# CHAPTER 102

## SEDIMENTATION PROBLEMS AT OFFSHORE DREDGED CHANNELS

by

A. A. Kadib

Coastal Engineering Specialist, Bechtel Inc.,

San Francisco, California U.S.A.

ABSTRACT

Estimating the rate of sediment deposition and annual maintenance dredging at offshore dredged channels have been two of the most challenging tasks confronting coastal engineers in the past 10 to 15 years. Because of the complexity of the mechanism of sediment-flow interaction and the lack of available practical methods for estimating the sediment transport rate under waves and current action, it is felt that a simple and rational method is needed for describing sediment behavior at offshore dredged channels and estimating accretion rates. It is hoped that this paper contributes to the answer of this problem.

The paper describes the mechanism of sediment deposition and presents a simple method for estimating the rate of annual maintenance dredging. The effect of using a submerged breakwater for relieving the sedimentation problem within the dredged channel is also presented.

## INTRODUCTION

Along any reach of coastline where navigation works and other coastal structures exists or are contemplated, patterns and rates of long-term littoral and offshore sand movement and expected accretion are vital information for proper engineering, design and maintenance. Sediment movement along the breaker zone and at the offshore area is controlled mainly by the action of the prevailing waves and currents of these locations. When moving sediment loads encounter a partial obstruction such as a dredged channel, a condition is realized that is conductive to sediment deposition. There are at least three basic types of man-made works at the offshore area which function as sediment barriers (Figure 1). These consist of: (a) dredged navigation channels connecting super-tanker harbors with deep water offshore and up to 25 meter water depth; (b) dredged offshore channels for cooling water intakes for nuclear and liquefied natural gas plants; and (c) dredged offshore areas for open-sea loading and berthing terminals. In a recent study, the question

came up concerning the economical feasibility of such offshore dredging activities and their impact on the overall shoreline processes operative in the project area. In order to answer this question, estimates of the rate of sediment movement and the expected annual maintenance dredging are necessary preliminaries. Unfortunately, there is no proven prediction method of general validity for quantitative estimates of onshore-offshore and longshore sediment transport rates, and designers usually rely on limited field data of questionable accuracy to formulate some feeling for the problem under consideration. Because of the above difficulties and the fact that more accurate field data are usually expensive and difficult to get, it is felt that a simplified method is needed to estimate the rate of sediment movement for water depths of up to at least 20 meters.

The approach described here is based on available theoretical studies[2, 3, 4, 5, 6] and experiences gained with maintenance dredging at the Suez Canal offshore dredged channel, located at Port Said Harbor, Egypt[7, 8, 9]. Items considered are: (a) factors contributing to sedimentation; (b) method of estimating deposition rate; (c) effect of using a submerged breakwater for relieving the sedimentation problem, and (d) optimum design for protection against accretion.

## FACTORS CONTRIBUTING TO SEDIMENTATION

Consider any section along the offshore part of a dredged channel shown in Figure 2. Assume that both the current and wave climatology in the vicinity of the dredged channel are known. This could be considered either as (1) an average steady current characterized by a velocity U, a wave height H, and a wave period T, or (2) as a known number of storms with a given duration and direction. For the first case, the average currents and wave condition can be used to estimate the annual sediment effect, whereas for the second case, the effect of each storm can be evaluated separately and the annual effect can be obtained by integrating the effects of all expected storms within a given year. In either case the basic flow field is the same. This flow field (Figure 2-a) may be simplified as:

- Steady current with an average velocity $U_1$ at water depth $d_1$. By continuity, this current will have velocity $U_2$ at depth $d_2$.
- Maximum oscillatory current $U_{bed\ max}$ at the bed, due to wave action. This current may be expressed by the equation

$$U_{bed\ max} = \frac{\pi H}{T} \frac{1}{\text{Sinh } 2\pi \frac{d}{L}} \qquad (1)$$

where

$H$ = wave height,
T = wave period,
L = wave length at water depth d.

It is believed that the above flow velocities are the most important factors contributing to sediment movement in the vicinity of the dredged channel and their contribution may be summarized as follows:

1. Bed Load ($Q_b$).

Einstein[5], Kalkanis[3] and Abou-Seida[2], proposed the use of a modified unidirectional bed load function, shown in Figure 3, for estimating the rate of bed load movement under wave action. In order to use Figure 3, one has to calculate flow intensity $\Psi_*$ defined as

$$\Psi_* = \xi \frac{\gamma s - \gamma f}{\gamma f} \frac{g D}{U_a^2} \tag{2}$$

where

$\xi$ = "hiding factor" for small particles in a sediment mixture and may be assumed unity for uniform grains,
$\gamma s$ = specific weight of sediment,
$\gamma f$ = specific weight of water,
$g$ = acceleration of gravity,
$D$ = sediment size,
$U_a$ = wave particle velocity at 0.35 D from the boundary.

References (2), (3) and (5) show $U_a$ is the most difficult factor to calculate in equation (2). Analysis of the data reported by Abou-Seida[2] show that $U_a$ can be approximated by

$$U_a = 0.5\, U_{\text{bed max}}. \tag{3}$$

Now with a known value of flow intensity $\Psi_*$, the oscillatory bed load intensity $\phi_*$ can be obtained from Figure 3. The oscillatory bed load rate $q_b$ is given by the equation

$$q_b = \phi_* \gamma s \left(\frac{\gamma s - \gamma f}{\gamma f}\right)^{1/2} g^{1/2} D^{3/2}. \tag{4}$$

The sediment concentration in the bed layer, $C_a$, is given by Abou-Seida[2] as

$$C_a = \frac{q_b}{2DU_a} \tag{5}$$

and the bed load rate $Q_b$ is given by

$$Q_b = C_a \; a \; U_c \tag{6}$$

where

$a$ = thickness of the bed layer, assumed in this study as equal to 2 cm,
$U_c$ = local current velocity near the bed and including mass transport velocity due to wave action.

2. Suspended Load $Q_s$

Theoretically speaking, wave motion, other than the breaking wave effect, lacks the existence of turbulence which is responsible for suspended sediment. On the other hand, it has been observed that considerable amounts of sediment move in suspension under the combined action of waves and currents[4, 7, 11]. Therefore, it was decided to attack the suspension problem by assuming that the steady current effect, only, is responsible for suspended sediment distribution within any cross section along the dredged channel.

If it is assumed that bed load takes place within a certain layer, the average concentration within this layer can be computed from equation (5). From this concentration, $C_a$, at height, $a$, above the bed, the concentraction $C_h$ at a hieght, $h$, above the bed can be expressed by the well known relationship (1)

$$\frac{C_h}{C_a} = \left[\frac{(d-h)a}{(d-a)h}\right]^Z \tag{7}$$

in which $Z = \frac{V_s}{0.4U_*}$ with $V_s$ = fall velocity of the sediment grain, $U_*$ = bed shear velocity; and $d$ = the total water depth.

According to Einstein[1], the suspended load $Q_s$ can be written as

$$Q_s = 11.6 \; U_* \; C_a \; a \; [P \; I_1 + I_2] \tag{8}$$

where

$I_1$ and $I_2$ can be obtained from reference 1.

P is determined from $P = 2.3 \frac{h}{h_o}$ in which

$h_o$ = bed roughness.

From equation (8), the suspended sediment load to the updrift side of the dredged channel and inside the channel can be estimated.

## METHOD OF ESTIMATING DEPOSITION RATE

When an offshore channel is dredged, both the flow and sediment patterns, approaching from the updrift side of the channel experience some changes as the flow crosses the dredged channel. This is shown in Figure 2. Consider Figure 2-a where the channel is dredged to depth $d_2$ below mean sea level, and the natural water depth to the updrift side of the channel is $d_1$. Flow approaching the channel has a certain sediment load capacity which could be estimated using equations (6) and (8). As the flow approaches the dredged channel, two main mechanisms will take place:

- The dredged channel will act as a sand trap along most of its length and consequently most of the bed load $Q_b$ approaching the channel will deposit within the channel.
- The suspended load, $Q_s$, on the updrift side of the channel will reduce to $Q_{s_2}$ across the channel. This reduction is caused by a decrease in the steady flow velocity within the dredged channel.

These considerations permit calculation of the rate of sediment deposition per channel unit width, $Q_d$, according to the following equation

$$Q_d = Q_{s_1} - Q_{s_2} + Q_b \qquad (9)$$

where

$Q_{s_1}$ = rate of suspended load reaching the channel/unit width,

$Q_{s_2}$ = rate of suspended load across the channel/unit width,

$Q_b$ = rate of bed load reaching the channel/unit width.

Equation (9) can be used for various natural water depths, $d_1$, along the channel thus permitting calculation of the total deposition rate along the channel.

As an example consider a dredged channel depth of 20 meters with a natural water depth of 10 meters. The annual rate of sediment deposition, $Q_d$, is estimated under the following assumed conditions:

average wave height (H) = 2.00 meters;
average wave period T = 8 seconds;
average bed material grain size D = 0.10 mm.

Results of the computations are summarized in Table 1.

TABLE 1

Example of Estimating Sediment Deposition Along a Dredged Channel Section

| Item | Sediment Rate $m^3/m/Year$ |
|---|---|
| $Q_b$ | 340 |
| $Q_{s_1}$ | 1700 |
| $Q_{total} = Q_b + Q_{s_1}$ | 2040 |
| $Q_{s_2}$ | 940 |
| $Q_{deposition}$ | 1100 |

## SUBMERGED BREAKWATER EFFECT

Submerged breakwaters have been used successfully for relieving and reducing the sediment deposition along offshore dredged channels. An example is the Suez Canal navigation channel which extends from the Port Said Harbor to natural water depth of about 15 meters. (The Suez Canal Authority is presently deepening the navigation channel to accommodate ships with drafts up to 22 m). Table 2 summarizes the annual maintenance dredging conditions along the offshore navigation channel during the period 1901 to 1966[7, 8].

TABLE 2

Variation of Annual Maintenance Dredging
Along the Suez Canal Navigation Channel
(Port-Said Harbor) During the Period 1901-1966

| Period (Years) | Average Depth of Navigation Channel (m) | Mean Annual Dredging (million $m^3$) | Type of Protection Against Accretion (Updrift Side) |
|---|---|---|---|
| 1901-1906 | 9.5 | 0.65 | Full breakwater to water depth of 7.00 meters |
| 1911-1916 | 11.50 | 2.25 | Full breakwater to water depth of 9.00 meters |
| 1917-1920 | 12.00 | 0.35 | Partial construction of a submerged breakwater about 4 meters high |
| 1921-1923 | 12.00 | 1.25 | |
| 1939-1945 | 12.00 | 0.600 | Submerged breakwater to water depth of 11.5 meters and about 4 meters high above bottom |
| 1951-1955 | 13.00 | 1.4 | Submerged breakwater to water depth of 11.5 meters |
| 1961-1966 | 14.00 | 2.4 | |

Table 2 shows that: (1) increasing the depth of the navigation channel causes an increase in the annual maintenance dredging; and (2) construction of the submerged breakwater has considerable effect on reducing the annual maintenance dredging.

## EFFECT OF SUBMERGED BREAKWATERS ON SEDIMENT AND FLOW PATTERN

Consider a submerged breakwater with average height h above the bed and located to the updrift side of the dredged channel (Figure 5). The use of such a breakwater would have the following principal effects on the sediment and flow conditions in the vicinity of the dredged channel:

- The submerged breakwater could cause the bed load to either go around it or settle to the updrift side of the breakwater.
- Portion of the suspended sediment load of relatively high concentration near the bed would also be partially prevented from reaching the dredged channel.
- The submerged breakwater will generate a longitudinal current along its entire length which will transport sediment in the offshore direction away from the dredged channel.

Quantitative analysis of the effect of submerged breakwaters in relieving the sedimentation problem along the dredged channel is rather difficult. It is believed that a reasonable answer to this problem is given by the rational method developed below.

1. Submerged Breakwater Efficiency $\eta$.

Consider a submerged breakwater with variable relative heights $\frac{h}{d}$, where h is the breakwater height above the natural bed and d is the water depth as shown in Figure 5. For any breakwater relative height $\frac{h}{d}$ the breakwater's sediment trapping efficiency, $\eta$, may be defined by the equation

$$\eta = \frac{Q_t(h/d)}{Q_d(h/d=0)} \tag{10}$$

where

$Q_t(h/d)$ = rate of sediment trapped by the breakwater for any relative height h/d,

$Q_d(h/d=0)$ = rate of channel deposition without the breakwater.

2. Sediment Risk Factor "R"

Figure 4 shows the definition of the sediment risk factor R. The physical meaning of R may be explained as follows:

(a) For h/d = 0; R = 1 and the expected annual dredging to maintain the dredged channel is equal to the annual rate of sediment deposition $Q_d$.

(b) For h/d = 1; R = 0 and expected annual dredging = 0.

(c) For h/d = any ratio, the expected annual dredging can be approximated by the equation

$$Q_{dredging} = Q_d \times R \qquad (11)$$

where

$Q_{dredging}$ = annual maintenance dredging; and

$Q_d$ = annual rate of channel deposition for h/d = 0.

Using the definition of R as shown in Figure 5, i.e.,

$$R = \frac{\int_a^h [\frac{(d-h)a}{(d-a)h}]^{\frac{V_s}{0.4 U_*}} dh}{\int_a^d [\frac{(d-h)a}{(d-a)h}]^{\frac{V_s}{0.4 U_*}} dh} \qquad (12)$$

and considering sediment particle grain size range from 0.075 mm to 0.2 mm and average steady flow velocities between 0.2 m/sec and 1.00 m/sec, the average values of the risk factor R for various h/d ratios are shown in Table 3.

TABLE 3

Average Values by Risk Factor R

| Breakwater Relative Height h/d | Average Value of R |
|---|---|
| 0 | 1 |
| 0.2 | 0.36 |
| 0.3 | 0.25 |
| 0.5 | 0.125 |
| 1.00 | 0 |

Using the sediment risk factors obtained in Table 3 as a reduction in the deposition rate for h/d = o case, and equation (11), the annual rate of deposition for various breakwater relative height can be estimated. The breakwater sediment trapping efficiency, η, can be computed from equation (10).

Using the results of the example given in Table 1, the submerged breakwater efficiency and the estimated annual maintenance dredging is given in Table 4.

TABLE 4

Effect of h/d on % Annual Dredging and Breakwater Efficiency η

| h/d | R | $Q_d$ $m^3$/year | $Q_t$ $m^3$/year | η % | % Annual Dredging w.r.t. h/d = 0 |
|---|---|---|---|---|---|
| 0 | 1 | 1100 | 0 | 0 | 100 |
| 0.2 | 0.36 | 400 | 700 | 64 | 36 |
| 0.3 | 0.25 | 275 | 825 | 75 | 25 |
| 0.5 | 0.125 | 140 | 960 | 87 | 13 |
| 1.00 | 0 | 0 | 1100 | 100 | 0 |

It can be observed from Table 4, that submerged breakwaters with relative heights, h/d, between 0.3 and 0.5 would have greater effect in reducing sedimentation problems inside the dredged channel. Figure 5 shows the relationship between h/d and percent annual dredging needed to maintain the dredged channel. The annual dredging is plotted as: (a) percentage of the total sediment load ($Q = Q_s + Q_b$) estimated to the updrift side of the breakwater, and (b) percentage of the expected channel deposition rate without the use of a submerged breakwater ($\frac{h}{d} = 0$).

Examination of the data reported in Table 2 shows that the annual maintenance dredging for the Suez Canal navigation channel (Port Said Harbor) reached 2.25 million $m^3$/year during the period 1911-1916. A submerged breakwater ($\frac{h}{d} \simeq 0.4$) was constructed and completed during the period 1939-1945. After the submerged breakwater was completed, annual maintenance dredging reduced to 0.6 million $m^3$/year which is

about 25% of the annual dredging without the submerged breakwater. To the writer's knowledge, this is the only field data available on the submerged breakwater effect which could be used to check the theoretical curve shown in Figure 5.

## OPTIMUM DESIGN FOR OFFSHORE DREDGED CHANNEL AND PRACTICAL APPLICATION

The results of studies reported in this paper are useful for feasibility and economical evaluation of offshore dredging projects. In practice the following steps are suggested:

Step 1. Collect field data on waves and current climatology, and bed material characteristics.

Step 2. For the proposed dredged channel geometry, estimate annual rate of deposition (which is equivalent to the expected rate of annual maintenance dredging). This can be obtained from equation (9).

Step 3. Estimate the average annual cost of dredging the dredged channel without the use of any breakwater protection.

Step 4. Consider submerged breakwater protection schemes with various $\frac{h}{d}$ ratios. For each $\frac{h}{d}$, estimate average annual cost for:

- Breakwater construction.
- Expected annual maintenance dredging. The rate of maintenance dredging can be obtained from Figure 5.
- Estimate average maintenance cost for the breakwater. It should be noted that submerged breakwater does not need frequent maintenance as compared with full breakwater.

Step 5. Form step 4, get the average annual cost for various submerged breakwater schemes and plot the data as shown in Figure 6.

Step 6: From a plotting similar to that shown in Figure 6, one can usually find a design scheme which will minimize the average annual cost. This scheme will give the most economical design.

## SUMMARY AND CONCLUSIONS

A rational method is presented to estimate annual maintenance dredging along offshore dredged channels. The method is based on available theoretical studies on the subject of mechanism of sediment transport under wave and current action.

The effect of protecting the dredged channel against accretion is discussed. Efficiency of using submerged breakwaters with various relative height for relieving the sediment deposition rate are analyzed; breakwaters with relative height 0.3 to 0.5 were found to have high efficiency in reducing sediment deposition within the dredged channel.

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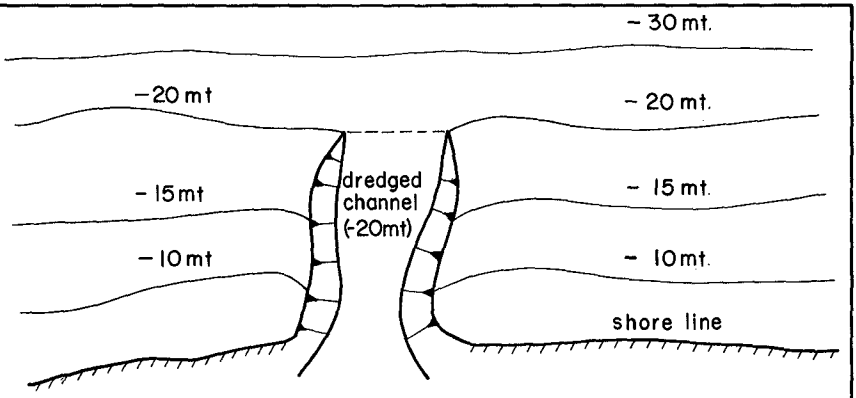



Fig. 1-a DREDGED NAVIGATION CHANNEL

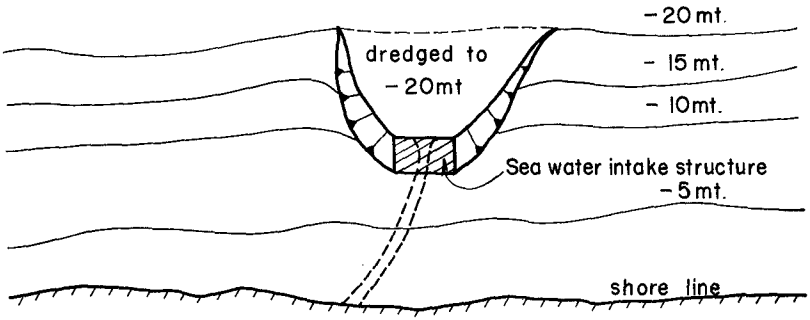



Fig. 1-b OFFSHORE DREDGING FOR COOLING WATER INTAKES

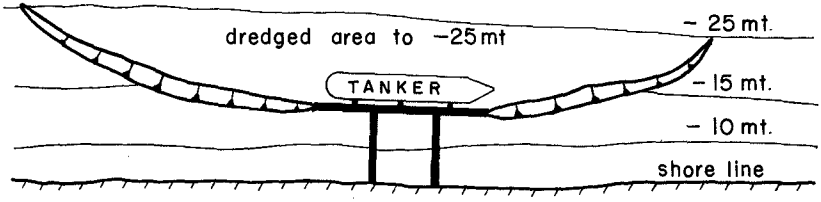
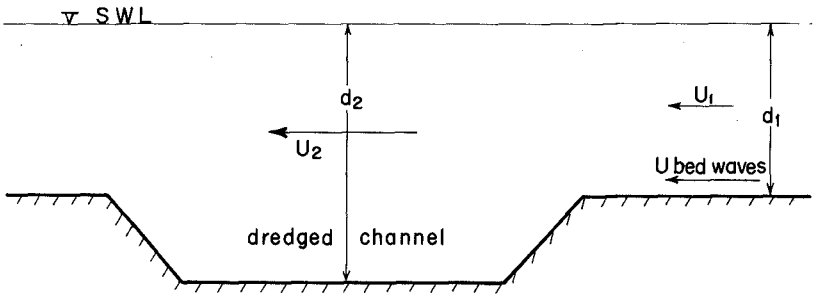
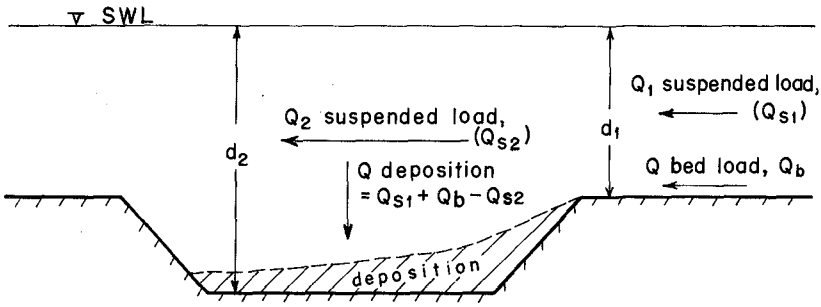



Fig. 1-c DREDGING FOR OFFSHORE LOADING OF SUPER TANKERS

Fig. 1 EXAMPLES OF OFFSHORE DREDGING




a. FLOW VELOCITIES CONTRIBUTING TO SEDIMENT MOVEMENT




b. SEDIMENT PATTERN ACROSS THE DREDGED CHANNEL

Fig. 2 MAIN FACTORS CONTRIBUTING TO SEDIMENT DEPOSITION

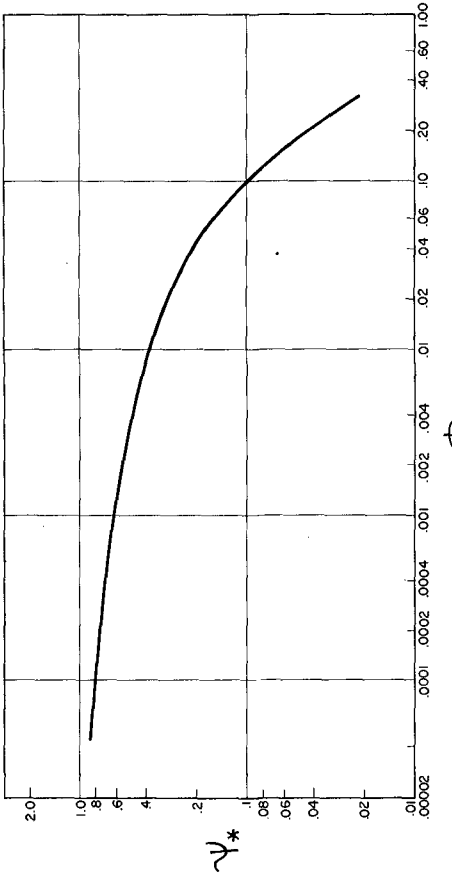
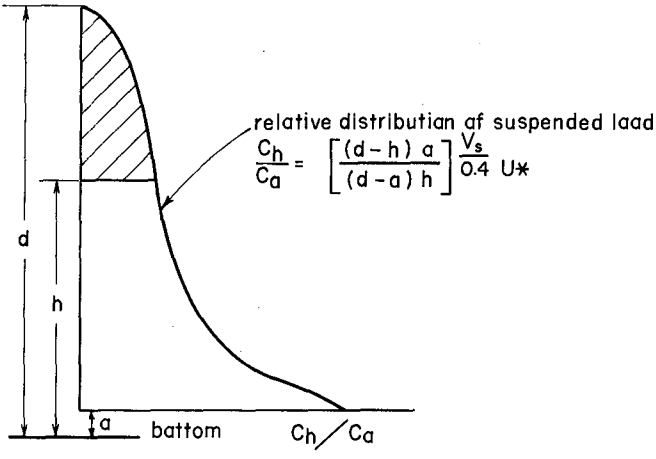



Fig. 3 GRAPHICAL REPRESENTATION OF THE BED LOAD EQUATION, CURVE
(after Kalkanis and Abo Saida)




Risk factar $R = \frac{\text{Suspended sediment abave height } h}{\text{Tatal suspended sediment available}}$

Fig. 4 DEFINITION OF THE RISK FACTOR R

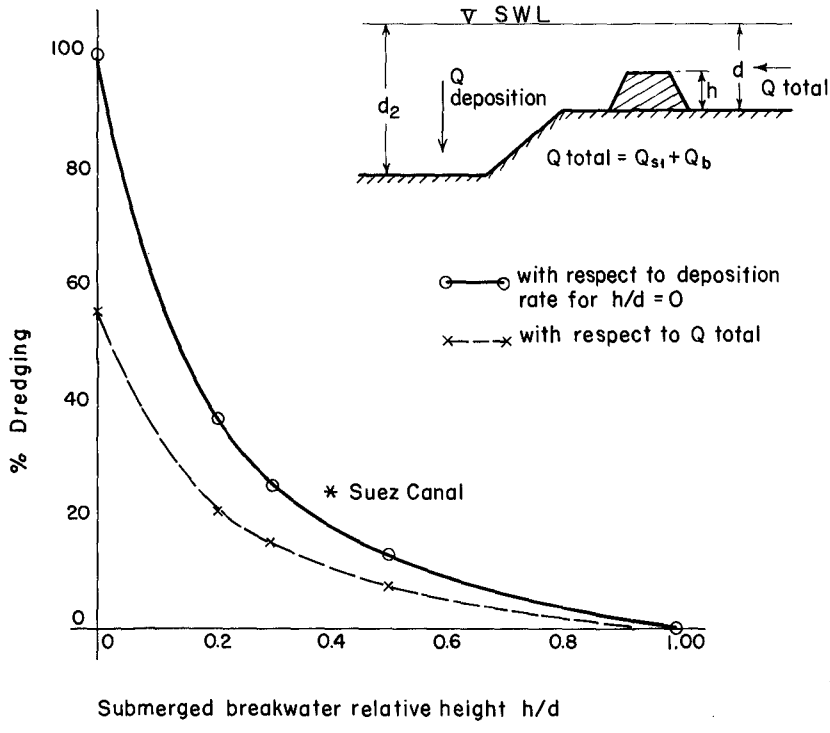



Fig.5 EFFECT OF SUBMERGED BREAKWATER RELATIVE HEIGHT ON MAINTENANCE DREDGING

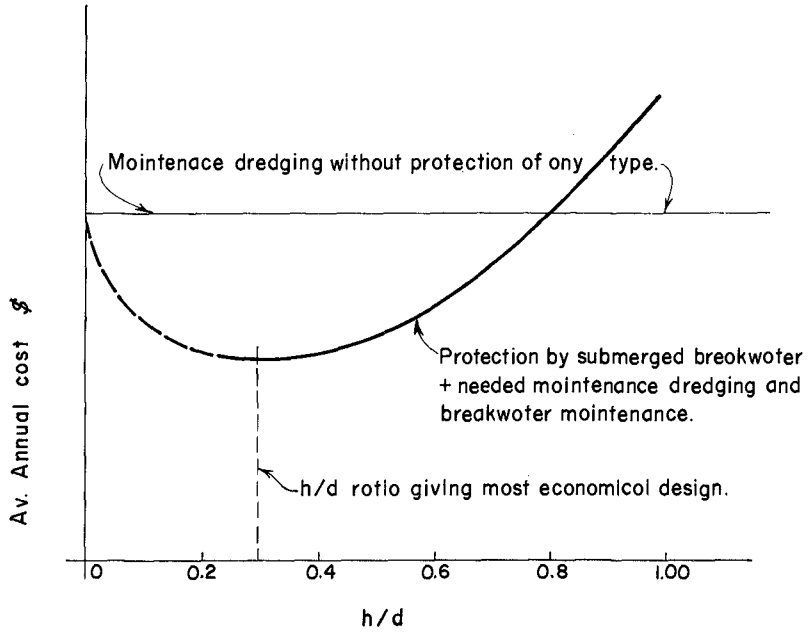



Fig. 6 OPTIMUM ANALYSIS FOR THE MOST ECONOMICAL DESIGN