CHAPTER 126

SEDIMENTATION STUDIES ON THE NIGER RIVER DELTA

Ramiro Mayor-Mora, D. Eng. (1)
Preben Mortensen, M.Sc. (2)
Jorgen Fredsoe, M.Sc. (2)

1. Introduction

An area of the Niger River Delta was studied from October 1974 to October 1975 in connection with feasibility studies and preliminary design for the development of a deep draught port in the Western portion of the Delta. The provision of a 100-kilometer, 8 or 10 m navigation channel through one of the entrances from the sea, up to new port facilities at Warri required comprehensive hydraulic, hydrographic and sedimentation surveys over such period.

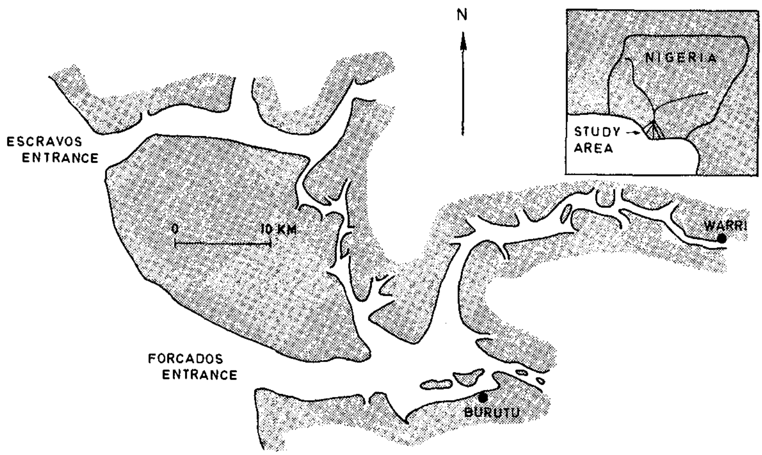


Figure 1. Location Map

(1) SNC Inc. (Consultants), Montréal, Canada
(2) Danish Hydraulic Institute, (DHI), Copenhagen, Denmark

The sedimentation studies dealt primarily with the conditions at the entrances. The main entrance to the existing ports of the Western Niger Delta used today by ships of up to 6 m draught is the partly protected entrance of Escravos. At such entrance, two moles were constructed around 1960 following intensive hydraulic studies that included testing on physical models.

However, the sedimentation is concluded to be in the order of 2 million cubic meters per year in the lee of the breakwaters. This sedimentation has been explained and possible solutions discussed.

An unprotected channel through the Forcados Entrance was considered as an alternative to improvement of the Escravos Entrance. Such a channel would be dredged through sand and the sedimentation due to combined current and wave actions was studied.

A theory for sedimentation of suspended load in an unprotected dredged channel in non-cohesive material was developed in connection with the study of Forcados Entrance. This theory is presented herein as an appendix.

2. Escravos Entrance

2.1 Background

The present entrance to the ports of the Western Niger Delta for ships drawing less than 4 to 5 m was chosen following hydrographic and hydraulic studies in the period 1953-1955. The minimum natural depth of Escravos bar was about 4.0 m and those studies concluded that a dredged 6 m deep channel through Escravos Entrance was required and that it had to be protected from sedimentation.

Based on hydraulic model tests, it was decided to construct a breakwater system consisting of a main breakwater (length 9 km) on the southern side of the channel and a detached breakwater (length 1 km) on the northern side of the channel, as illustrated on Figure 2 below.

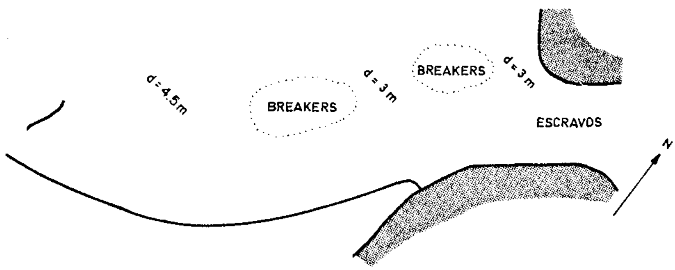


Figure 2. Present Escravos Entrance Protection

The purpose of the breakwater protection was

- to protect the navigation channel from deposition of material coming from the south due to the northgoing littoral drift.
- to guide the main part of the ebb current over the Escravos Bar creating current velocities sufficient for natural maintenance of the dredged channel.

The model studies concluded that the flow had to be concentrated further by means of an island breakwater, whereas the last 2 to 3 km of the dredged channel beyond the tip of the main breakwater were suggested to be left unprotected.

2.2 Monitoring of Sedimentation

One of the main objectives of the study was to investigate and explain the heavy siltation that was known to take place in lee of the breakwaters.

After a maintenance dredging carried out in November-December, 1974, a field investigation program including frequent soundings on the bar was initiated and continued until August, 1975. The monitoring yielded definitive answers to the important questions of where and when sedimentation occurs and which kind of material is depositing in the channel.

It was calculated that if the dredged channel had been constantly maintained with a navigation depth of 6.0 m, the annual maintenance dredging would be in the order of 2.0 million cubic meters depending on the assumptions made (frequency of dredging, overdredging, etc.).

Apparently, sedimentation in the channel in the lee of the breakwater takes place throughout the year. It is difficult to calculate any seasonal variation of the sedimentation based on the results of the monitoring, since a depth close to the natural depth was achieved about half a year after completion of the dredging. But it is assumed that the sedimentation rate is constant throughout the year, since no significant change is found from the period December to March (when the fresh water season ends) to the period April to May (when the rough-wave season starts).

The sediments deposited in the dredged channel were found to consist of extremely fine, silty materials.

2.3 Sedimentation Mechanism

An explanation to the heavy siltation in the channel in the lee of the mole is found through a study of the current patterns through the Escravos Entrance, which are strongly dominated by the tides.

During the ebb current, the flow is concentrated at the mouth of the Escravos River. At some distance seawards from the mouth, the depth in the main channel decreases, the current velocities increase slightly and a flow out of the channel into the shallow area north of the channel is found.

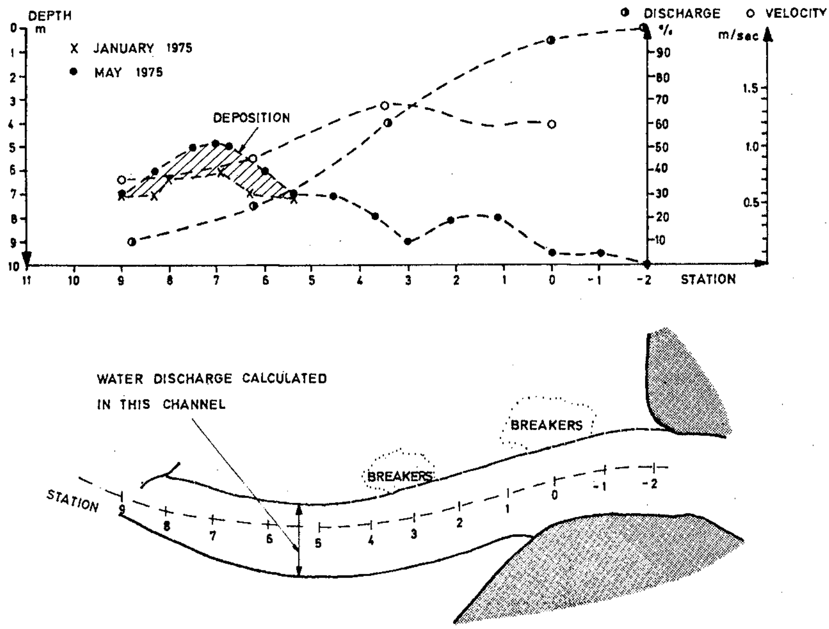


Figure 3. Sedimentation and Ebb Discharges in the Lee of the Breakwater

It is evident that a major part of the flow turns north before reaching the tip of the breakwater, especially in the area between the breakers and the island breakwater. The resulting effect is a decrease in current velocity east of the tip of the breakwater.

Figure 3 shows a characteristic ebb discharge across a section along the navigation channel in percentage of the total water discharge leaving the mouth of the Escravos River. It can be seen that only about 10% of the total discharge passes over the sedimentation area.

It is therefore concluded that the breakwaters do not create the desired effect, except for a local increase in current velocities between the breakwaters which does occur. The region of heavy siltation is found in the lee of the main breakwater, where current velocities decrease.

It should be emphasized that the clay and silt depositing in the channel do not necessarily originate directly in the Escravos River. North of the channel the bed consists of silt and clay exposed directly to wave action, the magnitude of sediment concentrations at the river mouth being very close for either the rough or the mild wave seasons. Therefore, considerable quantities of suspended silt and clay are being brought into the Escravos River during the flood current and out again during ebb current. The sedimentation in the channel may therefore be considered a transport from one area of the Escravos Entrance to another due to the difference in the current patterns during flood and ebb.

2.4 Possible Improvements

The most straightforward way to reduce sedimentation would be to construct a northern breakwater which should run more or less parallel to the existing main breakwater and be connected to the coast north of the Escravos Entrance as shown on Figure 4. This new arrangement would reduce the quantity of fine material being brought into the system from the north and at the same time, because of the flow concentration, create a scouring effect between and beyond the breakwaters.

By confining the navigation channel between two breakwaters the flow conditions between them would be similar to those at the mouth of the Escravos River in the present situation:

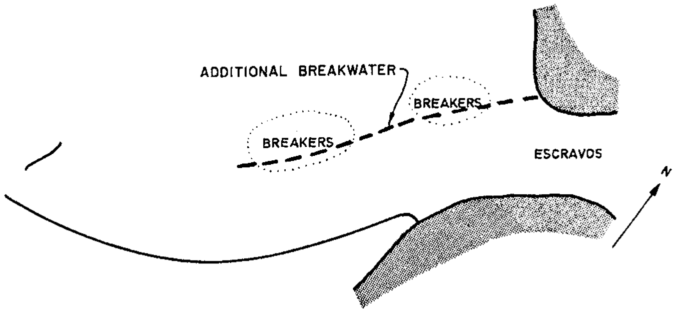


Figure 4. Escravos Entrance Improvement

During ebbing the flow acts as a jet and during flooding its behaviour is similar to that characteristic of a drain. Hence, in order to avoid sedimentation or significantly reduce it in the new navigation channel, the tip of the new breakwater should necessarily be placed at such a distance from the coast that the erosion zone beyond the new mouth extends across the whole of the present bar region in order to obtain sufficient natural depths throughout that shallow region.

The difference in flow pattern between ebb and flood currents would, along with other mechanisms, be able to generate erosion of the bed to a new natural depth similar to the present depth at the mouth of Escravos River (11 m).

3. Forcados Entrance

3.1 Proposed Navigation Channel

A navigation channel through the Forcados Entrance was studied because a route through Forcados to Burutu and to Warri would be much shorter and involve much less capital dredging within the estuary than a waterway to the same ports through the Escravos Entrance (see Figure 1).

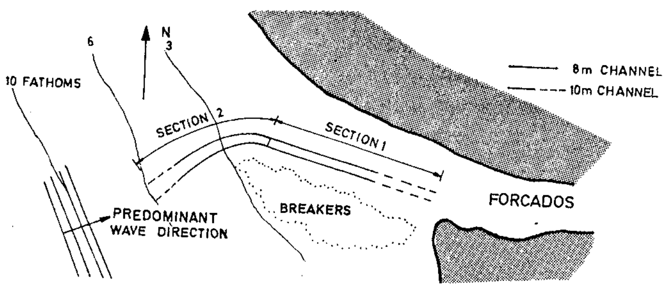


Figure 5. Navigation Channel through the Forcados Entrance

The outermost part of the channel has a direction perpendicular to the depth contours in order to minimize capital dredging.

3.2 Present Conditions

At the Forcados Entrance the present natural depth of the bar at the threshold is about 4.8 m according to soundings made in September 1975. The depth of 4.8 m is about equal to the natural depth on the Escravos Bar before construction of the breakwaters.

The main difference between the entrances of Escravos and Forcados is the vast breaker zone south of the Forcados entrance channel that creates an asymmetrical configuration of the entrance.

The breaker zone, reaching more than 10 km into the sea, is exposed to direct wave attack.

The ebb currents concentrate along the area north of the breaker zone with typical velocities of about 1.0 m/sec. at the mouth of the river. The current velocities have been found to decrease only slightly before reaching the Forcados Bar.

While flooding, the Forcados Entrance acts like a drain. The incoming currents just north of the breaker zone are very weak compared to the outgoing currents. Most of the tidal volume going in through the Entrance while flooding passes through the breaker zone.

In general, the bottom configuration in the Forcados Entrance area is found to be rather stable, charts covering a period of 100 years showing little change in the same configuration. But the vast southern area directly exposed to wave action and the interaction between northgoing and westgoing sand transports results in fluctuations of the bottom configuration around the breaker zone.

3.3 Sedimentation Mechanisms

On Figure 5, the navigation channel has been divided into two sections which, from a sedimentation point of view, are different since the principal mechanisms causing sedimentation are different.

Section 1 of the channel runs from the mouth of the Forcados River to the eastern side of threshold of Forcados Bar. Within section 1, the main sedimentation mechanism will then be flattening of the channel sides due to currents parallel to the channel alignment.

Section 2 of the channel is exposed to direct wave action, and the predominant current directions are perpendicular to the channel alignment.

In the channel where the bed consists of fine sand the concentration of suspended sediments is determined by the waves and the currents. Concentrations a few centimeters from the bottom are determined by the wave action (wave height and wave period) while the distribution of the concentration from the thin bottom layer to the surface is determined by the current.

The bottom concentration determined by the waves will, in general, decrease as the depth increases.

As the current passes over the side slope of the dredged channel, the concentration profile determined by the waves and the current will change, and in principle a quantity of suspended sediment corresponding to the difference in concentration profiles will settle in the dredged channel.

This sedimentation mechanism is dominating in section 2 of the navigation channel through Forcados Entrance. However, the mechanisms described for section 1 have also some effect although in a modified manner.

3.4 Calculated Sedimentation Rates

In section 1 of the entrance, the future sedimentation rates are calculated on the basis of the theory developed in Ref. 1 Levelling of Side Slopes in River Navigation Channels.

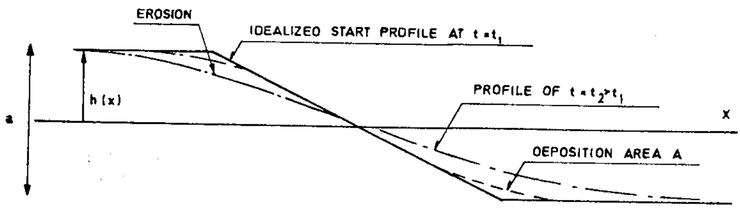


Figure 6.

The depositing volume per meter of channel (deposition area A shown on Figure 6 above) is found as the difference between the profile h(x) at the time $t = t_2 > t_1$ and the profile at the time $t = 1_1$:

$$A = a \frac{\sqrt{\nu}}{\sqrt{\pi}} \cdot (\sqrt{t+t_1} - \sqrt{t_1})$$

This general solution to the problem of instability of a transverse slope in an unidirectional flow yields the deposition volume at the bottom of the slope as a function of the time t after a certain start condition at time t_1.

ν is a function of the longitudinal bed-load transport rate.

In section 1 of the channel sedimentation rates of about 50 cubic meters per meter channel per year were found.

In section 2 of the channel the main sedimentation process is the one described in the Appendix, Changes in the Profile of Concentrations Due to Changes in Water Depth.

The general expression for the sedimentation rate in the dredged channel is:

$$q_r = \left\{ q_{10} \left(1-\exp^{-\frac{W}{\varepsilon}\frac{W}{V_b}\frac{D_1}{D_2}\frac{B}{\cos\alpha}}\right) - q_{20}\left(1-\exp^{-\frac{W}{\varepsilon}\frac{W}{V_b}\frac{B}{\cos\alpha}}\right)\right\} \cos\alpha.$$

where

q_{10} = transport of suspended sediments, equilibrium conditions at depth D_1

q_{20} = transport of suspended sediments, equilibrium conditions at depth D_2

W = settling velocity of the sand grains

ε = current eddy viscosity

V_b = "slip" velocity

B = total channel width

α = angle between current direction and the perpendicular to the channel alignment

D_1 = present depth

D_2 = dredged depth

From the expression above, it is seen that the relative rate of sedimentation (the expression inside the main bracket) increases as the width of the channel B and the current angle α increase, and that the rate decreases as the current velocity V increases.

In the present case it was found that more than 95% of the material, corresponding to the difference in equilibrium transport at water depth D_1 and equilibrium transport at water depth D_2 would settle in the channel.

For the calculation of the equilibrium transport the concentration of suspended load in a reference level 5 cm above the bottom, C_a, was determined from experiments in an oscillating flume.

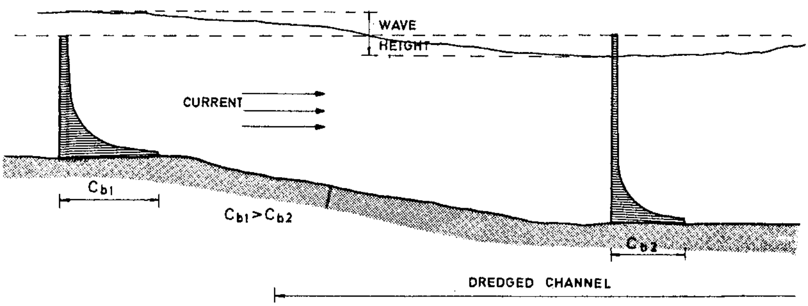
The sedimentation rates in section 2 of the channel were calculated to be in the order of 1000 cubic meters per meter channel per year (conservative estimate).

APPENDIX

Changes in the Profile of Concentrations of Suspended Material Due to Changes in Water Depth.

A1 Introduction

In the following discussion a flow over the side slope of a dredged channel is considered. The bed beyond the slope is assumed horizontal and the width of the horizontal channel bottom is assumed to be of infinite length, as shown in the sketch below.



As the flow passes the side of the channel, its velocity changes and therefore the total sediment load, carried as bed load and suspended load, changes accordingly.

While the bed load is able to respond very quickly to changes in the flow, changes in the suspended load take place over a period of time due to the finite settling velocity of the suspended grains.

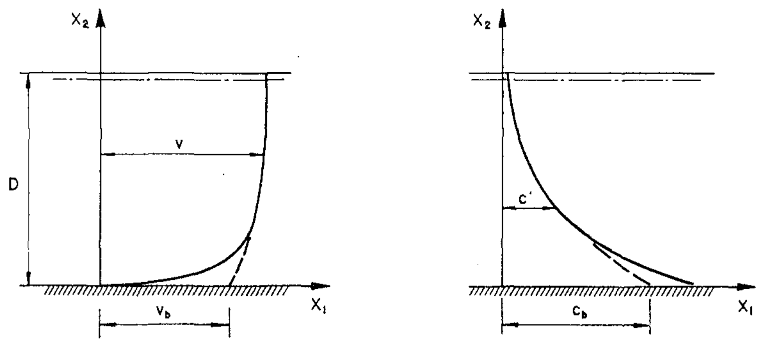
The purpose of this appendix is to describe how the concentrations of suspended material respond to the change in depth conditions. The theory is developed in two steps:

- In the first step the equilibrium concentration profile is determined by the bottom concentration only. The latter decreases as the depth increases, but the shape of the upper part of the concentration profile does not change.

- The shape of the concentration profile changes as the depth increases. The profile is stretched due to the divergence of the stream lines as the flow passes over the channel side.

A2 The Calculation Model

The calculation model is based on the "slip-velocity" method, described in Refs. 2 and 3. The basic idea behind this calculation method is to assume that the current eddy viscosity ε is constant over the depth (rather than decreasing to zero at the bottom). This method (or approximation) makes it necessary to introduce a finite velocity at the bottom, the so-called "slip-velocity".



In the following introduction to the basic equations, x_1 is the horizontal coordinate and x_2 is the vertical coordinate. The vertical distribution of concentration is considered in two situations.

In the steady, iniform condition the vertical distribution of the concentration c_o is determined by the equilibrium between settling and diffusion.

$$Wc_o + \varepsilon \frac{dc_o}{dx_2} = 0 \tag{A2.1}$$

where W is the settling velocity of the grains.

The solution to equation A2.1 is

$$c_o = c_{bo} \cdot e^{(-\frac{W}{\varepsilon}x_2)} \tag{A2.2}$$

where c_{bo} is a nominal bottom concentration and ε is the current eddy viscosity.

In the non-uniform situation the distribution of concentration of suspended material is determined by an equilibrium between settling, diffusion and convection:

$$\frac{dc}{dt} = W \frac{\partial c}{\partial x_2} + \varepsilon \nabla^2 c \tag{A2.3}$$

As mentioned above the theory will be developed in two steps. In both steps the approximation is made that the current field is steady and uniform, while the distribution of concentrations of suspended sediments is steady but non-uniform in the x_1-direction. Using this approximation equation A2.3 may be written

$$v \frac{\partial c}{\partial x_1} = W \frac{\partial c}{\partial x_2} + \varepsilon \left(\frac{\partial^2 c}{\partial x_1{}^2} + \frac{\partial^2 c}{\partial x_2{}^2}\right) \tag{A2.4}$$

Introducing the "slip-velocity" method the variation in the velocity v over the depth may be neglected, the velocity is constant, equal to the "slip-velocity", v_b.

A3 General Solution to the Problem

a) First Step

On the horizontal bed before reaching the side of the channel ($x_1 = 0$), the concentrations are considered to be stationary and uniform, and accordingly the concentration profile is given by equation A2.2. As the depth increases on the side of the channel the bottom concentration changes and equation A2.2 has to be modified in order to satisfy the non-uniform condition.

In order to find a general solution to equation A2.4 the distribution of concentrations is written as

$$c = c_1 \cdot e^{-\frac{W}{\varepsilon}x_2} + f\,(x_2)\; e^{-\lambda x_1} \qquad \text{(A3.1)}$$

where c_1 and λ are constants and $f(x_2)$ an unknown function of x_2.

Substituting c in equation A2.4 for the expression for c in equation A3.1 we find:

$$\frac{d^2 f}{dx_2} + W\frac{df}{dx_2} + (\varepsilon\lambda^2 + V\lambda)\; f = 0 \qquad \text{(A3.2)}$$

The solution for equation A3.2 is

$$f(x_2) = \alpha_1 \cdot e^{(-\frac{W}{\varepsilon} + \frac{\varepsilon}{W}(\lambda^2 + \frac{\lambda V}{\varepsilon}))x_2} + \alpha_2 e^{-\frac{\varepsilon}{W}(\lambda^2 + \frac{\lambda V}{\varepsilon})x_2} \qquad \text{(A3.3)}$$

The constants α_1, α_2 and λ are determined from the boundary conditions as follows:

On the horizontal bed on top of the slope ($x_1 = 0$) the boundary condition is determined by equation A2.2.

$$c = c_{b1}\; e^{-\frac{W}{\varepsilon}x_2} \quad \text{for } x_1 = 0$$

At an indefinite distance from $x_1 = 0$ a new uniform solution, corresponding to equation A2.2 but with a different bottom concentration, is found:

$$c = c_{b2}\; e^{-\frac{W}{\varepsilon}x_2} \quad \text{for } x_1 = \infty$$

The only set of equations that satisfies the first boundary condition is:

$$\frac{W}{\varepsilon} = \frac{\varepsilon}{W}\;(\lambda^2 + \frac{\lambda v}{\varepsilon})$$

$$\alpha_1 = 0$$

$$c_{b1} = c_1 + \alpha_2$$

The second boundary condition is satisfied by

$$c_1 = c_{b2}$$

From these four equations the unknown constants in the solution to equation A3.1 are found:

$$\alpha_1 = 0, \ \alpha_2 = c_{b1} - c_{b2}, \ \lambda = \frac{W^2}{\varepsilon^v}$$

yielding the solution

$$c = c_{b2}\ e^{-\frac{W}{\varepsilon}x_2} + (c_{b1} - c_{b2})e^{-\frac{W}{\varepsilon}x_2} \cdot e^{-\frac{W^2}{\varepsilon v}x_1} \qquad \text{(A3.4)}$$

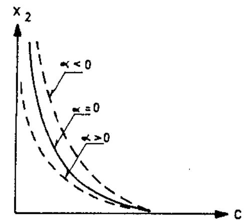
when W^2/v^2 tend to zero, that is $W<<v$.

b) Second Step

In the previous step the calculation was made under the assumption that the concentration profile was in equilibrium with a certain bottom concentration changing as the depth increased but the "shape" of the profile was unchanged.

In the second step it is assumed that the concentration profile is stretched due to the divergence of the streamlines as the flow passes over the channel side.

A simple exact solution to the problem of this step is not possible but the effects of the stretched profile may be described by changing the boundary conditions.



If the first boundary condition is given by the equation

$$c = c_{b1}\ e^{-\frac{W}{\varepsilon}(1-\alpha)x_2} \qquad x_1 = 0,$$

this condition will be fulfilled by equation A3.3, if

$\alpha_1 = 0$, $\alpha_2 = c_{b1}$ and $\lambda = (1-\alpha)\frac{W^2}{\varepsilon v}$, considering $W << v$.

That is, for $c = c_{b1}\ e^{-\frac{W}{\varepsilon}(1+\alpha)x_2} \cdot e^{-(1+\alpha)\frac{W^2}{\varepsilon v}x_1}$ (A3.5)

To this solution, a solution

$$c_2 = f(x_1)\ e^{-\frac{W}{\varepsilon}x_2} \quad \text{(A3.6)}$$

to equation A3.4 that satisfies the boundary conditions

$c_2 = c_{b2}\ d^{-\frac{W}{\varepsilon}x_2}$ for $x_1 = \infty$

$c_2 = 0$ for $x_1 = 0$

has to be added. This solution is

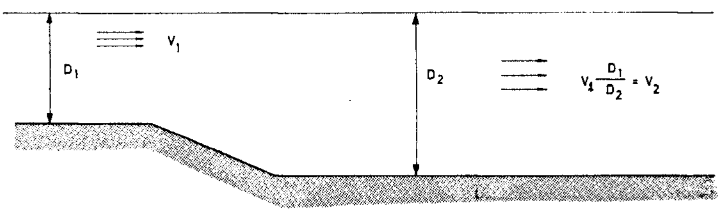
$$c_2 = c_{b2}\ e^{-\frac{W}{\varepsilon}x_2}\ (1 - e^{-\frac{W^2}{\varepsilon v}x_1}) \quad \text{(A3.7)}$$

Therefore the total solution to the problem presented in the two steps is

$$c = c_{b1}\ e^{-\frac{W}{\varepsilon}(1+\alpha)x_2} \cdot e^{-\frac{W^2}{\varepsilon v}(1-\alpha)x_1} + c_{b2}\ e^{-\frac{W}{\varepsilon}x_2}(1-e^{-\frac{W^2}{\varepsilon v}x_1}) \quad \text{(A3.8)}$$

A4 Application of the General Solution

For the present application of the theory developed above, a situation determined by a combination of waves and a moderate current is considered.

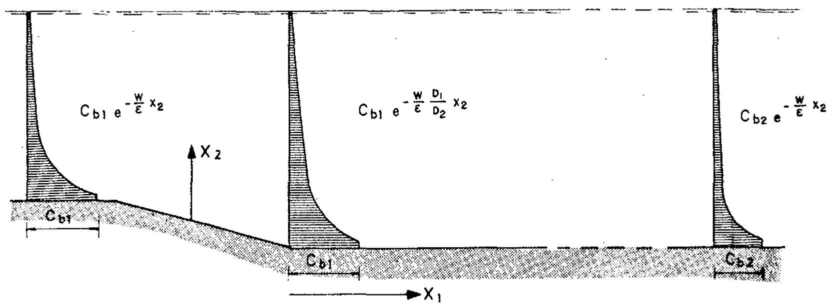


The undredged depth is called D_1, and the corresponding current velocity V_1. The depth in the channel is called D_2 and the corresponding current velocity V_2.

The concentration of suspended material in a bottom layer a few centimeters thick (bottom concentration) is determined by the wave action, as the bed shear stress due to the wave action is much greater than the current shear stress, whereas the vertical distribution of the concentrations from the bottom to the surface is governed by the currents.

The bottom concentration on the horizontal bed beyond the side slope is called c_{b1} and the vertical distribution of concentration is described by

$$c_{b1} \cdot e^{-\frac{W}{\varepsilon}x_2} \qquad \text{(A4.1)}$$



At the toe of the side slope of the channel the approximation is made that the bottom concentration is unchanged, but the concentration profile is stretched with the same ratio as the depth is changed, i.e. $\frac{D_1}{D_2}$. Therefore the concentration is given by

$$c_{b1} \cdot e^{-\frac{W}{\varepsilon}\frac{D_1}{D_2}x_2} \qquad \text{(A4.2)}$$

At an indefinite distance from the channel side a new equilibrium profile is reached. The bottom concentration is given by C_{b2} and the concentration profile is accordingly given by

$$c_{b2} \cdot e^{-\frac{W}{\varepsilon}x_2} \qquad \text{(A4.3)}$$

Keeping in mind that the eddy viscosity is assumed to be constant and that the current velocity in the applied calculation model may be replaced by the constant "slip-velocity", the transport of suspended material q may be easily calculated as

$$\int_o^D (c \cdot v)\, dx_2 \tag{A4.4}$$

At the un-dredged depth D_1, the sediment transport q_{10} is

$$q_{1o} = \int_o^{D_1} c_{b1}\, e^{-\frac{W}{\varepsilon}x_2} \cdot v\, dx_2 \approx V_{b1} \cdot \frac{\varepsilon}{W} c_{b1} \cdot (1-e^{-\frac{W}{\varepsilon} D}) \tag{A4.5}$$

In the case of sand particles (high W),

$$q_{10} = V_{b1} \cdot \frac{\varepsilon}{W} c_{b1} \tag{A4.6}$$

At an infinite distance from the side slope ($x_1 = \infty$), the sediment transport is given by

$$q_{20} = \int_o^{D_2} c_{b2} \cdot e^{-\frac{W}{\varepsilon}x_2} \cdot v dx_2 \approx V_{b2} \frac{\varepsilon}{W} c_{b2} \tag{A4.7}$$

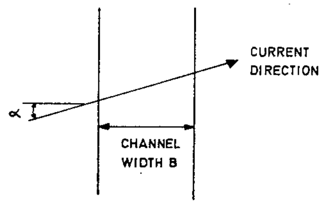
The sediment transport $q_2(x_1)$ between the two boundaries is given by an integration of equation A4.4

$$\begin{aligned} q_{20} &= \int_o^{D_2} \Big\{ c_{b1} \cdot e^{-\frac{W}{\varepsilon} \frac{D_1}{D_2} x_2}\, e^{-\frac{W}{\varepsilon}\frac{W}{v}\frac{D_1}{D_2}x_1} - c_{b2}\, e^{-\frac{W}{\varepsilon}x_2} \\ &\quad \cdot (1-e^{-\frac{W}{\varepsilon}\frac{W}{v}x_1}) \Big\} \cdot V\frac{D_1}{D_2}\, dx_2 = \\ q_{10} &\cdot e^{-\frac{W}{\varepsilon}\frac{W}{v}\frac{D_1}{D_2}x_1} - q_{20}\,(1-e^{-\frac{W}{\varepsilon}\frac{W}{v}x_1}) \end{aligned} \tag{A4.8}$$

The overall aim of the above calculation is to evaluate the rate of sedimentation between the two boundary conditions corresponding to the two equilibrium situations at $x_1 = 0$ and $x_1 = \infty$. The rate of sedimentation as well as the distribution of sedimentation is found by subtracting the sediment transport $q_2 = q_2\ (x_1)$ from the sediment transport at $x_1 = 0$. The rate of sedimentation $q_\gamma\ (x_1)$ is given by

$$q_{10} - q_2 = q_\gamma\ (x_1) = q_{10}\ (1-e^{-\frac{W}{\varepsilon}\frac{W}{v}\frac{D_1}{D_2}x_1}) - q_{20}\ (1-e^{-\frac{W}{\varepsilon}\frac{W}{v}x_1}) \quad (A.4.9)$$

If the current crosses the channel at an arbitrary angle α, the following sedimentation rate q_r per meter of navigation channel length is found:



$$q_r = \left\{ q_{10}\ (1-e^{-\frac{W}{\varepsilon}\frac{W}{v}\frac{D_1}{D_2}\frac{B}{\cos\alpha}}) - q_{20}\ (1-e^{-\frac{W}{\varepsilon}\frac{W}{v}\frac{B}{\cos\alpha}}) \right\} \cos\alpha \quad (A4.10)$$

This general expression has been developed for application to sand bed material (non-cohesive materials only).

4. Acknowledgement

The results of the studies have been published with the permission of the Controller of Engineering, Nigeria Ports Authority, Lagos, Nigeria.

Director, T. Sorensen of the Danish Hydraulic Institute has contributed by interpretations of the sedimentation mechanisms and by inspiring discussions.

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