods for slope may be found on standard texts.^{11,12}
2. Design of Filter: Filters are of two main categories granular filters and geotextiles. The use of geotextiles in shore protection works

is in vogue because of its cost effectiveness, sand tightness with a limited thickness. Design should be executed to avoid blocking (sudden) or clogging (a gradual closure of the filter aperture in the textile). In order to prevent blocking and clogging of the filters, permeability 10 times larger than that of the subsoil is usually adopted to prevent pressure build-up.¹³

3. River Training: In view of the asymmetrical nature of the river sections at the bends which also coincide with the human settlement locations. The river flow is confined or realigned to a more regular course than that which occurs in nature. The realignment should ensure that the river possesses a sinuosity S close to 1.57 and the stability criterion $Scr. > 0.2$. A number of examples of river training schemes may be found in Jansen et al., (1979).

4. Morphological computational and Physical Modelling: There is no existing designed code of practice for River and Channel revetment. Only standard procedures exist and each project presents a unique challenge and generally site specific. Modelling is one of the States-of-the-Art- methods for simulating the behaviour of a physical system. A number of computational river models exist that can predict morphological changes due to the introduction of river engineering works. For example, ISIS (Wallingford Software Ltd, and Halcrow Group Ltd., 2003, Mike II (DH1 Software 2013), and HEC-RAS (US Army Corps of Engineers, 2002) Chadwich et al. (2006).

Impact of design on successful project implementation

Quality design is a *sine-qua-non* for successful implementation of the construction phase. Quality in construction is defined as conformance with requirement, as defined by the owner, designer, contractor, and the regulatory agencies.¹⁴ The objective of achieving these requirements rests with the design and constructions. Farooq¹⁵ enumerated the triple tasks of any consulting organization as follows

1. Acquisition of relevant data and estimation of design parameters necessary for implementation of design projects.
2. Sound understanding of the relevant data, analysis and design and production of design drawings and specifications and
3. Contractor's understanding, technical knowhow and competence to implement the owner's requirements through drawings and specifications. Any deficiency in any aspect of the tasks can lead to quality deviations in the complete project due to faulty design. This corroborates with Ransom¹⁶ who found that fifty eight percent (58 %) of building failures were due to faulty design, while poor execution scored thirty percent (30%) and twelve percent (12%) for use of poor quality materials. Also ICE (2009) observed that the successful design of a project demands not only expertise in technical details, but also a wide understanding of engineering principles, construction methods, costing, and safety, health legal and environmental requirements.

These findings were evaluated against recent Expression of Interest (EoI) adverts for prospective consultants by government agencies for design of infrastructure in the Niger Delta Basin. Conversely, it was observed that core competence in River/hydraulic engineering is not a criterion in the selection of design consultants on river basin development projects. The neglect of core competence underpins the prevalence of faulty designs and attendant project failures being observed in the Niger Delta Basin.

Conclusion and recommendation

This paper assessed the mechanism of channel pattern change and found that the observed that prevailing patterns in the Lower Niger River Basin agreed with a stability criterion proposed by Deng & Sing.⁵ Further, this paper evaluated the performances of existing shore protection schemes to underpin the best scheme in terms of durability. This study found that the best performed schemes were those of Otuokpoti and Sagbama, designed using Pilarczyk's equations. The scheme at Sagbagraia failed due to absence drainage, pour water pressure development behind the geotextile and gabion mattress which generated rotational slope failures. The steel-sheet pile revetment adopted for Opokuma/Kolokuma is inappropriate, in view of the prevailing river bank geometry. The use of Pilarczyk equations involves several uncertainties, therefore, experimental verification

and further improvement of design methods through research studies is recommended. Designers should pay special attention to

- i) Flood frequency analysis.
- ii) Slope stability analysis.
- iii) River training depending on the size of project.
- iv) The need for mathematical and hydraulic modeling.
- v) Engagement of consultants with core competence in River/hydraulic engineering and geotechnics as consultants for the design of shore protection works.

There is a tripartite nexus between mathematical, hydraulic modeling and water resource development. Both water resources development and management is strongly dependent on the availability of data, yet data collection and hydrometric measurement are less appreciated.¹⁷ In the Lower Niger River Basin, there is no functional hydrological station. Consequently, water resources planning and management is mission impossible unless the dearth of data is addressed. Accordingly, no meaningful designs can be executed in the Niger Delta and Lower Niger River Basin in the face of current-data problems. Finally, I wish to make the following recommendation:

- a. Reiterate the need for institutional reforms to resuscitate the abandoned hydrometric stations shown in Figure 2, coupled with the training of local agencies and researcher in Hydraulic engineering, water resources planning and management.
- b. Adopt the use of cable concrete block, box gabbions and gabion mattress option as appropriate revetment structure and research in narrowing the uncertainties in the Pilarczyk's equation.¹⁸⁻²⁰

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None.

Conflicts of interest

The author declares there is no conflict of interest.

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