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3-D Modelling of Protection Works for an Aspect of Lagos Coast

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Abstract
The study investigates the erosion envisaged to be caused by the hard protection works provided for Eko Atlantic City, the contributory factors and sediment variability along Lagos Coast. Alpha Beach along the Lagos coast was modelled with a distortion of 1: 21.36 using a horizontal scale of 1:1,068, a vertical scale of 1:50, model wave period of 1.7s and wave height of 0.02m. Cross-shore profiles were taken before and after the experiment. Laboratory analyses of beach sediments obtained from field investigations were also carried out. The experiment confirmed large-scale erosion on Lagos coast, with erosion greatest in places farthest from the protection works, followed by the site closest to the protection works. Cross-shore sediment transport observed in the model was driven largely by rip currents while longshore currents were responsible for longshore sediment transport. The physical and empirical measurements of longshore transported sediments during the experiment were 1,339kg and 2,097kg respectively. Laboratory analyses confirmed sediment variability in the run-up faces of beaches in Lagos coast as a result of continuous mixing by wave attacks. Measures should be put in place to mitigate the large-scale erosion and flooding envisaged in the eastward end of the vast project.

Keywords: cross-shore transport, erosion, protection, longshore transport, coast

INTRODUCTION

Worldwide, within the last three decades, the exponential increase in the value of coasts as a result of location of huge assets, gigantic infrastructural developments and concentration of one-tenth of the world population within 5km of the coasts (Kron, 2008) make their protection very crucial and critical. Likewise, the increasing vulnerabilities of coastal regions as a result of increasing climatic forces such as rising sea levels, increased storm intensities, unprecedented flood experiences and geogenic forces such as tsunamis continue to attract significant attention globally.

EKO ATLANTIC CITY

Eko Atlantic City, a new coastal city under construction adjacent to Victoria Island on a reclaimed land of approximately 9km^2 (Figure 1), is a public-private partnership project between Lagos State and her partners. The protection system for the City, designed at Danish Hydraulic Institute(DHI), Denmark , consists of breakwater- revetment system utilizing advanced concrete accropodes (Figure 2), designed to dissipate energy from storm waves of return period of 100 years.

STATEMENT OF THE PROBLEM

Evolution of past protection measures provided for Lagos coast failed consistently owing to the unprofessional approach utilized to solve the problem (Table 1). As a consequence of the hard protection being provided for the city, flooding and erosion is shifted eastwards towards the Lekki corridor and may impact navigability into the Lagos Port endangering the assets and population in the region. In addition, the EIA of the project was inaccessible while measures to mitigate the adverse impacts were not disclosed. The objectives of this paper are: to model erosion along the Lagos coast, highlight contributory factors, show the variability of sediments along the Lagos coast and proffer measures to ameliorate erosion in Lekki coastal region.

METHODOLOGY AND MATERIALS

The study area was Alpha Beach, an aspect of Lagos coastal region. An optimum scale of 1:1,068(horizontal) and 1:50(vertical), giving a distortion of 1: 21.36 was chosen after consideration of seven different scales. The study area covers a backshore distance of 1.55km and a surf zone distance of 1.29km. Soil samples were collected from several beaches and sites in the Lagos coastal region. These include Lekki beach, Alpha beach, Eleko beach, Majidun, Bariga and Hydraulic Research Unit within University of Lagos. They were all analysed at the Soil Mechanics Laboratory, Faculty of Engineering, University of Lagos. The essence of the physical analyses was to determine the soil sample with the closest similarity to the prototype beach sediment to be used in the model experiment and confirm the variability in properties of soil samples along and across the beach faces in the region.

The wave height data obtained by Oyegoke and Oremodu (2005) shown in table 3 were analysed using the Gumbel distribution method. The mean significant wave height from the data was 0.88 while the standard deviation was 0.0402. With a return period of 100 years, the significant wave height was obtained as:

$$H_s = H_{s,m} + ks \quad (1)$$

$$\text{where } k = \frac{\sqrt{6}}{\pi}(0.5772 + In In\frac{100}{99}) = 3.137 \quad (2)$$

and s= standard deviation of wave height values = 0.0402

H_s = 0.88 + (3.137 x 0.0402) = 1.006m, which is the significant wave height for the Lagos coast.

From Oyegoke and Ayankogbe (2005), the model characteristics obtained for modelling the Lagos coast were:

Wavelength scale, $\eta_L = \eta_D = 50$; (3)
wave period scale, $\eta_T = \eta_D^{0.5} = 7.07$; (4)
wave celerity scale, $\eta_C = \eta_D^{0.5} = 7.07$; (5)
wave height scale, $\eta_H = \eta_L = 50$; (6)
wave direction, $\eta_A = 1$ (7)

From Oyegoke and Oremodu (2005), the significant wave period for the Lagos coast is 12s. Therefore, the model wave characteristics were obtained as follows:

$$\text{Model wave period, } T_m = \frac{T_s}{\eta_T} \quad (8)$$

$$= \frac{12s}{7.07} = 1.7s \text{ and}$$

$$\text{Model wave height, } H_m = \frac{H_s}{\eta_D} \quad (9)$$

$$= \frac{1.006m}{50} = 0.02m$$

The model experiment was performed at the Hydraulic Research Unit of the University of Lagos. The model was oriented such that oblique, inclined waves were incident on the shore similar to the prototype at an angle of 15^0(Oyegoke and Oremodu 2005; Ayankogbe 1985).The model basin was reconstructed to provide a better controlled environment for the experiment. In addition, some measures were taken to improve the structural integrity of the exposed basin concrete walls such as provision of buttress walls, filling with broken bricks and cement mortar and plastering of the wall surfaces. Furthermore, rubble stones were provided at strategic points in the basin to dissipate reflected waves from the walls of the basin.

The soil with the closest similitude obtained from the hydraulic basin was selected and used in the model area. The landward part of the model beach has a slope of 1:15 being almost a flat topography; the beach face had a slope of 1:7.6 while the underwater portion had a slope of 1:3.3 giving an average slope of 1:5.5 for the beach face and surf zone, which is close to slope of 1:5 to 1:6 prevalent in Lagos coastal region.

After setting the stroke of the wave generator, water was pumped into the basin at a controlled rate. The wave generator was then set in motion to generate the desired wave height after the water has reached appreciable height in the basin. The period of oscillation was timed and averaged to determine the wave period for waves generated while the mean of the generated wave heights measured with wave meter was computed, which was equal to the required model wave period and height.

The mean water depth was 0.805m at the model area which translates to 0.305m on the wave board. Coloured ping pong balls were released to monitor the current pattern while a video of the event at the beach area was recorded. The beach profile was taken after the experiment and so also was sediment measurements taken to compute the rate of littoral transport.

RESULTS AND DISCUSSION

The grain size analyses for the various soil samples considered for use in the experiment are shown in table 4. From the soil sample analyses shown in table 4, Majidun and Hydraulic basin sand samples showed high similarity to Alpha beach samples. To show the variability in grain size for Lekki and Eleko beaches, soil samples were taken at three points namely the top of the beach face(denoted as subscript 3), 4m from the top of the beach face(denoted as subscript 2) and the limit of the uprush of the breaking waves(denoted as subscript 1). The grain size analyses results are shown in table 4. This clearly shows that particle sizes vary along the beach faces for the two beaches. There is higher variability in Lekki having a wider range of 0.12mm compared to Alpha with 0.07mm range using d_{50} parameter. Furthermore, for Eleko and Alpha beaches, the degree of saturation of the beach sediments were found to increase as the coastline is approached as shown in table 6. This agrees with what happens logically.

The beach profile displayed some significant changes after the experiment as depicted by figure 5. This implied that both cross-shore and alongshore movement of beach sediments occurred in the model, similar to what is being experienced along Alpha beach and Lagos coast in general. The experiment displayed the occurrence of cross-shore and alongshore sediment transport in the model similar to what obtains in the prototype. For all the three profiles, the seaward limit (end) after the experiment extended beyond the end of the beach profile prior to beginning the experiment. The differences in the three beach profile showed that erosion and sediment transport rates vary along and across the model. This implies that erosion and sediment transport rates vary for different sites in Alpha Beach in particular and along the Lagos Coast in general.

Based on analyses of the video record of the hydraulic experiment and physical observation during the experiment, the dominant factor responsible for the cross-shore sediment movement was the rip current while the dominant factor for the alongshore sediment transport was the longshore current with the rip current playing a secondary role.

The longshore sediment transported was obtained using two methods: Experimental measurement and empirical (mathematical) calculations. The alongshore sediments were collected and measured using a container of known volume. Thereafter, the bulk density was determined in the Soil Mechanics Laboratory of Faculty of Engineering, University of Lagos.

Total number of buckets of sediments = 28

Volume of bucket = $\frac{\pi D^2 H}{4}$ (10)

$= \frac{\pi \times 0.3^2 \times 0.373}{4} = 0.0264\ m^3$

Volume of sand transported = Volume of bucket x Total number of buckets (11)

= 0.0264 x 0.0264 = 0.7392 m^3

Bulk density of sand transported = $\frac{Weight\ of\ sand}{Volume\ of\ sand}$ =

$\frac{0.22}{0.000214}$ = 1.812 kg/m^3

Total mass of longshore sediment transported = Bulk density x Volume of sand transported = 1.812 x 0.7392 = 1,339.43kg.

Two empirical formulas were used namely CERC equation(USACE, 1984) and LCHF as discussed by Migniot et al. (1975). According to Oyegoke (2009) which was corroborated by Smith et al(2004), the most widely used formula in coastal engineering practice for the total longshore sediment transport rate(LST) is the CERC equation(USACE, 1984).

It is based on the principle that the volume of sand transport, Q is proportional to the longshore wave power per unit length of beach and is given by:

$$Q_V = \frac{\rho K \sqrt{g/\gamma_b}}{16(\rho_s - \rho)(1-a0} H_{s,b}^{2.5} Sin\,(2\theta_b) \quad (12)$$

Where Q_V = Volumetric transport rate in m^3/s; ρ_s= specific gravity of submerged sand; ρ = specific gravity of water; k = empirical coefficient = 0.39 derived from the original field study by Komar (1970).

γ_b = breaker index often assumed as 0.78(Smith et al. 2004); g = acceleration due to gravity

a = porosity; $H_{s,b}$ = significant wave height at breaking

θ_b = wave angle at breaking = 15^0 (Oyegoke and Oremodu 2005; Ayankogbe 1985)

$Q_V = \frac{1 \times 0.39 \sqrt{(9.81/0.78)}}{16(2.65-1.0)(1-0.4)}$ x Sin (2 x 15) = 2.47 x $10^{-6}$$m^3$/s

Volumetric transport for the entire period of experiment = Volumetric transport rate x total time of experiment = 2.47 x 10^{-6} x 60 x 45 = 6.67 x $10^{-3}$$m^3$

Mass of sediment transported, Q = Q_V $(\rho_s - \rho)$(1-a) g x 10^4 (13)

= 6.67 x 10^{-3}(2.65-1)(1-0.4) x 9.81 x 10^4 = 648kg

The formula of LCHF (Laboratoire Central d'Hydraulique de France) as discussed by Migniot et al. (1975) may be written as:

$$Q = H^2 T t f(\alpha) \frac{gr}{s} \quad (14)$$

Where H = significant wave height, T = wave period, t = action time of wave,

F (α) = empirical function obtained as 0.42 from the graph using a wave angle approach of 15^0

g = acceleration due to gravity, r = empirical constant obtained as 0.3307 using sand grain size D_{50} of 0.51

$$S = wave\ steepness = \frac{H_0}{L_0} \quad (15)$$

$= \frac{0.02}{(9.31 \times 1.7^2)}$ = 7.054 x 10^{-4}

Q = 0.02^2 x 1.7 x 60 x 45 x 0.42 x $\frac{9.81 \times 0.3307}{7.054 \times 10^{-4}}$ = 3,546kg

The mean longshore transported sediment from the two empirical results = $\frac{648+3546}{2}$ = 2097kg

Comparing the two values of 1,339.43kg (measured) and that of 2,097kg (calculated), the results are reasonably close taking into cognisance the limitations of the experiment and assumptions made during the experiment.

CONCLUSION AND RECOMMENDATION

Rip currents play dominant role in the cross-shore movement of beach sediments. Sediment variability was confirmed at the Lekki and Alpha beaches, an evidence of the continuous mixing by the oblique waves. The Longshore Sediment Transported obtained experimentally and empirically compares reasonably well. The construction of hard protection works for Eko Atlantic City is envisaged to cause enormous erosion along Lagos Coast but with greater consequences for sites farthest and nearest the site of development. It is recommended that adequate protective measures should be put in place to safeguard lives and assets in the eastward region of the Lagos Coast.

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NOTATIONS

a = porosity (dimensionless)

d_{50} = mean grain size (m)

F (α) = empirical function for wave angle (dimensionless)

g = acceleration due to gravity (ms^{-2})

H and H_s = significant wave height (m)

H_m = model wave height (m)

$H_{s,b}$ = significant wave height at breaking (m)

$H_{s,m}$ = mean significant wave height (m)

K = empirical coefficient for grain sand and wave (dimensionless)

k = gumbel coefficient (dimensionless)

Q_v = volumetric transport rate (m^3s^{-1})

r = empirical constant for sand (dimensionless)

s = standard deviation (dimensionless)

S = wave steepness (dimensionless)

T = wave period (s)

T_m = model wave period (s)

t = time action of wave (s)

η_l = wavelength scale (dimensionless)

η_c = wave celerity scale (dimensionless)

η_h = wave height scale (dimensionless)

η_A = wave direction scale (dimensionless)

ρ_s = specific gravity of submerged sand (dimensionless)

ρ = specific gravity of water (dimensionless)

γ_b = breaker index (dimensionless)

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APPENDIX

Table 1. Evolution of Lagos coastal protection works (Oyegoke et al, 1983; Awosika et al. 1991; Odofin, 2004; and Oyegoke, et al, 2009)

Period	Measures Applied
1958	Construction of a groyne at the foot of the eastern breakwater to avoid undermining of the Breakwater
1958-1960	Dumping of sediment dredged from Commodore channel of the extremity of eastern Breakwater for disposal along the beach by waves
1960-1968	Permanent pumping station built on the eastern breakwater, supplying an average of 0.66million m^3per annum of sediment from the Commodore channel to the beach. In between in 1964, a 'zig-zag'timber groin running parallel to the coastline was driven in some 26m from the shoreline
1969-1974	Some artificial sand replenishment
1974-1975	3 million m^3 of sand dumped and spread on the beach
1981	2 million m^3 of sand dumped and spread on the beach
1985-1986	3 million m^3 of sand dumped and spread on the beach
1990-1991	5 million m^3 of sand dumped on the beach after undermining of nearby fences by waves
1995-1997	6 million m^3 (2 million m^3per year) was dumped
1998	A groyne was constructed at the back of Federal School of Fisheries
2002-2003	Dredging of more than 2 million m^3 of sand and rehabilitation of Ahmadu Bello Way
2004-2005	Beach replenishment
2005-2006	X-blocs, boulders, geotextiles and concrete beds were used
2008	Breakwater-revetment system utilizing advanced concrete accropodes

Table 2. Wave data for Lagos coast (Oyegoke and Oremodu, 2005)

Month	Significant wave height, H_s (m)
January	-
February	0.930
March	0.975
April	0.938
May	-
June	0.905
July	1.078
August	1.050
September	1.009
October	0.829
November	0.576
December	0.472

Table 3 Results of Particle grain size analyses for some sites in Lagos coastal region

Soil parameters	Eleko beach	Lekki beach *(mean)	Alpha beach *(mean)	Hydraulic basin	Majidun	Bariga
D_{50}(m x 10^{-3})	0.43	0.45	0.43	0.51	0.5	0.7
D_{10}(m x 10^{-3})	0.33	0.27	0.28	0.27	0.24	0.28
D_{30}(m x 10^{-3})	0.37	0.36	0.36	0.38	0.36	0.47
D_{60}(m x 10^{-3})	0.47	0.52	0.47	0.62	0.60	0.85
C_u(m x 10^{-3})	1.42	1.93	1.68	2.30	2.5	3.04
C_c(m x 10^{-3})	0.88	0.92	0.98	0.86	0.9	0.93

*Note: Mean represents the average values for Lekki beach and Alpha beach run-up faces respectively

Table 4 Variability in grain size for Lekki and Alpha Beaches

Soil parameters	Lekki L_1	Lekki L_2	Lekki L_3	Alpha A_1	Alpha A_2	Alpha A_3
D_{50}(m x 10^{-3})	0.39	0.51	0.44	0.46	0.45	0.39
D_{10}(m x 10^{-3})	0.25	0.28	0.27	0.29	0.30	0.25
D_{30}(m x 10^{-3})	0.33	0.38	0.36	0.38	0.38	0.33
D_{60}(m x 10^{-3})	0.44	0.63	0.49	0.49	0.49	0.43
C_u(m x 10^{-3})	1.76	2.25	1.82	1.69	1.63	1.72
C_c(m x 10^{-3})	0.99	0.82	0.98	1.02	0.98	1.01

Figure 1. Layout and Districts of Eko Atlantic City

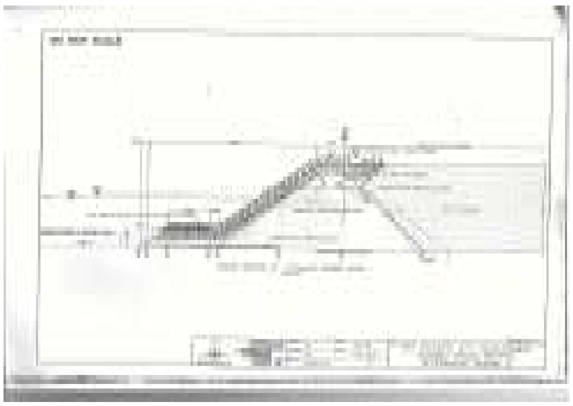

Figure 2. Breakwater-revetment system utilized in protecting Eko Atlantic City under construction

Figure 3. Waves generated during the experiment at University of Lagos Hydraulic Research Unit

Figure 4. Rip currents eroding the model beach at University of Lagos Hydraulic Research Unit

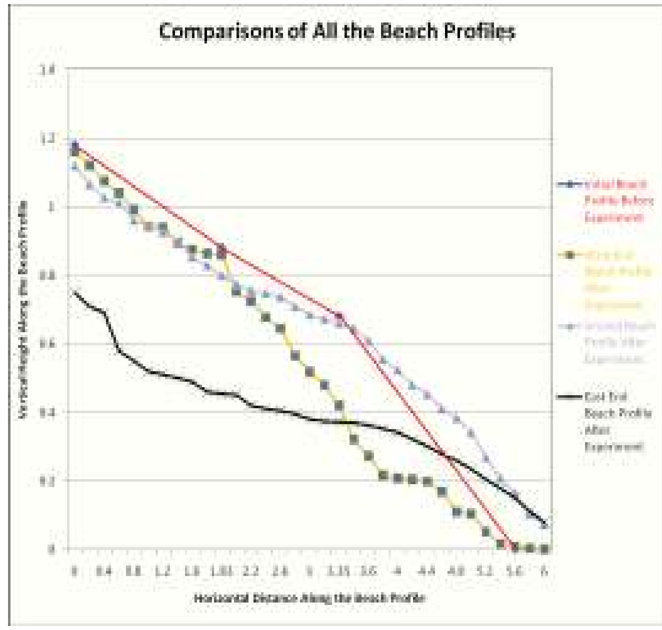

Figure 5. Comparison of beach profiles at different sections before and after the experiment