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35 Prediction of the siltation in the northern entrance of the Suez Canal for the second development stage

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ABSTRACT

The northern entrance of the Suez Canal consists of two intersecting approach channels; the deeper eastern channel and the western channel. A study is undertaken for the development of the Suez Canal (second development stage). There are four development alternatives to enable larger loaded tankers with draughts 56, 62, 68 and 72 feet for the four development schemes, respectively to use the Suez Canal. The development projects will require the deepening and widening of the eastern channel. An important part of the study deals with the prediction of the siltation rates in the eastern approach channel of the Suez Canal for the proposed development alternatives.

The present paper deals with the development and application of the SUTRENCH-model to predict the siltation rates in the eastern approach channel of the Suez Canal for the four proposed development alternatives. The SUTRENCH-model is a two dimensional detailed sediment transport model to be applied to pré-defined streamtubes covering the area of interest. As the model was originally developed for cohessionless sediment,the first stage of this research work is the development of the model to be applied to the mud sediment of the project area. The calibration of the model is performed for present conditions based on the recorded dredging quantities and the siltation heights calculated from soundings. The model is then used in the prediction of the siltation rates in the eastern channel for the four development alternatives. A senstivity analysis is performed for the SUTRENCH-model to test its senstivity to variations in wave heights and deviations in channel cross-section dimensions.

1. Introduction

The northern entrance of the Suez Canal (Figure 1) consists of two intersecting approach channels; the deeper eastern channel extending from Port Said bypass channel and extending offshore and the western channel passing by Port Said harbour. The western entrance channel of the Suez Canal is protected by two breakwaters. The western breakwater consists of a submerged part and an emerged part. The relatively deep Port Said bypass approach channel, eastern channel, was dredged in 1980 (first development stage) intersecting the western channel and extending about 12 km offshore without any sheltering effects.

A study is undertaken for the second development stage for the Suez Canal. There are four development alternatives that require to be evaluated. The development of the Suez Canal will require the deepening and widening of the eastern channel to enable the traffic of larger sized loaded tankers with draughts up to 56, 62, 68 and 72 feet for the four development alternative schemes, respectively to use the Suez Canal. The present paper deals with the prediction of the siltation rates in the eastern channel using existing data and numerical modelling techniques to determine the annual maintenance dredging for the development alternatives up till year 2015.

2. Environmental and sedimentological conditions

2.1 Flow pattern

Currents in the Port Said area are moderate and generally variable in direction and magnitude and have a large spatial variation, especially in the vertical direction. The only current measurements performed at the northern entrance of the Suez Canal were in 1936-1937 and 1938-1939. According to these measurements, the effect of the relatively recent dredged eastern approach channel is not included in the flow pattern.

When a current crosses an approach channel inclined to the current direction, it is refracted by the channel. Deviation in the flow pattern and change in streamtube width will occur resulting in the change of the average current velocity. Therefore, the ratio of the average current in the channel to the average current approaching the channel is a function of the current approaching angle relative to the channel direction and the difference in depth between the channel and the natural sea bed. A simplified current refraction approach (1) is developed to be applied to the northern entrance, using the previously mentioned field current measurements to determine the flow pattern for the present conditions, and for the four development alternatives. The year is divided into two seasons, summer (from May to October) and winter (from November to April). In order to minimize the error resulting from this simplified approach (1), smoothing of streamlines is performed to account for the sudden increase or decrease in the width of the streamlines. Figure 2 shows the flow pattern for the present summer condition. Flow patterns for the four development alternatives are also performed.

2.2 Wave height patterns

Deep water wave climate along the Egyptian Mediterranean are available from Summary of Synoptic Meteorological Observations. The analysis of data is illustrated in Figure 3 for the four seasons. Prevailing wave periods vary from 6 to 8 seconds.

Wave propagation runs using geo-optical approximation refraction models with a very coarse grid system were performed for the existing conditions for winter and summer seasons.

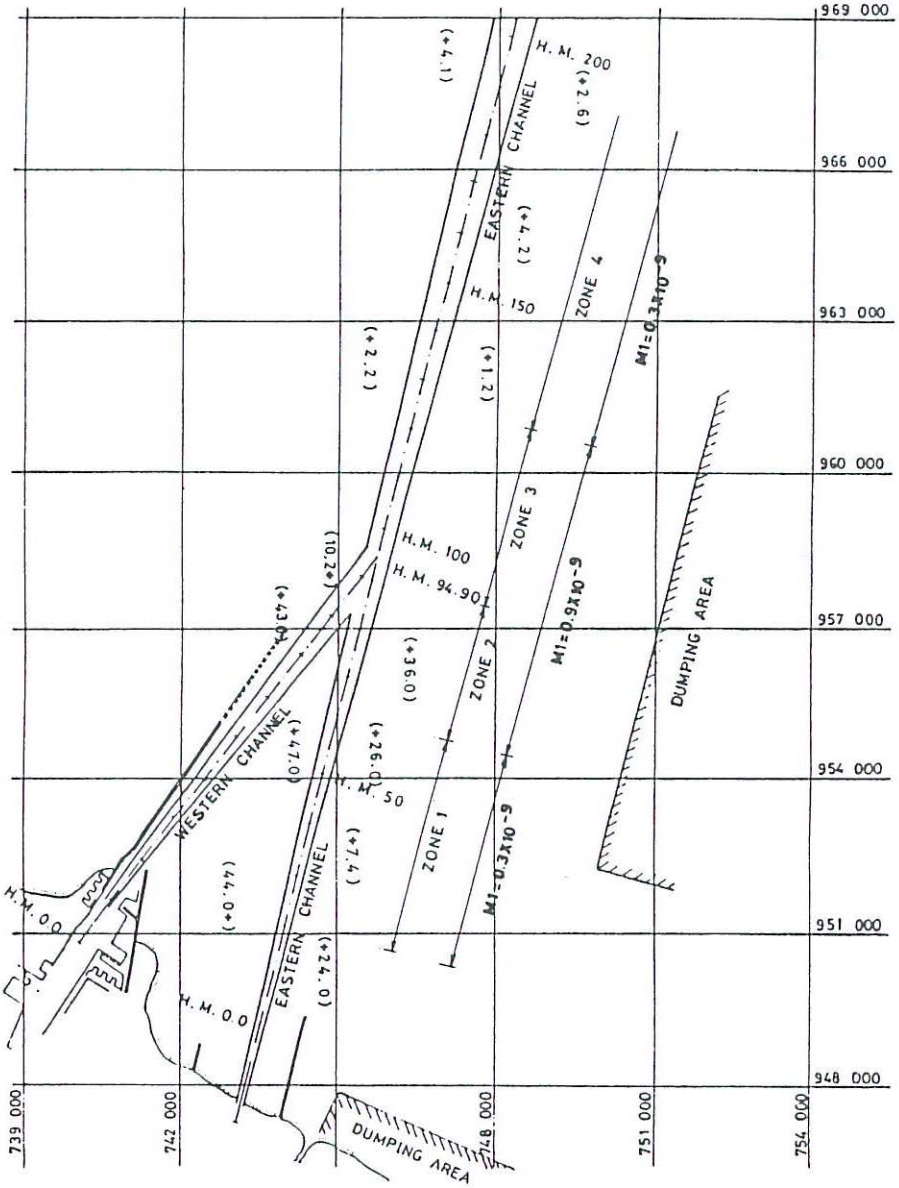

FIGURE 1 *Layout of the northern entrance of the SUEZ Canal showing median grain diameters of sea bed materials (μm), representative zones for calibration and M1 values*

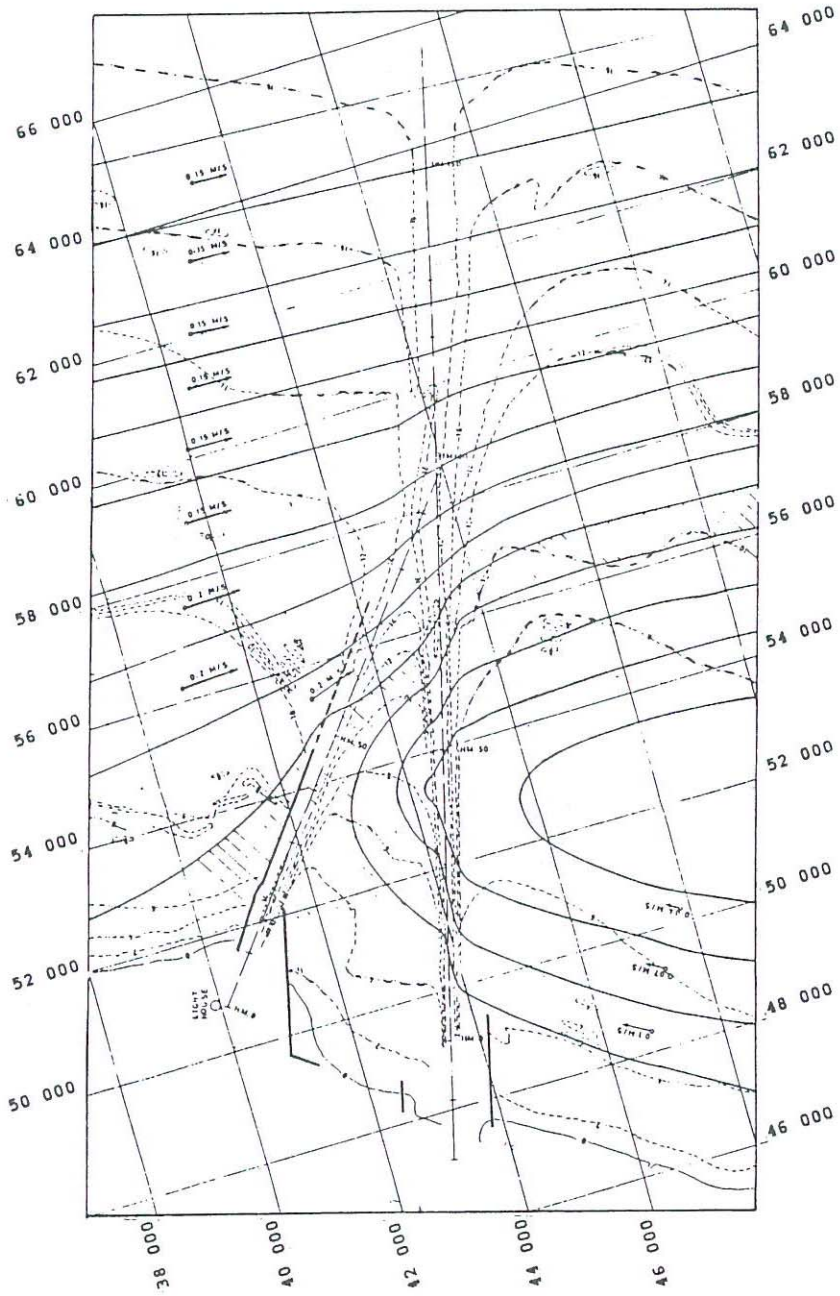

FIGURE 2 *Flow pattern for the existing summer condition*

For the winter season, the significant deep water wave height with 50 percent exceedance is taken as 1.2 meters and wave period 7 seconds for the north-west direction. For the summer season, the corresponding significant deep water wave height is taken 0.8 meter and wave period 6 seconds for the north-north-west direction. No wave height data are available to verify the predicted wave height patterns.

Due to the lack of field data, wave heights for the first and second development alternatives are taken as the present conditions. Due to the relatively deeper eastern channel for the third and fourth development alternatives, 10% increase in wave heights are considered.

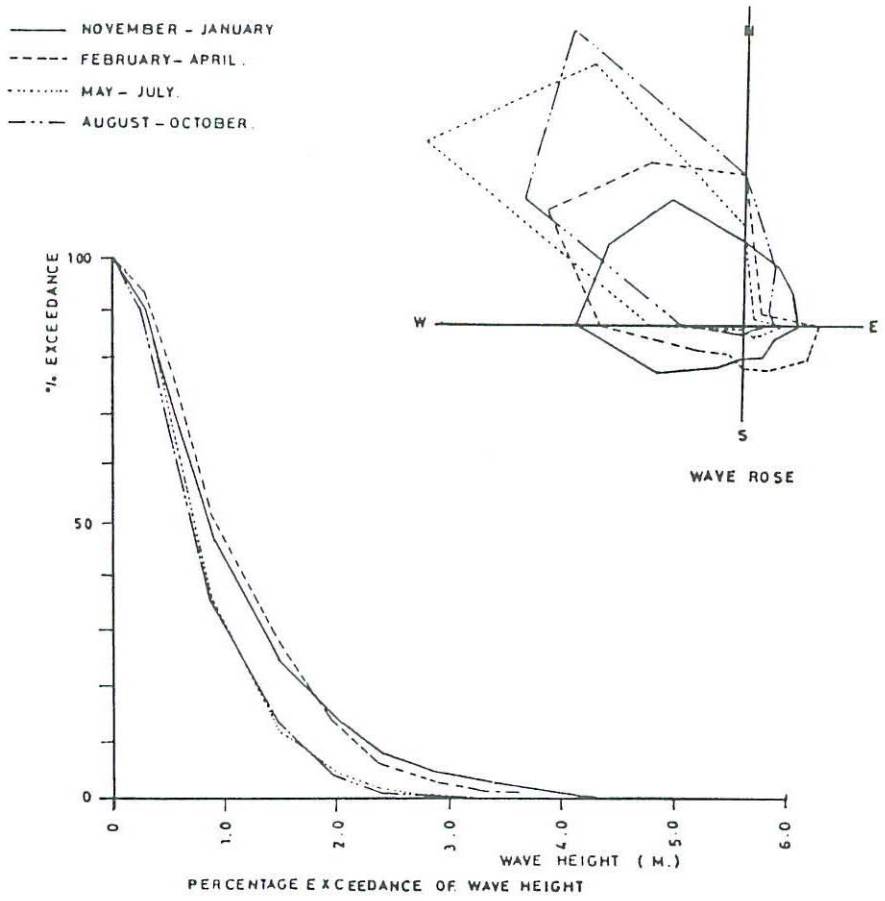

FIGURE 3 *Percentage of exceedance of wave heights and wave rose in deep water*

2.3 Sea bed materials

The sea bed material at the northern entrance of the Suez Canal is generally very fine and ranges from dark-grey very soft silty clay to sandy silt. The median grain sizes distribution at the northern entrance are shown in Figure 1.

2.4 *Siltation rates, heights and dredging quantities*

Siltation rates at the eastern channel are determined from periodic bathymetry surveys for different hectometers along the channel during periods not interrupted by maintenance dredging from 1980 to 1989. The periodic surveys are limited to the bottom width of the channel. Thus the siltation rates are only valid for the surveyed parts of the channel and are expected to be less than the maintenance dredging quantities. The average siltation height per year are thus determined along the channel based on the surveyed width. Based on the siltation heights and the nominal channel bottom widths, the average siltation rates along the eastern channel are plotted in Figure 4. On the same figure, the average annual dredging quantities are plotted assuming linear distribution of recorded dredging quantities in a recorded stretch. The average yearly total recorded dredging quantities for the eastern channel is 7.2 million cubic meters. The average yearly total siltation rates based on the channel design bottom width is 4.8 million cubic meters, i.e. two third of the corresponding recorded dredging quantities. By considering an increase of 20 to 40 percent in the siltation rates due to side slope effect, the siltation rates is equal to 6.2 million cubic meter per year. This discrepancy can be due to the underestimation of the siltation rates limited to the bottom width of the channel only or probably the overestimation of the dredging records.

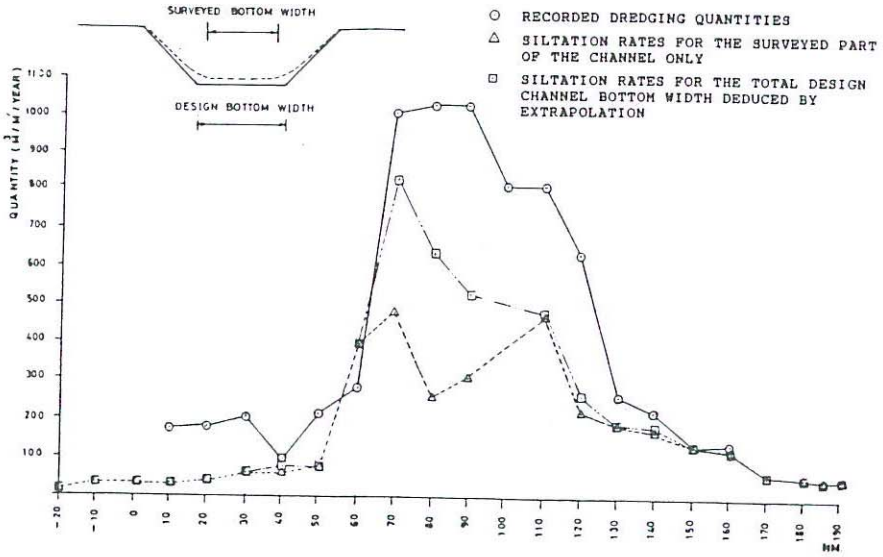

FIGURE 4 *Comparison between the calculated siltation rates and the recorded dredging quantities for the eastern channel*

2.5 *Suspended sediment*

The only data available of the suspended sediment concentration was from field survey performed in 1976 (2). Concentration of suspended solids measured during July were generally less than 20 ppm (weight by volume). Concentration up to 300 ppm were measured during stormier conditions in February.

3. Mathematical model for sedimentation in channels (SUTRENCH-model)

The SUTRENCH-model is a two-dimensional-vertical mathematical model for sediment transport by currents and waves that was developed at Delft Hydraulics (6),(8) to study morphological processes, specially the prediction of sedimentation in dredged channels.

The basic equation used in computing the concentration is the convection-diffusion equation assuming steady conditions and neglecting the transport by longitudinal mixing, expressed as:

$$\frac{\partial}{\partial x}(buc) + \frac{\partial}{\partial z}\left[b\,(w-w_s)\,c\right] - \frac{\partial}{\partial z}\left(b\epsilon_{s,cw}\frac{\partial c}{\partial z}\right) = 0 \qquad (1)$$

where u = longitudinal velocity at height z above the bed; c = sediment concentration; w = vertical flow velocity; w_s = particle fall velocity of suspended sediment; $\epsilon_{s,cw}$ = sediment mixing coefficient by currents and waves; b = flow width; x,z = longitudinal and vertical coordinates, respectively. The following boundary conditions are to be specified:

Flow domain : initial bed levels,water depths, flow widths, wave characteristics, particle fall velocity, effective bed roughness, size, composition and porosity of bed material.

Inlet boundary : discharge, flow velocities, mixing coefficients, concentrations.

Water surface : net vertical transport is assumed to be zero.

Bed surface : bed concentration or upward sediment flux at bed as a function of local hydraulic and sediment parameters.

The bed boundary condition is specified at a small height (z=a) above the mean bed. Using this approach, the bed concentration or the upward sediment flux can be represented by its equilibruim value assuming that there is an almost instantaneous adjustment to equilibruim conditions close to the bed.

The bed concentration for silt is calculated according to the approach of Partheniades (3) as follows:

$$C_a = M1\left(\frac{\bar{\tau}'_{b,cw} - \bar{\tau}_{cr,silt}}{\tau_{cr,silt}}\right) \qquad (2)$$

in which C_a = bed boundary concentration; a = reference level above bed; $\bar{\tau}'_{b,cw} = \mu_c\tau_{b,c} + \mu_w\bar{\tau}_{b,w}$ = effective bed-shear stress; $\bar{\tau}_{b,c}$ = current-related bed shear stress; $\bar{\tau}_{b,w}$ = wave related bed shear stress according to linear wave theory (based on significant wave height,length and period); μ_c = current-related efficiency factor; μ_w = wave related efficiency factor; $\bar{\tau}_{cr,silt}$ = critical bed shear stress for silt; M1 = material constant.

The upward sediment flux at the bed for the case of silt is defined as (4), (5), (6), (7):

$$E_a = -\left(\epsilon_s\frac{\partial c}{\partial z}\right)_{z=a} = w_s C_a = M1.w_s\left(\frac{\bar{\tau}'_{b,cw} - \bar{\tau}_{cr,silt}}{\bar{\tau}_{cr,silt}}\right) \qquad (3)$$

Either equation (2) or (3) can be selected as input parameters. Bed level changes are computed from a cross-section integrated sediment continuity equation; in the form:

$$\frac{\partial}{\partial t}(b\,Z_b) + \frac{1}{\rho_s}(1-p)\frac{\partial}{\partial x}(S_s + S_b) = 0 \qquad (4)$$

in which t = time; b = flow width; z = bed level above a horizontal datum; p = porosity factor; S_b = suspended load transport; and S = bed load transport. The suspended load transport is computed as:

$$S_s = b \int_a^h u\ c\ dz \tag{5}$$

where h = water depth. In case of silty conditions, there may be a near-bed transport of fluid mud and the near bed transport of fluid mud $S_{b,fm}$ ($m^3/s/m$) is represented by (6):

$$S_{b,fm} = M2 \left(\bar{\tau}_{b,cw} - \bar{\tau}_{cr,silt}\right) (U_c + U_w) \tag{6}$$

in which $\tau_{b,cw}$ = bed-shear stress related to currents and waves; U_c = near-bed current velocity (= $0.05\bar{U}$); $\bar{U}$ = depth-averaged velocity; U_w = near-bed wave induced drift velocity; M2 = calibration coefficient.

4. Calibration of the SUTRENCH-model

The SUTRENCH-model is applied to the eastern approach channel using pre-determined streamtubes for the current refraction diagrams for the present conditions. The year is divided into summer and winter seasons. In the calibration of the SUTRENCH-model, the eastern channel is divided into four representative zones (Figure 1) chosen according to the trend of the siltation rates. The cross-sections of the channel at the different zones are determined from bathymetry surveys and the sea bed material characteristics (sizes, density of sea bed material, wet bulk density, porosity) are determined from surveys. The wave heights at the different locations are determined from the runs of the wave propagation model.

Three parameters are used for the calibration of Sutrench-model; the fall velocity, w_s, critical shear stress for erosion, $\tau_{cr,silt}$, and the material constant, M1. The fluid mud transport was assumed to be zero (M2 = 0). Values of the fall velocity for similar cases as for Port Said approach area are in the range of 0.1 to 1 mm/sec (9). Accurate values of the fall velocity can be only be obtained from in-situ field measurements, which were not available. Several computer runs are performed to determine the fall velocity as a part of the calibration procedure, yielding reasonable siltation estimates for all zones for a fall velocity of 0.3 mm/sec. Based on these trials, it was decided to apply a constant fall velocity of 0.3 mm/sec. In reality, there may be variations in the fall velocity along the channel because of differences in sizes of the bed materials. The differences are, however, small and do not justify a change of the fall velocity because other processes such as flocculation and presence of organic materials are important.

The critical bed shear stress for erosion should be in the range of 0.1 to 0.3 N/m^2 for consolidated silt deposits (9). In this calibration procedure, a value of 0.2 N/m^2 was chosen. More accurate values can be obtained from flume tests using natural mud-samples taken from the channel bed.

The material constant, M1, should be in the range of 10^{-8} to 10^{-10} m/sec (9) depending on the type of bed material. Since the fall velocity (w_s) and the critical bed shear stress ($\tau_{cr,silt}$) are taken constant, the M1 constant can vary along the channel to cope with variations in fall velocity, critical shear stress, etc., i.e. errors made in the estimation of the fall velocity, critical bed shear stress and the hydraulic parameters will be represented by variation of the M1 constant, which is a basic feature of any model calibration.

Calibration is performed for the different zones of the eastern channel based on the calculated yearly average siltation height and the concentration of the suspended sediment. The values of the M1 constant for different zones are presented in Figure 1.

Figure 5 shows the siltation heights calculated from the model together with the siltation heights calculated from periodic surveys.

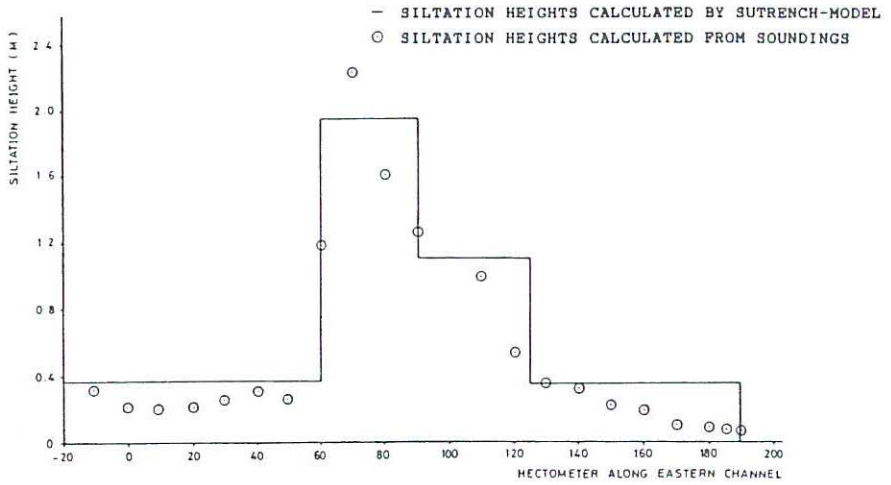

FIGURE 5 *Comparison between siltation heights calculated by the SUTRENCH-model and siltation heights from soundings*

5. Prediction of siltation rates for the development alternatives

After calibration, the SUTRENCH-model is applied for the prediction of the siltation rates in the eastern channel for the four development alternatives using pre-determined streamtubes covering the study area. The year is divided into two seasons each of six months. In order to predict the siltation rates in the eastern channel, the channel is divided into six representative zones. The choice of the representative zones is based on the expected trend of the siltation in the eastern channel. One cross-section is selected to represent each zone, and the siltation rate and height are assumed to be constant throughout the zone.

For each development alternative, there are six representative zones for summer and winter seasons. Thus forty eight different input data are prepared for the development alternatives.

The siltation rates in the eastern channel for the four development alternative schemes are predicted from the SUTRENCH-model as follows:

Alternative 1: 8.5 millions in-situ cubic meters per year;
Alternative 2: 9.0 millions in-situ cubic meters per year;
Alternative 3: 11.3 millions in-situ cubic meters per year;
Alternative 4: 13.2 millions in-situ cubic meters per year,

and may be compared to the 7 millions in-situ cubic meters per year for the present existing condition.

6. Senstivity analysis

A senstivity analysis was performed to determine the effect of the accuracy of the input data to the SUTRENCH-model (mud version). The senstivity of the model is first tested for the percentage increase in wave height. For the fourth development alternative, the wave heights are assumed to be 10% more than the present existing condition. To test the sensitivity of the SUTRENCH-model, a 20% increase in wave heights are considered. For a 10% increase in wave height for the fourth development alternative (20% increase in wave height than the existing condition) there is an increase in the siltation rate by 15%.

Secondly, the senstivity of Sutrench-model to deviation in channel dimensions due to dredging and/or survey tolerances, channel evolution and siltation is tested. The following results were obtained by considering a hypothetical channel cross-section:

- A decrease in the channel bottom depth from 20 m to 19 m resulted in a decrease of 5.8% in the sedimentation volume.
- An increase in the channel bottom depth from 20 m to 21 m resulted in an increase of 2.9% in the sedimentation volume.
- A decrease in the channel bottom width from 200 m to 150 m resulted in a decrease of 4% in the sedimentation volume.
- An increase in the channel bottom width from 200 m to 250 m resulted in an increase of 3.1% in the sedimentation volume.
- A decrease in the channel top width by 50 m by changing the channel side slope from 25:1 to 20:1 resulted in a decrease of 4.2% in the sedimentation volume.
- An increase in the channel top width by 50 m by changing the channel slope from 25:1 to 30:1 resulted in an increase of 4.8% in the sedimentation volume.

The above senstivity analysis shows that the SUTRENCH-model (mud version) is not sensitive to small and moderate deviation in the channel cross-section dimensions.

7. Conclusions

The SUTRENCH-model has been developed to simulate changes in the level of the sea bed (mud) of the Port Said area. The calibration of the SUTRENCH-model (mud version) is performed successfully for the present existing conditions (summer and winter) based on siltation heights calculated from periodic surveys. The calibrated model is applied for four development alternative schemes for the eastern approach channel after including the effect of the deepening and widening of the channel on the current and wave patterns, yielding siltation rates in the range of 8.5 to 13.2 millions in-situ cubic meters per year.

A senstivity analysis is performed for the SUTRENCH-model (mud version). The model is sensitive to variations in wave heights but not sensitive to small or moderate deviation in the channel cross-section dimensions.

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