CHAPTER 208

PREDICTION OF CURRENT AND SEDIMENT DEPOSITION PATTERNS IN PUERTO MIRANDA OIL TERMINAL USING 2-D MATHEMATICAL MODELS

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ABSTRACT

Puerto Miranda oil terminal, located in the Maracaibo Strait, Venezuela (see figures 1 and 2), is one of the main venezuelan oil industry loading facilities of crude oils. Ships access the terminal from the Gulf of Venezuela by a 40 km long, 300 m wide and 13.7 m depth main channel, which is periodically dredged in order to keep the design depth. A secondary channel leads from the main channel to the terminal itself (See figure 3). Over the last few years the increase in sedimentation rates in the secondary channel has motivated the need for studies that would determine alternatives to reduce dredging costs.

A previous work [0], based on the circulation and sedimentation patterns in the area under study, proposed the construction of a new access channel with a different orientation regarding the prevailing current direction, that would reduce the sedimentation rate and dredging frequency.

The venezuelan oil industry through its R & D filiate (INTEVEP), has developed a 2-D finite element mathematical model to simulate suspended sediment transport and a 2-D finite difference circulation model for coastal regions.

In this work, these models are applied to determine the evolution of the secondary old and new dredged access channels to Puerto Miranda oil terminal. Both models were calibrated and validated with field data and results are presented for the complex circulation and sedimentation patterns that occur in the area of Puerto Miranda terminal.

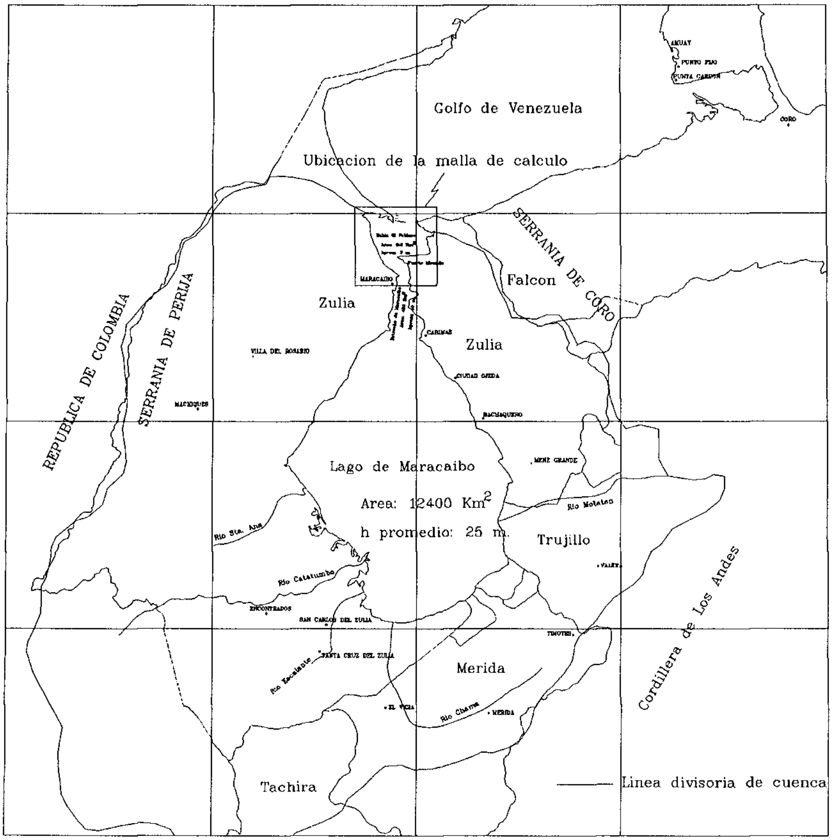

Figure 1.- Map indicating the North-Western Venezuela region. Box indicate study area.

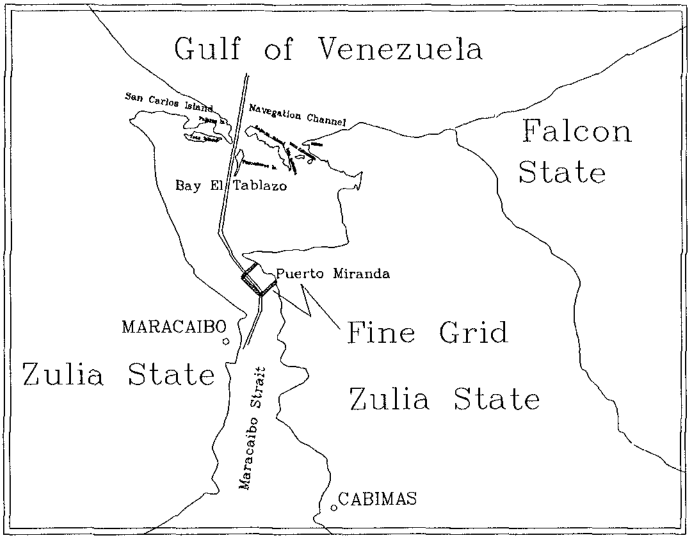

Figure 2.- Detail of study area.

CIRCULATION MODEL

The circulation model solves the Shallow-Water equations by the MacCormack finite difference scheme as implemented by García and Kahawita [2]. This explicit model has been previously applied to several river and coastal problems, and for this case has been calibrated and validated using field measurements including tidal elevations and velocities at various locations.

In order to resolve the complex circulation patterns that exist in the area, two finite difference grids are used. The first is formed by 250 x 250 m cells and covers a region that includes the El Tablazo bay and the Maracaibo Strait. This grid has 11,480 nodes for a total of 34,440 degrees of freedom, since two velocity componets and one tidal elevation is calculated for each node. The tidal elevations and velocities resulting from the simulations on this grid are then transfered to a finer grid composed of 50 x 50 m cells just arround the Puerto Miranda area. Results for each time step for several tidal cycles is recorded in a binary file for latter interfacing with the sediment transport model.

Figure 4 shows the comparison between the tidal gage and the model results for the week Apr-01-1989 to Apr-07-1989. These where obtained after adjusting the depth varying Manning coeficient until model results compared favorably with measurements. To investigate how the model performed for a different tidal period, the week of Nov-

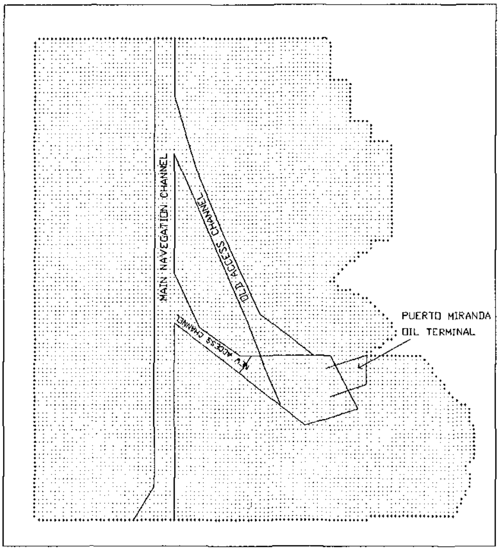

Figure 3.- Puerto Miranda oil terminal area showing the main navegation channel, the old access channel and the proposed or new channel. Points indicate fine grid where velocities are calculated.

08-1989 to Nov-14-1989 was chosen and the model was applied using the same Manning coefficients. As can be seen in figure 5 the model results reproduce correctly the tidal measurements.

Figure 6 and 7 present two flow fields for the fine grid arround Miranda terminal. It can be appreciated the occurrence of large scale eddies that have also been observed in the area.

SEDIMENT TRANSPORT MODELLING

Sediment transport modelling involves the process of advection, erosion and deposition.

For general flow conditions the suspendend sediment transport modelling can be formulated in terms of four partial differential equations. Two momentum equations and one consevation of water mass equation that forms the so-called Saint Venant equations, solved by the hydrodynamic model [2], and the two-dimensional (verticaly averaged) convection–dispersion sediment mass conservation equation that can be expresed in the following form:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = \frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(D_y\frac{\partial c}{\partial y}) + \frac{1}{h}S \qquad (1)$$

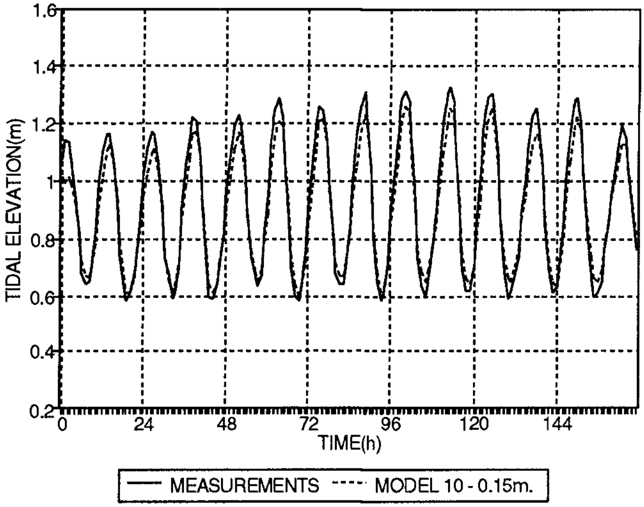

Figure 4.- Comparison of measured tidal elevations with model results (Apr-01-89 to Apr-07-89). Measurements taken from Punta de Palmas tidal gage at the entrance of Maracaibo Strait.

where $c(x,y,t)$ is the sediment concentration averaged along the vertical direction z, $u(x,y,t)$ is the mean flow velocity in the horizontal x direction, $v(x,y,t)$ is the mean flow velocity in the horizontal y direction, $h(x,y,t)$ is the flow depth, D_x and D_y are the turbulent dispersion coefficients in x and y directions respectively, and S is the source-sink term.

Equation (1) is obtained by integrating the three-dimensional convection-difussion equation along the vertical direction.

The source-sink term S takes into account the erosion and deposition processes. The vertical deposition is equal to $w\ \partial c/\partial z$, being w the sediment settling velocity which for fine particles is given by the Stokes law and c is the local concentration.

In this study we consider that the sediment concentration is zero at the free surface. In that case, integrating the vertical deposition term gives $w\ C_o$ where C_o is the sediment concentration in the bottom layer that will be taken proportional to the average vertical concentration. In this manner, the source term, corresponding to deposition, is proportional to the local bottom sediment concentration and to the settling velocity w. (See [1]).

The sink term, also called erosion or resuspension term, determines the remaining boundary condition to satisfy the equilibrium in the bottom layer. There are many for-

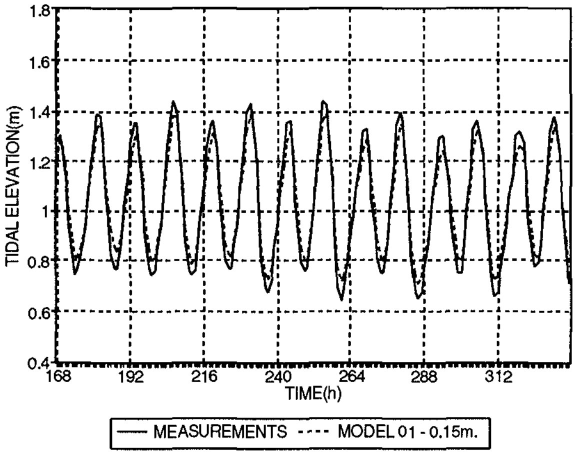

Figure 5.- Comparison of measured tidal elevations with model results (Nov-08-89 to Nov-15-89). Measurements taken from Punta de Palmas tidal gage at the entrance of Maracaibo Strait.

mulae available to represent this term that go from those obtained by semi-analytical methods through integration of the movement equations of the sediment particles to those obtained empirically. The analytical formulae usually come in terms of integrals that complicates the application of the mathematical model and do not give much better results for the extra effort required [4], [5]. On the other hand, the empirical formulations are given in terms of the flow variables and are generally of simple mathematical form giving reasonable results. In this work the formulation for the sink (erosion) term will be based on an empirical formulation proportional to the square of the velocity, $q^2 = u^2 + v^2$, and inversally proportional to the local flow depth h.

Using the source and sink term so defined, S can be written as:

$$S = \alpha \; w \; c - \beta \frac{q^2}{h} H(\frac{\tau_b}{\tau_c} - 1) \tag{2}$$

where α and β are proportionality factors, τ_b is the bottom surface shear stress, τ_c is the bottom surface critical shear stress for the iniciation of sediment movement which is determined by the Shields criterion [6]. $H(\tau_b/\tau_c - 1)$ is the Heaveside function defined as $H = 1$ for $\tau_b \geq \tau_c$ and $H = 0$ for $\tau_b < \tau_c$,

The bottom layer equilibrium equation expressed as:

$$(1 - p)\frac{\partial z}{\partial t} = S \tag{3}$$

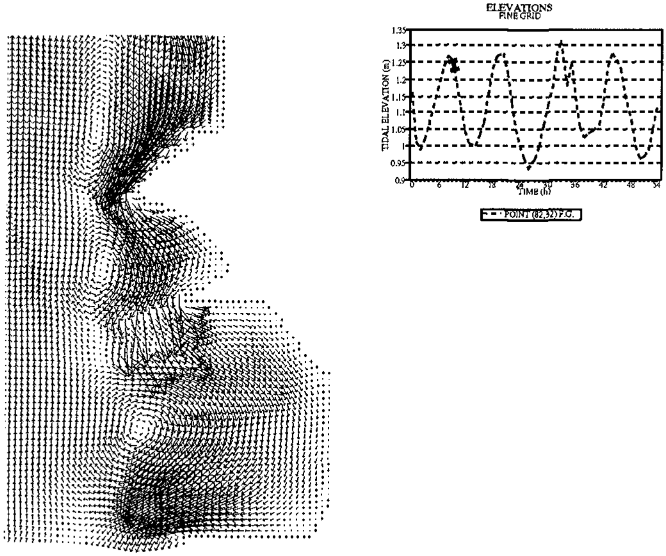

Figure 6.- Flow field in the Puerto Miranda terminal area for the tidal elevation at 9 hours shown in box.

defines the time evolution of the bottom elevation z, being p the porosity of the bed sediment.

Lin et al [1], make a mass balance in the bottom layer considering the layer thickness equal to two times the sediment diameter d and following Einstein sediment transport theory, obtain the following approximate relation for α and β in equation (2):

$$\alpha \approx \frac{1}{3}\left(\frac{h}{2d}\right)^{w/\psi k u^*} \qquad \text{and} \qquad \beta \approx \phi\,\alpha \tag{4}$$

wheree ψ and ϕ are empirical coefficients, $u^* = \sqrt{\tau_b/\rho}$ is the shear velocity in the bottom, ρ is the water density and $k = 0.40$ is the Von-Kármán constant in the logarithmic equation for the turbulent vertical velocity distribution.

Finally, the bottom layer equilibrium equation is expressed as:

$$\frac{\partial z}{\partial t} = \frac{1}{3}\left(\frac{h}{2d}\right)^{w/\psi k u^*} \frac{1}{(1-p)}\left[w\,c - \phi\,\frac{q^2}{h} H\left(\frac{\tau_b}{\tau_c} - 1\right)\right] \tag{5}$$

The parameter ϕ can be determined applying equation (5) in a bottom control point of the region where the erosion and deposition rates are equal (zone of no change in the bottom elevation $\partial z/\partial t = 0$). Applying this condition:

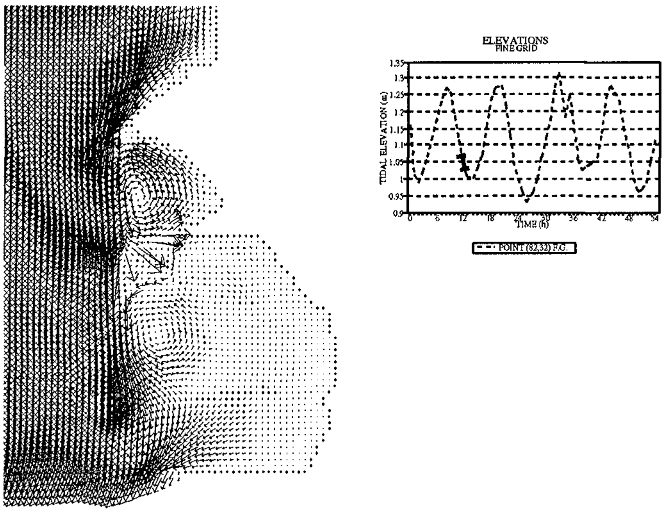

Figure 7.- Flow field in the Puerto Miranda terminal area for the tidal elevation at 12 hours shown in box.

$$\phi = \left(\frac{w\ c\ h}{q^2} \right) \tag{6}$$

In the model the bottom shear stress τ_b will be calculated by:

$$\tau_b = \frac{\rho\ g\ q^2}{C^2} \tag{7}$$

where g is the gravity acceleration and C is the Chezy coefficient that for turbulent flow can be expresed in terms of the Manning n as $C = h^{1/6}/n$.

Substituting equations (2,4,5,6 and 7) in equations (1) and (3) we obtain a system of two partial differential equations for $c(x,y,t)$ and $z(x,y,t)$ in terms of three parameters: D_x, D_y, ψ. These parameters have to be determined in the calibation process. The final system is given by:

$$\begin{aligned} \frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} &= \frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(D_y\frac{\partial c}{\partial y}) + \frac{1}{h}\ \alpha\ w\ c - \beta\frac{q^2}{h}H(\frac{\tau_b}{\tau_c} - 1) \\ (1-p)\frac{\partial z}{\partial t} &= \alpha\ w\ c - \beta\frac{q^2}{h}H(\frac{\tau_b}{\tau_c} - 1) \end{aligned} \tag{8}$$

with the corresponding expressions for the parameters given by equations: (4), (6) and (7).

The model described has three calibration parameters given by the two dispersion coefficients, D_x and D_y, and one of the erosion or deposition factors, α o β. This is possible since, given a fluvial control point where the bottom elevation is constant, then $\partial z/\partial t = 0$ and from equation (2) we obtain a relation between α and β.

Starting from a system equivalent to equations (5) and (8) but for one-dimensional problems, Lin et al [1] simulated the sediment transport of the Qiantang river in China. In that reference it is shown that with the preceding approximations, the suspended sediment discharge hydrogram can be accurately predicted for a series of tidal cycles.

In the present work, the two-dimensional system given by equations (5) and (8) that model the sediment transport of fine non-cohesive sediments was solved numerically by the *finite element method.* In any event, for the application of the model, the velocity and depth field is determined by the hydrodynamic model. Then, equation (8) is solved for the sediment concentration given proper initial and boundary conditions and the bottom elevation evolution is obtained applying equation (5).

The finite element mesh is composed of 750 cuadrileteral elements and is superimposed over the 50×50 m. finite difference grid in the area of the terminal. Since the nodes of the finite element mesh do not generally have corresponding nodes of the finite difference grid, interpolation of the velocity and tidal elevations is required.

The sediment model was calibrated comparing computed bottom elevations with a series of bathymetries available for the terminal zone. Two calibration paramenters where used to reproduce the field measurements. Figure 8 presents the bottom elevation results along a transversal section in the old access channel computed by the model together with the profile obtained from the bathymetries of November 1988 and May 1989. The results in figure 8 show that the model reproduces the evolution of the old access channel with adecuate resolution.

Once calibrated, the sediment model was used to predict the bottom evolution of the whole region. The results of this computations, shown in figure 9 indicate that the model correctly reproduces the bottom profile evolution in other areas.

CONCLUSIONS AND RECOMENDATIONS

In this work, a circulation model and a suspended sediment transport model have been applied to predict the velocity and sediment deposition in the area of Puerto Miranda oil terminal, located in the Maracaibo Strait, Venezuela.

Model results predict the evolution of the dredged access channels to the terminal. Both models were calibrated and validated with field data and results are presented for the complex circulation and sedimentation patterns that occur in the area of Puerto Miranda.

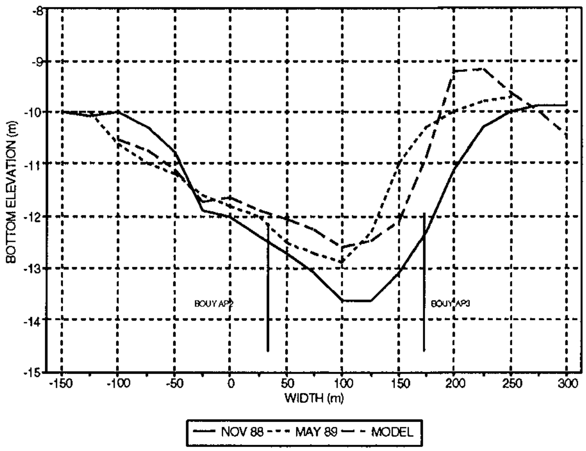

Figure 8.- Bottom elevation results along a cross section of the old access channel. Comparison of computed elevations with measured data.

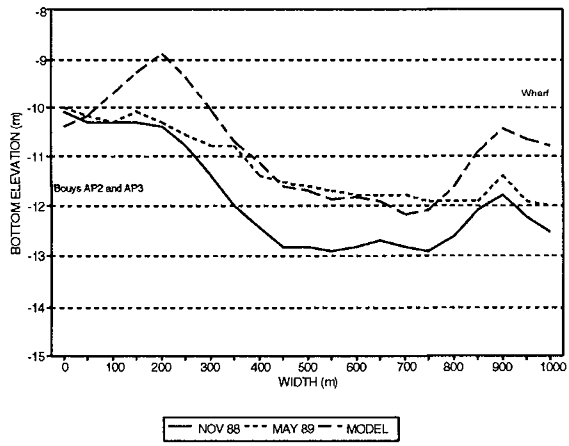

Figure 9.- Bottom elevation results along a cross section of the maneuvring zone. Comparison of computed elevations with measured data.

The proposed models correctly reproduce the measured bottom profile evolution. Field measurements of sediment fall velocity, vertical distribution of suspended sediment concentrations as well as bed load transport at various locations in the access channel and its surroundings are recommended in order to evaluate the importance of bed load sediment transport (not considered in this model) with respect to suspended sediment transport in the long range sedimentation process acting in Puerto Miranda.

REFERENCES

[0] COSA-Incostas **Evaluación del Problema de Sedimentación en la Rada y en Canal de Acceso de Puerto Miranda. Alternativa de Mejoramiento.** Caracas–Maracaibo, March, 1979.

[1] Lin, Pin-nam, Juqing Huan and Xinquen Li. **Unsteady Transport of Suspended Load at Small Concentrations**. ASCE H109, 1, 1983.

[2] García R. and Kahawita R. **Numerical Solution of the Saint Venant Equations by the MacCormack Finite-Difference Scheme.** Int. Journal for Num. Meth in Fluids. May, 1986.

[3] MacCormack, R. W. **The effect of viscosity in hypervelocity impact cratering.** AIAA paper 69-354 (1969)

[4] Murphy, Peter J. **Equilibrium Boundary Conditions for Suspension**. Journal of Hydraulics, ASCE H111, 1, 1985.

[5] Tsujimoto, Tetsuro and Tatsuo Yamamoto. **Sediment Suspension Affected by Transition from Bed-Load Motion into Suspension**. J. Hydroscience and Hyd. Eng. Vol. 6, No. 1, 1988.

[6] Shields, I.A. **Application of Similarity Principles and Turbulence Research to Bed-Load Movement**. U.S. Soil Conserv. Serv. Coop. Lab. California Institute of Technology, Pasadena, California, 1936.

[7] Zienkiewicz, O.C. **The Finite Element Method in Engineering Science.** MacGraw Hill. London Publication, 1971.